An integrated ventilation and cooling strategy for mechanised deep-level mining

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ABSTRACT

Planning of mine ventilation and cooling ensures acceptable environmental conditions underground. To this end, simulation-based planning tools are used for their advantages over calculation-based planning techniques. Various studies and literature on mine ventilation planning exist but tend to neglect certain heat sources, life-of-mine planning considerations, and continuous monitoring. Deep-level mining operations have an increased need for temperature control while pollutant emissions decline with the application of improved technologies. By analysing literature on mine planning strategies, a generic methodology was proposed in this study with a focus on the simulation of life-of-mine models, temperature and pollutant control, integration with existing planning structures, and continuous monitoring. Surveys and plans for the mining environment were used to construct the baseline and future models, which were verified by calculations and audit values. Required airflows and temperatures were calculated from regulation and used to analyse future model results, alongside mine management. Solutions to identified issues were proposed, evaluated, and implemented alongside future model updates. In the case study, an additional 6.5-MW surface cooling plant was constructed to address the cooling shortfall identified. Post-construction surveys of the mining environment revealed a model error of 36.6% for airflow, 16.5% for wet- and 17.8% for dry-bulb temperatures. The errors were subsequently reduced to 12.2%, 5.4% and 5.5% respectively after implementing updates related to deviations from the plan. The errors were deemed acceptable in the light of measurement limitations and the proposed methodology was successfully used to predict the ventilation and cooling infrastructure requirements and impact thereof on one mechanised deep-level mine, while improving on the inherent errors related to non-continuous planning strategies.

ACKNOWLEDGEMENTS

Let this represent an acknowledgement of the inputs of those entities, individuals, and organisations without whom the following work could not be accomplished. Although the work was my own, your contributions to it were beyond critical.

1. The God of the Christians.
    a. Thessalonians 5:16-18
        Rejoice always, pray continually, give thanks in all circumstances;
        for this is God’s will for you in Christ Jesus.
2. My family.
    a. Proverbs 6:20
        My son, keep your father’s command;
        don’t abandon your mother’s instruction.
3. My lovely wife.
    a. Proverbs 31:29
        Many women have done excellently, but you surpass them all.
4. ETA Operations (Pty) Ltd.
    a. 2 Thessalonians 3:10
        If anyone is not willing to work, let him not eat.

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List of abbreviations

ACU	Air cooling unit
AQI	Air quality index
BAC	Bulk air cooler
CC	Cooling car
DB	Dry-bulb temperature
DPM	Diesel particulate matter
LHD	Loader, hauler, and dumper
MAE	Mean absolute error
MHSA	Mine Health and Safety Act 29 of 1996
MVSSA	Mine ventilation society of South Africa
OEL	Occupational exposure limit (8-hour TWA)
PNOC	Particles not otherwise classified
RAW	Return airway
SLOS	Sub-level open stope
TWA	Time-weighted average
VRT	Virgin rock temperature
WB	Wet-bulb temperature
WBGT	Wet-bulb globe temperature

Glossary

Air cooling capacity	The capacity of air to absorb heat in the mining environment.
Auto-compression	The conversion of potential energy to thermal energy by the compression of a fluid, such as air, moving downward, such as in a shaft.
Brattice/curtain	A partition typically made of cloth, rubber flaps, or plastic curtains meant to direct the movement of air.
Bulk air cooler	An installation which cools and handles large quantities of air (approx. > 60 m^3/s)
Chill pond	A cooling installation, typically using open sprays for contact cooling with chilled water, with a basin to gather excess water.
Development	A dead-end haulage where blasting, excavation, and expansion of the travelling way takes place.
Diesel particulate matter	The portion of diesel exhaust consisting of carbon particles and any attached organic or inorganic chemicals.
Dry-bulb temperature	The temperature reading from a dry thermometer.
Elemental carbon	Inert graphitic carbon formed during the combustion of diesel fuel without oxygen.
Face	In the case of a development, the end-wall of a development where new holes are drilled and blasted to further extend the development. In the case of a stope, the sidewall where the ore is typically found, and the stope is extended laterally.
Fissure	Long, narrow cracks or openings in the rock.
Footwall	The ‘floor’ of a haulage, stope, or development.
Geothermal heat	Heat originating from exposed rock with a typically high VRT.
Grade	The concentration of a desired material in ore.
Hanging wall	The ‘roof’ of a haulage, stope, or development.
Haulage	Relatively small, long, and uniform excavations underground wherein man, materials, air, and machine travel between locations.
Intake	The network of underground haulages wherein fresh, cool air travels down to working areas and level return points from the downcast shaft.
Life-of-mine	The full timeframe for which a mine has been planned out with regards to specifics such as the tonnage profile and expected ore grade.
Massive	Referring to a massive stope, which is a large, mechanised stope.
Mechanised	Equipped with machinery.
Microclimate	The climate in a small, localised space such as inside a room.
Mining block	The general space containing the ore deposits, stopes, production areas, and mining activities.

Occupational exposure limit	The upper-limit time-weighted average concentration of a substance to which most workers may be exposed for an eight-hour workday and 40-hour work week without suffering adverse health effects.
Organic carbon	Complex organic carbon compounds formed from the incomplete oxidation of diesel fuel.
Psychrometry	The study of air-vapour mixtures.
Quantity	The amount or quantity of airflow.
Regulator	A construction intended to produce a restriction in an airflow path to effectively control the airflow quantity. Typically brattices, curtains, louvres, or wooden boards dropped into slots.
Relative humidity	An indicator of the amount of water vapour present in a sample of air as compared to the maximum amount possible at the same dry-bulb temperature.
Return	The network of underground haulages intended to facilitate the travel of hot, humid, contaminated air to an upcast shaft.
Return fan cluster	A grouping of fans acting as return fans for a level, located in the same wall which separates the intake from the return.
Shaft	A vertical excavation into the earth intended for airflow or man/material movement.
Sidewall	The ‘wall’ of a haulage, stope, or development.
Sigma heat	A measure of the specific energy of humid air. Equal to the enthalpy of humid air minus the sensible heat of the water contained in the mixture if this water were present in a liquid state at the same wet-bulb temperature.
Snapshot	A file storing the most recent simulation results which may be used as the initial parameters for the next simulation attempt.
Spot cooler	Typically, small, and mobile cooling equipment intended to cool air close to the working face.
Stope	An underground excavation where ore is removed, typically at an angle. Both conventional and mechanised stopes exist but differ significantly in size and shape.
Total carbon	The sum of elemental and organic carbon.
Validation	Checking that the model/simulation adequately represents the system being modelled.
Verification	Checking that the model/simulation output is consistent with the expected output.
Wet-bulb temperature	The temperature reading from a thermometer whose bulb is covered in a wetted muslin or cotton sleeve over which air flows with a speed of at least 3 m/s.

List of symbols

Symbol	**Description**	**Units**
w	Air density	kg/m^3
$AQ_{D,S,M}$	Air quantity required for developments, stopes, and massives	$m^3/s\,/kW$
AQ_{Diesel}	Air quantity required for diesel engines	m^3/s
Q	Airflow quantity	m^3/s
R	Airway resistance	Ns^2/m^8
A	Area	m^2
TDD_i	Design duty of machine i	kW
DA	Development area	m^2
DF_{Diesel}	Dilution factor for diesel engines	$m^3/s\,/kW$
FtC	Face to curtain distance in stope	m
K	Friction factor	Ns^2/m^4
n	Individual data point	$-$

L	Length	m
$MAE_{\%}$	Mean absolute error percentage	$\%$
A_n	Measured data point	$-$
C	Perimeter	m
P	Pressure/-loss	Pa
MAV	Required air volume to ventilate a massive stope	m^3/s
DAF	Required development per face area	$m^3/s/m^2$
SFV	Required stope face velocity	m/s
S_n	Simulated data point	$-$
SA	Stope area	m^2
SLF	Stope leakage factor	$-$
$Dair$	Total development air quantity	m^3/s
$Mair$	Total massive stope air quantity	m^3/s

N	Total number of data points	$-$
$Sair$	Total stope air quantity	m^3/s

1 INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction and background

Commercial quantities of gold were first discovered in the Free State region of South Africa in 1886, leading to the subsequent erection of approximately 150 mines. About 55% of the total gold ever produced has been extracted from the Witwatersrand area, and South Africa dominated the industry until 2009 [1]. China, Australia, Russia and the USA have since surpassed South Africa in terms of gold production capability, and the industry is only predicted to last until 2039, despite comparatively high mineral reserves [2], [3].

South Africa's gold mining sector faces various economic, operational, social, and technical challenges. These include the exponential increase in energy consumption as ore grades decline while mines expand ever deeper into warmer areas [2], [4], [5]. Figure 1-1 shows this declining gold grade in the South African reserves as mining continues. As if to exacerbate the effects of higher energy consumption and low ore grades, the average cost of electricity in South Africa has also risen by approximately 530% between 2003 and 2019 [6].

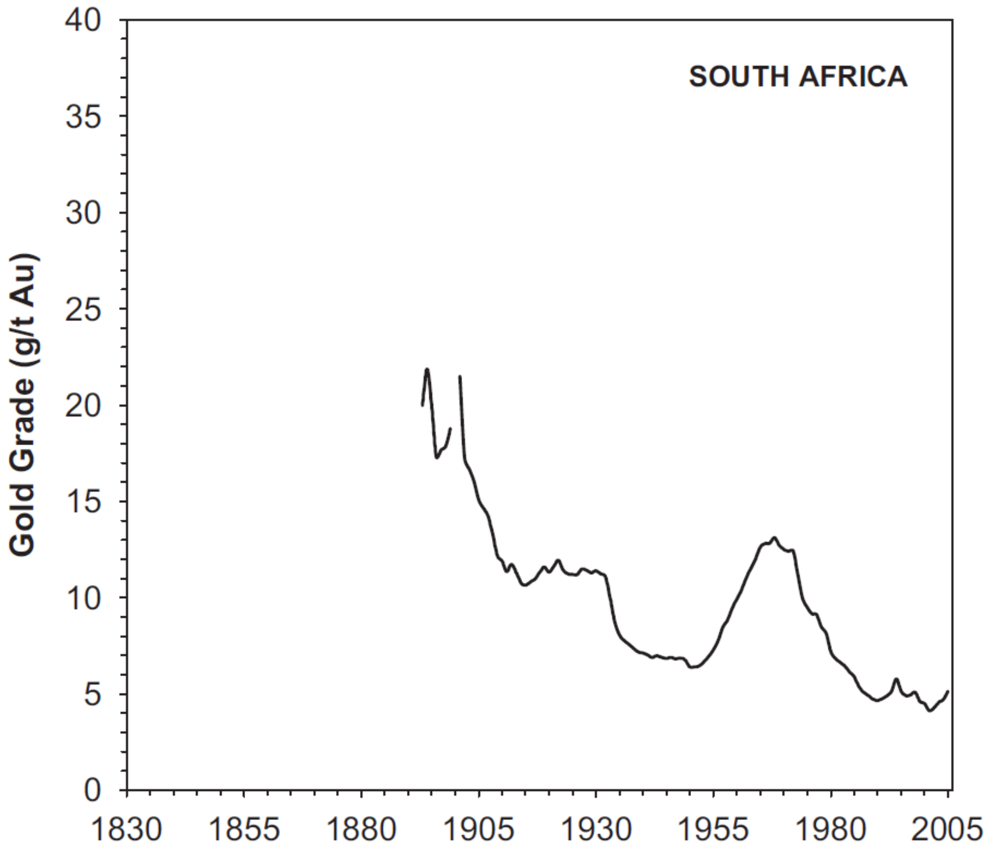

Figure 1-1: Average gold ore grade in South Africa until 2005 (adopted from [5])

To hinder these forces while remaining profitable in an expanding market, companies in the mining sector must operate and invest both cautiously and effectively. Diligent planning is key to avoiding errors and omissions between the planning and implementation stages. Oversight in these aspects could otherwise lead to high operational costs, cost overruns, and delays [7]. Although unforeseen changes and some oversight remain unavoidable, correct and regular planning can mitigate their effects.

1.1.1 Basic planning concepts

Mine planning typically takes place in five main stages throughout the life of mine, namely: 1) prospecting, 2) exploration, 3) development, 4) full production, and 5) reclamation [7], [8]. The first two stages require visual inspection and core drilling to estimate the deposit value. During capital development, permanent infrastructure such as shafts, main fans, and refrigeration plants are constructed. In the full production phase, the capital developments are complete and ore mining becomes the largest activity underground [9], [10].

The actual mining is done via one of two methods, namely: conventional or mechanised mining. Conventional mines use more workers, stope-based mining techniques, and smaller haulages. Mechanised mining uses more vehicles, mechanised techniques, large haulages, more workshops, and generally results in higher heat, air pollutant, and ore yields when compared to conventional mining [11]-[13]. Figure 1-2 shows an example of mechanised mining and indicates the use of the typical large machinery.

The full production phase requires some additional development to reach new ore bodies, but generally, capital expenditure decreases. During the last phase, the area of mining activity is restored as far as is practically achievable to its natural condition [7], [9], [10].

Many aspects of the mine planning process are highly interdependent. For instance, pipe sizing and maximum air velocities are influenced by the chosen cross-sectional area of excavation, while total cooling required is influenced by the quantity of rock excavated and the number of machines [11]. The most important aspects to plan for are ventilation and cooling, which require capital-intensive investments such as fan installations and refrigeration plant commissioning [10].

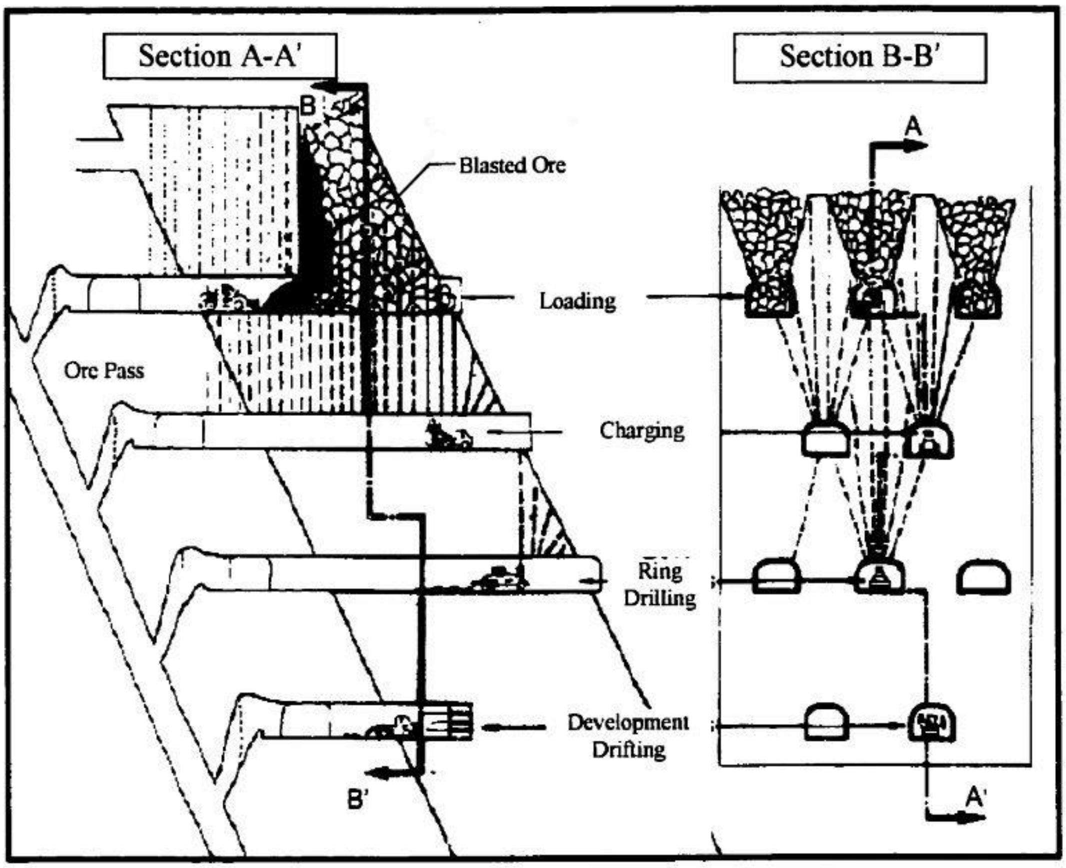

Figure 1-2: Mechanised mining – Sub-level open stoping (adapted from [13])

1.1.2 Concepts in ventilation and cooling

The purpose of ventilation is to create a safe environment for mining activities by means of adequate air supply and acceptable environmental conditions. The air supply needed is typically a derivation of the minimum face airflow quantities and minimum airflow velocities. The environmental condition refers to, amongst others, the dust and gases present in, as well as the temperature of, the air [14]. Most mining companies have internal standards for these values, but they must always match or improve upon the minimum requirements set by legislation.

In South Africa, the Mine Health and Safety Act (MHSA) governs the standards and sets regulations to which mining operations should adhere [11], [15]–[17]. Table 1-1 exhibits the maximum legal thermal stress limits, as set by the MHSA [16]:

Table 1-1: MHSA legal thermal stress limits

Parameter	Upper limit
Wet-bulb Temperature (°C)	32.5
Dry-bulb Temperature (°C)	37

As discussed, the minimum air quantities are usually defined based on the area of the haulage and type of mining activity, ranging between 0.15 m^3/s to 0.5 m^3/s per m^2, but may also be specified as dilution factors. Regulation also specifies various maximum dust and gas concentrations/exposures [11], [12], [16].

Control of ventilation requires an understanding of psychrometry, which is the study of air-vapour mixtures. Much work has already been done in the field of psychrometry, such as that by Barenburg [18] in compiling many easy-to-use graphics and information [11], [19]–[23].

The psychrometric state of any system is a function of three factors. These are the relative humidity, pressure, and heat content of the air [11], [18]. In practice, however, the relative humidity and internal energy are not measured directly. Instead, the pressure, wet-bulb, and dry-bulb temperatures are measured and correlations are used to determine any other factors.

- **Relative humidity**

The relative humidity is an indicator of the amount of water in the air as compared to saturated air. The Mine Ventilation Society of South Africa (MVSSA) defines it as: “the ratio of the partial pressure of the water vapour actually present to the saturated vapour pressure at the same (dry-bulb) temperature” [19]. When the relative humidity is low, there is a large difference between the wet-bulb and dry-bulb temperatures of the air, while the opposite is true for high humidity.

- **Underground temperature**

The wet-bulb temperature is the temperature measured by a thermometer with its bulb covered in a wetted muslin or cotton sleeve and subjected to an airflow speed of at least 3 m/s [19]. This temperature is related to that which a human would experience when working underground and covered in sweat. Measuring the wet-bulb temperature in this way has some shortcomings, such as that it caters mostly to convective heat transfer while neglecting radiation and conduction. Other measurements exist which do address these, such as the wet-bulb globe temperature (WBGT), the wet kata reading, and the effective temperature, but each also has its own shortfalls. Currently, the wet- and dry-bulb temperatures are the industry standards for measuring thermal conditions underground [11], [12], [16], [19].

The dry-bulb temperature is the temperature measured by a dry thermometer in the underground environment and is comparable to the same measurement commonly used in homes and offices. When air is more saturated, water is less likely to evaporate into it, causing lower convective heat transfer from a wetted sleeve. Thus, similar readings would be observed between the wet- and dry-bulb temperature measurements [19]. Both wet- and dry-bulb thermometers are present in an instrument called the 'whirling hygrometer', also known as a sling psychrometer, which is currently widely in use and is shown in Figure 1-3.

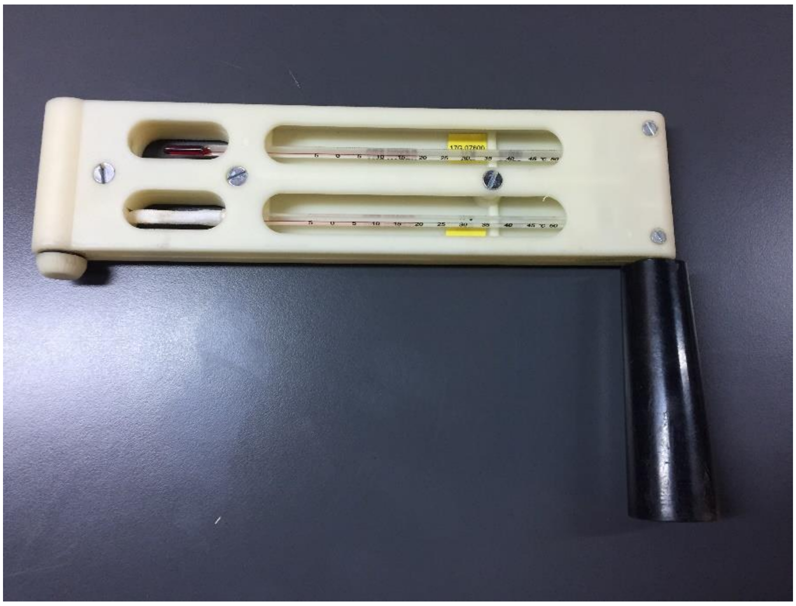

Figure 1-3: Whirling hygrometer

o Underground pressure

Underground pressures are measured with a barometer, where the absolute pressure is used. Differential pressures are also measured by a vertical or inclined manometer, digital manometer, and possibly a pitot tube, depending on the application. Figure 1-4 illustrates a typical barometer and vertical manometer used underground.

Figure 1-4: Barometer and vertical manometer (adapted from [24])

- **Heat content**

The heat content of a mixture of water vapour and air is the sum of the sensible internal energy and pressure energy [19]. In the application of psychrometry to the mining environment, preference has been given to the use of sigma heat over enthalpy for the heat content parameter. Sigma heat is equal to enthalpy minus the sensible heat of the water contained in the mixture if it were present in a liquid state at the same wet-bulb temperature [11], [19].

1.1.3 Methods for environmental control

Wallace *et al*. [25] note that control of the underground environment is achieved by identifying hazards and implementing controls. The MVSSA [26] expands on this strategy under the concept of risk management, explaining and elaborating on the various steps to be taken to control heat and environmental conditions.

- **Heat control**

Control of the heat content, and subsequently temperature of the air underground reduces to a heat balance. Any heat sources and sinks which can be controlled may be used to ensure the temperature of the air does not rise above allowable limits [7], [11].

Heat is generated underground by various sources, and numerous studies on the correct application of an underground heat balance have been completed [11], [27]–[29]. Below is an overview of the most notable heat sources found underground:

- Geothermal heat;
- air auto-compression;
- machinery;
- diesel equipment;
- human body heat;
- oxidation of materials;
- explosives;
- hot cabling and pipes;
- fissure water;
- rock movement; and
- surface air temperature.

The amount of heat that each of these sources contributes to the total heat load is highly dependent on the layout, operation, depth, and mining method, among others. In general, human body heat, fissure water, and hot cabling and pipes contribute the least to the overall heat load. Oxidation of materials is important in traditional mining and coal mines, while the contribution of diesel equipment is highly impactful in mechanised mines [11], [19], [30].

The heat sinks found underground are generally classed as [11], [27]:

- air cooling capacity;
- water-cooling duty; and
- refrigeration cycle.

The cooling capacity of air refers to the natural ability of air to absorb heat, mainly by way of convection and conduction. As the air becomes hotter, there is a decrease in the temperature differential with heat sources, thus reducing its ability to absorb heat. The water-cooling duty is very similar, in that water is sourced at a relatively low temperature and thus absorbs heat inside the mining environment.

The refrigeration cycle refers to all artificial cooling produced by cooling infrastructure and systems which reject their heat into the return airways or surface atmosphere [19], [27], [29].

Many forms of artificial cooling systems may be found in surface or underground installations. Some examples include:

- bulk air coolers (BACs);
- mobile and spot coolers;
- ice-cooling systems; and
- microclimate cooling systems.

BACs are large installations that cool large quantities of air, while spot coolers encompass air cooling units (ACUs), cooling cars (CCs), or stagnant spot coolers, which have much lower duties. Ice-cooling systems can be effective in deep mines, and microclimate coolers refer to vehicle or office cabin coolers [7], [10], [27], [31]–[33].

- **Dust, gas, and particulates control**

In most cases, control of dust, gases and particulates is very similar to that of heat. Sources include:

- diesel engines;
- mechanical scraping;
- ore handling;
- transport;
- drilling;
- gaseous emissions;
- spillage;
- blasting;
- construction;
- geological movement; and
- excessive airflow velocities.

This list is not comprehensive and, in practice, sources of pollutants are determined by risk management techniques, including empirical sampling and investigation as well as historical data [26]. Some notable pollutant sinks include [34]:

- settling chambers;
- inertial collectors;
- cyclones;

- spray towers;
- venturi scrubbers;
- fabric filters;
- electrostatic precipitators;
- exhaust hoods;
- water sprays;
- wetting agents, foams, and surfactants; and
- chemical scrubbers.

Most of these examples are focussed on dust control, since gases, particulates and aerosolised contaminants are relatively more difficult to capture [35]. For this reason, control strategies for these focus on dilution, removal through exhaust systems, or control at the source [26], [34]. Diesel particulate matter (DPM) is one such airborne pollutant, generally found in diesel engine exhaust emissions. Exposure to DPM is known to cause cancer in humans and its dilution is often a major factor in the initial airflow planning process. The dilution factors range from 0.045 m^3/s/kW to 1.00 m^3/s/kW and depend on how much DPM the engine produces [11], [25], [36]–[39].

Efforts to control these pollutants at the source have led to new generations of mechanised machines which can reduce particulate exhaust emissions by up to 90% (EPA Tier IV/EURO Stage IV) [25], [36], [38]. Other efforts involved moving toward the use of electric machinery with zero emissions [40]. As a result of this, studies such as that done by [36]–[38] on mechanization and ventilation requirements for underground mines have concluded that future ventilation planning should consider other factors such as heat for determining ventilation quantities because, while particulate emissions have decreased, heat concerns have not, especially as mines grow deeper.

- **Ventilation control**

When an acceptable quantity of ventilating air is determined, the air must next be managed. Airflow circuit planning ensures that the required air distributes effectively throughout the mine. These circuits function based on simple airflow laws, the most basic concept of which is pressure; air always flows from a high-pressure point to a low-pressure point. The governing law of this mostly turbulent airflow in the mining environment is described by Atkinson's formula, in Equation (1-1) [41]:

$$P = \frac{KCLQ^2}{A^3} \times \frac{w}{1.2} \tag{1-1}$$

where:

P = Pressure loss	Pa
K = Friction factor	Ns^2/m^4
C = Perimeter	m
L = Length	m
Q = Airflow quantity	m^3/s
A = Area	m^2
w = Air density	kg/m^3

Atkinson's formula can also be reduced to Equation (1-2):

$$P = RQ^2 \tag{1-2}$$

where:

R = Airway resistance	Ns^2/m^8

and includes all the missing terms. Distribution of the airflow is done according to parallel and series airflow laws [41]. The parallel airflow laws are shown in Equations (1-3) to (1-5) and apply to tunnels in parallel.

$$P_T = P_1 = P_2 \tag{1-3}$$

$$\frac{1}{\sqrt{R_T}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}} \tag{1-4}$$

$$Q_T = Q_1 + Q_2 \tag{1-5}$$

The series airflow laws are shown in Equations (1-6) to (1-8) and apply to tunnels in series.

$$P_T = P_1 + P_2 \tag{1-6}$$

$$R_T = R_1 + R_2 \tag{1-7}$$

$$Q_T = Q_1 = Q_2 \tag{1-8}$$

Where a quantity of air must be moved between two points, a pressure inducer is required, which comes in various forms as seen in Table 1-2 [42], [43].

Table 1-2: Examples of mining pressure inducers

Pressure inducer	Description
Primary fans	Large fans usually located on the surface and positioned at the outlet side of the airflow from the mine.
Booster fans	Medium-sized fans usually in series with other fans which assist in overcoming airflow resistances.
Circuit fans	Smaller fans used to direct air through a specific circuit or mining district.
Auxiliary fans	Some of the smallest fans, used to ventilate areas with no through-ventilation.
N.V.P.	Natural ventilation pressure is a phenomenon ascribed to the “difference between the mass column in an intake and that in a return”. A slight airflow is induced by the difference in density between intake and return air, which results from temperature differences.

These inducers are used to overcome the airflow resistances in the ventilation circuit. For the opposite effects, regulators and stoppings are used to introduce additional resistance to a tunnel. This allows air to distribute to parts of the network which would otherwise have poor airflow due to relatively higher tunnel resistances. Various forms and types of these regulators and stoppings exist, including [11], [44]:

- drop board regulators;
- louvres;
- rubber flaps;
- ventilation doors;
- bulkheads;
- temporary seals; and
- walls.

Since these controls usually are not perfect and some unintended leakage occurs, mine planning typically requires the use of leakage factors. These factors can be quite sizable, with a typically recommended factor of around 30% of the entire airflow quantity [11].

1.2 Literature on mine ventilation planning

Ventilation planning is achieved by one of two main methods, namely calculation or simulation [7], [8], [12], [30], [45]–[48].

1.2.1 Calculation and first estimates planning

Calculations are an established method for planning mine ventilation and cooling based on empirical relationships. They make use of the decades of literature, recommendations and experience in the industry, which has been summarised in various works [11], [17]. Figure 1-5 shows one such graph depicting a correlation between the cooling capacity of downcast air with various surface air temperatures. These surface air temperatures are usually selected to represent the worst-case, highest-average wet-bulb temperature scenario in the specific region [27], [46].

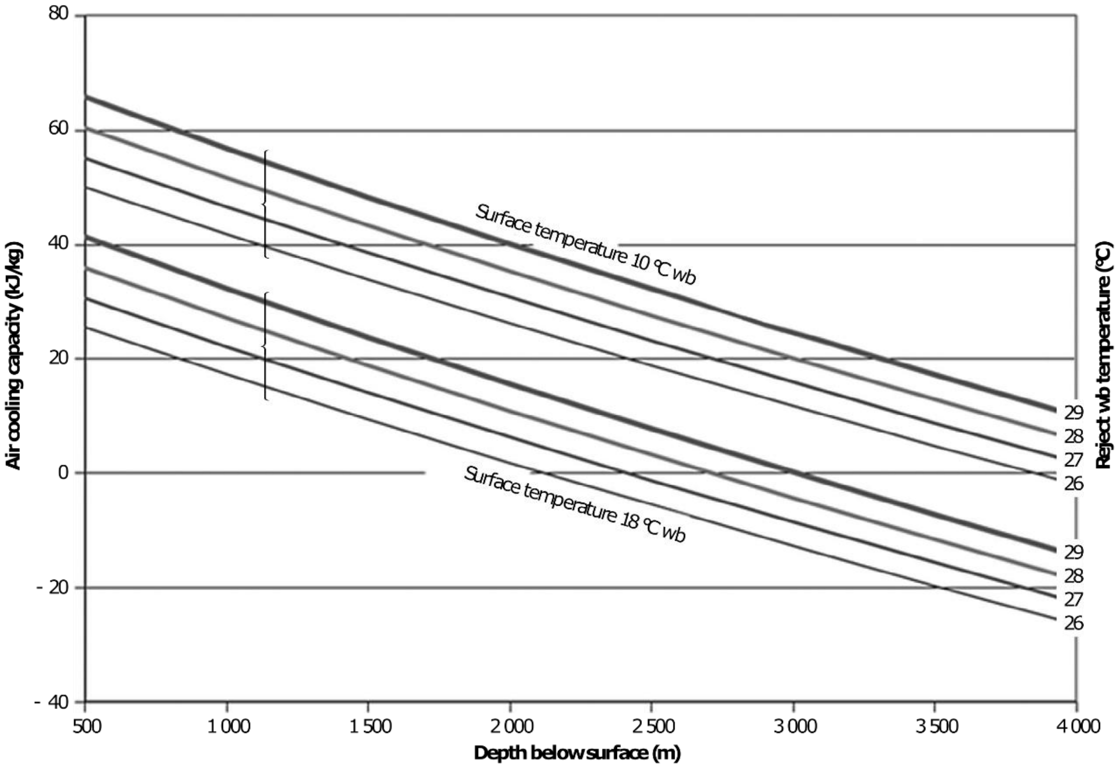

Figure 1-5: Graph showing the cooling capacity of downcast air (adopted from [11])

Knowing or selecting the mining input parameters such as surface air temperature, depth, mechanised machinery used, rock thermal gradient, and reject temperature allows for the use of these various graphs, nomograms, tables, and figures. From these figures, parameters such as underground temperatures and ventilation rates among others may be estimated. Table 1-3 shows an example of some typical input parameters that are required to use these figures [11], [27], [41], [48].

Table 1-3: Some typical planning input parameters

Parameter	Unit
Production rate	ktonne/month
Mean rock-breaking depth	m below surface
Design reject temperature	°C wet-bulb
Face velocity in stopes	m/s
Surface air temperature	°C wet-bulb
Surface air relative humidity	%
Maximum distance from shaft	m
Service water consumption	tonne/tonne rock broken
Mechanised heat	kW
Number of underground employees	employees

The various figures discussed were compiled from the empirical data of various mines [48], although they have some significant shortcomings, namely that they tend to be too general, neglect mechanization, and are quite specific to the region from which most of the data was sourced [27]. Literature sources recommend using calculation-based planning for initial high-level estimates and then moving on to simulation-based planning once more detail is required [11], [17].

An alternative and more detailed method for some of these factors exists in the form of heat load calculations. Here, a more in-depth look is taken at the true mining environment. Theoretical correlations of various parameters are used, which may be adapted with empirical data. Various studies have also focussed on the proper execution of these mine heat loads [27]–[29], [48].

1.2.2 Simulation-based planning

When a detailed and in-depth estimation of the ventilation and cooling network is required, simulation-based planning is key. Software packages utilise the fundamental theory and equations which underpin psychrometry and ventilation to solve for various parameters in the ventilation network. These packages are numerous and have differing areas of focus such as those described in Table 1-4.

Table 1-4: Comparison of simulation software

Package	Description
Vuma [12], [49], [50]	3D ventilation modelling. Difficulty simulating complicated auxiliary ventilation systems. Steady-state solutions.
Ventsim [30], [46], [51], [52]	Intended for planning. Requires skilled personnel to operate. Steady-state solutions.
Process Toolbox (PTB) [27], [53], [54]	3D ventilation modelling and planning. Drag-and-drop ease of use. Steady state and transient solutions.

Many other packages also exist, such as fire simulators, refrigeration simulators, and water system simulators, each with their own specific applications [11]. Generally, the software allows a user to recreate a model of the actual mine system being simulated.

In the case of a ventilation model, the tunnels, fans, and other components are placed at their respective true coordinates, with the final product closely resembling the actual mine. Various input parameters are specified, which allow for the automatic calculation of temperature, pressure, humidity, volume flow, mass flow, resistance, fan operating points, and more. Some simulation software, such as PTB, even allow transient simulation of the mining environment for estimating change propagation with time.

Table 1-5 lists some of the various inputs required by a ventilation and cooling simulator.

Table 1-5: Some typical ventilation simulation input parameters

Parameter	Unit
Tunnel area	m^2
Tunnel circumference	m
Friction factor	Ns^2/m^4
Wet area fraction	N/A
Surface air temperature	°C dry-bulb
Surface air relative humidity	%
Surface air pressure	kPa
Rock thermal properties	N/A
Heat sources	W

This list is not comprehensive, as some input parameters differ between simulators due to differences in simulation strategies, purpose, and required accuracy. To correctly simulate the mining environment, calibration of the various input parameters and components is needed. Calibration is generally done by comparing model output to recently measured data typically originating from a mass mine audit and adjusting the simulation accordingly. Other examples of data sources for comparison include [26]:

- databases;
- design specifications;
- daily reports;
- exception reports;
- investigation reports;
- recommendatory reports;
- progress reports;
- comprehensive reports; and
- calculations.

The accuracy of the model is then determined by comparing the model outputs with the measured data. The mean absolute error (MAE) equation, shown in Equation (1-9), is used for this purpose [54]:

$$MAE_{\%} = \frac{\frac{1}{N}\sum_{n=1}^{N}|A_n - S_n|}{\frac{1}{N}\sum_{n=1}^{N}|A_n|} \times 100\% \tag{1-9}$$

with:

$MAE_{\%}$ = Mean Absolute Error Percentage %

N = Total number of data points –

n = Individual data point –

A_n = Measured data point –

S_n = Simulated data point –

1.2.3 Critical literature on mine ventilation planning

Various studies exist which pertain to mine ventilation and cooling planning. In identifying the relevant studies, keywords such as “mine ventilation”, “mine planning”, “ventilation planning”, “mine cooling”, “mine simulation”, “mine heat load” and more were furnished to search engines such as EBSCOhost, Science Direct and Google Scholar. The journals and other publications of the MVSSA and similar bodies were also reviewed along with the relevant citations found therein. Generally, works published after 2010 were preferred but some historical works were also included to illustrate the change in planning methodologies over time. In this section, studies that attempt to use some method of approach for mine ventilation and cooling planning are analysed. A brief overview of each study is given as well as a discussion of the shortcomings and the method of planning used.

1. ***Establishing total airflow requirements for underground metal/non-metal mines with tier IV diesel equipment* (2013) [36]**

Overview : The study analyses calculation-based methods of determining airflow requirements with a focus on small mining sections and the diesel equipment therein. Results show general underventilation when excluding heat and dust generation. A general planning methodology is given.

Shortcomings : The study neglects simulation-based planning, planning for the whole life-of-mine, and various heat sources. The planning methodology given has limited scope in terms of ventilation layout planning and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine design parameters → Diesel fleet assessment → Regulatory requirements → Calculation → Comparison. See Appendix A, Appendix-figure 1: Alternative ventilation planning methodology (adopted from [36]).

2. ***Planning of ventilation requirements for deep mechanised long wall faces - A case study of Adriyala longwall project of the Singareni Collieries Company Limited (SCCL)* (2015) [30]**

Overview : This study discusses the results of calculation-based mine ventilation planning of a mechanised coal mine based on regulatory airflow recommendations. Simulation was used to confirm the determined airflow quantity and cooling was proposed due to high working temperatures.

Shortcomings : The study neglects planning for the whole life-of-mine as well as DPM control. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.

Planning method	: Mine specifications → Regulatory airflow rates → Calculation → Simulation → Temperature assessment → Estimation of cooling requirements.

3. ***Life of mine ventilation requirements for Bronzewing mine using VentSim*** **(2013) [51]**

Overview	: This study centres on the planning of ventilation for a mine expansion. Simulation is used to estimate required airflows and minimum quantities are based on regulations for DPM.
Shortcomings	: The study neglects planning for the whole life-of-mine as well as temperature control. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.
Planning method	: Mine specifications → Regulatory airflow rates → Calculation → Simulation.

4. ***A framework for life-of-mine ventilation planning with a case study of the Diavik diamond mine*** **(2017) [46]**

Overview	: This study focusses on the application of a general planning methodology for economic optimisation of ventilation planning. Simulation of the whole life-of-mine is used. Temperature control is overlooked due to temperate conditions in the case study. Ventilation quantities are determined by DPM dilution factors.
Shortcomings	: The study neglects temperature control. The planning methodology used is also not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications → Regulatory airflow rates → Calculation → Simulation → Future simulation → Results assessment and problem identification → Idea generation and solution assessment → Planning adjustments. See Appendix A, Appendix-figure 2: Alternative ventilation planning methodology (adopted from [46]).

