

Evaluating localised ventilation improvements on deep-level mines using simulation models

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ABSTRACT

Title: Evaluating localised ventilation improvements on deep-level mines using simulation models

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The ventilation system of a mine is responsible for providing sufficient airflow in terms of quantity and quality. To ensure a safe and healthy environment, the main fans dilute and exhaust poisonous gases and dust throughout the mine. Due to the mine's vast networks and depths, the ventilation system is challenging to manage and considerable time is spent investigating and identifying ventilation inefficiencies.

The objectives of this study focused on developing a methodology that would identify ventilation problems on a localised ventilation network. The ventilation inefficiencies were mitigated through a simulation model. The localised network made it easier and less time-consuming to investigate, analyse and implement ventilation improvements. The methodology consisted of three phases, namely: Phase 1) identifying localised ventilation problems; Phase 2) building and verifying the simulation model; and Phase 3) implementing an optimised solution.

At first, it was necessary to understand the mining network of the case study. In the case study, there were ventilation concerns regarding one particular level of the mine, which required further investigations. Key performance indicators and measurement locations were identified before a ventilation audit was conducted. These parameters and locations ensured that adequate data would

be obtained for the baseline conditions and simulation model. After the ventilation audit, the data was analysed and restrictions, which largely influenced the airflow measurements, were noted. Assumptions were made to establish the final actual baseline conditions. From the actual baseline conditions, inefficiencies such as high temperatures and low to no airflow were recorded at the workshop area of the affected level.

A simulation model was built in Process Toolbox 3D using all the information and data obtained. A discrepancy of 4% occurred between the simulation model and actual baseline conditions after verification and calibration. Three scenarios were simulated during which the ventilation inefficiencies of the level were mitigated and different ventilation plans were introduced to improve the conditions.

After simulation, Scenario 3 was selected as the most feasible solution, which was implemented with no additional electricity costs added to the ventilation system. The scenario was validated by repeating the audit on the level. During the audit, the conditions proposed by Scenario 3 differed from the actual conditions due to a constructed wall leaking air and a fan being switched off. As a result, the validation of the air mass flow had a defect of 22.64%. The simulation model was adjusted through mass balancing to align with the conditions recorded during the audit. Subsequently, a defect of 0.08% was achieved for the average air mass flow through the workshop area. The actual average air mass flow recorded through the workshop area increased with 21.47 kg/s. The temperature recorded had a defect of 1.01% and 1.83% for the wet-bulb and dry-bulb temperatures, respectively. The actual average wet-bulb temperature over the workshop area decreased with 1.16°C. Thus, the overall percentage error determined for the entire system between the simulation model and actual results was 0.98%, which indicates the accuracy of the simulation model. Thus, all the objectives for this study were met.

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LIST OF ABBREVIATIONS

3D	Three-dimensional
KPI	Key Performance Indicator
PTB 3D	Process Toolbox
RAW	Return Airway
VRT	Virgin Rock Temperature
VUMA	Ventilation of Underground Mine Atmospheres
X/Cut	Cross-cut

LIST OF SYMBOLS

Symbols	Description	Units
T_{wb}	Wet-bulb temperature	$^{\circ}\text{C}$
T_{db}	Dry-bulb temperature	$^{\circ}\text{C}$
V	Air velocity	m/s
Q	Volumetric airflow	m^3/s
$\dot{m}$	Air mass flow	kg/s
P_{ba}	Barometric pressure	kPa
P_s	Static pressure	kPa
H	Height	m
W	Width	m
D	Diameter	m
A_{cs}	Cross-sectional area	m^2
ρ_{air}	Air density	kg/m^3

CHAPTER 1

1 INTRODUCTION AND BACKGROUND

1.1 Background

The mining industry consumes a significant amount of energy. Gold and platinum mines are responsible for consuming 47% and 33% of the energy, respectively, making the gold mining sector the most energy intensive mining sector in South Africa. The remainder of the energy (20%) is consumed by other mines, such as coal, zinc and copper mines [1].

The gold mining industry has expanded and reached depths up to 4 kilometres. As the mines get deeper, large amounts of ground are blasted and excavated, which need to be transported and processed. This vast industry demands large amounts of electrical energy, which enables them to comply with all their processes; thus, it is crucial to use electrical energy efficiently [2]. Considering the ventilation network of a mine, which mainly comprises ventilation fans, the total amount of energy consumed could be between 25% and 50% of the total electrical energy consumed by the mine. The potential exists to save on electrical costs by using different optimisation methods [3], [4].

The primary purpose of a mine's ventilation network is to ensure that the conditions for underground workings are safe and healthy [5]. The ventilation network of a mine addresses two factors, namely supplying health, safety and comfort, and addressing economic constraints. Ventilation throughout the mine could be excessive or insufficient, which has a direct influence on the productivity of mineworkers, gold production and electrical consumption [5].

Short-circuits or leakages are responsible for ventilation inefficiencies. Minimising the occurrence thereof contributes to an optimised ventilation system. Comfortable working conditions and a more economically feasible system are created by ensuring that the ventilation network of a mine supplies sufficient airflow to all working areas according to regulation [5].

1.2 Deep-level mine ventilation systems and components

It is crucial to be familiar with the operation of the ventilation system and its components. Acceptable ventilation conditions and limits are important factors that should be understood. This section describes a ventilation network, provides the acceptable ventilation conditions and different air velocity limits, and discusses the different ventilation control components.

1.2.1 Ventilation network in deep-level mines

A ventilation network is a complex system that consists of hundreds of connected airways, called haulages. The airways are further divided into branches, called cross-cuts [4]. There are various applications in different sections of a ventilation network, such as fans, stoppings, regulators and doors [4], [6]. Figure 1-1 represents a ventilation circuit of a deep-level mine.

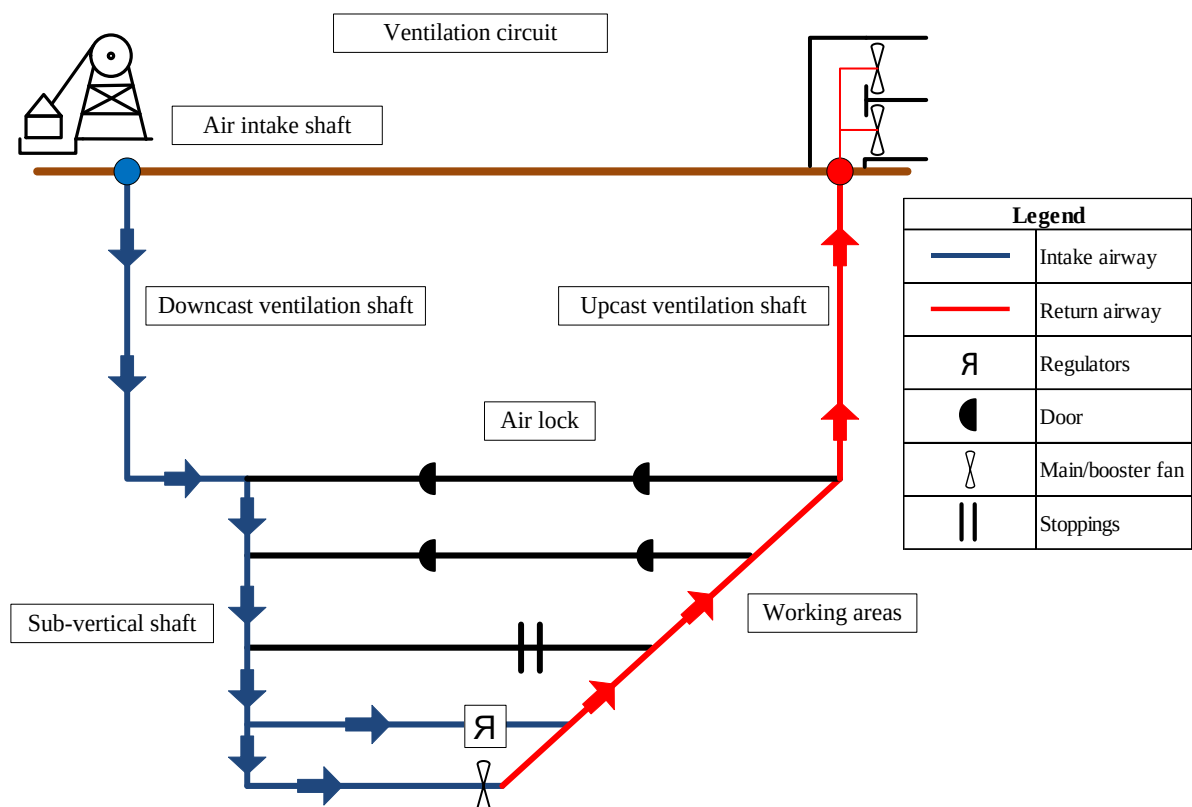


Figure 1-1: Deep-level mine ventilation circuit [6]

Fresh air enters the mine from the surface through the downcast shaft or any other connected airway. The air flows through all the intake airways to the active working areas, which contain pollutants such as dust, flammable gases or toxic gases. Hazards also exist in the form of heat, radiation and high humidity, which must also be removed by the air flowing through the area. This hot contaminated air flows through to the return airway (RAW) and is extracted from the mine. The main fans on surface extract the return air through an upcast shaft [6]. The amount of contaminated air must never exceed the regulations provided by the Mine Ventilation Society of South Africa. All the airways, including RAWs, must always be safe to enter [6].

If excessive air is recorded in a specific area, regulators are installed to reduce the quantity of air. Conversely, if insufficient airflow is recorded in a specific area, booster fans are usually installed [6]. Fans with ventilation ducting are also used for auxiliary ventilation purposes. These are mostly required at tips, shaft loading boxes, developing ends and hoist chambers [6]. The working areas must receive adequate air volumes. It is necessary to seal inactive areas and travel ways to prevent the air from being wasted and not reaching the required areas. The air will bypass all the active working panels if the air is not controlled since air follows the path of least resistance [7].

1.2.2 Acceptable mine ventilation conditions and limits

In the South African mining industry, two important factors affect mine ventilation operations, namely air-cooling power, which is the heat transferred from a person to the environment, [8] and wet-bulb temperature (T_{wb}) [9]. Table 1-1 represents the acceptable ventilation conditions and limits for a ventilation network [9]-[15].

Table 1-1: Acceptable ventilation conditions and limits

Acceptable ventilation conditions and limits	
Wet-bulb temperature	$\leq 32.5^{\circ}\text{C}$
Dry-bulb temperature	$\leq 37^{\circ}\text{C}$
Air mass flow	3.5–5 kg/s
Air volumetric flow (average)	4 m ³ /s
Air-cooling power	300 W/m ²

Regulations specify that mining activities may not proceed when the dry-bulb temperature exceeds 37°C or when the wet-bulb temperature exceeds 32.5°C [10], [11]. However, a minimum air-

cooling power of 300 W/m² is acceptable in an underground working environment [11]-[13]. Velocities (v_a) and wet-bulb temperatures are considered when determining air-cooling power per working area. A general guideline is to use a ventilation mass flow of 3.5 kg/s per kilotonne of rock hoisted for shallow mines and 5 kg/s per kilotonne of rock hoisted for deeper mines [14]. A sufficient average volumetric flow rate for productive operations is 4 m³/s per kilotonne per month [15].

If a mine does not comply with the conditions and legal limits described in Table 1-1, it must stop mining activities in the sections where the legal limits are exceeded. Therefore, mining operations will be inefficient if a mine struggles to comply with these limits and conditions.

1.2.3 Underground air velocity limits

The amount of air volume flow is important when it comes to the dilution of pollutants. The velocity of air is a good indication of whether the regulations given in Table 1-1 are met. When air velocities are too high, it brings discomfort to mine personnel and could exacerbate dust problems. Inefficient air velocity results in excessive ventilation costs [16].

Both maximum and minimum air velocity limits are mandated by regulating prescribed airways. The lower air velocity limit is 0.3 m/s where mine personnel travel and where mineworks are, which is hardly noticeable [16]. At working faces, an air velocity between 1 m/s and 3 m/s is preferred. If the velocity exceeds 4 m/s, mineworkers may experience discomfort [16]. Table 1-2 provides all the upper boundary air velocities that are recommended for an underground ventilation network [16].

Table 1-2: Upper boundary recommended air velocities [16]

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

If the air velocity is between 7 m/s and 12 m/s, water blanketing could occur in wet upcast shafts, which results in airborne droplets that form due to water emissions or condensation [16]. Any variation of shaft resistance creates an oscillating load on the surface fans. This can lead to large irregular water cascades which then fall to the bottom of the shaft [16].

1.2.4 Ventilation control components

Ventilation components are used to direct air effectively into workplaces to ensure satisfactory environmental conditions. These ventilation components are included in Table 1-3.

Table 1-3: Ventilation control components

Component	Description
Primary or main fans	Two to three fans are installed on the surface and form part of the upcast shaft. These could be axial or centrifugal fans, which handle large quantities of air. Usually, the bulk of air that passes through a mine is extracted through these fans, creating large pressure differences in the system [17]. ¹ Approximately 1–4 MW duty.
Booster fans	Booster fans are mainly installed at selected and specific areas underground. Their purpose is to support the main surface fans to overcome additional pressure loss wherever an increased resistance in the ventilation system occurred [17]. ¹ Approximately 50–75 kW duty.
Auxiliary fans	Auxiliary fans are usually axial flow fans that are used to ventilate workplaces, dead ends, stopes, development ends, dams, pump chambers, filter units, stores, underground workshops and cooling coils [17]. ¹ Approximately 4–45 kW duty.
Ventilation doors	The main purpose of a ventilation door is to create an airlock that prevents air flowing to workplaces. The doors allow mineworkers to travel and transport to pass through [7]. ¹
Pressure-release flaps	Pressure-release flaps must be installed on every ventilation door to equalise the pressure across a door. The release flaps need to be large enough so that equalisation happens quickly, which makes it easier for miners to open the door when travelling. ¹
Water traps	Water traps are designed for water to flow through the airlock (ventilation door) without any air leaking through. It is based on the same principle as the vertical manometer. The pressure loss across the door is portrayed through the water level of the water trap. ¹

¹ WorkSafe New Zealand, “Approved code of practice: Ventilation in underground mines and tunnels,” February 2014. [Online]. Available: <https://worksafe.govt.nz/dmsdocument/140-acop-ventilation-in-underground-mines-and-tunnels> [Accessed: 22 November 2018].

Component	Description
Stoppings or seals	Stoppings or seals are installed to block air completely. There are two categories, namely temporary and permanent stoppings. Temporary stoppings are mainly used for ventilation testing if any ventilation changeover is needed. Materials, such as conveyor belts or brattice sheeting, cover a timber frame. These are easy to remove when the temporary stopping is no longer needed [6]. ¹ Permanent stoppings are solid walls built using vermiculite, concrete, or concrete bricks after a ventilation changeover has been completed [6]. ¹
Regulators	Regulators are designed to regulate the amount of air flowing through a stopping. It is an opening or hole that allows enough air to flow through to a specific area. This increases the resistance of the airway and decreases the air quantity [6]. ¹
Brattices or tubing	Brattices are made of conveyor belts and strips. They are hung from a wooden frame in travelling gullies and centre gullies, which prevents intake air from travelling past the working faces and straight to the RAW. The wooden frame used to hang the conveyor belts is big enough for mineworkers and material to travel through. The outside of the frame is sealed adequately with suitable material, leaving the hanging conveyor strips open for any damage done by mineworkers and mining activities. Damaged material is easy to replace [7]. ¹
Air crossings	Air crossings are used to cross intake airways and RAWs without mixing them. If the airways require mixing, the air crossing must be controlled [6]. ¹

Table 1-3 summarised the ventilation components that play an important part in directing air in a mine. Each component has its own function: they either operate on their own or they depend on one another to achieve a specific goal together. Therefore, it is important to understand how the ventilation components work when analysing a ventilation system.

This section provided background on how energy intensive the mining sector is. The section further discussed the vastness and complexity of a ventilation network with its different components, conditions and legal limits. The mine environment was described, which leads to the following section that simulates and presents ventilation systems digitally. The new industrial era allows the mining industry to simulate and make digital changes to its ventilation network. These simulations allow informed decisions to be made by illustrating different outcomes without changing the actual ventilation network.

1.3 Simulation models in industry

1.3.1 Simulation background

Literature suggests that simulation models are the only software that can evaluate a complex system thoroughly [18]-[20]. The digital age has grown over the past years and simulation software has been incorporated into the mining sector to simulate large ventilation networks [3]. Simulation software requires numerous inputs and information to produce accurate results, which are labour and time intensive [21].

Recent studies have addressed the techniques for optimising and modelling mine ventilation sections or localised ventilation networks [3], [19]. Acuña and Lowndes concluded that there is still a shortcoming regarding the effect of both service delivery and costs in optimisation techniques for ventilation networks [19]. Not only are these techniques used in industry not integrated with simulation software, but they also use tedious manual calculations [19]. The techniques do not fully consider the effect of operational changes but rather only consider a single service delivery evaluation [18].

Panigrahi and Mishra used computation fluid dynamics simulations to optimise the blade profiles of an axial flow fan [22]. Their method is promising and further research on axial and centrifugal ventilation fans should be put forth. However, this method is mostly used for, and limited to component design; therefore, it would not be possible to use their method to optimise a ventilation network.

Chatterjee and Xia developed and optimised a ventilation-on-demand simulation model. Their method only supplied sufficient airflow to the mining areas, which minimised ventilation operating costs [23]. The optimal fan speed was set hourly for each day by using the time-of-use electricity tariffs [10]. Although the model is well-formulated, further research is necessary on ventilation-on-demand methods. Further research will allow the optimisation of the network and techniques addressing different network problems to be combined, which will result in an integrated solution.

The mining industry uses a broad range of ventilation simulation packages for doing design and mine planning [19]. Most simulation packages are not used for evaluation or optimisation purposes and mines in the private sector do not use these packages for any operational change simulations [10], [19], [24]. Mines implement operational changes to go forth with development, but do not

include ventilation planning. Operations are only stopped when legal conditions are not met or if accidents occur [19]. Evaluation and optimisation of operational changes through ventilation simulation are therefore needed in the mining industry.

Ventilation simulation packages used in the 1960s were based on Newton's incompressible flow law [24]. These simulation packages are outdated and are unable to work with the different air densities that vary underground. Mine ventilation software started to evolve in the 1970s when thermodynamic principles and relationships were included [24]. The development in the early stages formed the basis of the new era of ventilation simulations. These simulations use fluid dynamic and thermodynamic principles as well as mass balances to simulate the actual mine ventilation networks accurately [18], [19], [24].

1.3.2 Current ventilation simulation packages

Mines have vast underground systems and networks with a significant amount of data that needs to be processed by specialised computer software and technologies [25]. A ventilation network is divided into vertical and horizontal expanding. Vertical expanding includes the main shaft and sub-shaft of the network. Horizontal expanding consists of interconnected nodes and branches that can reach up to tens of kilometres: crossing galleries, diagonal galleries and directional galleries [25], [26].

Simulation software makes it possible to solve these complex ventilation networks [27], [28]. The purpose of ventilation simulation packages is to achieve optimal airflow throughout the individual levels of a ventilation network [25]. Different simulation software packages are available for mine ventilation networks. These packages have evolved and developed tremendously over the past years. It is important to choose a cost-effective and flexible simulation package that will be suitable for addressing the inefficiencies and problems of a specific ventilation network [18], [25].

The following simulation software packages will be discussed, whereafter the most applicable package will be chosen for this study:

- Process Toolbox (PTB 3D) [29]-[32].
- VentSim [25], [33].
- Environ [32], [34].
- Ventilation of Underground Mine Atmospheres (VUMA) [35].

PTB 3D simulation software

PTB 3D is a dynamic simulation software package with thermal-hydraulic principles [32]. The graphical interface allows the user to view the model in three dimensions, which gives an optimal understanding of the mine workings. The simulation software is used to simulate different mine operations and systems such as compressed air, dewatering, refrigeration and ventilation systems [32]. PTB 3D further allows the user to build an integrated mine system that can simulate and present all operating systems simultaneously. The user can import DXF² files of mine layouts, which provide coordinates.

The simulation software has various capabilities that enable the user to determine the optimal operation of equipment and potential cost saving initiatives of load management. PTB 3D allows the user to optimise, analyse and design the performances of the different mine systems [32]. The PTB 3D graphical user interface makes it easy to drag and drop different system components [32]. Each system consists of components such as pipes, pumps, fridge plants, compressors, fans, tunnels and nodes. These components are built according to a preferred model to represent a mine network that can be used to calculate thermal-hydraulic properties and flow of fluids [32].

The accuracy of PTB simulation software has been proven by previous refrigeration system studies done by Oberholzer [29], Vermeulen [30], Maré [31] and Peach [32]. Case studies were simulated and the results obtained were compared with the actual results, which corresponded accurately.

VentSim

VentSim allows the user to import mine layouts with coordinates in DXF format. A full 3D mine network can be built with the required inputs, which serves the purpose of viewing and altering the mine network in a simulation model. The ventilation network is characterised through a list of inputs with different applications [25], [33]. The main purpose of VentSim is to simulate ventilation for a more complex system. The software cannot account for the influence of other systems, which is a disadvantage if various mine system changes have to be solved simultaneously. VentSim auxiliary ventilation systems are unable to perform a realistic simulation, which leads to inaccurate results [33].

² Graphic image format used with AutoCAD software.

VUMA

VUMA simulation software assists mine personnel with designing, planning and operating their mine ventilation network [35]. The simulation software is interactive and simultaneously simulates the air thermodynamic behaviour of gas, airflow and dust emissions in an underground network [34], [35].

The following design criteria were mainly used in VUMA development [35]:

- Developed and designed for the mining industry.
- Usable across all Windows platforms.
- Incorporates the majority of mining methods.
- Interactive and simultaneous simulation of the air thermodynamic behaviour of gas, airflow and contaminants in a ventilation network.

VUMA requires a large amount of input data to deliver an optimised ventilation or refrigeration network with accurate results and solutions [32], [35]. Experienced personnel are required to operate the software and built the simulation model [32], [35].

Environ

Environ simulation software is one of the most commonly used packages in the mining industry [34]. Environ is used for designing mine systems and simulating and solving airflow ventilation strategies underground. The simulation software is not dynamic and it cannot be used to integrate different systems [32], [34].

Comparison of simulation software packages

The mentioned simulation software packages were tested on a mine. The advantages and disadvantages were evaluated and are listed in Table 1-4.

Table 1-4: Evaluation of different simulation software packages

Simulation software	Advantages	Disadvantages
PTB 3D	• User friendly and graphical interface capabilities. • Cost savings can be calculated. • Results are simulated accurately. • System optimisation and optimal operating points can be determined.	• Large amount of data required for accurate simulation and results.
VentSim	• New ventilation network designs and proposals can be simulated. • Different systems, such as auxiliary ventilation systems, can be simulated.	• Difficult to simulate complicated networks.
VUMA	• Simulations can be done simultaneously. • Underground thermodynamic properties can be analysed.	• Large amount of data required for accurate simulation and results. • Experienced personnel required to operate the software.
ENVIRON	• New ventilation networks design and proposals can be simulated. • Auxiliary systems can be simulated.	• Lacks integration.

After evaluating the different simulation packages and summarising the advantages and disadvantages in Table 1-4, PTB 3D is considered the most suitable simulation package for the purpose as it is user friendly and will provide accurate results. However, the other simulation packages could also be considered suitable for the purpose of this study.

1.4 Previous studies

Numerous studies on mine ventilation systems and simulation modelling were found while doing research for this study. The main reason for analysing the following 6 studies were due to their specific focus on mine ventilation and the use of simulation software. The information and literature obtained from these studies provided a thorough understanding and background on which this study is based on.

Study 1 – The use of 3D simulation system in mine ventilation management [28]

Authors: F. Wei, Z. Fangping, and L. Huiqing

Overview and objectives

This study used a 3D simulation model, namely VentSim, to solve high resistances in laneways and high fan air pressures. Three mining areas shared the same return shaft and this complex ventilation system was also used in simulation software for ventilation management.

Outcomes

To simulate and apply ventilation management strategies, laneways were measured underground and data processing was done. The construction of the simulation model required DXF layouts that were imported into the VentSim 3D software. Thereafter, laneways were constructed and each node was assigned elevation. The data obtained was used as inputs for the simulation model. The current situation was simulated to verify that the data was accurate. The simulation model was used to reduce the resistance of certain laneways, which reduced the overall system resistance, which in turn lowered the fan pressures and consumption. The model was used for management purposes as well; for instance, how to make emergency rescues by simulating contaminants.

Shortcomings

The study focused on reducing resistances of laneways and did not verify whether suitable temperatures were met. The project was only simulated and not implemented. No actual results were recorded to validate the simulation model.

Study 2 – Improving the operational efficiency of deep-level mine ventilation systems [7]

Author: SW Hancock

Overview and objectives

In this study, a series of ventilation inefficiencies were identified, such as inactive working areas that received ventilation. Auxiliary ventilation components were used to direct the air to active working areas. The ventilation system was built and simulated in PTB 3D. The results delivered better air power and surface fan performance and decreased the system resistance.

Outcomes

A generic solution methodology was developed to identify ventilation network inefficiencies. Data and measurements were needed to build and develop a simulation model for verification. After an inefficiency was identified, a solution strategy was implemented. The results were evaluated and validated through the simulation model. The ventilation network was optimised by increasing air power and surface fan efficiency, which decreased system resistance.

Shortcomings

A simulation model with more detail for ventilation auxiliaries and the model structure would make decision-making easier and results more accurate. However, such a model requires more data input.

Study 3 – Mine ventilation characterisation through simulation [36]

Author: AJH Nel

Overview and objectives

The study used simulation software packages to characterise mine ventilation systems, which improved its operational efficiencies and decision-making.

Outcomes

The ventilation system was evaluated through simulation packages, which improved decision-making capabilities, operational efficiencies and profitability. The simulation model was used to quantify the financial impact on energy projects. To achieve the most feasible method, the author integrated different simulation planning procedures that involved evaluating, selecting and implementing the primary ventilation network. Ventilation on demand was also developed through medium-voltage variable speed drives.

Shortcomings

The methods applied to the ventilation systems were based on theoretical applications and numerical procedures. Actual results of the ventilation system could not be validated as the system was not implemented.

Study 4 – Ventilation surveys and modelling: Execution and suggested outputs [21]

Author: JA Rowland

Overview and objectives

This study focused on the method and level of survey detail. The challenge was to determine the level of survey required to make appropriate changes to the simulation model or to determine the appropriate amount of data collected for the new model that had to be built. Ventilation personnel should consider report outputs to understand their ventilation system in order to prepare for or manage changes that occur.

Outcomes

At first, the study determined the survey scope because the client did not know what information was required to build the simulation model. Thereafter, a detailed survey planning was done, which included determining airflow directions and identifying obstructions, station locations and any other activities found on a level or section of the mine.

On the day of the survey, the execution of the survey was discussed, and items were checked against a checklist to ensure that everything was in order before conducting the survey. Any new information of any kind was marked on the layout during the survey, and the results were noted. The results were used to build easy understandable reports. The ventilation model was constructed using the survey data, which was used in the report to display airflow and pressure to demonstrate the validity against the assembled schematic. The model showed the simulated values of the problem and proposed new improvements to address any issues. Mine site personnel were assisted until the process was adopted and they could take full control of their ventilation system.

Shortcomings

The study was not applied to an actual case study; therefore, any difficulties or inefficiencies regarding the process could not be identified. As a result, it is unknown what the response would have been if a particular problem occurred.

Study 5 – Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff [10]

Authors: A. Chatterjee, L. Zhang, and X. Xia

Overview and objectives

This study investigated the potential of applying actual energy savings and energy cost savings to the mining industry by implementing variable speed drives on ventilation fans. The study also focused on ventilation on demand where airflow was controlled or adjusted according to the demand during the day with time-of-use tariffs as basis. Demand-side management initiatives, such as load management and energy efficiencies, were applied. Various theories and laws were used to model the network.

Outcomes

The problem formulation was divided into two different categories, namely energy efficiency and load management. Implementing energy efficiency was achieved by adjusting the speed of the fans according to varying airflow demand throughout the day. Load management was applied by finding the optimal starting time based on the mining schedule, which was optimised according to the time-of-use tariffs.

The study was based on two case studies. The active areas were identified and a ventilation network was modelled using Kirchhoff's laws and Tellegen's theorem to achieve energy efficiency. The complex ventilation network was presented as a simple network to understand the principles and network better. Fan laws were adhered to throughout the study. The study showed that significant savings could be achieved when energy efficiency and energy cost saving methods were applied to ventilation fans.

Shortcomings

The methods were based on a model built from laws and theories. The case studies were only investigated and not implemented; therefore, the results and model were not validated.

Study 6 – Advanced software for mine ventilation networks solving [25]

Authors: M. Suvar, D. Cioclea, I. Gherghe, and V. Pasculescu

Overview and objectives

The study supported the importance and use of simulation software in the industrial industry, especially mining. Solving underground ventilation systems is too complex and cannot be done manually; therefore, ventilation software is needed to help with planning, developing and decision-making.

Outcomes

The study used VentSim simulation software. Its technical characteristics and the method for constructing a simulation model for a mine were described. A case study was used to show the complexity of such a network, which supported the use of simulation models. The method was summarised into two main steps: The first step was the data collection phase, which involved obtaining layouts, airflow directions, measurements and a level understanding. The second step was the engineering phase, which entailed using collected data for analysis, calculations, solving, modelling and simulating. The model helped to increase safety and decision-making, and optimised airflow through levels.

Shortcomings

Although the method was described in detail, the study did not discuss the results and difficulties. The simulation model was not verified and validated. Therefore, the accuracy of the simulation model and whether requirements were met are unknown.

Comparison of previous research

Various studies were performed, each with different objectives and outcomes. These studies were mostly based on improving ventilation using various techniques and methods. Table 1-5 summarises the studies discussed. The aim is to compare and evaluate the focus of each study. This highlights the need for this study and its different outcomes.

Table 1-5: Summary and comparison of previous studies

Criteria	Study 1	Study 2	Study 3	Study 4	Study 5	Study 6
Improving operational efficiency using a simulation model.	x	x	x	x		x

Criteria	Study 1	Study 2	Study 3	Study 4	Study 5	Study 6
Improving operational efficiency using theoretical principles.			x		x	
Optimising fan and underground ventilation.		x			x	
Applying energy cost savings and energy efficiency initiatives on ventilation systems.			x		x	
Surveying scope and method for simulation inputs.	x			x		x
Evaluating localised ventilation improvements on deep-level mines using simulation models.						

Most studies are based on improving operational efficiency through simulations. Verification is mostly done using simulation models, which are validated after implementation. This simulation and verification strategy is, therefore, a reliable method that can be performed to ensure that results are obtained successfully and can be explained fully. Although most of these studies demonstrate similar ventilation improvements on deep-level mines using simulation models, no studies were found that focused on localised methods to improve ventilation systems, thus supporting the need for this study.

1.5 Problem statement and objective of this study

1.5.1 Problem statement

Mine ventilation systems play a vital role in health and safety, mine production and the productivity of each worker underground. Without any form of ventilation, mines would cease to exist. A ventilation system described by Wallace, Prosser and Stinnette, is responsible for providing sufficient airflow in terms of quantity and quality. The system dilutes and exhausts poisonous gases and dust throughout the mine environment where mineworkers and personnel are required to travel and work [37].

Mines are becoming deeper and, as a result, have vast ventilation networks that are becoming more difficult to manage. Various factors and systems contribute to high temperatures and the exposure of dangerous gases, which increase temperatures, decrease production and escalate health and safety risks. However, it is not easy to adhere to ventilation regulations when considering an entire mine. The mine environment changes over time as it develops and expands continuously, thereby making it difficult for specific systems, such as ventilation, to adapt to its structural environment.

Every change and development in new areas increase resistance to the entire system and influence ventilation somewhere else.

It is a time-consuming process to investigate and understand a mine ventilation system. When a ventilation system is viewed in its entirety, problem areas are difficult to solve. A global network has to be subdivided into a localised ventilation network, which makes it easier to manage and mitigate all ventilation inefficiencies. The methodology must, therefore, capture the necessary data to build a simulation model, which mitigates the inefficiencies and supplies different ventilation improvements for the localised ventilation network.

1.5.2 Need and objective of this study

The need for the study is to build a localised simulation model of a problem area to mitigate ventilation inefficiencies and improve the ventilation conditions. A localised ventilation simulation model is simple to build and calibrate. Different scenarios must be simulated and presented, which can be done in a shorter period due to a localised network being used.

The objectives for this study are based on localised ventilation systems of deep-level gold mines. The following objectives are set to be accomplished in this study:

- Identify ventilation problem areas or local inefficiencies in a mine environment by using acceptable mine ventilation conditions and limits as guidelines.
- Develop a methodology to record accurate data that will be used to build a ventilation simulation model and to verify the findings.
- Simulate different ventilation improvements and scenarios using the simulation model and select the best possible solution.
- Implement the optimised ventilation improvement and validate the results.

1.6 Overview of the study

Chapter 1: Introduction and background

The introduction and background provided an overview of mine ventilation principles and systems, and the different challenges and changes that occur in the ventilation sector of the mine environment. The importance of underground ventilation was discussed. Different studies that

were implemented previously were analysed to provide insightful and applicable information. The shortcomings of these studies were highlighted and could benefit the outcome of this study.

Using the findings and literature of previous studies and investigations, a problem statement and need for the study were compiled. The objectives of this study were generated.

Chapter 2: Method for evaluating ventilation improvements

In the research methodology, the general engineering process is used to develop a method that identifies ventilation improvements on a localised scale of a mine. These improvements are developed and optimised through a simulation model that can be implemented.

Chapter 3: Implementing localised ventilation improvements

The method developed in Chapter 2 is applied to an actual case study. The ventilation improvements identified and evaluated in the case study are simulated and verified in the model, which provide a series of solutions. These solutions are optimised and the most feasible solution is chosen for implementation. To ensure that each objective is completed, the new ventilation improvements are validated and explained.

Chapter 4: Conclusion and recommendation

The results and outcomes of the ventilation improvements of the case study are summarised and compared with the objectives of this study. The main conclusion is formulated using all the findings that were recorded. This chapter concludes with a recommendation, which is discussed for any further studies.

1.7 Summary

This chapter summarised the main concepts, operations and systems of a ventilation network found in a deep-level mine. It is important to understand how the mining industry works and how the ventilation network operates in such a vast system. Not only did the literature help with identifying methods and developing possible solutions, but it also ensured that accurate and realistic results could be obtained.

