



Simulation-based verification of stope heat loads in deep-level mines

PA Galamadien

 **orcid.org/ 0000-0002-8998-5007**

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Supervisor: Dr JC Vosloo

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ABSTRACT

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Author: P.A. Galamadien

Supervisor: Dr J.C. Vosloo

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As gold mines continually increase their mining depths and distances from shafts, the difficulty of providing effective cooling also increases. This increases the need for effective planning, which requires accurate knowledge of the contributions of different areas to the mine's total heat load, especially the production areas (stopes). Few heat load quantification methods isolate the heat of production areas. A simulation-based approach can be used, but such a method's accuracy must be validated.

The systematic literature review process revealed a gap in the literature which is if simulations as a predictive tool can be used to determine stope heat loads and whether it can be used to compare with heat loads determined by industry accepted methods. Therefore, this study focuses on validating whether the simulation method can be used to compare calculations done on stope heat loads.

In this study, the heat loads of three stopes of an operational mine were quantified by considering their energy balances. Focus was placed on the main heat sinks – ventilation air and service water. Thermo-hydraulic simulations were set up to duplicate the real-world setting as closely as possible. Certain simulation parameters were fixed based on real-world knowledge, while unknown parameters were adjusted to match real-world measurements as best as possible. The simulated heat loads were compared to the energy balance method. The Van der Walt's method was determined and also compared to the simulation method. The entire process was repeated for two case studies from literature.

For the in-field measured stopes, the total stope heat generated was approximately 700 kW at a depth of approximately 3.6 km. The heat removed by the ventilation air and service water was 254 kW and 441 kW, respectively. Overall (including both the in-field measured stopes and case studies), the mean absolute errors produced by the simulation and Van der Walt's method were 10.9% and 29.6%, respectively. The simulation method was validated by applying the method to external case studies. Overall, it was demonstrated that the simulation method can be used to make predictions about expected stope heats and can compare with industry methods.

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LIST OF ABBREVIATIONS

Abbreviations	Description
CS	Case Study
DB	Dry-bulb temperature
DCHE	Direct contact heat exchanger
DXF	Drawing Exchange Format
EWM	Entropy Weighted Method
HVAC	Heating Ventilation and Air-conditioning
IGU	Insulated Glass Unit window
LCS	Literature Case Study
LOM	Life-Of-Mine
OPEX	Operational expenditure
PI	Proportional-integral
PTB	Process Toolbox
PRV	Pressure Relief Valves
RSA	Republic of South Africa

SGUL	Single-pane Laminated Glass Unit window
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution method
UA	Overall heat transfer coefficient
VDW	Van der Walt's method
VRT	Virgin Rock Temperature
WB	Wet-bulb temperature
XC	Crosscut

CHAPTER 1: INTRODUCTION AND LITERATURE

1.1 Preamble

The South African (RSA) gold mining industry faces challenges. These include increased heat generation due to deeper operations and the risk of interrupted electricity being supplied by Eskom to power cooling infrastructure, all of which heighten the need for effective planning regarding the thermal demands of production areas [1-3].

Simulation programs can be used as tools to predict future mine heat loads and cooling needs in advance, enabling mines to make provisions for installing the necessary infrastructure to address this heat in a timely manner [4].

Mine ventilation practitioners' reliance on simulation programs has increased over the years, and they use these programs to make decisions that impact the thermal conditions of the production area [5]. Therefore, it is crucial to ensure that simulation programs are validated for accurately predicting heat load requirements.

1.2 Background

Every mining operation undergoes a mining cycle from its inception to its end. Mining operations generally follow similar routes with minimal deviations¹. Figure 1-1 shows what the typical mining cycle is for gold mining operations.