5. ***Agnew gold mine expansion mine ventilation evaluation using VentSim*** **(2011) [55]**

Overview : This study considers the economic evaluation of fan installation scenarios for a planned mining expansion. DPM regulations are used to set airflow quantity requirements.

Shortcomings : The study neglects planning for the whole life-of-mine, ventilation network planning, and temperature control. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications → Regulatory airflow rates → Calculation → Simulation → Economic evaluation of scenarios → Fan selection.

6. ***Improving the operational efficiency of deep-level mine ventilation systems*** **(2019) [53]**

Overview : This study focusses on the optimisation of ventilation efficiency. A general planning method is proposed. Temperature control is overlooked due to temperate conditions in the case study. Simulation was used to predict energy and cost savings when reducing unnecessary air wastage.

Shortcomings : The study does not make use of temperature control and neglects any calculation-based planning, the influence of mechanised machinery, planning for the whole life-of-mine, and DPM control. The planning methodology is also unclear and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications → Mass mine audit → Simulation → Results assessment and problem identification → Idea generation and solution assessment → Solution optimisation. See Appendix A, Appendix-figure 3: Alternative ventilation planning methodology (adopted from [53]).

7. ***Planning ventilation and refrigeration requirements & PC-based planning tools (2014) [11]***

Overview : Two chapters in the book *Ventilation and occupational Environmental Engineering in Mines* consider the practice of mine ventilation and cooling planning. Simulation software is mentioned, but only the calculation-based planning of specific scenarios is discussed in detail. A general methodology is proposed, with ventilation control strategies discussed elsewhere.

Shortcomings : Simulation-based planning is not done. The work neglects planning for the whole life-of-mine. The planning methodology is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications → Regulatory requirements → Calculation → Ventilation layout design → Alternatives and optimisation. See Appendix A, Appendix-figure 4: Alternative ventilation planning methodology (adopted from [11]).

8. ***Life-of-mine ventilation and refrigeration planning for Resolution copper mine (2013) [12]***

Overview : This study focusses on the ventilation and cooling planning of a new, large, deep, mechanised mine. Focus is placed on the control of DPM, dust, and temperature. By simulating various scenarios, the final recommendation is made to construct a large refrigeration system.

The study also includes a ventilation control strategy.

Shortcomings : The study neglects planning for the whole life-of-mine. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications → Simulation → Heat load, ventilation, and refrigeration estimation → Benchmark comparison → Ventilation layout design → Dust management design.

*9. **Heat Treatment and Ventilation Optimization in a Deep Mine*** **(2018) [29]**

Overview : In this study, the problem of excessive heat in the mining environment is addressed through the implementation of new technology. Focus is placed on temperature control and improving ventilation rates. Heat-loads, as well as practical implementation and analysis, are used to identify and quantify the improvement.

Shortcomings : The study neglects simulation-based planning, planning for the whole life-of-mine, and DPM control. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine heat load and ventilation survey → Analysis and problem identification → Technology survey and selection → Implementation → Improvement survey.

*10. **The estimation of ventilation air temperatures in deep mines*** **(1950) [56]**

Overview : In this paper, the author attempts to quantify the empirical correlation between the inlet wet-bulb temperature, virgin rock temperature (VRT), and the heat pickup in any tunnel. Various figures are produced which estimate the heat pickup and are intended for planning purposes. The study is quite old, and modern mines prefer modern techniques, although empirical techniques are still in use, and this study is a good example of the application of these historical methods.

Shortcomings : The study neglects all planning factors beyond heat and temperature control.

Planning method : Ventilation and VRT survey → Empirical heat pickup estimation.

11. ***Ventilation planning and design of the Omerler B mine*** **(2012) [47]**

Overview : This study is about the planning of a new mechanised mine. The study discusses the ventilation layout design process with a focus on dust and gases, since the mine is identified as a gassy mine. Only very basic airflow network solution software is employed.

Shortcomings : The study neglects planning for the whole life-of-mine, DPM, and temperature control. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications/Data acquisition → Ventilation network layout → Regulatory airflow rates → Calculation → Simulation → Scenario assessment.

12. ***The integration of mine simulation and ventilation simulation to develop a 'Life-Cycle' mine ventilation system*** **(2003)** [57]

Overview : This study focusses on the assessment of new technology and its applicability to mine ventilation planning. Benefits and uses of various contemporary technologies such as ventilation on demand (VOD) and telemining are mentioned. The study discusses the conventional, as well as the more contemporary, life-cycle planning techniques with a general method for both. Life-cycle mine ventilation planning is identical to life-of-mine ventilation planning. The study seems to suggest a continuous process but is not clear on this.

Shortcomings : The study neglects specific scenario planning, with no application to showcase the use of the proposed methodology. Temperature and DPM control are only mentioned briefly, and the planning methodology suggests being continuous but does not showcase or discuss this further.

Planning method : Mine specifications/Mass mine audit → Simulation → System optimisation → Climate assessment → Ventilation adjustment → Technology implementation. See Appendix A, Appendix-figure 5: Alternative ventilation planning methodology (adopted from [57]) and Appendix-figure 6: Alternative ventilation planning methodology (adopted from [57]).

*13. **Ventilation planning and design of the Derin Sahalar mine*** **(2013) [45]**

Overview : This study focusses on the planning of a new mechanised mine. It was conducted by the same authors as the study on the Omerler B mine (See Study 11) and thus is very similar. The study discusses the ventilation layout design process of a gassy mine with a focus on dust and gases. Only very basic airflow network solution software is employed.

Shortcomings : The study neglects planning for the whole life-of-mine, DPM, and temperature control. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.

Planning method : Mine specifications/Data acquisition → Ventilation network layout → Regulatory airflow rates → Calculation → Simulation → Scenario assessment

14. ***The use of 3D simulation system in mine ventilation management*** **(2011) [52]**

Overview : In this study, the use of 3D simulation software to replace outdated 2D ventilation network software is discussed. A ventilation audit is used to build the model. This is then used to identify high resistance airways, detect recirculation, and simulate emergency scenarios for improved planning.

Shortcomings : The study neglects calculation-based planning, the influence of mechanised machinery, planning for the whole life-of-mine, DPM, and temperature control. The planning methodology used is specific to the case study and is not continuous, neglecting possible deviation from the plan.

Planning method : Mine network audit → Construction of simulation → Network analysis → Identification of inefficiencies

15. ***Benefit of using mine process simulators to design a "life-cycle" mine ventilation system*** **(2004) [39]**

Overview : This study focusses on the assessment of new technology and its applicability to mine ventilation planning. It was completed by the same author as "*The integration of mine simulation and ventilation simulation to develop a 'Life-Cycle' mine ventilation system"* (See *Study* 12) and is very similar. Benefits and uses of various contemporary technologies such as ventilation on demand (VOD) and telemining are discussed. The study mentions conventional as well as more contemporary, life-cycle planning techniques with a general method for both, which differs slightly from the previous study. Life-cycle mine ventilation planning is identical to life-of-mine ventilation planning.

Shortcomings	:	The study neglects specific scenario planning with no application to showcase the use of the proposed methodology. Temperature and DPM control are only mentioned briefly. The planning methodology used is specific to the case study and is not continuous, thus neglecting possible deviation from the plan.
Planning method	:	Mine specifications/Mass mine audit → Technology specifications → Simulation → Discreet event analysis → Ventilation adjustment → Optimisation. See Appendix A, Appendix-figure 7: Alternative ventilation planning methodology (adopted from [39]) and Appendix-figure 8: Alternative ventilation planning methodology (adopted from [39]).

16. ***Underground mine ventilation planning, heat loads, and diesel equipment*** **(2006) [58]**

Overview	:	This study focusses on the planning process of a mechanised mine section. Emphasis is placed on determining airflow quantity and controlling pollutants such as dust, DPM, and heat. The process also indicates the airflow requirements with time over the life-of-mine. The quantities were based on the maximum requirement of any pollutant. A general planning methodology is given.
Shortcomings	:	The study neglects to showcase the simulation-based planning portion as well as not planning for the whole life-of-mine. The planning methodology flowchart proposed is too simplistic, which therefore does not sufficiently represent the whole process and is not continuous, thus neglecting possible deviation from the plan.
Planning method	:	Mine specifications → Regulatory requirements → Calculation → Heat load, ventilation, and refrigeration estimation → Simulation → Optimise alternatives. See Appendix A, Appendix-figure 9: Alternative ventilation planning methodology (adopted from [58]).

1.2.4 Summary of critical literature

The studies discussed above show that life-of-mine planning is generally overlooked in favour of specific scenario planning. Some studies neglect temperature control and others focus on heat directly generated by machinery while ignoring other sources which may contribute to heightened ventilation or refrigeration requirements. This is concerning the given tendency of mines to grow deeper and more mechanised, which therefore require more diligent consideration of temperature [36]–[38]. Some good work has been done on proposing generic methodologies, but many of these are too specific while others are too simplistic. In general, there was a significant lack of studies emphasising the need for continuous mine planning in which plans are updated regularly as major deviations occur. These deviations are fairly common in the mining environment when incidents, accidents, unintended excavation intersections, or other events occur [7], [59]–[61]. In this regard, most studies did not do any follow-ups after the implementation of changes to determine the accuracy of the plans and predictions.

The most comprehensive methodologies were given in Study 4, 12 and 15, represented by Appendix-figure 2, Appendix-figure 5, Appendix-figure 6, and Appendix-figure 7. Nevertheless, Appendix-figure 5 and Appendix-figure 7 both neglected to include life-of-mine planning. Both methods given in Study 12 neglected results validation, while Study 4 and 15 neglected temperature control.

Furthermore, Study 15 confused verification with validation, with the former being defined as “the process of checking that the program output is consistent with the outcomes which should result from the… simulation” – meaning that the initial model successfully produces output resembling the data used during its construction – and the latter being “the process of ensuring a simulation is an adequate representation of the reality it is attempting to model” and referring to a simulation which accurately predicts the effects of changes [62].

Table 1-6 shows the summarised results of the literature analysis with green, checked boxes representing fields in which studies adequately addressed the specific planning topic. The main topics on which the current study focusses have also been highlighted.

Table 1-6: Research matrix of related literature (summary)

Study No.	Simulation-based planning	Calculation and first estimates	Mechanised	Scenario planning	Life-of-mine planning	DPM control	Heat/temperature control	Ventilation control	Generic methodology	Continuous planning
1 [36]	✗	✓	✓	✓	✗	✓	✓	✓	✓	✗
2 [30]	✓	✓	✓	✓	✗	✗	✓	✓	✗	✗
3 [51]	✓	✓	✓	✓	✗	✓	✗	✓	✗	✗
4 [46]	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗
5 [55]	✓	✓	✓	✓	✗	✓	✗	✗	✗	✗
6 [53]	✓	✗	✗	✓	✗	✗	✗	✓	✓	✗
7 [11]	✗	✓	✓	✓	✗	✓	✓	✗	✓	✗
8 [12]	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗
9 [29]	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗
10 [56]	✗	✗	✗	✗	✗	✗	✓	✗	✗	✗
11 [47]	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
12 [57]	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗
13 [45]	✓	✓	✓	✓	✗	✗	✗	✓	✗	✗
14 [52]	✓	✗	✗	✓	✗	✗	✗	✓	✗	✗
15 [39]	✓	✓	✓	✗	✓	✓	✓	✓	✓	✗
16 [58]	✗	✓	✓	✓	✗	✓	✓	✓	✓	✗

1.3 Need for the study

The literature review indicated a large shortage of studies on life-of-mine ventilation and cooling planning. Furthermore, existing studies failed to address temperature control sufficiently with regards to the current trends of increasing mining depth and mechanization. Generic methodologies had some shortcomings and studies failed to include considerations for continuous planning. Therefore:

A need exists to develop a methodology for simulation-based planning of ventilation and cooling in deep-level mechanised mines throughout the life-of-mine.

1.4 Objectives

The main objective of this study was to develop a generic methodology for ventilation and cooling planning in mechanised mines. This was achieved inter alia via the following sub-objectives:

1. Make use of simulation software;
2. Account for all heat sources;
3. Plan for the life-of-mine; and
4. Monitor continuously for deviations.

1.5 Dissertation layout

- **Chapter 1: Introduction and literature review**

Chapter 1 discussed the current state of the mining industry with context on the setting of the current study. A detailed literature review on the process of mine planning with a focus on ventilation and cooling planning and the various studies on the topic was completed. Finally, a detailed review of the shortcomings and definition of the current problem statement and objectives was given.

- **Chapter 2: Methodology**

Chapter 2 introduces the proposed methodology for mine ventilation planning with a detailed explanation of the steps. The construction of the model, gathering of empirical data, construction of future scenarios and identification of controls are then discussed.

- **Chapter 3: Case study and results**

Chapter 3 revolves around the application of the methodology to a case study mine. The results of the simulation construction and future mine plans are discussed. Finally, the control methods identified and results of any controls implemented are given.

- **Chapter 4: Conclusion and recommendations**

Chapter 4 presents a synopsis of and conclusion to the study, after which recommendations and limitations are discussed.

2 METHODOLOGY

2.1 Preface

In this chapter, the general methodology that was used to satisfy the objectives given in Section 1.4 is discussed. The chapter also discusses the various steps in the mine ventilation planning methodology with the aim of being as applicable to most mechanised mines as possible while also including some showcase-specific examples from the application of the method to mine X. In satisfying the first objective given in Section 1.4, Process Toolbox (PTB) was selected as the preferred simulation package for its ease of use and applicability.

2.2 Generic planning methodology

Section 1.3 discussed the need for a generic methodology that addresses the gaps in the literature and expands on shortcomings identified in Sections 1.2.3 and 1.2.4. In developing this generic planning methodology, the strengths, weaknesses, and differences of the existing alternatives were considered.

Appendix-figure 1 of Study 1 depicts the method for analysing multiple pollutant sources to determine the required airflow for each [36]. Many studies implemented similar methods, and the proposed methodology agrees well with that proposed in Study 15 [39]. As discussed in Section 1.1.2, pollutant control is required to ensure that regulatory limits are not exceeded [16]. The method proposed in Study 1 was adapted into the current study to address these pollutants sufficiently.

Appendix-figure 3 of Study 6 and Appendix-figure 5 of Study 12 both highlight the use of surveys of the mining environment alongside any available mine plans [53], [57]. As discussed in Section 1.2, this information is critical as input to calculation- and simulation-based planning techniques. Appendix-figure 2 of Study 4 along with Appendix-figure 6 of Study 12 represent reasonably comprehensive predictive modelling methodologies. Both include the construction of a baseline model and future modelling [46], [57]. Baseline models serve as the starting point for predictive modelling, being representations of the system being modelled in its current form and allowing for confident extrapolation during future modelling [46].

Studies 1, 4, 12 and 16 all include checks on the environmental conditions and heat loads [36], [46], [57], [58]. These ensure that the modelled results are acceptable and realistic. Appendix-figure 6 of Study 12 and Appendix-figure 8 of Study 15 highlight the integration of whole life-of-mine modelling strategies [39], [57]. This allows planners to gain a full picture of the future mine and the long-term impact of changes.

Finally, Study 4, 6, 7, 12, 15 and 16 highlight the nature of iterative modelling [11], [39], [46], [53], [57], [58]. When models are not sufficiently accurate or predictions do not agree with measured values, the cause may be investigated and problems corrected to improve accuracy.

One aspect not addressed in the studies is that of continuous monitoring or the continuous planning process. The mining environment is not stagnant and, due to unexpected deviations, it is also not truly predictable. Some deviations have significant impacts on future planning, rendering some plans impractical and others non-optimal [7]. It is important to remain abreast of these deviations to adjust plans accordingly.

After integrating these aspects into a new, coherent methodology, three distinct phases of the planning process could be discerned, namely: 1) baseline modelling; 2) air quantity estimation; and 3) continuous predictive modelling.

Of these three phases, baseline modelling and air quantity estimation occur in parallel, after which continuous predictive modelling is done.

2.2.1 Baseline modelling

- **Mining plans**

Mining companies keep detailed plans on their mining activities which may be necessary for mine planning and modelling purposes. The mining method is one such plan, sourced from the ore reserves department. Mining infrastructure, locations, and information on mechanised machinery are found with the engineering department. Information on refrigeration and cooling infrastructure, as well as specifications on fans and their locations, comes from the services engineer. Mine-specific environmental standards are found with the environmental engineering/occupational hygiene department. Information on labour comes from human resources, and updated maps, future development plans, and tonnage profiles are from the survey and planning departments.

It is also necessary to gather specific details on the local rock thermal properties such as VRT gradient, rock thermal conductivity, and rock specific heat. In [11], various values for these and other properties required for modelling in a South African context have already been determined. In addition to these, some specific examples of plans which may be gathered before modelling include:

- digital ‘dxf’-type mine drawings with development dates;
- cooling infrastructure operational data;
- fan curves;
- specifics on planned infrastructure;
- friction coefficients; and
- haulage sizes.

Some mining plans, such as future network layouts, change so frequently that it is necessary to specify the time period to be modelled [46]. Multiple time periods across the life-of-mine are selected for simulation to represent the whole life-of-mine. In achieving this, consideration is given to selecting periods that represent worst-case or critical scenarios in each timeframe [12].

With respect to ventilation planning, worst-case scenarios are subject to the circumstances of the mine being simulated. A deep-level mine in South Africa might consider the week with the highest average surface wet-bulb temperature as the worst-case scenario unless, for example, dust exposure is more pressing and has its own time-based cyclical concentration pattern. However, a mine in Canada or Alaska may have the opposite concerns, favouring a time period wherein the highest number of employees are exposed to extreme cold [46].

o Ventilation survey

According to Section 11 and Regulation 9.2 of the MHSA, a mine is required to have a system of occupational hygiene measurements based on the mine’s risk assessment. These measurements may be made in real time with instrumentation but are typically done through an audit by qualified personnel in the occupational hygiene department [16], [51]. These audits on airflow, pressure, DPM, gas, dust, and temperature exposure, among others, are stored and used for modelling purposes [26]. It may sometimes be necessary to gather additional data, such as specific underground tunnel sizes or surface ambient condition histories, by conducting a custom audit or sourcing them from other agencies.

The *Handbook on Mine Occupational Hygiene Measurements* describes the method used to take ventilation flow measurements using a rotating vane anemometer [24, pp. 314-317]. In the case of this study, the mechanical vane anemometer and the Kestrel-type digital anemometer were used. It is specified that the velocity being measured should be greater than 0.5 m/s when using the mechanical vane and more than 0.3 m/s for the Kestrel-type anemometer. The method used when determining the wet- and dry-bulb temperatures with a whirling hygrometer is also described in [24, pp. 217-219].

The mine ventilation planning process should integrate with existing processes and departments, and data should be gathered from various department audits and applied for planning purposes to ensure coordination and consensus. Shortcomings of this reapplication of data may be identified and, from this, the need may arise to refine and improve upon the audit process in future and where practical.

- **Model development**

The next step is to use the data gathered to develop and tune the baseline model of the mine. According to [46], the goal is to accurately model the current system, matching airflows, temperatures and pressures to allow for confident extrapolation, later. The plans and information gathered as well as digital resources, such as ‘dxf’-type drawings, are used to start construction. The digital drawings already contain data on depth and location, assisting in the drag-and-drop construction of nodes and tunnels to mimic the existing mine layout. Air pressure boundaries are used to terminate the network on the surface and wherever the air destination or source cannot be determined.

When initial construction is complete, fine details are added by setting the area, perimeter, surface elevation, tunnel age, friction coefficients, VRT gradient, rock thermal conductivity, rock specific heat, terminal pressures, terminal temperatures, and component configurations such as stope, door, or tunnel. Other visual effects such as colouring of tunnel connections for ease of reference may also be introduced. As an example, in the case study, all intake air sections were coloured blue, and all return air sections orange. Stopes and working places were made green and closed areas grey. The exact definition of the colour boundaries is subjective.

Table 2-1 shows some suggested initial tunnel properties to be implemented. The values of the wet area fraction and heat properties were chosen from the author’s experience and will be refined later, during the calibration process.

Table 2-1: Suggested initial tunnel properties

Parameter	Variations	Property	Values	Units
General	-	Virgin rock temperature gradient	0.0146	°C/m
		Rock thermal conductivity	0.00574	kW/m/°C
		Rock density	2 690	kg/m3
		Rock specific heat	0.837	kJ/kg/°C
		Friction coefficient	0.011	Ns2/m4
Shaft	Intake	Wet area fraction	0.16	-
		Heat	0.00	kW/m
	Return	Wet area fraction	0.10	-
		Heat	0.00	kW/m
Haulage	Intake	Wet area fraction	0.16	-
		Heat	0.25	kW/m
	Return	Wet area fraction	0.10	-
		Heat	0.00	kW/m
Stope	Conventional	Wet area fraction	0.30	-
		Heat	0.25	kW/m
	Massive	Wet area fraction	0.30	-
		Heat	0.25	kW/m

At this stage the infrastructure, including auxiliary fans, return fan clusters, booster fans, surface fans, BACs, ACUs, CCs, crushers, workshops, refrigeration plants etcetera are added. Drawing from the plans and ventilation surveys the infrastructure is independently calibrated including efficiency, heating, and cooling effects.

PTB allows for the selection of certain simulation settings. These simulation settings are chosen to ensure stability, speed of solution and accuracy by allowing enough iterations for a stable, steady-state solution to be achieved. The simulation settings used for modelling mine X were:

- Number of time periods = 6
- Period size = 3600

When transient modelling is enabled, the period size represents the number of seconds in a period. From the settings given this would amount to a one hour per period. The number of time periods refers to the total number of distinct outputs to be displayed to the user. With reference to the above settings, any output graph drawn from the simulation with these settings would have six datapoints representing whatever the dynamic change of the specific variable would be over six hours. When steady-state modelling is used, the settings simply set the maximum number of iterations to be allowed during the search for the true steady-state solution.

When the network is complete and simulation properties specified, the model is simulated to return initial flow and temperature estimates. From this point, the model is calibrated in three stages, namely 1) flowrate calibration; 2) temperature calibration; and 3) pollutant calibration.

1. Flowrate calibration

First, the flow rates are corrected, as they are semi-independent of the temperature. This is achieved by adjusting door fractions manually and placing calibration controllers on leaks and restrictions where the exact size and properties of the airway are unknown. The previously determined airflow quantities are used and adjustments made until flowrates are within approximately 10% of the specified values [46]. Simulation snapshots or similar functionalities in other programs can be used to start each run closer to the end of the previous, cutting down on simulation time.

In some isolated areas, values may fall outside acceptable limits due to discrepancies between measurements and mass balances attributable to measurement errors. Caution is advised when calibrating a model based on ventilation audit data, as these measurements are often taken over several days and over multiple hours in each session [51], [53]. The mining environment is not stagnant and, thus, these values should be taken as approximations of reality for calibration purposes.

2. Temperature calibration

Once the airflow measurements are satisfied, the next step is to calibrate the wet- and dry-bulb temperatures. Various heat sources exist underground, as discussed in Section 1.1.3. Large sections of the mining environment are also quite similar in-depth, infrastructure, and operations such as mining levels, workshops, and stopes. It is appropriate to divide the mine into these sections for temperature calibration purposes [12], [49].

The ‘heat’ and ‘wet area fraction’ properties of each of these sections are calibrated to ensure the simulated temperatures agree with measurements. This method of heat calibration is in agreement with that used by other authors such as [12]. The wet area fraction represents the presence of water, typically in the underground mining environment. As with airflow, the temperatures measured should be taken as approximations, and a reasonable amount of divergence is acceptable. In this case, the aim was to keep wet- and dry-bulb temperatures within 1.5 °C and 2 °C of the measured values, respectively. With this calibration step, the second objective given in Section 1.4 is satisfied.

3. Pollutant calibration

Finally, the pollutants are calibrated. Section 1.1.3 discussed some of the sources of the various pollutants found underground. Pollutant calibration is similar to temperature calibration in the sense that specific areas may be calibrated in-depth while others are calibrated as a whole [63]. Here too some divergence is acceptable.

In some instances, the occupational hygiene department may neglect to take static spot measurements or quantify pollutant sources. Instead, use is often made of personal sampling to determine exposures [12], [35], [63]. In lieu of static measurement pollutant calibration, it may be assumed that determining and assessing the air quantity required for sufficient dilution of personal pollutant exposures would be sufficient for planning purposes [64]. The use of these values allows for full integration of the planning process with the existing ventilation department audits.

The *Handbook on Mine Occupational Hygiene Measurements* describes the procedure and calculations used for personal dust sampling [24, pp. 24-29] and personal DPM exposure sampling [24, pp. 42-44]. The samples taken are then analysed according to standard methods such as ASTM D1739/SANS 1929 for dust, and NIOSH 5040 for DPM.

- **Verify model**

Once all three calibration stages are concluded, the individual model MAEs are determined by comparing the model's output values with the audit values. If the errors are too large, the model or individual level/area calibration steps are repeated to increase the accuracy. Typically, a model with an error of up to 10% in each category is acceptable for selection as the baseline model [46], [54], [65], [66]. Other methods for verification, such as heat loads, are also used [27], [58].

2.2.2 Air quantity estimation

- **Regulations, codes of practice and standards**

Regulations as well as various codes of practice and standards are given in the MHSA and are available from authorities such as the MVSSA, mining companies, and government sources. Values such as the occupational exposure limit (OEL) of various pollutants are used to determine the air quality index (AQI) and the minimum air quantities required to maintain AQIs below one, according to published guidelines [63].

In addition to this information, most mines should complete their own risk assessments, as per regulatory requirements, to determine the level and acceptability of risks and corrective actions to be taken with regard to airborne pollutants [16], [26]. Minimum standards for stope, development, massive stope, and diesel engine ventilation quantities determined in this manner are intended to represent airflow quantities sufficient to deal with all pollutants.

- **Determine minimum airflow quantities**

Depending on the data available and the most pressing concerns of the mine, various methods for determining minimum airflow quantities are used [11], [36]. Methods may be based on considerations of explosive gas dilution, simple production correlations, exhaust gas dilution, minimum airflow standards, dust dilution and pollutant removal. Here, four different factors, and the three methods for basing airflow requirements thereon, are discussed, namely: 1) stoping, development and massive stoping requirements; 2) diesel exhaust dilution requirements; and 3) DPM and dust exposure requirements.

1. Stoping, development and massive stoping requirements

Equations (2-1) to (2-6) show the method used to calculate the total air quantity according to the development, stoping, and massive stope airflow requirements [48].

$$DA = Haulage\ width \times Haulage\ height \tag{2-1}$$

$$Dair = DA \times \mathrm{DAF} \times Number\ of\ developments \tag{2-2}$$

$$SA = Stope\ height \times FtC \times Stope\ sides + Gully\ height \times Gully\ width \tag{2-3}$$

$$Sair = SA \times SFV \times Number\ of\ stopes \div SLF \tag{2-4}$$

$$Mair = MAV \times Number\ of\ massives \tag{2-5}$$

$$AQ_{D,S,M} = Dair + Sair + M_{air} \tag{2-6}$$

where:

DA = Development area m^2

$Haulage\ width$ = Mechanised haulage width m

$Haulage\ height$ = Mechanised haulage height m

$Dair$ = Total development air quantity	m^3/s
DAF = Required development airflow per face area	$m^3/s/m^2$
$Number\ of\ developments$ = Total number of developments	$Development\ ends$
SA = Stope area	m^2
$Stope\ height$ = Height from footwall to hanging wall in stope	m
FtC = Face to curtain distance in stope	m
$Stope\ sides$ = Number of sides per stope	$Sides/stope$
$Gully\ height$ = Height from footwall to hanging wall in centre gully	m
$Gully\ height$ = Width from curtain to curtain in centre gully	m
$Sair$ = Total stope air quantity	m^3/s
SFV = Required stope face velocity	m/s
$Number\ of\ stopes$ = Total number of stopes	$Stopes$
SLF = Stope leakage factor	-
$Mair$ = Total massive stope air quantity	m^3/s

MAV = Required air volume to ventilate a massive stope m^3/s

$Number\ of\ massives$ = Total number of massive stopes -

$AQ_{D,S,M}$ = Air quantity required for developments, stopes, and massives $m^3/s\ /kW$

Note that the stope leakage factor accounts for leakage through brattices and auxiliary air usage for winches, among others [48].

2. Diesel exhaust dilution requirements

Equations (2-7) to (2-9) show the method used to calculate the total air quantity required according to diesel engine dilution. Note that machinery does not operate continually at full load, thus necessitating the use of utilisation factors [27].

$$TDD_i = Design\ duty_i \times Number\ of\ machines_i \tag{2-7}$$

$$Total\ Duty = \sum_{i=1}^{n} (TDD_i \times \frac{Utilisation_i}{100\ \%}) \tag{2-8}$$

$$AQ_{Diesel} = Total\ Duty \times DF_{Diesel} \tag{2-9}$$

where:

TDD_i = Total design duty of machine i kW

$Design\ duty_i$ = Design duty of machine i kW

$Number\ of\ machines_i$ = Number of machines of type i $Machines$

$Total\ Duty$ = Total duty of all machines kW

$Utilisation_i$ = Utilisation factor of machine i $\%$

AQ_{Diesel} = Air quantity required for diesel engines m^3/s

DF_{Diesel} = Dilution factor for diesel engines $m^3/s\ /kW$

3. DPM and dust exposure requirements

DPM and dust AQIs are determined according to the methods described in [64]. These AQI values provide an indication of the air quantity shortfall and the effectiveness of air distribution throughout the mining environment. Each AQI can be multiplied by the local airflow quantity to give an estimate of the locally required quantity and thus the total required quantity.

In the case of personal sampling, the overall AQIs may be multiplied by the total airflow handled by the return fan clusters, to determine the total required airflow quantity. Cognisance should be taken of the effects of leakage or recirculation on the total fresh airflow. Note that the nature of this sampling system produces an approximate indicator and not a scientifically accurate value.

- **Determine peak airflow requirements**

Drawing from the quantities previously calculated, the peak airflow requirements can be determined based on the equipment, personnel, infrastructure, and pollutant sources. To do this, the development and stope, diesel exhaust dilution, DPM dilution, and dust dilution airflow quantities are compared and the largest selected as the required flowrate. This method is in agreement with those used by [36] among various other publications [35], [38], [45].

2.2.3 Continuous predictive modelling

- **Develop/update future life-of-mine models**

Drawing from the mining plans, future sections of the mine are constructed, simulated and, where necessary, calibrated as previously described. For each period, the unknown variables, such as surface ambient conditions, are estimated from historical values while planned infrastructure, machinery, workings, and more are incorporated according to planning specifications. Consideration is also given to new and expanded heat sources. Table 2-2 shows some example properties for new tunnels, which originate from the properties of new levels and haulages as previously measured on one South African mine.

Table 2-2: Suggested new tunnel properties

Parameter	Variations	Property	Values	Units
New haulage	-	Virgin rock temperature gradient	0.0146	°C/m
		Rock thermal conductivity	0.00574	kW/m/°C
		Rock density	2 690	kg/m^3
		Rock specific heat	0.837	kJ/kg/°C
		Friction coefficient	0.011	Ns^2/m^4
		Wet area fraction	0.2	-
		Heat	0.25	kW/m

These values may be refined later during recalibration of the future sections or as new data becomes available. For each year simulated, these haulages should be updated according to the temperature calibration method previously described. With this, the third objective given in Section 1.4 is satisfied.

- **Determine critical points to monitor**

Mining personnel often know of critical points of concern within the mining environment that need to be monitored. These range from workshop entrances, crosscut inlets, and level entrances to level returns and return airways. Points of concern are typically locations where the environmental conditions determine the ability for work to take place safely in related areas.

Examples of such relationships are: The total mining block return airflow is related to the amount of air available in all workings; the quantity and temperature of air provided to a workshop are related to the number of heat-related illnesses and shutdowns experienced there; the dust concentration at a crusher outlet is related to penalties and work-related illnesses in the immediate vicinity; and inlet conditions and airflow to a working level are related to the conditions in that level.

Although individuals at the mine may have different ideas of what constitutes a critical location to monitor, these locations should still be determined and redundancy eliminated to ensure effective reporting [53]. Some consideration should also be given to critical points to be monitored in future which may then be combined with development plans for integration into the model.

- **Evaluate temperatures and ventilation quantities for life-of-mine at each point**

Comparison of simulated airflow quantities and temperatures at various points with the peak and legal requirements allows for failings and shortcomings to be identified [11], [36], [39], [46], [53], [57], [58]. Here, consideration is given to the airflow network layout, air flowing in series or splitting in parallel, and how sources of pollutants and heat function and interact in order to understand and determine causes as well as solutions. For example, a loader, hauler, and dumper (LHD) requires a certain quantity of air but is itself moving through the mine, and thus, the air provided may not always be sufficient or applied at the correct location. This issue should be addressed as far as is practical.

- **Adjust ventilation distribution or determine infrastructure requirements**

Once the cause and course of shortcomings are understood, a suitable solution can be identified as discussed in Section 1.1.3. In the case of quantities, the airflow network may be redesigned to allow for less or more flow to specific areas. If the total air quantity is deemed insufficient, other methods such as additional infrastructure like surface fans, replacement fans or controlled recirculation could be considered. Similarly, for temperature or pollutants, the airflow network can be redesigned or infrastructure such as refrigeration plants, bulk air coolers, and filters introduced. The selected changes are implemented with future models, after which they are re-assessed.

In these proposed solutions, heed should be given to the operational constraints of the mining environment. For example, in some cases, the risks associated with high AQI values may be deemed acceptable with respect to infrastructure costs and other constraints. Mine management decides which risks to accept and which to act on, bearing legal responsibility for these decisions [16], [26]. In other cases, the actions taken to correct the problems may have long timeframes for implementation, such as the development of a new shaft over several years [7]. These aspects are considered in the planning process, as planning should be realistic when considering issues such as budgetary or other constraints.

○ Implementation

Once the temperatures and quantities are satisfied or associated risks deemed to be at acceptable levels, the changes are implemented in real time. Some changes may require years to implement, such as changes to infrastructure, while others change multiple times over the course of a single year to suit the changing environment.

○ Validate simulation results

When implementation is complete, the underground environment is re-audited on the appropriate date and the results used for simulation validation. If the audit and simulated values have an MAE of more than 10%, the root cause of such difference is investigated. Faults in initial assumptions, snowballing of high baseline MAEs, differences between the modelled and actual mining environment and others may all contribute to increased error. Once the possible causes for the high MAEs are determined, the future models can be corrected and reassessed. Here too, just as with initial model verification, a complete life-of-mine heat load study may be used for validation [27].

- **Monitor for changes**

The last step is to ensure the process remains continuous. Any permanent changes to the mining environment are identified and implemented into all future models on a continuous basis. This ensures model accuracy and up-to-date simulation results as well as timely identification of possible problems. With this, the final objective given in Section 1.4 is satisfied.

2.3 Flowchart

Figure 2-1 shows the proposed generic planning methodology flowchart, summarising the steps, showcasing the interactions, and indicating the decisions to be made.

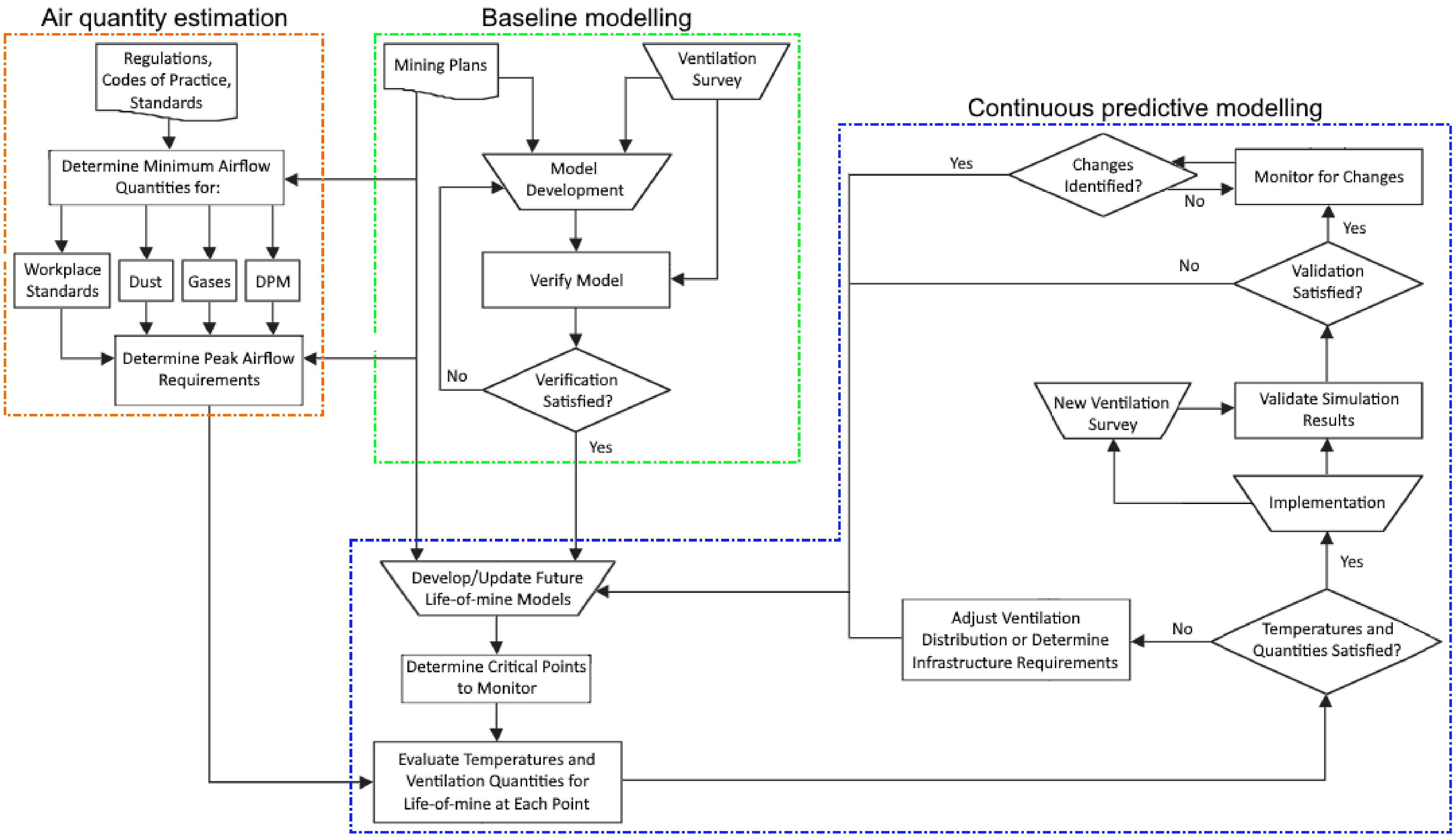

Figure 2-1: Generic ventilation and cooling planning methodology for mechanised mines

2.4 Summary

In Chapter 2, a generic methodology was proposed to satisfy the need for the study as identified in Section 1.3. The methodology addressed each of the objectives listed in Section 1.4 which involved making use of simulation, accounting for all heat sources in said simulation, and ensuring continuous life-of-mine planning. Each step of the methodology was elaborated on, describing the generalised approach while also giving specifics from the application of the methodology to the case study mine, mine X, when necessary. Finally, the methodology was proposed in the form of a flowchart to highlight the decisions made and interaction between the various steps.