The energy sector of the mining industry uses a significant amount of energy. Mines have different consumers, with the ventilation network being one of the highest energy consumer. The ventilation

network and its different components were discussed together with all the important ventilation regulations to stress the vital role that the ventilation system plays in mining. Ventilation has a direct influence on the productivity of mine personnel and the production of the mine. Thus, it is important to ensure that airflow through the mine is efficient and that all the necessary regulations are met.

Newly developed technologies and simulation software are important in the mining industry in terms of planning, developing and solving various system inefficiencies. These inefficiencies found in a ventilation system such as high temperatures, low airflow and short-circuiting can be managed and resolved through the simulation software. The use of simulation software makes it possible to change the ventilation network system of a model, which provides possible solutions without physically changing the system underground. This is a powerful and advantageous tool as it can do various iterations of a problem and provide solutions that can be tested without consequence. This study discussed different simulation software packages to determine a suitable package that could be used to simulate a ventilation network.

The need for this study was highlighted by summarising and critically analysing previous studies on ventilation systems. The discussion indicated the literature gap by evaluating localised ventilation improvements on deep-level mines using simulation models. The literature was used to develop a generic method for evaluating ventilation improvements.

CHAPTER 2

2 METHOD FOR EVALUATING VENTILATION IMPROVEMENTS

2.1 Introduction

The problem identified in the previous chapter stated that mine ventilation systems are challenging to manage due to their vastness and complexity. As a result, underground temperatures increase, production decreases, there is insufficient airflow and health and safety risks escalate. Therefore, a generic solution strategy is developed to evaluate localised ventilation improvements of a mine, which entails changing the area or level ventilation network to ensure that airflow is sufficient and temperatures are adequate.

The purpose of this study is not only to evaluate ventilation improvements using simulations models on unfavourable areas, but also to implement these proposed solutions. The generic solution strategy is presented in Figure 2-1.

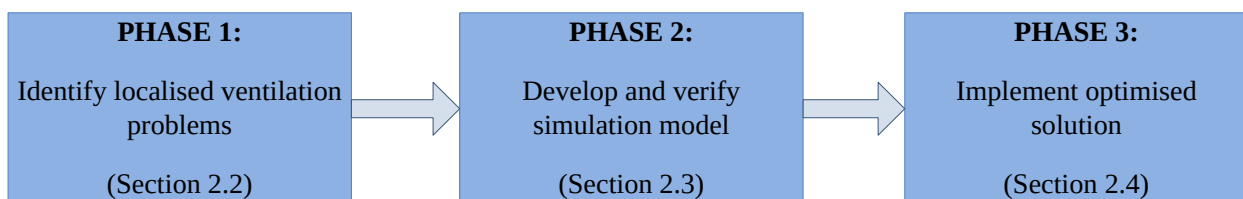


Figure 2-1: Generic solution strategy to evaluate ventilation improvements using simulation models

Phase 1 of the generic solution strategy is to identify the localised ventilation problem areas as discussed in Section 2.2. The focus is on gathering information from specific mine personnel, which ensures that there is good background information that can be used to do a successful ventilation audit. Thereafter, the process of a ventilation audit is discussed, and the measurement process and instruments required are described.

After the audit has been completed, the data must be analysed and evaluated. Phase 2 of the solution strategy focuses on developing a simulation model that is verified with the audit data from underground. Subsequently, the ventilation network is optimised to indicate ventilation improvements. The simulation model provides different scenarios, and the best solution is implemented.

Phase 3, namely, validation of results, must be done after implementing the ventilation improvements. Each step of the methodology is discussed in detail in the following sections.

2.2 Phase 1: Identify localised ventilation problems

The first phase of the methodology entails identifying localised ventilation problems in the specified mine. This is done by following the three steps defined in Figure 2-2.

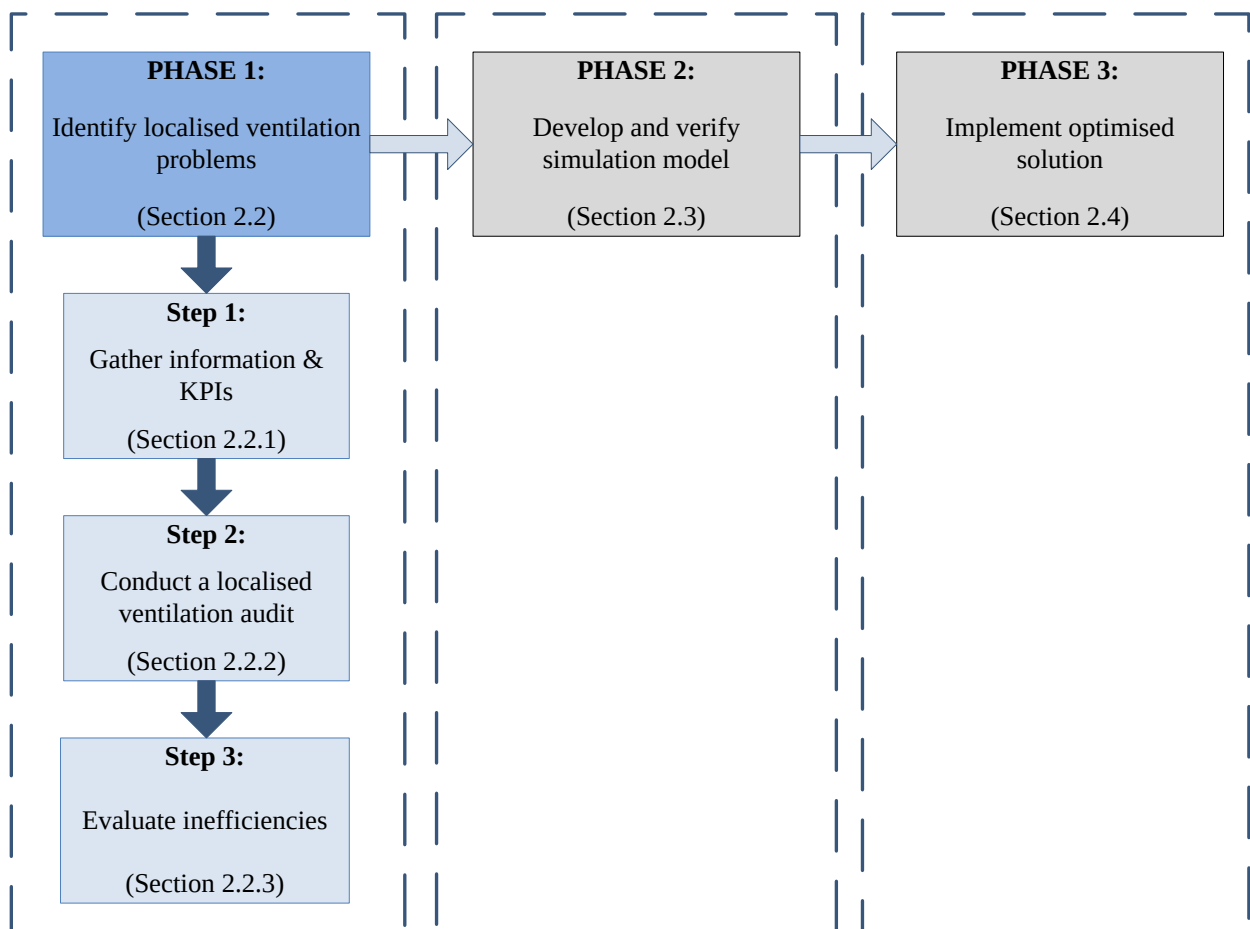


Figure 2-2: Steps for identifying localised ventilation problems – Phase 1

Step 1 is to gather all the relevant information through discussions with site personnel and to choose the correct key performance indicators (KPIs). This ensures that the ventilation network of the mine is understood before an audit is conducted. The KPIs focus on the critical parameters that are required to analyse the ventilation network and evaluate all inefficiencies.

Step 2 is to obtain the data from underground through a ventilation audit. This step discusses the purpose of an audit and how it is carried out. The different equipment and the use thereof are also discussed.

After the data has been collected and analysed, all the inefficiencies are identified and evaluated in the third and final step. Each of these steps are discussed in more detail in the next sections: Step 1, Step 2 and Step 3 are discussed in Section 2.2.1, 2.2.2 and 2.2.3, respectively.

2.2.1 Step 1: Gather information and KPIs

The first step of the methodology is an essential and helpful tool to prepare for an underground ventilation audit. If this step is executed fully, valuable time is saved, and a comprehensive understanding of the problem is obtained. Gathering information from mine personnel or occupational hygienists is a broad concept, but it is necessary to know exactly which information to obtain. Thus, a checklist such as given in Table 2-1 is compiled before going underground to ensure that time is not wasted when collecting the necessary data.

Table 2-1: Checklist to gather information

Checklist	
Obtain the following items:	
a) Obtain hard or electronic copies of fan curves.	
b) Obtain hard copies and DXF file format of each level.	
Indicate and discuss the following with occupational hygienists and engineers:	
c) Indicate airflow directions on layouts.	
d) Indicate high-temperature areas on layouts.	
e) Indicate low-airflow areas on layouts.	
f) Indicate all the fans, doors, seals, cooling cars, workshops and workplaces on the layouts.	
g) Collect layouts of previous audits conducted by ventilation officers.	
h) Note if any other problems are found on level, e.g. fall of ground or significant amounts of water on the level.	

Each item in the checklist in Table 2-1 is discussed hereafter:

a) Obtain hard or electronic copies of fan curves

The fan curves are used to determine the airflow of the fan by only measuring the static pressure of the fan. The measurement procedure and examples of fan curves are included in Appendix A (Determining the static pressure of an auxiliary fan) and Appendix B (Figure B-2 and Figure B-3), respectively.

b) Obtain hard copies and DXF file format of each level

The hard copies of the levels provide a map during the ventilation audit. The necessary information and data are indicated on the layout during the audit. Thereafter, the DXF files are imported into the simulation model. The DXF file of each level serves as a 3D map, which is used as a skeleton to construct the specific level of the mine in the simulation model.

c–h) Discussions with personnel

Discussions with occupational hygienists and engineers contribute to the overall understanding of the level and help to identify possible problem areas before the audit is conducted.

Figure 2-3 is an example of a layout which was provided by an occupational hygienist. This layout illustrates a ventilation network that indicates the different aspects discussed in the checklist presented in Table 2-1. The typical ventilation layout shows the airflow directions, various ventilation components and problem areas that were noted and discussed during the meetings with the occupational hygienist and engineers.

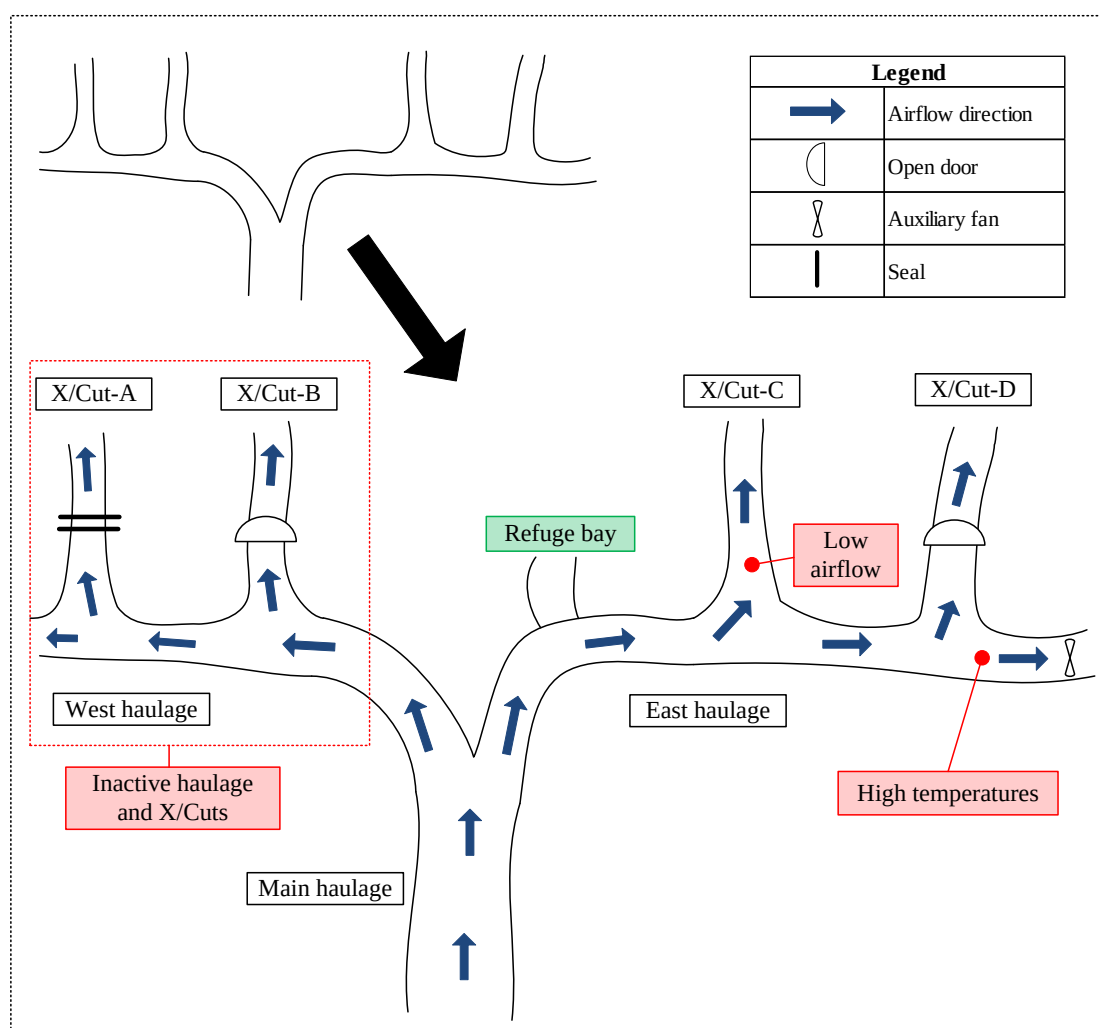


Figure 2-3: Typical ventilation layout

X/Cut: Cross-cut

It is essential that the different parameters in such a network are identified, which ensures that adequate data is obtained. This leads to the formulation of KPIs as discussed in the next section.

Key performance indicators

KPIs ensure that a detailed localised ventilation model is built as the KPIs identify specific problem areas. These KPIs include all the parameters that must be measured, which will be used to develop an accurate model. The KPIs are divided into two categories, namely primary KPIs and secondary KPIs. Primary KPIs provide data that is measured throughout the entire audit or level. Secondary KPIs are based on ventilation components or auxiliaries, which are found in specific areas underground.

Table 2-2: Main and secondary KPIs

Parameters to be measured				Location/Area of measurement
Primary KPIs	Description	Symbol	Unit	Primary KPI parameters are measured in general underground areas in the mine, e.g. in the main travel ways, haulages, cross-cuts, active working areas, and inactive working areas.
	Wet-bulb temperatures	T_{wb}	°C	
	Dry-bulb temperatures	T_{db}	°C	
	Volumetric airflow	Q	m^3/s	
	Air mass flow	$\dot{m}$	kg/s	
	Barometric pressure	P_{ba}	kPa	
	Height and width	H & W	m	
Secondary KPIs	Wet-bulb temperatures	T_{wb}	°C	Secondary KPI parameters are measured at the fan or ventilation auxiliary.
	Dry-bulb temperatures	T_{db}	°C	
	Volumetric airflow	Q	m^3/s	
	Air mass flow	$\dot{m}$	kg/s	
	Static pressure	P_s	kPa	
	Diameter	D	m	

After the KPIs have been listed, further investigation is required. The KPIs are measured through a ventilation audit to verify the problem areas discussed with the occupational hygienist. If the occupational hygienist can't indicate or identify any ventilation inefficiencies, problem areas, high temperatures or low airflows, ventilation audits must be done on all the levels of the mine.

The next section describes the second step of the first phase of the methodology, which focuses on gathering information underground.

2.2.2 Step 2: Conduct a localised ventilation audit

In the previous section, different KPIs were identified, which must now be measured. KPIs ensure that a detailed localised ventilation model is built and that further problem areas are identified.

This section focuses on doing a ventilation audit, determining audit measurement locations, using ventilation audit sheets, determining measurement methods, and processing audit data.

Purpose of ventilation audit

To audit an area means to investigate and collect data to obtain knowledge regarding a problem that needs to be solved. A localised ventilation audit is the planned task of collecting data on a

specific level or section in the mine. This audit quantifies the distributions of pressure, airflow, air quality and temperatures throughout the airflow paths of a ventilation system of a mine [38]. Defining the purpose of an audit allows us to determine the depth and precision of the measurements as well as how thoroughly the data should be analysed [38].

As stipulated by the law, airflow measurements must be taken underground at each section and facility during a ventilation audit. Even areas that are not regulated should be evaluated and measured to ensure a safe and healthy environment with sufficient airflow [38]. The following list summarises the main reasons for conducting a general ventilation audit in a mine:

- Ensuring that the required airflow is supplied efficiently and effectively to all workplaces.
- Confirming that ventilation layouts and plans are accurate and up to date.
- Verifying and maintaining the airflow directions and quantities.

A localised ventilation audit has a similar purpose as a general ventilation audit. One of the biggest challenges when planning an audit is to decide how thorough the audit should be. The data and information obtained from the audit determine the present and future site needs for the mine and the model. A rudimentary operational model can be built remotely by using raw experience, empirical values and audit data supplied from the site [21].

To gain as much information from the mine as possible, a full pressure quantity audit is required, which entails calculating the resistance of all active areas and open areas. This type of audit is costly; therefore, it is necessary to determine the amount of work needed to complete a ventilation model before doing a full pressure quantity audit [21]. A localised ventilation audit is conducted with a small number of data sets, which is sufficient for building a simulation model. These data sets relate to the measurement locations, which have a significant influence on the calibration and accuracy of the simulation model.

Audit measurement locations

All the measurement locations must be determined. However, if these locations are determined incorrectly or unnecessarily, time is wasted and the data will be unreliable. Thus, measurement locations must be selected critically throughout the entire level. When the measurement locations are plotted on the level layout, it is essential that the measurements are located away from any restrictions. These restrictions include bends in a haulage or cross-cut, near shaft stations, and any

obstructions that can cause inconsistent or turbulent airflow in the area of measurement. Figure 2-4 was adapted from Figure 2-3 to illustrate the layout of a certain level that has previously been supplied by the mine.

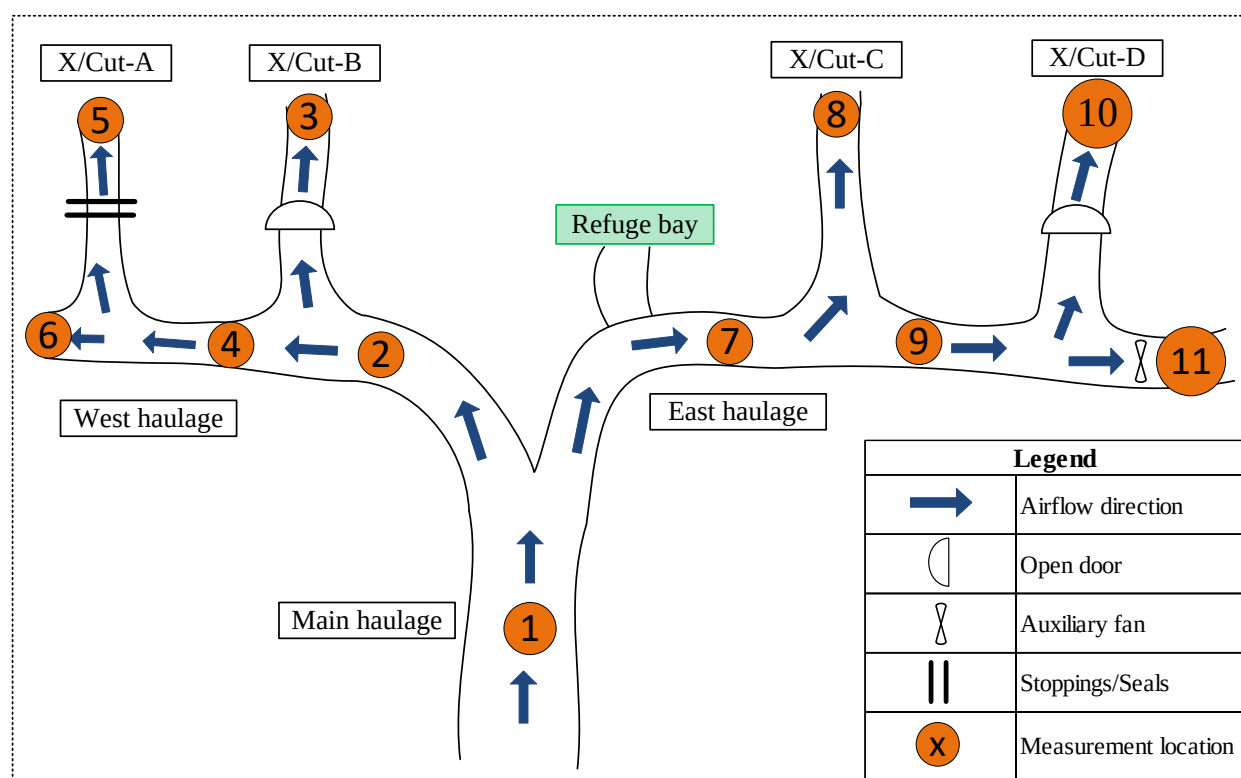


Figure 2-4: Typical ventilation layout with measurement locations indicated (adapted from Figure 2-3)

Figure 2-4 represents the different measurement locations on the level layout. The main haulage has one measurement location (Measurement Location 1). Each split that is east and west from the main haulage are measured (Measurement Locations 2 and 7). Thereafter, each cross-cut (Measurement Locations 3, 5, 8 and 10) and in between each cross-cut (Measurement Locations 2, 4, 6, 7, 9 and 11) are measured.

Underground ventilation audit sheet

Table 2-3 and Table 2-4, respectively, illustrate an underground ventilation audit sheet and a fan audit sheet, which are used during the underground ventilation audit. These tables have been constructed to capture all identified KPIs. Table 2-3 represents a ventilation audit sheet, which records parameters at different measurement locations in haulages and cross-cuts. These parameters include velocity (m/s) measurements of the airflow in an airway, barometric

pressure (kPa), wet- and dry-bulb temperatures (°C), and three widths and heights (m) of haulages or cross-cuts.

Table 2-3: Underground ventilation audit sheet

No.	Velocity (m/s)												Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Width (m)			Height (m)		
	1	2	3	4	5	6	7	8	9	10	11	12				1	2	3	1	2	3
1																					
2																					
3																					
:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:	:
11																					

Table 2-4 shows a fan audit sheet, which records the different fan parameters on a level. These fan parameters are the velocity (m/s) measurements, barometric pressure (kPa), wet- and dry-bulb temperatures (°C), static pressure (kPa), and the diameter (m).

Table 2-4: Underground fan audit sheet

No.	Velocity (m/s)						Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Static pressure (kPa)	Diameter (m)
	1	2	3	4	5	6					
11											

These parameters are necessary for the final calculations and analysis. The audit sheet assists with recording all the measurements neatly, which helps to avoid any confusion and misunderstanding of the data. A full underground ventilation audit sheet and fan audit sheet are included in Appendix A (Table A-1 and Table A-2).

The section that follows describes the measurement methods.

Ventilation measurement method and processing of data

Before conducting a ventilation audit, it is essential to understand the measurement procedure and to determine which equipment is required to obtain all the necessary parameters and KPIs required to build an accurate simulation. Table 2-5 lists all the equipment needed to conduct a successful localised ventilation audit.

Table 2-5: Ventilation audit instruments

Equipment	Measured parameter	Unit
Vane velocity meter	Air velocity at measurement points	m/s
Whirling hygrometer	Wet-bulb and dry-bulb temperatures	°C
Distance meter	Dimension of haulage	m
Barometer	Ambient pressure	kPa
Vertical manometer	Static pressure	kPa
Pitot-static tube	Static, dynamic, and total pressure	kPa
Digital manometer	Various parameters (air velocities and static pressures)	m/s and kPa

Figure 2-5 gives a cross-sectional view of a haulage or cross-cut in a mine. H_1 , H_2 and H_3 represent three different height locations, and W_1 , W_2 and W_3 represent three different width locations. P_{ba} , T_{wb} and T_{db} represents the barometric pressure, wet-bulb and dry-bulb temperature measurement locations.

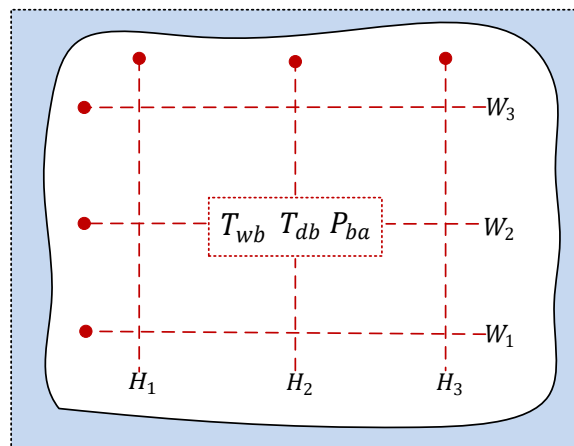


Figure 2-5: Measurement method for area, temperature and pressure [7], [38]-[41]

Figure 2-5 illustrates where to use the distance meter, whirling hygrometer and barometer to take measurements in a haulage or cross-cut [7], [38]-[41]. The measurement methods for these parameters are discussed in the following sections.

Determine the cross-sectional area of a haulage or a cross-cut

The cross-sectional area of a mine tunnel must be determined to calculate the volumetric airflow through the haulage or cross-cut. Assuming the method described by both Hancock [7] and Tien [40] is accurate and correct, the cross-sectional area is determined using Equation 2-1 (refer to parameters illustrated in Figure 2-5). The measurements are done using a digital distance meter.

$$A_{CS} = \frac{H_1 + H_2 + H_3}{3} \times \frac{W_1 + W_2 + W_3}{3}$$

Equation 2-1: Cross-sectional area [12], [49]

- A_{CS} = cross-sectional area (m²)
- H_{1-3} = height measurements (m)
- W_{1-3} = width measurements (m)

Equation 2-1 considers the average of the three height measurements (H_1 , H_2 and H_3) and the average of the three width measurements (W_1 , W_2 and W_3) in order to estimate the cross-sectional area (A_{CS}).

Measure the barometric pressure in a haulage or cross-cut

A digital barometer must be used, which is easy and quick to operate: Switch on the barometer to indicate the barometric pressure of the airway. Hold the barometer at the position indicated by the symbol P_{ba} in Figure 2-5. Stand in the streamline of the airflow and away from any obstructions and bends when taking the measurement. Wait for the value given by the barometer to stabilise. After the value has stabilised, write down the two-decimal barometric pressure reading.

Measure the wet-bulb and dry-bulb temperatures in a haulage or cross-cut

The wet-bulb and dry-bulb temperatures are essential parameters as they help to identify problem areas and calibrate the simulation model. They are further used to calculate the air density and humidity in the simulation model. A whirling hygrometer is used to measure the wet- and dry-bulb temperatures. A description of the whirling hygrometer and the method for use are described by Hancock [7] and Kingery [39]. The literature based on the whirling hygrometer is assumed to be accurate and correct.

Figure 2-5 illustrates the position (T_{wb} and T_{db}) to hold the whirling hygrometer in a haulage or cross-cut. Before measuring the temperatures, one must make sure that the whirling hygrometer is in an operational condition: Fill the reservoir with water before going underground. When measuring, it is important to stand in a haulage or cross-cut away from any obstructions and bends. Rotate the whirling hygrometer at approximately 200 rpm for 30 seconds. Firstly, display the wet-

bulb temperature and, secondly, the dry-bulb temperature [7]. Repeat the process until constant values are reached [7].

Determine the average air velocity in a haulage or cross-cut

A vane velocity meter is required to calculate the air velocity through a haulage or cross-cut. The measurement method has been described by both Hancock [7] and Tien [40]. Their method is used in this study and is assumed to be accurate and correct.

Divide the haulage or cross-cut where the measurement is required into equal sections. Place the vane velocity meter in the centre of each section until the reading of the velocity vane stabilises. Figure 2-6 demonstrates the measurement method with the symbols V_{1-9} indicating each velocity measurement [7], [40].

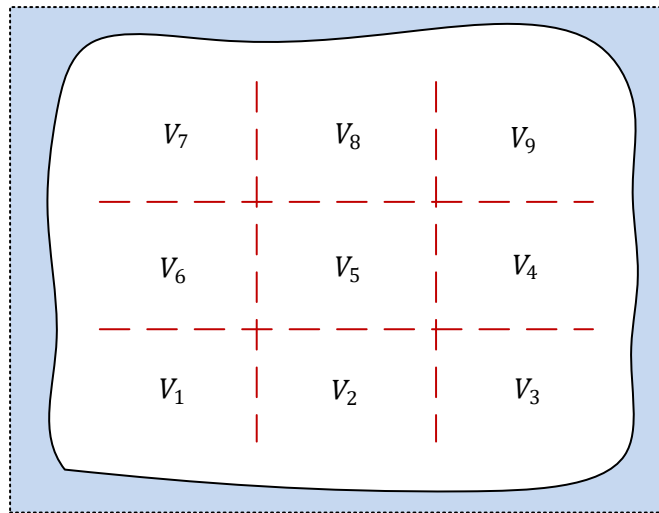


Figure 2-6: Measurement method for air quantities

The position of each measurement point (V_{1-9}) is indicated. The average air velocity through the section is calculated using Equation 2-2.

$$V_{ave} = \frac{V_1 + V_2 + V_3 + V_4 + V_5 + V_6 + V_7 + V_8 + V_9}{9}$$

Equation 2-2: Average air velocity

- V_{ave} = average air velocity (m/s)
- V_{1-9} = air velocity (m/s)

Equation 2-2 considers the air velocity measurements (V_{1-9}) in order to estimate the average air velocity (V_{ave}).

Audit an underground fan

An underground auxiliary fan is audited using various instruments and methods. Instruments such as a vertical manometer, pitot-static tube and a digital manometer are used to measure fan pressures and airflows (which are listed in Table 2-5). The methods used for the following techniques are described in detail by Hancock [7] and McPherson [38].³ The method for auditing an underground fan is included in Appendix A.

Calculate the volumetric airflow

The average velocity and the cross-sectional area are used to calculate the volumetric airflow of the haulage, cross-cut or fan in a duct as is given by Equation 2-3.

$$Q_{air} = A_{CS} \times V_{ave}$$

Equation 2-3: Volumetric airflow

- Q_{air} = volumetric airflow (m^3/s)
- A_{CS} = area (m^2)
- V_{ave} = velocity (m/s)

Equation 2-3 considers the average calculated air velocity (V_{ave}) and the cross-sectional area (A_{CS}) in order to estimate the volumetric airflow (Q_{air}).

Determine the air mass flow

The air mass flow is calculated from the volumetric airflow (given by Equation 2-3) and air density. A psychrometric chart, included in Appendix A, Figure A-3, is used to determine the air density. Parameters such as wet-bulb (T_{wb}) and dry-bulb (T_{db}) temperatures are used to determine the density (kg/m^3) of air [42].

³ TSI Instruments Ltd., “Traversing a duct to determine average air velocity or volume,” pp. 4–7, 2014.

The air mass flow is calculated by using Equation 2-4:

$$\dot{m}_{air} = Q_{air} \times \rho_{air} \quad \text{Equation 2-4: Air mass flow}$$

- $\dot{m}_{air}$ = air mass flow (kg/s)
- Q_{air} = volumetric airflow (m³/s)
- ρ_{air} = air density (kg/m³)

Equation 2-4 considers the calculated volumetric airflow (Q_{air}) and air density (ρ_{air}) in order to estimate the air mass flow ($\dot{m}_{air}$).

2.2.3 Step 3: Evaluate ventilation inefficiencies

Baseline of ventilation network

After completing the level audit and processing the data, it is important to organise the data in a table format and indicate the measurements and results on the layout. This contributes to the general understanding of the ventilation network, whereafter the inefficiencies can be identified.

Table 2-6 illustrates the template sheet for the underground level audit data. This data is used as the baseline conditions for the identified ventilation network, which must be investigated for any ventilation improvements. The data in Table 2-6 will be used in the simulation model for calibration purposes.

Table 2-6: Underground level audit sheet template

No.	Wet-bulb (°C)	Dry-bulb (°C)	Volumetric airflow (m ³ /s)	Air mass flow (kg/s)	Barometric pressure (kPa)
1					
2					
3					
:	:	:	:	:	:
11					

Table 2-7 illustrates the template sheet for the underground auxiliary fan audit data. The measurements of the fans, which are captured in Table 2-7, together with the relevant fan curves, will be used for the calibration process of the simulation model.

Table 2-7: Underground fan audit sheet template

No.	Wet-bulb (°C)	Dry-bulb (°C)	Volumetric airflow (m ³ /s)	Air mass flow (kg/s)	Static pressure difference (kPa)
11					

After the audit data are tabulated (Table 2-6 and Table 2-7), all the data that has been summarised is analysed and indicated on the ventilation layout. Figure 2-7 shows the ventilation layout with each measurement location's results from the audit and the final baseline conditions.