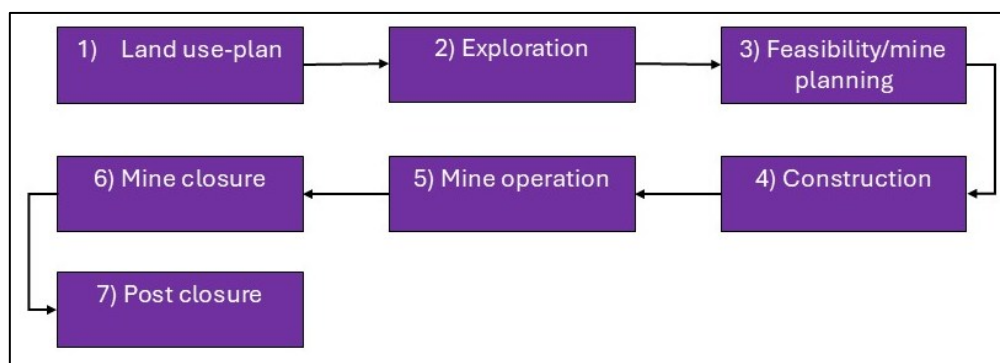


Figure 1-1: The mining cycle¹

The mining cycle starts with acquiring the rights and determining what is to be done on the land. Thereafter, the mine initiates the exploration process, which involves determining the location of the commodity underground. Samples will also be extracted to determine the yield or grade of the gold bearing ore. From the information gathered, feasibility studies are conducted in the exploration phase to determine how much revenue can be generated from the ore, and what the

1: Adapted from <https://miningnorthworks.com/mining-cycle/> (accessed July 2025)

capital and operational costs would be to extract the gold. Should the project be deemed feasible, construction will begin to erect the necessary infrastructure to conduct mining operations, after which the mine operation will follow¹.

The typical process involved in this step is executing the mining production phases, extracting the gold, and planning for the extraction of gold [6]. This study primarily focuses on the planning aspect. Mining operations continuously evaluate the challenges associated with extracting the gold [7]. One particular challenge is providing sufficient cooling to make working areas habitable and productive for mine workers. The last two steps of the mining cycle are mine closure and post-closure¹.

Mines are legally required to restore the land to its original state before mining began, which is part of the mine closure process. If the mine faces issues, such as revenue not meeting certain levels to cover expenses and remain profitable, it can prompt earlier mine closure than originally planned. After closure, the post-closure phase continuously monitors the land's health following the mine's shutdown. To prevent early mine closure, effective planning in the mine operation phase needs to be conducted to overcome challenges that will arise¹.

The gold mining industry in RSA has always faced heat-related problems [2]. RSA gold mines are currently exhausting their accessible ore deposits [8]. To continue their mining operations and extend their life-of-mine (LOM), mines need to go deeper² [7]. However, this results in even greater challenges when combating the heat and providing safe, habitable thermal conditions for the workforce [9, 10].

The largest source of heat in gold mines is heat emitted from the rock [11]. The consequence of deepening operations to extend mine LOM is that the virgin rock temperature (VRT) continues to increase, which raises the heat generated in the mines. Figure 1-2 shows the VRT trend across different regions of RSA.

1: <https://miningnorthworks.com/mining-cycle/> (accessed July 2025)

2: <https://miningforschools.co.za/lets-explore/gold/factors-that-favour-or-hinder-gold-mining> (accessed July 2025).