3 CASE STUDY AND RESULTS

3.1 Preface

In this chapter, the three-phase methodology proposed in Chapter 2 is applied to a case study mine, referred to as mine X. These phases are:

1. baseline modelling;
2. air quantity estimation; and
3. continuous predictive modelling.

The content of this chapter includes a discussion of the case study background, calculations and simulations, results obtained from these, as well as the assumptions, deviation from expectation, flaws, and comparison with literature.

3.2 Case study background

Mine X is a 2.4-km deep gold mine located in the Free State, South Africa and within the Witwatersrand goldfields. It is classified as a deep-level mechanised mine because of its use of trackless machinery. The mine was opened in 2002 but was already at a depth below the surface of approximately 2.1 km before production started.

Developed out of a previously existing mine, mine X incorporates three of the existing shafts as well as one sub-shaft. A new decline was also developed, where conveyor belts are used to transport man and material over the approximately 4.5-km distance between the shaft station and mining block. Some use is also made of underground transport vehicles for special purposes.

Due to the nature of mechanised mining various connections, declines and ramps are used inside the mining block to allow for vehicle access. These routes twist, turn, intersect, ascend, and descend as the planners deemed necessary at the time of development. This means that the mining block is more reminiscent of ‘spaghetti’ than a conventional mine, and the distinction between levels becomes difficult to understand.

Each level typically consists of intake points and return points. Air is drawn down the downcast shafts, along the belts and intakes, through the level, and up to a return fan cluster. These fan clusters are usually two 75-kW fans operating in parallel inside a wall separating the intake and return air side. From here, the air is forced up through the East and West RAWs, which combine before being split between four 450-kW centrifugal booster fans operating in parallel. From there the air is forced through sections of the previously existing mine, which were designated as RAWs, and up through the upcast shaft to be expelled by the 1-MW surface fan. Figure 3-1 shows the layout of mine X.

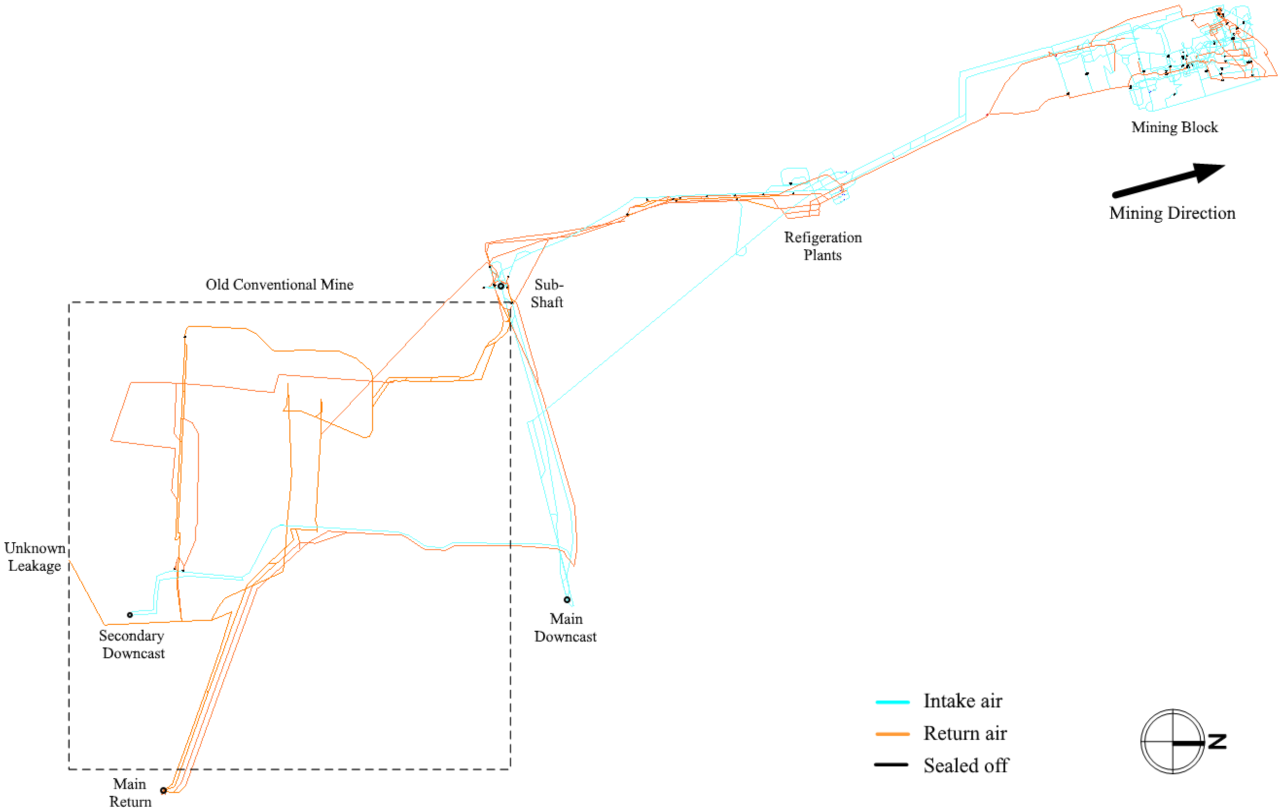

Figure 3-1: Mine X layout

Due to the depth and distance travelled, mine X has serious temperature concerns. To resolve this, underground refrigeration circuits were installed approximately halfway down the intake decline, which produce chilled water. This water is used to feed the chill ponds (BACs) located close to the refrigeration plants, as well as two additional BACs inside the mining block along with various CCs and ACUs.

3.3 Application of methodology

3.3.1 Baseline modelling

- **Mining plans**

The primary mining method employed on mine X is that of massive open stoping (MOS). Unless through-ventilation can be established, these ‘massives’ (massive stopes) are ventilated by forcing air into them with a 45-kW fan and column before letting the air flow back out through the entrance. Air then rejoins the general airflow of the level while travelling to the appropriate return fan cluster. This ventilation strategy is also applied to all development ends, which means that any contaminants found in these working areas are distributed to all subsequent areas.

Some use is made of conventional narrow-reef stoping, while plans include the development of a new sub-level open stope (SLOS). These methods allow for through-ventilation flow, meaning that air returns at the back of the stope where it is taken directly to the RAW without contaminating intake air.

Alongside the mechanised heat, geothermal heat is a large contributor to the heat load due to the depth of mine X [27], [48]. In fact, the VRT at a depth of 2.4 km in the region of mine X is found to be between 51 °C and 55 °C, according to various sources [11], [19]. For this reason, the occupational hygiene department of mine X specified their maximum environmental temperature standards as those of the legal limit: 32.5 °C wet-bulb and 37 °C dry-bulb. Furthermore, the mine uses the OEL standards for dust, gas, and DPM exposure due to airflow supply limitations.

Mine X employs approximately 1 100 underground workers and has a predicted life-of-mine of around seven years. Of these seven years, only three were fully planned out, namely financial years 2021, 2022, and 2023. These financial years range from July of the previous year to June of the year for which it is named.

A March modelling timeframe was selected for mine X, since this is the hottest underground month according to historical data and would represent the worst-case scenario. For these years, the planned average tonnage profile for March of each year is represented by Table 3-1.

Table 3-1: Tonnage profile for mine X

	2020	2021	2022	2023
Average tons per month	55 000	59 500	72 700	77 000

Mine X maintained approximately 10.1 MW of underground cooling in 2020, despite a design duty of 19.8 MW. The shortfall is attributed to maintenance shutdowns and heat rejection capacity issues caused by insufficient heat rejection capability. Along with the six BACs, two 100-kW CCs and two 250-kW ACUs were also spread throughout the mining block.

Approximate definitions of the future developments, placement of stopes, working areas and the development schedule of these were gathered from the planning department in the form of digital ‘dxf’-type drawings with development dates. Fan curves were sourced from the occupational hygienist and the friction factors for various tunnels were found to be 0.011 Ns^2/m^4 for stopes and haulages but between 0.007 and 0.011 Ns^2/m^4 for shafts. These values are in agreement with those used in various other studies, such as [46], [53], [55]. From [11], the rock thermal conductivity in the area was found to be 5.74 W/m°C, with a thermal capacity of 837 J/kg°C, a density of 2 690 kg/m^3, and a VRT gradient of 14.6 °C/km.

Significant changes had already been planned for mine X, such as the conversion of an old intake into a new RAW while closing off the second intake shaft. Furthermore, the development of the new SLOS section meant significant expansion of three lower levels while developing two new levels entirely. A new RAW bypass, as well as the construction of a new belt and crusher for the new mining sections, was also planned. Plans were also devised to increase the number of mobile cooling units to four 100-kW CCs and six 250-kW ACUs while also sealing 59 leaky walls.

According to planning documents, the specifics for narrow-reef stoping sections on mine X are:

- stope height [m] = 2.3;
- stope face to curtain distance [m] = 9;
- number of stope sides = 1; and
- total stope leakage factor = 0.65

Table 3-2 shows the planned total number of stopes, massives, and development ends in use during March of each year as well as during the baseline audit in 2020.

Table 3-2: Planned stopes, massives and development ends

	2020	2021	2022	2023
Stopes	8	5	7	6
Massives	9	8	6	11
Development ends	5	21	11	9

Table 3-3 shows the specifications and operating conditions of the mechanised machinery in use on mine X. Note that planning documents indicated the intent to reduce the number of trucks by 50% in 2022.

Table 3-3: Mechanised machinery specifications

Class	Machinery	Design duty [kW]	Number of machines	Utilisation [%]
Loader, hauler, and dumper (LHD)	Sandvik 514	256	5	42.5
LHD	Atlas Copco ST	136	1	42.6
LHD	Toro 1400	160	1	42.5
Wagner haul truck (WHT)	Trucks	300	10	50.1
Trackless drill rig (TDR)	Drill rigs	110	8	8.8
Support	Charging-up machines	120	3	4.7
	Graders	94	2	21.8
	Forklifts	55	3	22.4
	AGI cars	264	1	10.2
	Deutz 1013	200	21	22.3
	Deutz 1914	130	1	22.3
	4.2 ℓ Toyota	158	15	21.6
	3.0 ℓ Toyota	150	10	21.7
	Locomotives	51	7	79.3

- **Ventilation survey**

The volume, dust, temperature, pressure, and DPM surveys for the year 2020 were gathered from the occupational hygiene department. Weather data for the same period was sourced from a surface weather station approximately 15 km from mine X. Finally, BAC duties and haulage sizes were determined by conducting in-depth audits and by referring to the planning documents.

The occupational hygiene department did not take static spot measurements or quantify sources of DPM, gas or dust. Instead, use was made of personal sampling to determine exposures and is the more common practice for legal, medical, operational, and safety reasons [26]. The personal sampling data is given in the appendix.

The week-average surface ambient conditions for the time of audit as gathered from weather data amounted to a BP of 86.8 kPa at 8.89 °C wet-bulb and 9.63 °C dry-bulb. A week average was chosen because the rock lining of underground tunnels acts as a thermal energy storage and temperature buffer, known as a 'thermal flywheel'. This makes the environmental conditions underground insensitive to frequent surface temperature fluctuations and is in agreement with many published works such as [27], [67], [68].

Table 3-4 shows the cooling duties and airflows measured at each chill pond (BAC).

Table 3-4: Mine X air cooler properties

Location	Variations	Property	Values	Units
Intermediate decline refrigeration plants	Chill pond 1	Airflow	48	kg/s
		Cooling duty	1 831	kW
	Chill pond 2	Airflow	27	kg/s
		Cooling duty	1 015	kW
	Chill pond 3	Airflow	51	kg/s
		Cooling duty	1 825	kW
	Chill pond 4	Airflow	51	kg/s
		Cooling duty	1 827	kW
Upper mining block	Chill pond	Airflow	47	kg/s
		Cooling duty	1 053	kW
Lower mining block	Chill pond	Airflow	76	kg/s
		Cooling duty	1 858	kW

A total of five 45-kW and sixteen 75-kW fans were used at return fan cluster points, as well as 22 45-kW and various 15-kW and 22-kW fans for ventilating stopes, developments, massive stopes, workshops, and waiting places. Table 3-5 shows the general haulage sizes for different sections in mine X.

Table 3-5: Mine X haulage sizes

Parameter	Variations	Property	Values	Units
Haulage size	Mechanised	Width	5	m
		Height	5	m
	Conventional	Width	3	m
		Height	3	m

Note that mine X contained both conventional and mechanised haulages, but all newer developments were made as mechanised haulages.

o Model development

Model construction was completed as described in Section 2.2. One air pressure boundary was required inside the old mining environment where an audit of the airflow source could not be completed. This air likely originates from a connected mine, and the boundary pressure and temperature were specified as measured at that point. The effect of this unknown should be minimal, as this air flows directly to the RAW.

In simulating each BAC in the mine, the total of the cooling duties achieved at each cooling unit was approximately 9.8 MW. The difference of 3.5% between this and the 10.1 MW previously measured is well within the acceptable 5% measurement error, according to sources such as [19]. The total measured cooling duty of 10.1 MW was also measured on the water-side of the decline refrigeration plant chilled-water circuit, meaning line losses up to the mining block BACs are not accounted for. These losses would inevitably appear in ventilation audit values, reducing the actual simulation error and justifying the choice of a conservative cooling duty. Table 3-6 shows the cooling duties simulated for each chill pond.

Table 3-6: Mine X simulated air cooler properties.

Location	Variations	Property	Values	Units
Intermediate decline refrigeration plants	Chill pond 1	Airflow	48	kg/s
		Cooling duty	1 806	kW
	Chill pond 2	Airflow	27	kg/s
		Cooling duty	997	kW
	Chill pond 3	Airflow	51	kg/s
		Cooling duty	1 807	kW
	Chill pond 4	Airflow	51	kg/s
		Cooling duty	1 807	kW
Upper mining block	Chill pond	Airflow	47	kg/s
		Cooling duty	943	kW
Lower mining block	Chill pond	Airflow	76	kg/s
		Cooling duty	1 698	kW

The model was calibrated in three stages, namely 1) flowrate calibration; 2) temperature calibration; and 3) pollutant calibration, as discussed in section 2.2.1: Model development.

1. Flowrate calibration

After simulating the initial airflows and temperatures, model calibration was completed as described in the methodology section. Although most airflows could be calibrated to within 10% of specified values, some could not be reconciled with the data from the mass flow audit. When this occurred, the areas were re-audited to determine the cause. In some cases, leakages could be determined as the cause and corrections made but, in other cases, the audit values were clearly in error, as confirmed by mass balances on related airflows.

The reason for such deviations was typically attributable to measurement errors related to low-flow conditions outside the measurement range, incorrect flow instrument usage, turbulent flow conditions, and haulage sizes exceeding the distance for safe measurement. Such errors are also not atypical in the mining environment, as shown in [54]. Subsequent measurements would often be similarly erroneous for the same reasons or would indicate significant changes in the overall airflow patterns and thus be discarded. As mentioned in Section 2.2, the mining environment is not stagnant, and thus measured values should be taken as approximations of reality.

2. Temperature calibration

After calibrating the ‘heat’ properties of various sections of the mine, the lowest value was found as 0.05 kW/m in an old level with little to no mining or trackless machinery present. The highest value of 0.55 kW/m was found on a newer level where massive mining was commonplace, with mechanised machinery often being present as well as regularly scheduled blasting. Most other heat values ranged from 0.1 kW/m to 0.2 kW/m.

Wet area fractions were typically between 0.2 and 0.35, with the lowest, newest level having a wet area fraction of 0.5, likely due to water accumulation in these lower levels. Temperature calibration was much more accurate than volume calibration, with wet-bulb temperatures generally being kept within 1.5 °C of audit values. Some divergence was observed with the dry-bulb temperatures due to the low heat capacitance of dry air, resulting in a sensitivity to wet area fraction calibration. The final values were typically within 2 °C of audit values, and both temperatures were well within the 10% error margin.

3. Pollutant calibration

As mentioned, due to the lack of static spot measurements and source quantification, the pollutant sources could not be calibrated. With the available personal sampling data, it was possible to calibrate a theoretical time-weighted average (TWA) mine-wide pollutant concentration accounting for sample population size. The average TWA DPM concentration was found to be 0.088 mg/m3. After assessing the dust sampling results, the average TWA concentration for silica/quartz dust was found to be 0.073 mg/m^3, and 0.209 mg/m^3 for particles not otherwise classified (PNOC).

o Verify model

The final temperature MAEs achieved were 5.1% for wet-bulb temperatures and 5.9% for dry-bulb temperatures. These errors correlate to 1.3 °C and 1.8 °C average errors, respectively. The final airflow MAE achieved over all measured points was 13.1%, correlating to an average error of approximately 3.6 m^3/s.

These errors are in agreement with the findings of other studies such as [66]. As stated previously, the difference in volume flow is likely caused by measurement errors related to large haulage sizes and low flow velocities [54]. Of the 118 points audited, 30% had velocities lower than 0.5 m/s and 12% were lower than 0.3 m/s, which are the respective instrument measurement limits.

The total modelled heat load came to 22.2 MW as compared to the 22.7 MW predicted for the same period using the method described by [27]. The 2% error indicates a good correlation between the model and calculations. For these reasons, the MAEs were deemed acceptable, and the model was chosen as the 2020 baseline for future modelling.

3.3.2 Air quantity estimation

o Regulations, codes of practice and standards

The following were the occupational exposure limits (OELs) for airborne pollutants gathered from regulation and in force at mine X [16]:

- DPM : 0.16 mg/m^3
- Crystalline silica/Quartz : 0.1 mg/m^3
- PNOC : 3 mg/m^3

The minimum airflow standards, determined by risk assessment processes on mine X, were:

- Development airflow per face area ≥ 0.4 $m^3/s/m^2$
- Stope face velocity ≥ 0.4 m/s
- Massive stope air quantity ≥ 12 m^3/s
- Air quantity per kW diesel engine ≥ 0.1 $m^3/s/kW$

Note that these values are meant to represent a quantity of air sufficient to dilute all pollutants generated [26].

- **Determine minimum airflow quantities**

1. Stoping, development and massive stoping requirements

From the plans of the number of stopes, massives, and development ends in use during March of each year, the total quantity of air required for mining activities was determined to be 275 m^3/s for 2020. This is in agreement with the approximately 264 m^3/s measured at the return fan clusters during the baseline audit. The total fresh airflow was measured as 186 m^3/s with the remaining 71 m^3/s, adjusted for density differences, determined to originate from uncontrolled recirculation. This fresh air quantity correlates with a mass-of-air to mass-of-ore ratio of 11.3 tonnes of air/tonne of ore and is in agreement with the typical air usage of similar, large and not fully mechanised metal mines [25].

2. Diesel exhaust dilution requirements

According to the plans for mechanised machinery usage and minimum airflow standards, 446 m^3/s of air was required for diesel engine dilution in 2020. This large discrepancy between the determined airflow requirements may be attributed to the conservative nature of risk assessments but also indicates that 275 m^3/s of airflow may be insufficient in some locations.

3. DPM and dust exposure requirements

The average AQI, as determined from DPM sampling, amounted to 0.55 with the average AQI of those overly exposed as 1.32. Dust sampling resulted in an average AQI of 0.73, with the average AQI of those overly exposed as 1.49. Since AQIs should always be kept below a value of one, these results indicate that, generally, sufficient air is provided for these pollutants and that the specific areas or occupations wherein overexposure occurs should be investigated to remedy each situation individually.

Still, 14% of employees were overexposed to DPM and 17% were overexposed to dust. An improved airflow volume was determined by multiplying the overexposure AQIs with the 2020 fresh airflow quantity of 186 m^3/s. This value was then multiplied by a recirculation factor of 1.38 to account for the 71 m^3/s of air already recirculating, uncontrolled, in 2020. The resulting, highly-conservative estimates for the airflows required to sufficiently dilute DPM and dust in all areas of the mine are 339 m^3/s and 384 m^3/s, respectively. In this, consideration was given to possible over-estimation of these quantities, but since the values had not yet exceeded the 446 m^3/s required for diesel engine dilution, they were deemed acceptable.

- **Determine peak airflow requirements**

Table 3-7 shows the required airflow quantities as determined by the different methods.

Table 3-7: Required airflow quantities according to different calculation methods

Air quantity [m^3/s], based on:	2020	2021	2022	2023
Stopes, developments, massives	275	379	284	310
Diesel exhaust dilution	446	483	490	519
DPM AQI	339	339	339	339
Dust AQI	384	384	384	384

From these calculated quantities, the peak airflow requirements were determined by selecting the largest airflow in each year, correlating to those of the diesel exhaust dilution method.

3.3.3 Continuous predictive modelling

- **Develop/update future life-of-mine models**

The surface temperatures selected for future modelling were 18 °C wet-bulb and 24 °C dry-bulb, corresponding to those of the worst-case week-average temperatures. Future mine sections were constructed from planning documents, indicating the relative progress by March of each year. Initial tunnel properties were assigned as described in Section 2.2 with a development date as specified by planning documents and updated for each subsequent year.

- **Determine critical points to monitor**

After consultation with mining personnel, the critical locations to monitor in mine X were identified as:

- level intakes;
- level returns;
- total mining block intakes; and
- decline refrigeration plant intakes.

The total number of critical locations to monitor underground was 25, later increasing to 26 after planning deviations.

- **Evaluate temperatures and ventilation quantities for life-of-mine at each point**

Figure 3-2 shows the predicted airflow for mine X in March of 2021.

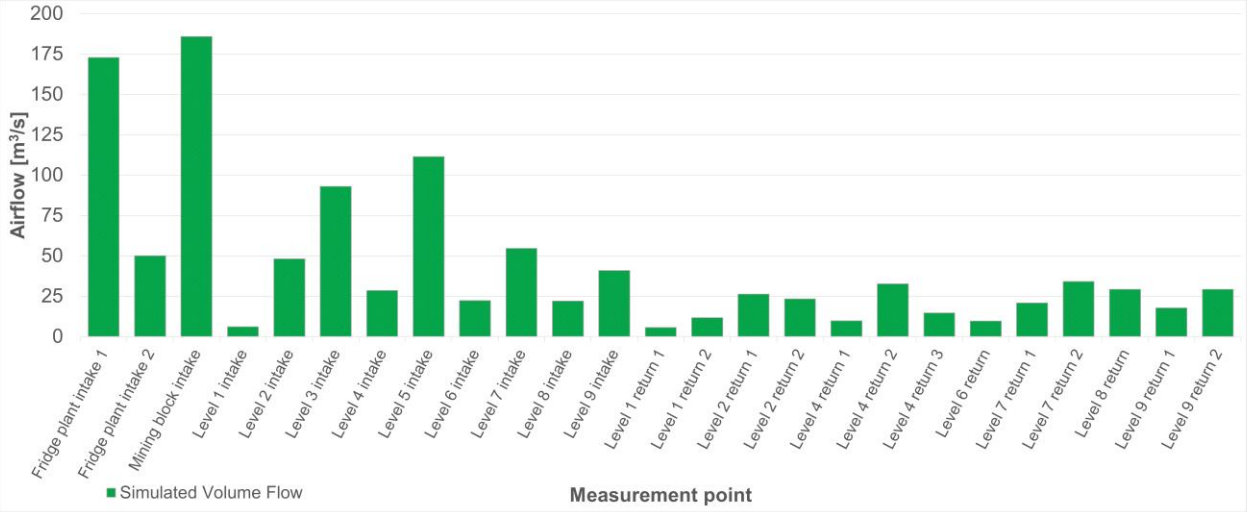

Figure 3-2: 2021 1st predicted airflow

The total airflow quantity simulated was insufficient, with 186 m^3/s of fresh air provided while return fan clusters handled only 253 m^3/s. This quantity is far removed from the required peak total return quantity of 483 m^3/s. Furthermore, the observed decrease of 11 m^3/s in the total return airflow from 2020 is attributed to effective sealing strategies applied in the simulated mine. From the results it is clear that insufficient strategies for addressing peak airflow requirements had been implemented.

Since the peak airflow quantity represents the worst-case requirement, it is possible for the mine to function without meeting this peak requirement. However, in this case, the total return quantity also fell short of the most conservative airflow requirement estimate of 339 m^3/s. This meant that, unless the mine seriously addressed the airflow issue, production would be cut back, uncontrolled recirculation increased, and serious deviations from planning would occur until the required and supplied airflows were met once more.

The wet- and dry-bulb temperatures achieved in the 2021 model prediction are displayed in Figure 3-3 and Figure 3-4. Evaluation of these temperatures clearly indicates a serious heat problem, as is common in deep mines [33], [36], [38].

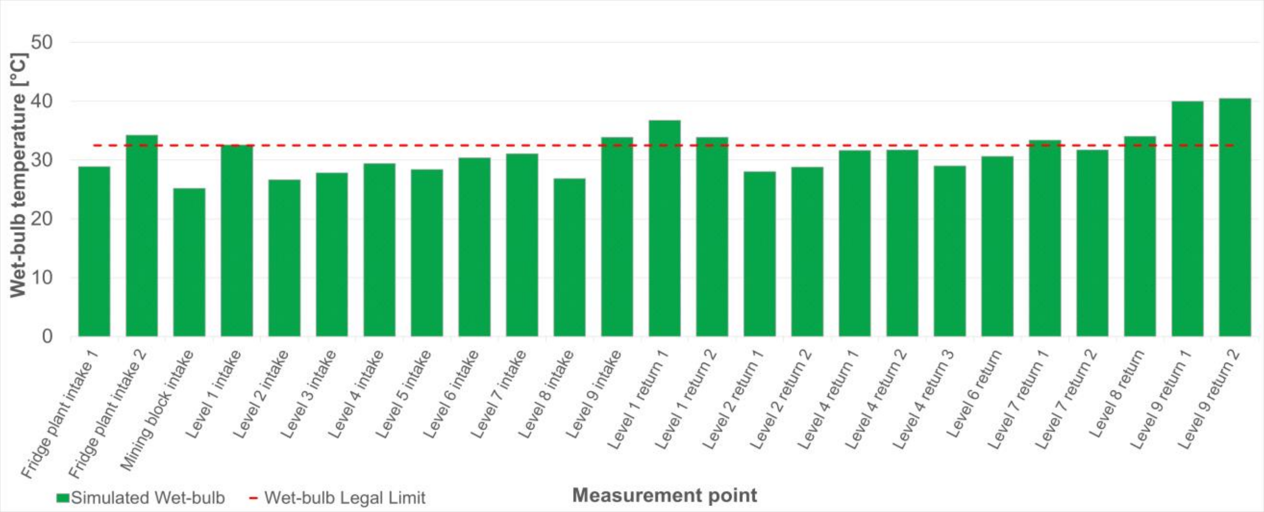

Figure 3-3: 2021 1st predicted wet-bulb temperatures

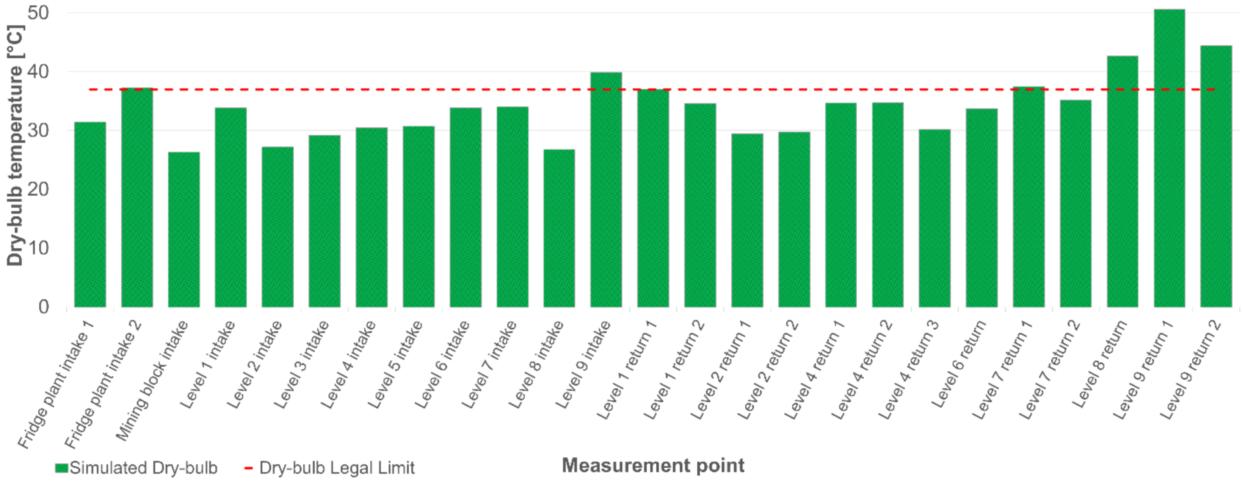

Figure 3-4: 2021 1st predicted dry-bulb temperatures

The average mining level return wet-bulb temperature for 2021 was 33.4 °C with the highest being 40.5 °C. Actual mining ceases around the legal limit of 32.5 °C wet-bulb and thus the latter temperature would be negated by a reduction in production. The total modelled heat load came to 25.8 MW as compared to the 24.3 MW predicted for the same period using the method described by [27]. The 6% error indicates a good correlation between the model and calculation.

- **Adjust ventilation distribution or determine infrastructure requirements**

To address the issues identified, the following solutions were considered:

- Additional bulk air cooling infrastructure;
- additional shafts;
- additional surface fans;
- RAW cleaning;
- vehicle electrification; and
- controlled recirculation.

After working closely with the occupational hygienist, mine management, and engineering, the possibility of expanding underground cooling capacity, installing a new surface bulk air cooler, RAW cleaning, and vehicle electrification was explored. In selecting these solutions, the operational constraints of the mining environment were considered. The sinking of additional shafts was deemed too expensive considering the value of the remaining mineral deposit. Additional surface fans were also deemed too expensive and would require additional RAWs, as some sections of the existing RAWs were restricted and inaccessible. Controlled recirculation was not well received due to concerns about excessive recirculation of air and the costs of gas and dust scrubbers.

The final selection of the required cooling infrastructure was made according to heat load and simulation temperature predictions. The modelled 2020 heat load indicated an average cooling shortfall of 3.1 MW, which agrees with the value determined by the heat load study as 3.6 MW and rising to 7.5 MW by 2024. To counteract this, a decision was made to construct a new surface bulk air cooler by 2021 along with a new underground condenser pond and booster fan unit by 2022. The latter two would maintain the underground cooling capacity at 14.1 MW, constituting an additional 4 MW of cooling capacity. They would also have the added benefit of increasing the total fresh airflow to the mining block to approximately 211 m^3/s, as predicted by simulation.

The final surface bulk air cooler design was intended to deliver 6.5 MW of cooling in peak summer in order to functionally negate the effects of the summer temperatures, as compared to those in winter, on underground conditions. The new average downcast temperature during these summer conditions of 18 °C wet-bulb and 24 °C dry-bulb would be 11 °C wet-bulb and 12.5 °C dry-bulb. Mining management also committed to a RAW clean-up programme where old ore and materials dumped in the RAWs would be reclaimed or moved to more appropriate locations. The programme was set to conclude by 2024, but the exact impact could not be determined due to the unsafe working conditions in the RAWs.

A new project investigating mechanised vehicle electrification was also started to determine the advantages and possible impact of this on the approximately 5-MW mechanised heat load, but results were not yet available.

Upper management of the company had raised concerns regarding dust exposure on mine X, partially driven by a need to reach the goal of ‘zero harm’ as undertaken by the company. A request from upper management to address the exposure led to the formation of a ‘dust task team’ to identify and remove/neutralise dust sources. Some changes planned for completion by 2022 included:

- clean-up around shaft headgear;
- cleaning of shaft barrel;
- cleaning of surface conveyor area;
- skip redesign;
- installation of additional sprays;
- closing old sections;
- installation of foggers at loading points;
- installation of a new crusher dust suppression sprays;
- washing of decline conveyor; and
- real-time dust monitoring.

With regards to the airflow quantity shortages, the mine decided to tolerate the risks, as the dust pollutants were being addressed and the average DPM AQI was lower than one, with only 14% of employees overexposed. Furthermore, the affected employees were mostly mechanised vehicle operators, and it was believed that the move toward cabbed or electrified vehicles would reduce these exposures.

Figure 3-5 shows the new airflows as predicted by the 2021 future model of mine X. Note that it was planned to temporarily close off Level 1 due to insufficient airflow to the mining block, allowing only minimal leakage into that level.

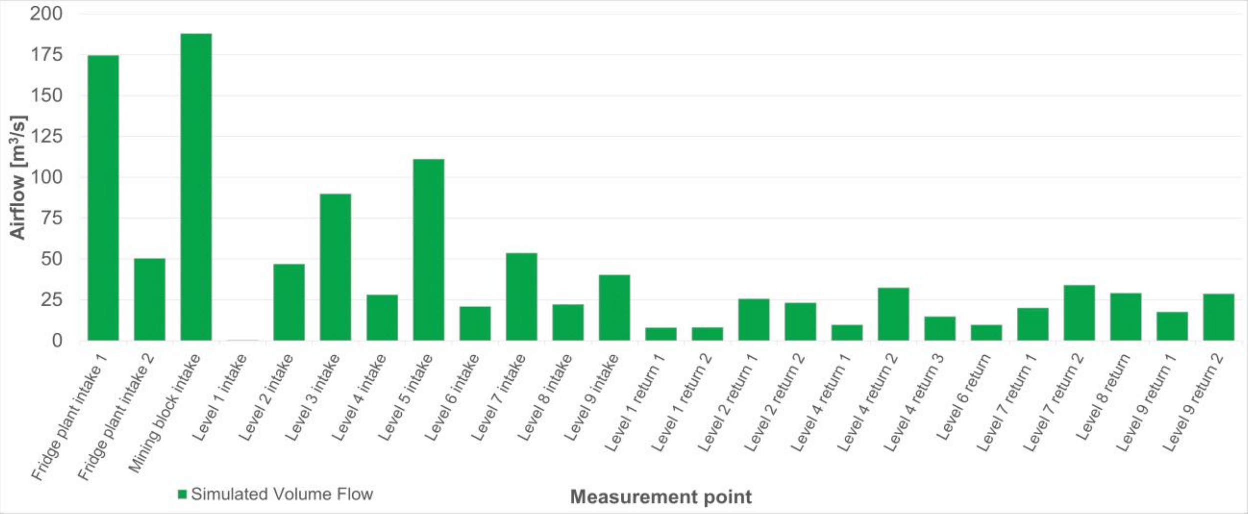

Figure 3-5: 2021 predicted airflow

Figure 3-6 and Figure 3-7 show the wet-bulb and dry-bulb temperatures predicted by the 2021 model. In general, the temperatures remain below the legal limits with an upward trend toward the lower levels, represented by Level 7–9. The temperatures on Level 1 did rise above legal limits, but this is due to leakage from the RAW, as the level was effectively sealed.

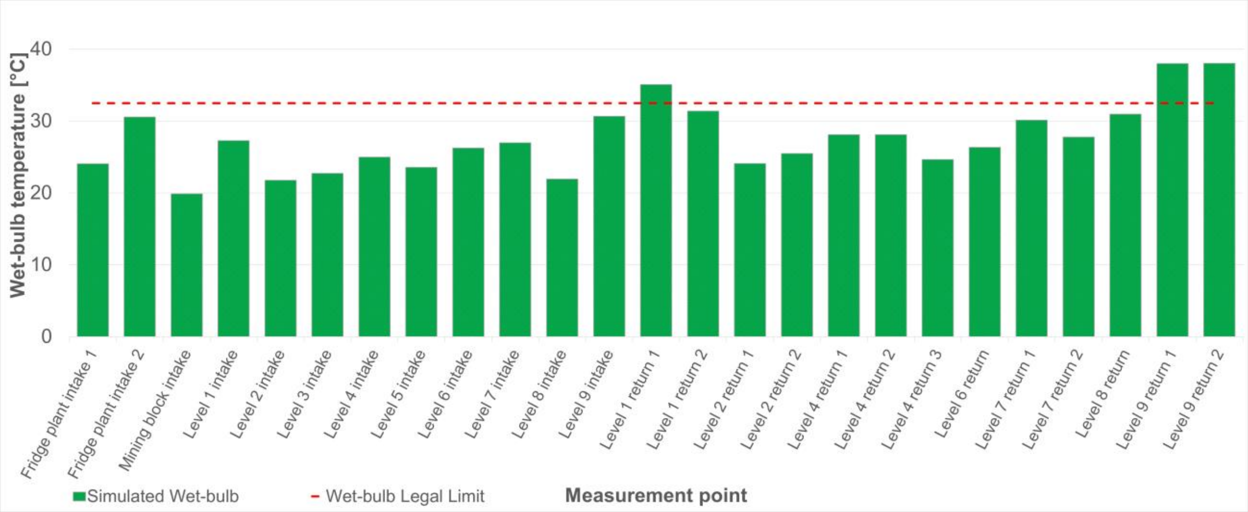

Figure 3-6: 2021 predicted wet-bulb temperatures

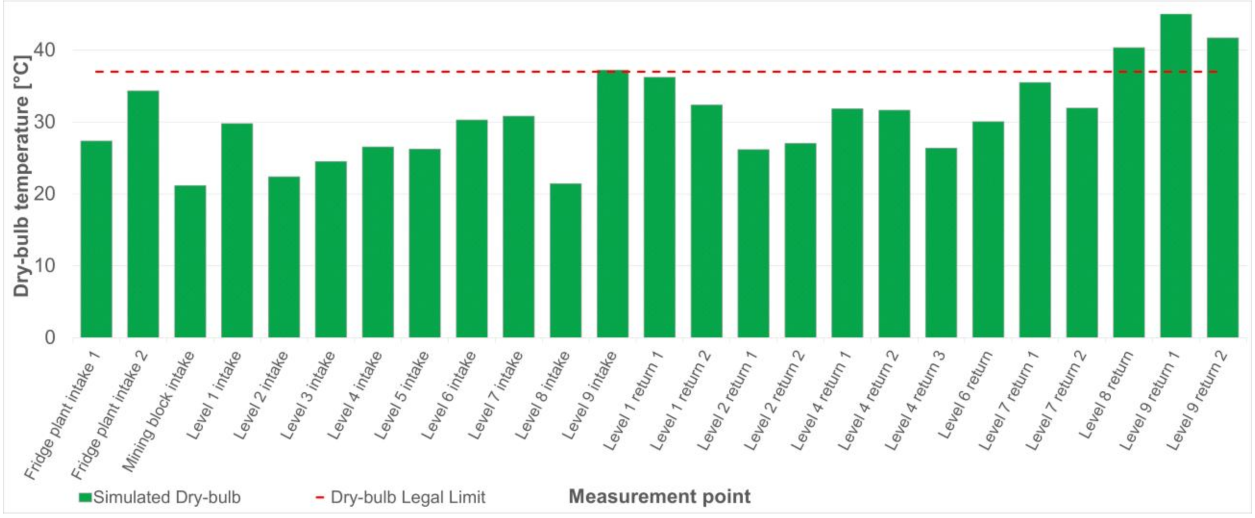

Figure 3-7: 2021 predicted dry-bulb temperatures

The high temperatures on Level 8–9 were a cause for concern for mine management, which opted to move a BAC installation from the decline refrigeration plant level to Level 9. This would allow for less cold air to be drawn from the Level-8 BAC while also providing cooling for the two deeper future levels. It was planned that this relocation should conclude by 2024.