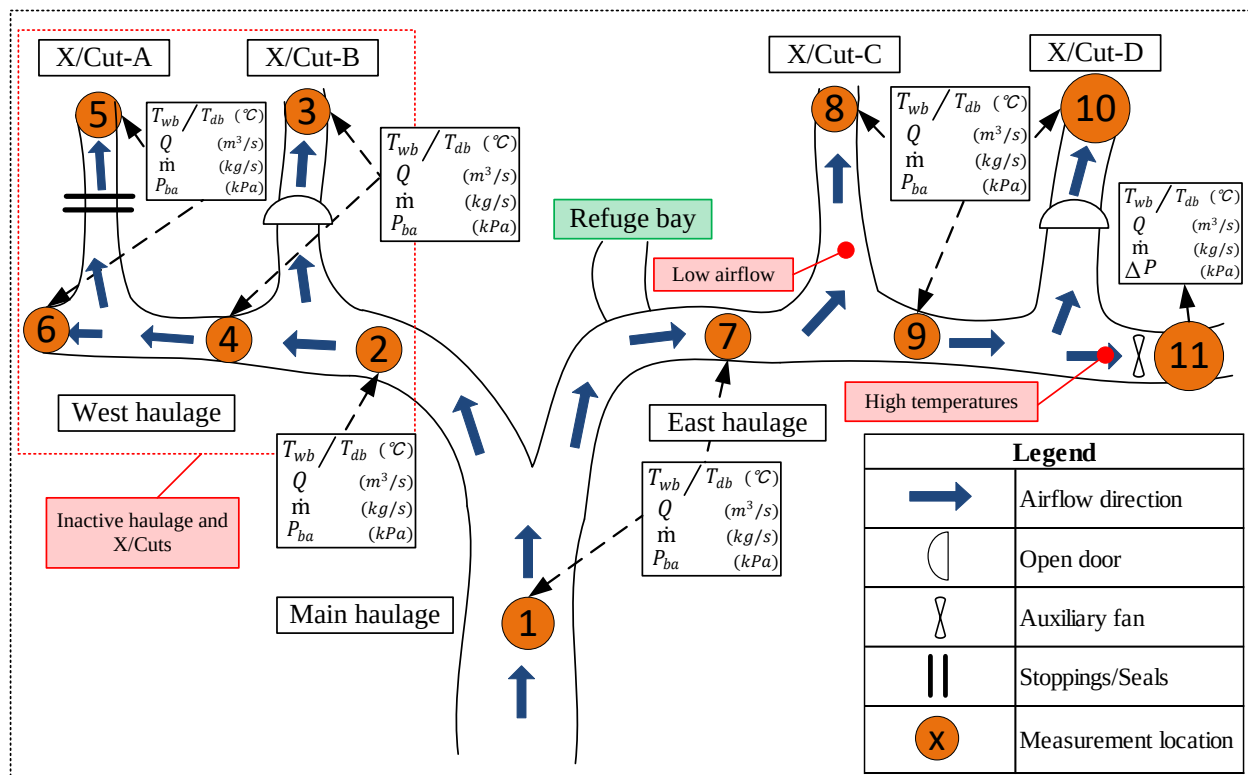


Figure 2-7: Audit results indication

The red highlighted text boxes indicated in Figure 2-7 illustrate ventilation concerns or inefficiencies noted during the underground audit, which are discussed further in the following section.

Evaluate inefficiencies

The previous section explained how to establish the baseline conditions of a level ventilation network. At this stage, a good understanding of the ventilation network has been achieved and any ventilation inefficiencies and system constraints can be evaluated. The following inefficiencies could arise in a ventilation network and must be noted:

- Inactive workplaces, haulages and cross-cuts receiving air.
- Short-circuiting or recirculation of air within a level or between levels.
- Ineffective regulators.
- High temperatures.
- Inadequate air supply to active areas.
- Fall of ground in RAWs.
- Ineffective use of air.
- Oversupply of air through workplaces, haulages and cross-cuts.
- Ventilation components operating ineffectively and wrongly positioned.

With the necessary understanding of the airflow through the mine and levels, it is possible and easy to identify the ventilation network inefficiencies.

In Phase 1, namely, identify localised ventilation problems, Step 1 described the importance of gathering information and choosing the correct KPIs before conducting an underground audit. This step not only prepares for the ventilation audit, but also ensures that all the necessary parameters are correct for the simulation model. Step 2 described the ventilation audit method and explained how to process and tabulate the data from underground. After processing the data, Step 3 indicated how to organise and process the data using different tables and a level ventilation layout. Thereafter, the processed data was evaluated. Different ventilation inefficiencies that could occur in a ventilation network were discussed. A general understanding of a level ventilation network and necessary data was obtained. This knowledge can now be used to develop a simulation model. This leads to Phase 2 of the methodology, namely, to develop and verify the simulation model.

2.3 Phase 2: Develop and verify simulation model

In the development and verification phase, the data obtained in Section 2.2 will be used to construct a simulation model. The simulation model will be verified through the baseline audit conditions. The accuracy will be determined between the baseline of the actual measurements and the simulation model values. If the percentage error is below 5% [43], [44], the simulation model is considered as an accurate model that will provide accurate results.

The simulation model will be used later to optimise the ventilation network until suitable scenarios are identified that are feasible and easy to accomplish. Constructing and simulating a localised ventilation network model is easier and less time-consuming than simulating an entire mine.

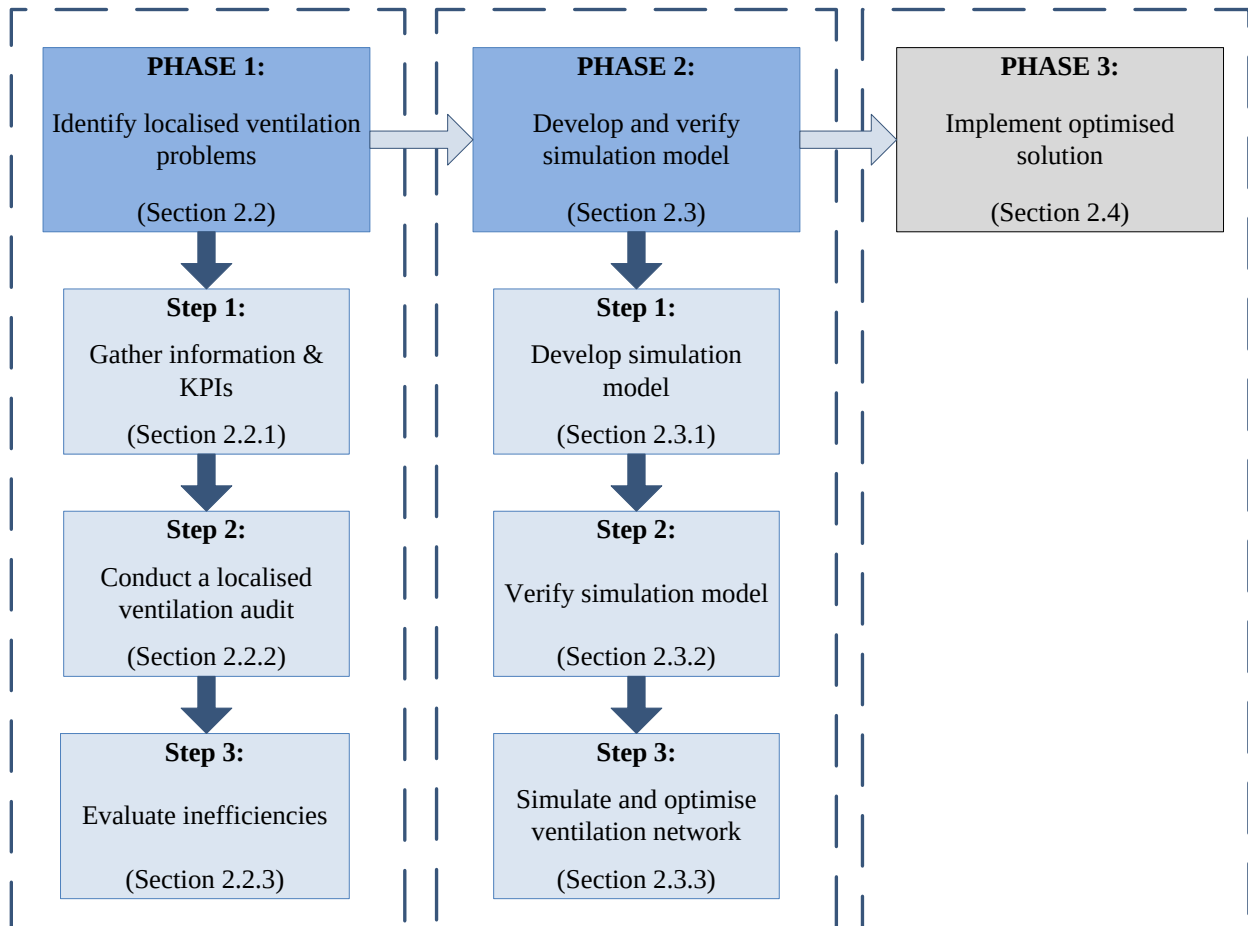


Figure 2-8: Develop and verify simulation model

Figure 2-8 presents the steps of the development and verification phase of the methodology, which are discussed in this section. These steps include developing the simulation model (Section 2.3.1), verifying the simulation model (Section 2.3.2), and simulating and optimising the ventilation network (Section 2.3.3).

2.3.1 Step 1: Develop simulation model

The PTB 3D simulation package is used to construct and simulate a localised ventilation network with ventilation inefficiencies. The identified level is constructed by using the analysed data obtained from Section 2.2. The baseline conditions, or KPIs, are the main parameters and components on which the simulation model is based.

Figure 2-9a illustrates a simulation model of ventilation network or level that has been identified with inefficiencies. Figure 2-9b indicates the different types of components used to construct the simulation model. Figure 2-9c shows a detailed view of the simulation model.

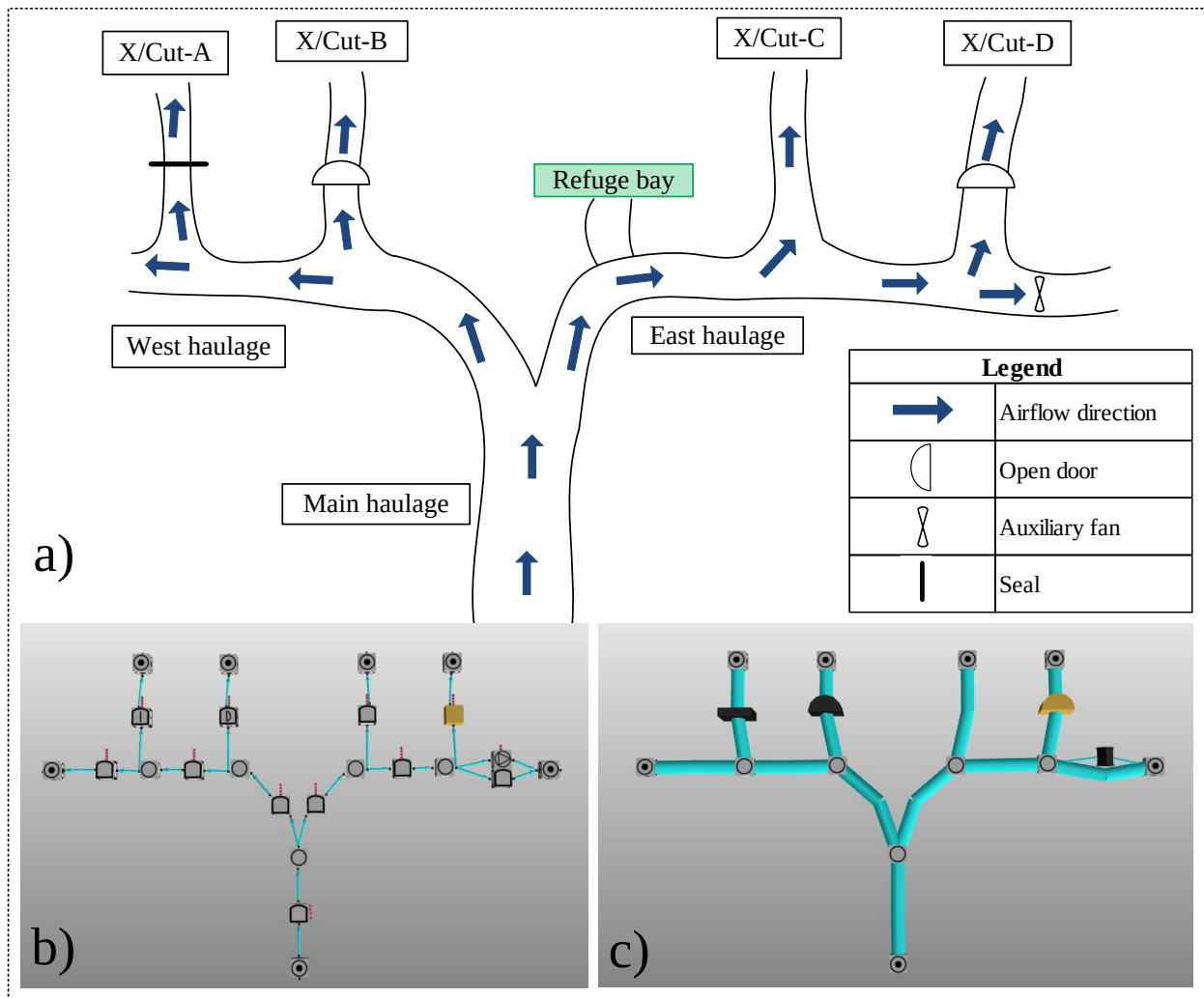


Figure 2-9: PTB 3D simulation model of the ventilation network

Each component in the simulation model has a specific function and purpose. The basic components and their functions are discussed in Table 2-8.

Table 2-8: PTB 3D simulation components

Components	Function
Air pressure boundary	The air pressure boundary is the boundary condition of the ventilation network. This component induces airflow and temperatures throughout the area or level. This component requires input values, which are obtained from the ventilation audit.

Components	Function
Air node	Air nodes do not require input values. They are mainly used for solving purposes in the simulation model. The air node further indicates the pressure value and is used to combine or split tunnels/haulages or cross-cuts.
Air tunnel	Air tunnels represent the haulages or cross-cuts of a mine. These require a few input values such as haulage size, heat added to the system, friction coefficient and door fraction. Different configurations, such as doors and seals, can be set for an air tunnel.
Air fans	Air fans are auxiliary components that require input values. An air fan helps to ventilate the level or area.
Calibration control	The controller is used to help calibrate the model.

Once all the components relevant to the ventilation network have been listed, the ventilation simulation model is constructed. To build this simulation model in PTB 3D, the following steps must be followed:

- Import the DXF file of the level into PTB 3D.
- Drag and drop the components onto the level.
- Arrange the components neatly and connect them according to the airflow direction.
- Ensure that air nodes are placed between the air tunnels.
- Begin and end with air pressure boundaries.
- Use colour, for example; blue represents intake air and orange represents return air.

Phase 2, Step 1 demonstrated the process for developing a simulation model from the data obtained in Phase 1 (Section 2.2). The section discussed all the relevant components and how they are used. Phase 2, Step 2, as discussed in Section 2.3.2, verifies the simulation model (as constructed in Section 2.3.1) by using the audit data and information from Section 2.2 (Phase 1). If another simulation package is used, the steps will differ from the steps used with the PTB 3D simulation package.

2.3.2 Step 2: Verify simulation model

In order to simulate different scenarios (evaluate suggestions for ventilation improvements), the simulation model must first be verified. The actual measurements and analysed data from the audit in Section 2.2.3, which are considered as the baseline conditions, are used as input values for the simulation model.

The model must be calibrated using calibration controllers to obtain the correct airflow through the level or area. If the airflow of the actual measurements is similar to that of the simulation model, then heat is added to the system to calibrate the temperatures throughout the level or area. The discrepancy between the actual measurements and simulation model values is considered as the percentage error for the results. This error must be lower than 5% to ensure an accurate and reliable simulation model.

Boundary conditions (air pressure boundaries)

The blue frames in Figure 2-10 illustrate the air pressure boundary conditions of the simulation model. The air pressure boundaries create airflow throughout the level due to a difference in air pressure. Air flows from a high to a low pressure point. If there are no external heat sources on the level, the input temperature of the starting air pressure boundary will increase continuously by a small amount throughout the level until it matches the end air pressure boundary temperature. This gradual temperature increase throughout the level is due to the virgin rock temperature (VRT). If any external heat sources are present on the level, such as fans, vehicles, lights, small compressors and water, heat is added to the air tunnel component.

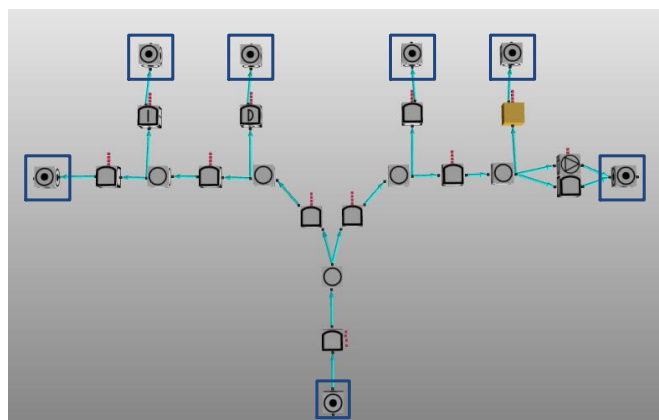


Figure 2-10: Air pressure boundaries

The air pressure boundaries values, illustrated in Figure 2-10, are obtained from Table 2-6: Underground level audit and Figure 2-7: Audit results indication, which are the baseline conditions. Figure 2-7 indicates the corresponding positions of the air pressure boundaries in Figure 2-10. The default values of the air pressure boundaries must be changed to the values recorded in Table 2-6 and Figure 2-7. The following parameters' input values of the air pressure boundary must be changed to calibrate the simulation model:

- Wet-bulb and dry-bulb temperatures.
- Barometric pressure.
- Relative humidity (from the psychrometric chart [42] in Figure A-3, Appendix A).

The air pressure boundary is a sensitive component to simulate. One of the first steps is to ensure that the airflow is correct through the level and corresponds with the underground audit data. This is done through an iterative process.

Air tunnel

The air tunnel components, which are illustrated in Figure 2-11 using orange and red blocks, represent the haulages and cross-cuts of a mine. The air tunnel input values are also obtained from Table 2-6: Underground level audit and Figure 2-7: Audit results indication.

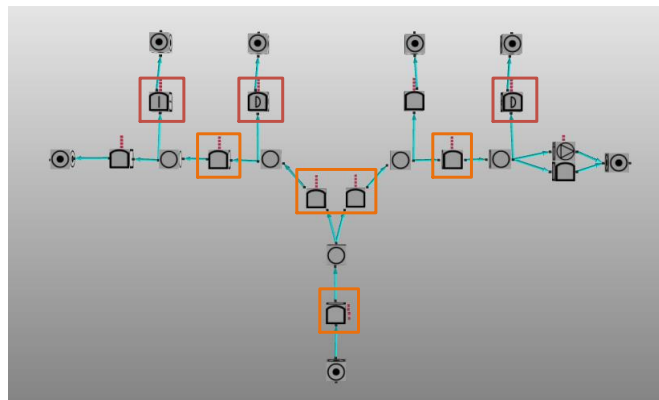


Figure 2-11: Air tunnels and their configuration

The air tunnel in the simulation model indicates the airflow rate between two air nodes. The following parameters of the air tunnel must be changed to calibrate the simulation model:

- Inlet and outlet VRT (values obtained from Jones [45] and Grave and Stroh [46]).
- Wet area fraction – Increases the wet-bulb temperature of the area.
- Heat – Adds heat to the specific area, which increases the dry-bulb temperature.
- Door fraction – Allows the user to control the amount of air through the haulage or cross-cut. This function will be discussed later in the section under calibration method.
- Configuration type – The air tunnel can be changed to different configurations such as door, seal, wall, fall of ground and brattice wall. Configurations types are changed to build

the actual underground ventilation layout as accurately as possible in the simulation model. These components will also be used to solve the inefficiencies of the ventilation network.

Air fan

Figure 2-12 indicates an air fan component in the simulation model using a purple block. The air fan input values are mostly obtained from the fan curve (included in Appendix B), as is supplied by the mine personnel.

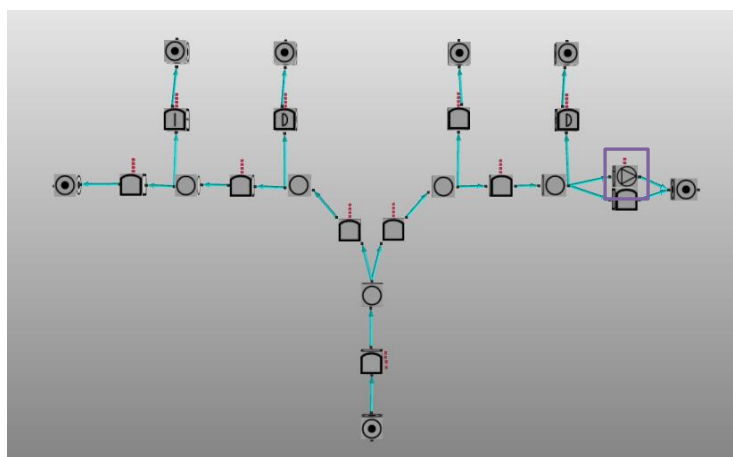


Figure 2-12: Air fan

The audit data of Table 2-7 and Figure 2-7 is used to calibrate the air fan in the simulation model. Three pressure values and three flow values of the fan curve must be used as inputs. The audit data is used to calculate the fan efficiency and capture the overall performance. Some component properties are adjusted to ensure that the fan is calibrated correctly and performs according to actual measurements.

Air node

In Figure 2-13, the air nodes are indicated by the green blocks. The purpose of an air node in the simulation model is to connect different components. More than one component can be connected to an air node. Thus, the air node is usually placed at bends and turns, e.g. cross-cuts that serve as branches of a haulage. The air node further indicates the temperatures and pressure of its location. The air node is important for connecting all the components and as a solver for the simulation model.

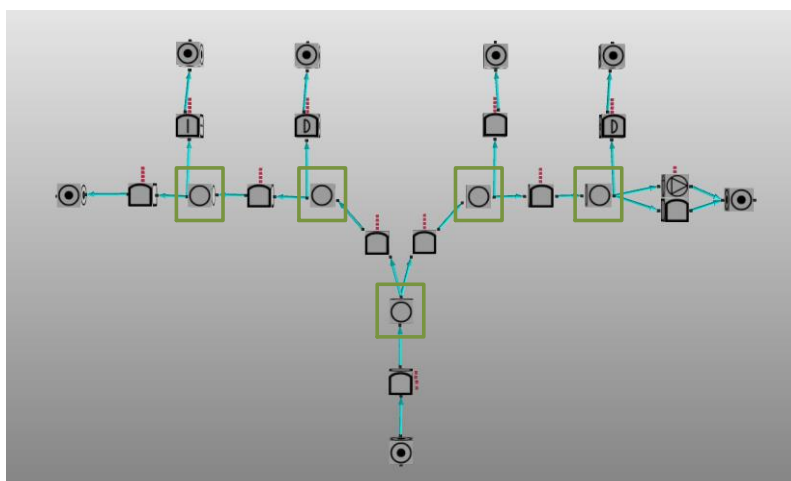


Figure 2-13: Air node

Calibration method

The calibration controller, as is illustrated in Figure 2-14, assists in calibrating the area or level. The controller is connected to an air tunnel (haulage or cross-cut). The most suitable place to connect a calibration controller is usually close to the air pressure boundaries of the level or area.

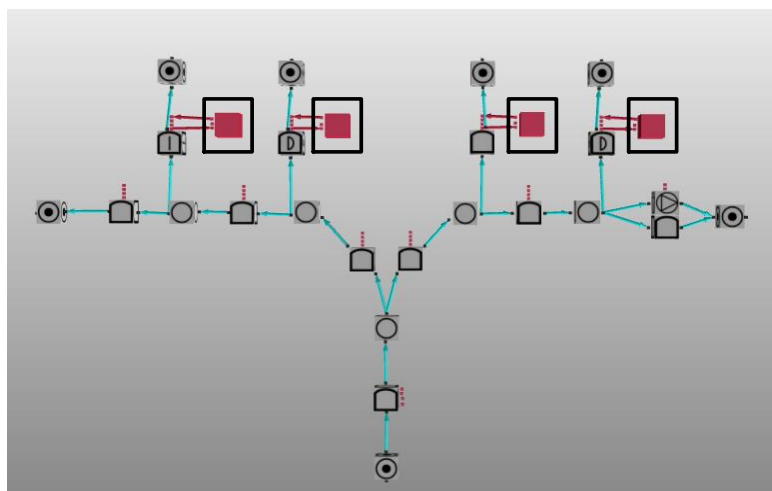


Figure 2-14: Calibration controller

First, the calibration controller must be connected to the door fraction property of the air tunnel. Thereafter, the controller must be set to control the air mass flow (kg/s) of the air tunnel. The following properties are changed to enable a calibrated area or level:

- Control Limit 1 (or Control Limit 2) must be set in the range of the value that must be calibrated.

- To ensure that the model reaches stability, the integral gain may range between 0.001 and 0.00001.
- The set point of the calibration controller must be equal to the mass flow measurement recorded during the ventilation audit.

When the simulation is started, the door fraction is changed automatically by the controller until the value of the set point is reached in the haulage or cross-cut. If the correct flow is simulated throughout the level or area, the values provided by the calibration controller are used as the final door fraction of the air tunnel. Thereafter, each calibration controller is disconnected because the simulation model has been calibrated successfully.

Comparing level measurements with baseline simulation model

The discrepancy between the simulation model baseline and the audit baseline (measured values from underground) is important. This discrepancy indicates the accuracy of the simulation model, which will be used to mitigate any inefficiencies. The percentage error between the simulation model and the actual baseline is calculated by comparing the corresponding parameters, such as temperatures and air mass flow for both systems. A general percentage error must be calculated for the entire system. If the percentage error of the system's parameters is above 5% [43], [44], the model is considered as inaccurate. The entire calibration procedure for the simulation model must be repeated until an accurate simulation model is obtained.

2.3.3 Step 3: Simulate and optimise ventilation network

Section 2.2.3 (Evaluate ventilation inefficiencies) provided information regarding the different inefficiencies that could occur in a ventilation network. The calibrated simulation model is used to portray the impact of these ventilation inefficiencies in the network. Once it is known where these inefficiencies are located on the level of the mine and in the simulation model, the following are done or changed in the model to mitigate these inefficiencies:

- Inactive workplaces, haulages and cross-cuts receiving air:
 - Close the sections by installing seals, e.g. building walls or doors.
- Short-circuiting or recirculation of air within a level or between levels:
 - Close the sections by installing seals, e.g. building walls or doors.

- Ineffective regulators:
 - Investigate why the regulator is ineffective. Ensure the required amount of air is regulated and the regulator is sealed properly.
- High temperatures:
 - High temperatures could be caused by insufficient airflow in the area or insufficient cooling. Ensure air being supplied is sufficient and necessary cooling auxiliaries are situated in the area.
- Inadequate air supply to active areas:
 - Ensure that the air supply is utilised fully. Investigate whether there are inactive areas or any recirculation of air.
- Fall of ground in RAW:
 - Fall of ground increases the pressure on surface fans and restricts the airflow. Make sure that the airflow path is clear from obstructions.
- Ineffective utilisation of air:
 - Investigate the cause, which could be due to inactive areas and recirculation of air.
- Oversupply of air through workplaces, haulages and cross-cuts:
 - Install regulators.
- Ventilation components operating ineffectively and wrongly positioned:
 - Investigate the possible reason for low efficiencies. The ventilation components could be damaged or installed incorrectly. The installation of the ventilation components does not comply with the regulations.

All potential ventilation inefficiencies are addressed with possible solutions. These changes are evaluated in the simulation model without making any physical changes underground as the simulation model displays the effect thereof. Therefore, the simulation model makes it possible to create various solutions or scenarios that are proposed to the mining personnel.

Figure 2-15 illustrates different parameters, such as wet-bulb temperature, dry-bulb temperature, volumetric airflow and air mass flow that can be compared between the simulation baseline conditions and various solutions or scenarios simulated through the simulation package.

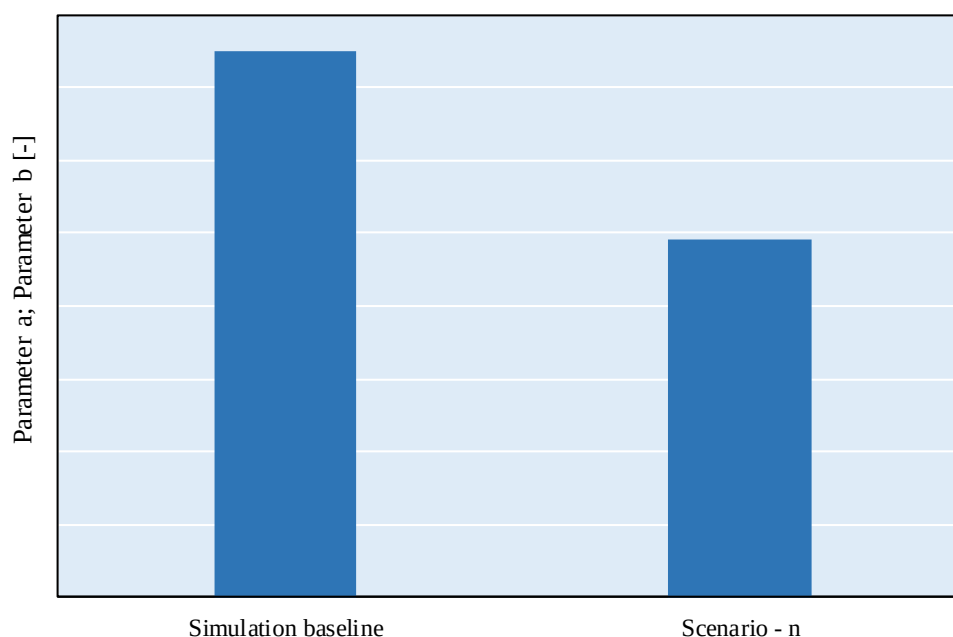


Figure 2-15: Simulation baseline conditions compared with various scenarios

Figure 2-15 also indicates that various scenarios or solutions (scenario – n) can be simulated. Each solution can have its own ventilation plan and estimated costs. From all the proposed ventilation plans the most suitable solution can be selected for the implementation phase.

Phase 2, namely to develop and verify the simulation model, illustrated the process of developing a simulation model using PTB 3D. Note that other simulation packages can also be used, but their steps and processes to construct a model can differ. Process data from Phase 1 (Section 2.2) was used in Phase 2, Step 1 (Section 2.3.1) to construct the simulation model. Step 2 (Section 2.3.2) addressed the calibration method, and the simulation model was verified. Step 3 (Section 2.3.3) mitigated all the ventilation inefficiencies and proposed that different scenarios or solutions can be simulated.

The next section discusses the last phase for evaluating ventilation improvements, which is to implement the most feasible or suitable scenario or solution.

2.4 Phase 3: Implement optimised solution

Phase 1 of the developed solution strategy entailed gathering information and data for each level of a mine. Through this process, a level was identified with possible ventilation concerns. An underground audit was conducted, and how to process the data. From the audit, ventilation

efficiencies were noted and a thorough understanding of the ventilation network was obtained. In Phase 2, a simulation was built of the level identified. All the ventilation inefficiencies were mitigated through the simulation model, which is presented through various scenarios or solutions. The implementation phase illustrated by Figure 2-16 is the final phase, which involves implementing and validating the best suitable scenario or solution.

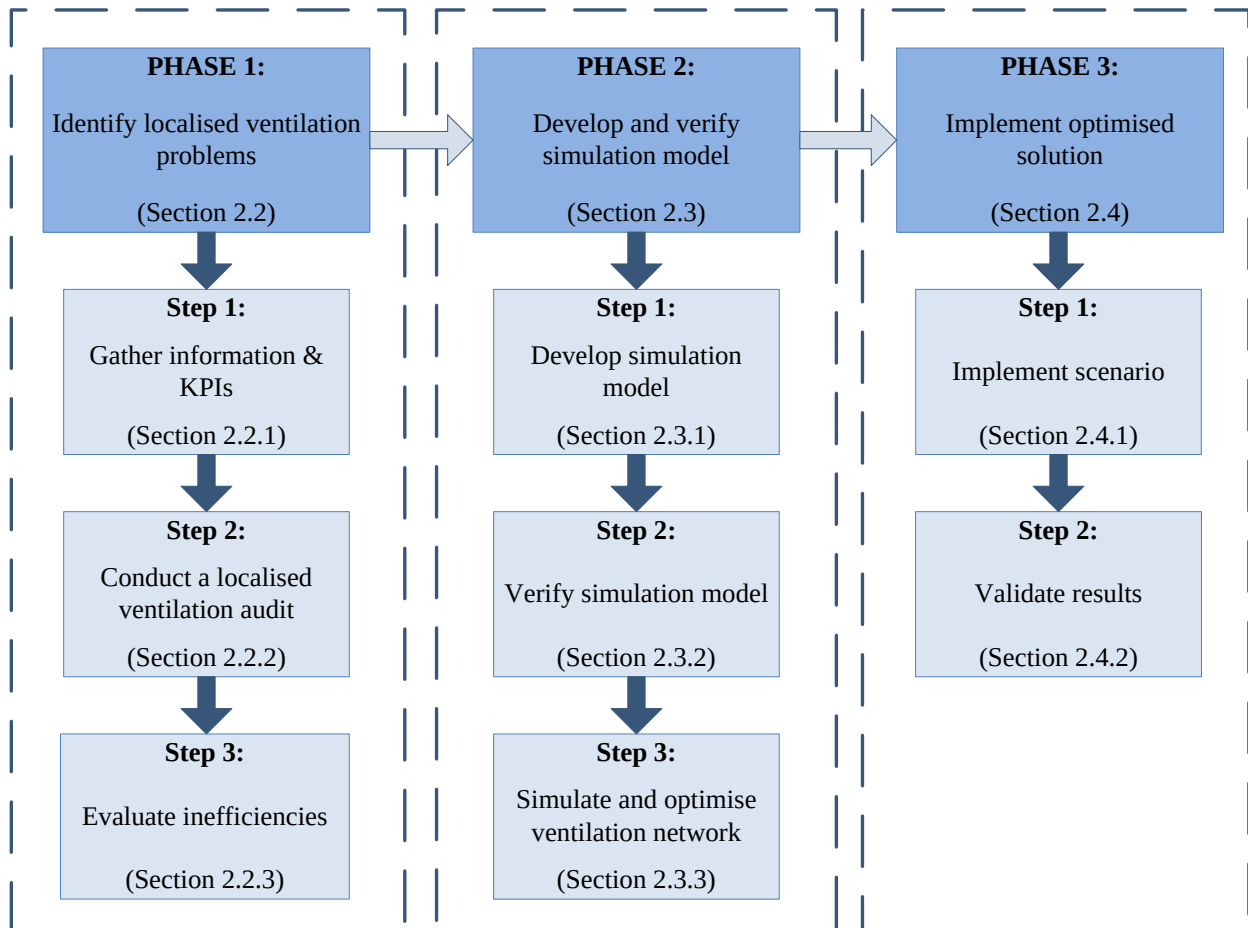


Figure 2-16: Implementing the optimised solution

After implementing the changes in Step 1 (Section 2.4.1), the optimised localised ventilation network must be validated in Step 2. This is done by auditing the area once again, which will be discussed in Section 2.4.2. The actual results are compared with the scenario simulation model results. The difference between the actual and simulation model results indicates the percentage error. If the percentage error is lower than 5% [43], [44], it is assumed that the simulation model is accurate. The percentage error serves as an error factor, which allows the user to make better decisions when new scenarios are simulated. Any shortcomings from this process can be identified and noted.