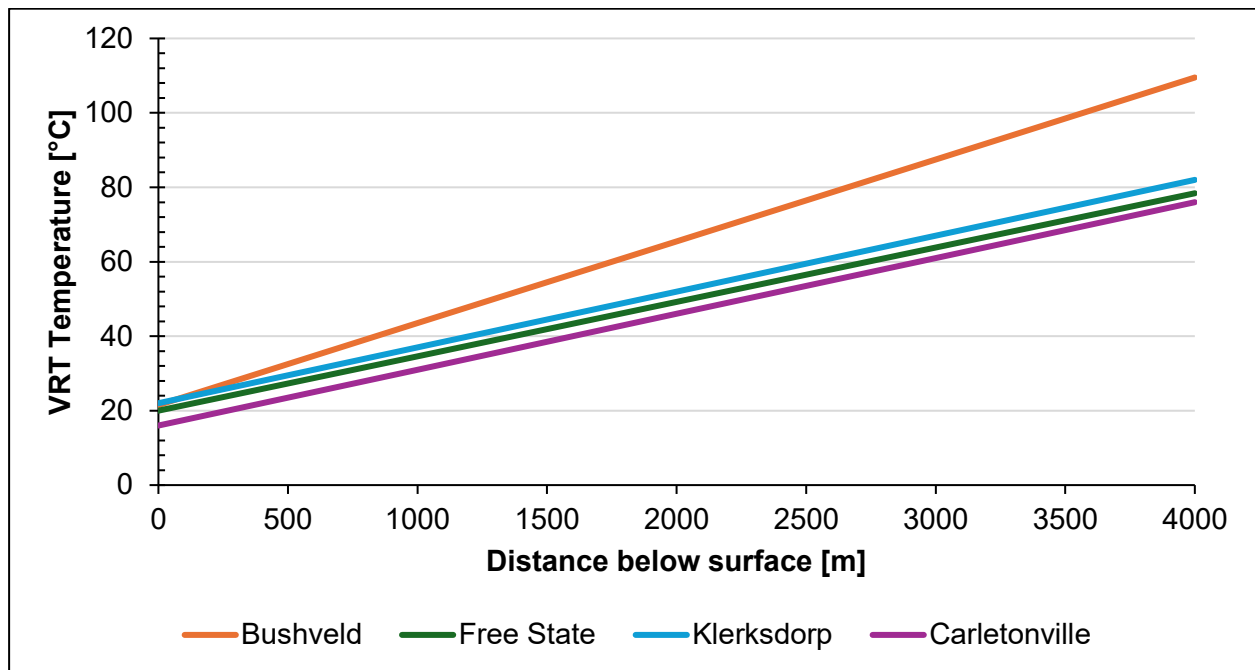


Figure 1-2: VRT comparison across regions (adapted from [12])

To protect workers in underground thermal hazardous environments, continuous planning is essential to ensure that enough cooling is supplied to reduce strain and risks. It should also consider the type of work being performed underground, as more strenuous tasks increase workers' body temperatures [13, 14]. Given these risks, it is crucial to conduct effective planning and assessment of thermal conditions in the production areas to provide adequate cooling.

Current socio-economic challenges in RSA include the cost and availability of electricity from the national grid, complicating the operation of cooling systems [3, 15]. This often causes mines to reduce cooling to stay financially viable [16]. Mines have reached depths where cooling is essential and can no longer depend on natural or surface bulk-air cooling alone [17, 18]. This requires mine ventilation practitioners to think of ways to provide the maximum cooling to the production area while still being financially sound about the energy consumption of the cooling infrastructure. These challenges heighten the importance of effective planning for cooling in production areas where most of the workforce is located during mining operations.

The underground mining industry is a highly complex environment. With the advent of simulation programs, they are able to reduce the strain on mine ventilation practitioners, as these programs are designed to compute complex scenarios, predict outcomes specific to each mine, and aid in streamlined decision-making [19, 20]. Using simulations to support operational planning and predict future environmental conditions has become standard practice in recent years [4, 21].

The increased reliance of the mining industry on simulation can be demonstrated. A search was conducted using the Scopus research database with the keywords "Mine, simulation and heat",

and the frequency of studies mentioning these keywords in their titles, abstracts, and keyword lists were recorded [5] (search was conducted in November 2025). The results indicate a significant increase in the use of simulation programs within the mining industry. This trend can be seen in Figure 1-3.