Implementation

Over the course of the 2021 financial year, many of the planned changes were initiated but only the installation of the new surface BAC and conversion of the old intake airway into a RAW were completed. Development of the new SLOS section, excavation of the new BAC location, RAW cleaning, excavation of the RAW bypass, and construction of the new belt and crusher were all underway. In total, only four 100-kW CCs and five 250-kW ACUs were operating, with two 250-kW ACUs under repair. Of the 59 walls to be sealed, only 33 had been completed.

Significant deviation from the 2021 plan was also observed, such as the reduction of refrigeration plant cooling capacity to 8.6 MW, the decision to keep Level 1 open, the addition of a third return fan cluster to Level 7, changes to the ventilation network layout, and changes to the tonnage profile, thus causing a reduction in mechanised heat load from 4.8 MW to 3.5 MW. These adjustments were a response to other issues experienced throughout that year, such as condenser pond maintenance, major flooding in lower levels, return fan cluster failures on Levels 4, 8 and 9, as well as several cases of heat exhaustion.

The tonnage profile with the final planned tonnages for March of each year is shown in Table 3-8. Note that the tonnage profile for 2020 is unchanged, as the baseline period had already passed by the time of updating the planned tonnes.

Table 3-8: Updated tonnage profile for mine X

	2020	2021	2022	2023
Average tons per month	55 000	43 700	52 900	57 100

- **Validate simulation results**

During March of 2021, the critical locations were re-audited seven times over multiple days to get a representative indication of the airflow conditions. Figure 3-8, Figure 3-9 and Figure 3-10 show the comparison between the airflow, wet-bulb, and dry-bulb temperatures originally predicted and those measured in March of 2021. Note that, due to return fan cluster failures on Levels 4 and 8 during this period, some of the values on those levels could not be audited safely.

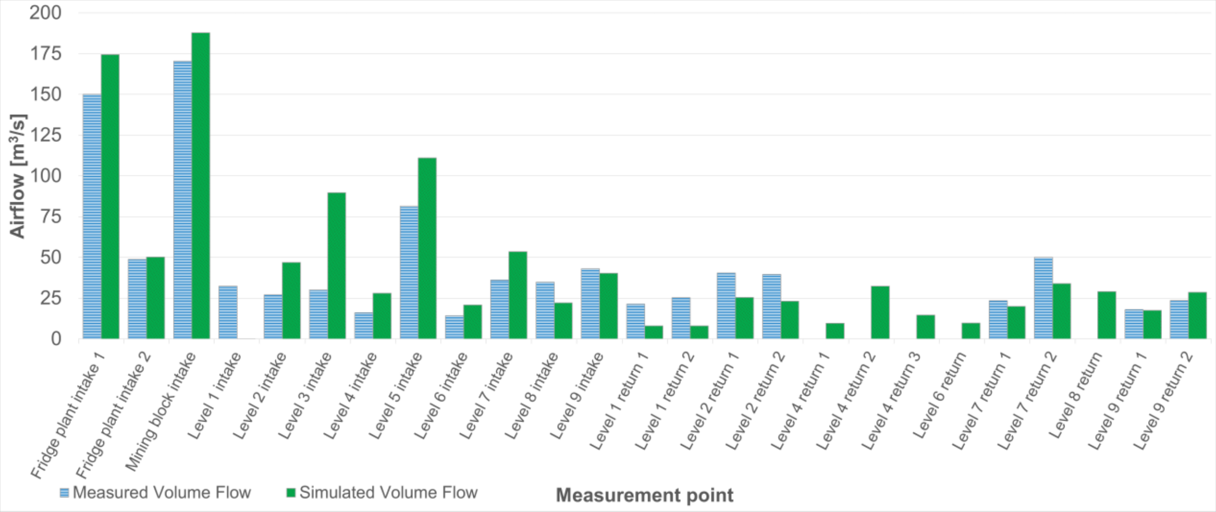

Figure 3-8: 2021 measured vs. predicted airflow

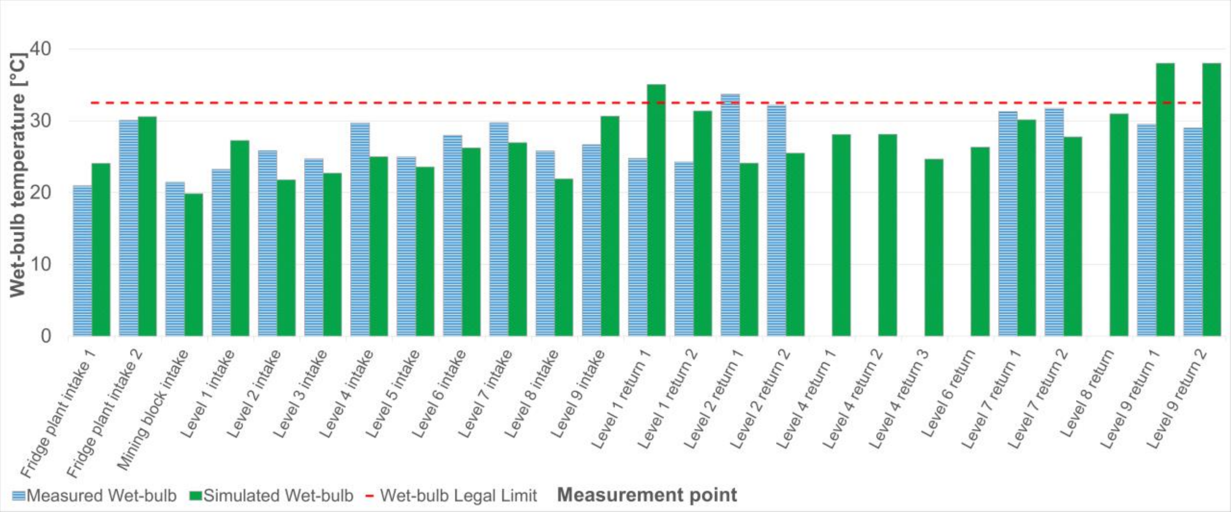

Figure 3-9: 2021 measured vs. predicted wet-bulb temperatures

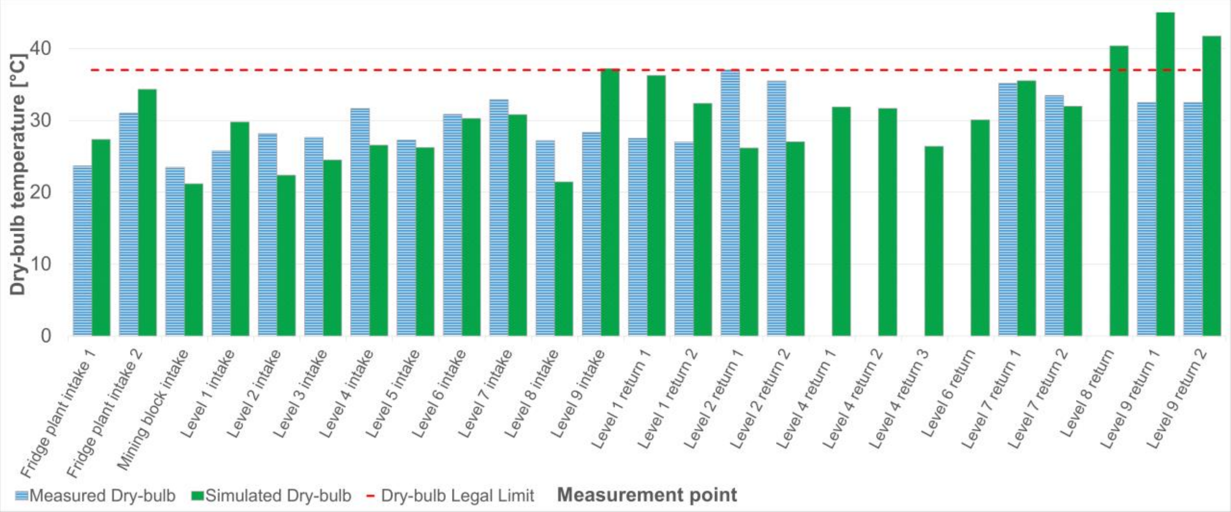

Figure 3-10: 2021 measured vs. predicted dry-bulb temperatures

The MAEs of this original prediction were 36.6% for airflow, 16.5% for wet-bulb temperatures, and 17.8% for dry-bulb temperatures. Subsequently, the deviations and changes identified over the course of the 2021 financial year were implemented into the future models, as the proposed methodology suggests. Figure 3-11, Figure 3-12 and Figure 3-13 show the comparison between the audited and updated prediction values.

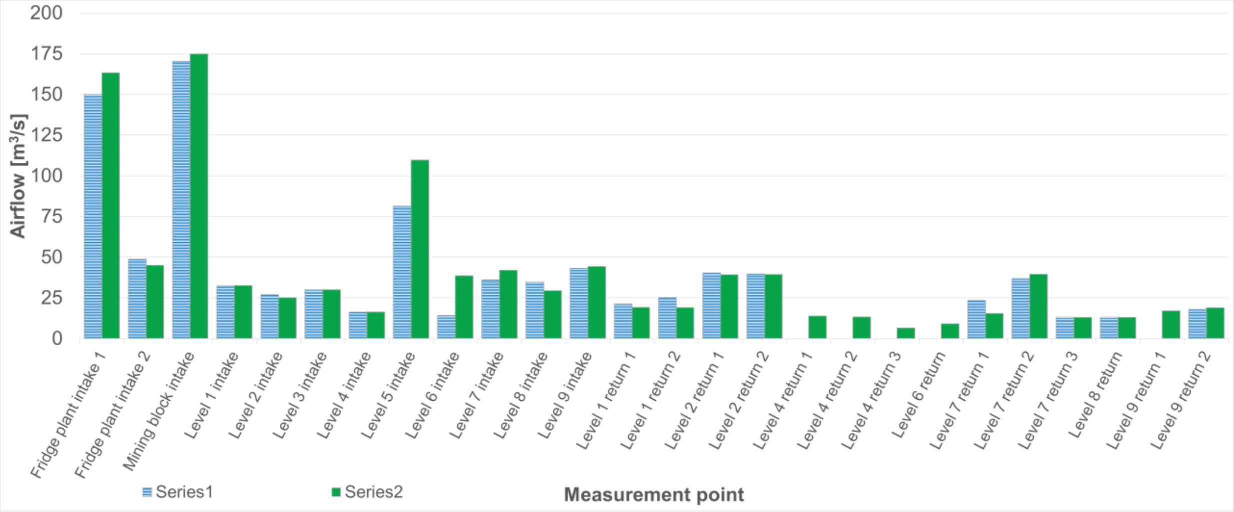

Figure 3-11: 2021 updated measured vs. predicted airflow

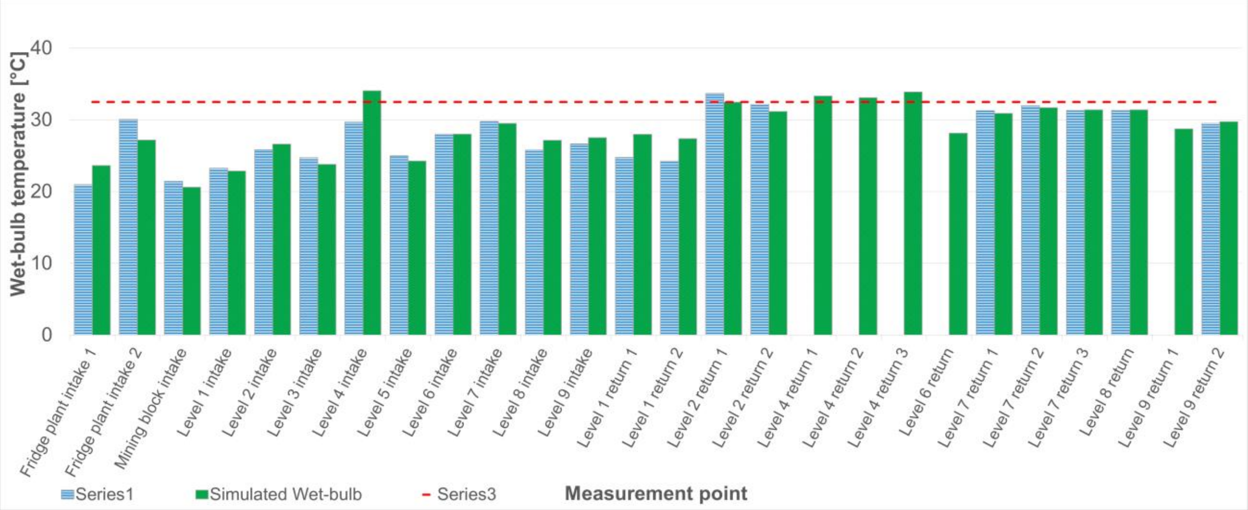

Figure 3-12: 2021 updated measured vs. predicted wet-bulb temperatures

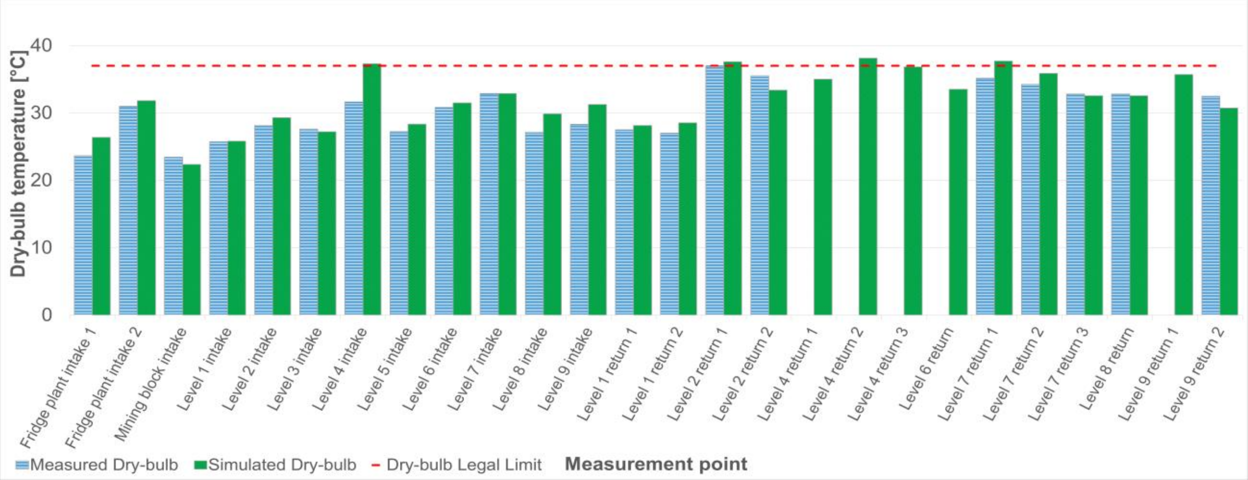

Figure 3-13: 2021 updated measured vs. predicted dry-bulb temperatures

As can be seen from a comparison of the new temperatures with those previously predicted, there was a clear adjustment of heat sources away from areas that were already too hot, such as Levels 8 and 9. This adjustment correlates with the movement of spot cooling units or the reduction of production-related activities due to legal constraints. This limitation was also predicted in the original 2021 model.

The MAEs achieved with the updated 2021 model were 12.2% for airflow, 5.4% for wet-bulb temperatures, and 5.5% for dry-bulb temperatures. These temperature errors are in agreement with the findings of similar simulation studies, such as [54] and [66]. Here, as was the case with the 2020 baseline, the high airflow MAE may be attributed to the large haulage sizes and low airflow velocities. The final predicted airflows and temperatures for 2022 and 2023 are provided in Appendix B.

- **Monitor for changes**

The significant difference in MAEs between the original and updated 2021 predictions is a clear indicator of the importance of continuity in the planning process. Permanent changes to the mining environment should be identified and implemented with all future models to ensure accuracy and up-to-date simulation results. The proposed methodology significantly improved on the error inherent in any non-continuous method.

3.4 Discussion

In this chapter, the proposed methodology was applied to a mechanised deep-level mine utilising narrow-reef and massive stoping. The proposed method and application thereof showed a focus on heat as well as good cognisance of other pollutants. Sampling of personal pollutant exposures had been carried out and was used to determine exposures. All pollutants which were actively being measured were addressed and planned for, although airflow limitations were identified. Use was made of legal limits for planning purposes, but the methodology would be simple to apply with any specified pollutant goals.

The proposed planning method emphasises integration with the existing mine planning processes. Integration with mine management is both a strength and a hindrance, as mine management may effectively dictate environmental standards and assist with the identification and implementation of practical, large-scale projects to address identified issues. In this way, the planning methodology becomes very robust, with a large pool of knowledge and experience to draw from when deciding on the acceptability of conditions. Mines differ with regard to what is considered important to control, and in the case of mine X, management focussed on addressing heat issues, which were the most prominent problem for continued mining activities. However, mine management has their own biases and may sometimes allow problems such as high temperatures on lower levels to remain without addressing the issues thoroughly and timeously.

A large limiting factor in the case study was the measurement errors experienced on volume flows, as flow velocities tended to be too low in the large cross-sectioned mechanised mine. Another issue faced was the non-stagnant nature of mining activities, which hindered re-auditing. Despite this, acceptable results were obtained, and this limitation should not affect conventional mining operations where measurement of airflows should be more accurate.

Much deviation from planning was observed in mine X, which is a critical flaw in any planning strategy that does not incorporate follow-ups and continuity. These changes are another indication of the non-stagnant nature of mining operations. The final mine plan produced must be useful and robust, and focus should be placed on practically executable projects and up-to-date predictions of current and future operations and developments to ensure this. After updates, the modelled mine results were well-validated with good correlation to the heat load study, indicating a desired level of robustness and successful prediction of the cooling infrastructure requirements and impact thereof on mine X. The proposed methodology improved on the error inherent in any non-continuous planning methodology.

4 CONCLUSION AND RECOMMENDATIONS

4.1. Study synopsis

In this study, a generic methodology for mine ventilation planning was proposed. Chapter 1 discussed the state of the mining sector and the need for proper planning. An introduction to mine planning, ventilation, and cooling planning as well as psychrometry was given. Methods for control of pollutants, heat, and ventilation were discussed together with the calculation- and simulation-based planning techniques in use. Finally, an analysis of critical literature and shortcomings therein, such as planning for life-of-mine, continuity, neglection of heat and genericity, was made.

A need was identified to develop a methodology for simulation-based planning of ventilation and cooling in deep-level mechanised mines throughout the life-of-mine. In achieving this objective, four main sub-objectives were identified:

1. Make use of simulation software;
2. Account for all heat sources;
3. Plan for the life-of-mine; and
4. Monitor continuously for deviations.

In Chapter 2, the methodology referred to in the first objective was developed and proposed, and each individual step was discussed. The discussions were as generalised as possible but had some reference to specifics from the case study where necessary. The method used in the construction of the model, gathering of empirical data, and sample laboratory analysis techniques used were provided. The use of personal sampling and how it integrates with the planning method along with other pollutant planning techniques and regulations was noted. The methods for verification and validation of the models, analysis of shortcomings, identification of solutions, integration with mining personnel and processes were also discussed.

PTB was selected as modelling platform, and the heat source integration techniques used were addressed. Throughout the discussion of the proposed methodology, the iterative, continuous, and integrated nature of the planning process was highlighted. Finally, a flowchart of the entire methodology was provided to showcase the interaction of the proposed steps. With this, all four study objectives had been addressed.

Chapter 3 revolved around the application of the case study to mine X. A brief background on mine X was given before the results of each step in the methodology were discussed. The various plans and information gathered as well as audit information and parameters used in the model construction were provided along with explanations of the nuances. The baseline simulation results compared well with the audit values delivering MAEs for airflow and wet- and dry-bulb temperatures of 13.1%, 5.1% and 5.9% respectively. The airflow measurement limitations and re-audits were explained. Additional confirmation was provided by the correlation of 98% between the model and heat load, and the model was deemed verified for use as baseline.

Each of the standards and regulations in force at mine X during 2020-2021 were provided and applied in conjunction with pollutant sampling results to establish various required airflow quantities ranging from 275 m^3/s to 519 m^3/s over the life-of-mine. These were used alongside temperature requirements to evaluate future models. Various issues were identified, the most important of which was the large cooling shortfall of 3.1 MW to 7.5 MW. The results of brainstorming sessions with mining management yielded several projects aimed at rectifying the various problems, one of which was the construction of a 6.5-MW surface cooling plant.

From these, the final life-of-mine models were constructed and predictions made, with the 2021 model having only a 6% error as compared to heat load calculations. However, initial model predictions of 2021 were inaccurate when compared to measured data, with MAEs of 36.6% for airflow, 16.5% for wet- and 17.8% for dry-bulb temperatures. Various deviations from planning had occurred and the models were updated to reflect these changes. Updated model MAEs were 12.2%, 5.4% and 5.5%, respectively. These differences highlighted the need for continuity in the planning process.

4.2. Conclusion

The final model is deemed well-validated, with the infrastructure requirements and impact thereof on mine X having been successfully predicted. The conclusion is made that the proposed methodology was successful in its application to this deep-level mechanised mine, managed to improve on the errors inherent in non-continuous planning strategies, and successfully satisfy the study objectives.

4.3. Recommendations

Some recommendations for future work include:

- use dynamic surface conditions for modelling future and baseline models;
- make use of airflow measurement techniques/equipment with an improved operating range;
- implement spot measurement/measurements of pollutants sources, and addition of these to the simulation;
- integrate methods for solution idea generation, evaluation and ranking, along with economic evaluation techniques;
- investigate applicability to shallow and coal mines to ensure general applicability; and
- integrate methods for the analysis and optimisation of infrastructure location.

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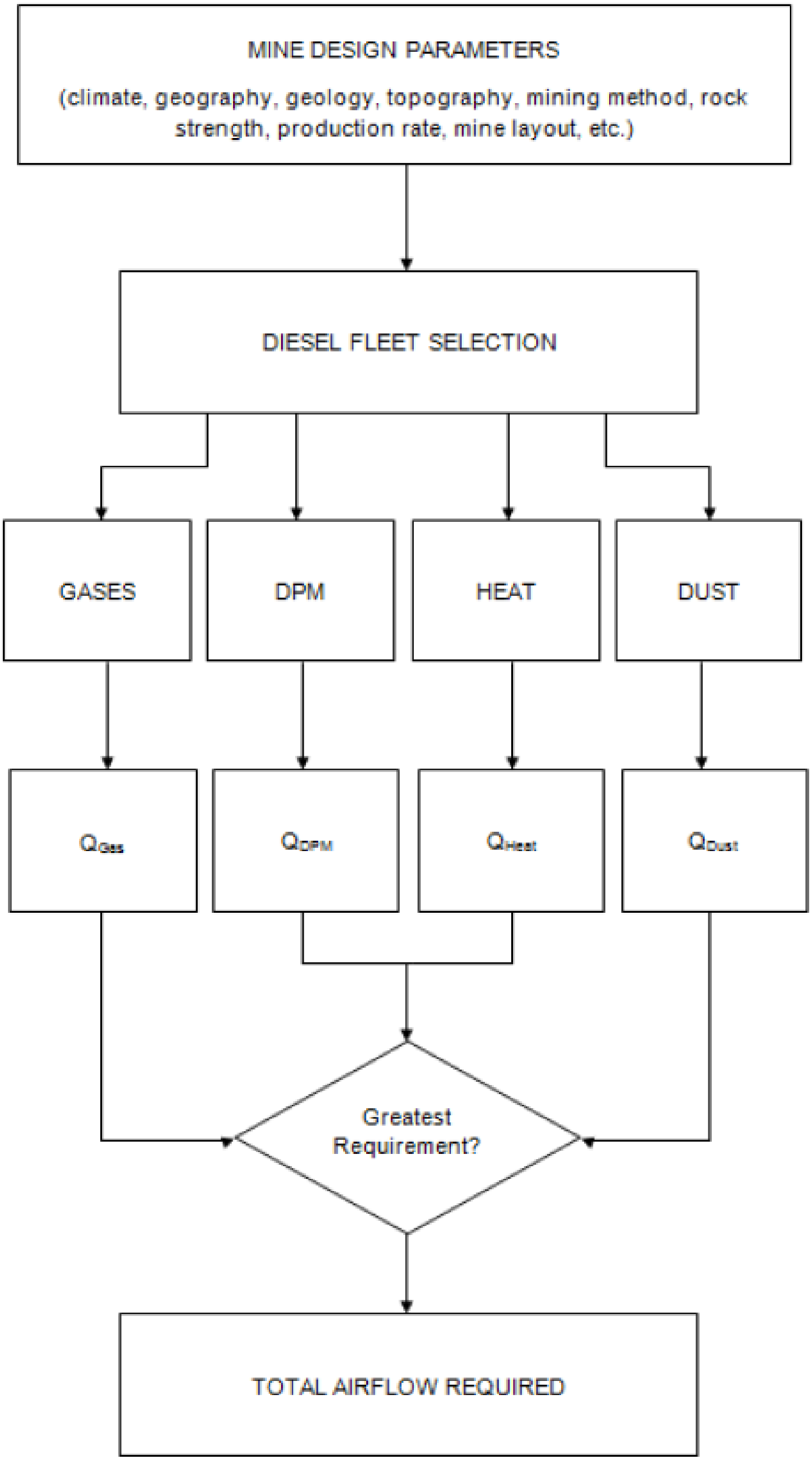
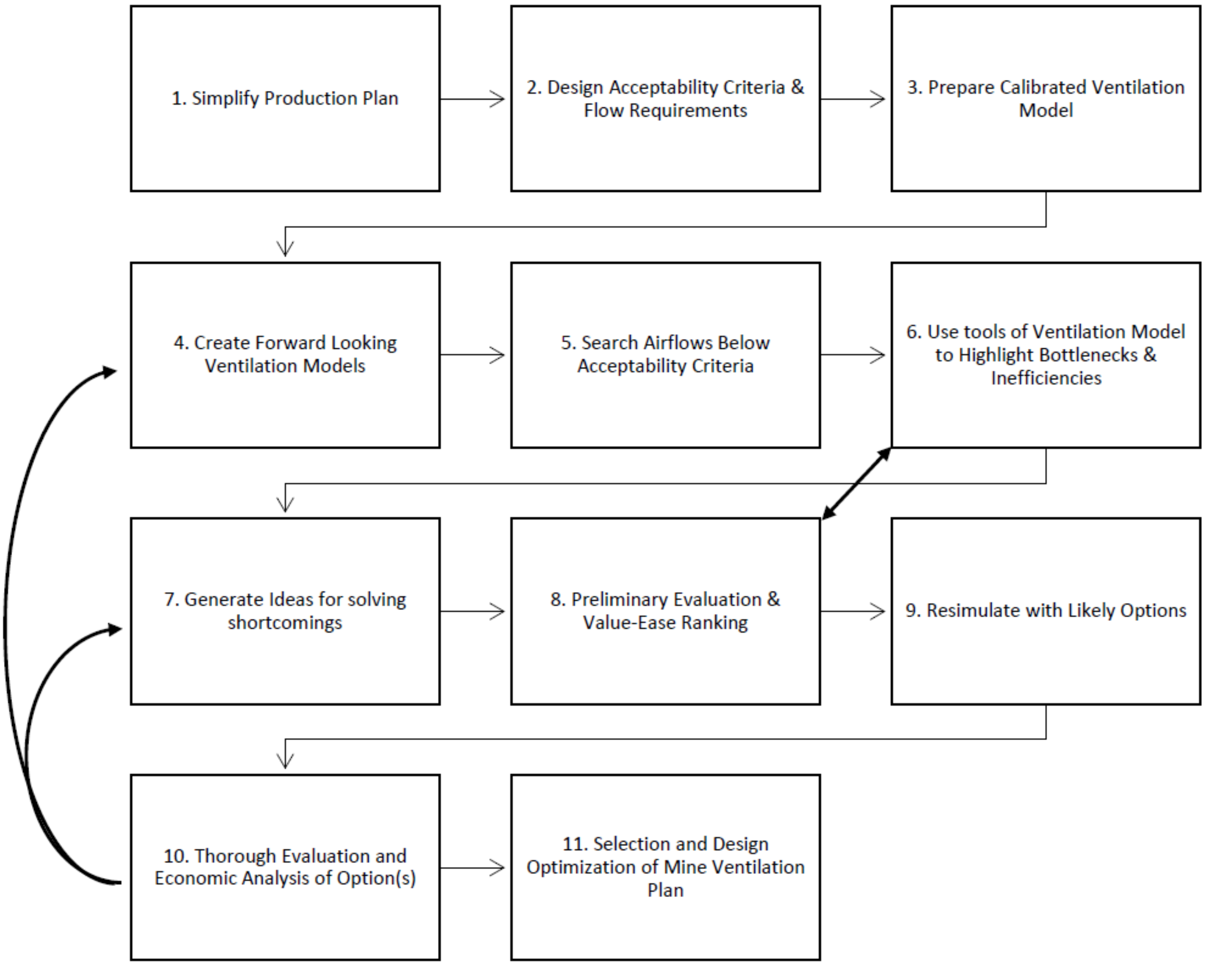
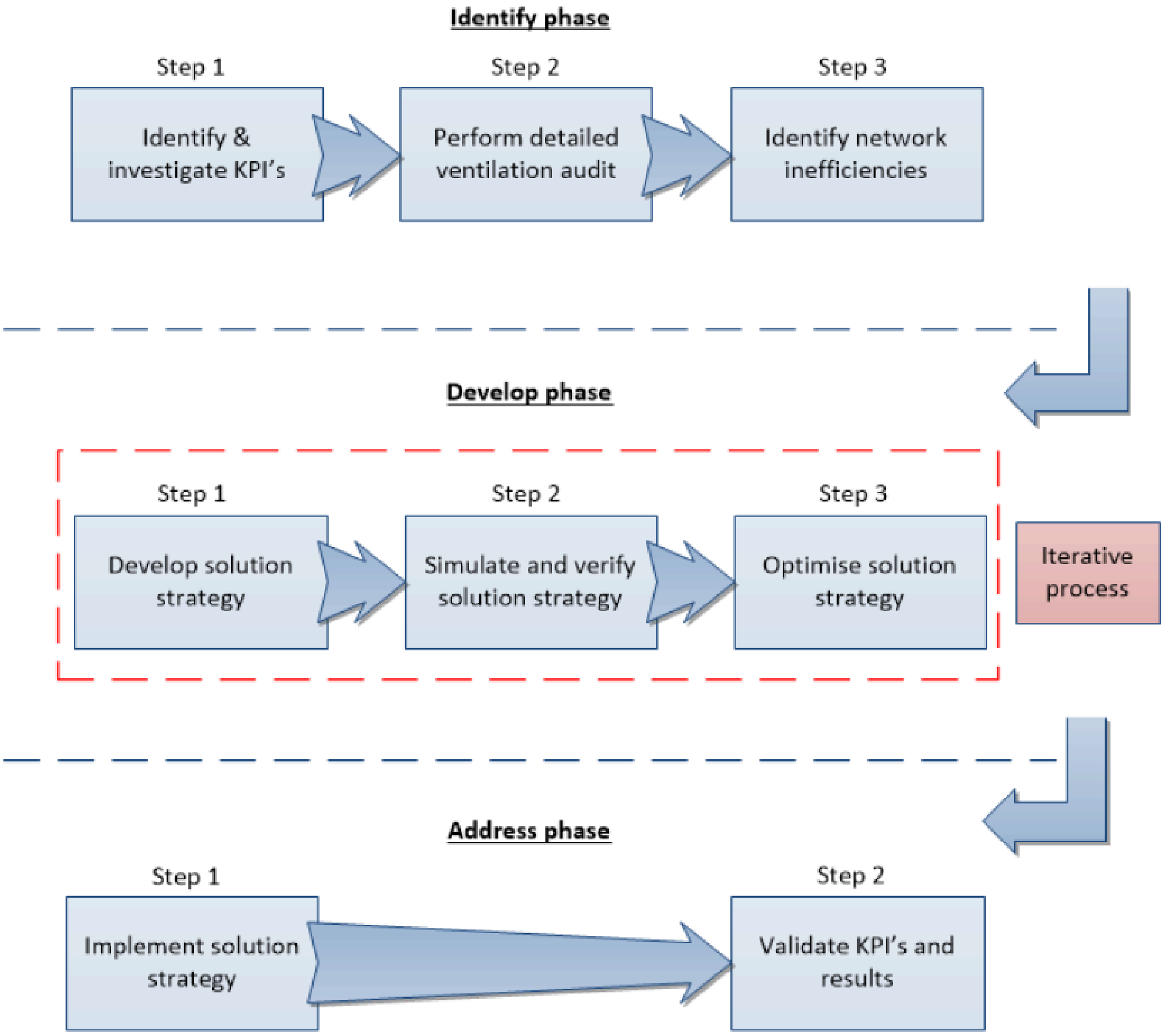
Appendix A General planning methodologies in literature



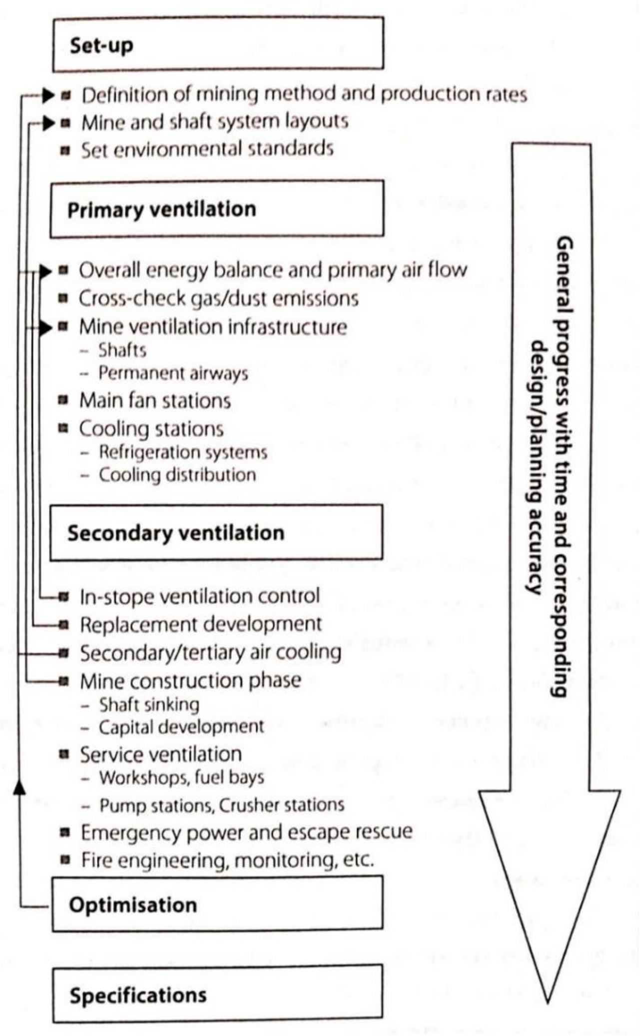
Appendix-figure 1: Alternative ventilation planning methodology (adopted from [36]**)**



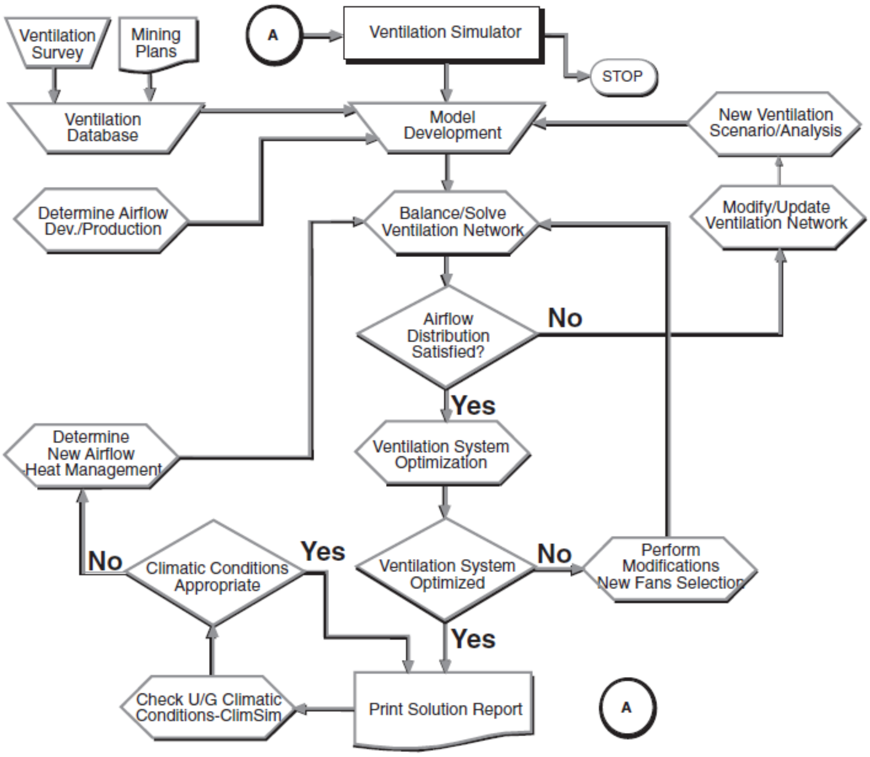
Appendix-figure 2: Alternative ventilation planning methodology (adopted from [46]**)**



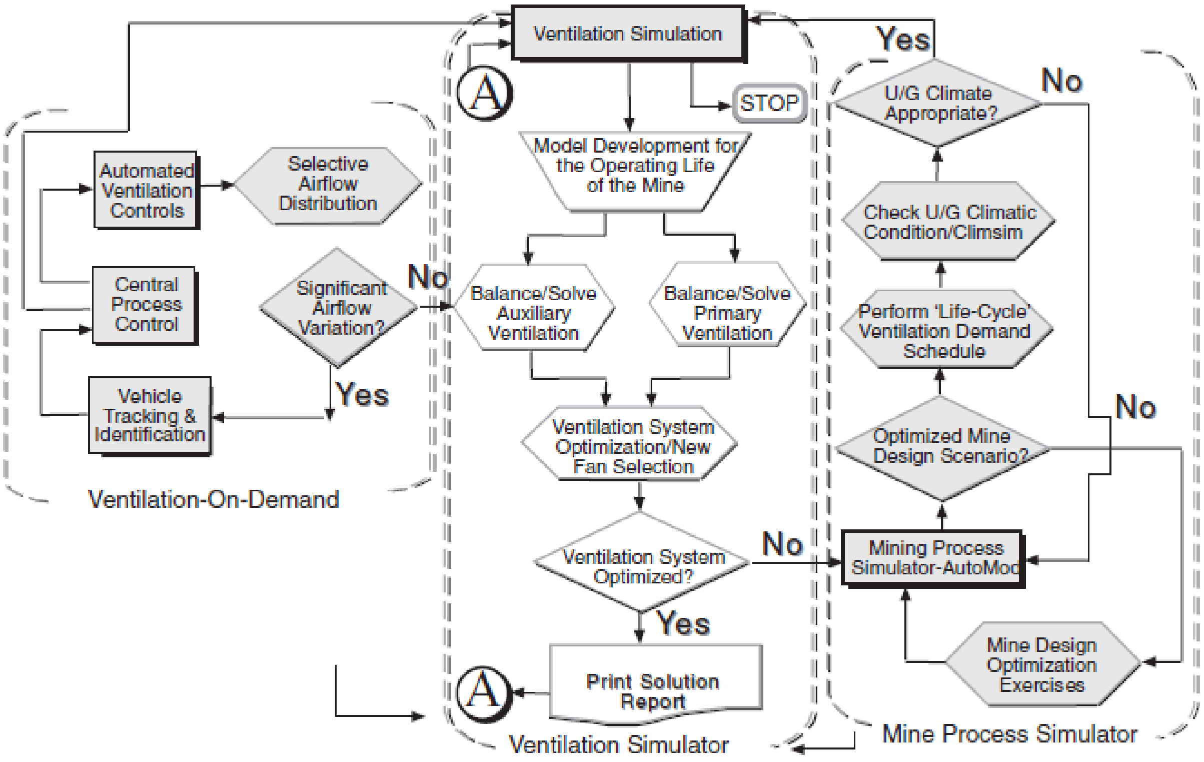
Appendix-figure 3: Alternative ventilation planning methodology (adopted from [53]**)**