2.4.1 Step 1: Implement scenario

The most feasible or suitable solution with its respective tasks can be implemented. Each task must be prioritised to complete the solution strategy of the scenario successfully. To avoid any misinterpretations, any data obtained from surface and underground must be documented properly and neatly. After implementing the most suitable scenario, the simulation model must be validated, which is discussed in the last step in Section 2.4.2.

2.4.2 Step 2: Validate simulation model through measurements

After implementing the relevant changes, the simulation model must be validated to determine whether the project is successful. A detailed underground ventilation audit is required on the entire level where the inefficiencies were corrected. The process of auditing the underground level must be repeated to obtain new data from underground. Figure 2-17 is a possible illustration to compare each step of the methodology.

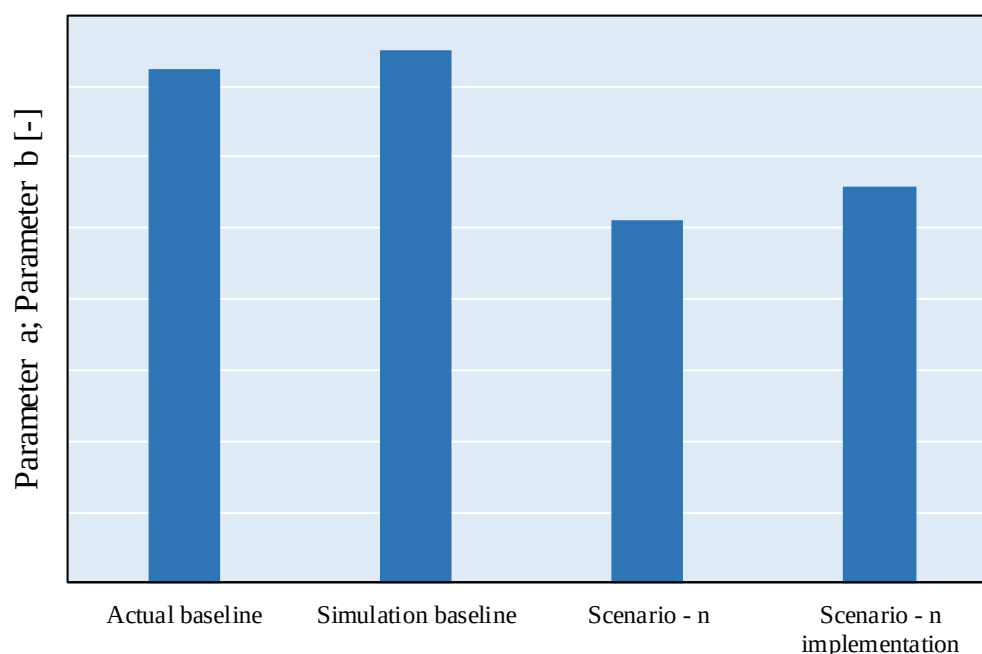


Figure 2-17: Possible illustration of the validation phase (step 2)

The actual baseline obtained from the audit is compared with the simulation baseline, which portrays the accuracy of the simulation model. After implementing the suitable scenario or solution the audit is repeated to capture the new ventilation conditions. The results of the actual and simulation model are analysed and interpreted. During the comparison between the two conditions,

a percentage error is calculated stating the accuracy of the project. If the percentage error is within 5% [43], [44], it is assumed that the project is successful and accurate.

The simulation model is applied to different scenarios. The calibrated model is used to present and motivate proper proposals. Possible shortcomings are identified and noted through the developed solution strategy or by processing and analysing the data. These shortcomings should be addressed, and all new information gathered is used to make necessary changes to the developed solution strategy, which will influence the results.

2.5 Summary

A mine ventilation network is a vast and complex system that is challenging to manage. The system requires maintenance or improvements throughout its lifetime. Temperature increases, production decreases and health and safety risks occur if the ventilation network is not maintained or improved. This study described how a localised ventilation simulation model could be used to evaluate networks that are insufficient or do not meet ventilation requirements.

In this chapter, a method for evaluating ventilation improvements was developed from the objectives and problem statement given in Chapter 1. The developed solution strategy was divided into three main phases, namely: Phase 1) identifying localised ventilation problems; Phase 2) developing and verifying the simulation model; and Phase 3) implementing the optimised solution. These main phases were further divided into steps for completing each phase.

In order to identify localised ventilation problems, the ventilation network has to be understood. To gain this understanding, level layouts of the mine and fan curves should be collected. All the layouts have to be discussed with mine personnel, and important information can be noted on the layouts. Each level must be discussed before the underground ventilation audit is conducted to obtain the data needed to build an accurate simulation model. This data will be used to develop and verify the simulation model. First, the model must be constructed, verified and calibrated. The calibrated simulation model will be used to resolve all the inefficiencies in the localised ventilation network. Different scenarios or solutions can then be presented, and the most feasible or suitable scenario can be selected for implementation.

Implementing the scenario require adequate planning and documentation to avoid any misinterpretations. An audit is required after implementing the changes made to the ventilation

network. The actual results of the implemented ventilation plan are used to validate the simulated scenario or solution. The accuracy and percentage errors are then determined by comparing actual audit results with the simulation results.

The developed solution strategy described in Chapter 2 will be used in Chapter 3 to implement an actual case study.

CHAPTER 3

3 IMPLEMENTING LOCALISED VENTILATION IMPROVEMENTS

3.1 Introduction

Mines have vast ventilation networks that are difficult to manage and maintain. Various mining activities contribute to temperature increases, production decreases and health and safety risks. It is time-consuming to investigate and understand a mine ventilation network, which makes it difficult to solve ventilation inefficiencies across the entire mine. Therefore, the methodology was developed to capture the necessary data to build a simulation model, which will mitigate the inefficiencies for a localised ventilation network.

A case study mine is used to verify the methodology provided in Chapter 2. The three phases illustrated by Figure 3-1 are applied to the specific mine (case study).

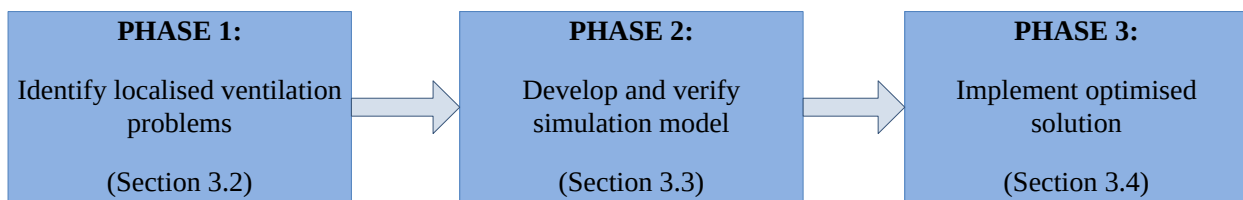


Figure 3-1: Generic solution strategy applied to case study

Phase 1 of the developed methodology entails identifying the localised ventilation problem areas in the specific mine. This phase focuses on gathering information from specific mine personnel whereafter a ventilation audit is done. The data obtained from the underground ventilation audit is analysed and evaluated.

Phase 2 focuses on developing a simulation model and verifying it using the underground audit data. The ventilation network is optimised to indicate ventilation improvements. Thereafter, the simulation model is used to simulate different scenarios. The best solution is implemented and validated in the last phase.

The methodology is applied to a deep-level gold mine, namely Mine A, situated in the Free State area. The three phases of the methodology are discussed in detail in Sections 3.2, Section 3.3 and Section 3.4, respectively. The chapter concludes with Section 3.5.

3.2 Phase 1: Identify localised ventilation problems

The first phase of the methodology is to identify localised ventilation problems in the specified mine. The three steps, defined in Figure 3-2, are followed to identify these problems.

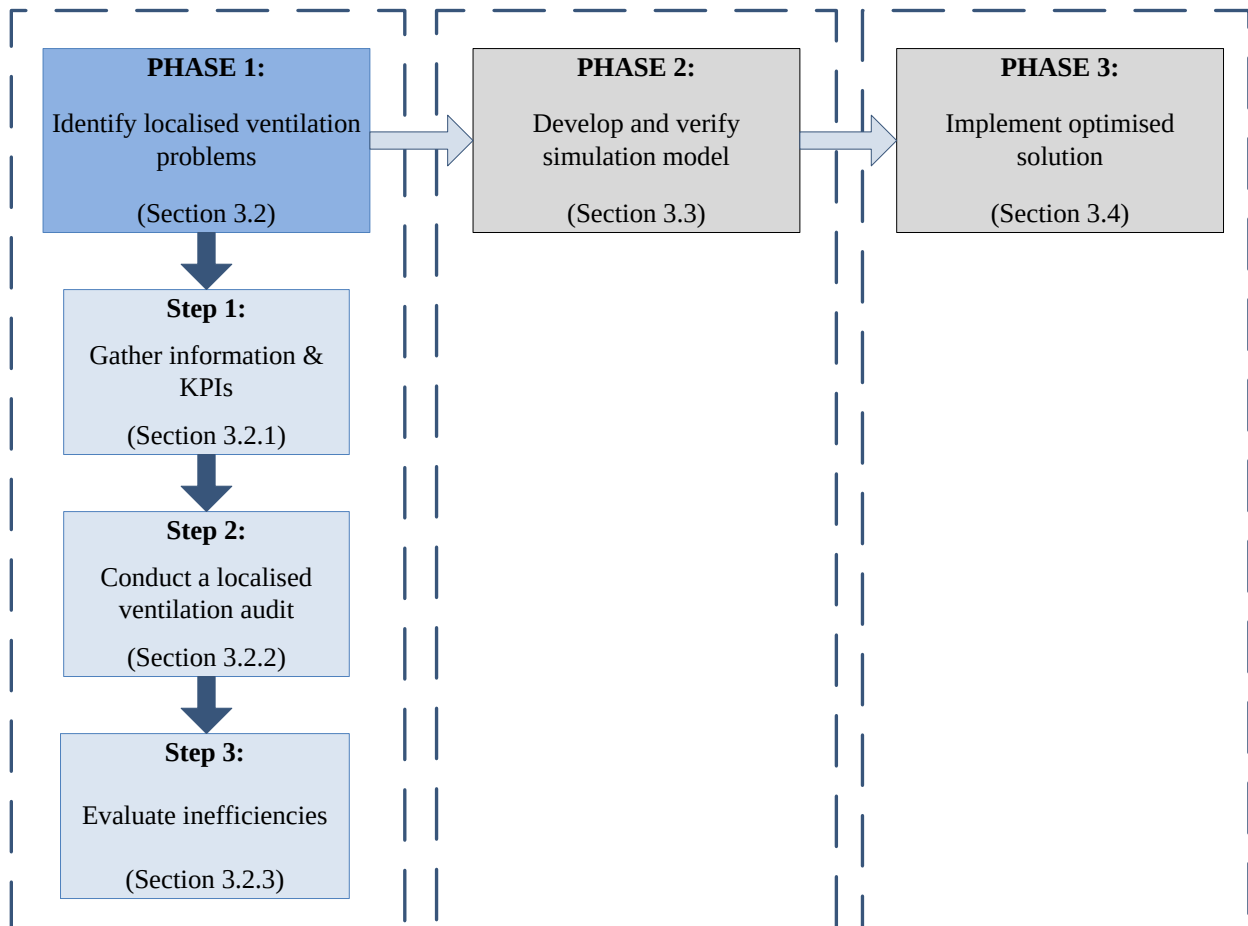


Figure 3-2: Identify localised ventilation problems of case study

Step 1 is to gather all the relevant information through site personnel and choose the correct KPIs. This ensures that the ventilation network of the mine is understood before an audit is conducted. The KPIs focus on the critical parameters that are required to analyse the ventilation network and to evaluate all inefficiencies. Step 2 is to obtain the data from underground through a ventilation audit. After the data is collected and analysed, inefficiencies are identified and evaluated in Step 3, the final step of this phase. Each step is discussed in more detail in Section 3.2.1 (Step 1), 3.2.2 (Step 2) and 3.2.3 (Step 3), respectively.

3.2.1 Step 1: Gather information and KPIs

The checklist (developed in Section 2.2.1) had to be completed in this step (Phase 1, Step 1) in order to gather the specific mine's information and KPIs. This checklist was beneficial and sped up the process. All the necessary information was gathered, and thorough preparation was done before the ventilation audit. Completing all the checklist items in Table 3-1 provided a good understanding of the operations of Mine A.

Table 3-1: Checklist to gather information for Mine A

Checklist	
Obtain the following items:	
a) Obtain hard or electronic copies of fan curves.	X
b) Obtain hard copies and DXF file format of each level.	X
Indicate and discuss the following with occupational hygienists and engineers:	
c) Indicate airflow directions on layouts.	X
d) Indicate high-temperature areas on layouts.	X
e) Indicate low-airflow areas on layouts.	X
f) Indicate all the fans, doors, seals, cooling cars, workshops and workplaces on the layouts.	X
g) Collect layouts of previous audits conducted by ventilation officers.	X
h) Note if any other problems are found on level, e.g. fall of ground or significant amounts of water on the level.	X

A discussion of each item in the checklist of Table 3-1 follows:

- a) The occupational hygienist supplied two fan curves. The fan curves are included in Appendix B, Figure B-2 and Figure B-3. Not all the fan curves were available. These fans would have to be audited and their performance recorded if it could be measured. If the fan curve of a specific fan was unavailable and could not be measured, further assumptions would have to be made according to its size in order to calibrate the simulation model.
- b) Layouts of all the mine levels were collected in hard copy and DXF file format. The DXF files of each level were imported into PTB 3D simulation software (see Appendix B, Figure B-1). Note that only the level discussed in Step c–h is included.

- c–h) The airflow directions, high-temperature- and low-airflow areas were shown on the level layouts of Mine A. The layouts also indicated all the ventilation components (e.g. fans, doors and cooling cars). This information was used to identify low airflow and high temperatures through the workshop area of one specific level (Level X).

Figure 3-3 illustrates the airflow direction, fan locations, level activities, high temperatures and low airflows. Appendix B (Figure B-1) shows a full-size layout of Level X. After having a discussion with the engineers and occupational hygienist and gathering information, Level X was identified as a health and safety concern. Thus, Level X required further discussion and analyses before going underground for any ventilation audits.

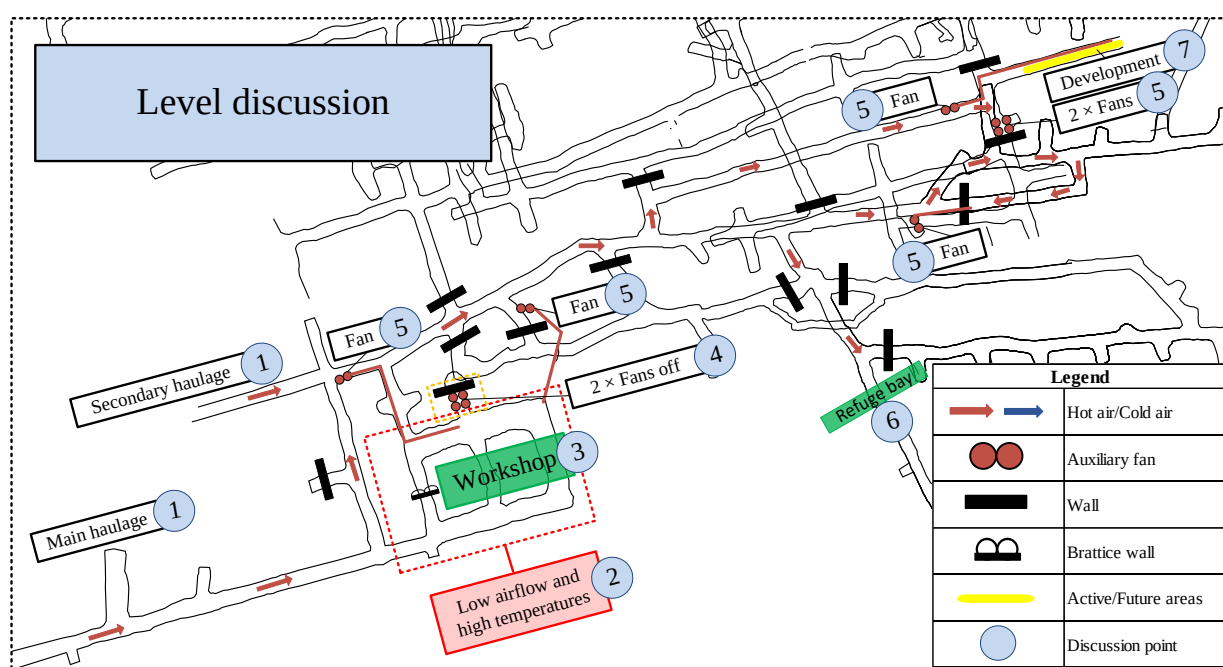


Figure 3-3: Layout of Level X (Mine A) with indicated components and areas

All issues and concerns identified for Level X were discussed thoroughly with the engineers and the occupational hygienist. The points numbered 1 to 7 on the layout (Figure 3-3) indicate certain problematic components or areas, which are explained further in Table 3-2. This table provides detail and information regarding Level X and the main concerns.

Table 3-2: Discussion of Level X

No.	Discussion or description
1	The main and secondary haulage supply Level X with intake air. The main haulage intake is situated close to a chill pond, and the secondary haulage travels to a different level.

No.	Discussion or description
2	The section highlighted by the red dotted block indicates the workshop area of Level X, which has high temperatures and low airflows. This area could cause health and safety problems. New ventilation improvements must be formulated to mitigate this problem.
3	The green text box indicates the workshop area.
4	This point indicates the position of two non-operational auxiliary fans.
5	All the operational auxiliary and booster fans on Level X are indicated.
6	Point 4 indicates the refuge bay on Level X.
7	Level X is still under development, and any changes made to the ventilation network are not allowed to influence this section negatively.

Table 3-2 provides adequate detail to understand the ventilation network and address all the concerns related to Level X.

Key performance indicators

The primary and secondary KPIs are listed in Table 3-3 (repeat of Table 2-2). These are essential parameters, which were measured during the ventilation audit to verify problem areas discussed with the occupational hygienist; for example, workshop area no. 2 in Figure 3-3. The table provides the primary and secondary KPIs, the symbols and units of each, and a general description.

Table 3-3: Primary and secondary KPIs listed

Parameters to be measured				Location/Area of measurement
Primary KPIs	Description	Symbol	Unit	Primary KPI parameters are measured in general areas in the mine underground, e.g. in the main travel ways, haulages, cross-cuts, active working areas, and inactive working areas.
	Wet-bulb temperatures	T_{wb}	°C	
	Dry-bulb temperatures	T_{db}	°C	
	Volumetric airflow	Q	m^3/s	
	Air mass flow	$\dot{m}$	kg/s	
	Barometric pressure	P_{ba}	kPa	
	Height and width	$H \text{ \& } W$	m	
Secondary KPIs	Wet-bulb temperatures	T_{wb}	°C	Secondary KPI parameters are measured at the fan or ventilation auxiliary.
	Dry-bulb temperatures	T_{db}	°C	
	Volumetric airflow	Q	m^3/s	
	Air mass flow	$\dot{m}$	kg/s	
	Static pressure	P_s	kPa	
	Diameter	D	m	

The main focus was to identify these KPIs correctly and in as much detail as possible while preparing for the underground ventilation audit. Where specific measurements could not be done underground or measurements were defined as inaccurate, assumptions were made to ensure that the simulation model was calibrated and as accurate as possible.

The next step of this phase, Step 2 of Phase 1, entails doing a ventilation audit to obtain the ventilation data. This data is required to understand the problem on Level X and to construct an accurate simulation model.

3.2.2 Step 2: Conduct a localised ventilation audit

The first step of Phase 1 aimed to gather all information and identify the KPIs required for the underground audit. In Step 2, a full ventilation audit was conducted on Level X, whereafter the data was analysed. The measurement locations on Level X, illustrated in Figure 3-4, were planned before the ventilation audit. The strategic locations of the measurements ensured that sufficient data could be obtained to build the simulation model in PTB 3D. The information or knowledge was mainly obtained from discussions with the occupational hygienist and engineers of Mine A (Step 1, Phase 1). The method as described in Section 2.2.2 was followed to develop Figure 3-4.

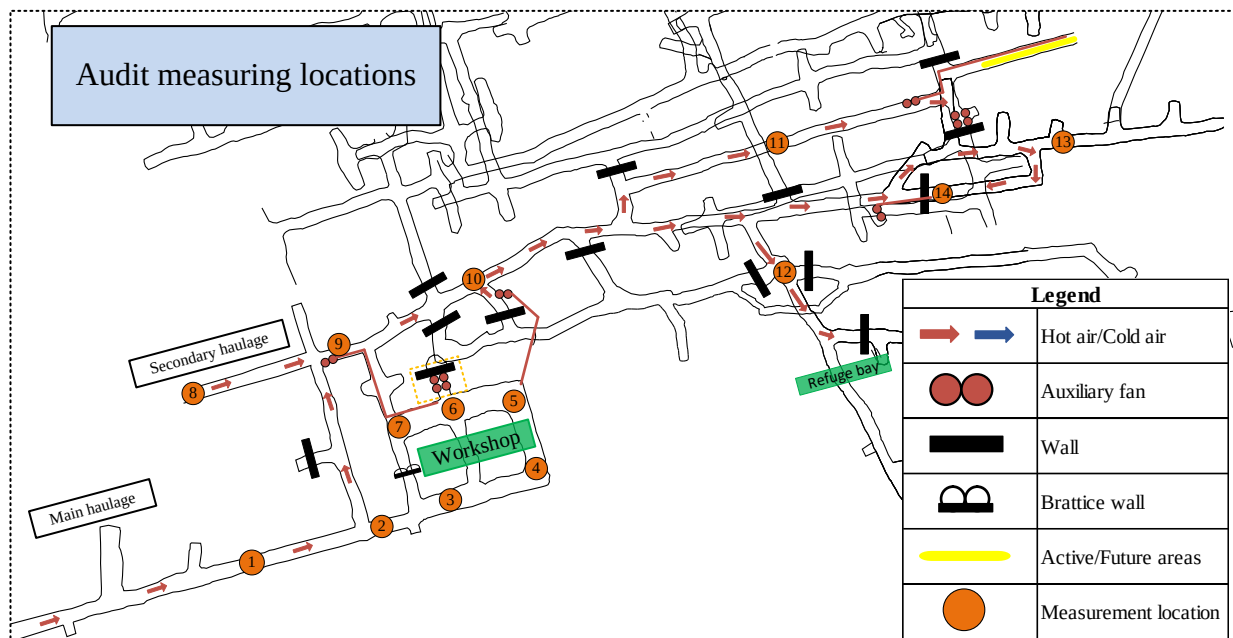


Figure 3-4: Layout of Level X (Mine A) audit measurement locations

Figure 3-4 illustrates the identified measurement locations, numbered 1 to 14. The method explained in Section 2.2.2 was carried out using the applicable measurement equipment to ensure accurate readings. The following parameters were measured at the fourteen different locations: dry-bulb and wet-bulb temperatures, air velocities, barometric pressure, haulage height and width. These parameters were used to calculate the air density, air mass flow and volumetric airflow. The measured and calculated parameters are given in Appendix A (Table A-1 and Table A-2). After conducting the underground ventilation audit, the data was analysed and processed. The raw data of each measurement location of the ventilation audit is included in Appendix B, Table B-1 and Table B-2. Figure 3-5 illustrates the audit results of each measurement location.

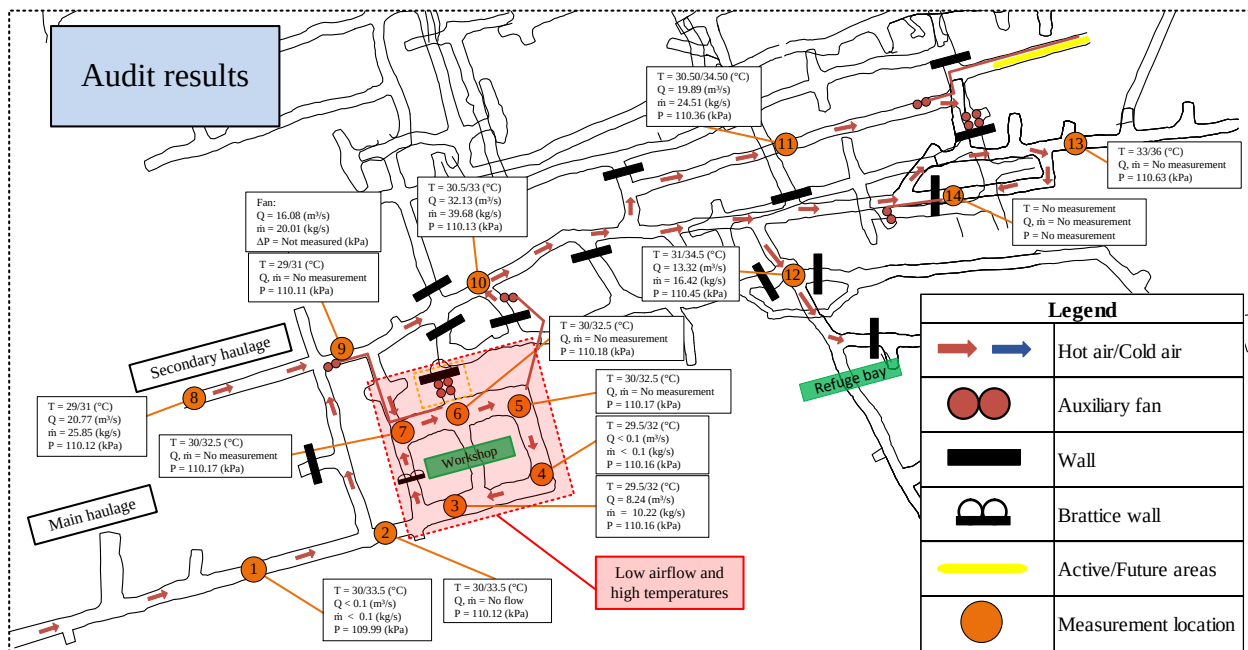


Figure 3-5: Layout of Level X (Mine A) with ventilation audit results

A few concerns were noted during the audit of Level X that influenced most measurements throughout the level. The haulages of Level X are large, which made it difficult to measure the entire haulage section for airflow. Low to no airflow was recorded in the workshop area, and high temperatures were also measured, as illustrated by the red boxes in Figure 3-5. Measurement Locations 3 to 7 given in Figure 3-5 in the workshop area were tough to measure due to large haulages. Mine vehicles were also found at Measurement Locations 2 and 7, which could have caused the turbulent airflow at Measurement Location 3, potentially resulting in an inaccurate measurement.

The following list explains the findings of the auxiliary fans and some of the measurement locations illustrated in Figure 3-5:

- The static pressure of the fan at Location 9 could not be measured as there was no measurement point for the vertical manometer in the fan duct. The fan curves in Appendix B, Figure B-2 and Figure B-3, were therefore used for further calibration in Section 3.3.2. Table 3-4 illustrates the processed audit data of the fan at Location 9.

Table 3-4: Processed fan audit data of Level X (Mine A)

No.	T _{wb} (°C)	T _{db} (°C)	Q (m ³ /s)	$\dot{m}$ (kg/s)	P _{ba} (kPa)
9	29.0	31.0	16.08	20.01	–

- The fan ventilating from Location 5 to Location 10 was not measured, and the fan curve (Appendix B) was used for calibration. Location 10 was measured in the haulage away from the fan.
- Measurements at Location 11 were inaccurate due to large haulage and restrictions. The fans found after Location 11 could not be measured as they were unreachable due to restrictions in the haulage. A fan would be used in the simulation model to create the airflow recorded at Location 11 through the haulage.
- The static pressure and airflow of the fan at Location 14 could not be measured as it was difficult to access the area. Airflow through the haulage was recorded but could not be measured accurately due to the large haulage.

Table 3-5 illustrates the processed data of the ventilation audit and gives comments about each measurement location. Fourteen measurement locations were measured as planned.

Table 3-5: Processed audit data of Level X (Mine A)

No.	T _{wb} (°C)	T _{db} (°C)	Q (m ³ /s)	$\dot{m}$ (kg/s)	P _{ba} (kPa)	Comments
1	30.0	33.5	0.00	0.00	109.99	Minimal airflow was recorded; unable to measure. Haulage was too large for accurate measurements.
2	30.0	33.5	0.00	0.00	110.12	
3	29.5	32.0	8.24	10.22	110.16	Turbulent airflow was recorded, measurement is inaccurate.
4	29.5	32.0	0.00	0.00	110.16	Minimal airflow; unable to measure. Haulage was too large and restrictions were noted for accurate measurements.
5	30.0	32.5	0.00	0.00	110.17	

No.	T _{wb} (°C)	T _{db} (°C)	Q (m ³ /s)	m (kg/s)	P _{ba} (kPa)	Comments
6	30.0	32.5	0.00	0.00	110.18	Minimal airflow; unable to measure. Haulage was too large and restrictions were noted for accurate measurements.
7	30.0	32.5	0.00	0.00	110.17	
8	29.0	31.0	20.77	25.85	110.12	Accurate measurement. No restrictions found in area.
9	29.0	31.0	0.00	0.00	110.11	Inaccurate measurements due to restrictions on level.
10	30.5	33.0	32.13	39.68	110.13	
11	30.5	34.5	19.89	24.51	110.36	
12	31.0	34.5	13.32	16.42	110.45	
13	33.0	36.0	0.00	0.00	110.63	N/A.
14	0.0	0.0	0.00	N/A	0.0	Could not be measured.

A mass balance check was done to verify the accuracy of the measurements. If the flow at Location 10 had been measured correctly, theoretically, the sum of the airflow at Location 8 (25.85 kg/s) and Location 1 (an airflow of 3 kg/s was assumed due to minimal data recorded during the audit) would be equal to the airflow at Location 10: $25.85 \text{ kg/s} + 3 \text{ kg/s} = 28.85 \text{ kg/s}$. Since the airflow at Location 10 was measured as 39.68 kg/s, the mass balance check verified that the measurement was inaccurate. Location 10 was an overall check to verify whether the rest of the locations were measured accurately. This is also indicated in Table 3-5 and stated individually at each number. Further assumptions were required to determine an accurate baseline, which are discussed in the next step.

This step focused on doing a ventilation audit to obtain data and to understand the ventilation network. Restrictions on the level caused unreliable data to be obtained during the audit. In the next step, the data is analysed further, and assumptions are made to determine an accurate baseline.

3.2.3 Step 3: Evaluate ventilation inefficiencies

Some of the haulages of Level X were too large to measure and a few restrictions occurred on the level during the ventilation audit. Due to these difficulties, the assumptions listed in Table 3-6 and illustrated by Figure 3-6 were required to determine an accurate baseline for the simulation model.

Table 3-6: List of assumptions and mass balance for the audit data of Level X (Mine A)

Components and nodes (refer to Figure 3-6)	Assumption	Reason for assumption
The fan at Node 9.	The fan delivers 14.5 kg/s from Node 9 to Node 6.	A 45 kW fan delivers between 10 kg/s and 15 kg/s.
The fan at Node 10.	The fan delivers 25 kg/s from node 5 to Node 10.	A 75 kW fan delivers between 15 kg/s and 25 kg/s.
The fans after Node 11.	The fans at the end of the haulage deliver 10 kg/s through the haulage.	A 45 kW fan delivers between 10 kg/s and 15 kg/s. Due to large haulage and restrictions in the airway, fan inefficiency was accounted for.
The fan at Node 14.	The fan delivers 5.35 kg/s airflow through the haulage.	A 45 kW fan delivers between 10 kg/s and 15 kg/s. Due to little airflow recorded in the haulage, the fan was set to operate inefficiently.
The brattice wall between Node 2 and 7.	The brattice wall allows 3.5 kg/s airflow through.	Little airflow was recorded going through the brattice wall and was unable to measure due to large haulage and mine vehicles.
Node 1.	3 kg/s air flows into the level at no. 1.	Minimal airflow was recorded at the main haulage of the level due to the large size of the haulage.
Airflow between Node 1 and 8.	1 kg/s air flows into the workshop (to Node 2), and 2 kg/s air flows between Node 1 and Node 8.	Airflow was recorded during the audit between Node 1 and 8 as well as Node 1 and 2 in the direction of the arrows. The brattice wall created an airflow restriction and less air would, therefore, flow between Node 1 and 2.
Mass balance		
Airflow from Node 5 to 2.	The brattice allowed 3.5 kg/s air through, and 1 kg/s air was assumed to flow into the workshop haulage. Thus, the mass balance indicated that 2.5 kg/s air flows from Node 5 to 2 ($2.5 \text{ kg/s} + 1 \text{ kg/s} = 3.5 \text{ kg/s}$).	
Airflow at Node 5.	The fan at Node 10 was assumed to deliver 25 kg/s, and 2.5 kg/s was flowing from Node 5 to Node 2. With mass balancing, the total airflow at Node 5 is, therefore 27.5 kg/s.	
Airflow between Node 9 and 7.	Mass balance calculations: $9.5 \text{ kg/s} = 27.5 \text{ kg/s} - 3.5 \text{ kg/s} - 14.5 \text{ kg/s}$	
Airflow to Node 12.	Mass balance calculations: $13.5 \text{ kg/s} = 28.85 \text{ kg/s} - 10 \text{ kg/s} - 5.35 \text{ kg/s}$	

Table 3-6 listed and discussed all the assumptions that were made and how the mass balanced was carried out. Figure 3-6 is a schematic diagram of the identified level.