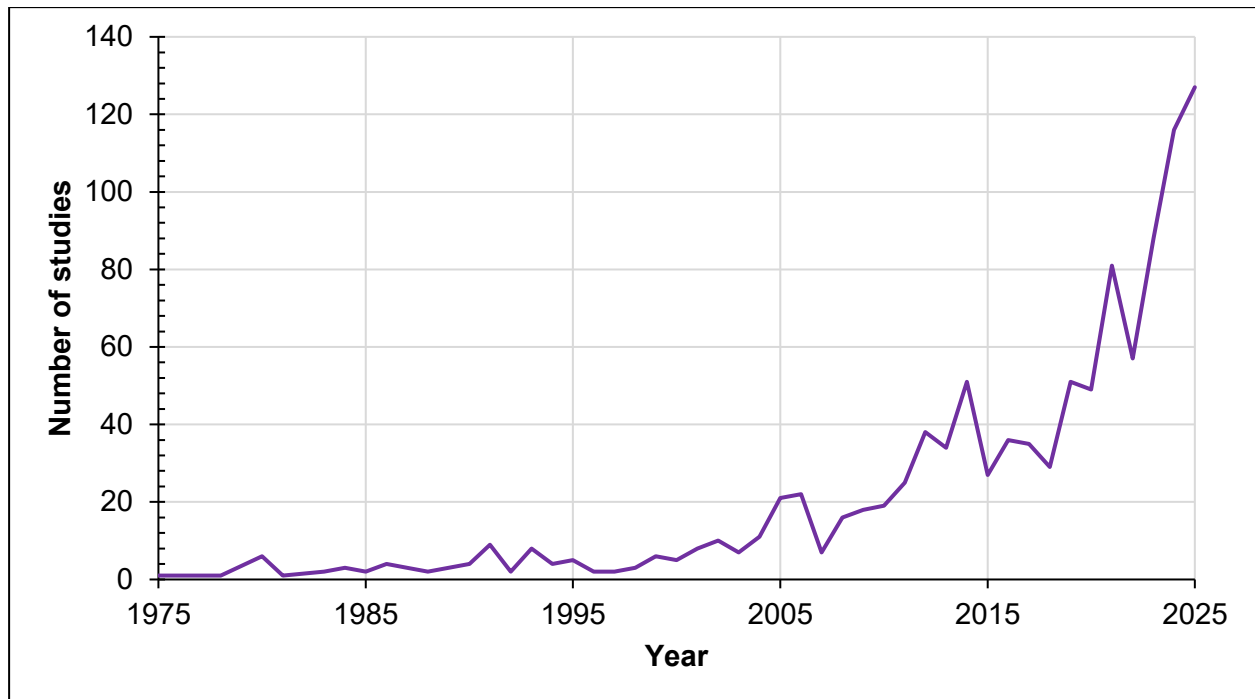


Figure 1-3: Trend of mining, simulation, and heat-related studies over the years (adapted from [5])

The use of simulation has increased over the years, and mines have become more reliant on the data provided by these simulation programs to assist in mine planning. Critical decisions made by ventilation practitioners are influenced by simulation results. It is essential that the simulation programs are verified and proven accurate in predicting thermal conditions and heat load planning to ensure the safety of the workforce.

1.2.1 Rock thermal energy and heat flow

The dominant heat that is generated within the stopes is geothermal energy [11]. As previously discussed, mining operations are operating in depths in which the VRT is very high and severely contributes to the heat load of a stope. In this section, the different heat transfer mechanisms will be discussed.

Heat transfer by convection

The first heat transfer mechanism is thermal convection. As the rock face has been blasted, a new layer forms which is exposed to the ambient air temperature. The hot rock would transfer heat with the cooler ambient air temperature flow over rock [22]. This results in the air temperature

increasing and surface temperature of the rock decreasing [23]. Figure 1-4 shows the simplified diagram of the thermal convection process taking place.

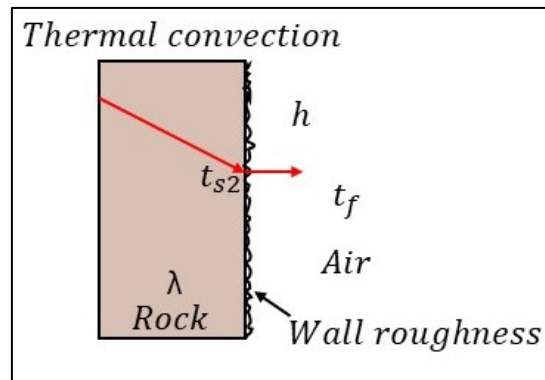


Figure 1-4: Convection heat transfer between ventilation air and rock surface (adapted from [23])

Heat transfer by conduction

This principal follows after the convection heat transfer mechanism and works on the temperature gradient that is experienced within the rock. As ventilation air cools the surface by convection, the rock temperature increases as function of depth, situated deeper in the rock at its saturation temperature, which is the VRT temperature. Figure 1-5 shows the simplified diagram of the thermal conduction process taking place.