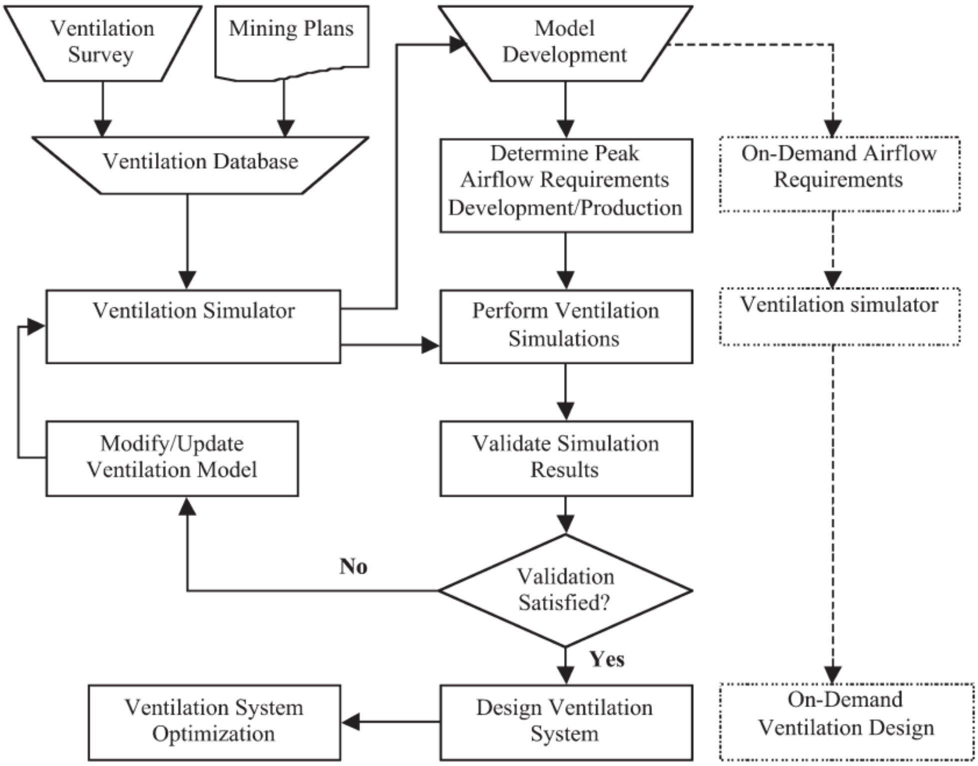
Appendix-figure 4: Alternative ventilation planning methodology (adopted from [11])



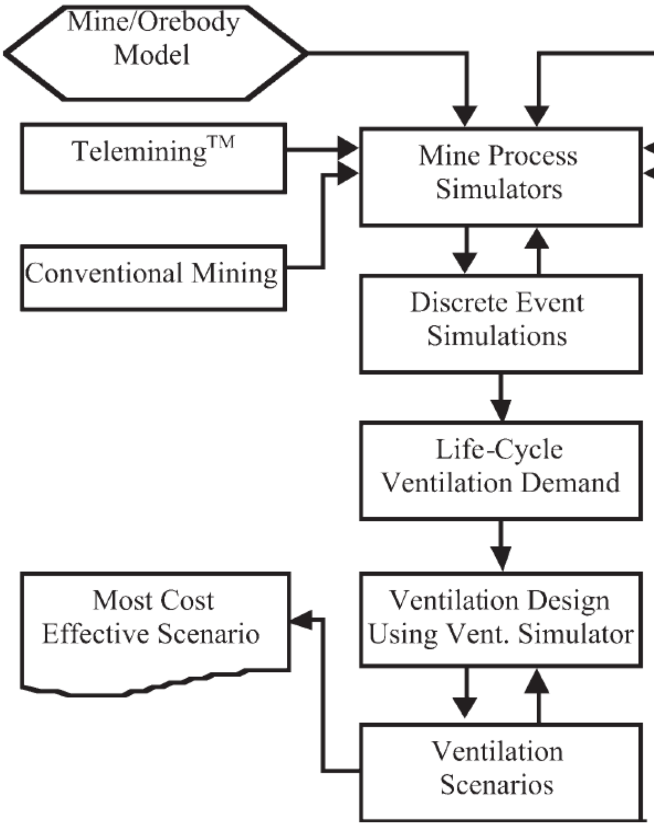
Appendix-figure 5: Alternative ventilation planning methodology (adopted from [57]**)**



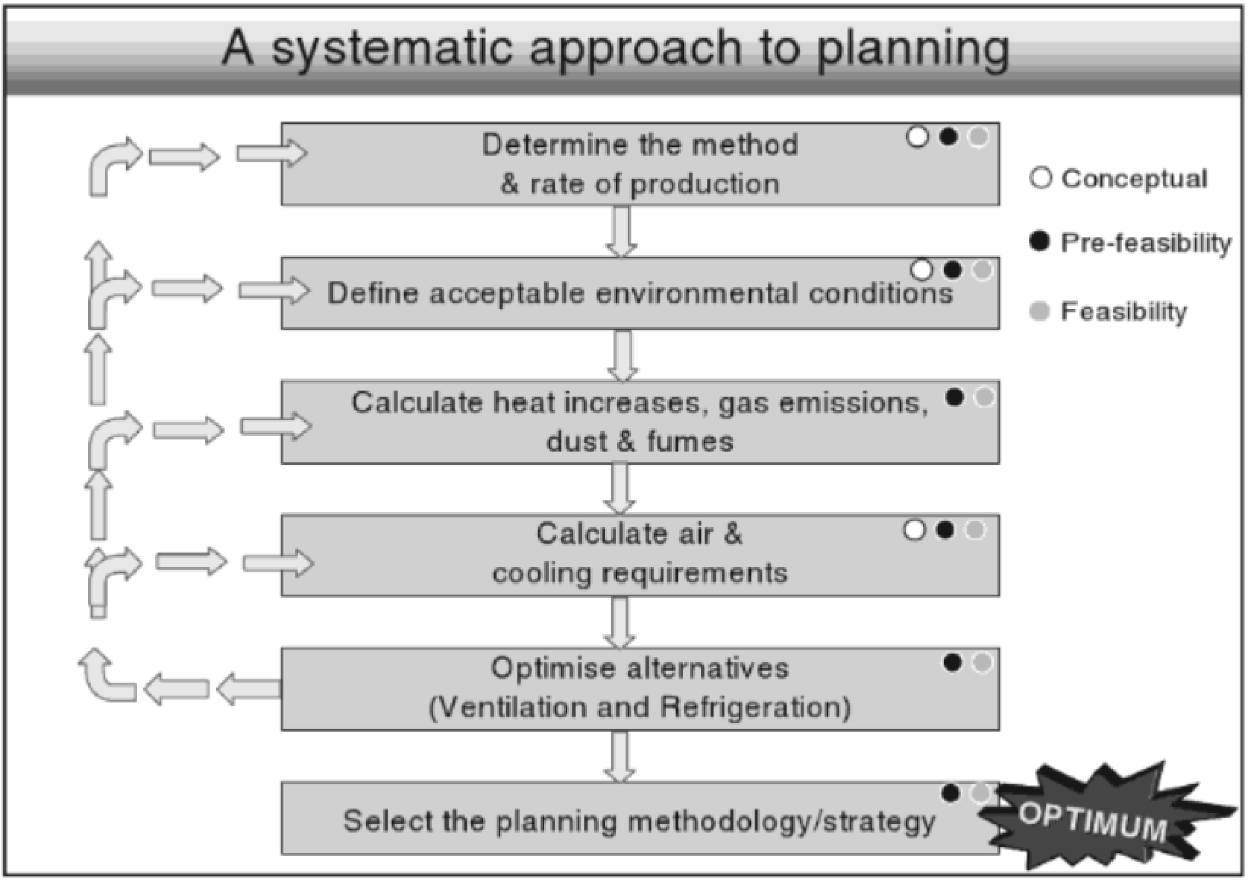
Appendix-figure 6: Alternative ventilation planning methodology (adopted from [57])



Appendix-figure 7: Alternative ventilation planning methodology (adopted from [39])



Appendix-figure 8: Alternative ventilation planning methodology (adopted from [39]**)**



A systematic approach to planning

Determine the method & rate of production ○ ● ◍

Define acceptable environmental conditions ○ ● ◍

Calculate heat increases, gas emissions, dust & fumes ● ◍

Calculate air & cooling requirements ○ ● ◍

Optimise alternatives (Ventilation and Refrigeration) ● ◍

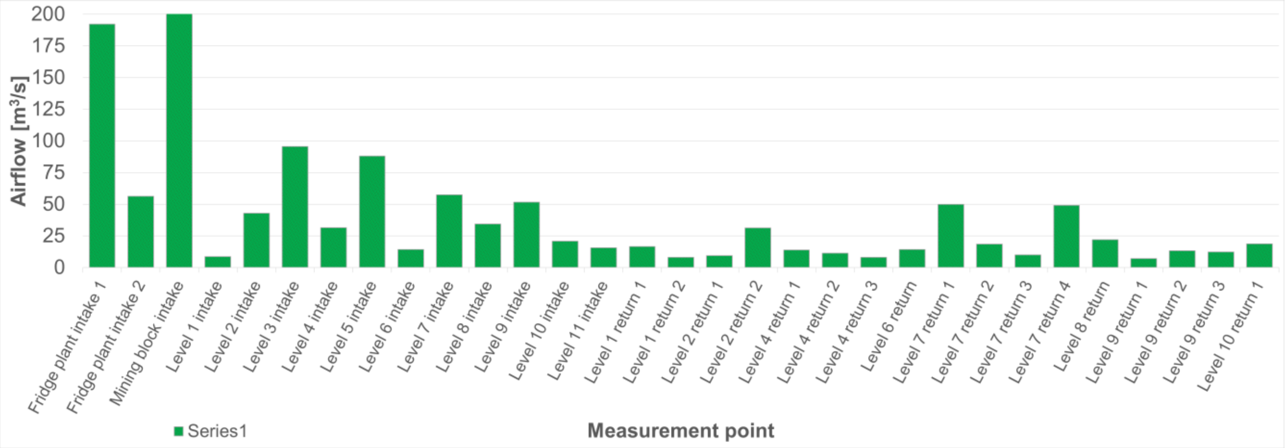
Select the planning methodology/strategy ● ◍

OPTIMUM

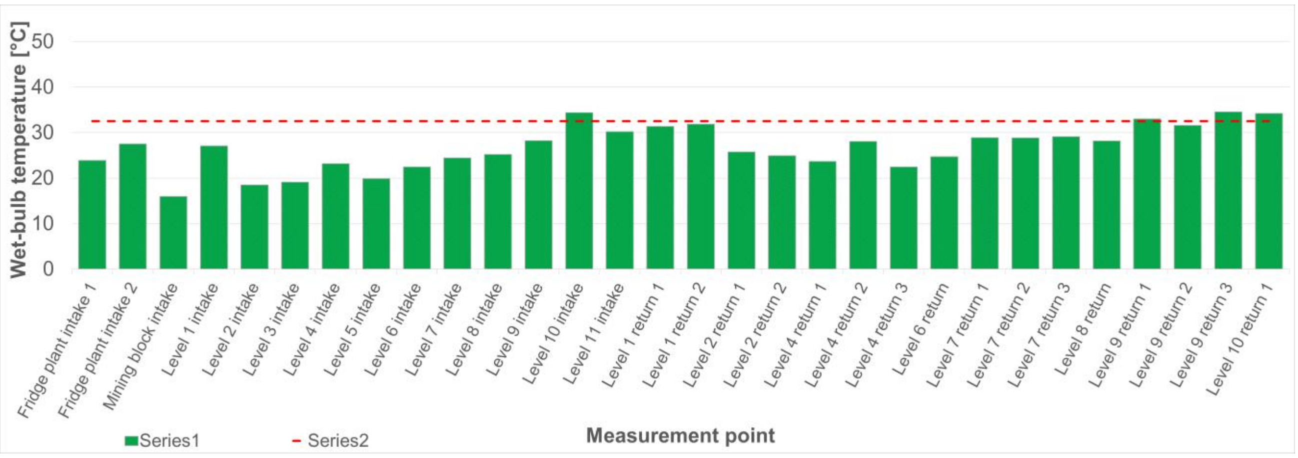
○ Conceptual
● Pre-feasibility
◍ Feasibility

Appendix-figure 9: Alternative ventilation planning methodology (adopted from [58]**)**

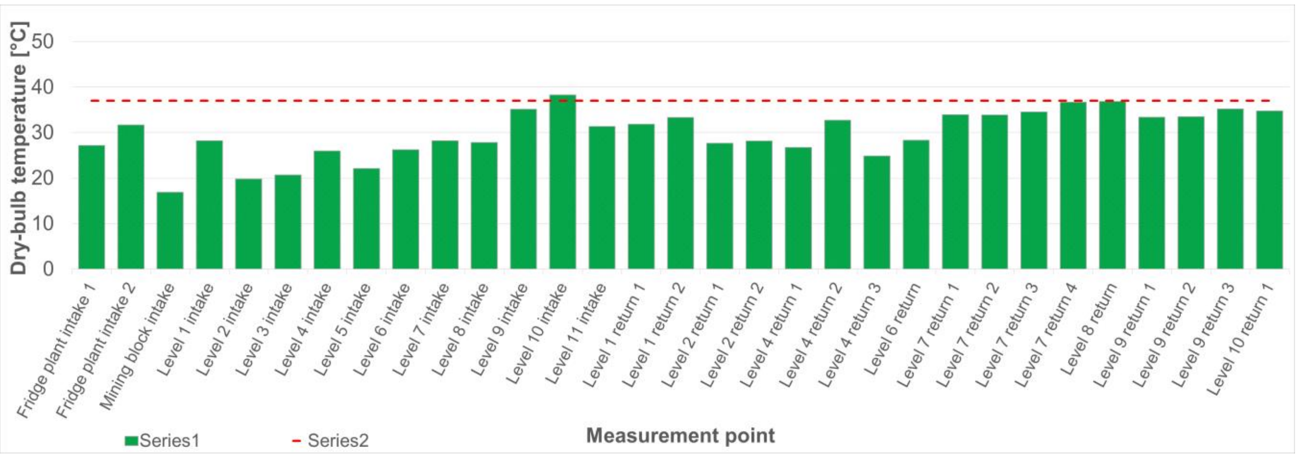
Appendix B 2022 and 2023 predictions



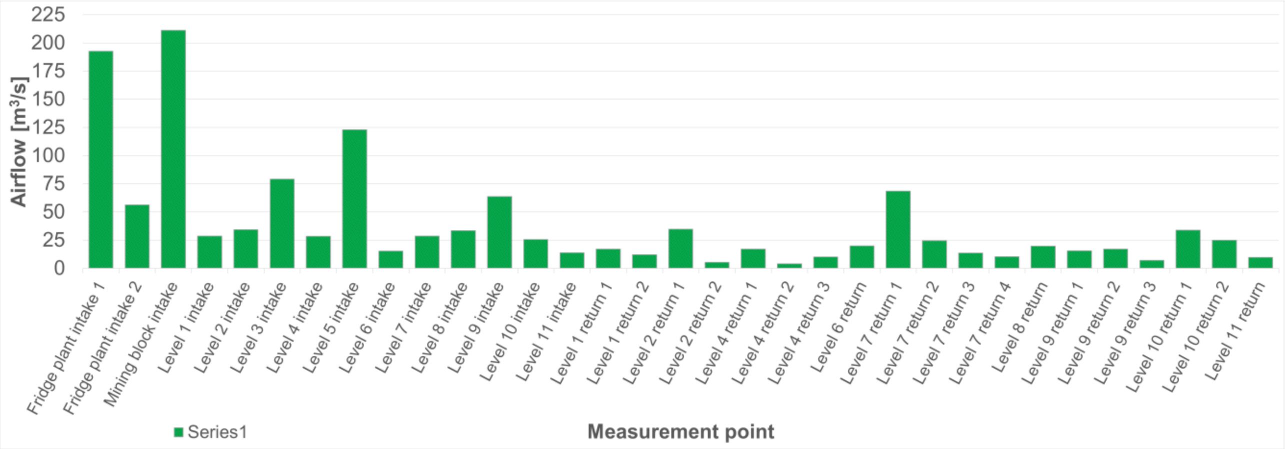
Appendix-figure 10: 2022 predicted airflow



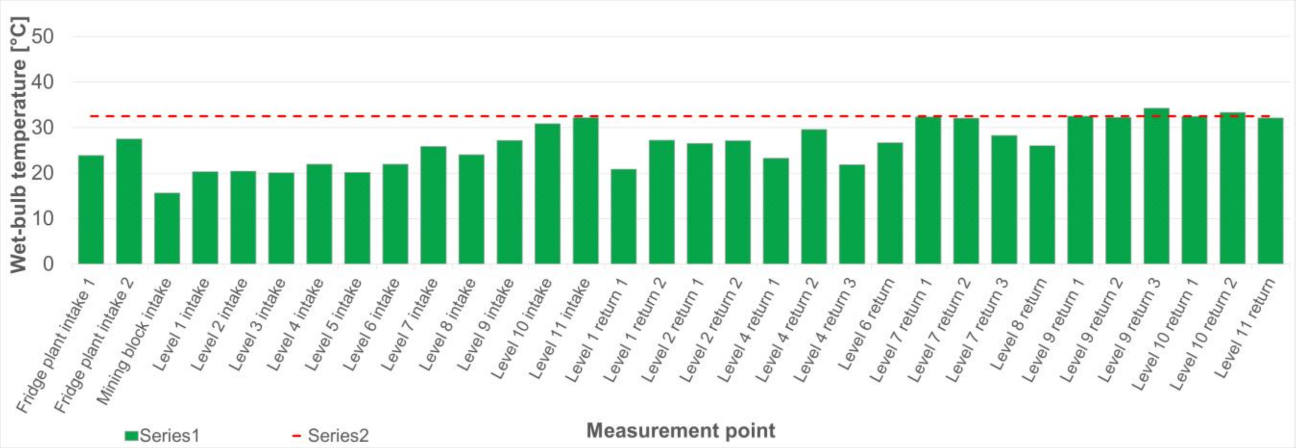
Appendix-figure 11: 2022 predicted wet-bulb temperatures



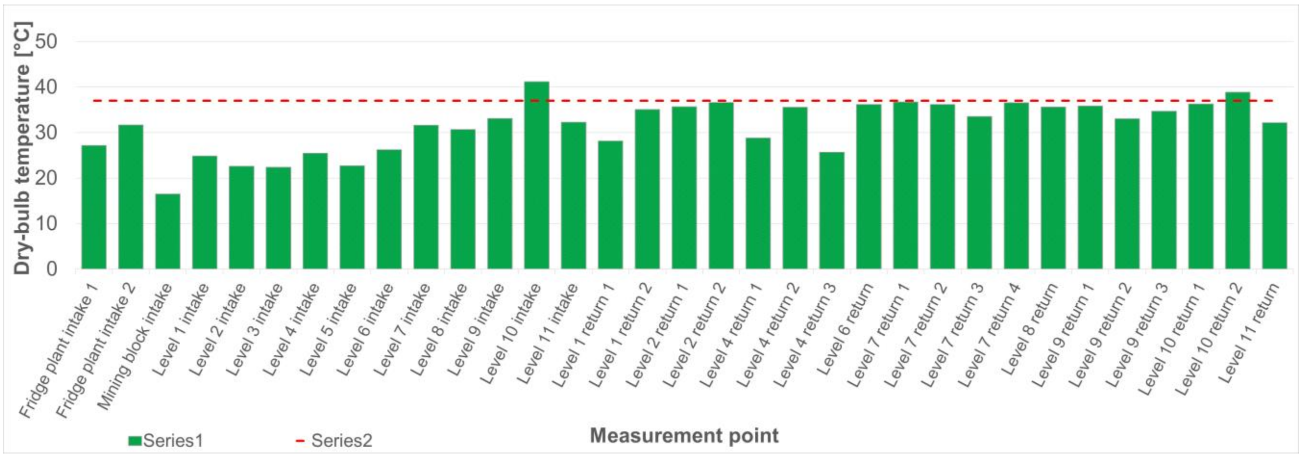
Appendix-figure 12: 2022 predicted dry-bulb temperatures



Appendix-figure 13: 2023 predicted airflow



Appendix-figure 14: 2023 predicted wet-bulb temperatures



Appendix-figure 15: 2023 predicted dry-bulb temperatures

Appendix C Dust sampling data

RF Pre mass 1	RF Pre mass 2	RF Pre mass 3	RF Premass Avg	RF Post Mass 1	RF Post Mass 2	RF Post Mass 3	RFPostMassAvg	Pollutant	SF Pre Mass 1	SF Pre Mass 2	SF Pre Mass 3	SF Pre Mass Avg	SF Post Mass 1	SF Post Mass 2	SF Post Mass 3	SF Post Mass Avg	Pump Flow Rate Before	Pump Flow Rate After	Avg Pump Flow Rate	Pump Start Time	Pump Stop Time	Sample Mass	Corrected Sample Mass	Correction Factor	Silica Concentration	PNOC Concentration	Sample Concentration	Sample Volume m3	OEL	DMR Occupation Description	Quartz MG	Quarts %	TWA Quarts	TWA PNOC
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	163.57	163.58	163.58	163.58	163.61	163.6	163.61	163.61	2.2	2.209	2.205	07:01	16:47	0.03	0.02	0.01	0.004	0.012	0.015	1.292	0.1	Auto electrician	0.005	0.250	0.005	0.014
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	161.96	161.95	161.95	161.95	162.65	162.65	162.66	162.65	2.2	2.2	2.200	06:07	14:07	0.70	0.70	0.00	0.121	0.542	0.663	1.056	0.1	Auto electrician	0.128	0.183	0.121	0.542
143.42	143.41	143.41	143.41	143.41	143.4	143.41	143.41	Silica Quartz	169.73	169.72	169.72	169.72	170.19	170.21	170.23	170.21	2.217	2.231	2.224	05:48	20:35	0.49	0.49	-0.01	0.045	0.205	0.250	1.973	0.1	Backfill worker	0.088	0.178	0.082	0.380
153.88	153.89	153.88	153.88	153.87	153.88	153.89	153.88	Silica Quartz	170.77	170.78	170.77	170.77	170.92	170.92	170.92	170.92	2.2	2.194	2.197	04:31	12:37	0.15	0.15	0.00	0.028	0.112	0.140	1.068	0.1	Banksman/onsetter	0.03	0.200	0.028	0.114
153.88	153.88	153.89	153.88	153.88	153.88	153.88	153.88	Silica Quartz	160.97	160.97	160.96	160.97	161.06	161.08	161.08	161.07	2.2	2.199	2.200	12:11	19:30	0.11	0.11	0.00	0.028	0.086	0.114	0.966	0.1	Banksman/onsetter		0.247	0.026	0.078
180.57	180.58	180.58	180.58	180.59	180.58	180.59	180.59	Silica Quartz	163.91	163.92	163.91	163.91	164.52	164.52	164.52	164.52	2.202	2.242	2.222	04:58	16:16	0.61	0.60	0.01	0.145	0.251	0.396	1.507	0.1	Banksman/onsetter	0.218	0.365	0.204	0.355
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	167.81	167.81	167.79	167.80	167.91	167.92	167.92	167.92	2.2	2.2	2.200	04:22	12:22	0.11	0.11	0.00	0.021	0.086	0.107	1.056	0.1	Banksman/onsetter	0.022	0.194	0.021	0.086
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	168.39	168.4	168.41	168.40	168.95	168.96	168.94	168.95	2.202	2.217	2.210	04:19	12:56	0.55	0.53	0.02	0.159	0.308	0.467	1.142	0.1	Banksman/onsetter	0.182	0.341	0.172	0.331
162.61	162.61	162.61	162.61	162.62	162.62	162.61	162.62	Silica Quartz	162.81	162.8	162.81	162.81	163.36	163.35	163.35	163.35	2.204	2.167	2.186	05:47	14:44	0.55	0.54	0.01	0.232	0.228	0.460	1.174	0.1	Beltsman	0.272	0.504	0.259	0.255
167.47	167.48	167.48	167.48	167.49	167.48	167.5	167.49	Silica Quartz	170.6	170.6	170.62	170.61	170.85	170.88	170.88	170.87	2.205	2.202	2.204	05:35	13:14	0.26	0.25	0.01	0.086	0.161	0.247	1.011	0.1	Beltsman	0.087	0.348	0.082	0.154
159.09	159.1	159.09	159.09	159.09	159.09	159.1	159.09	Silica Quartz	157.73	157.71	157.72	157.72	157.98	157.97	157.96	157.97	2.2	2.158	2.179	05:51	13:26	0.25	0.25	0.00	0.041	0.211	0.252	0.991	0.1	Boilermaker: operative (gr 1)	0.041	0.164	0.039	0.200
153.88	153.9	153.88	153.89	153.88	153.88	153.88	153.88	Silica Quartz	169.15	169.14	169.14	169.14	169.66	169.67	169.65	169.66	2.201	2.226	2.214	05:12	17:49	0.52	0.52	-0.01	0.077	0.235	0.312	1.676	0.1	Boilermaker: operative (gr 1)		0.247	0.122	0.371
153.88	153.9	153.88	153.89	153.87	153.88	153.88	153.88	Silica Quartz	144.02	144.02	144.02	144.02	144.35	144.37	144.37	144.36	2.202	2.232	2.217	04:37	13:13	0.34	0.35	-0.01	0.086	0.223	0.309	1.144	0.1	Cementation worker (n.e.c.)	0.098	0.277	0.092	0.240
159.08	159.1	159.08	159.09	159.1	159.1	159.1	159.10	Silica Quartz	168.06	168.06	168.05	168.06	168.28	168.28	168.27	168.28	2.203	2.256	2.230	05:28	13:37	0.22	0.21	0.01	0.070	0.120	0.190	1.090	0.1	Cementation worker (n.e.c.)	0.076	0.368	0.071	0.122
167.47	167.48	167.48	167.48	167.5	167.49	167.48	167.49	Silica Quartz	163.86	163.87	163.86	163.86	164.25	164.26	164.27	164.26	2.2	2.223	2.212	04:56	13:25	0.40	0.38	0.01	0.075	0.266	0.341	1.126	0.1	Cementation worker (n.e.c.)	0.084	0.219	0.079	0.282
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	177.1	177.12	177.12	177.11	177.27	177.26	177.26	177.26	2.207	2.23	2.219	04:23	12:47	0.15	0.13	0.02	0.035	0.084	0.119	1.118	0.1	Cementation worker (n.e.c.)	0.039	0.293	0.037	0.089
153.88	153.89	153.88	153.88	153.88	153.88	153.88	153.88	Silica Quartz	151.94	151.95	151.96	151.95	152	152.01	151.99	152.00	2.201	2.218	2.210	07:06	15:51	0.05	0.05	0.00	0.011	0.035	0.046	1.160	0.1	Changehouse worker		0.247	0.012	0.038
143.41	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	138.48	138.49	138.5	138.49	138.5	138.54	138.52	138.52	2.201	2.228	2.215	07:28	13:37	0.03	0.03	0.00	0.006	0.035	0.041	0.817	0.1	Changehouse worker	0.005	0.150	0.005	0.027
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	167.47	167.48	167.48	167.48	167.61	167.61	167.61	167.61	2.1	2.1	2.100	05:43	13:43	0.13	0.13	0.00	0.011	0.118	0.129	1.008	0.1	Changehouse worker	0.011	0.085	0.011	0.118
187.46	187.48	187.47	187.47	187.47	187.48	187.48	187.48	Silica Quartz	162.71	162.72	162.71	162.71	162.74	162.76	162.74	162.75	2.206	2.156	2.181	06:20	14:00	0.03	0.03	0.01	0.005	0.022	0.027	1.003	0.1	Changehouse worker	0.005	0.187	0.005	0.021
143.41	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	173.92	173.92	173.92	173.92	173.95	173.95	173.94	173.95	2.2	2.167	2.184	07:16	17:18	0.03	0.03	0.00	0.004	0.019	0.023	1.314	0.1	Clerk (payrole/timekeeping)	0.005	0.167	0.005	0.024
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	171.46	171.45	171.45	171.45	171.54	171.53	171.54	171.54	2.2	2.2	2.200	06:36	13:36	0.08	0.08	0.01	0.005	0.078	0.083	0.924	0.1	Control room operator	0.005	0.065	0.005	0.068
159.09	159.1	159.09	159.09	159.09	159.09	159.09	159.09	Silica Quartz	163.21	163.23	163.23	163.22	163.35	163.37	163.37	163.36	2.201	2.21	2.206	04:49	12:47	0.14	0.14	0.00	0.034	0.102	0.136	1.054	0.1	Conveyer belt attendant		0.247	0.033	0.102
153.88	153.88	153.89	153.88	153.87	153.88	153.89	153.88	Silica Quartz	169.51	169.52	169.5	169.51	170.73	170.72	170.71	170.72	2.202	2.249	2.226	04:13	18:45	1.21	1.21	0.00	0.276	0.350	0.625	1.941	0.1	Conveyer belt attendant	0.535	0.441	0.501	0.635
153.88	153.88	153.89	153.88	153.87	153.88	153.88	153.88	Silica Quartz	159.34	159.37	159.35	159.35	159.54	159.55	159.52	159.54	2.2	2.182	2.191	04:44	14:48	0.18	0.19	-0.01	0.021	0.122	0.144	1.323	0.1	Conveyer belt attendant	0.028	0.147	0.027	0.154
143.42	143.4	143.41	143.41	143.4	143.4	143.41	143.40	Silica Quartz	176.28	176.3	176.28	176.29	176.44	176.45	176.47	176.45	2.2	2.178	2.189	05:20	12:02	0.17	0.17	-0.01	0.051	0.146	0.197	0.880	0.1	Conveyer belt attendant	0.045	0.260	0.043	0.122
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	167.89	167.88	167.88	167.88	167.94	167.94	167.94	167.94	2.2	2.2	2.200	04:13	12:13	0.06	0.05	0.01	0.011	0.036	0.047	1.056	0.1	Conveyer belt attendant	0.012	0.240	0.011	0.036
167.47	167.48	167.48	167.48	167.48	167.48	167.48	167.48	Silica Quartz	157.99	157.98	157.99	157.99	158.28	158.29	158.28	158.28	2.205	2.193	2.199	05:05	13:48	0.30	0.29	0.00	0.124	0.131	0.255	1.150	0.1	Conveyer belt attendant	0.143	0.488	0.135	0.142
142.78	142.77	142.79	142.78	142.75	142.74	142.75	142.75	Silica Quartz	155	155.01	155	155.00	155.19	155.18	155.18	155.18	2.2	2.216	2.208	04:35	18:16	0.18	0.21	-0.03	0.031	0.087	0.118	1.813	0.1	Conveyer belt attendant	0.056	0.262	0.053	0.148
143.42	143.41	143.41	143.41	143.38	143.41	143.39	143.39	Silica Quartz	165.65	165.65	165.66	165.65	166.03	166.01	166.01	166.02	2.205	2.192	2.199	04:58	20:35	0.36	0.38	-0.02	0.025	0.161	0.186	2.060	0.1	Conveyer belt attendant	0.052	0.136	0.049	0.314
187.46	187.44	187.45	187.45	187.47	187.46	187.47	187.47	Silica Quartz	162.22	162.23	162.22	162.22	162.51	162.51	162.52	162.51	2.204	2.203	2.204	04:21	18:43	0.29	0.27	0.02	0.089	0.055	0.144	1.899	0.1	Conveyer belt attendant	0.169	0.618	0.160	0.099
187.46	187.48	187.47	187.47	187.48	187.47	187.46	187.47	Silica Quartz	135.35	135.37	135.36	135.36	135.97	135.97	135.96	135.97	2.2	2.211	2.206	04:58	18:30	0.61	0.61	0.00	0.157	0.182	0.339	1.791	0.1	Conveyer belt attendant	0.281	0.463	0.265	0.308
142.78	142.77	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	164.15	164.16	164.15	164.15	164.59	164.59	164.6	164.59	2.202	2.227	2.215	05:25	13:57	0.44	0.47	-0.03	0.106	0.309	0.415	1.134	0.1	Conveyer belt team leader/supervisor	0.12	0.255	0.113	0.329
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	167.91	167.9	167.91	167.91	168.52	168.51	168.51	168.51	2.203	2.249	2.226	04:07	15:31	0.61	0.60	0.01	0.157	0.235	0.392	1.523	0.1	Conveyer belt team leader/supervisor	0.239	0.401	0.224	0.335
163.02	163	163	163.01	163.01	163.01	163.01	163.01	Silica Quartz	161.08	161.09	161.08	161.08	161.32	161.31	161.3	161.31	2.184	2.188	2.186	04:50	16:37	0.23	0.22	0.00	0.043	0.102	0.145	1.546	0.1	Conveyer belt team leader/supervisor	0.066	0.296	0.063	0.150
142.78	142.77	142.79	142.78	142.74	142.76	142.73	142.74	Silica Quartz	160.96	160.96	160.97	160.96	163.36	163.34	163.34	163.35	2.201	2.178	2.190	04:00	19:08	2.38	2.42	-0.04	0.660	0.557	1.217	1.988	0.1	Crusher attendant	1.312	0.542	1.248	1.054
143.41	143.41	143.41	143.41	143.4	143.39	143.39	143.39	Silica Quartz	140.97	140.99	140.99	140.98	142.61	142.6	142.61	142.61	2.202	2.233	2.218	04:31	16:58	1.62	1.64	-0.02	0.672	0.318	0.990	1.656	0.1	Crusher attendant	1.113	0.679	1.046	0.495
143.39	143.4	143.4	143.40	143.4	143.4	143.41	143.40	Silica Quartz	172.35	172.36	172.37	172.36	172.52	172.53	172.53	172.53	2.203	2.212	2.208	04:45	12:30	0.17	0.16	0.01	0.073	0.083	0.156	1.026	0.1	Crusher attendant	0.075	0.469	0.071	0.080
187.46	187.44	187.45	187.45	187.48	187.48	187.49	187.48	Silica Quartz	152.53	152.52	152.52	152.52	154.82	154.81	154.81	154.81	2.203	2.202	2.203	04:25	17:20	2.29	2.26	0.03	0.032	1.290	1.322	1.707	0.1	Crusher attendant	0.055	0.024	0.052	2.083
153.88	153.9	153.88	153.89	153.87	153.88	153.88	153.88	Silica Quartz	151.8	151.79	151.79	151.79	152.12	152.11	152.12	152.12	2.201	2.236	2.219	05:53	12:49	0.32	0.33	-0.01	0.053	0.308	0.361	0.923	0.1	Developer	0.049	0.147	0.046	0.267
180.54	180.58	180.56	180.56	180.58	180.59	180.58	180.58	Silica Quartz	179.73	179.75	179.77	179.75	179.99	179.99	179.96	179.98	2.234	2.215	2.225	06:04	14:04	0.23	0.21	0.02	0.057	0.136	0.194	1.068	0.1	Developer	0.061	0.295	0.057	0.136
187.47	187.47	187.47	187.47	187.48	187.47	187.46	187.47	Silica Quartz	177.74	177.76	177.73	177.74	178.19	178.21	178.2	178.20	2.21	2.263	2.237	06:03	17:41	0.46	0.46	0.00	0.061	0.232	0.293	1.561	0.1	Developer	0.095	0.208	0.088	0.337
143.42	143.41	143.41	143.41	143.4	143.4	143.41	143.40	Silica Quartz	162.66	162.65	162.65	162.65	163.22	163.2	163.23	163.22	2.204	2.186	2.195	06:40	17:25	0.56	0.57	-0.01	0.042	0.363	0.405	1.416	0.1	Developer	0.06	0.105	0.057	0.487
142.78	142.77	142.79	142.78	142.75	142.74	142.73	142.74	Silica Quartz	152.44	152.44	152.45	152.44	153.48	153.47	153.48	153.48	2.202	2.237	2.220	05:59	18:15	1.03	1.07	-0.04	0.197	0.461	0.657	1.634	0.1	Developer	0.321	0.299	0.301	0.706
142.77	142.79	142.79	142.78	142.75	142.76	142.76	142.76	Silica Quartz	153.01	153.02	153.01	153.01	153.43	153.43	153.42	153.43	2.202	2.241	2.222	05:26	14:29	0.41	0.44	-0.03	0.061	0.304	0.365	1.206	0.1	Development team leader/supervisor	0.073	0.166	0.068	0.344
165.18	165.17	165.2	165.18	165.19	165.19	165.21	165.20	Silica Quartz	164.02	164.02	164.02	164.02	164.19	164.2	164.19	164.19	2.205	2.228	2.217	08:24	14:33	0.17	0.16	0.01	0.066	0.130	0.196	0.818	0.1	Development team leader/supervisor	0.054	0.338	0.051	0.100
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	162.28	162.3	162.29	162.29	162.75	162.74	162.75	162.75	2.201	2.216	2.209	04:51	12:35	0.46	0.47	-0.01	0.047	0.412	0.459	1.025	0.1	Development team leader/supervisor	0.048	0.102	0.045	0.398
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	161.74	161.73	161.73	161.73	162.02	162.02	162.01	162.02	2.206	2.193	2.200	05:45	14:11	0.28	0.27	0.02	0.030	0.210	0.240	1.113	0.1	Development team leader/supervisor	0.033	0.124	0.031	0.221
162.99	162.99	162.99	162.99	163	163.01	163	163.00	Silica Quartz	168.9	168.89	168.9	168.90	170.06	170.05	170.06	170.06	2.204	2.187	2.196	06:00	17:33	1.16	1.15	0.01	0.174	0.579	0.754	1.521	0.1	Development team leader/supervisor	0.265	0.231	0.251	0.837
153.88	153.88	153.89	153.88	153.89	153.89	153.88	153.89	Silica Quartz	142.16	142.18	142.16	142.17	143.04	143.04	143.03	143.04	2.203	2.173	2.188	06:07	14:19	0.87	0.87	0.00	0.226	0.579	0.805	1.076	0.1	Development team worker	0.243	0.280	0.231	0.594
153.88	153.89	153.88	153.88	153.89	153.89	153.88	153.89	Silica Quartz	163.96	163.98	163.96	163.97	164.5	164.5	164.53	164.51	2.2	2.233	2.217	06:02	14:16	0.54	0.54	0.00	0.079	0.414	0.493	1.095	0.1	Development team worker	0.087	0.161	0.082	0.426
143.41	143.41	143.41	143.41	143.4	143.39	143.39	143.39	Silica Quartz	147.14	147.13	147.14	147.14	147.32	147.3	147.31	147.31	2.2	2.211	2.206	05:10	12:56	0.17	0.19	-0.02	0.037	0.148	0.185	1.028	0.1	Development team worker	0.038	0.200	0.036	0.144
143.41	143.41	143.41	143.41	143.4	143.39	143.39	143.39	Silica Quartz	143.79	143.78	143.79	143.79	143.9	143.9	143.9	143.90	2.203	2.199	2.201	05:36	13:20	0.11	0.13	-0.02	0.031	0.096	0.127	1.021	0.1	Development team worker	0.032	0.246	0.030	0.093
143.42	143.41	143.41	143.41	143.38	143.41	143.39	143.39	Silica Quartz	166.2	166.21	166.2	166.20	166.43	166.41	166.41	166.42	2.203	2.172	2.188	05:41	11:50	0.21	0.23	-0.02	0.047	0.242	0.289	0.807	0.1	Development team worker	0.038	0.163	0.036	0.186
187.46	187.44	187.45	187.45	187.47	187.48	187.48	187.48	Silica Quartz	156.18	156.19	156.19	156.19	156.5	156.5	156.5	156.50	2.204	2.211	2.208	06:27	14:39	0.31	0.29	0.03	0.035	0.229	0.264	1.086	0.1	Development team worker	0.038	0.133	0.036	0.235
167.46	167.48	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	149.5	149.48	149.49	149.49	149.78	149.79	149.78	149.78	2.178	2.176	2.177	06:09	13:57	0.29	0.28	0.02	0.055	0.217	0.272	1.019	0.1	Development team worker	0.056	0.202	0.054	0.211
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	172.8	172.8	172.81	172.80	173.3	173.28	173.28	173.29	2.2	2.201	2.201	05:57	15:36	0.48	0.47	0.02	0.111	0.256	0.366	1.274	0.1	Development team worker	0.141	0.302	0.133	0.308
142.77	142.79	142.79	142.78	142.74	142.76	142.73	142.74	Silica Quartz	165.45	165.46	165.45	165.45	165.99	166	165.97	165.99	2.202	2.205	2.204	05:28	15:31	0.53	0.57	-0.04	0.110	0.322	0.431	1.329	0.1	Diesel mechanic	0.146	0.255	0.138	0.404
153.88	153.89	153.88	153.88	153.88	153.88	153.88	153.88	Silica Quartz	170.29	170.3	170.3	170.30	171.29	171.29	171.28	171.29	2.2	2.231	2.216	06:20	17:42	0.99	0.99	0.00	0.163	0.495	0.657	1.511	0.1	Drill rig operator (jumbo)		0.247	0.231	0.703
142.79	142.79	142.79	142.79	142.74	142.76	142.75	142.75	Silica Quartz	171.55	171.54	171.55	171.55	172.09	172.08	172.09	172.09	2.203	2.207	2.205	05:56	14:52	0.54	0.58	-0.04	0.069	0.421	0.491	1.182	0.1	Drill rig operator (jumbo)	0.082	0.141	0.077	0.471
143.42	143.41	143.41	143.41	143.41	143.4	143.41	143.41	Silica Quartz	161.22	161.22	161.22	161.22	161.44	161.42	161.45	161.44	2.202	2.147	2.175	07:08	14:30	0.22	0.22	-0.01	0.029	0.203	0.232	0.961	0.1	Drill rig operator (jumbo)	0.028	0.125	0.027	0.187
143.42	143.41	143.41	143.41	143.41	143.4	143.41	143.41	Silica Quartz	172.05	172.04	172.04	172.04	172.37	172.35	172.37	172.36	2.203	2.168	2.186	05:56	13:03	0.32	0.33	-0.01	0.100	0.250	0.350	0.933	0.1	Drill rig operator (jumbo)	0.093	0.285	0.089	0.223
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	163.11	163.11	163.12	163.11	163.37	163.37	163.37	163.37	2.206	2.23	2.218	06:14	16:03	0.26	0.27	-0.01	0.020	0.187	0.207	1.306	0.1	Drill rig operator (jumbo)	0.026	0.096	0.024	0.229
153.88	153.88	153.89	153.88	153.87	153.88	153.88	153.88	Silica Quartz	165.11	165.12	165.13	165.12	165.33	165.33	165.32	165.33	2.201	2.261	2.231	05:50	17:15	0.21	0.21	-0.01	0.025	0.115	0.140	1.528	0.1	Driller: hand percussion/jackhammer	0.038	0.178	0.035	0.164
153.88	153.88	153.89	153.88	153.87	153.88	153.89	153.88	Silica Quartz	169.79	169.81	169.79	169.80	170.07	170.06	170.07	170.07	2.203	2.187	2.195	06:14	12:53	0.27	0.27	0.00	0.059	0.253	0.312	0.876	0.1	Driller: hand percussion/jackhammer	0.052	0.190	0.049	0.210
153.88	153.89	153.88	153.88	153.88	153.88	153.88	153.88	Silica Quartz	150.66	150.68	150.67	150.67	150.87	150.88	150.86	150.87	2.202	2.224	2.213	05:09	11:35	0.20	0.20	0.00	0.059	0.179	0.238	0.854	0.1	Driller: hand percussion/jackhammer		0.247	0.047	0.144
153.88	153.9	153.88	153.89	153.89	153.89	153.88	153.89	Silica Quartz	163.29	163.26	163.28	163.28	163.6	163.6	163.59	163.60	2.201	2.309	2.255	05:14	11:42	0.32	0.32	0.00	0.093	0.273	0.366	0.875	0.1	Driller: hand percussion/jackhammer	0.081	0.253	0.075	0.221
142.78	142.77	142.79	142.78	142.75	142.74	142.75	142.75	Silica Quartz	146.85	146.86	146.86	146.86	147.32	147.32	147.31	147.32	2.2	2.212	2.206	05:17	17:05	0.46	0.49	-0.03	0.061	0.255	0.316	1.562	0.1	Driller: hand percussion/jackhammer	0.095	0.193	0.090	0.376
143.39	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	171.11	171.11	171.11	171.11	171.19	171.19	171.2	171.19	2.203	2.203	2.203	05:42	12:50	0.08	0.08	0.00	0.023	0.062	0.085	0.943	0.1	Driller: hand percussion/jackhammer	0.022	0.275	0.021	0.055
159.08	159.09	159.09	159.09	159.1	159.1	159.1	159.10	Silica Quartz	159.68	159.65	159.66	159.66	160.03	160.03	160.03	160.03	2.201	2.141	2.171	05:20	13:40	0.37	0.35	0.01	0.022	0.303	0.326	1.086	0.1	Driller: hand percussion/jackhammer	0.024	0.068	0.023	0.316
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	164.69	164.68	164.69	164.69	164.84	164.84	164.83	164.84	2.204	2.227	2.216	04:39	16:21	0.15	0.16	-0.01	0.027	0.078	0.105	1.555	0.1	Driller: hand percussion/jackhammer	0.042	0.257	0.039	0.114
142.79	142.79	142.79	142.79	142.75	142.74	142.75	142.75	Silica Quartz	135.85	135.85	135.85	135.85	136.09	136.07	136.08	136.08	2.205	2.212	2.209	06:00	14:05	0.23	0.27	-0.04	0.046	0.209	0.255	1.071	0.1	Driller: hand percussion/jackhammer	0.049	0.179	0.046	0.212
142.79	142.79	142.79	142.79	142.75	142.74	142.75	142.75	Silica Quartz	134.74	134.74	134.74	134.74	134.96	134.99	134.98	134.98	2.201	2.216	2.209	05:46	13:17	0.24	0.28	-0.04	0.045	0.236	0.281	0.996	0.1	Driller: hand percussion/jackhammer	0.045	0.161	0.042	0.222
180.57	180.58	180.58	180.58	180.58	180.59	180.58	180.58	Silica Quartz	178.74	178.75	178.76	178.75	178.93	178.93	178.94	178.93	2.201	2.212	2.207	05:58	12:04	0.18	0.18	0.01	0.031	0.188	0.219	0.808	0.1	Driller: hand percussion/jackhammer	0.025	0.142	0.024	0.143
143.41	143.41	143.41	143.41	143.4	143.39	143.39	143.39	Silica Quartz	170.19	170.19	170.19	170.19	170.7	170.69	170.67	170.69	2.201	2.129	2.165	05:30	21:14	0.50	0.51	-0.02	0.106	0.145	0.251	2.044	0.1	Driller: hand percussion/jackhammer	0.216	0.421	0.208	0.286