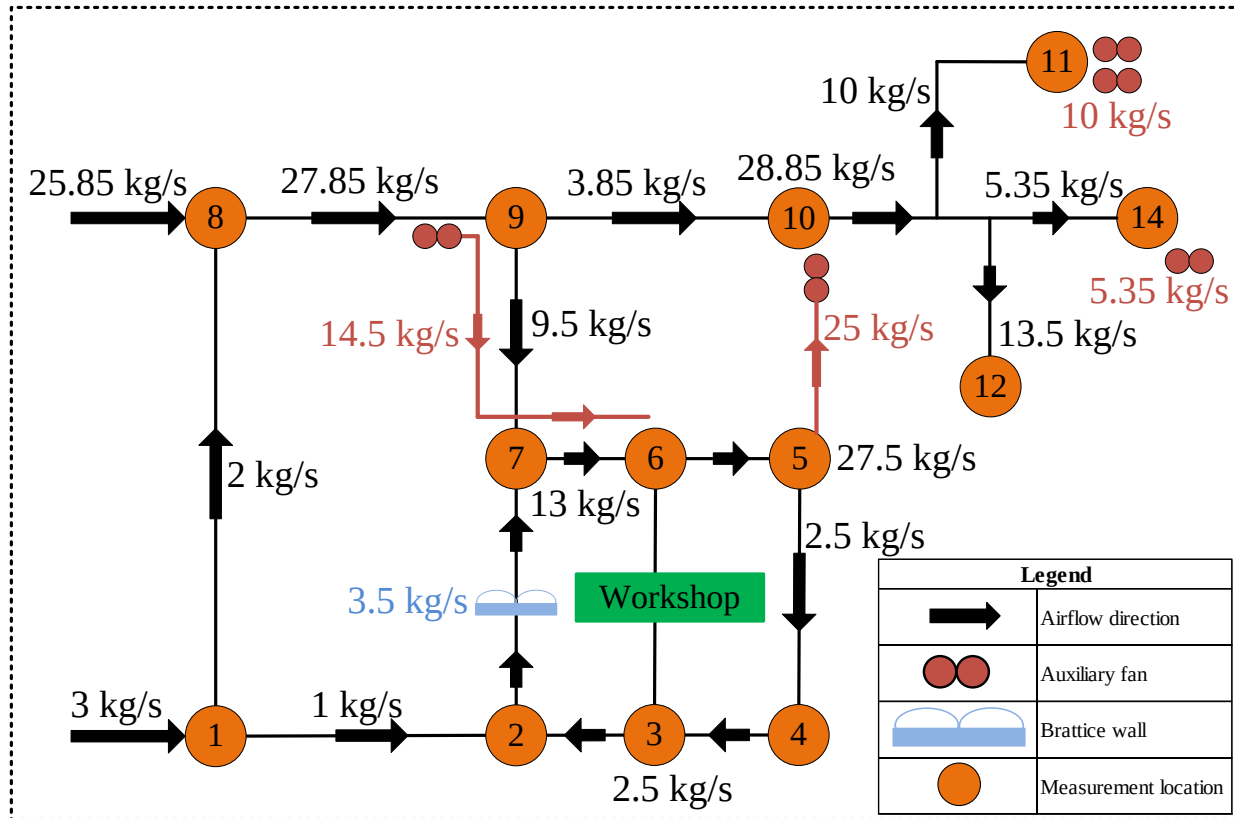


Figure 3-6: Assumptions and mass balance calculations for ventilation network

The orange numbers in Figure 3-6 represent the measurement locations of the underground audit. The final air mass flow values for the baseline were derived from the assumptions and the mass balance calculations as described and listed in Table 3-6 and Figure 3-6.

Figure 3-7 illustrates the actual baseline conditions after the assumptions and mass balance were considered. An enlarge layout is included in Appendix B (Figure B-4).

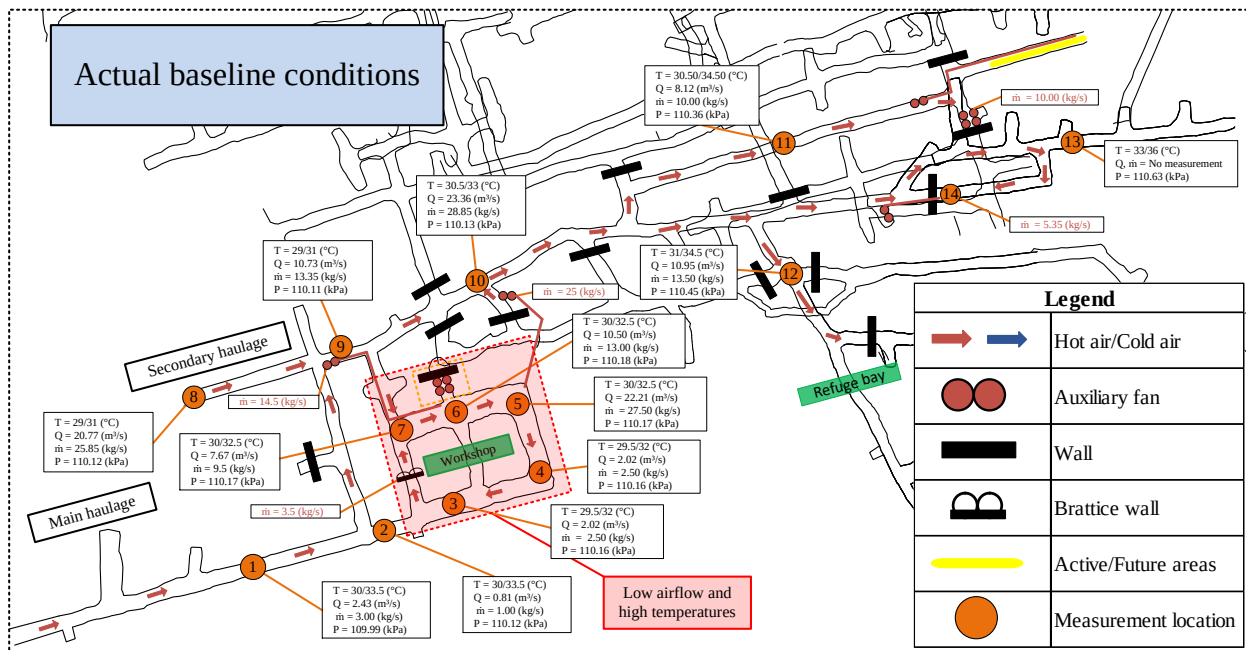


Figure 3-7: Layout of Level X (Mine A) with corrected audit results as baseline conditions

The corrected baseline conditions illustrated by Figure 3-7 show low airflow and high temperatures at the workshop area. The inefficiencies thereof are evaluated next.

This section established the actual baseline conditions of the inefficient ventilation network. A good understanding of this level and its ventilation conditions was obtained through the audit and data analysis. Section 3.2.2 indicated that the only ventilation inefficiencies identified on Level X were the insufficient airflow and high temperatures in the workshop area. Phase 2 of the developed solution strategy is provided next, which describes how the inefficiencies were mitigated using the simulation model in PTB 3D.

3.3 Phase 2: Develop and verify simulation model

Phase 2 of the methodology entails developing and verifying the simulation model from the data obtained and analysed in Phase 1. The three steps, defined in Figure 3-8, were followed to develop, verify and simulate different scenarios of the localised ventilation network of Level X.

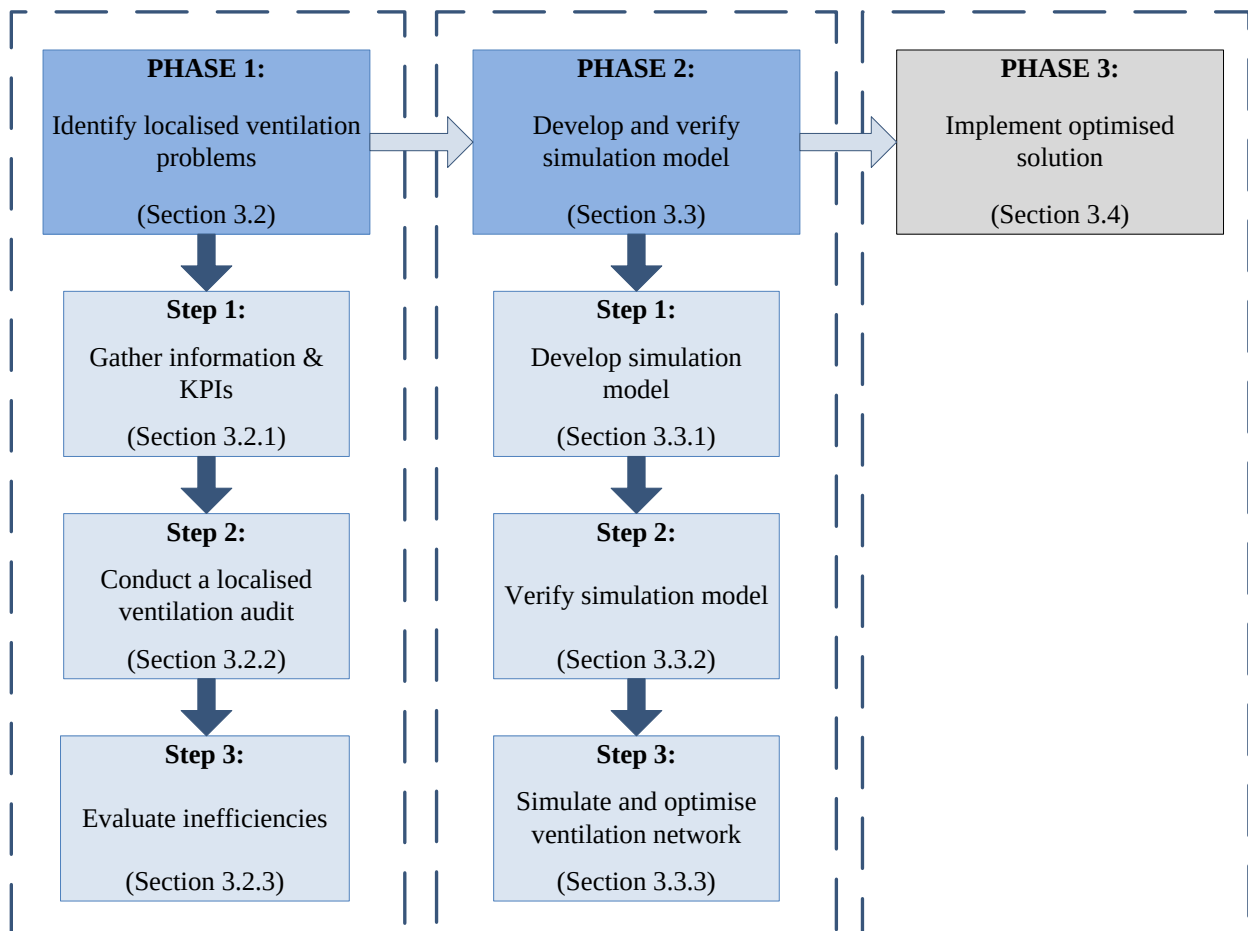


Figure 3-8: Develop and verify simulation model of the case study

The data obtained from the audit and relevant mine personnel was used and analysed in Phase 1, which assisted in constructing the simulation model in Phase 2, Step 1. PTB 3D, which was described and discussed in Section 1.3.2, was found to be the most suitable simulation package; therefore, it was used for the case study of Level X at Mine A.

In Phase 1, Step 2, the simulation model was verified and calibrated through the actual baseline conditions determined in Section 3.2.3. Thereafter, the accuracy was determined between the actual baseline conditions and the calibrated simulation results. The simulation model was used in Phase 1, Step 3 to optimise the ventilation network until suitable scenarios were found that were feasible and easy to accomplish.

3.3.1 Step 1: Develop simulation model

As mentioned, the PTB simulation package was used to construct and simulate the localised case study ventilation network (Level X), which was identified with ventilation inefficiencies. Level X was constructed using all the data and information obtained in Section 3.2. The actual baseline conditions and KPIs were the main parameters and components on which the simulation model was based.

It is essential to follow the instructions to build the simulation model given in Section 2.3.1. Figure 3-7 (the final baseline conditions of Level X in Section 3.2.3) was used as guidance to construct the simulation model. Figure 3-9 illustrates the component view of Level X constructed in PTB 3D simulation software.



Figure 3-9: PTB 3D simulation model component view of Level X

The view in Figure 3-9 is known as the component view. It shows all the types of components as discussed in Section 2.3.1 individually. Figure 3-10 illustrates a clear view of the level in PTB 3D, which is also known as the engineering view.



Figure 3-10: PTB 3D simulation model engineering view of Level X

The engineering view in Figure 3-10 indicates more detail regarding ventilation components, such as brattice walls, auxiliary fans and walls, which are clearly seen on the level. An enlarged 3D view of the localised simulation model is included in Appendix B, Figure B-5. The ventilation network of Level X was constructed in Step 1 of Phase 2. The following section, Step 2, focuses on verifying and calibrating the simulation model. The actual baseline conditions and the calibrated simulation results are compared. After the verification, the simulation model is used to mitigate all ventilation inefficiencies, and different scenarios are simulated.

3.3.2 Step 2: Verify simulation model

The actual baseline conditions determined in Section 3.2.3 (and illustrated by Figure 3-7) were used as input values for the simulation model. The baseline measurement locations were classified as nodes and tunnels in the PTB 3D simulation model. The process to calibrate the simulation model (described in Section 2.3.2) was followed in detail, and the following was done:

- Location 1 and Location 8 in Figure 3-7 were used as the inlet boundary conditions.
- The fan curves as well as the assumption and calibration controls regarding the fans were used throughout the localised simulation model to obtain the airflow in different sections of the level.

- Calibration controllers were used throughout the entire simulation model to control the resistance of the tunnels and brattice walls accurately.
- The VRT of each tunnel and heat pick-up was adjusted to match the temperatures measured during the audit.
- The furthest measurement locations and their values in Figure 3-7 were used as the outlet boundary conditions.

Thereafter, the simulation model was calibrated. Figure 3-11 illustrates the simulation model results after calibration. An enlarged view is included in Appendix B, Figure B-6.

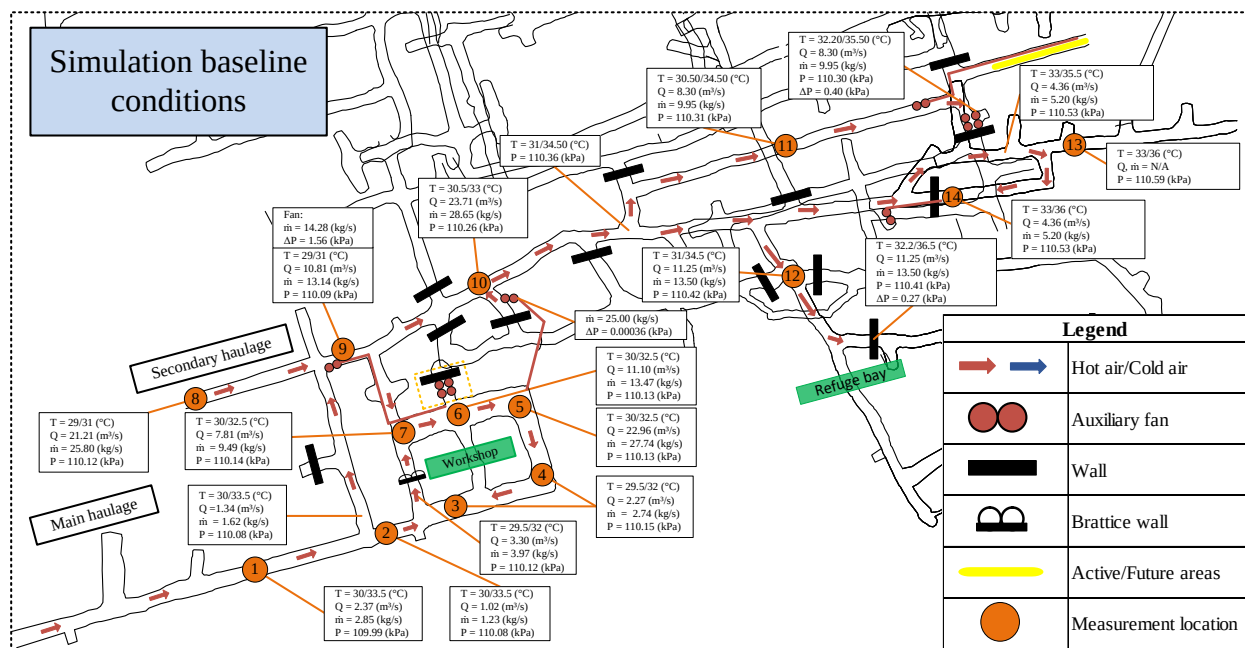


Figure 3-11: Simulation baseline conditions of Level X

The simulation baseline conditions of Level X, illustrated by Figure 3-11, were determined through PTB 3D. Next, the actual baseline conditions are compared with the simulated baseline conditions to indicate the accuracy of the model (with a percentage error) and verify the simulation.

Compare simulation baseline conditions with actual baseline conditions

Table 3-7 indicates the percentage error of each measurement location between the actual baseline conditions and simulation baseline conditions. The table shows that the average wet-bulb and dry-bulb temperatures were calibrated accurately and did not show any significant percentage error difference. The average percentage error of the air mass flow indicates a value of 4%. Thus, the

average percentage error between the actual baseline and the simulation model is 4% and therefore under 5%.

Table 3-7: Actual baseline conditions vs. simulation baseline conditions

Measurement location	Actual baseline conditions			Simulation baseline conditions			Percentage error (%)		
	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)
1: Level inlet	30.0	33.5	3.0	30.0	33.5	2.9	0.0	0.0	5.3
2: Workshop inlet	30.0	33.5	1.0	30.0	33.5	1.2	0.0	0.0	18.7
3: Workshop	29.5	32.0	2.5	29.5	32.0	2.7	0.0	0.0	8.8
4: Workshop	29.5	32.0	2.5	29.5	32.0	2.7	0.0	0.0	8.8
5: Workshop	30.0	32.5	27.5	30.0	32.5	27.7	0.0	0.0	0.9
6: Workshop	30.0	32.5	13.0	30.0	32.5	13.5	0.0	0.0	3.5
7: Workshop	30.0	32.5	9.5	30.0	32.5	9.5	0.0	0.0	0.1
8: Secondary inlet	29.0	31.0	25.9	29.0	31.0	25.8	0.0	0.0	0.2
9: Behind workshop	29.0	31.0	13.4	29.0	31.0	13.1	0.0	0.0	1.6
10: To mining area	30.5	33.0	28.9	30.5	33.0	28.7	0.0	0.0	0.7
11: Dos 7 flow	30.5	34.5	10.0	30.5	34.5	10.0	0.0	0.0	0.5
12: RAW flow	31.0	34.5	13.5	31.0	34.5	13.5	0.0	0.0	0.0
13: Development end	33.0	36.0	N/A	33.0	36.0	0.0	0.0	0.0	N/A
14: RAW flow	N/M	N/M	5.4	33.0	36.0	5.2	N/A	N/A	2.9
Average:	30.2	33.0	12.0	30.2	33.0	11.2	0.0	0.0	4.0

The average errors of all three parameters are also illustrated in Figure 3-12.

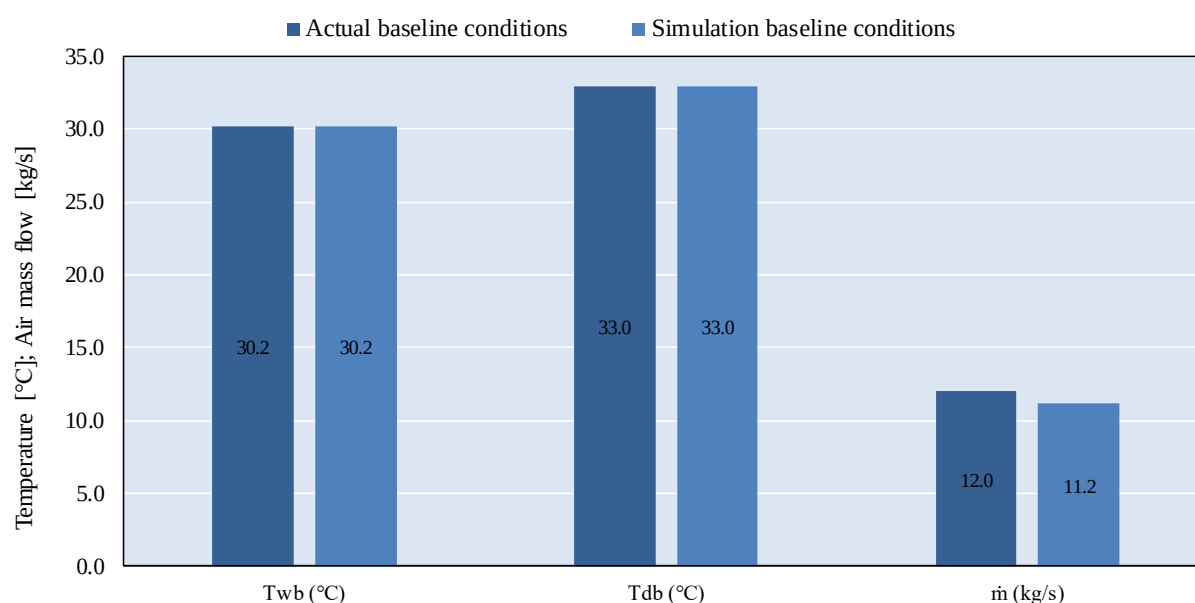


Figure 3-12: Actual baseline conditions vs. simulation baseline conditions of Level X

The simulation model was considered as accurate and could be used to mitigate the ventilation inefficiencies. Three scenarios are proposed in Section 3.3.3, the final step of the second phase.

3.3.3 Step 3: Simulate and optimise ventilation network

The inefficient ventilation network of Level X was built and calibrated to obtain a simulation baseline model. The different ventilation inefficiencies discussed in Section 2.2.3 were used to identify the inefficient areas of the level. The simulation model was used to mitigate these inefficiencies and optimise the ventilation network. Different scenarios were simulated to provide unique solutions for the level inefficiencies. These scenarios ensured sufficient airflow through the workshop area and decreased the temperature throughout the level.

Scenario 1

The following assumptions were made in order to calibrate Scenario 1 accurately:

- Chill pond outlet airflow temperature conditions are 20°C (T_{wb}) and 23°C (T_{db}).
 - As mentioned in Phase 1, Step 1 (Section 3.2.1), a chill pond is situated close to the Level X entrance and delivers the approximate air temperatures provided.
- The two new 45 kW fans installed in the workshop deliver 25.61 m³/s (31.06 kg/s) combined.
 - A 45 kW fan delivers between 10 kg/s and 15 kg/s.

- The ducting extracts 9.65 kg/s of chill pond air.
 - The brattice walls allow a maximum of 9 kg/s air through.
 - The inlet boundary conditions were held constant for both the baseline and three scenarios.
- This will not always be the case as the inlet conditions vary according to the resistance changes at the intake of the level and the amount of air flowing from the other level.

Scenario 1 was simulated with the changes shown in Figure 3-13 (enlarged view available in Appendix B). Figure 3-13 shows symbols A – H, which are explained in Table 3-8.

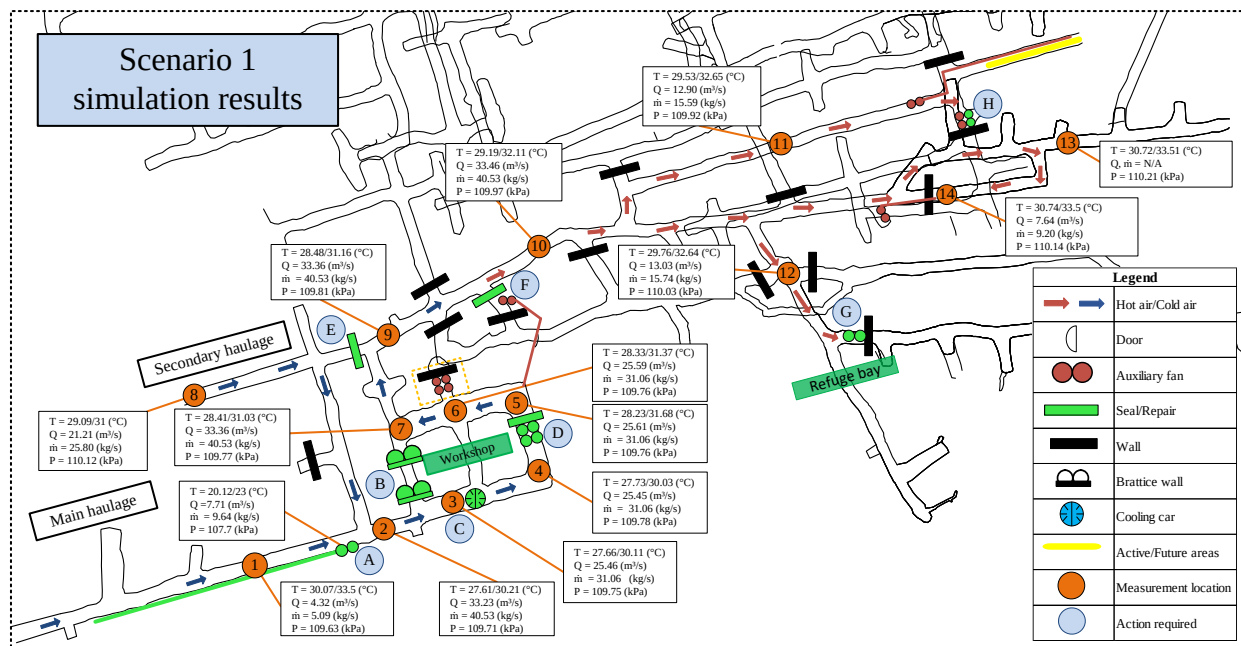


Figure 3-13: Scenario 1 simulation results

The actions listed in Table 3-8 must be carried out to obtain the estimated results of Scenario 1, illustrated in Figure 3-13:

Table 3-8: Action list for Scenario 1

Action	Description	Comment
A	Install fan with ducting.	Relocate fan on the level and install ducting.
B	Install double brattice wall.	Use the materials of the mine. There is no additional cost.
C	Install cooling car.	Use existing cooling car of mine and relocate the cooling car. No additional cost.
D	Build a wall with two 45 kW fans.	Install two new fans.
E	Build a wall.	Use the materials of the mine. There is no additional cost.

Action	Description	Comment
F	Build a wall.	Use the materials of the mine. There is no additional cost.
G	Install a 75 kW fan.	Install new fan, which adds cost.
H	Install a 75 kW fan.	Existing fan. There is no additional cost.
Annual electricity cost increase:		R 683 827.24*

*PTB 3D calculated the costs by inserting the electrical rating of the fan and Eskom time-of-use tariffs.

If all the actions of Scenario 1 were to be implemented, an approximate R700 000 would be contributed to the annual electricity costs due to the new fan installations under Action D and Action G. Table 3-9 provides a detailed comparison of the conditions at each measurement location between the simulation baseline and Scenario 1.

Table 3-9: Comparison between simulation baseline and Scenario 1 conditions

Measurement location	Simulation baseline conditions			Scenario 1			Difference (–)		
	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)
1: Level inlet	30.0	33.5	2.85	30.07	33.5	5.09	0.07	0.0	2.24
2: Workshop inlet	30.0	33.5	1.23	27.61	30.21	40.53	–2.39	–3.29	39.30 ^c
3: Workshop	29.5	32.0	2.74	27.66	30.11	31.06	–1.84	–1.89	28.32
4: Workshop	29.5	32.0	2.74	27.73	30.03	31.06	–1.77	–1.97	28.32
5: Workshop	30.0	32.5	27.74	28.23	31.68	31.06	–1.77	–0.82	3.32
6: Workshop	30.0	32.5	13.47	28.33	31.37	31.06	–1.67	–1.13	17.59
7: Workshop	30.0	32.5	9.49	28.41	31.03	40.53	–1.59	–1.47	31.04
8: Secondary inlet	29.0	31.0	25.8	29.09	31.0	25.80	0.09	0.0	0.0
9: Behind workshop	29.0	31.0	13.14	28.48	31.16	40.53	–0.52	0.16	27.39
10: To mining area	30.5	33.0	28.65	29.19	32.11	40.53	–1.31	–0.89	11.88
11: Dos 7 flow	30.5	34.5	9.95	29.53	32.65	15.59	–0.97	–1.85	5.64
12: RAW flow	31.0	34.5	13.5	29.76	32.64	15.74	–1.24	–1.86	2.24
13: Development end	33.0	36.0	0.0	30.72	33.51	N/A	–2.28	–2.49	N/A
14: RAW flow	33.0	36.0	5.2	30.74	33.5	9.2	–2.26	–2.5	4.0
Average (no. 3–7) workshop area	29.8	32.3	11.24	28.07	30.84	32.95	–1.73^b	–1.46	21.72^d
Average entire level	30.36	33.18	11.18	28.97	31.75	27.52	–1.39^a	–1.67	16.77

The average wet-bulb temperature was estimated to decrease by 1.39°C^a over the entire level and it was estimated to decrease by 1.73°C^b in the workshop. The inlet airflow to the workshop (Location 2) was estimated to increase by 39.30 kg/s^c. The average airflow through the workshop (Locations 3–7) was estimated to increase by 21.72 kg/s^d if the Scenario 1 ventilation plan was to be implemented.

Scenario 2

The following assumptions were made in order to calibrate Scenario 2 accurately:

- Chill pond outlet airflow temperature conditions are 20°C (T_{wb}) and 23°C (T_{db}).
 - As mentioned in Phase 1, Step 1 (Section 3.2.1), a chill pond is situated close to the Level X entrance and delivers the approximate air temperatures provided.
- The ducting extracts 9.65 kg/s of chill pond air.
- The brattice walls allow a maximum of 9 kg/s air through.
- The inlet boundary conditions were held constant for both the baseline and three scenarios. This would not always be the case as the inlet conditions vary according to the resistance changes at the intake of the level and the amount of air flowing from the other level.

Scenario 2 was simulated with the changes shown in Figure 3-14. An enlarged view of Figure 3-14 is included in Appendix B, Figure B-8. Again, the figure contains symbols A–G, which are explained in Table 3-10.

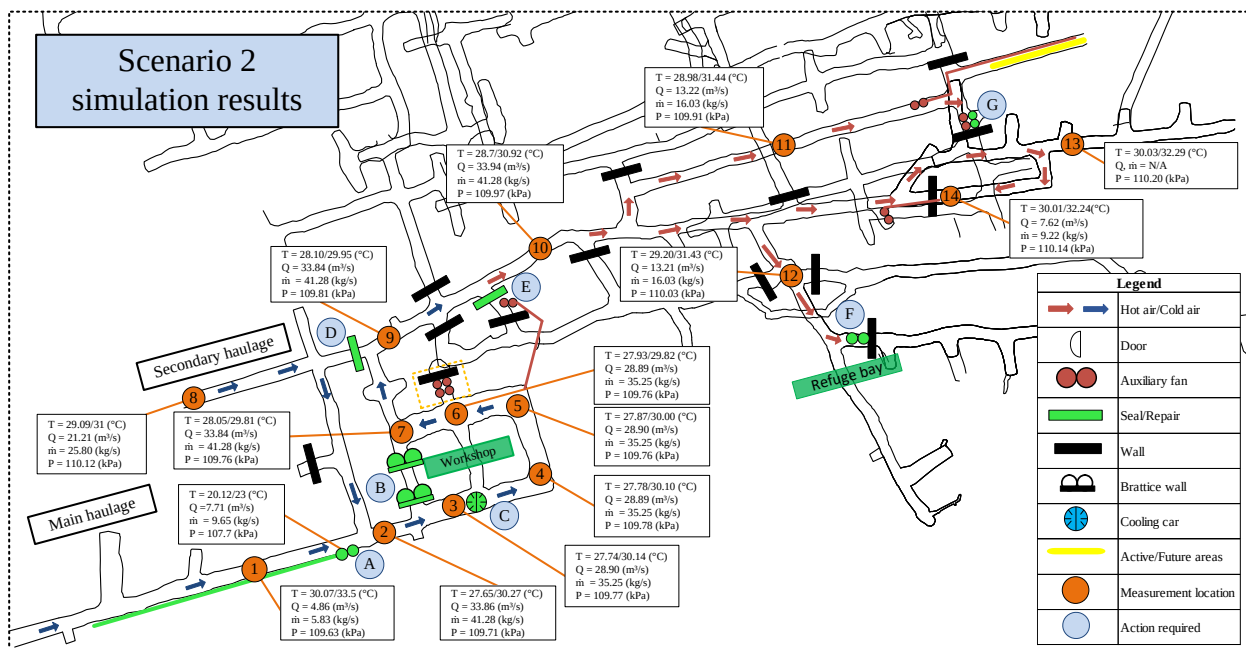


Figure 3-14: Scenario 2 simulation results

The actions listed in Table 3-10 must be carried out to obtain the estimated results of Scenario 2, illustrated in Figure 3-14.

Table 3-10: Action list for Scenario 2

Action	Description	Comment
A	Install fan with ducting.	Relocate fan on the level and install ducting. There is no additional cost.
B	Install double brattice wall.	Use the materials of the mine. There is no additional cost.
C	Install cooling car.	Use existing cooling car of mine and relocate the cooling car. There is no additional cost.
D	Build a wall.	Use the materials of the mine. There is no additional cost.
E	Build a wall.	Use the materials of the mine. There is no additional cost.
F	Install a 75 kW fan.	Install new fan, which adds cost.
G	Install a 75 kW fan.	Install new fan, which adds cost.
Annual electricity cost increase:		R 170 956.81*

*PTB 3D calculated the costs by inserting the electrical rating of the fan and Eskom time-of-use tariffs.

If all the actions of Scenario 2 were to be implemented, an approximate of R200 000 would be contributed to the annual electricity costs due to the new fan installations under action F and G. Table 3-11 shows a detailed comparison of the conditions at each measurement location between the simulation baseline and Scenario 2.

Table 3-11: Comparison between simulation baseline and Scenario 2 conditions

Measurement location	Simulation baseline conditions			Scenario 2			Difference (-)		
	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)
1: Level inlet	30.0	33.5	2.85	30.07	33.5	5.83	0.07	0.0	2.98
2: Workshop inlet	30.0	33.5	1.23	27.65	30.27	41.28	-2.35	-3.23	40.05 ^c
3: Workshop	29.5	32.0	2.74	27.74	30.14	35.25	-1.76	-1.86	32.51
4: Workshop	29.5	32.0	2.74	27.78	30.1	35.25	-1.72	-1.90	32.51
5: Workshop	30.0	32.5	27.74	27.87	30.0	35.25	-2.13	-2.50	7.51
6: Workshop	30.0	32.5	13.47	27.93	29.82	35.25	-2.07	-2.68	21.78
7: Workshop	30.0	32.5	9.49	28.05	29.81	41.28	-1.95	-2.69	31.79
8: Secondary inlet	29.0	31.0	25.8	29.09	31.0	25.8	0.09	0.0	0.0
9: Behind workshop	29.0	31.0	13.14	28.1	29.95	41.28	-0.90	-1.05	28.14
10: To mining area	30.5	33.0	28.65	28.7	30.92	41.28	-1.80	-2.08	12.63
11: Dos 7 flow	30.5	34.5	9.95	28.89	31.44	16.03	-1.61	-3.06	6.08
12: RAW flow	31.0	34.5	13.5	29.2	31.43	16.03	-1.8	-3.07	2.53
13: Development end	33.0	36.0	0.0	30.03	32.29	N/A	-2.97	-3.71	N/A
14: RAW flow	33.0	36.0	5.2	30.01	32.24	9.22	-2.99	-3.76	4.02

Measurement location	Simulation baseline conditions			Scenario 2			Difference (–)		
	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)
Average (no. 3–7) workshop area	29.8	32.3	11.24	27.87	29.97	36.46	–1.93 ^b	–2.33	25.22 ^d
Average entire level	30.36	33.18	11.18	28.65	30.92	29.16	–1.71 ^a	–2.63	18.54

The average wet-bulb temperature was estimated to decrease by 1.71°C^a over the entire level and by 1.93°C^b in the workshop area. The inlet airflow to the workshop (no. 2) was estimated to increase by 40.05 kg/s^c. The average airflow through the workshop (no. 3–7) was estimated to increase by 25.22 kg/s^d should Scenario 2 be implemented.