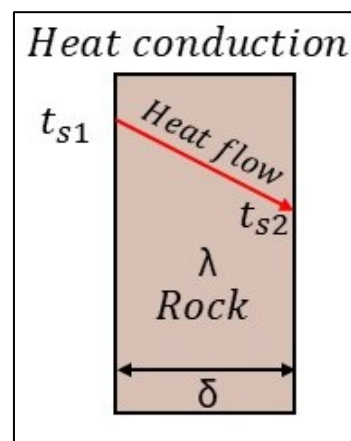


Figure 1-5: Conduction heat transfer through rock (adapted from [26])

Heat transfer by radiation

The final heat transfer mechanism is thermal radiation. This is usually omitted in heat studies, because its contribution is significantly lower than that of the previous two mechanisms. This works on the principle that the surface of the rock face radiates heat onto objects or surfaces in the surroundings, such as pipes, equipment, backfill, and mining faces, which then adds more

heat to the area [22, 23]. Figure 1-6 shows the simplified diagram of the thermal radiation process taking place.

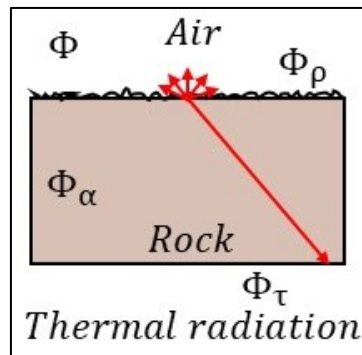


Figure 1-6: Radiation heat transfer between ventilation air and rock surface (adapted from [23])

Application of heat transfer mechanisms in the mines

Figure 1-7 shows the different heat transfer mechanisms in play on a typical underground mine tunnel. An opening is excavated into the rock in which the ventilation air is allowed to flow through to provide safe habitable conditions for mine personnel.

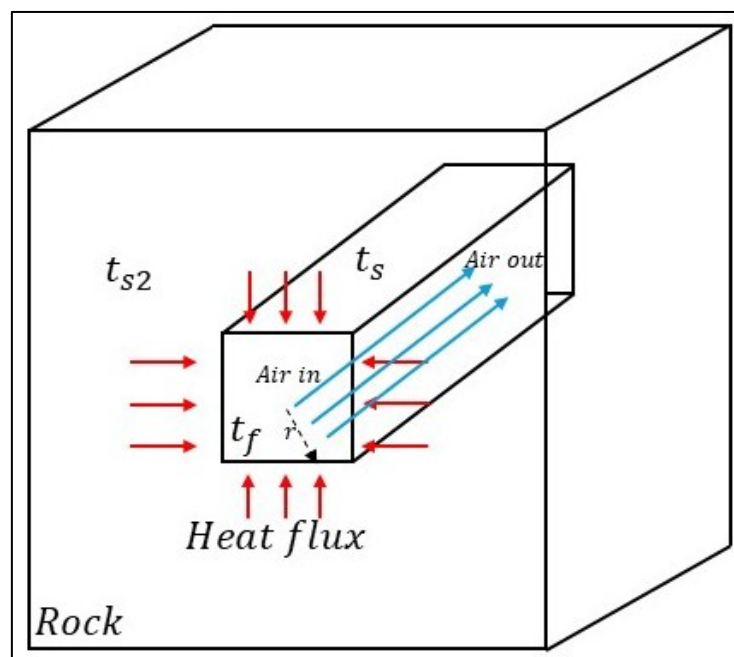


Figure 1-7: Heat flux of rock acting on excavated tunnel (adapted from [23])

As the ventilation air flows through the tunnel, convection allows the surface of the rock to get cooler, resulting in the ventilation air absorbing that energy. This in turns allows heat conduction to take place as a temperature gradient is formed. The heat flux continuously pumps heat to the surface, and the rate of the heat flux diminishes over time as the VRT front is pushed deeper and

deeper into the rock. The R- value increases over time, and shows how the VRT front is pushed deeper into the rock. This phenomenon is showcased in Figure 1-8.