RF Pre mass 1	RF Pre mass 2	RF Pre mass 3	RF Premass Avg	RF Post Mass 1	RF Post Mass 2	RF Post Mass 3	RFPostMassAvg	Pollutant	SF Pre Mass 1	SF Pre Mass 2	SF Pre Mass 3	SF Pre Mass Avg	SF Post Mass 1	SF Post Mass 2	SF Post Mass 3	SF Post Mass Avg	Pump Flow Rate Before	Pump Flow Rate After	Avg Pump Flow Rate	Pump Start Time	Pump Stop Time	Sample Mass	Corrected Sample Mass	Correction Factor	Silica Concentration	PNOC Concentration	Sample Concentration	Sample Volume m3	OEL	DMR Occupation Description	Quartz MG	Quarts %	TWA Quarts	TWA PNOC
159.08	159.1	159.08	159.09	159.08	159.1	159.1	159.09	Silica Quartz	162.72	162.73	162.72	162.72	162.96	162.94	162.94	162.95	2.2	2.201	2.201	05:06	16:59	0.22	0.22	0.01	0.025	0.113	0.138	1.569	0.1	Driller: hand percussion/jackhammer	0.04	0.185	0.038	0.167
159.08	159.09	159.09	159.09	159.1	159.1	159.1	159.10	Silica Quartz	155.07	155.07	155.07	155.07	155.38	155.38	155.38	155.38	2.204	2.156	2.180	05:14	12:41	0.31	0.30	0.01	0.058	0.246	0.304	0.974	0.1	Driller: hand percussion/jackhammer	0.057	0.192	0.054	0.229
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	158.66	158.66	158.66	158.66	158.86	158.86	158.87	158.86	2.2	2.2	2.200	05:25	13:25	0.20	0.20	0.00	0.035	0.158	0.193	1.056	0.1	Driller: hand percussion/jackhammer	0.037	0.182	0.035	0.158
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	174.7	174.7	174.69	174.70	174.95	174.96	174.95	174.95	2.2	2.2	2.200	05:09	13:09	0.26	0.26	0.00	0.020	0.223	0.243	1.056	0.1	Driller: hand percussion/jackhammer	0.021	0.082	0.020	0.223
163.02	163	163	163.01	163.01	163.01	163.01	163.01	Silica Quartz	159.88	159.89	159.89	159.89	160.27	160.27	160.28	160.27	2.195	2.154	2.175	05:23	17:32	0.39	0.38	0.00	0.067	0.175	0.242	1.585	0.1	Driller: hand percussion/jackhammer	0.106	0.277	0.102	0.266
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	159.53	159.53	159.54	159.53	159.82	159.82	159.83	159.82	2.201	2.262	2.232	05:32	13:04	0.29	0.30	-0.01	0.043	0.258	0.301	1.009	0.1	Driller: hand percussion/jackhammer	0.043	0.142	0.040	0.243
167.46	167.48	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	162.46	162.46	162.45	162.46	163.22	163.21	163.22	163.22	2.22	2.214	2.217	05:20	14:35	0.76	0.74	0.02	0.036	0.568	0.604	1.230	0.1	Driller: hand percussion/jackhammer	0.044	0.059	0.041	0.657
167.48	167.47	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	172.46	172.46	172.47	172.46	172.61	172.61	172.61	172.61	2.179	2.2	2.190	04:56	13:10	0.15	0.13	0.01	0.020	0.103	0.123	1.082	0.1	Driller: hand percussion/jackhammer	0.022	0.165	0.021	0.106
167.47	167.49	167.48	167.48	167.5	167.49	167.48	167.49	Silica Quartz	166.14	166.16	166.14	166.15	166.54	166.54	166.53	166.54	2.201	2.236	2.219	06:08	12:53	0.39	0.38	0.01	0.085	0.338	0.423	0.898	0.1	Driller: hand percussion/jackhammer	0.076	0.200	0.071	0.285
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	156.38	156.36	156.38	156.37	156.51	156.5	156.5	156.50	2.204	2.194	2.199	06:13	15:00	0.13	0.12	0.01	0.018	0.085	0.104	1.159	0.1	Driller: hand percussion/jackhammer	0.021	0.175	0.020	0.094
153.88	153.89	153.88	153.88	153.87	153.88	153.89	153.88	Silica Quartz	162.9	162.91	162.9	162.90	163.02	163.02	163.03	163.02	2.203	2.201	2.202	06:41	11:08	0.12	0.12	0.00	0.032	0.177	0.210	0.588	0.1	Driver: forklift	0.019	0.154	0.018	0.099
143.41	143.41	143.41	143.41	143.38	143.41	143.39	143.39	Silica Quartz	174.47	174.48	174.48	174.48	174.95	174.96	174.97	174.96	2.2	2.224	2.212	04:40	13:22	0.48	0.50	-0.02	0.079	0.354	0.433	1.155	0.1	Driver: forklift	0.091	0.182	0.086	0.385
187.46	187.44	187.45	187.45	187.48	187.48	187.49	187.48	Silica Quartz	152.38	152.37	152.38	152.38	152.5	152.51	152.51	152.51	2.202	2.225	2.214	05:07	15:53	0.13	0.10	0.03	0.011	0.056	0.068	1.430	0.1	Driver: forklift	0.016	0.166	0.015	0.076
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	166.28	166.27	166.28	166.28	166.45	166.44	166.45	166.45	2.1	2.1	2.100	05:40	13:40	0.17	0.17	0.00	0.058	0.108	0.165	1.008	0.1	Driver: haul truck (underground and opencast)	0.058	0.348	0.058	0.108
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	175.18	175.2	175.19	175.19	175.74	175.74	175.74	175.74	2.2	2.2	2.200	05:31	14:31	0.55	0.55	0.00	0.190	0.270	0.460	1.188	0.1	Driver: haul truck (underground and opencast)	0.226	0.413	0.214	0.304
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	181.25	181.26	181.26	181.26	181.5	181.51	181.51	181.51	2	2.1	2.050	05:25	13:25	0.25	0.24	0.01	0.062	0.185	0.247	0.984	0.1	Driver: haul truck (underground and opencast)	0.061	0.251	0.062	0.185
180.57	180.58	180.58	180.58	180.59	180.6	180.59	180.59	Silica Quartz	180.51	180.53	180.5	180.51	180.76	180.75	180.76	180.76	2.201	2.204	2.203	05:56	21:55	0.24	0.23	0.02	0.013	0.094	0.107	2.112	0.1	Electrician	0.028	0.124	0.026	0.188
162.61	162.62	162.62	162.62	162.6	162.61	162.62	162.61	Silica Quartz	164.51	164.52	164.49	164.51	164.61	164.63	164.62	164.62	2.206	2.197	2.202	05:52	12:48	0.11	0.12	-0.01	0.025	0.106	0.131	0.916	0.1	Electrician	0.023	0.192	0.022	0.092
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	165.09	165.1	165.1	165.10	165.33	165.32	165.32	165.32	2.2	2.1	2.150	05:26	13:26	0.23	0.22	0.01	0.079	0.134	0.213	1.032	0.1	Electrician	0.082	0.373	0.079	0.134
167.46	167.48	167.47	167.47	167.48	167.48	167.48	167.48	Silica Quartz	166.63	166.63	166.63	166.63	167.17	167.16	167.16	167.16	2.208	2.217	2.213	06:35	15:05	0.53	0.52	0.01	0.102	0.362	0.464	1.128	0.1	Electrician	0.115	0.220	0.108	0.384
187.46	187.44	187.45	187.45	187.48	187.48	187.49	187.48	Silica Quartz	156.87	156.87	156.87	156.87	157.38	157.4	157.4	157.39	2.202	2.227	2.215	06:04	18:24	0.52	0.49	0.03	0.184	0.115	0.299	1.639	0.1	Electrician	0.301	0.614	0.283	0.178
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	171.56	171.56	171.55	171.56	171.64	171.63	171.64	171.64	2.2	2.2	2.200	05:28	13:28	0.08	0.07	0.01	0.017	0.052	0.069	1.056	0.1	Engineering assistant (n.e.c.)	0.018	0.245	0.017	0.052
153.88	153.89	153.88	153.88	153.9	153.88	153.89	153.89	Silica Quartz	161.63	161.64	161.63	161.63	161.96	161.94	161.94	161.95	2.2	2.304	2.252	06:18	14:36	0.31	0.31	0.01	0.029	0.244	0.273	1.121	0.1	Engineering assistant (n.e.c.)	0.033	0.108	0.031	0.253
162.61	162.62	162.62	162.62	162.61	162.63	162.63	162.62	Silica Quartz	162.15	162.15	162.16	162.15	162.42	162.42	162.41	162.42	2.2	2.138	2.169	06:35	12:38	0.26	0.26	0.01	0.122	0.204	0.326	0.787	0.1	Engineering assistant (n.e.c.)	0.096	0.374	0.092	0.154
187.47	187.47	187.47	187.47	187.48	187.47	187.46	187.47	Silica Quartz	154.15	154.15	154.15	154.15	155.22	155.23	155.23	155.23	2.2	2.228	2.214	05:58	18:13	1.08	1.08	0.00	0.034	0.627	0.662	1.627	0.1	Engineering assistant (n.e.c.)	0.056	0.052	0.053	0.960
142.78	142.78	142.78	142.78	142.75	142.76	142.75	142.75	Silica Quartz	152.1	152.11	152.11	152.11	152.37	152.37	152.38	152.37	2.211	2.23	2.221	05:48	17:50	0.27	0.29	-0.03	0.036	0.147	0.183	1.603	0.1	Engineering assistant (n.e.c.)	0.057	0.194	0.053	0.222
142.79	142.79	142.79	142.79	142.75	142.74	142.75	142.75	Silica Quartz	157.62	157.6	157.62	157.61	157.75	157.75	157.76	157.75	2.2	2.269	2.235	05:23	13:13	0.14	0.18	-0.04	0.020	0.155	0.175	1.050	0.1	Engineering assistant (n.e.c.)	0.021	0.115	0.020	0.151
143.39	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	174.46	174.46	174.45	174.46	174.77	174.78	174.77	174.77	2.2	2.205	2.203	04:37	12:43	0.32	0.31	0.00	0.092	0.201	0.293	1.070	0.1	Engineering assistant (n.e.c.)	0.098	0.313	0.093	0.204
187.46	187.48	187.47	187.47	187.47	187.48	187.48	187.48	Silica Quartz	159.64	159.63	159.63	159.63	159.96	159.97	159.97	159.97	2.233	2.234	2.234	05:26	14:27	0.33	0.33	0.01	0.075	0.195	0.270	1.208	0.1	Engineering assistant (n.e.c.)	0.091	0.279	0.085	0.220
142.79	142.79	142.79	142.79	142.8	142.8	142.76	142.79	Silica Quartz	155.76	155.76	155.75	155.76	155.88	155.88	155.87	155.88	2.2	2.227	2.214	05:24	13:24	0.12	0.12	0.00	0.024	0.093	0.116	1.062	0.1	Engineering assistant (n.e.c.)	0.025	0.203	0.024	0.093
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	167.78	167.77	167.78	167.78	167.84	167.84	167.84	167.84	2.2	2.2	2.200	05:34	13:33	0.06	0.06	0.00	0.020	0.040	0.060	1.054	0.1	Engineering assistant (n.e.c.)	0.021	0.332	0.020	0.040
167.46	167.48	167.47	167.47	167.48	167.48	167.48	167.48	Silica Quartz	169.13	169.13	169.14	169.13	169.44	169.43	169.43	169.43	2.202	2.199	2.201	06:31	20:10	0.30	0.29	0.01	0.041	0.120	0.161	1.802	0.1	Engineering assistant (n.e.c.)	0.074	0.255	0.070	0.204
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	168.11	168.09	168.09	168.10	168.31	168.3	168.31	168.31	2.208	2.223	2.216	06:43	12:50	0.21	0.19	0.02	0.055	0.182	0.238	0.813	0.1	Engineering assistant (n.e.c.)	0.045	0.233	0.042	0.139
180.57	180.58	180.58	180.58	180.61	180.6	180.58	180.60	Silica Quartz	146.84	146.85	146.84	146.84	146.95	146.97	146.95	146.96	2.207	2.234	2.221	05:44	13:45	0.11	0.09	0.02	0.018	0.070	0.087	1.068	0.1	Engineering assistant (n.e.c.)	0.019	0.204	0.018	0.070
180.58	180.58	180.58	180.58	180.59	180.6	180.59	180.59	Silica Quartz	178.11	178.12	178.11	178.11	178.48	178.48	178.49	178.48	2.207	2.169	2.188	05:24	13:29	0.37	0.36	0.01	0.097	0.239	0.336	1.061	0.1	Engineering assistant (n.e.c.)	0.103	0.289	0.098	0.242
143.41	143.4	143.4	143.40	143.4	143.4	143.41	143.40	Silica Quartz	173.5	173.5	173.51	173.50	173.83	173.81	173.79	173.81	2.2	2.224	2.212	05:29	11:25	0.31	0.31	0.00	0.046	0.344	0.389	0.787	0.1	Engineering assistant (n.e.c.)	0.036	0.117	0.034	0.255
143.42	143.4	143.41	143.41	143.4	143.4	143.41	143.40	Silica Quartz	167.82	167.82	167.82	167.82	167.96	167.96	167.99	167.97	2.202	2.216	2.209	06:09	12:45	0.15	0.16	-0.01	0.055	0.124	0.179	0.875	0.1	Engineering assistant (n.e.c.)	0.048	0.306	0.045	0.102
159.08	159.1	159.08	159.09	159.09	159.1	159.1	159.10	Silica Quartz	150.71	150.69	150.69	150.70	151.42	151.42	151.42	151.42	2.202	2.235	2.219	05:36	14:32	0.72	0.71	0.01	0.206	0.394	0.600	1.189	0.1	Engineering assistant (n.e.c.)	0.245	0.343	0.230	0.440
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	161.07	161.07	161.08	161.07	161.62	161.63	161.63	161.63	2.2	2.2	2.200	04:42	12:42	0.55	0.55	0.00	0.077	0.444	0.521	1.056	0.1	Engineering assistant (n.e.c.)	0.081	0.147	0.077	0.444
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	157.22	157.23	157.24	157.23	157.29	157.28	157.26	157.28	2.201	2.209	2.205	05:49	14:48	0.05	0.03	0.01	0.010	0.018	0.028	1.188	0.1	Engineering assistant (n.e.c.)	0.012	0.360	0.011	0.020
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	153.52	153.53	153.53	153.53	154.03	154.02	154.03	154.03	2.202	2.306	2.254	06:42	19:14	0.50	0.49	0.01	0.126	0.161	0.287	1.695	0.1	Engineering assistant (n.e.c.)	0.213	0.438	0.197	0.253
187.46	187.48	187.47	187.47	187.48	187.48	187.47	187.48	Silica Quartz	160.69	160.7	160.68	160.69	161.05	161.05	161.05	161.05	2.2	2.166	2.183	05:26	16:25	0.36	0.35	0.01	0.090	0.155	0.246	1.439	0.1	Engineering assistant (n.e.c.)	0.13	0.368	0.124	0.213
142.78	142.78	142.78	142.78	142.75	142.76	142.75	142.75	Silica Quartz	161.46	161.46	161.47	161.46	161.64	161.66	161.65	161.65	2.204	2.205	2.205	06:41	12:57	0.19	0.21	-0.03	0.064	0.193	0.257	0.829	0.1	Engineering assistant (n.e.c.)	0.053	0.248	0.050	0.152
142.78	142.78	142.78	142.78	142.75	142.76	142.75	142.75	Silica Quartz	160.88	160.88	160.87	160.88	161.19	161.18	161.18	161.18	2.2	2.216	2.208	06:21	13:16	0.31	0.33	-0.03	0.111	0.252	0.364	0.916	0.1	Engineering assistant (n.e.c.)	0.102	0.306	0.096	0.218
142.79	142.79	142.79	142.79	142.79	142.79	142.75	142.78	Silica Quartz	158.65	158.66	158.66	158.66	158.87	158.89	158.88	158.88	2.202	2.226	2.214	05:24	13:59	0.22	0.24	-0.01	0.078	0.130	0.208	1.140	0.1	Engineering assistant (n.e.c.)	0.089	0.376	0.084	0.139
167.47	167.48	167.48	167.48	167.48	167.48	167.48	167.48	Silica Quartz	158.22	158.22	158.22	158.22	158.7	158.7	158.7	158.70	2.205	2.159	2.182	06:10	15:23	0.48	0.48	0.00	0.203	0.192	0.395	1.207	0.1	Engineering assistant (n.e.c.)	0.245	0.514	0.234	0.221
159.08	159.1	159.08	159.09	159.1	159.1	159.1	159.10	Silica Quartz	160.19	160.18	160.19	160.19	160.29	160.29	160.29	160.29	2.2	2.187	2.194	04:54	13:01	0.10	0.09	0.01	0.005	0.080	0.084	1.068	0.1	Engineering assistant (n.e.c.)	0.005	0.056	0.005	0.081
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	176.31	176.31	176.3	176.31	176.35	176.34	176.35	176.35	2.2	2.2	2.200	05:53	13:53	0.04	0.03	0.01	0.005	0.027	0.032	1.056	0.1	Engineering assistant (n.e.c.)	0.005	0.150	0.005	0.027
143.42	143.4	143.41	143.41	143.4	143.41	143.4	143.40	Silica Quartz	166.72	166.71	166.72	166.72	166.77	166.77	166.76	166.77	2.2	2.284	2.242	05:29	12:10	0.05	0.06	-0.01	0.006	0.057	0.063	0.899	0.1	Engineering assistant (n.e.c.)	0.005	0.088	0.005	0.048
162.61	162.62	162.62	162.62	162.61	162.63	162.63	162.62	Silica Quartz	178.59	178.57	178.59	178.58	179.43	179.43	179.41	179.42	2.2	2.159	2.180	05:04	15:57	0.84	0.83	0.01	0.227	0.359	0.586	1.423	0.1	Engineering assistant (n.e.c.)	0.323	0.388	0.309	0.488
159.08	159.1	159.08	159.09	159.08	159.1	159.1	159.09	Silica Quartz	163.43	163.46	163.44	163.44	163.85	163.82	163.82	163.83	2.202	2.232	2.217	05:25	13:39	0.39	0.38	0.01	0.067	0.280	0.347	1.095	0.1	Engineering assistant (n.e.c.)	0.073	0.192	0.069	0.288
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	172.94	172.94	172.95	172.94	173.12	173.12	173.12	173.12	2.2	2.2	2.200	05:37	13:37	0.18	0.18	0.00	0.010	0.157	0.167	1.056	0.1	Engineering assistant (n.e.c.)	0.011	0.062	0.010	0.157
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	147.52	147.54	147.54	147.53	148.5	148.5	148.49	148.50	2.201	2.244	2.223	05:51	17:05	0.96	0.95	0.01	0.274	0.360	0.634	1.498	0.1	Engineering assistant (n.e.c.)	0.41	0.432	0.384	0.506
159.09	159.1	159.09	159.09	159.09	159.09	159.09	159.09	Silica Quartz	168.14	168.13	168.14	168.14	168.2	168.2	168.2	168.20	2.203	2.255	2.229	05:34	18:36	0.06	0.07	0.00	0.009	0.029	0.038	1.743	0.1	Engineering team leader (n.e.c.)		0.247	0.015	0.047
153.88	153.88	153.89	153.88	153.88	153.88	153.88	153.88	Silica Quartz	169.87	169.86	169.88	169.87	169.9	169.91	169.91	169.91	2.203	2.314	2.259	06:30	14:06	0.04	0.04	0.00	0.010	0.029	0.039	1.030	0.1	Engineering team leader (n.e.c.)		0.247	0.009	0.028
153.88	153.89	153.88	153.88	153.88	153.88	153.88	153.88	Silica Quartz	148.28	148.28	148.28	148.28	148.31	148.3	148.28	148.30	2.2	2.253	2.227	07:13	12:30	0.02	0.02	0.00	0.007	0.021	0.028	0.706	0.1	Engineering team leader (n.e.c.)		0.247	0.005	0.014
153.88	153.89	153.88	153.88	153.87	153.88	153.88	153.88	Silica Quartz	147.55	147.55	147.55	147.55	148.05	148.05	148.06	148.05	2.202	2.308	2.255	05:35	15:38	0.50	0.51	-0.01	0.104	0.271	0.375	1.360	0.1	Engineering team leader (n.e.c.)	0.142	0.278	0.131	0.340
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	165.12	165.13	165.12	165.12	165.18	165.2	165.19	165.19	2.1	2.1	2.100	06:09	14:09	0.07	0.06	0.01	0.017	0.043	0.060	1.008	0.1	Engineering team leader (n.e.c.)	0.017	0.283	0.017	0.043
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	168.17	168.16	168.17	168.17	168.21	168.22	168.22	168.22	2.2	2.2	2.200	06:31	14:31	0.05	0.05	0.00	0.005	0.043	0.047	1.056	0.1	Engineering team leader (n.e.c.)	0.005	0.100	0.005	0.043
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	169.83	169.84	169.84	169.84	169.88	169.89	169.88	169.88	2.1	2.1	2.100	07:06	15:06	0.05	0.04	0.00	0.005	0.038	0.043	1.008	0.1	Engineering team leader (n.e.c.)	0.005	0.115	0.005	0.038
143.42	143.4	143.41	143.41	143.4	143.41	143.4	143.40	Silica Quartz	154.5	154.52	154.5	154.51	154.61	154.61	154.59	154.60	2.203	2.277	2.240	06:04	13:15	0.10	0.10	-0.01	0.020	0.087	0.107	0.965	0.1	Engineering technical worker (n.e.c.)	0.019	0.184	0.018	0.078
143.39	143.4	143.4	143.40	143.4	143.39	143.39	143.39	Silica Quartz	178.19	178.21	178.19	178.20	178.4	178.41	178.4	178.40	2.202	2.195	2.199	06:54	13:36	0.21	0.21	0.00	0.067	0.171	0.238	0.884	0.1	Engineering technician (n.e.c.)	0.059	0.281	0.056	0.143
142.79	142.78	142.79	142.79	142.74	142.76	142.73	142.74	Silica Quartz	155.29	155.3	155.29	155.29	155.54	155.54	155.53	155.54	2.202	2.209	2.206	05:38	16:44	0.24	0.29	-0.04	0.050	0.145	0.195	1.469	0.1	Engineering technician (n.e.c.)	0.074	0.258	0.070	0.201
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	170.13	170.13	170.13	170.13	170.31	170.31	170.31	170.31	2.1	2.2	2.150	05:29	13:29	0.18	0.18	0.00	0.017	0.157	0.174	1.032	0.1	Engineering technician (n.e.c.)	0.018	0.100	0.017	0.157
162.99	162.99	162.99	162.99	162.99	162.99	163	162.99	Silica Quartz	171.24	171.24	171.26	171.25	171.29	171.28	171.32	171.30	2.204	2.283	2.244	07:55	14:30	0.05	0.05	0.00	0.016	0.037	0.053	0.886	0.1	Environmental worker (n.e.c.)	0.014	0.300	0.013	0.030
165.2	165.19	165.2	165.20	165.19	165.19	165.21	165.20	Silica Quartz	157.99	158.01	157.99	158.00	158.35	158.35	158.35	158.35	2.202	2.111	2.157	07:31	16:41	0.35	0.35	0.00	0.099	0.198	0.298	1.186	0.1	Environmental worker (n.e.c.)	0.118	0.334	0.114	0.227
180.54	180.58	180.56	180.56	180.58	180.59	180.58	180.58	Silica Quartz	172.02	172.04	172.03	172.03	172.19	172.19	172.18	172.19	2.214	2.212	2.213	05:37	12:45	0.16	0.13	0.02	0.031	0.110	0.141	0.947	0.1	Environmental worker (n.e.c.)	0.029	0.218	0.027	0.098
159.08	159.09	159.09	159.09	159.1	159.1	159.1	159.10	Silica Quartz	167.91	167.91	167.9	167.91	168.26	168.26	168.26	168.26	2.201	2.243	2.222	06:06	12:44	0.35	0.34	0.01	0.115	0.269	0.384	0.884	0.1	Environmental worker (n.e.c.)	0.102	0.300	0.096	0.223
187.46	187.48	187.47	187.47	187.48	187.47	187.46	187.47	Silica Quartz	162.19	162.18	162.18	162.18	163.21	163.21	163.21	163.21	2.2	2.234	2.217	05:33	14:48	1.03	1.03	0.00	0.028	0.806	0.834	1.230	0.1	Environmental worker (n.e.c.)	0.035	0.034	0.033	0.932
162.99	162.99	162.99	162.99	162.99	162.99	163	162.99	Silica Quartz	159.57	159.57	159.56	159.57	159.9	159.89	159.86	159.88	2.2	2.09	2.145	08:08	17:26	0.32	0.31	0.00	0.079	0.183	0.262	1.197	0.1	Environmental worker (n.e.c.)	0.094	0.300	0.091	0.213
162.99	162.99	162.99	162.99	162.99	162.99	163	162.99	Silica Quartz	152.52	152.53	152.52	152.52	153	152.97	152.99	152.99	2.2	2.198	2.199	07:58	16:57	0.46	0.46	0.00	0.107	0.281	0.388	1.185	0.1	Environmental worker (n.e.c.)	0.127	0.276	0.120	0.315
180.58	180.58	180.58	180.58	180.59	180.6	180.59	180.59	Silica Quartz	157.7	157.71	157.73	157.71	158.08	158.07	158.06	158.07	2.2	2.196	2.198	05:49	13:03	0.36	0.34	0.01	0.069	0.291	0.360	0.954	0.1	Environmental worker (n.e.c.)	0.066	0.192	0.063	0.263
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	161.65	161.64	161.63	161.64	162.17	162.17	162.18	162.17	2.1	2.1	2.100	06:16	13:16	0.53	0.53	0.00	0.205	0.396	0.601	0.882	0.1	Environmental worker (n.e.c.)	0.181	0.342	0.180	0.346
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	138.6	138.6	138.6	138.60	138.83	138.82	138.82	138.82	2.203	2.209	2.206	05:37	16:00	0.22	0.24	-0.01	0.019	0.153	0.172	1.374	0.1	Environmental worker (n.e.c.)	0.026	0.110	0.025	0.199
167.46	167.48	167.47	167.47	167.48	167.48	167.48	167.48	Silica Quartz	169.52	169.52	169.52	169.52	170	170.01	170.01	170.01	2.201	2.218	2.210	06:00	12:51	0.49	0.48	0.01	0.070	0.454	0.525	0.908	0.1	Environmental worker (n.e.c.)	0.064	0.134	0.060	0.389
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	165.87	165.86	165.86	165.86	166.54	166.55	166.54	166.54	2.205	2.234	2.220	05:53	14:04	0.68	0.66	0.02	0.012	0.597	0.609	1.090	0.1	Environmental worker (n.e.c.)	0.013	0.020	0.012	0.610
167.48	167.47	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	156.89	156.89	156.9	156.89	157.08	157.08	157.09	157.08	2.24	2.244	2.242	06:42	13:18	0.19	0.18	0.01	0.037	0.162	0.199	0.888	0.1	Environmental worker (n.e.c.)	0.033	0.187	0.031	0.133
167.47	167.49	167.48	167.48	167.5	167.49	167.48	167.49	Silica Quartz	171.12	171.1	171.1	171.11	171.72	171.73	171.71	171.72	2.203	2.243	2.223	06:08	13:11	0.61	0.60	0.01	0.247	0.395	0.642	0.940	0.1	Environmental worker (n.e.c.)	0.232	0.385	0.217	0.348
159.09	159.1	159.09	159.09	159.1	159.09	159.1	159.10	Silica Quartz	165.08	165.09	165.07	165.08	165.32	165.32	165.31	165.32	2.2	2.253	2.227	06:09	12:30	0.24	0.23	0.00	0.041	0.234	0.275	0.848	0.1	Explosives issuer	0.035	0.150	0.033	0.186
142.79	142.79	142.79	142.79	142.79	142.79	142.75	142.78	Silica Quartz	157.71	157.71	157.71	157.71	157.87	157.87	157.87	157.87	2.201	2.179	2.190	05:28	12:36	0.16	0.17	-0.01	0.053	0.132	0.185	0.937	0.1	Explosives issuer	0.05	0.288	0.048	0.117
153.88	153.9	153.88	153.89	153.87	153.88	153.89	153.88	Silica Quartz	141.41	141.4	141.39	141.40	141.42	141.41	141.41	141.41	2.263	2.172	2.218	06:17	12:15	0.01	0.02	-0.01	0.006	0.019	0.025	0.794	0.1	Fitter and turner	0.005	0.250	0.005	0.014
162.99	162.99	162.99	162.99	163	163.01	163	163.00	Silica Quartz	147.7	147.7	147.7	147.70	147.8	147.79	147.8	147.80	2.201	2.2174	2.209	04:33	13:04	0.10	0.08	0.01	0.026	0.048	0.074	1.129	0.1	Fitter and turner	0.029	0.348	0.027	0.051