Scenario 3

The following assumptions were made in order to calibrate Scenario 3 accurately:

- Chill pond outlet airflow temperature conditions are 20°C (T_{wb}) and 23°C (T_{db}).
 - As mentioned in Phase 1, Step 1 (Section 3.2.1), a chill pond is situated close to the Level X entrance and delivers approximately the air temperatures provided.
- The brattice walls allow a maximum of 9 kg/s air through.
- The inlet boundary conditions were held constant for both the baseline and three scenarios. This would not always be the case as the inlet conditions vary according to the resistance changes at the intake of the level and the amount of air flowing from the other level.

Scenario 3 was simulated with the changes shown in Figure 3-15. An enlarged view of Figure 3-15 is included in Appendix B.

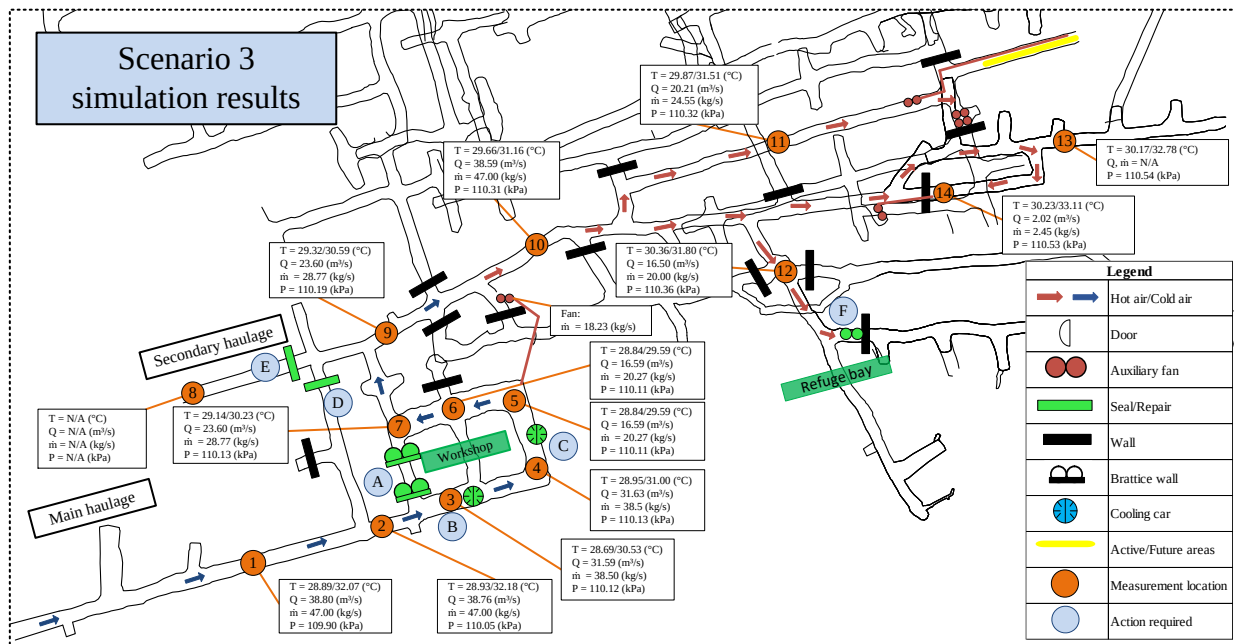


Figure 3-15: Scenario 3 simulation results

The actions listed in Table 3-12 must be carried out to obtain the estimated results of Scenario 3, illustrated in Figure 3-15.

Table 3-12: Action list for Scenario 3

Action	Description	Comment
A	Install double brattice wall.	Use the materials of the mine. There is no additional cost.
B	Install cooling car.	Relocate the existing cooling car of the mine. There is no additional cost.
C	Install cooling car.	Relocate the existing cooling car of the mine. There is no additional cost.
D	Build a wall.	Use the materials of the mine. There is no additional cost.
E	Build a wall.	Use the materials of the mine. There is no additional cost.
F	Install a 75 kW fan.	Existing fan. There is no additional cost.
Annual electricity cost increase:		R 0.00*

*PTB 3D calculated the costs by inserting the electrical rating of the fan and Eskom time-of-use tariffs.

If all the actions of Scenario 3 were to be implemented, no additional cost would be contributed to the annual electricity costs. Table 3-13 shows a detailed comparison of the conditions at each measurement location between the simulation baseline and Scenario 3.

Table 3-13: Comparison between simulation baseline and Scenario 3 conditions

Measurement location	Simulation baseline conditions			Scenario 3			Difference (–)		
	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)
1: Level inlet	30.0	33.5	2.85	28.89	32.07	47.0	–1.11	–1.43	44.15
2: Workshop inlet	30.0	33.5	1.23	28.93	32.18	47.0	–1.07	–1.32	45.77 ^c
3: Workshop	29.5	32.0	2.74	28.69	30.53	38.5	–0.81	–1.47	35.76
4: Workshop	29.5	32.0	2.74	28.95	31.00	38.5	–0.55	–1.00	35.76
5: Workshop	30.0	32.5	27.74	28.84	29.59	20.27	–1.16	–2.91	–7.47
6: Workshop	30.0	32.5	13.47	28.84	29.59	20.27	–1.16	–2.91	6.80
7: Workshop	30.0	32.5	9.49	29.14	30.23	28.77	–0.86	–2.27	19.28
8: Secondary inlet	29.0	31.0	25.8	N/A	N/A	N/A	N/A	N/A	N/A
9: Behind workshop	29.0	31.0	13.14	29.32	30.59	28.77	0.32	–0.41	15.63
10: To mining area	30.5	33.0	28.65	29.66	31.16	47.0	–0.84	–1.84	18.35
11: Dos 7 flow	30.5	34.5	9.95	29.87	31.51	24.55	–0.63	–2.99	14.60
12: RAW flow	31.0	34.5	13.5	30.36	31.8	20.0	–0.64	–2.70	6.50
13: Development end	33.0	36.0	0.0	30.17	32.78	N/A	–2.83	–3.22	N/A
14: RAW flow	33.0	36.0	5.2	30.23	33.11	2.45	–2.77	–2.89	–2.75
Average (no. 3–7) workshop area	29.8	32.3	11.24	28.89	30.19	29.26	–0.91^b	–2.11	18.03^d
Average entire level	30.36	33.18	11.18	29.38	31.24	30.26	–1.09^a	–2.16	19.37

The average wet-bulb temperature was estimated to decrease by 1.09°C^a over the entire level and by 0.91°C^b in the workshop. The inlet airflow to the workshop (no. 2) was estimated to increase by 45.77 kg/s^c. The average airflow through the workshop (no. 3–7) was estimated to increase by 18.03 kg/s^d should the Scenario 3 ventilation plan be implemented.

Comparison between simulation baseline and scenarios

The simulation baseline model, which has already been confirmed as accurate in Figure 3-12, was compared with the different scenarios. The wet-bulb temperatures and air mass flows were considered the essential parameters for comparison. These KPIs were used to indicate which of the scenarios would be the most feasible and best possible solution for the ventilation network of Level X.

Figure 3-16 illustrates the average simulated wet-bulb temperature over the workshop area (Location 3–7) for the simulation baseline and each of the scenarios.

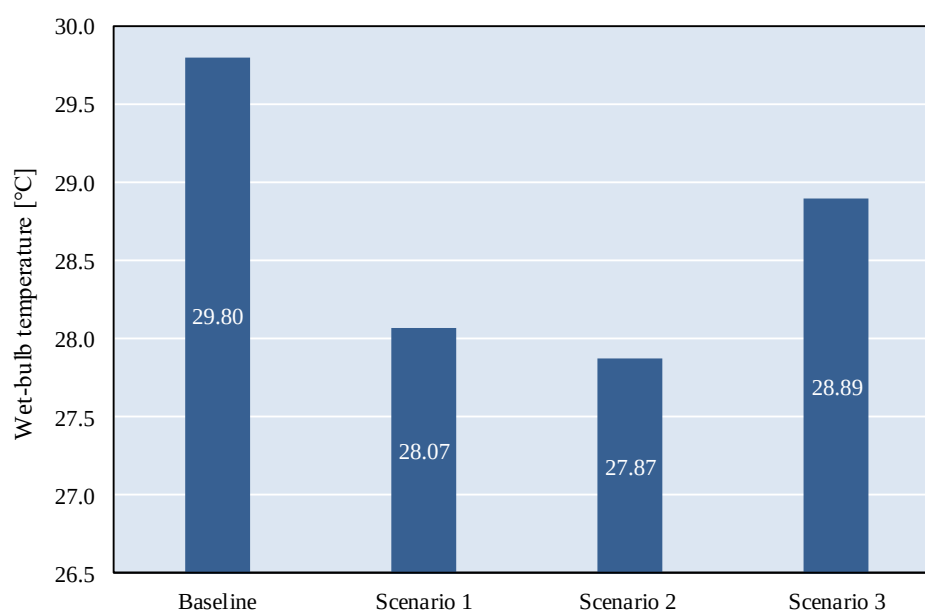


Figure 3-16: Average simulated wet-bulb temperatures over the workshop area

The baseline wet-bulb temperature decreased in each scenario; therefore, any of the three scenarios could be considered favourable. However, Scenario 2 resulted in the most significant decrease in workshop temperatures with a 1.93°C decrease. Scenario 1 resulted in the second-highest decrease of 1.73°C , whereas Scenario 3 showed a decrease of 0.91°C .

Figure 3-17 illustrates the average simulated air mass flow through the workshop area for the simulation baseline and each of the scenarios.

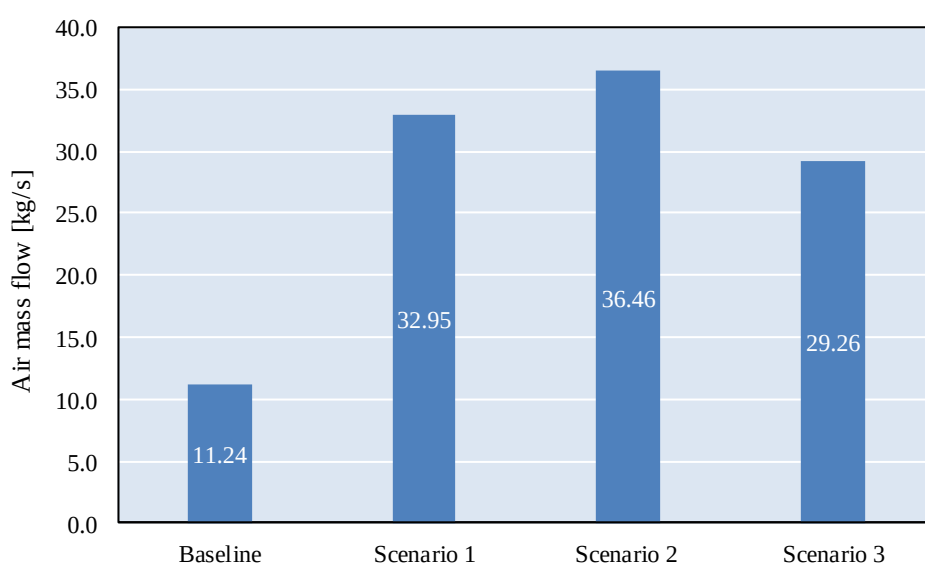


Figure 3-17: Average simulated air mass flow through the workshop area

The baseline air mass flow increased in each scenario; therefore, any scenario would be favourable. Scenario 2 resulted in the highest increase of 25.22 kg/s in air mass flow through the workshop area. Scenario 1 had the second-highest increase of air mass flow of 21.72 kg/s. Scenario 3 had the lowest increase of air mass flow of 18.03 kg/s through the workshop area.

From Figure 3-16 and Figure 3-17 it would appear that Scenario 2 delivered the most desirable results, followed by Scenario 1. The annual electricity cost for Scenario 2 is also approximately R513 000 less than annual electricity cost for Scenario 1. However, Scenario 3 has no annual electricity cost due to the relocation of ventilation component and the use of existing materials on the mine. Additionally, Scenario 2 and Scenario 3 require less labour as only two walls are required as opposed to the three walls in Scenario 1. Scenario 3 requires the lowest number of actions that must be completed to implement the ventilation plan and was therefore selected as the most feasible option. Note that Scenario 3 does not necessarily deliver the best results of the three. Scenario 3 must be reconsidered if more capital expenditure and time are available for additional installations.

In Phase 2, Step 1 aimed to construct a simulation model of an inefficient ventilation network of Level X. The data, information and calculations from Phase 1 were used to verify the simulation model in Step 2. In Step 3, the calibrated simulation model optimised the ventilation network of Level X, and three scenarios were presented. The last phase (Phase 3) of the methodology focuses on implementing and validating the selected scenario.

3.4 Phase 3: Implement optimised solution

The purpose of the first phase of the developed solution strategy was to gather information and data for each level of a mine. Through this process, a level was identified with possible ventilation concerns. An underground audit was conducted and the data processed. From the audit, ventilation inefficiencies were noted and a thorough understanding of the ventilation network was obtained. In the second phase, a simulation model was built of the level. All the ventilation inefficiencies were mitigated with three different scenarios. The implementation phase illustrated by Figure 3-18 is the final phase, which involves implementing and validating the best suitable scenario.

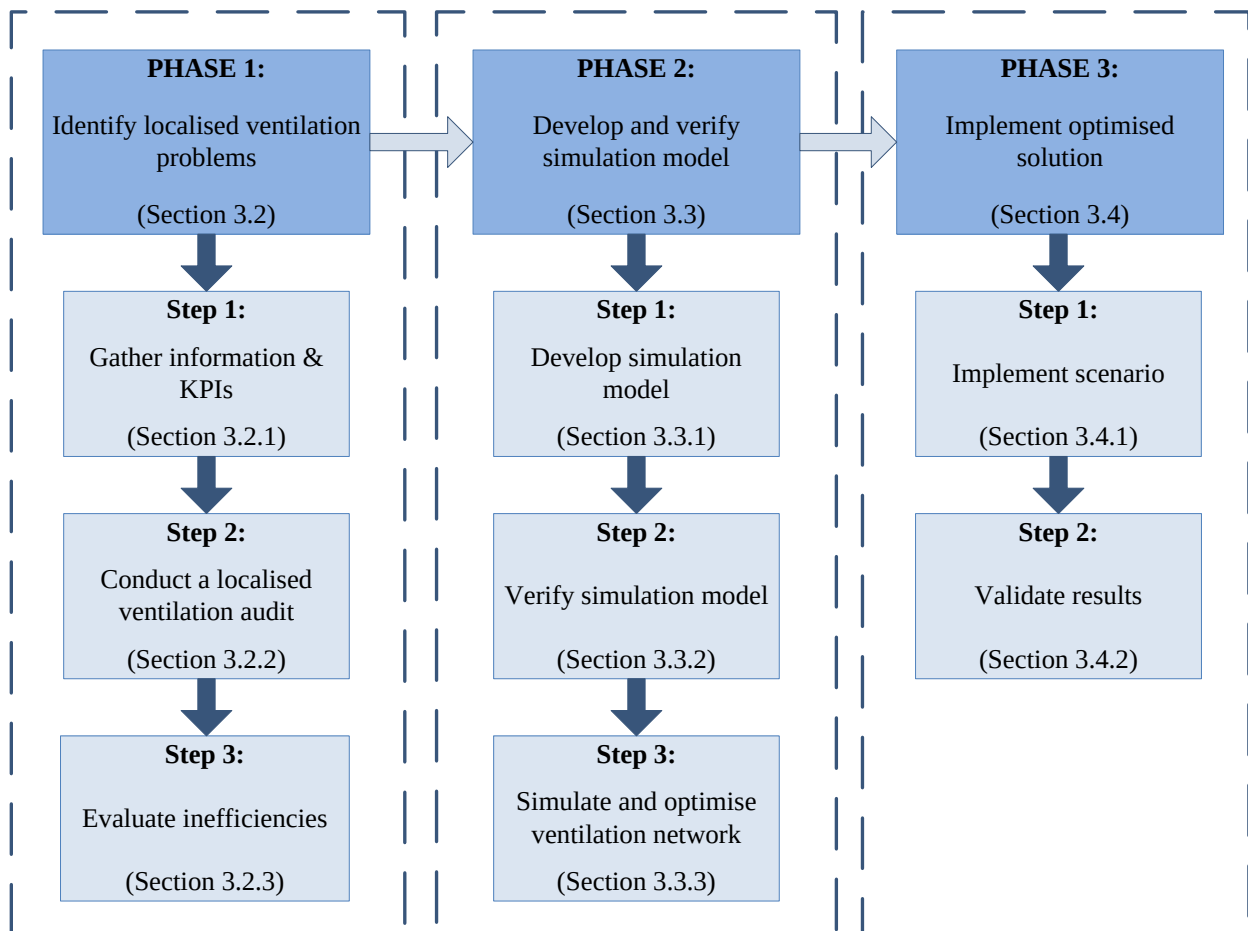


Figure 3-18: Implementing optimised solution of the case study

After implementing the selected scenario actions (discussed in Section 3.3.3) in the first step, the optimised localised ventilation network must be validated in the last step of the final phase. The area is audited once again, which is discussed in Section 3.4.2. The actual results are compared with the scenario simulation model results. The difference between the actual and simulation model results indicates the percentage error. Any shortcomings from the entire methodology are identified and noted.

3.4.1 Step 1: Implement scenario

Scenario 3 was selected as the most feasible scenario as there were no additional costs for executing the ventilation plan. Figure 3-19 (a simplification of Figure 3-16) illustrates the expected outcome of the average T_{wb} over the workshop area after implementing the Scenario 3 changes to the ventilation network of Level X.

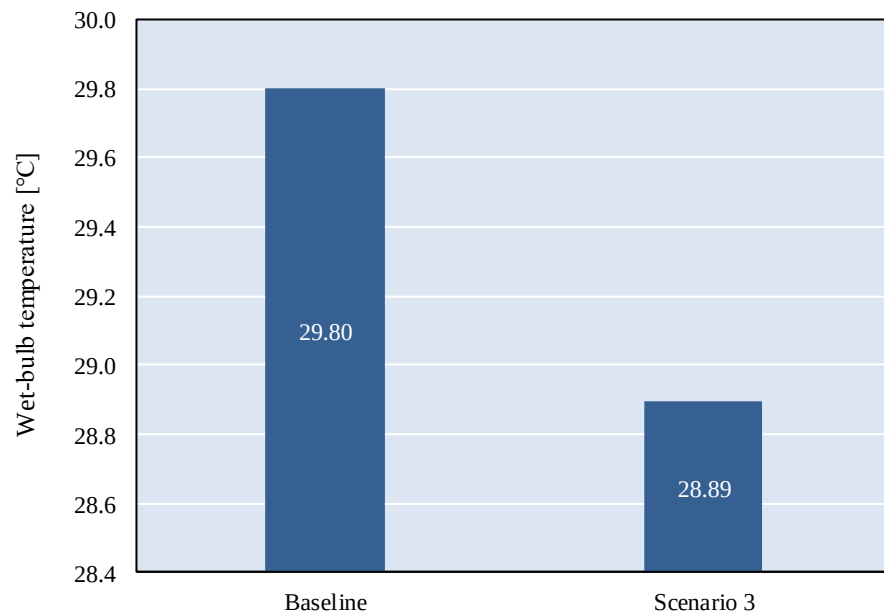


Figure 3-19: Simulation baseline vs Scenario 3 average wet-bulb temperature over the workshop area

The average wet-bulb temperature was estimated to decrease by 1.09°C over the entire level and by 0.91°C in the workshop area as indicated by Figure 3-19. Figure 3-20 (a simplification of Figure 3-17) illustrates the expected outcome of the average air mass flow through the workshop area after implementing the Scenario 3 changes to the ventilation network.

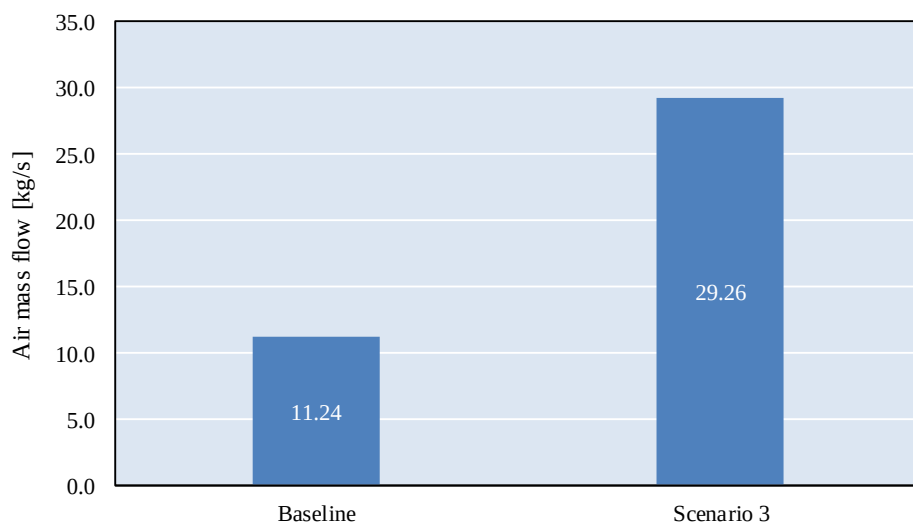


Figure 3-20: Simulation baseline vs Scenario 3 average air mass flow through the workshop area

The implementation of the Scenario 3 ventilation plan was estimated to increase the inlet airflow to the workshop by 45.77 kg/s, and the average airflow through the workshop by 18.03 kg/s. Scenario 3 was implemented as there were no additional costs and minimum labour was needed to complete the actions of the ventilation plan. The mine personnel who carried out the ventilation plan were the occupational hygienist and the ventilation officers. They worked a full week to complete the ventilation plan. The actions listed in Table 3-12 were carried out. The new changes made to the ventilation network of the workshop level are validated in the next and final step (Section 3.4.2).

3.4.2 Step 2: Validate case study results

Figure 3-21 illustrates the audit data after Scenario 3 was implemented. An enlarged view is included in Appendix B, Figure B-10. Only the first ten measurement locations were measured and validated to capture the changes made to the ventilation network. The audit results in Figure 3-21 and processed data are included in Appendix B, Table B-3 and Table B-4.

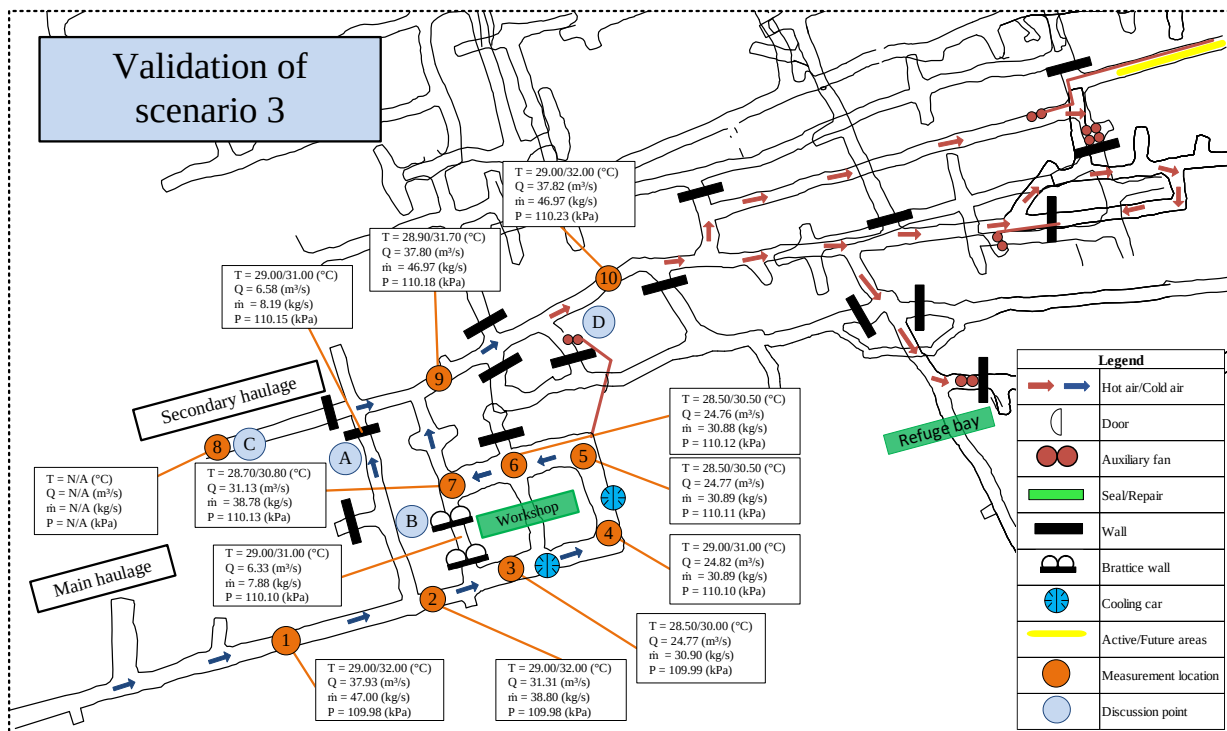


Figure 3-21: Validation of Scenario 3

The following discussion points, as indicated by A to D in Figure 3-21, were noted during the validation audit of Scenario 3:

- A. Airflow was measured to be leaking 8.19 kg/s through the wall that was built.
- B. The Scenario 3 simulation model allowed 8.5 kg/s through the brattice wall, and the audit value after implementation was 7.88 kg/s.
- C. Measurement Point 8 in Scenario 3 was left out due to the ventilation plan excluding the measurement point from the localised ventilation network.
- D. The fan was switched off during the audit.

The conditions proposed by Scenario 3 simulation model differed from the conditions recorded during the validation audit underground. The conditions created by the leakage through the wall and the fan that was switched off are compared next.

Scenario 3 simulation results vs. actual results

Table 3-14 indicates the percentage error of the wet-bulb and dry-bulb temperatures, as well as the air mass flow between the simulation and actual results after implementing Scenario 3.

Table 3-14: Comparison between scenario simulation and actual results

Measurement location	Scenario 3 simulation model			Actual results after Scenario 3 implementation			Percentage error (%)		
	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)	T _{wb} (°C)	T _{db} (°C)	$\dot{m}$ (kg/s)
1: Level inlet	28.89	32.07	47.0	29.0	32.0	47.0	0.38	0.22	0.0
2: Workshop inlet	28.93	32.18	47.0	29.0	32.0	38.8	0.24	0.56	21.13
3: Workshop	28.69	30.53	38.5	28.5	30.0	30.9	0.67	1.77	24.60
4: Workshop	28.95	31.00	38.5	29.0	31.0	30.89	0.17	0.00	24.64
5: Workshop	28.84	29.59	20.27	28.5	30.5	30.89	1.19	2.98	34.38
6: Workshop	28.84	29.59	20.27	28.5	30.5	30.88	1.19	2.98	34.36
7: Workshop	29.14	30.23	28.77	28.7	30.8	38.78	1.53	1.85	25.81
8: Secondary inlet	Measurement point excluded								
9: Behind workshop	29.32	30.59	28.77	28.9	31.7	46.97	1.45	3.50	38.75
10: To mining area	29.66	31.16	47.0	29.0	32.0	46.97	2.28	2.63	0.06
Average	29.03	30.77	35.12	28.79	31.17	38.01	1.01	1.83	22.64

Due to different conditions compared in Table 3-14, the average percentage error for the air mass flow was 22.64%, which was well above 5%. This discrepancy, which was discussed at the discussion points of the validation audit A-D, had a substantial effect on the overall accuracy of the air mass flow. The percentage error for the wet-bulb and dry-bulb temperatures were 1.01% and 1.83%, respectively. Figure 3-22 compares the average wet-bulb temperatures over the workshop area between the actual baseline, simulation baseline, scenario simulation and actual results after implementation.

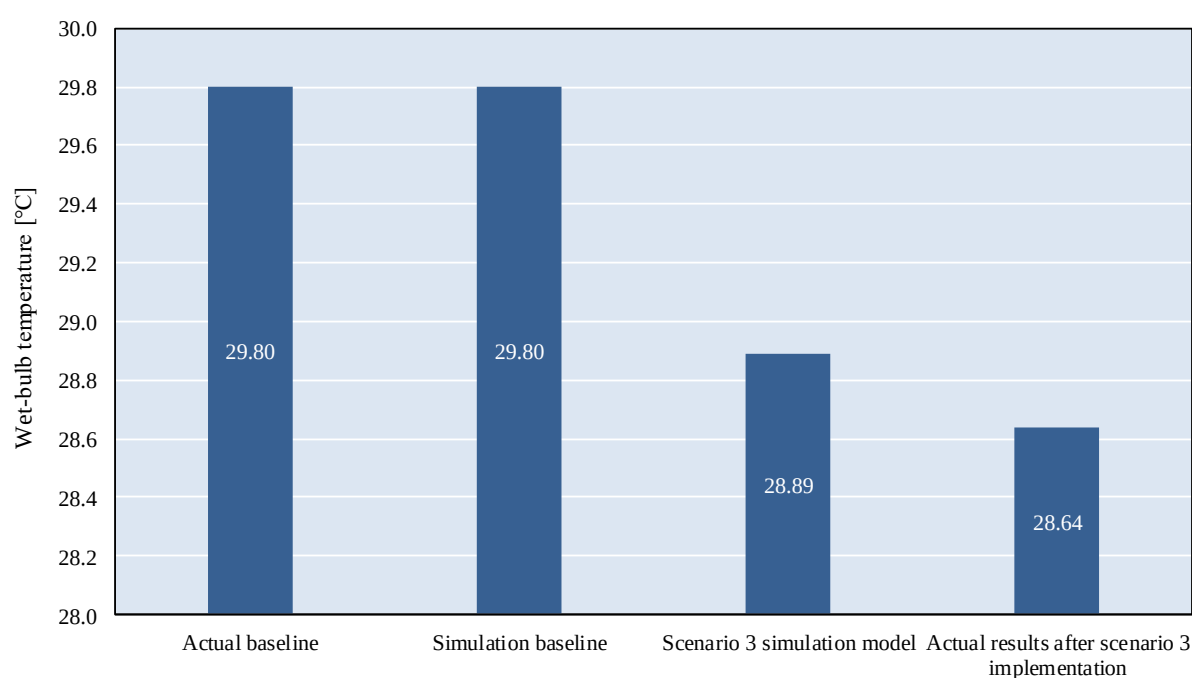


Figure 3-22: Comparison of average wet-bulb temperatures over workshop area

A comparison of the average wet-bulb temperature over the workshop area, as illustrated in Figure 3-22, between the actual baseline and simulation baseline showed no difference. It was calibrated accurately with a temperature of 29.8°C. The simulation model based on Scenario 3 estimated a decrease of 0.91°C in wet-bulb temperature. The actual measured temperature after implementing Scenario 3 was 28.64°C. Regardless of the defects during the implementation phase, the wet-bulb temperature difference in Figure 3-22 between the scenario and actual results was only 0.2°C, thus leaving the workshop area colder than simulated.

Figure 3-23 compares the average air mass flow through the workshop area between the actual baseline, simulation baseline, scenario simulation and actual results after implementation.

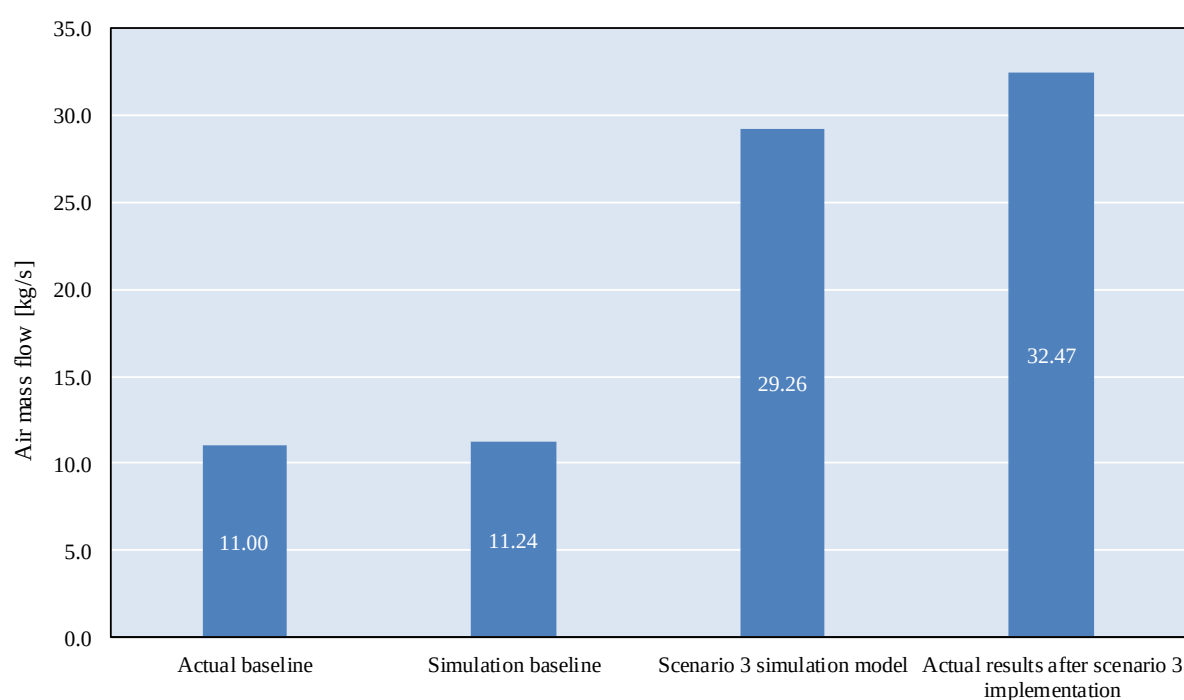


Figure 3-23: Comparison of average air mass flow through the workshop area

The average airflow through the workshop area, as illustrated in Figure 3-23, between the actual baseline and the simulation model differed by 0.24 kg/s. The overall percentage error was 4%, which indicated that the simulation model was calibrated accurately. Figure 3-23 shows the influence of the discrepancy on the air mass flow through the workshop area. The average air mass flow through the workshop area differed by 3.21 kg/s between the scenario simulation and actual results. Thus, the final airflow through the workshop area was 32.47 kg/s, which was higher than simulated. The percentage error of the air mass flow of the overall ventilation network was 22.64%.