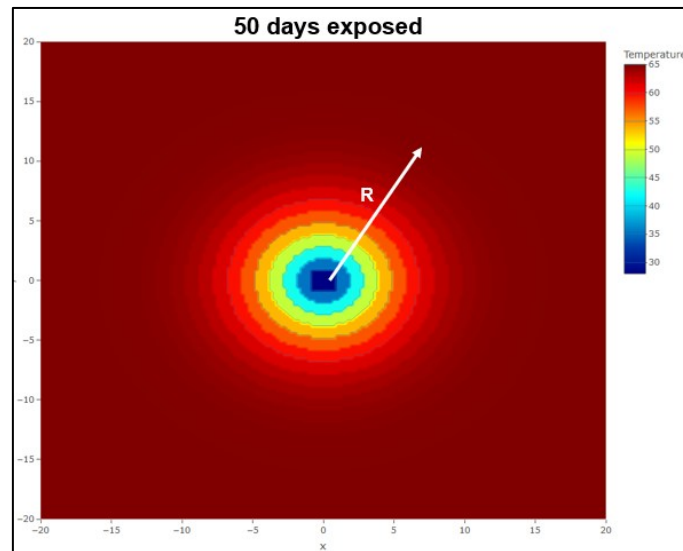


Figure 1-8: Position of VRT temperature with tunnel of constant ventilation air stream after a number of days (adapted from [23])

Figure 1-8 shows the VRT position in the rock after 50 days. The distance of concentric circles to the VRT point is known as the radius of influence (R).

Figure 1-9 shows how the amount of heat released by the rock reduces over time as the ventilation air cools the rock surface. Initially geothermal heat released at low days exposed is high but quickly decays over time.

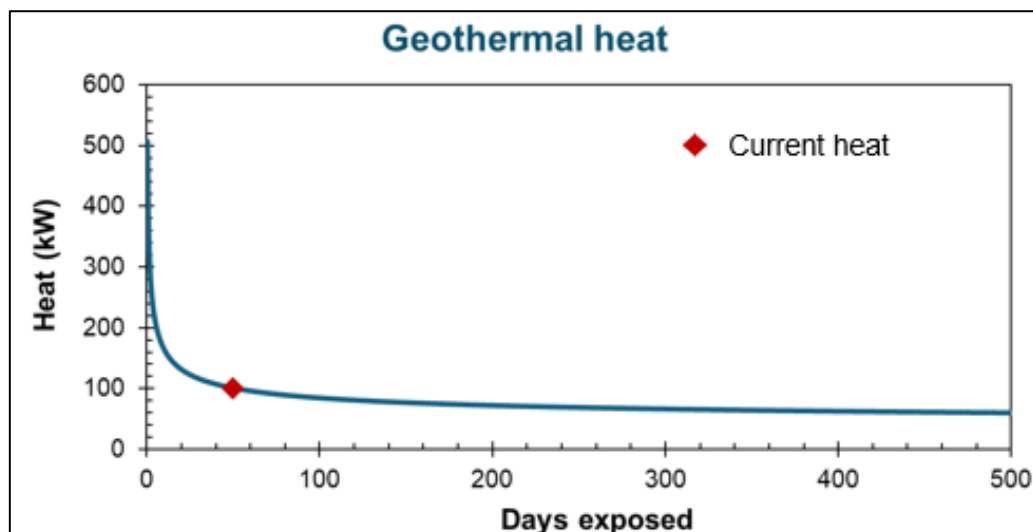


Figure 1-9: General rock temperature and geothermal heat profiles of a mine tunnel over time (adapted from [23, 24])

1.2.2 Heat load estimations

One way the mining industry estimates cooling requirements is through heat load estimations [8]. This is done by determining all the sources of heat which increase the temperature of the mine, as well as heat sinks that absorb or remove heat. The operational cooling of the mine is then determined to quantify the amount of cooling surplus or deficit by using an energy balance [8].

The literature tries to determine in-stope heat by theoretically or empirically quantifying the heat sources and sinks. However, the ideal method would be to use an energy balance that would be able to deduce heat sources or sinks that cannot be determined theoretically or measured by equating the total heat generation and removal and using the difference [25].

An accurate heat load/energy balance model requires identifying all the sources of heat and heat sinks within the production area, along with the accurate quantification of the contribution of each component. Production areas are supplied with air and water (air for ventilation purposes and water for cleaning and equipment cooling). The heat generated in the production area transfers to the heat sinks (air, water, and compressed air).