RF Pre mass 1	RF Pre mass 2	RF Pre mass 3	RF Premass Avg	RF Post Mass 1	RF Post Mass 2	RF Post Mass 3	RFPostMassAvg	Pollutant	SF Pre Mass 1	SF Pre Mass 2	SF Pre Mass 3	SF Pre Mass Avg	SF Post Mass 1	SF Post Mass 2	SF Post Mass 3	SF Post Mass Avg	Pump Flow Rate Before	Pump Flow Rate After	Avg Pump Flow Rate	Pump Start Time	Pump Stop Time	Sample Mass	Corrected Sample Mass	Correction Factor	Silica Concentration	PNOC Concentration	Sample Concentration	Sample Volume m3	OEL	DMR Occupation Description	Quartz MG	Quarts %	TWA Quarts	TWA PNOC
159.08	159.09	159.09	159.09	159.09	159.09	159.1	159.09	Silica Quartz	156.6	156.61	156.62	156.61	156.63	156.64	156.63	156.63	2.2	2.282	2.241	06:08	12:15	0.02	0.02	0.01	0.006	0.014	0.020	0.822	0.1	Fitter and turner	0.005	0.300	0.005	0.011
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	168.78	168.77	168.77	168.77	169.02	169.02	169.02	169.02	2.2	2.1	2.150	05:57	14:57	0.25	0.24	0.01	0.026	0.181	0.207	1.161	0.1	Fitter and turner	0.03	0.125	0.029	0.203
180.54	180.58	180.56	180.56	180.58	180.59	180.58	180.58	Silica Quartz	177.94	177.94	177.92	177.93	178.05	178.03	178.03	178.04	2.235	2.199	2.217	06:34	13:00	0.10	0.08	0.02	0.016	0.077	0.093	0.856	0.1	General engineering worker (n.e.c.)	0.014	0.175	0.013	0.062
142.79	142.79	142.79	142.79	142.75	142.76	142.75	142.75	Silica Quartz	153.8	153.81	153.81	153.81	154.28	154.29	154.29	154.29	2.2	2.236	2.218	04:43	13:01	0.48	0.52	-0.04	0.082	0.385	0.468	1.105	0.1	General engineering worker (n.e.c.)	0.091	0.176	0.085	0.400
187.47	187.47	187.47	187.47	187.48	187.47	187.46	187.47	Silica Quartz	157.32	157.31	157.31	157.31	157.5	157.5	157.48	157.49	2.209	2.295	2.252	06:04	17:39	0.18	0.18	0.00	0.022	0.093	0.115	1.565	0.1	General engineering worker (n.e.c.)	0.034	0.189	0.031	0.135
159.09	159.1	159.09	159.09	159.09	159.09	159.09	159.09	Silica Quartz	166.83	166.83	166.83	166.83	166.99	167	166.98	166.99	2.203	2.266	2.235	06:29	10:29	0.16	0.16	0.00	0.075	0.229	0.305	0.536	0.1	General miner		0.247	0.038	0.115
159.09	159.1	159.09	159.09	159.09	159.09	159.09	159.09	Silica Quartz	160.56	160.58	160.57	160.57	160.8	160.8	160.8	160.80	2.203	2.24	2.222	06:11	13:53	0.23	0.23	0.00	0.056	0.171	0.227	1.026	0.1	General miner		0.247	0.054	0.165
142.77	142.79	142.79	142.78	142.74	142.76	142.73	142.74	Silica Quartz	160.19	160.2	160.19	160.19	160.39	160.42	160.42	160.41	2.202	2.219	2.211	06:22	13:09	0.22	0.26	-0.04	0.060	0.225	0.285	0.900	0.1	General miner	0.054	0.210	0.051	0.191
142.79	142.78	142.79	142.79	142.77	142.75	142.75	142.76	Silica Quartz	163.39	163.4	163.4	163.40	163.47	163.46	163.47	163.47	2.202	2.214	2.208	04:37	12:04	0.07	0.10	-0.03	0.012	0.089	0.101	0.987	0.1	Haulage team leader/supervisor	0.012	0.120	0.011	0.083
143.41	143.4	143.4	143.40	143.38	143.41	143.39	143.39	Silica Quartz	182.27	182.27	182.28	182.27	182.34	182.33	182.34	182.34	2.2	2.191	2.196	04:52	11:13	0.06	0.07	-0.01	0.024	0.064	0.088	0.836	0.1	Haulage team leader/supervisor	0.02	0.273	0.019	0.051
187.46	187.48	187.47	187.47	187.48	187.48	187.47	187.48	Silica Quartz	159.3	159.32	159.3	159.31	160.72	160.72	160.72	160.72	2.2	2.228	2.214	05:49	13:42	1.41	1.41	0.01	0.756	0.587	1.343	1.047	0.1	Haulage/underground rail transport worker (n.e.c.)	0.792	0.563	0.745	0.578
143.41	143.41	143.41	143.41	143.4	143.39	143.39	143.39	Silica Quartz	169.26	169.28	169.27	169.27	169.64	169.63	169.64	169.64	2.2	2.233	2.217	04:52	11:52	0.37	0.38	-0.02	0.101	0.311	0.412	0.931	0.1	Haulage/underground rail transport worker (n.e.c.)	0.094	0.245	0.088	0.272
162.61	162.62	162.62	162.62	162.62	162.62	162.61	162.62	Silica Quartz	170.06	170.06	170.06	170.06	170.59	170.6	170.59	170.59	2.204	2.173	2.189	05:14	16:56	0.53	0.53	0.00	0.097	0.250	0.347	1.536	0.1	Haulage/underground rail transport worker (n.e.c.)	0.149	0.279	0.142	0.366
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	147.47	147.47	147.45	147.46	147.85	147.85	147.86	147.85	2.201	2.202	2.202	05:39	14:13	0.39	0.38	0.01	0.080	0.253	0.333	1.132	0.1	Haulage/underground rail transport worker (n.e.c.)	0.09	0.239	0.085	0.271
142.78	142.78	142.78	142.78	142.75	142.76	142.75	142.75	Silica Quartz	149.26	149.27	149.26	149.26	149.59	149.59	149.59	149.59	2.281	2.236	2.259	04:47	12:58	0.33	0.35	-0.03	0.117	0.201	0.319	1.109	0.1	Haulage/underground rail transport worker (n.e.c.)	0.13	0.368	0.120	0.206
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	160.39	160.4	160.39	160.39	160.7	160.69	160.71	160.70	2.201	2.225	2.213	05:15	13:36	0.31	0.29	0.02	0.036	0.225	0.262	1.109	0.1	Haulage/underground rail transport worker (n.e.c.)	0.04	0.138	0.038	0.235
153.88	153.89	153.88	153.88	153.88	153.88	153.88	153.88	Silica Quartz	168.43	168.43	168.43	168.43	168.48	168.46	168.45	168.46	2.203	2.211	2.207	12:15	17:38	0.03	0.04	0.00	0.013	0.039	0.051	0.713	0.1	Hoisting worker (n.e.c.)		0.247	0.009	0.026
153.88	153.89	153.88	153.88	153.87	153.88	153.88	153.88	Silica Quartz	158.63	158.62	158.63	158.63	158.73	158.73	158.73	158.73	2.2	2.305	2.253	04:11	17:03	0.10	0.11	-0.01	0.010	0.053	0.063	1.739	0.1	Hoisting worker (n.e.c.)	0.017	0.155	0.016	0.086
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	154.58	154.59	154.59	154.59	156.16	156.15	156.14	156.15	2.203	2.221	2.212	05:47	12:52	1.56	1.58	-0.01	0.057	1.620	1.677	0.940	0.1	Hoisting worker (n.e.c.)	0.054	0.034	0.051	1.434
142.77	142.79	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	168.63	168.62	168.62	168.62	168.96	168.97	168.94	168.96	2.203	2.223	2.213	04:44	13:11	0.33	0.37	-0.03	0.111	0.216	0.327	1.122	0.1	Hoisting worker (n.e.c.)	0.124	0.338	0.117	0.228
142.79	142.78	142.79	142.79	142.74	142.76	142.73	142.74	Silica Quartz	155.59	155.59	155.6	155.59	156.1	156.08	156.12	156.10	2.2	2.21	2.205	07:07	16:11	0.51	0.55	-0.04	0.187	0.272	0.459	1.200	0.1	Hoisting worker (n.e.c.)	0.224	0.407	0.212	0.308
162.99	162.99	162.99	162.99	162.99	162.99	163	162.99	Silica Quartz	149.87	149.86	149.87	149.87	149.94	149.93	149.94	149.94	2.2	2.222	2.211	12:07	20:09	0.07	0.07	0.00	0.016	0.047	0.063	1.066	0.1	Hoisting worker (n.e.c.)	0.017	0.255	0.016	0.047
143.42	143.4	143.41	143.41	143.4	143.39	143.42	143.40	Silica Quartz	167.3	167.31	167.3	167.30	167.89	167.89	167.89	167.89	2.235	2.22	2.228	06:54	17:18	0.59	0.59	-0.01	0.135	0.292	0.427	1.390	0.1	Hoisting worker (n.e.c.)	0.187	0.315	0.175	0.380
163.02	163	163	163.01	163.01	163.01	163.01	163.01	Silica Quartz	162.44	162.44	162.44	162.44	162.63	162.63	162.64	162.63	2.2	2.204	2.202	05:38	13:01	0.19	0.19	0.00	0.034	0.161	0.195	0.975	0.1	Hoisting worker (n.e.c.)	0.033	0.174	0.031	0.149
167.47	167.48	167.48	167.48	167.49	167.48	167.49	167.49	Silica Quartz	167.12	167.12	167.13	167.12	167.23	167.26	167.25	167.25	2.215	2.174	2.195	04:58	13:06	0.12	0.11	0.01	0.049	0.057	0.106	1.071	0.1	Hoisting worker (n.e.c.)	0.052	0.459	0.049	0.058
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	164.8	164.81	164.8	164.80	164.88	164.86	164.86	164.87	2.205	2.188	2.197	04:11	12:15	0.06	0.05	0.02	0.016	0.028	0.044	1.063	0.1	Hoisting worker (n.e.c.)	0.017	0.364	0.016	0.028
142.77	142.79	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	165.88	165.89	165.88	165.88	166.19	166.2	166.21	166.20	2.201	2.269	2.235	05:05	13:35	0.32	0.35	-0.03	0.080	0.227	0.307	1.140	0.1	Hoisting worker (n.e.c.)	0.091	0.260	0.085	0.241
180.58	180.58	180.58	180.58	180.61	180.6	180.58	180.60	Silica Quartz	170.83	170.85	170.84	170.84	171.03	171.06	171.05	171.05	2.227	2.179	2.203	05:50	13:09	0.21	0.19	0.02	0.056	0.141	0.196	0.967	0.1	Hoisting worker (n.e.c.)	0.054	0.284	0.051	0.129
143.42	143.4	143.41	143.41	143.4	143.41	143.4	143.40	Silica Quartz	163.72	163.73	163.72	163.72	163.84	163.84	163.83	163.84	2.201	2.227	2.214	06:02	13:15	0.11	0.12	-0.01	0.040	0.086	0.125	0.959	0.1	Hoisting worker (n.e.c.)	0.038	0.317	0.036	0.077
159.08	159.1	159.08	159.09	159.1	159.1	159.1	159.10	Silica Quartz	164.2	164.21	164.2	164.20	164.47	164.47	164.47	164.47	2.203	2.231	2.217	05:32	13:28	0.27	0.25	0.01	0.076	0.164	0.240	1.055	0.1	Hoisting worker (n.e.c.)	0.08	0.316	0.075	0.163
159.08	159.09	159.09	159.09	159.08	159.1	159.1	159.09	Silica Quartz	161.28	161.28	161.27	161.28	161.47	161.47	161.48	161.47	2.202	2.204	2.203	05:18	13:28	0.20	0.19	0.01	0.039	0.137	0.176	1.079	0.1	Hoisting worker (n.e.c.)	0.042	0.221	0.040	0.140
159.08	159.09	159.09	159.09	159.08	159.1	159.1	159.09	Silica Quartz	170.79	170.81	170.78	170.79	171.13	171.13	171.13	171.13	2.203	2.233	2.218	05:17	16:58	0.34	0.33	0.01	0.066	0.146	0.212	1.555	0.1	Hoisting worker (n.e.c.)	0.103	0.312	0.097	0.213
187.46	187.48	187.47	187.47	187.48	187.48	187.47	187.48	Silica Quartz	151.14	151.14	151.15	151.14	151.25	151.24	151.25	151.25	2.2	2.178	2.189	05:31	12:49	0.10	0.10	0.01	0.028	0.073	0.101	0.959	0.1	Hoisting worker (n.e.c.)	0.027	0.279	0.026	0.066
142.78	142.78	142.78	142.78	142.79	142.79	142.75	142.78	Silica Quartz	133.73	133.72	133.72	133.72	133.99	134	134	134.00	2.2	2.214	2.207	06:10	13:20	0.27	0.28	0.00	0.111	0.181	0.292	0.949	0.1	Hoisting worker (n.e.c.)	0.105	0.380	0.099	0.162
167.47	167.48	167.48	167.48	167.49	167.48	167.49	167.49	Silica Quartz	169.32	169.33	169.33	169.33	169.59	169.6	169.59	169.59	2.194	2.192	2.193	05:27	17:35	0.27	0.26	0.01	0.091	0.069	0.161	1.597	0.1	Hoisting worker (n.e.c.)	0.146	0.569	0.139	0.105
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	176.25	176.27	176.27	176.26	176.46	176.44	176.45	176.45	2.209	2.237	2.223	05:41	12:52	0.19	0.17	0.02	0.053	0.124	0.177	0.958	0.1	Hoisting worker (n.e.c.)	0.051	0.300	0.048	0.112
143.39	143.4	143.4	143.40	143.38	143.41	143.39	143.39	Silica Quartz	178.01	178.02	178.03	178.02	178.15	178.17	178.17	178.16	2.203	2.155	2.179	05:56	16:34	0.14	0.15	0.00	0.020	0.085	0.106	1.390	0.1	Instrument technician	0.028	0.191	0.027	0.113
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	168.43	168.43	168.43	168.43	168.62	168.61	168.62	168.62	2.1	2.2	2.150	06:31	14:31	0.19	0.18	0.00	0.082	0.095	0.178	1.032	0.1	Instrument technician	0.085	0.464	0.082	0.095
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	172.79	172.8	172.79	172.79	172.95	172.94	172.94	172.94	2.2	2.195	2.198	05:33	13:41	0.15	0.13	0.02	0.028	0.096	0.124	1.072	0.1	Instrument technician	0.03	0.225	0.028	0.098
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	143.06	143.07	143.06	143.06	143.08	143.07	143.08	143.08	2.201	2.22	2.211	07:09	13:23	0.01	0.00	0.01	0.006	-0.002	0.004	0.827	0.1	Lamp room worker	0.005	1.500	0.005	-0.002
143.39	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	167.03	167.03	167.02	167.03	167.05	167.07	167.06	167.06	2.203	2.174	2.189	07:18	14:50	0.03	0.03	0.00	0.005	0.025	0.030	0.989	0.1	Lamp room worker	0.005	0.167	0.005	0.024
187.46	187.48	187.47	187.47	187.47	187.48	187.48	187.48	Silica Quartz	155.15	155.14	155.14	155.14	155.15	155.15	155.15	155.15	2.203	2.228	2.216	06:34	17:14	0.01	0.00	0.01	0.000	0.000	0.000	1.418	0.1	Lamp room worker	0	0.247	0.000	0.000
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	166.25	166.24	166.25	166.25	166.28	166.27	166.27	166.27	2.1	2.1	2.100	05:40	13:40	0.03	0.02	0.00	0.005	0.018	0.023	1.008	0.1	Lampsman	0.005	0.214	0.005	0.018
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	154.78	154.82	154.81	154.80	155.66	155.65	155.65	155.65	2.27	2.223	2.247	07:02	16:20	0.85	0.86	-0.01	0.385	0.304	0.689	1.254	0.1	Load haul dump driver	0.482	0.558	0.447	0.354
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	166.19	166.19	166.2	166.19	166.31	166.3	166.3	166.30	2.201	2.233	2.217	05:41	12:20	0.11	0.10	0.01	0.015	0.098	0.113	0.885	0.1	Load haul dump driver	0.013	0.130	0.012	0.082
143.42	143.41	143.41	143.41	143.38	143.41	143.39	143.39	Silica Quartz	172.17	172.18	172.19	172.18	172.3	172.31	172.32	172.31	2.205	2.181	2.193	05:57	13:18	0.13	0.15	-0.02	0.017	0.139	0.155	0.967	0.1	Load haul dump driver	0.016	0.107	0.015	0.127
142.78	142.78	142.78	142.78	142.79	142.79	142.75	142.78	Silica Quartz	157.65	157.66	157.65	157.65	158.29	158.3	158.3	158.30	2.201	2.236	2.219	06:21	17:24	0.64	0.65	0.00	0.067	0.372	0.440	1.471	0.1	Load haul dump driver	0.099	0.153	0.093	0.514
153.88	153.89	153.88	153.88	153.9	153.88	153.89	153.89	Silica Quartz	166.14	166.14	166.13	166.14	166.42	166.42	166.42	166.42	2.201	2.238	2.220	04:56	11:17	0.28	0.28	0.01	0.045	0.282	0.327	0.846	0.1	Mine construction team leader/supervisor (n.e.c.)	0.038	0.137	0.036	0.224
142.79	142.78	142.79	142.79	142.74	142.76	142.73	142.74	Silica Quartz	157.85	157.85	157.87	157.86	158.18	158.19	158.19	158.19	2.206	2.22	2.213	04:34	16:30	0.33	0.37	-0.04	0.066	0.169	0.236	1.585	0.1	Mine construction team leader/supervisor (n.e.c.)	0.105	0.281	0.099	0.253
180.58	180.58	180.58	180.58	180.6	180.59	180.58	180.59	Silica Quartz	157.01	157.01	157.01	157.01	157.14	157.14	157.13	157.14	2.205	2.183	2.194	06:31	14:00	0.13	0.12	0.01	0.013	0.105	0.118	0.985	0.1	Mine construction team leader/supervisor (n.e.c.)	0.013	0.111	0.012	0.098
180.57	180.58	180.58	180.58	180.58	180.59	180.58	180.58	Silica Quartz	180.26	180.27	180.26	180.26	180.36	180.39	180.36	180.37	2.2	2.211	2.206	05:57	17:35	0.11	0.10	0.01	0.017	0.048	0.065	1.539	0.1	Mine construction team leader/supervisor (n.e.c.)	0.026	0.260	0.025	0.070
180.54	180.58	180.56	180.56	180.59	180.58	180.59	180.59	Silica Quartz	179.67	179.66	179.67	179.67	179.77	179.76	179.76	179.76	2.2	2.206	2.203	07:07	19:15	0.10	0.07	0.03	0.012	0.031	0.044	1.604	0.1	Mine police/security guard	0.02	0.286	0.019	0.047
143.39	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	178.05	178.06	178.05	178.05	178.06	178.07	178.08	178.07	2.2	2.23	2.215	07:28	13:00	0.02	0.01	0.00	0.007	0.011	0.018	0.735	0.1	Mine police/security guard	0.005	0.375	0.005	0.008
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	156.79	156.78	156.79	156.79	156.87	156.88	156.88	156.88	2.2	2.2	2.200	06:00	14:00	0.09	0.09	0.00	0.013	0.072	0.085	1.056	0.1	Mine police/security guard	0.014	0.156	0.013	0.072
153.88	153.89	153.88	153.88	153.87	153.88	153.88	153.88	Silica Quartz	161.9	161.9	161.91	161.90	162.36	162.36	162.37	162.36	2.202	2.3	2.251	06:14	14:07	0.46	0.47	-0.01	0.099	0.340	0.438	1.065	0.1	Miner's assistant (cheesa)	0.105	0.225	0.097	0.335
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	180.01	180.01	179.98	180.00	180.38	180.38	180.38	180.38	2.2	2.2	2.200	05:47	13:47	0.38	0.37	0.01	0.078	0.276	0.354	1.056	0.1	Miner's assistant (cheesa)	0.082	0.220	0.078	0.276
163	163	163	163.00	162.99	163	162.99	162.99	Silica Quartz	152.05	152.04	152.05	152.05	152.42	152.41	152.41	152.41	2.201	2.266	2.234	04:48	16:18	0.37	0.37	-0.01	0.049	0.194	0.242	1.541	0.1	Miner's assistant (cheesa)	0.075	0.201	0.070	0.278
167.47	167.49	167.48	167.48	167.49	167.47	167.51	167.49	Silica Quartz	170.69	170.67	170.69	170.68	170.95	170.95	170.95	170.95	2.205	2.214	2.210	06:00	12:53	0.27	0.26	0.01	0.106	0.175	0.281	0.913	0.1	Miner's assistant (cheesa)	0.097	0.378	0.091	0.151
167.47	167.48	167.48	167.48	167.48	167.48	167.48	167.48	Silica Quartz	163.42	163.41	163.42	163.42	163.61	163.61	163.6	163.61	2.207	2.208	2.208	06:36	13:08	0.19	0.19	0.00	0.030	0.186	0.216	0.865	0.1	Miner's assistant (cheesa)	0.026	0.139	0.025	0.152
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	169.87	169.86	169.86	169.86	170.27	170.28	170.27	170.27	2.201	2.22	2.211	04:36	12:41	0.41	0.42	-0.01	0.049	0.346	0.395	1.072	0.1	Miner's assistant (cheesa)	0.052	0.123	0.049	0.350
180.58	180.58	180.58	180.58	180.59	180.6	180.59	180.59	Silica Quartz	175.6	175.61	175.61	175.61	176.16	176.16	176.15	176.16	2.203	2.173	2.188	06:09	16:47	0.55	0.54	0.01	0.093	0.291	0.384	1.396	0.1	Miner's assistant (cheesa)	0.13	0.242	0.124	0.387
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	159.95	159.95	159.96	159.95	160.25	160.27	160.27	160.26	2.2	2.207	2.204	06:12	14:29	0.31	0.30	0.01	0.067	0.204	0.271	1.095	0.1	Miner's assistant (cheesa)	0.073	0.246	0.069	0.211
180.54	180.58	180.56	180.56	180.58	180.59	180.58	180.58	Silica Quartz	181.36	181.35	181.34	181.35	181.5	181.49	181.48	181.49	2.205	2.204	2.205	05:06	12:15	0.14	0.12	0.02	0.058	0.065	0.123	0.946	0.1	Monorail winch operator	0.055	0.471	0.052	0.058
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	158.29	158.28	158.28	158.28	158.37	158.38	158.38	158.38	2.2	2.2	2.200	06:47	14:47	0.09	0.09	0.00	0.019	0.069	0.088	1.056	0.1	Nurse (enrolled/staff)	0.02	0.214	0.019	0.069
187.46	187.48	187.47	187.47	187.47	187.48	187.48	187.48	Silica Quartz	144.94	144.95	144.93	144.94	144.96	144.95	144.96	144.96	2.205	2.193	2.199	06:08	13:45	0.02	0.01	0.01	0.005	0.005	0.010	1.005	0.1	Nursing assistant	0.005	0.500	0.005	0.005
143.39	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	170.5	170.51	170.51	170.51	170.54	170.55	170.53	170.54	2.202	2.301	2.252	07:11	20:31	0.03	0.03	0.00	0.003	0.014	0.017	1.801	0.1	Personnel assistant/masiza	0.005	0.167	0.005	0.023
180.54	180.58	180.56	180.56	180.59	180.58	180.59	180.59	Silica Quartz	179.92	179.96	179.95	179.94	180	180.01	180.01	180.01	2.2	2.214	2.207	07:02	13:30	0.06	0.04	0.03	0.006	0.037	0.043	0.856	0.1	Pharmaceutical worker (n.e.c.)	0.005	0.136	0.005	0.030
153.88	153.9	153.88	153.89	153.87	153.88	153.88	153.88	Silica Quartz	157.48	157.48	157.49	157.48	158.1	158.1	158.09	158.10	2.201	2.225	2.213	04:39	12:26	0.61	0.62	-0.01	0.089	0.514	0.603	1.033	0.1	Pipes and tracks worker	0.092	0.148	0.087	0.500
165.2	165.19	165.2	165.20	165.19	165.19	165.19	165.19	Silica Quartz	148.62	148.61	148.61	148.61	148.86	148.87	148.84	148.86	2.203	2.244	2.224	04:45	13:00	0.24	0.25	-0.01	0.116	0.111	0.227	1.101	0.1	Pipes and tracks worker	0.128	0.512	0.120	0.114
167.48	167.47	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	172.52	172.53	172.52	172.52	172.64	172.63	172.64	172.64	2.175	2.184	2.180	05:20	13:43	0.11	0.10	0.01	0.011	0.080	0.091	1.096	0.1	Pipes and tracks worker	0.012	0.120	0.011	0.084
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	149.99	149.96	149.97	149.97	150.34	150.36	150.35	150.35	2.205	2.202	2.204	06:11	14:37	0.38	0.37	0.01	0.030	0.299	0.329	1.115	0.1	Plater/boilermaker	0.033	0.090	0.031	0.315
178.38	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	166.77	166.77	166.78	166.77	166.94	166.94	166.95	166.94	2.1	2.1	2.100	05:47	14:47	0.17	0.17	0.00	0.010	0.137	0.147	1.134	0.1	Plater/boilermaker	0.011	0.066	0.011	0.154
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	153.28	153.28	153.28	153.28	153.48	153.5	153.5	153.49	2.205	2.216	2.211	06:48	17:20	0.21	0.23	-0.01	0.047	0.116	0.162	1.397	0.1	Plater/boilermaker	0.065	0.287	0.061	0.152
159.09	159.1	159.09	159.09	159.09	159.09	159.1	159.09	Silica Quartz	157.9	157.9	157.91	157.90	158.55	158.54	158.52	158.54	2.203	2.193	2.198	04:33	16:04	0.63	0.63	0.00	0.068	0.349	0.417	1.519	0.1	Pump worker	0.103	0.163	0.098	0.503
153.88	153.9	153.88	153.89	153.88	153.88	153.88	153.88	Silica Quartz	145.24	145.24	145.23	145.24	145.36	145.35	145.35	145.35	2.202	2.201	2.202	12:13	18:30	0.12	0.12	-0.01	0.037	0.112	0.149	0.830	0.1	Pump worker		0.247	0.029	0.088
153.88	153.88	153.89	153.88	153.88	153.88	153.89	153.88	Silica Quartz	150.08	150.08	150.07	150.08	150.15	150.14	150.13	150.14	2.203	2.2	2.202	11:58	19:01	0.06	0.06	0.00	0.017	0.051	0.068	0.931	0.1	Pump worker		0.247	0.015	0.045
165.2	165.19	165.2	165.20	165.19	165.19	165.21	165.20	Silica Quartz	172.98	173	172.97	172.98	173.24	173.24	173.25	173.24	2.205	2.243	2.224	06:56	17:18	0.26	0.26	0.00	0.065	0.123	0.188	1.383	0.1	Pump worker	0.09	0.346	0.084	0.159
143.42	143.4	143.41	143.41	143.4	143.39	143.42	143.40	Silica Quartz	171.29	171.29	171.29	171.29	171.4	171.4	171.4	171.40	2.248	2.26	2.254	07:04	13:30	0.11	0.12	-0.01	0.043	0.092	0.134	0.870	0.1	Pump worker	0.037	0.317	0.034	0.074
142.77	142.79	142.79	142.78	142.74	142.76	142.73	142.74	Silica Quartz	157.46	157.46	157.46	157.46	157.61	157.6	157.6	157.60	2.201	2.222	2.212	07:08	14:25	0.14	0.18	-0.04	0.031	0.159	0.190	0.966	0.1	Pump worker	0.03	0.164	0.028	0.144
143.41	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	170.1	170.1	170.08	170.09	170.3	170.31	170.3	170.30	2.296	2.226	2.261	07:21	13:31	0.21	0.21	0.00	0.026	0.229	0.255	0.837	0.1	Pump worker	0.022	0.103	0.020	0.176
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	159.22	159.23	159.23	159.23	159.66	159.67	159.65	159.66	2.201	2.22	2.211	04:41	14:21	0.43	0.42	0.01	0.056	0.271	0.328	1.282	0.1	Pump worker	0.072	0.171	0.068	0.328
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	161.18	161.18	161.17	161.18	161.61	161.62	161.62	161.62	2.208	2.23	2.219	04:21	13:04	0.44	0.42	0.02	0.083	0.282	0.365	1.161	0.1	Pump worker	0.096	0.227	0.090	0.307
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	159.96	159.95	159.95	159.95	160.19	160.18	160.19	160.19	2.2	2.2	2.200	05:06	13:06	0.23	0.23	0.00	0.101	0.120	0.221	1.056	0.1	Pump worker	0.107	0.459	0.101	0.120
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	177.25	177.23	177.23	177.24	177.37	177.37	177.36	177.37	2.207	2.24	2.224	04:40	12:39	0.13	0.11	0.02	0.027	0.079	0.106	1.065	0.1	Pump worker	0.029	0.256	0.027	0.079
142.79	142.78	142.79	142.79	142.77	142.75	142.75	142.76	Silica Quartz	156.5	156.51	156.51	156.51	156.94	156.94	156.93	156.94	2.2	2.2161	2.208	04:32	17:19	0.43	0.46	-0.03	0.101	0.171	0.272	1.694	0.1	Pump worker	0.171	0.372	0.161	0.273
142.79	142.78	142.79	142.79	142.77	142.75	142.75	142.76	Silica Quartz	162.29	162.29	162.29	162.29	162.47	162.48	162.48	162.48	2.203	2.294	2.249	04:36	12:00	0.19	0.22	-0.03	0.065	0.152	0.217	0.998	0.1	Pump worker	0.065	0.300	0.060	0.141
167.47	167.48	167.48	167.48	167.48	167.48	167.48	167.48	Silica Quartz	159.83	159.84	159.85	159.84	160.08	160.08	160.08	160.08	2.202	2.208	2.205	04:53	14:01	0.24	0.24	0.00	0.055	0.140	0.196	1.208	0.1	Pump worker	0.067	0.283	0.063	0.160
159.09	159.1	159.09	159.09	159.09	159.09	159.09	159.09	Silica Quartz	161.64	161.62	161.64	161.63	161.89	161.9	161.9	161.90	2.203	2.201	2.202	04:49	10:44	0.26	0.27	0.00	0.084	0.257	0.341	0.782	0.1	Refrigeration plant operator		0.247	0.062	0.190