Scenario 3 adjusted simulation results vs. actual results

Since the temperatures were validated accurately, the simulation model of Scenario 3's conditions was adjusted or simulated according to the conditions recorded during the validation of Scenario 3. This aligned the conditions of the validation results with the new simulated Scenario 3 conditions. Therefore, the air mass flow accuracy of the simulation model was determined.

Table 3-15 indicates the difference between the adjusted Scenario 3 simulation values that were simulated again, the actual results, and the percentage error. The following was done to align the simulation model of Scenario 3 with the actual results:

- Wall leaking 8.19 kg/s air at number A of Figure 3-21 (validation of Scenario 3).
 - Scenario 3 simulation calibration controller allowed 8.19 kg/s through the same wall.
- The fan at number D at the back of the workshop was switched off.
 - The fan was switched off in the simulation model of Scenario 3.
- The brattice wall allowed 7.88 kg/s air through at number B.
 - The calibration controller was set to allow 7.88 kg/s through the brattice wall.

Table 3-15: Comparison between adjusted scenario simulation and actual results

Measurement location	Scenario 3 simulation model adjustment	Actual results after Scenario 3 implementation	Percentage error (%)
	$\dot{m}$ (kg/s)	$\dot{m}$ (kg/s)	$\dot{m}$ (kg/s)
1: Level inlet	47.0	47.0	0.00
2: Workshop inlet	38.81	38.8	0.03
3: Workshop	30.93	30.9	0.10
4: Workshop	30.93	30.89	0.13
5: Workshop	30.93	30.89	0.13
6: Workshop	30.93	30.88	0.16
7: Workshop	38.81	38.78	0.08
8: Secondary inlet	Measurement point excluded		
9: Behind workshop	47.0	46.97	0.06
10: To mining area	47.0	46.97	0.06

After the values were adjusted, the average percentage error for the air mass flow decreased from 22.64% to 0.08%, which is well below 5%. The overall percentage error, after including temperatures from Table 3-14 (Comparison between scenario simulation and actual results), was 0.98%. It is concluded that with the percentage error lower than 5% and the actual results recorded through the validation step, that the simulation model is accurate and reliable.

Figure 3-24 compares the average air mass flow through the workshop area between the actual baseline, simulation baseline, adjusted Scenario 3 simulation model and actual results (repeat of Figure 3-23 with adjusted Scenario 3 simulation).

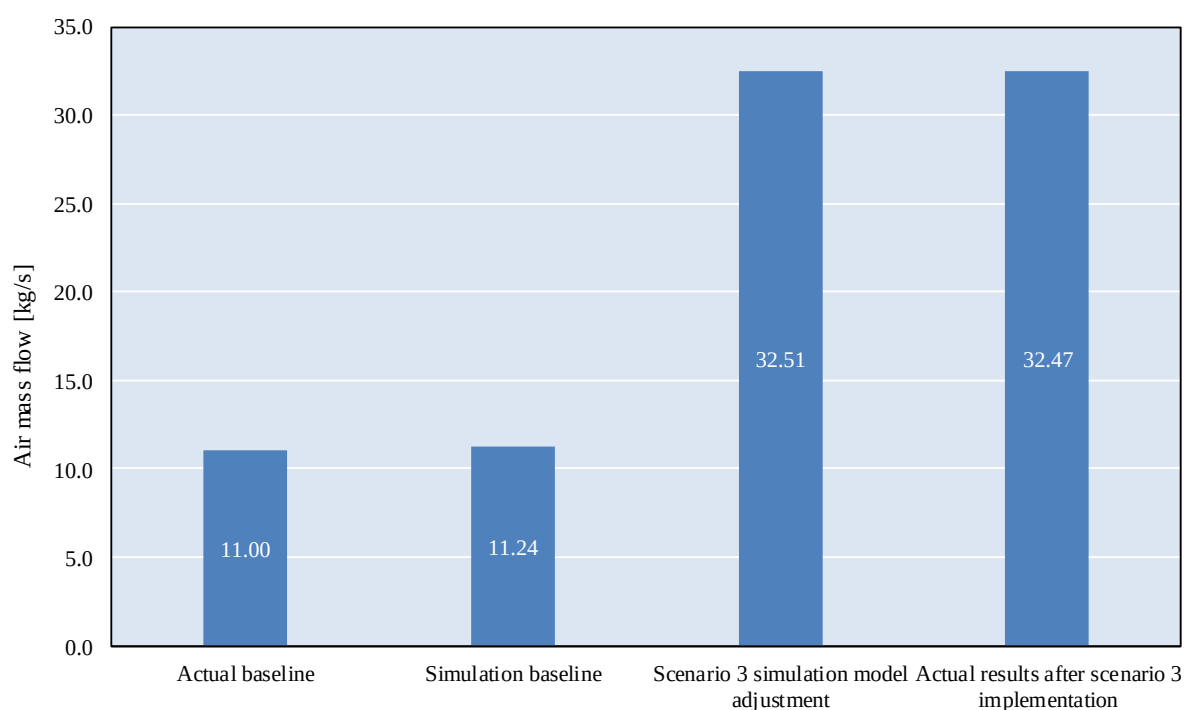


Figure 3-24: Comparison of average air mass flow through the workshop area with adjusted scenario simulation

The comparison between the actual and simulation baseline was discussed in Figure 3-23. The average air mass flow through the workshop area differed with 0.04 kg/s between the adjusted scenario simulation and actual results (0.12% difference).

Phase 3 focused on implementing one of the scenarios proposed in Section 3.3.3. Scenario 3 was selected in Step 1 as feasible and easy to accomplish. After implementing the changes to the inefficient ventilation network, the level was validated in the last step. The validation showed an overall percentage error of 0.98% between the simulation model and actual results.

3.5 Summary

In this chapter, the method developed in Chapter 2 was applied to an actual case study (Mine A). This method shown in Figure 3-1 is divided into three phases, namely: Phase 1) identify localised ventilation problems; Phase 2) develop and verify simulation model; and Phase 3) implement optimised solution.

Phase 1 identified localised ventilation problems by following three steps. In Step 1, Table 3-1 provided a checklist to gather information for the case study, showed where all level layouts and fan curves of Mine A were collected in hard copy and DXF file formats, and discussed the layout

with engineers and occupational hygienists. One particular level (Level X) was identified as having ventilation concerns. These concerns were noted and indicated in Figure 3-3 and in Table 3-2. The identified KPIs provided a platform for measuring all the essential parameters required for further analysis of the level and for constructing the simulation model in PTB 3D.

In Step 2, a ventilation audit was conducted to capture the conditions of Level X. The level had high temperatures and low airflow as illustrated in Figure 3-5. During the ventilation audit, a few restrictions were recorded. The haulages of the level were too large to measure accurately, which is indicated by Table 3-5. In Step 3, the assumptions listed in Table 3-6 were required to determine the actual baseline conditions of the level. After the actual baseline was established, illustrated by Figure 3-7, the workshop area of Level X was identified with low to no airflow, and the temperatures were too high. These inefficiencies were mitigated through PTB 3D in Phase 2.

Phase 2 consisted of three steps. Step 1 focused on constructing the simulation model in PTB 3D, which is illustrated in Figure 3-10. After the ventilation network was mimicked in PTB 3D in Step 1, it was necessary to verify the model with the actual baseline conditions determined in Section 3.2.3, which evaluated the ventilation inefficiencies.

The simulation model was calibrated in Step 2. The baseline conditions, illustrated in Figure 3-11, were compared with the actual baseline. A percentage error of 4% was achieved, which is below 5%, assuming that the model is accurate. In Step 3, different scenarios were simulated by PTB 3D. Each had a ventilation plan to increase the airflow through the workshop and decrease the temperatures. This led to the last phase of the generic solution strategy.

Phase 3 consisted of two steps. In Step 1, the Scenario 3 ventilation plan was selected as there were no additional electricity costs, the implementation only required a few actions, and it was considered easy to accomplish. The Scenario 3 simulation model estimated that the average wet-bulb temperature over the workshop area would decrease by 0.91°C and the average airflow through the workshop would increase by 18.03 kg/s.

After implementation, the changes made to the ventilation network of Level X were validated as illustrated in Figure 3-21 (Step 2). However, during the underground ventilation audit, the conditions proposed by the Scenario 3 simulation model were different from the actual conditions underground. Therefore, the air mass flow of the simulation values was adjusted, indicated by Table 3-15, to align with the conditions recorded underground. The average wet-bulb temperature

over the workshop area decreased by 1.16°C , which indicated a 0.25°C difference from what was estimated by Scenario 3. The air mass flow through the workshop area increased by 21.47 kg/s , indicating a 0.04 kg/s difference from what was estimated by the adjusted scenario. Therefore, the overall percentage error between the adjusted scenario and the actual results was 0.98% .

A localised simulation model of the problem area (Level X in Mine A) was built to mitigate the ventilation inefficiencies and improve the ventilation conditions on this level. The project timeline completing all the three phases took approximately 3 weeks. After Scenario 3 was simulated, tested and implemented, this chapter concluded that localised ventilation improvements could be evaluated using simulation models in a shorter time period.

CHAPTER 4

4 CONCLUSION AND RECOMMENDATION

4.1 Study summary

The gold mining industry has expanded over the last few years and mines have reached unexpected depths. The vast mining industry demands a large amount of electrical energy to support all of its processes. Thus, it is crucial to use electrical energy efficiently. The ventilation network of a mine consumes between 25% and 50% of the mine's total electrical energy. Different optimisation methods are available to save on the electrical costs of the ventilation system.

The ventilation network does not only consume a large amount of energy, but it also plays a vital role in the overall health and safety conditions of the mine environment. Each mineworker depends on an efficient ventilation network. If the network is inefficient, productivity decreases, which in turn decreases production. The importance of a ventilation network is stated clearly; without any form of ventilation, mines would cease to exist. A ventilation system is responsible for providing sufficient airflow in quantities and qualities to dilute and exhaust poisonous gases and dust throughout the mine environment.

Ventilation systems of the gold mining industry are challenging to manage due to the mines' vast networks and depths. Thus, factors and systems contribute to mine temperatures and expose dangerous gases on a much larger scale. The vast network consists of hundreds of connections, which make it complicated to ensure that ventilation regulations are followed. Therefore, it is time-consuming to investigate and understand the entire mine to identify any ventilation inefficiencies.

The study focused on developing a generic solution strategy that would identify ventilation problems on a localised ventilation network and mitigate the inefficiencies through a simulation model. A localised network would be easier and less time-consuming to investigate, analyse and implement ventilation improvements for optimisation. The method for evaluating localised ventilation improvements was divided into three phases: Phase 1 focused on identifying the localised ventilation problems of a level. Phase 2 required a simulation model to be constructed and verified in PTB 3D simulation software package. Thereafter, the model was used to simulate different scenarios, which were implemented and validated in Phase 3.

For Phase 1, it was necessary to understand the mining network of the case study before going underground to obtain further data. A checklist ensured that the information required was collected. A thorough discussion with relevant mine personnel supported the understanding of the ventilation network of the mine. During the discussion, one particular level (Level X) of the case study mine was identified with ventilation concerns and therefore required further investigation.

All the information collected for this level was indicated and noted on the layout of the level. The layout contributed to the process of the level, and further preparation could be done to ensure that the audit would be successful. Before going underground, essential KPIs were identified to ensure that sufficient data would be available for all the parameters for analysis and the simulation model. The measurement locations were indicated on the level layout to ensure adequate data points were obtained. These were used to compare the baseline conditions and different scenarios of the simulation model. The equipment described in Section 2.2.2 was used to conduct the ventilation audit.

The data was analysed further after the audit and a few restrictions were recorded, which largely influenced the airflow measurements. Assumptions had to be made through mass balances to determine the actual baseline conditions. The actual baseline conditions were established, which were used to record inefficiencies such as high temperatures and low to no airflow at the workshop area of Level X.

In Phase 2 of the generic solution strategy, a simulation model in PTB 3D was built in order to mitigate the ventilation inefficiencies of the workshop. The audit data and information gathered were used to construct the simulation model. Thereafter, the simulation model was verified and calibrated using the actual baseline conditions. There was a discrepancy of 4% between the actual baseline and the simulation baseline. Three scenarios were simulated to mitigate the ventilation inefficiencies of the level. Different ventilation plans were introduced to improve the conditions.

Scenario 3 was selected and implemented in Phase 3, which estimated that the average wet-bulb temperature over the workshop area would decrease by 0.91°C and the average airflow through the workshop would increase by 18.03 kg/s. The implementation of the Scenario 3 ventilation plan did not add any additional electricity costs and was easy to accomplish. The new ventilation network was validated by repeating the audit on the level. During the validation audit, the

conditions proposed by Scenario 3 were different due to a constructed wall leaking air and a fan being switched off.

The temperatures recorded had discrepancies of 1.01% and 1.83% for the wet-bulb and dry-bulb temperatures, respectively. The average wet-bulb temperature decreased by 1.16°C over the workshop area and had a final temperature of 28.64°C. There was a discrepancy of 22.64% for the validation of the air mass flow. The simulation model was adjusted by simulating Scenario 3 again to align the conditions recorded during the audit. After the adjustments, a discrepancy of 0.08% was achieved for the average air mass flow through the workshop area and increased with 21.47 kg/s. Thus, the overall percentage error determined for the entire system between the simulation model and actual results was 0.98%.

4.2 Achievement of study objectives

After developing the problem statement in Chapter 1, specific objectives had to be realised. These objectives have been achieved throughout the course of the study.

Table 4-1: Objectives as achieved during the study

Objective	Achieved
Identify ventilation problem areas or inefficiencies locally in a mine environment by using acceptable mine ventilation conditions and limits as guidelines.	Acceptable mine ventilation conditions and limits were used as KPIs and guidelines, which assisted in identifying ventilation problem areas or inefficiencies of Level X in Mine A.
Develop a methodology to record accurate data that will be used to build a ventilation simulation model and to verify the findings.	The methodology allowed different methods to capture and record underground ventilation data, which was processed and analysed. A simulation model of Level X was constructed in PTB 3D, which was used to verify the data obtained.
Simulate different ventilation improvements and scenarios using the simulation model and select the best possible solution.	Three scenarios were simulated using PTB 3D. Scenario 3 was selected as the best solution for Level X in Mine A.
Implement the optimised ventilation improvement and validate the results.	Scenario 3 and its ventilation plan were implemented and validated.

4.3 Recommendation for future work

The following additional work and recommendations for improvements are suggested:

Compare different measuring techniques and equipment in different mine environments measuring at the same sections

Only the ventilation measurement equipment listed in Chapter 2 was described. Mining conditions and their infrastructure differ. In this case study, the equipment used was not suitable for measuring large haulages and only one audit was conducted to capture the baseline data for the simulation model.

Further research can be done on the different measurement methods and equipment that are used during audits. This will ensure that accurate data is captured and that the equipment is able to measure the area or section successfully. Measurements must be done continuously until constant values are obtained. If any restrictions occur during an audit, the level or section must be re-audited to ensure airflow is consistent.

Quantify the impact of audit data on the same section at different schedules

The ventilation network airflow of a mine changes continuously. The mining industry has different schedules. During each schedule, different activities are carried out underground, which create inconsistent airflow throughout the different mining sections of the mine.

Measurements and underground ventilation audits should be conducted on the same level or sections at different time schedules to capture the impact of mining activities on the airflow. It will also include worst-case scenarios as the full mining schedule is considered. Therefore, suitable recommendations can be made to improve the ventilation network of that section or level.

Establish the influence of temperature on the productivity of miners and production of the mine

The ventilation network could be changed to decrease temperatures of the mine on different levels or sections. However, the decreased temperatures could still be inadequate to improve the productivity of the miners and the production of the mine.

Determine at which point temperature should decrease to improve the productivity of miners. Quantify the overall impact of more productive miners, which can increase production.

Simulate ventilation on demand for localised ventilation networks

The ventilation system of a mine contributes 25–50% to its electricity usage. As mentioned, the mine has different schedules; each with different activities.

During certain schedules, the workforce is smaller; therefore, the air supply could be monitored and controlled to the required needs. Further studies could determine how a dynamic ventilation network would influence the mine environment.

4.4 Challenges of study

There were a few challenges that occurred throughout the study. At first, obtaining all the necessary data from the mine, such as the correct fan curves and updated ventilation audit data, was difficult and not entirely successful. Some assumptions had to be made during the calibration of the fans in the simulation model. The study timeline, which was completed in 3 weeks would have been extended to 4 weeks if a second audit was conducted for more data and to accurately measure the fans underground.

During the underground audit, the airflow was very inconsistent due to large haulages and restrictions, such as mine vehicles and objects standing in the main airstream of the haulage. This caused inaccurate measurements during the underground audit. To verify the simulation model, mass balancing and a few assumptions were required to achieve an accurate actual baseline for the simulation model. In order to ensure that the measurements were accurate and successful, a second audit should have been done, and different measuring techniques and equipment should have been used as well. It is always good and secure to check and recheck until consistency is achieved.

During the implementation phase, the Scenario 3 ventilation plan was not carried out successfully before validation, which created conditions different than proposed by Scenario 3. Preferably, the validation would have been successful if the conditions were similar. Therefore, it is vital to ensure that everything is in place and carried out successfully before validation.

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A. APPENDIX A: AUDIT SHEETS AND VENTILATION LITERATURE

Table A-1 and Table A-2 represent the sheets for an underground ventilation audit. These sheets can only be used if the preferred ventilation equipment for the measurements is used.

Table A-1: Ventilation audit sheet

No.	Velocity (m/s)												Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Width (m)			Height (m)		
	1	2	3	4	5	6	7	8	9	10	11	12				1	2	3	1	2	3
1																					
2																					
3																					
4																					
5																					
6																					
7																					
8																					
9																					
10																					
11																					
12																					
13																					
14																					

Table A-2: Fan audit sheet

No.	Velocity (m/s)						Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Static pressure (kPa)	Diameter (m)
	1	2	3	4	5	6					
1											
2											
3											
4											
5											

Table A-3 and Table A-4 are used to process the audit datasheets. The sheets provide the results of the audit data in a neat table, which is easier to analyse further.

Table A-3: Ventilation audit process sheet

No.	Wet-bulb (°C)	Dry-bulb (°C)	Volumetric airflow (m ³ /s)	Air mass flow (kg/s)	Barometric pressure (kPa)
1					
2					
3					
4	:	:	:	:	:
5					
6					
7					
8					
9					
10					
11					
12					
13					
14					

Table A-4: Fan audit process sheet

No.	Wet-bulb (°C)	Dry-bulb (°C)	Volumetric airflow (m ³ /s)	Air mass flow (kg/s)	Static pressure difference (kPa)
1					
2					
3					
4					
5					

Determining the static pressure of an auxiliary fan

Figure A-1 illustrates the process of measuring the static pressure with a vertical manometer as well as the location of the measurements. Arrows indicate the airflow and diameter of the fan duct. When measuring the static pressure of a fan, the measurements should be taken at a minimum of 7.5 duct diameters from the discharge of the fan and 3 duct diameters from the inlet of the fan, which must be away from any turns or flow obstructions. Doing fewer measurements, for instance, 2 duct diameters downstream and 1 duct diameter upstream from obstructions, influences the accuracy.

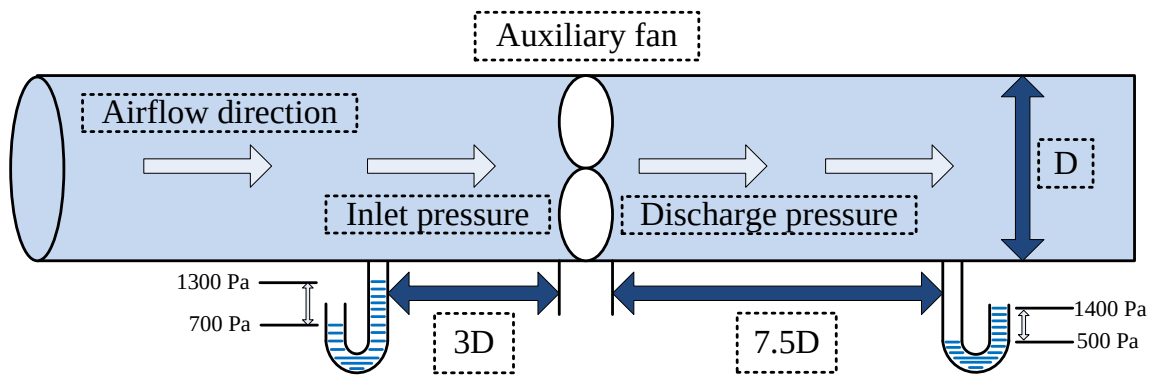


Figure A-1: Measuring static pressure of an auxiliary fan

Equation A-1 is used to determine the static pressure of the fan. An example is provided to explain how to determine the static pressure.

$$P_{static} = P_{discharge} - (-P_{inlet})$$

Equation A-1: Static pressure

Example

Readings obtained from Figure A-1:

$$P_{inlet} = 1300 \text{ Pa} - 700 \text{ Pa} = 600 \text{ Pa}$$

$$P_{discharge} = 1400 \text{ Pa} - 500 \text{ Pa} = 900 \text{ Pa}$$

$$P_{static} = 900 \text{ Pa} - (-600) \text{ Pa} = 1500 \text{ Pa}$$

Note that the inlet pressure is always negative.

Determining the air velocity of an auxiliary fan

A pitot-static tube and digital manometer are used to determine the air velocity of the fan. The log-Tchebycheff method is used by applying traversing on a round duct.⁴ The duct is divided into concentric circles at the measurement point. Ducts that are 255 mm and smaller use three concentric circles and ducts that are larger than 255 mm use four or five concentric circles. Measurements are more accurate when using three holes that are at 60° angles apart from one another than using two holes at 90° from each other. Figure A-2 shows the preferred method with three holes. Measurements are taken over three traverses across the duct and the velocities obtained at each point are averaged. After determining the velocity average, it is multiplied by the area of the duct to get the flow rate of the fan at that section.

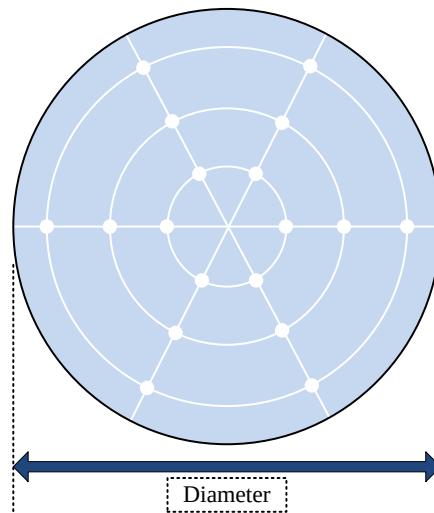


Figure A-2: Measurement points for traversing log-Tchebycheff method

Table A-5 provides the number of measurement points and their position. The position relative to the inner wall must be multiplied with the diameter of the duct to get the insertion depth for the pitot tube. Remember to use the inside dimension of the duct if there is any insulation.

⁴ TSI Instruments Ltd., "Traversing a duct to determine average air velocity or volume," pp. 4–7, 2014.

Table A-5: Number of measurement points and their position

No. of measurement points per diameter	Position relative to inner wall
6	0.032; 0.135; 0.321; 0.679; 0.865; 0.968
8	0.021; 0.117; 0.184; 0.345; 0.655; 0.816; 0.883; 0.979
10	0.019; 0.077; 0.153; 0.217; 0.361; 0.639; 0.783; 0.847; 0.923; 0.981

The average air velocity is measured through the pitot-static tube and the digital manometer. The process and method for using the pitot-static tube are discussed and explained by Hancock [7] and McPherson [38]. The digital manometer is handled the same way as a vertical manometer, and the connection between both manometers and the pitot-static tube is the same. This process is also discussed by Hancock [7] and McPherson [38] and is applied in this study. The digital manometer differs from the vertical manometer as the pressure readings are translated directly into velocities. By using the log-Tchebycheff method and the equipment, the average air velocity through the fan duct is calculated using Equation A-2.

$$V_{ave} = \frac{V_1 + V_2 + V_3 + V_4 + V_5 + V_6}{6}$$

Equation A-2: Average velocity of fan

Determining the area of a fan duct

The area of the fan duct is calculated by using Equation A-3.

$$A_{duct} = \pi \times \left(\frac{D}{2}\right)^2$$

Equation A-3: Area of fan duct

- Area of fan duct = A_{duct}
- Diameter = D

Figure A-3 provides the psychrometric chart for air [42], which is used to calculate the air density in Section 2.2.2.

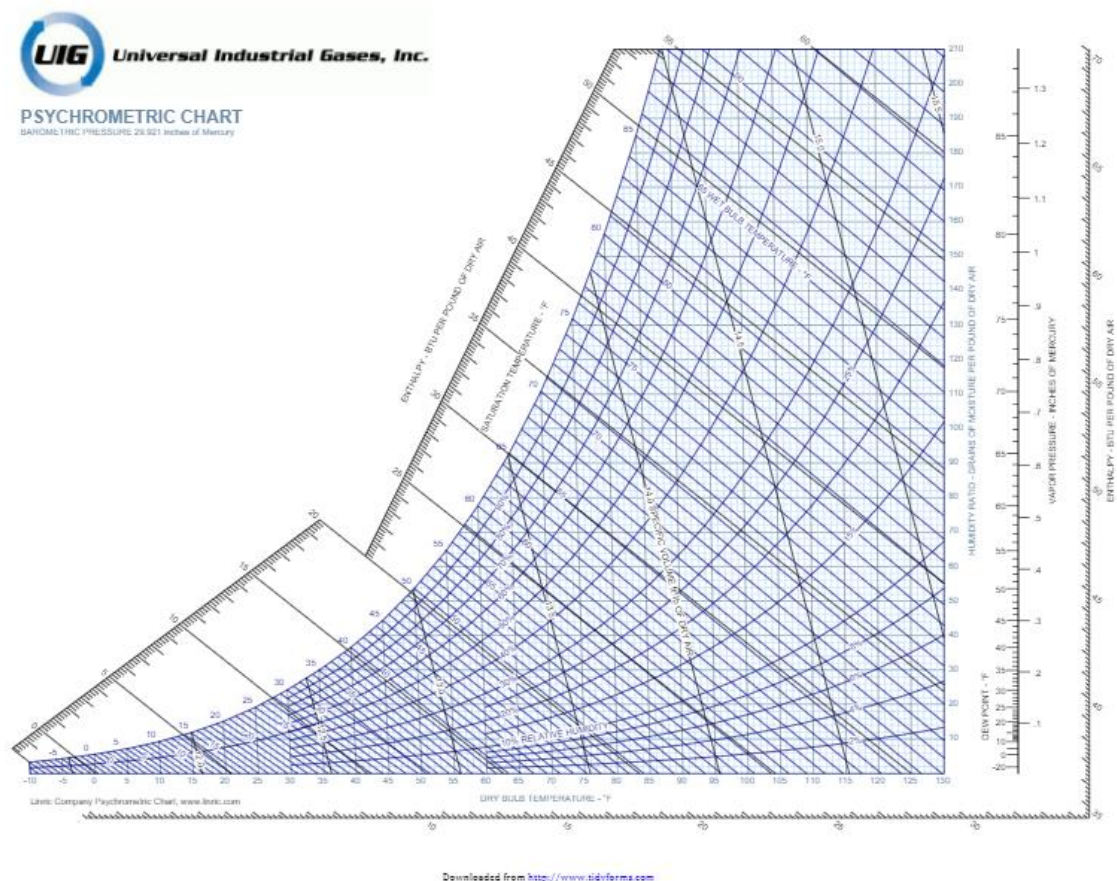


Figure A-3: Psychrometric chart for air [42]

B. APPENDIX B: CASE STUDY RESULTS AND LAYOUTS

Figure B-1 illustrates the level that was identified with ventilation inefficiencies and used as the case study. The layout was used to indicate airflow, activities on the level, and different ventilation components. The mine also provided a DXF format of the level, which was used in the simulation model.

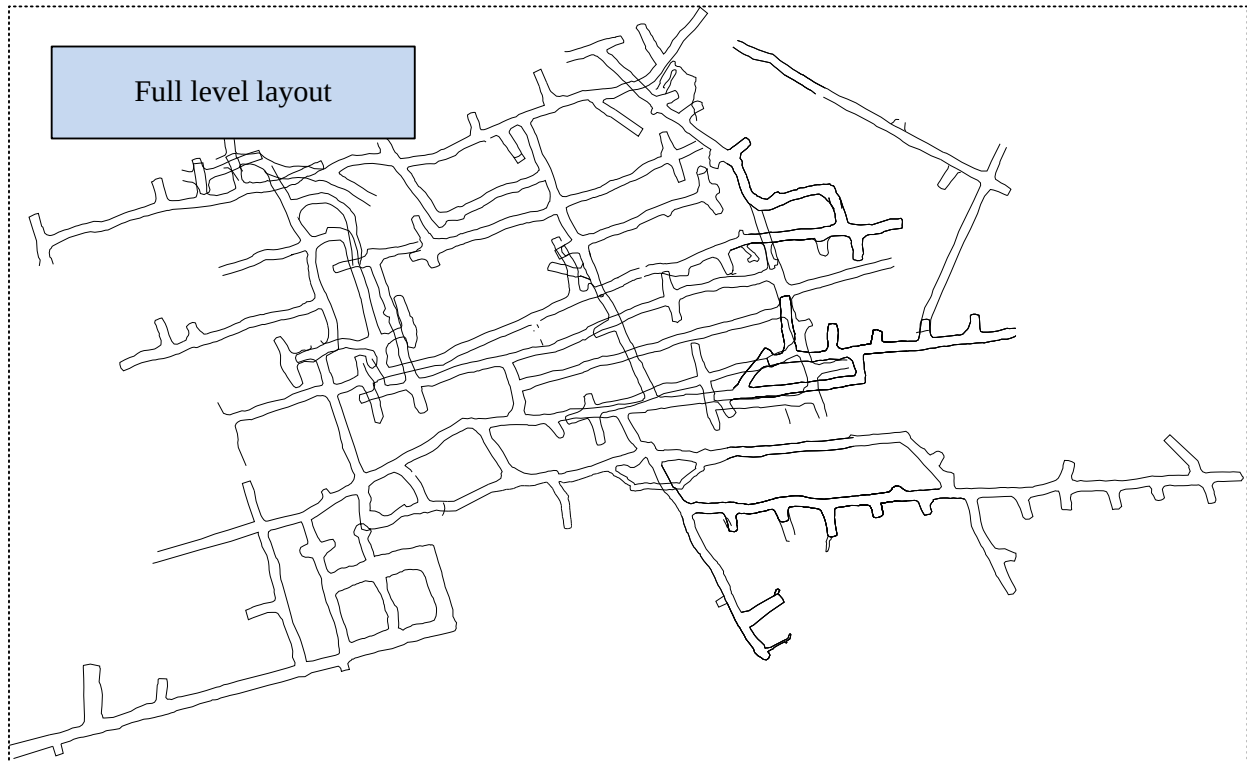


Figure B-1: Mine level layout

Figure B-2 and Figure B-3 show the two fan curves obtained from the occupational hygienist. Unfortunately, other fan curves were not possible to collect, and assumptions had to be made during the simulation phase of the developed solution method to calibrate the baseline simulation model in PTB 3D accurately.

45 kW Fan curve

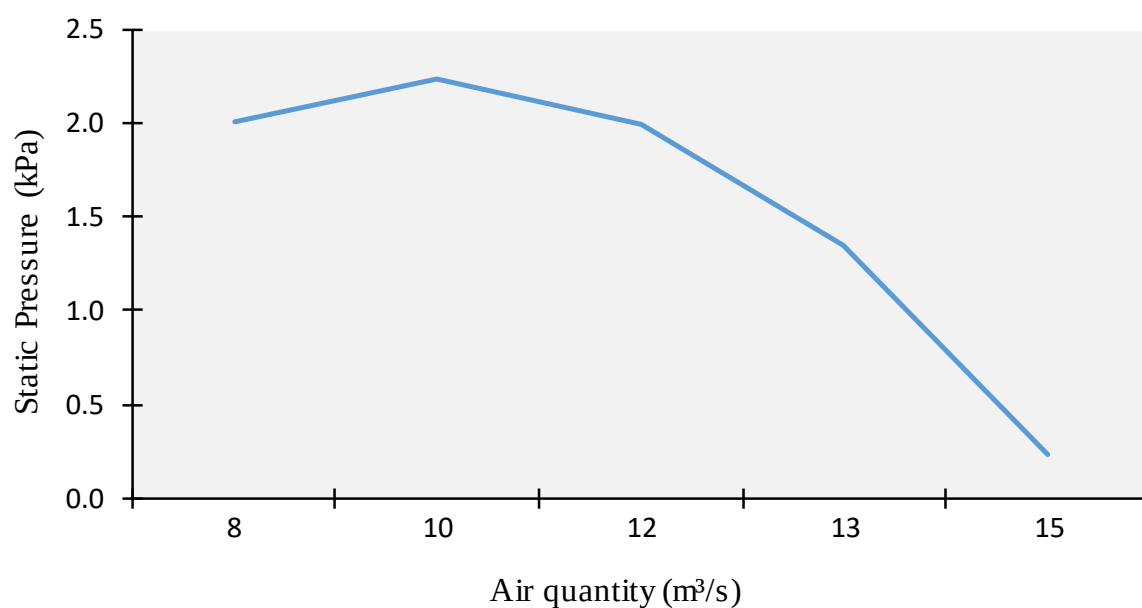


Figure B-2: 45 kW fan curve

75 kW Fan curve

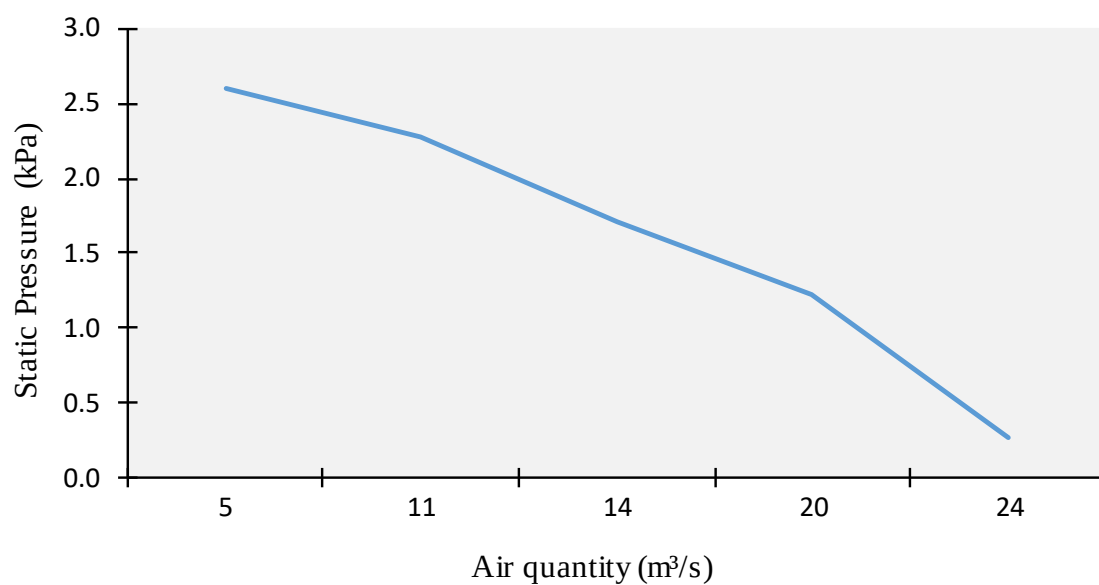


Figure B-3: 75 kW fan curve

Table B-1 and Table B-2 provide the raw data from the audit that was conducted on the level. Table B-1 shows all the ventilation audits and Table B-2 shows all the fan audits on the same level.