RF Pre mass 1	RF Pre mass 2	RF Pre mass 3	RF Premass Avg	RF Post Mass 1	RF Post Mass 2	RF Post Mass 3	RFPostMassAvg	Pollutant	SF Pre Mass 1	SF Pre Mass 2	SF Pre Mass 3	SF Pre Mass Avg	SF Post Mass 1	SF Post Mass 2	SF Post Mass 3	SF Post Mass Avg	Pump Flow Rate Before	Pump Flow Rate After	Avg Pump Flow Rate	Pump Start Time	Pump Stop Time	Sample Mass	Corrected Sample Mass	Correction Factor	Silica Concentration	PNOC Concentration	Sample Concentration	Sample Volume m3	OEL	DMR Occupation Description	Quartz MG	Quarts %	TWA Quarts	TWA PNOC
153.88	153.9	153.88	153.89	153.87	153.88	153.88	153.88	Silica Quartz	170.4	170.39	170.39	170.39	170.57	170.6	170.57	170.58	2.201	2.279	2.240	05:50	15:49	0.19	0.20	-0.01	0.037	0.110	0.147	1.342	0.1	Refrigeration plant operator	0.049	0.249	0.046	0.137
142.78	142.77	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	127.31	127.31	127.29	127.30	127.51	127.52	127.52	127.52	2.2	2.215	2.208	04:44	12:11	0.21	0.24	-0.03	0.096	0.150	0.247	0.987	0.1	Refrigeration plant operator	0.095	0.390	0.090	0.140
143.41	143.4	143.4	143.40	143.4	143.41	143.4	143.40	Silica Quartz	152.32	152.3	152.33	152.32	152.37	152.37	152.38	152.37	2.244	2.233	2.239	07:31	18:03	0.06	0.06	0.00	0.004	0.037	0.040	1.415	0.1	Refrigeration plant operator	0.005	0.088	0.005	0.048
142.79	142.79	142.79	142.79	142.8	142.8	142.76	142.79	Silica Quartz	147.38	147.38	147.37	147.38	147.66	147.68	147.67	147.67	2.202	2.171	2.187	04:51	14:37	0.29	0.30	0.00	0.030	0.201	0.232	1.281	0.1	Refrigeration plant operator	0.039	0.131	0.037	0.246
142.79	142.78	142.79	142.79	142.77	142.75	142.75	142.76	Silica Quartz	161.71	161.71	161.69	161.70	161.92	161.92	161.92	161.92	2.204	2.281	2.243	05:36	12:59	0.22	0.25	-0.03	0.040	0.208	0.248	0.993	0.1	Rigger and ropeman	0.04	0.162	0.037	0.192
187.46	187.44	187.45	187.45	187.47	187.46	187.47	187.47	Silica Quartz	141.44	141.45	141.44	141.44	141.56	141.56	141.56	141.56	2.202	2.152	2.177	05:22	13:43	0.12	0.10	0.02	0.017	0.074	0.092	1.091	0.1	Sample worker	0.019	0.190	0.018	0.078
142.78	142.77	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	156.34	156.35	156.33	156.34	156.58	156.58	156.58	156.58	2.2	2.202	2.201	06:29	13:09	0.24	0.27	-0.03	0.125	0.182	0.307	0.880	0.1	Sanitation worker	0.11	0.407	0.104	0.151
159.08	159.1	159.08	159.09	159.09	159.09	159.1	159.09	Silica Quartz	155.81	155.79	155.78	155.79	155.96	155.97	155.97	155.97	2.203	2.307	2.255	06:24	12:56	0.17	0.17	0.01	0.066	0.123	0.189	0.884	0.1	Sanitation worker	0.058	0.348	0.054	0.100
167.48	167.47	167.47	167.47	167.5	167.49	167.48	167.49	Silica Quartz	152.99	152.99	153	152.99	153.27	153.28	153.28	153.28	2.204	2.23	2.217	06:36	12:41	0.28	0.27	0.02	0.106	0.223	0.330	0.809	0.1	Sanitation worker	0.086	0.323	0.081	0.170
143.41	143.4	143.4	143.40	143.4	143.4	143.41	143.40	Silica Quartz	158.21	158.23	158.22	158.22	158.61	158.62	158.61	158.61	2.201	2.11	2.156	06:48	18:22	0.39	0.39	0.00	0.037	0.226	0.263	1.496	0.1	Self-propelled machine driver (n.e.c.)	0.055	0.140	0.053	0.327
143.41	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	177.12	177.13	177.13	177.13	177.36	177.37	177.35	177.36	2.256	2.201	2.229	08:10	17:38	0.23	0.24	0.00	0.027	0.160	0.187	1.266	0.1	Self-propelled machine driver (n.e.c.)	0.034	0.144	0.032	0.189
143.42	143.4	143.41	143.41	143.4	143.4	143.41	143.40	Silica Quartz	174.28	174.29	174.29	174.29	174.45	174.45	174.41	174.44	2.206	2.129	2.168	05:37	12:52	0.15	0.16	-0.01	0.032	0.134	0.166	0.943	0.1	Self-propelled machine driver (n.e.c.)	0.03	0.191	0.029	0.122
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	158.32	158.32	158.32	158.32	158.89	158.89	158.88	158.89	2.208	2.213	2.211	07:18	19:00	0.57	0.55	0.01	0.108	0.249	0.357	1.552	0.1	Self-propelled machine driver (n.e.c.)	0.167	0.302	0.157	0.364
142.78	142.78	142.78	142.78	142.75	142.76	142.75	142.75	Silica Quartz	162.19	162.2	162.2	162.20	162.38	162.37	162.38	162.38	2.205	2.239	2.222	07:07	14:27	0.18	0.21	-0.03	0.010	0.201	0.211	0.978	0.1	Self-propelled machine driver (n.e.c.)	0.01	0.048	0.009	0.184
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	171.85	171.85	171.83	171.84	172.22	172.22	172.2	172.21	2.205	2.203	2.204	06:00	15:07	0.37	0.35	0.02	0.051	0.242	0.293	1.206	0.1	Self-propelled machine driver (n.e.c.)	0.061	0.173	0.058	0.276
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	172.5	172.5	172.51	172.50	172.56	172.59	172.59	172.58	2.202	2.222	2.212	05:16	13:12	0.08	0.09	-0.01	0.022	0.064	0.085	1.053	0.1	Shaft timberman worker	0.023	0.256	0.022	0.063
143.39	143.4	143.4	143.40	143.38	143.41	143.39	143.39	Silica Quartz	168.81	168.82	168.83	168.82	168.87	168.86	168.86	168.86	2.201	2.203	2.202	04:51	11:41	0.04	0.05	0.00	0.018	0.034	0.052	0.903	0.1	Shaft timberman worker	0.016	0.343	0.015	0.029
142.77	142.79	142.79	142.78	142.74	142.76	142.73	142.74	Silica Quartz	161.34	161.35	161.35	161.35	161.56	161.56	161.59	161.57	2.201	2.227	2.214	05:24	13:15	0.22	0.26	-0.04	0.073	0.180	0.253	1.043	0.1	Shaft timberman/timberman	0.076	0.289	0.072	0.176
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	171.77	171.78	171.79	171.78	172.03	172.04	172.04	172.04	2.204	2.251	2.228	04:12	12:43	0.26	0.25	0.01	0.061	0.156	0.217	1.138	0.1	Slimes dam team leader/supervisor	0.069	0.280	0.065	0.166
162.99	162.99	162.99	162.99	162.99	162.99	163	162.99	Silica Quartz	162.37	162.36	162.36	162.36	162.4	162.39	162.4	162.40	2.202	2.233	2.218	07:05	13:44	0.03	0.03	0.00	0.006	0.028	0.034	0.885	0.1	Slimes dam team leader/supervisor	0.005	0.167	0.005	0.023
162.99	162.99	162.99	162.99	162.99	162.99	163	162.99	Silica Quartz	160.59	160.61	160.62	160.61	160.78	160.78	160.79	160.78	2.2	2.278	2.239	12:12	19:15	0.18	0.17	0.00	0.057	0.126	0.183	0.947	0.1	Slimes dam team leader/supervisor	0.054	0.312	0.050	0.111
162.61	162.62	162.62	162.62	162.6	162.61	162.62	162.61	Silica Quartz	170.4	170.41	170.41	170.41	170.48	170.5	170.5	170.49	2.201	2.171	2.186	05:26	13:21	0.09	0.09	-0.01	0.015	0.074	0.090	1.038	0.1	Slimes dam team leader/supervisor	0.016	0.171	0.015	0.074
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	178.77	178.75	178.77	178.76	178.85	178.86	178.85	178.85	2.1	2.1	2.100	05:08	13:08	0.09	0.09	0.00	0.026	0.063	0.089	1.008	0.1	Slimes dam team leader/supervisor	0.026	0.289	0.026	0.063
167.46	167.48	167.47	167.47	167.48	167.48	167.48	167.48	Silica Quartz	171.56	171.56	171.57	171.56	171.77	171.78	171.78	171.78	2.206	2.223	2.215	04:52	12:46	0.21	0.20	0.01	0.068	0.126	0.194	1.050	0.1	Slimes dam team leader/supervisor	0.071	0.349	0.067	0.124
187.46	187.48	187.47	187.47	187.47	187.48	187.48	187.48	Silica Quartz	157.58	157.58	157.58	157.58	157.62	157.63	157.62	157.62	2.2	2.219	2.210	06:33	14:30	0.04	0.04	0.01	0.005	0.030	0.035	1.054	0.1	Social worker	0.005	0.136	0.005	0.030
178.4	178.41	178.4	178.40	178.41	178.41	178.41	178.41	Silica Quartz	174.08	174.08	174.07	174.08	174.64	174.65	174.64	174.64	2.1	2.2	2.150	05:50	13:50	0.57	0.56	0.01	0.172	0.371	0.543	1.032	0.1	Spannerman/driller's assistant	0.177	0.316	0.172	0.371
163.02	163	163	163.01	162.99	163	162.99	162.99	Silica Quartz	142.27	142.28	142.28	142.28	142.59	142.58	142.59	142.59	2.201	2.212	2.207	06:39	16:00	0.31	0.32	-0.01	0.078	0.184	0.261	1.238	0.1	Spannerman/driller's assistant	0.096	0.297	0.091	0.215
167.46	167.48	167.47	167.47	167.48	167.48	167.48	167.48	Silica Quartz	163.15	163.15	163.15	163.15	163.96	163.96	163.97	163.96	2.202	2.186	2.194	05:52	16:40	0.81	0.80	0.01	0.203	0.362	0.565	1.422	0.1	Spannerman/driller's assistant	0.288	0.359	0.273	0.489
162.99	162.99	162.99	162.99	162.99	163.01	163	163.00	Silica Quartz	169.8	169.76	169.79	169.78	169.82	169.83	169.84	169.83	2.201	2.232	2.217	07:02	15:30	0.05	0.04	0.01	0.004	0.028	0.033	1.126	0.1	Spannerman/driller's assistant	0.005	0.136	0.005	0.030
142.77	142.79	142.79	142.78	142.75	142.76	142.76	142.76	Silica Quartz	162.71	162.73	162.71	162.72	163.09	163.1	163.08	163.09	2.203	2.218	2.211	05:09	14:26	0.37	0.40	-0.03	0.044	0.281	0.325	1.231	0.1	Stope team leader/supervisor	0.054	0.135	0.051	0.326
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	168.7	168.7	168.69	168.70	169.13	169.13	169.15	169.14	2.207	2.212	2.210	06:07	14:14	0.44	0.42	0.02	0.090	0.303	0.393	1.076	0.1	Stope team leader/supervisor	0.097	0.229	0.091	0.308
153.88	153.88	153.89	153.88	153.87	153.88	153.89	153.88	Silica Quartz	167.86	167.85	167.87	167.86	168.14	168.14	168.15	168.14	2.202	2.199	2.201	07:33	14:27	0.28	0.29	0.00	0.132	0.183	0.315	0.911	0.1	Stope team worker	0.12	0.419	0.114	0.158
142.78	142.77	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	161.37	161.37	161.37	161.37	161.57	161.56	161.58	161.57	2.201	2.233	2.217	06:04	12:05	0.20	0.23	-0.03	0.039	0.249	0.287	0.800	0.1	Stope team worker	0.031	0.135	0.029	0.187
142.77	142.79	142.79	142.78	142.75	142.76	142.76	142.76	Silica Quartz	157.39	157.39	157.37	157.38	157.73	157.74	157.73	157.73	2.2	2.231	2.216	05:45	13:17	0.35	0.38	-0.03	0.066	0.310	0.376	1.001	0.1	Stope team worker	0.066	0.175	0.062	0.292
159.08	159.1	159.08	159.09	159.1	159.1	159.1	159.10	Silica Quartz	166.15	166.15	166.16	166.15	166.25	166.24	166.24	166.24	2.204	2.252	2.228	06:27	12:43	0.09	0.08	0.01	0.023	0.069	0.092	0.838	0.1	Stope team worker	0.019	0.248	0.018	0.054
159.08	159.09	159.09	159.09	159.1	159.1	159.1	159.10	Silica Quartz	166.01	166	165.99	166.00	166.48	166.47	166.47	166.47	2.203	2.26	2.232	06:03	14:13	0.47	0.46	0.01	0.097	0.324	0.421	1.093	0.1	Stope team worker	0.106	0.230	0.099	0.330
159.08	159.09	159.09	159.09	159.1	159.1	159.1	159.10	Silica Quartz	163.26	163.27	163.27	163.27	163.49	163.49	163.49	163.49	2.203	2.156	2.180	05:50	13:54	0.22	0.21	0.01	0.020	0.179	0.199	1.055	0.1	Stope team worker	0.021	0.100	0.020	0.181
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	168.95	168.95	168.94	168.95	169.29	169.29	169.28	169.29	2.2	2.2	2.200	05:58	13:58	0.34	0.34	0.00	0.037	0.285	0.322	1.056	0.1	Stope team worker	0.039	0.115	0.037	0.285
167.46	167.48	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	173.79	173.79	173.79	173.79	173.97	173.98	173.98	173.98	2.214	2.249	2.232	05:56	12:36	0.19	0.17	0.02	0.043	0.148	0.190	0.893	0.1	Stope team worker	0.038	0.224	0.035	0.123
167.46	167.48	167.47	167.47	167.49	167.48	167.49	167.49	Silica Quartz	167.73	167.73	167.73	167.73	168.21	168.21	168.22	168.21	2.202	2.23	2.216	05:47	13:36	0.48	0.47	0.02	0.058	0.391	0.449	1.039	0.1	Stope team worker	0.06	0.129	0.056	0.382
167.47	167.48	167.48	167.48	167.48	167.48	167.48	167.48	Silica Quartz	164.06	164.07	164.07	164.07	164.21	164.22	164.22	164.22	2.206	2.221	2.214	06:57	12:40	0.15	0.15	0.00	0.040	0.154	0.193	0.759	0.1	Stope team worker	0.03	0.205	0.028	0.110
167.48	167.47	167.47	167.47	167.49	167.48	167.5	167.49	Silica Quartz	170.93	170.92	170.92	170.92	171.19	171.18	171.17	171.18	2.206	2.235	2.221	05:16	12:33	0.26	0.24	0.02	0.033	0.214	0.247	0.970	0.1	Stope team worker	0.032	0.133	0.030	0.195
162.99	162.99	162.99	162.99	163	163.01	163	163.00	Silica Quartz	168.61	168.61	168.61	168.61	168.94	168.94	168.94	168.94	2.202	2.203	2.203	06:17	13:18	0.33	0.32	0.01	0.071	0.270	0.342	0.927	0.1	Stoper	0.066	0.208	0.062	0.237
142.79	142.79	142.79	142.79	142.77	142.75	142.75	142.76	Silica Quartz	148.46	148.47	148.47	148.47	148.61	148.62	148.6	148.61	2.203	2.188	2.196	06:42	12:37	0.14	0.18	-0.03	0.013	0.214	0.227	0.779	0.1	Stores issuer (non-explosive)	0.01	0.057	0.009	0.158
180.57	180.58	180.58	180.58	180.59	180.58	180.59	180.59	Silica Quartz	153.73	153.73	153.73	153.73	154.37	154.37	154.37	154.37	2.202	2.2	2.201	05:57	17:19	0.64	0.63	0.01	0.171	0.249	0.420	1.501	0.1	Stores issuer (non-explosive)	0.256	0.406	0.242	0.354
143.41	143.4	143.4	143.40	143.39	143.4	143.41	143.40	Silica Quartz	166.85	166.84	166.86	166.85	166.91	166.91	166.92	166.91	2.27	2.291	2.281	08:11	13:37	0.06	0.07	0.00	0.015	0.075	0.090	0.743	0.1	Stores issuer (non-explosive)	0.011	0.165	0.010	0.051
143.42	143.41	143.41	143.41	143.38	143.41	143.39	143.39	Silica Quartz	172.76	172.76	172.76	172.76	173.04	173.05	173.04	173.04	2.203	2.183	2.193	05:36	18:40	0.28	0.30	-0.02	0.023	0.154	0.176	1.719	0.1	Stores issuer (non-explosive)	0.039	0.129	0.037	0.251
187.46	187.44	187.45	187.45	187.48	187.47	187.46	187.47	Silica Quartz	160.36	160.36	160.37	160.36	160.75	160.76	160.74	160.75	2.243	2.255	2.249	05:15	16:58	0.39	0.37	0.02	0.042	0.190	0.232	1.581	0.1	Stores issuer (non-explosive)	0.067	0.183	0.062	0.278
180.57	180.58	180.58	180.58	180.59	180.58	180.59	180.59	Silica Quartz	177.38	177.38	177.37	177.38	177.4	177.4	177.41	177.40	2.2	2.223	2.212	07:31	16:41	0.03	0.02	0.01	0.004	0.010	0.014	1.216	0.1	Stores worker (n.e.c.)	0.005	0.300	0.005	0.011
142.77	142.79	142.79	142.78	142.74	142.76	142.75	142.75	Silica Quartz	161.91	161.93	161.92	161.92	162.22	162.22	162.21	162.22	2.203	2.222	2.213	05:00	13:22	0.30	0.33	-0.03	0.087	0.210	0.297	1.111	0.1	Student (engineering n.e.c.)	0.097	0.294	0.091	0.219
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	150.27	150.29	150.28	150.28	150.47	150.49	150.48	150.48	2.205	2.258	2.232	06:14	12:47	0.20	0.21	-0.01	0.054	0.190	0.243	0.877	0.1	Student (engineering n.e.c.)	0.047	0.220	0.044	0.155
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	154.75	154.77	154.77	154.76	154.84	154.85	154.86	154.85	2.202	2.212	2.207	06:08	16:33	0.09	0.07	0.01	0.023	0.030	0.053	1.379	0.1	Survey worker (n.e.c.)	0.032	0.436	0.030	0.039
153.88	153.89	153.88	153.88	153.88	153.88	153.88	153.88	Silica Quartz	143.13	143.14	143.14	143.14	143.18	143.18	143.17	143.18	2.202	2.248	2.225	07:06	16:50	0.04	0.04	0.00	0.008	0.025	0.033	1.299	0.1	Telecommunications worker (n.e.c.)		0.247	0.010	0.031
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	174.62	174.62	174.61	174.62	174.67	174.68	174.69	174.68	2.2	2.2	2.200	05:37	13:37	0.06	0.06	0.00	0.005	0.055	0.060	1.056	0.1	Telecommunications worker (n.e.c.)	0.005	0.079	0.005	0.055
153.88	153.89	153.88	153.88	153.89	153.89	153.88	153.89	Silica Quartz	154.22	154.23	154.22	154.22	155.15	155.15	155.17	155.16	2.2	2.282	2.241	05:47	17:01	0.93	0.93	0.00	0.138	0.478	0.616	1.510	0.1	Trackless machine worker (n.e.c.)	0.208	0.224	0.193	0.671
187.46	187.44	187.45	187.45	187.48	187.48	187.49	187.48	Silica Quartz	162.81	162.82	162.82	162.82	163.04	163.06	163.04	163.05	2.203	2.207	2.205	06:22	15:50	0.23	0.20	0.03	0.021	0.136	0.157	1.252	0.1	Trackless machine worker (n.e.c.)	0.026	0.132	0.025	0.161
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	171.14	171.16	171.14	171.15	171.28	171.3	171.28	171.29	2.211	2.234	2.223	06:05	13:50	0.14	0.15	-0.01	0.043	0.106	0.148	1.033	0.1	Trackless machine worker (n.e.c.)	0.044	0.287	0.041	0.102
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	179.15	179.17	179.16	179.16	179.33	179.33	179.34	179.33	2.2	2.2	2.200	05:34	14:34	0.17	0.17	0.00	0.022	0.124	0.146	1.188	0.1	Trackless machine worker (n.e.c.)	0.026	0.150	0.025	0.140
167.47	167.48	167.48	167.48	167.49	167.48	167.49	167.49	Silica Quartz	163.72	163.71	163.71	163.71	164.22	164.21	164.21	164.21	2.198	2.201	2.200	05:37	14:38	0.50	0.49	0.01	0.153	0.259	0.412	1.190	0.1	Trackless machine worker (n.e.c.)	0.182	0.371	0.172	0.292
167.47	167.49	167.48	167.48	167.49	167.49	167.48	167.49	Silica Quartz	156	156	156	156.00	156.58	156.57	156.57	156.57	2.209	2.243	2.226	05:28	17:33	0.57	0.57	0.01	0.070	0.281	0.351	1.614	0.1	Trackless machine worker (n.e.c.)	0.113	0.199	0.106	0.425
180.54	180.58	180.56	180.56	180.59	180.58	180.59	180.59	Silica Quartz	179.09	179.1	179.09	179.09	179.25	179.25	179.26	179.25	2.203	2.201	2.202	07:11	23:34	0.16	0.13	0.03	0.014	0.048	0.062	2.165	0.1	Trackless machine worker (n.e.c.)	0.03	0.225	0.028	0.098
159.08	159.09	159.09	159.09	159.09	159.09	159.1	159.09	Silica Quartz	169.54	169.53	169.51	169.53	170.21	170.21	170.23	170.22	2.203	2.253	2.228	07:21	17:24	0.69	0.68	0.01	0.051	0.457	0.509	1.343	0.1	Trackless machine worker (n.e.c.)	0.069	0.101	0.065	0.574
187.46	187.44	187.45	187.45	187.47	187.46	187.47	187.47	Silica Quartz	158.88	158.89	158.9	158.89	159.7	159.69	159.7	159.70	2.225	2.202	2.214	05:59	14:48	0.81	0.79	0.02	0.247	0.428	0.675	1.171	0.1	Trackless machine worker (n.e.c.)	0.289	0.366	0.272	0.472
187.46	187.45	187.46	187.46	187.47	187.47	187.47	187.47	Silica Quartz	135.62	135.62	135.62	135.62	136.27	136.28	136.27	136.27	2.248	2.244	2.246	06:19	15:35	0.65	0.64	0.01	0.082	0.430	0.513	1.249	0.1	Trackless machine worker (n.e.c.)	0.103	0.161	0.096	0.498
142.79	142.78	142.79	142.79	142.74	142.76	142.73	142.74	Silica Quartz	166.17	166.17	166.17	166.17	166.41	166.39	166.38	166.39	2.201	2.213	2.207	05:52	13:03	0.22	0.27	-0.04	0.091	0.189	0.280	0.951	0.1	Trackless machine worker (n.e.c.)	0.087	0.326	0.082	0.170
165.2	165.19	165.2	165.20	165.19	165.18	165.18	165.18	Silica Quartz	154.75	154.75	154.77	154.76	155.21	155.21	155.22	155.21	2.203	2.258	2.231	05:41	13:58	0.46	0.47	-0.01	0.131	0.293	0.424	1.109	0.1	Trackless machine worker (n.e.c.)	0.145	0.309	0.135	0.304
159.08	159.1	159.08	159.09	159.08	159.1	159.1	159.09	Silica Quartz	155.02	155.02	155.02	155.02	155.16	155.17	155.18	155.17	2.2	2.211	2.206	05:34	17:18	0.15	0.14	0.01	0.013	0.079	0.092	1.553	0.1	Trackless machine worker (n.e.c.)	0.02	0.140	0.019	0.117
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	172.99	172.99	172.98	172.99	173.09	173.1	173.09	173.09	2	2	2.000	06:36	14:36	0.11	0.11	0.00	0.025	0.086	0.111	0.960	0.1	Trackless machine worker (n.e.c.)	0.024	0.225	0.025	0.086
167.47	167.49	167.48	167.48	167.48	167.48	167.49	167.48	Silica Quartz	170.19	170.19	170.19	170.19	170.47	170.48	170.47	170.47	2.202	2.237	2.220	05:02	12:56	0.28	0.28	0.00	0.073	0.193	0.266	1.052	0.1	Unclassified occupation (unknown/no specific skill)	0.077	0.275	0.072	0.191
159.08	159.1	159.08	159.09	159.09	159.1	159.1	159.10	Silica Quartz	161.24	161.24	161.24	161.24	161.61	161.6	161.6	161.60	2.202	2.26	2.231	06:08	13:23	0.36	0.35	0.01	0.128	0.236	0.364	0.970	0.1	Winch transporter team leader	0.124	0.351	0.116	0.214
180.57	180.58	180.58	180.58	180.58	180.59	180.58	180.58	Silica Quartz	180.03	180.01	180.02	180.02	180.87	180.86	180.88	180.87	2.2	2.185	2.193	06:15	16:40	0.85	0.84	0.01	0.181	0.434	0.615	1.370	0.1	Winch transporter team leader	0.248	0.294	0.236	0.566
187.46	187.44	187.45	187.45	187.47	187.46	187.47	187.47	Silica Quartz	166.79	166.79	166.79	166.79	167.11	167.12	167.12	167.12	2.2	2.183	2.192	05:42	14:27	0.33	0.31	0.02	0.062	0.208	0.269	1.151	0.1	Winch transporter/erector	0.071	0.229	0.067	0.227
178.39	178.39	178.4	178.39	178.39	178.39	178.4	178.39	Silica Quartz	168.73	168.74	168.74	168.74	169.07	169.07	169.07	169.07	2.1	2.2	2.150	06:05	14:05	0.33	0.33	0.00	0.098	0.225	0.323	1.032	0.1	Winch transporter/erector	0.101	0.303	0.098	0.225
178.39	178.41	178.4	178.40	178.4	178.4	178.4	178.40	Silica Quartz	179.83	179.82	179.83	179.83	180.19	180.2	180.21	180.20	2.1	2.1	2.100	06:09	13:09	0.37	0.37	0.00	0.111	0.312	0.423	0.882	0.1	Winch transporter/erector	0.098	0.262	0.097	0.273

Appendix D DPM sampling data

Occupation Sampled	Pre-Sample Flowrate(l/min)	Post Sample Flowrate(l/min)	Average Flowrate (l/min)	Sample Duration (min)	Sample volume (m3)	Organic Carbon	TWA Organic Carbon	Elemental Carbon	TWA Elemental Carbon	Total Carbon	TWA Total Carbon
Backfill Operator	1.804	1.793	1.7985	509	0.9154365	0.01181	0.013680382	0.005814	0.006734779	0.01766	0.006734779
Backfill Operator	1.802	1.8	1.801	756	1.361556	0.232	0.268369424	0.07159	0.082812789	0.303	0.082812789
Conveyor Belt Attendant	1.801	1.803	1.802	829	1.493858	0.111	0.128329634	0.02058	0.023793008	0.131	0.023793008
Cutting Torch	1.802	1.816	1.809	610	1.10349	0.261	0.300580431	0.106	0.122074811	0.368	0.122074811
Drill rig assistant	1.801	1.814	1.8075	715	1.2923625	0.282	0.325034578	0.151	0.174043338	0.433	0.174043338
Dump Truck Operator	1.802	1.751	1.7765	679	1.2062435	0.0263	0.030842481	0.173	0.202880195	0.436	0.202880195
Dump Truck Operator	1.802	1.811	1.8065	578	1.044157	0.153	0.176446167	0.05705	0.065792509	0.21	0.065792509
Dump Truck Operator	1.802	1.846	1.824	576	1.050624	0.13	0.148483187	0.103	0.117644371	0.232	0.117644371
Dump Truck Operator	1.801	1.788	1.7945	489	0.8775105	0.29	0.336676883	0.191	0.221742361	0.482	0.221742361
Dump Truck Operator	1.803	1.775	1.789	887	1.586843	0.258	0.300447177	0.01874	0.021823179	0.277	0.021823179
Dump Truck Operator	1.803	1.807	1.805	862	1.55591	0.298	0.343951985	0.195	0.225069252	0.492	0.225069252
Dump Truck Operator	1.802	1.904	1.853	649	1.202597	0.536	0.602626372	0.28	0.314804821	0.816	0.314804821
Emulsion Bay	1.802	1.797	1.7995	587	1.0563065	0.205	0.237334445	0.125	0.144716125	0.331	0.144716125
Engineering Assistant	1.82	1.828	1.824	406	0.740544	0.106	0.121070906	0.05257	0.060044317	0.159	0.060044317
Engineering Assistant	1.803	1.804	1.8035	315	0.5681025	0.05565	0.064284724	0.007553	0.008724933	0.0632	0.008724933
Engineering Assistant	1.822	1.821	1.8215	697	1.2695855	0.11	0.12581206	0.07123	0.081469027	0.182	0.081469027
Engineering Assistant	1.80	1.836	1.8185	464	0.843784	0.13	0.14893227	0.0526	0.060260288	0.183	0.060260288

Occupation Sampled	Pre-Sample Flowrate(l/min)	Post Sample Flowrate(l/min)	Average Flowrate (l/min)	Sample Duration (min)	Sample volume (m3)	Organic Carbon	TWA Organic Carbon	Elemental Carbon	TWA Elemental Carbon	Total Carbon	TWA Total Carbon
Engineering Assistant	1.807	1.82	1.8135	482	0.874107	0.166	0.190699384	0.0962	0.11051374	0.262	0.11051374
Engineering Assistant	1.807	1.791	1.799	667	1.199933	0.242	0.280248286	0.121	0.140124143	0.363	0.140124143
Engineering Assistant	1.81	1.801	1.803	497	0.896091	0.122	0.140968756	0.0974	0.112543908	0.22	0.112543908
Engineering Assistant	1.80	1.872	1.836	481	0.883116	0.115701357	0.131287851	0.061248041	0.069498957	0.061248041	0.069498957
Engineering Assistant	1.8	1.83	1.815	479	0.869385	0.115701357	0.132806884	0.061248041	0.070303077	0.061248041	0.070303077
Engineering Assistant	1.80	1.823	1.8125	408	0.7395	0.08781	0.100931034	0.04596	0.052827586	0.134	0.052827586
Engineering Assistant	1.8	1.82	1.81	479	0.86699	0.09534	0.109737569	0.05847	0.067299724	0.154	0.067299724
Engineering Assistant	1.801	1.77	1.7855	496	0.885608	0.13	0.151684869	0.126	0.147017642	0.256	0.147017642
Engineering Assistant	1.805	1.787	1.796	546	0.980616	0.07532	0.087370082	0.02887	0.033488771	0.104	0.033488771
Engineering Assistant	1.8	1.84	1.82	345	0.6279	0.05683	0.065052656	0.02687	0.030757784	0.0837	0.030757784
Engineering Assistant	1.802	1.777	1.7895	718	1.284861	0.000007	8.14939E-06	0.000012	1.39704E-05	0.000008	1.39704E-05
Engineering Assistant	1.801	1.8	1.8005	372	0.669786	0.008222	0.009513561	0.003827	0.004428168	0.01205	0.004428168
Engineering Assistant	1.8	1.797	1.7985	425	0.7643625	0.002635	0.003052312	0.000012	1.39005E-05	0.002635	1.39005E-05
Engineering Assistant	1.801	1.778	1.7895	561	1.0039095	0.09264	0.107851355	0.08384	0.097606408	0.176	0.097606408
Engineering Assistant	1.8	1.808	1.804	751	1.354804	0.138	0.159368071	0.118	0.136271249	0.256	0.136271249
Engineering Assistant	1.801	1.829	1.815	518	0.94017	0.153	0.175619835	0.13	0.149219467	0.283	0.149219467
Engineering Assistant	1.80	1.801	1.802	414	0.746028	0.157	0.181511284	0.08617	0.099623104	0.243	0.099623104
Engineering Assistant	1.882	1.801	1.8415	565	1.0404475	0.07492	0.084758802	0.01358	0.015363381	0.0885	0.015363381

Occupation Sampled	Pre-Sample Flowrate(l/min)	Post Sample Flowrate(l/min)	Average Flowrate (l/min)	Sample Duration (min)	Sample volume (m3)	Organic Carbon	TWA Organic Carbon	Elemental Carbon	TWA Elemental Carbon	Total Carbon	TWA Total Carbon
Engineering Assistant	1.78	1.771	1.7755	430	0.763465	0.09711	0.113946776	0.04114	0.048272787	0.138	0.048272787
Engineering Assistant	1.81	1.747	1.7785	724	1.287634	0.08311	0.097354981	0.0369	0.043224627	0.12	0.043224627
Engineering Assistant	1.85	1.809	1.8295	495	0.9056025	0.06059	0.068996538	0.01188	0.013528286	0.07247	0.013528286
Engineering Assistant	1.802	1.844	1.823	514	0.937022	0.125	0.142850613	0.05607	0.064077071	0.181	0.064077071
Engineering Assistant	1.801	1.811	1.806	485	0.87591	0.115701357	0.133468712	0.061248041	0.070653425	0.061248041	0.070653425
Engineering Assistant	1.803	1.769	1.786	716	1.278776	0.08655	0.100958847	0.01484	0.017310564	0.101	0.017310564
Engineering Assistant	1.8	1.739	1.7695	589	1.0422355	0.121	0.142460205	0.106	0.124799849	0.316	0.124799849
Engineering Assistant	1.806	1.761	1.7835	753	1.3429755	0.283	0.330576582	0.07579	0.088531446	0.359	0.088531446
Engineering Assistant	1.806	1.75	1.778	693	1.232154	0.194	0.227315336	0.102	0.11951631	0.296	0.11951631
Engineering Assistant	1.802	1.836	1.819	548	0.996812	0.267	0.30579989	0.009317	0.010670927	0.276	0.010670927
Engineering Assistant	1.802	1.834	1.818	614	1.116252	0.138	0.158140814	0.02044	0.023423176	0.158	0.023423176
Engineering Assistant	1.801	1.794	1.7975	391	0.7028225	0.04735	0.054879462	0.000495	0.000573713	0.04785	0.000573713
Engineering Assistant	1.801	1.775	1.788	354	0.632952	0.104	0.121178225	0.04105	0.047830444	0.145	0.047830444
Engineering Assistant	1.803	1.773	1.788	465	0.83142	0.07737	0.090149609	0.009398	0.010950317	0.08677	0.010950317
Engineering Assistant	1.8	1.796	1.798	527	0.947546	0.08174	0.094711717	0.03299	0.038225343	0.115	0.038225343
Engineering Assistant	1.801	1.751	1.776	316	0.561216	0.145	0.170091967	0.07044	0.082629505	0.215	0.082629505
Engineering Assistant	1.802	1.799	1.8005	549	0.9884745	0.151	0.174719985	0.08163	0.09445293	0.233	0.09445293
Engineering Assistant	1.8	1.699	1.7495	272	0.475864	0.04977	0.059266933	0.006813	0.008113032	0.05659	0.008113032

Occupation Sampled	Pre-Sample Flowrate(l/min)	Post Sample Flowrate(l/min)	Average Flowrate (l/min)	Sample Duration (min)	Sample volume (m3)	Organic Carbon	TWA Organic Carbon	Elemental Carbon	TWA Elemental Carbon	Total Carbon	TWA Total Carbon
Fermel Assistant	1.801	1.756	1.7785	489	0.8696865	0.182	0.21319464	0.108	0.126511105	0.29	0.126511105
General engineering worker	1.802	1.824	1.813	519	0.940947	0.115701357	0.132953389	0.061248041	0.070380632	0.061248041	0.070380632
General worker	1.8	1.81	1.805	424	0.76532	0.115701357	0.133542656	0.061248041	0.070692568	0.061248041	0.070692568
Generalistic	1.803	1.828	1.8155	548	0.994894	0.11	0.126227853	0.054	0.0619664	0.164	0.0619664
Generalistic logistic	1.799	1.793	1.796	437	0.784852	0.09442	0.109525798	0.04089	0.047431793	0.135	0.047431793
Generalistic logistic	1.798	1.811	1.8045	710	1.281195	0.13	0.150087744	0.07655	0.088378591	0.206	0.088378591
Hoisting worker	1.803	1.825	1.814	422	0.765508	0.05002	0.057446711	0.002709	0.003111218	0.05273	0.003111218
LDV Operator	1.802	1.779	1.7905	481	0.8612305	0.157	0.182677092	0.19	0.221074188	0.316	0.221074188
LHD Operator	1	1.767	1.3835	608	0.841168	0.234	0.352367185	0.276	0.415612577	0.51	0.415612577
Loco Operator	1.801	1.768	1.7845	558	0.995751	0.007619	0.008894882	0.002471	0.002884795	0.01009	0.002884795
PTV	1.801	1.796	1.7985	512	0.920832	0.09623	0.111470207	0.01733	0.020074599	0.114	0.020074599
Pump Attendant	1.801	1.784	1.7925	660	1.18305	0.195	0.226638773	0.155	0.180148768	0.35	0.180148768
RDO	1.801	1.77	1.7855	569	1.0159495	0.142	0.165686549	0.123	0.143517222	0.266	0.143517222
Rigger Assistant	1.8	1.79	1.795	729	1.308555	0.0679	0.078806871	0.01558	0.018082637	0.08348	0.018082637
Rigger Assistant	1.802	1.805	1.8035	543	0.9793005	0.08116	0.093752888	0.006441	0.007440394	0.0876	0.007440394
Rock Breaker Operator	1.821	1.901	1.861	707	1.315727	0.245	0.274270106	0.219	0.24516389	0.464	0.24516389
Rock Breaker Operator	1.803	1.772	1.7875	668	1.19405	0.208	0.242424242	0.146	0.17016317	0.355	0.17016317
Rock Breaker Operator	1.803	1.833	1.818	427	0.776286	0.128	0.146681335	0.07794	0.089315182	0.206	0.089315182
Scraper winch Operator	1.805	1.77	1.7875	539	0.9634625	0.00898	0.0104662	0.005309	0.006187646	0.01427	0.006187646
Stope Team Member	1.833	1.833	1.833	960	1.75968	0.113	0.128432442	0.06215	0.070637843	0.175	0.070637843
Stope team member	1.811	1.821	1.816	693	1.258488	0.116	0.133076358	0.0742	0.085122981	0.19	0.085122981
Stope Team Member	1.811	1.822	1.8165	635	1.1534775	0.03333	0.038225984	0.005289	0.006065923	0.03871	0.006065923
Stope Team Member	1.863	1.842	1.8525	459	0.8502975	0.01027	0.011549708	0.009626	0.010825461	0.01988	0.010825461

Occupation Sampled	Pre-Sample Flowrate(l/min)	Post Sample Flowrate(l/min)	Average Flowrate (l/min)	Sample Duration (min)	Sample volume (m3)	Organic Carbon	TWA Organic Carbon	Elemental Carbon	TWA Elemental Carbon	Total Carbon	TWA Total Carbon
Stope team member	1.802	1.808	1.805	509	0.918745	0.115701357	0.133542656	0.061248041	0.070692568	0.061248041	0.070692568
Stope team member	1.801	1.851	1.826	797	1.455322	0.115701357	0.132006842	0.061248041	0.069879565	0.061248041	0.069879565
Stope Team Member	1.803	1.802	1.8025	495	0.8922375	0.01263	0.014597781	0.005917	0.006838881	0.0186	0.006838881
Stope Team Member	1.801	1.789	1.795	565	1.014175	0.008113	0.009416202	0.006311	0.007324745	0.01439	0.007324745
Stope Team Member	1.803	1.819	1.811	682	1.235102	0.102	0.117338487	0.0863	0.099277563	0.188	0.099277563
Stope team member	1.805	1.785	1.795	413	0.741335	0.111	0.128830084	0.05396	0.062627669	0.165	0.062627669
Stope team member	1.802	1.779	1.7905	481	0.8612305	0.105	0.122172577	0.04812	0.055989947	0.153	0.055989947
Stope team member	1.8	1.84	1.82	479	0.87178	0.121	0.138507326	0.06202	0.07099359	0.183	0.07099359
Stope team member	1.803	1.8	1.8015	443	0.7980645	0.09912	0.1146267	0.09577	0.110752614	0.195	0.110752614
Transmixer Operator	1.801	1.798	1.7995	455	0.8187725	0.127	0.147031583	0.009606	0.011121145	0.137	0.011121145
UV Fermel Assistant	1.808	1.829	1.8185	491	0.8928835	0.008989	0.010298094	0.006553	0.007507332	0.01556	0.007507332
UV Fermel Assistant	1.80	1.866	1.8335	480	0.88008	0.115701357	0.131466863	0.061248041	0.06959372	0.061248041	0.06959372
UV Fermel Assistant	1.844	1.802	1.823	596	1.086508	0.111	0.126851344	0.0944	0.107880783	0.206	0.107880783
UV Fermel Operator	1.832	1.839	1.8355	496	0.910408	0.007043	0.007993962	0.004864	0.005520748	0.01193	0.005520748
UV Fermel Operator	1.826	1.828	1.827	686	1.253322	0.01392	0.015873016	0.01161	0.013238916	0.0255	0.013238916
UV Fermel Operator	1.844	1.84	1.842	460	0.84732	0.006205	0.007017961	0.001043	0.001179651	0.007248	0.001179651
UV Fermel Operator	1.80	1.814	1.8075	500	0.90375	0.129	0.14868603	0.0314	0.036191793	0.16	0.036191793
UV Fermel Operator	1.806	1.836	1.821	518	0.943278	0.06044	0.069146989	0.0152	0.017389713	0.07564	0.017389713
UV Fermel Operator	1.802	1.822	1.812	524	0.949488	0.04845	0.055705022	0.0001	0.000114974	0.04845	0.000114974
UV Fermel Operator	1.801	1.802	1.8015	481	0.8665215	0.13	0.150337682	0.0526	0.060828939	0.183	0.060828939
UV Fermel Operator	1.8	1.804	1.802	492	0.886584	0.02958	0.034198113	0.0001	0.000115612	0.02958	0.000115612
UV Fermel Operator	1.808	1.816	1.812	642	1.163304	0.08376	0.096302428	0.0608	0.069904341	0.145	0.069904341
UV Fermel Operator	1.801	1.798	1.7995	492	0.885354	0.02761	0.031964898	0.000102	0.000118088	0.02762	0.000118088
UV Fermel Operator	1.8	1.801	1.8005	543	0.9776715	0.08439	0.097646487	0.04989	0.05772702	0.134	0.05772702
UV Fermel Operator	1.802	1.813	1.8075	545	0.9850875	0.08127	0.093672199	0.04994	0.057561088	0.131	0.057561088

Occupation Sampled	Pre-Sample Flowrate(l/min)	Post Sample Flowrate(l/min)	Average Flowrate (l/min)	Sample Duration (min)	Sample volume (m3)	Organic Carbon	TWA Organic Carbon	Elemental Carbon	TWA Elemental Carbon	Total Carbon	TWA Total Carbon
UV Fermel Operator	1.801	1.778	1.7895	416	0.744432	0.0871	0.101401695	0.04596	0.053506566	0.134	0.053506566
UV Fermel Operator	1.803	1.806	1.8045	484	0.873378	0.0796	0.09189988	0.000107	0.000123534	0.07971	0.000123534
UV Fermel Operator	1.8	1.778	1.789	332	0.593948	0.07909	0.092102199	0.005186	0.006039221	0.08428	0.006039221
UV Fermel Operator	1.804	1.792	1.798	611	1.098578	0.176	0.203930293	0.09241	0.107074991	0.268	0.107074991
UV Fermel assistant	1.802	1.808	1.805	533	0.962065	0.115701357	0.133542656	0.061248041	0.070692568	0.061248041	0.070692568
Water Browser Operator	1.802	1.77	1.786	377	0.673322	0.09042	0.105473124	0.009423	0.010991741	0.09985	0.010991741

Appendix E Ventilation audit data

Baseline audit data												2021 audit				
Level	Index	P (kPa)	VOL (m3/s)	WB (°C)	DB (°C)	Level	Index	P (kPa)	VOL (m3/s)	WB (°C)	DB (°C)	Level	Index	VOL (m3/s)	WB (°C)	DB (°C)
Intakes & Returns	1	86.8		8.89	9.63	282L	65		36.5	23	26	Intakes	255 Decline	150.08	20.98	23.67
	2	104.63		17.59	24.12		66		16.3	23	26		255 1C	48.80	30.08	31.00
	3		45.3	36.2	36.7		67		44.1	21.5	25		MB Intake	170.32	21.44	23.46
	4		35.5	22.2	27.5		68		42.3	22.5	23		272 Intake	32.30	23.25	25.75
	5		14	21.5	25		69		36.1	21.5	23.5		273 Intake	26.98	25.83	28.17
	6			19.5	25		70		15.4	22	25		278 Intake	30.18	24.71	27.62
	7		44.4	21.4	26		71		48	22	24.5		280 Intake	-16.16	29.70	31.64
255L	8			31	34		72			23	26		282 Intake	81.51	24.98	27.26
	9	109.43		25	30		73		4.4	31	35		284 Intake	14.20	28.00	30.83
	10	109.29		30.62	33.43		74		15.4	24	27.5		287Intake	36.12	29.75	32.89
	11			25	30		75		29	23	26		289 Intake	34.83	25.80	27.19
	12		66.9	25	30		76		14.3	25	30		291 Intake	43.07	26.66	28.31
	13			25	30		77		8.2	23.5	28	Returns	272 Door Return	21.40	24.75	27.50
	14		6	24.5	25		78		25.4	25	29		272 Stope Return	25.30	24.25	27.00
	15		26.8	24	29		79		27.8	25	30		273 East Return	40.37	33.70	37.00
	16		9	24	27	284L	80		18.3	24.5	29.5		273 West Return	39.63	32.17	35.50
	17		96.7	15	15		81		65.8	23	26		280 Expl. Drive Return			
	18		47.7	29	31		82		31.8	23	26		280 West Return			
	19		29.8	29	31		83		36.6	23.5	27		280 WS Return			
	20		53.9	29	33		84		25.4	24.5	28.5		284 WS Return			
	21		130.2	29	33		85		33.9	23.5	26		287 East Return	23.43	31.27	35.17
	22		99.8	30.5	34		86		21.8	25	30		287 West Return 1	36.85	32.00	34.25
	23		54.4	26	27		87		11.45	25.5	29.5		287 West Return 2	13.23	31.33	32.83

	24		142.2	30.5	34		88		11.1	26	30			289 Return			
	25		193.3	30.5	34		89		7.7	27	31			291 Crusher Return	17.9	29.5	32.5
272L	26		31.1	21	24		90		20	25	30.5			291 Return	23.65	29	32.5
	27		31.1	21	24	287L	91		-11.6	32	35.5						
	28		20.2	22	26		92		-10.5	32	35						
	29		14.4	22	26		93		12.8	30	35						
	30		12.1	24	27		94		-24.5	30	35						
	31		20	25	28		95		19.6	29	34						
	32			31	35		96		-12.8	29	34						
	33		91.8	31	35.5		97		-10.2	29	34.3						
	34			31.5	38		98		10	28	33						
273L	35		19.7	24	25		99		18.9	28	33						
	36		8.8	29	34.5		100		13.3	25.7	30.5						
	37		9	27	31	289L	101		54.5	25	28						
	38		11.2	27	32		102		-4.6	21.2	22.7						
	39		11.1	26.8	31		103		34.1	20.5	21						
	40		22.5	30	35		104		22.9	21	22.2						
	41		19.9	33.5	41		105		16.9	26.2	29.6						
	42		12.5	27.5	33.8		106		2	28	30.5						
	43		5.5	28.5	34.9		107		6.4	24.5	27.4						
	44		12.2	30	36.5		108		16.7	24.8	27.5						
	45		0.00001	32	37		109		15.9	25.7	29						
	46		17.7	33	37		110		17.1								
	47		3.3	33	38.5		111		13.7	22.3	24.3						
278L	48		26.4	22.5	23.5		112		36	20.5	21						
	49		9.9	23	26		113		22.7	26.5	32.7						
	50		16.8	23.5	27.2	291L	114		12.4	27.5	32.2						
	51		5.6	25	30		115		46.1	23.7	32.2						

	52		-14	32	35		116		24.9	28	32						
	53		29.9	25	28		117		33	25	29						
	54		30	25.5	28.5		118		32.3	26.7	30.6						
	55		9.2	27	32.8		119		-11.1	29.5	38						
280L	56		17.9	27.5	29.5		120		27.4	28	28.8						
	57		10.9	26	29		121		21.6	30.2	35.6						
	58		15.4	29.5	31.5		122		15.5	30.4	36.2						
	59		14.9	30	35		123		6.2	29	33						
	60		7.4	30	33												
	61		-6.4	33	36												
	62		8.6	30	34												
	63		33.4	31	36												
	64		33.4	31	36												