Table B-1: Ventilation audit datasheet of case study

No.	Velocity (m/s)												Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Width (m)			Height (m)		
	1	2	3	4	5	6	7	8	9	10	11	12				1	2	3	1	2	3
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	109.99	30.00	33.50	6.32	6.32	6.32	5.04	5.04	5.04
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.12	30.00	33.50	6.02	6.02	6.02	4.93	4.93	4.93
3	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.30	0.20	0.40	0.40	0.00	110.16	29.50	32.00	9.49	9.49	9.49	6.13	6.13	6.13
4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.16	29.50	32.00	9.49	9.49	9.49	6.13	6.13	6.13
5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.17	30.00	32.50	9.16	9.16	9.16	8.18	8.18	8.18
6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.18	30.00	32.50	9.79	9.79	9.79	8.46	8.46	8.46
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.17	30.00	32.50	9.79	9.79	9.79	9.71	9.71	9.71
8	0.80	0.70	0.70	0.60	0.70	0.70	0.50	0.60	0.60	0.40	0.50	0.40	110.12	29.00	31.00	6.36	7.17	7.37	5.27	4.83	4.81
9	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.11	29.00	31.00	6.36	7.17	7.37	5.27	4.83	4.81
10	1.10	1.00	1.10	0.80	1.00	1.00	1.00	1.10	1.00	1.00	0.90	0.80	110.13	30.50	33.00	6.32	6.39	6.29	5.01	5.40	5.06
11	0.90	0.90	0.90	0.90	0.90	1.00	0.90	0.90	0.90	0.70	0.90	1.00	110.36	30.50	34.50	4.56	4.56	4.16	4.93	4.95	5.10
12	0.44	0.60	0.70	0.40	0.50	0.70	0.30	0.50	0.60	0.10	0.10	0.50	110.45	31.00	34.50	5.28	5.89	5.88	5.15	5.10	5.25
13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	110.63	33.00	36.00	0.00	0.00	0.00	0.00	0.00	0.00
14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table B-2: Fan audit datasheet of case study

No.	Velocity (m/s)						Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Static pressure (kPa)	Diameter (m)
	1	2	3	4	5	6					
9	13.40	15.90	16.20	12.20	13.40	0.00	110.11	29.00	31.00	-	1.20

Figure B-4 illustrates the actual baseline conditions with the results indicated on the layout.

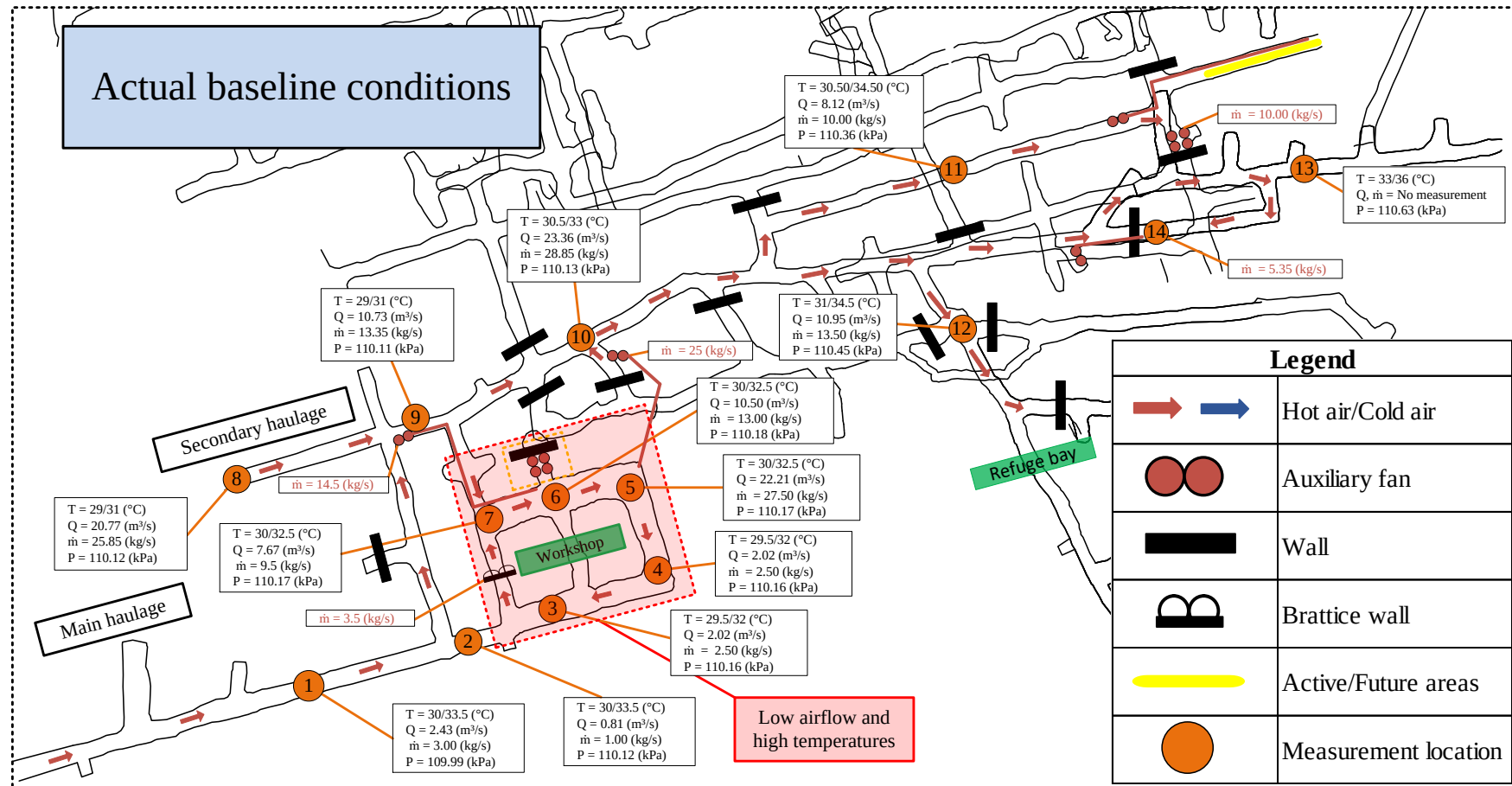


Figure B-4: Actual baseline conditions of the case study

Figure B-5 illustrates a full PTB 3D view of the actual ventilation layout of the case study.

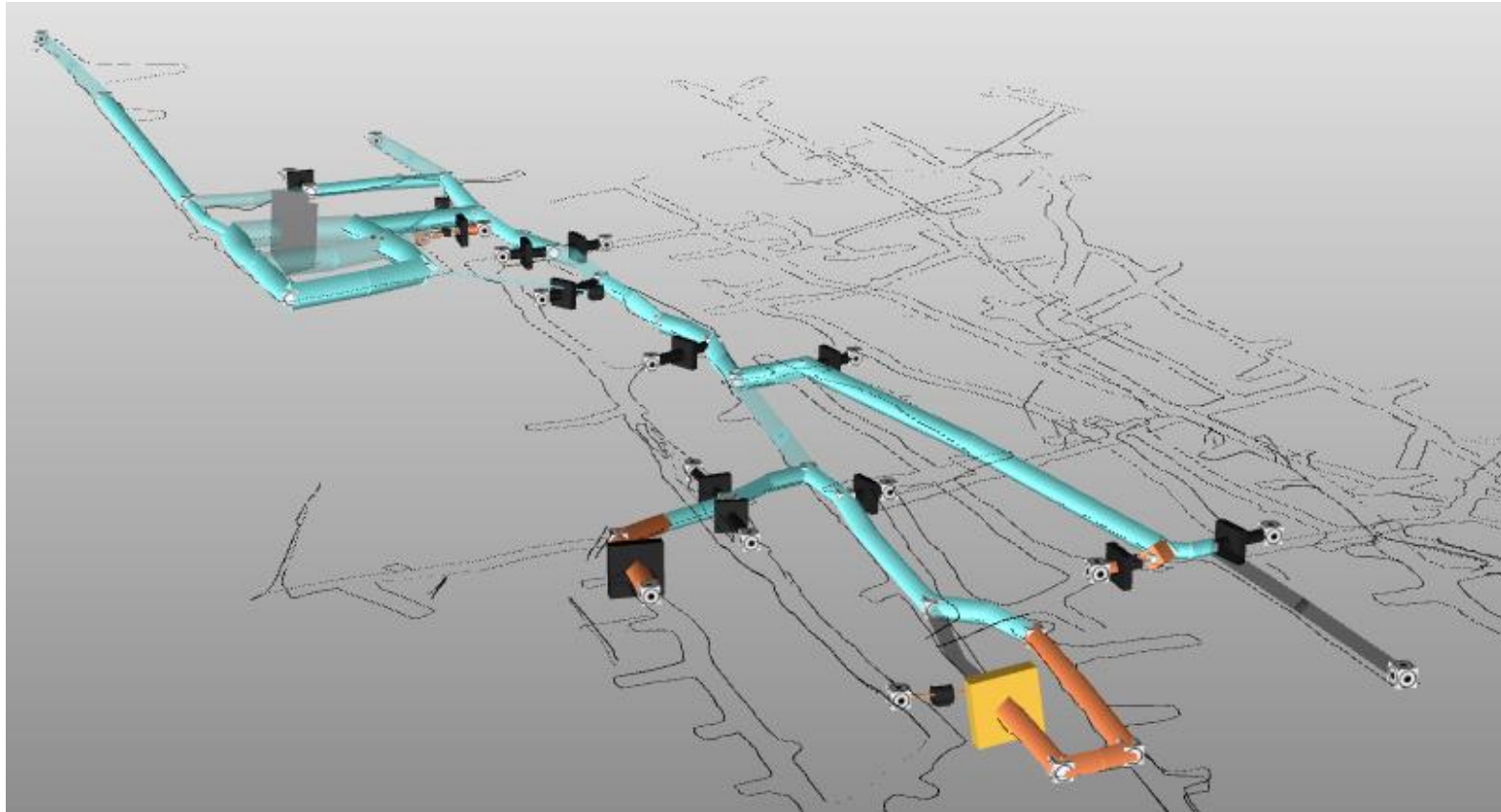


Figure B-5: Full PTB 3D view of case study

Figure B-6 illustrates the simulation baseline conditions.

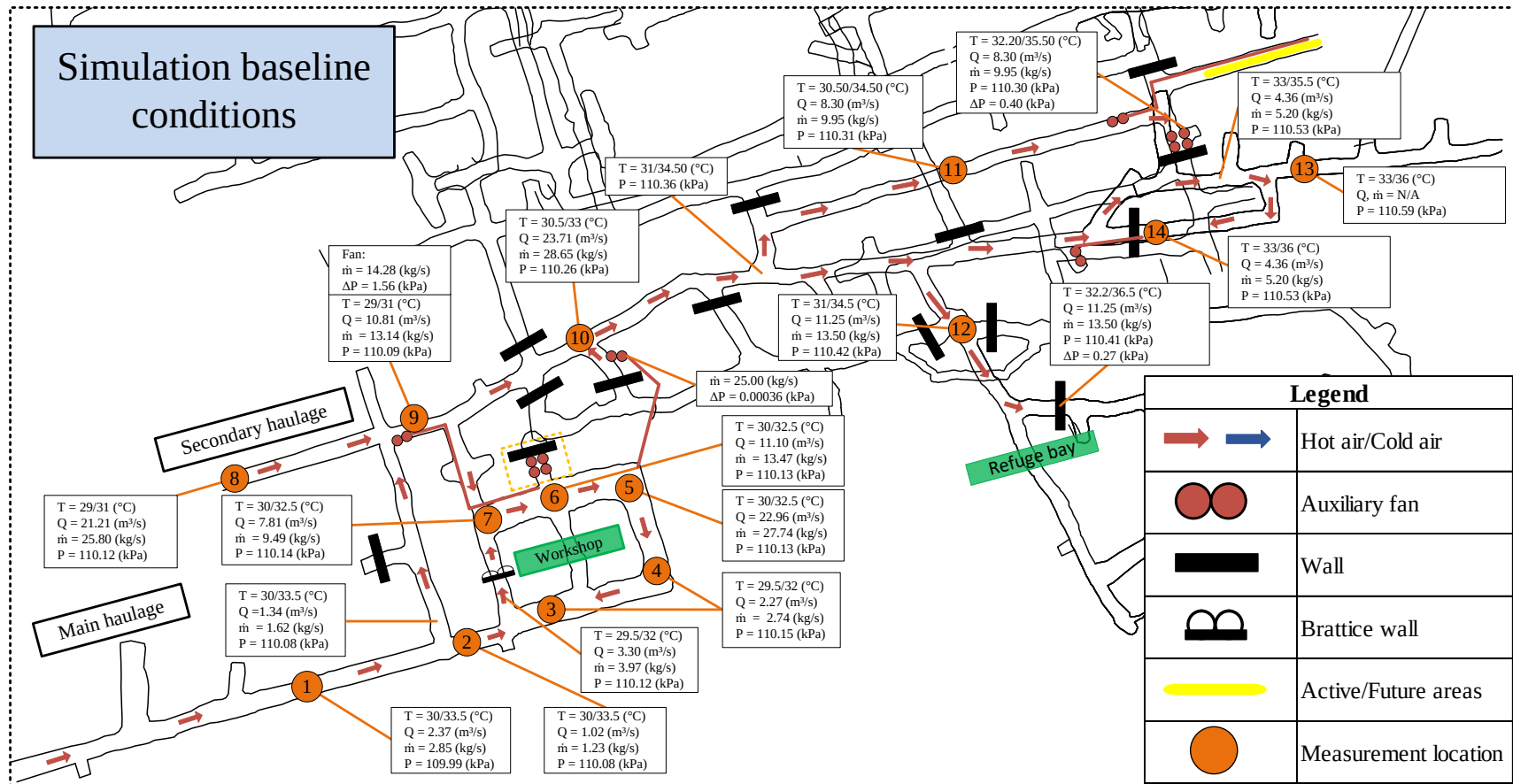


Figure B-6: Case study simulation baseline conditions

Figure B-7 illustrates Scenario 1's simulation results.

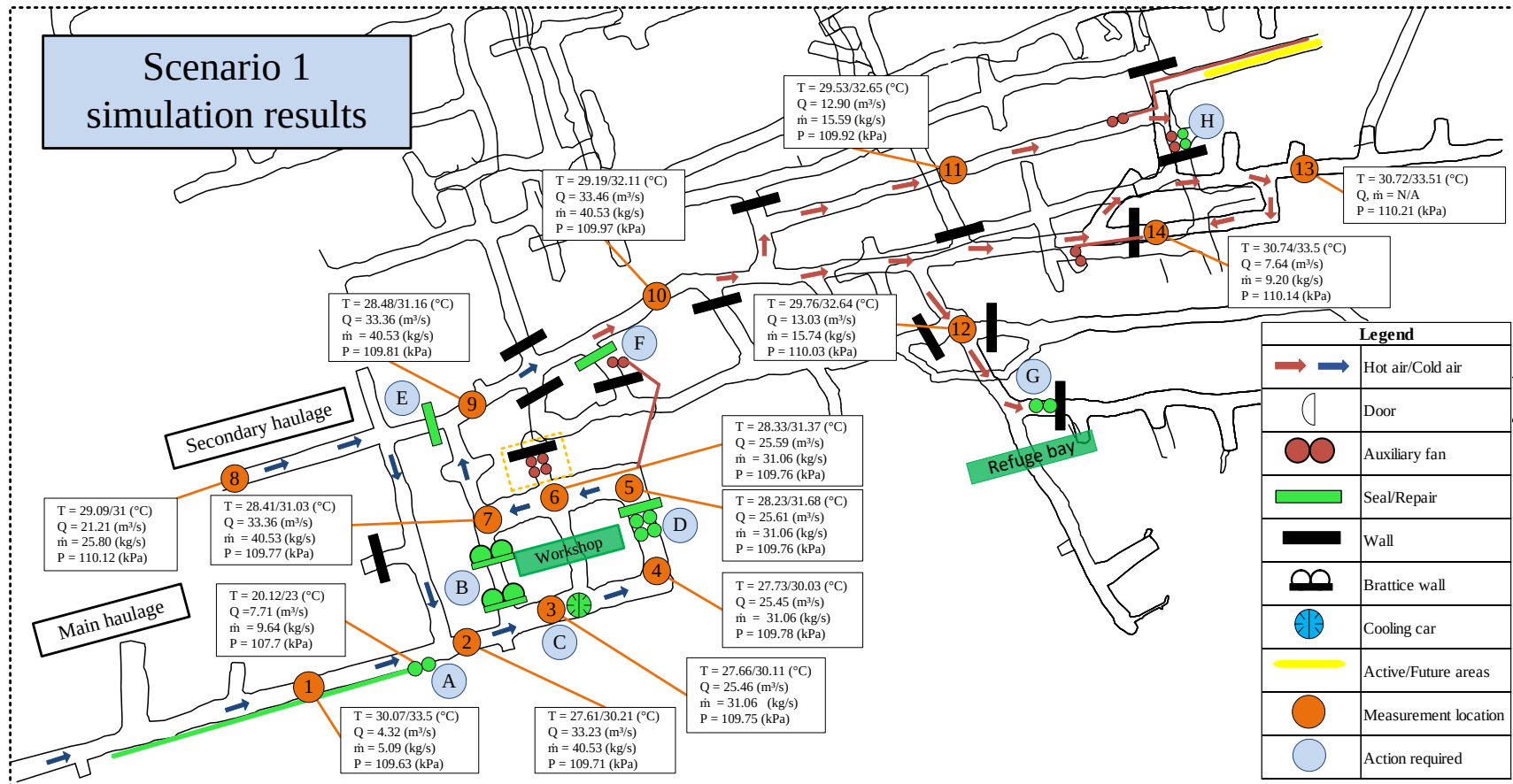


Figure B-7: Scenario 1 simulation results

Figure B-8 illustrates Scenario 2's simulation results.

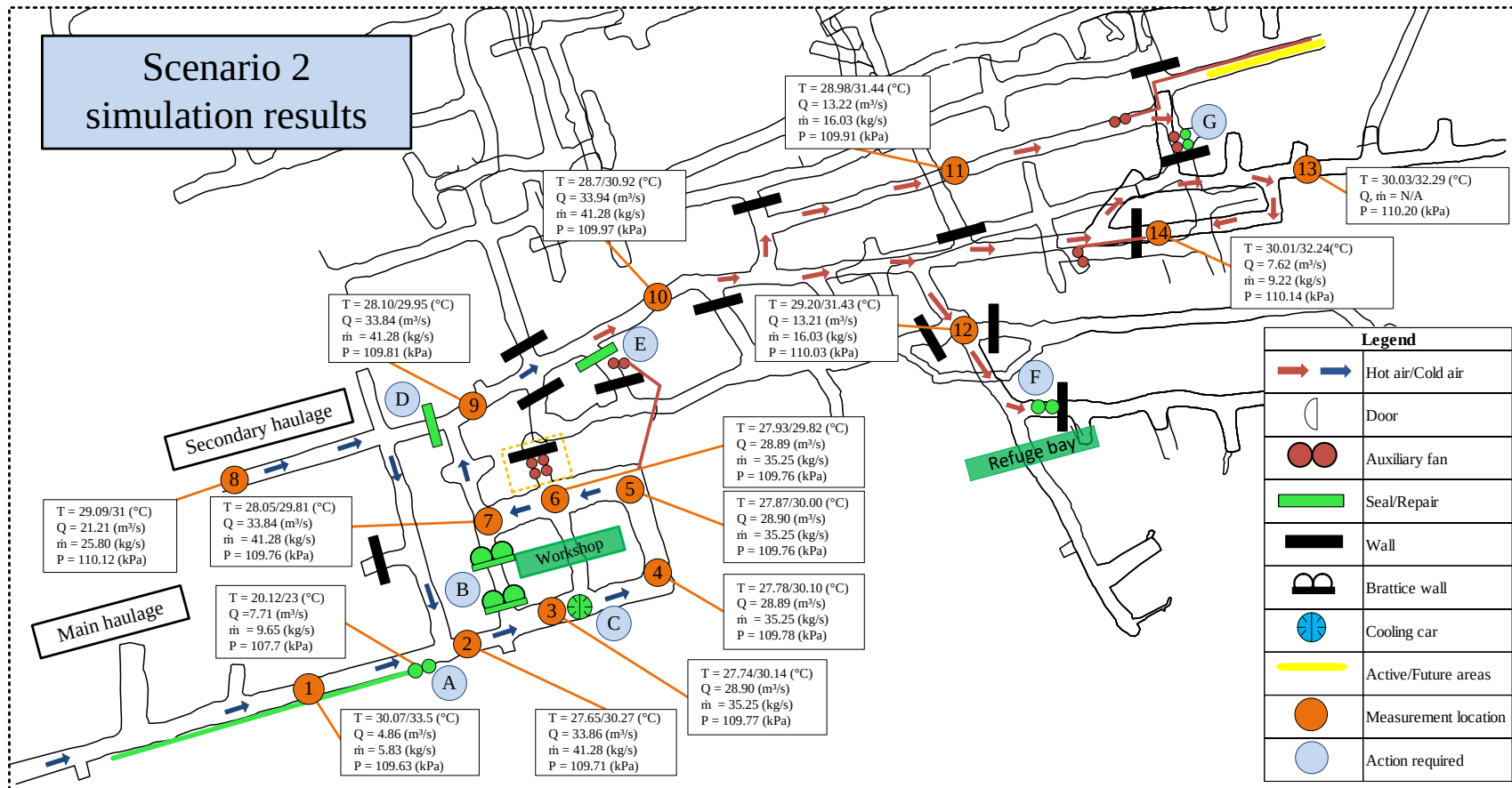


Figure B-8: Scenario 2 simulation results

Figure B-9 illustrates Scenario 3's simulation results.

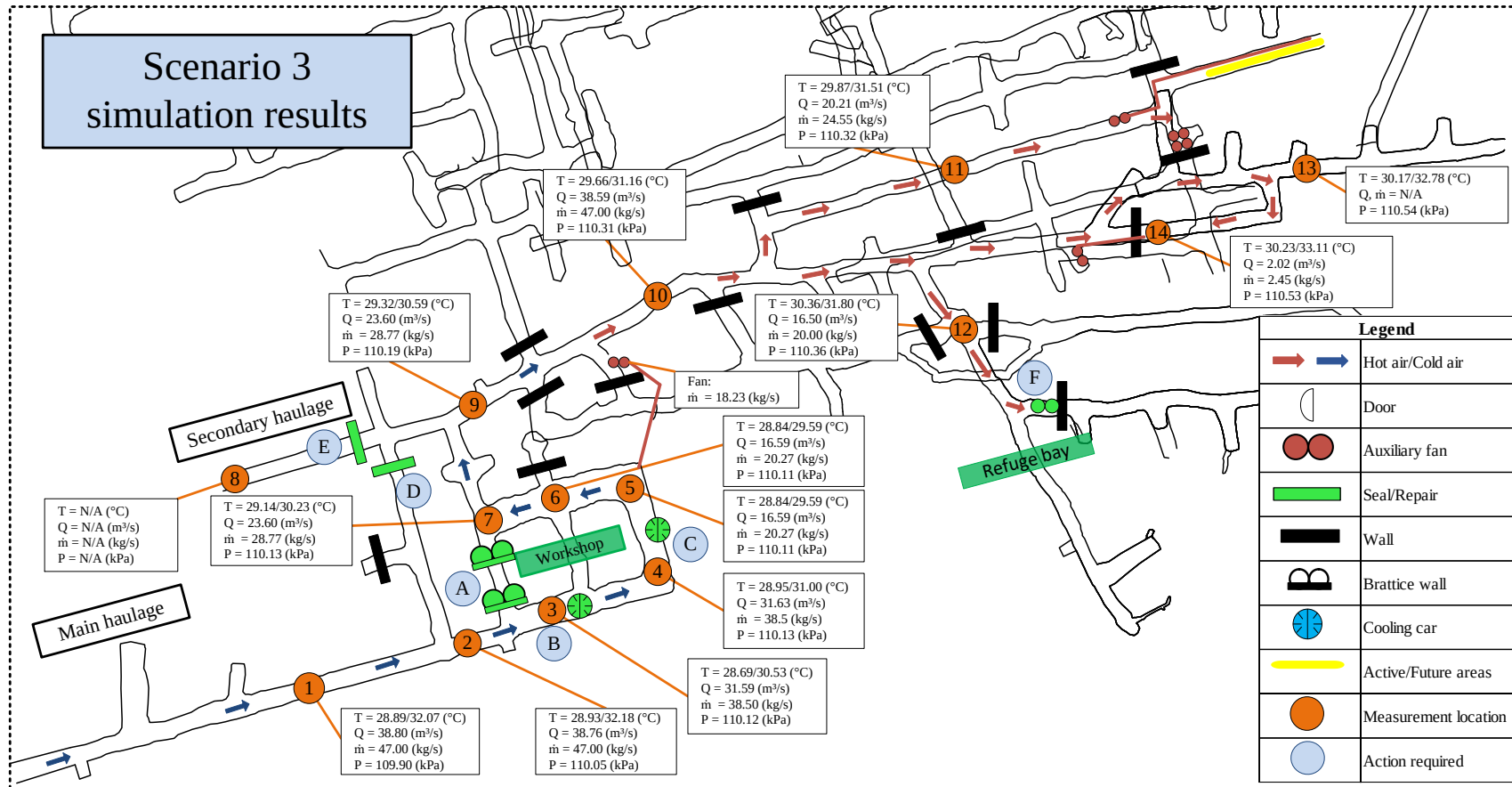


Figure B-9: Scenario 3 simulation results

Figure B-10 illustrates the validation of Scenario 3.

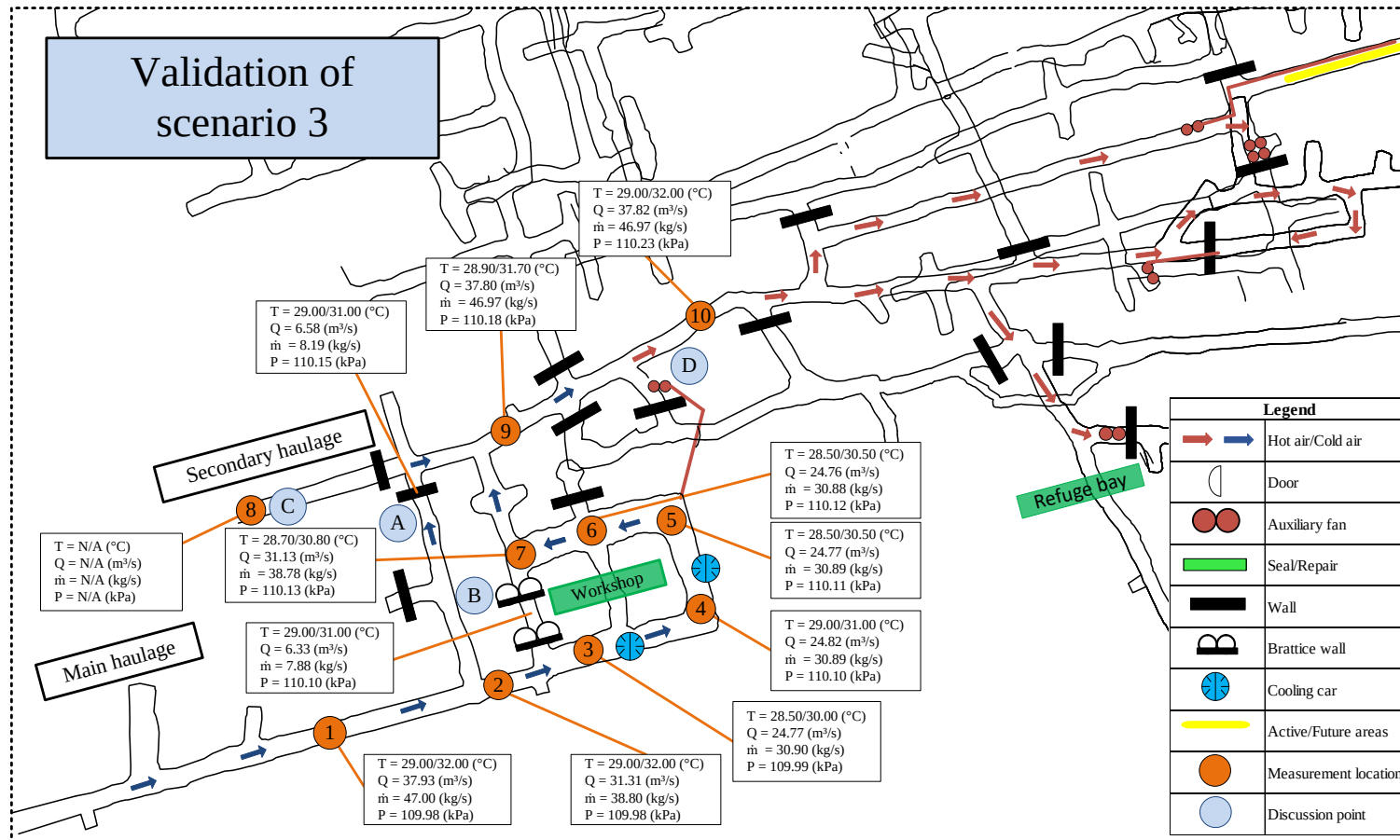


Figure B-10: Validation of Scenario 3

Table B-3 and Table B-4 illustrate the audit data and processed data that were taken after implementing the Scenario 3 ventilation plan.

Table B-3: Case study Scenario 3 implemented audit data

No.	Velocity (m/s)												Barometric pressure (kPa)	Wet-bulb (°C)	Dry-bulb (°C)	Width (m)			Height (m)		
	1	2	3	4	5	6	7	8	9	10	11	12				1	2	3	1	2	3
1	Mass balance												109.98	29.00	32.00	6.02	6.02	6.02	4.93	4.93	4.93
2	Mass balance												109.98	29.00	32.00	6.02	6.02	6.02	4.93	4.93	4.93
3	0.32	0.28	0.38	0.58	0.62	0.55	0.54	0.51	0.52	0.25	0.29	0.27	109.99	28.50	30.00	9.49	9.49	9.49	6.13	6.13	6.13
4	0.38	0.35	0.29	0.55	0.63	0.62	0.51	0.52	0.48	0.26	0.27	0.26	110.10	29.00	31.00	9.49	9.49	9.49	6.13	6.13	6.13
5	Mass balance												110.11	28.50	30.50	9.49	9.49	9.49	6.13	6.13	6.13
6	0.28	0.27	0.23	0.35	0.38	0.34	0.29	0.30	0.29	0.29	0.28	0.29	110.12	28.50	30.50	9.79	9.79	9.79	8.46	8.46	8.46
7	Mass balance												110.12	28.70	30.80	9.79	9.79	9.79	9.71	9.71	9.71
9	Mass balance												110.18	28.90	31.70	6.36	7.17	7.37	5.27	4.83	4.81
10	1.10	1.14	1.11	1.32	1.34	1.31	1.18	1.21	1.17	1.00	1.01	1.00	110.23	29.00	32.00	6.32	6.39	6.29	5.01	5.40	5.06
B	0.15	0.16	0.14	0.20	0.21	0.23	0.25	0.28	0.30	0.21	0.23	0.20	110.10	29.00	31.00	6.02	6.02	6.02	4.93	4.93	4.93
W	0.16	0.18	0.14	0.22	0.24	0.24	0.26	0.30	0.28	0.20	0.23	0.21	110.15	29.00	31.00	6.02	6.02	6.02	4.93	4.93	4.93

Table B-4: Case study Scenario 3 processed audit data

No.	Air density (kg/m ³)	Relative humidity (RH – %)	Area (m ²)	Average velocity (m/s)	Volumetric airflow (m ³ /s)	Air mass flow (kg/s)
1	1.24	0.80	29.68	MB	37.93	47.00
2	1.24	0.80	29.68	MB	31.31	38.80
3	1.25	0.89	58.17	0.43	24.77	30.90
4	1.24	0.86	58.17	0.43	24.82	30.89
5	1.25	0.86	58.17	MB	24.77	30.89
6	1.25	0.86	82.76	0.30	24.76	30.88
7	1.25	0.85	95.12	MB	31.13	38.78
9	1.24	0.81	34.61	MB	37.80	46.97
10	1.24	0.80	32.67	1.16	37.82	46.97
B	1.24	0.86	29.68	0.21	6.33	7.88
W	1.24	0.86	29.68	0.22	6.58	8.19