The temperature at which ventilation air leaves the workplace is referred to as the reject temperature. This relationship between intake, reject temperatures, and heat generation within the production area, allows mines to plan for a target reject temperature to provide safe and habitable conditions for mine personnel [8].

Other considerations for an energy balance model within a production area are: the intensity of the ore extracted (heat released per tonne extracted), stoping configurations, mining cycle (blasting and cleaning shifts will introduce fluctuations in the reject temperature), ventilation controls, etc. The generation and absorption of heat within a production area can be determined theoretically and empirically by using an energy balance [8], [26].

1.3 The problem the mining industry faces

From the above mentioned background the problem the gold mining industry faces in relation to mine planning can be summarised as follows:

The stope is hot and hazardous environment, which mine workers are continuously exposed to. These workers need to always be protected against these conditions. This is done by supplying the necessary cooling to the workplace to combat the heat and provide safe and habitable conditions. Heat load calculations are done by mines to determine how much cooling needs to be supplied to the workplaces by using industry accepted methods. These industry methods need to be continuously scrutinised whether they produce accurate heat loads since human lives are at

stake if not enough cooling is supplied. With simulation starting to become more prevalent in industry. Simulation can be used as a tool to determine heat loads but can also be compared to assess whether current industry methods are still relevant and accurate. However, firstly the simulation method needs to be validated and proven to be accurate to determine heat loads in the stopes.

1.4 Literature review

Conducting heat load estimations for stopes can be complex. Therefore, a thorough review of the literature is necessary to identify current shortcomings and possible solutions to address them where necessary. The literature review will examine existing methods that can be utilised. It will also discuss the shortcomings and advantages of these methods. The most suitable method will be included in the development of solution (Chapter 2) for implementation in the study.

1.4.1 Systematic literature review

To effectively gather all available literature for review, a systematic literature review will be adopted. The systematic literature is beneficial by going through all the available studies in literature and extensively review each study [27]. The overview of the process is shown in Figure 1-10.

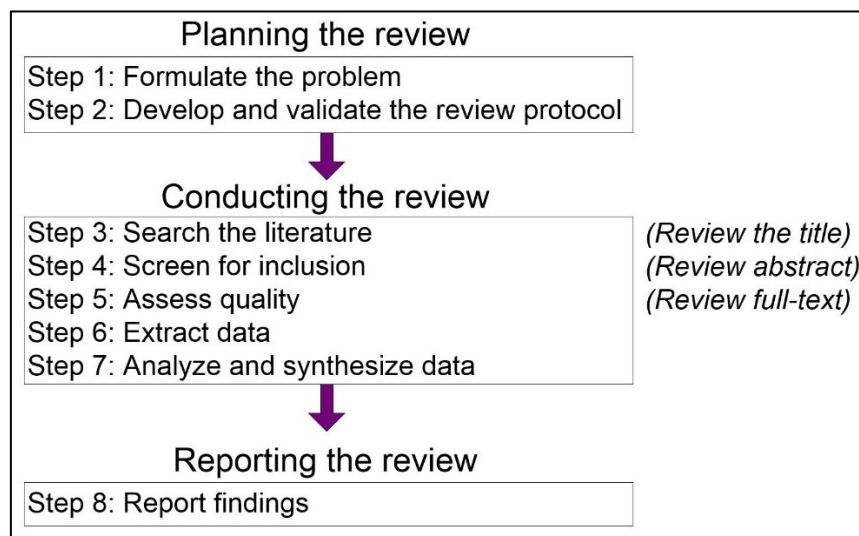


Figure 1-10: Overview of systematic literature review [27]

The overview is divided into three main parts: the first part covers the planning phase of the review, the second part focuses on conducting the review, and the last part discusses reporting on the review. Included in each of these main sections are the smaller systematic review outcomes of each phase.

Step 1: Formulate the problem

What methods are available in the literature for determining stope heat loads, either through calculation or simulation? Can the simulation method be used to compare stope heat loads?

Step 2: Develop and validate the review protocol

The process for conducting the literature review is a systematic literature review [27].

Step 3: Search the literature

An academic research database was used to search for literature. The aim of this step is to collect a broad and general selection of relevant sources. This was done by choosing keywords and their various combinations to search in titles, keywords, and abstracts within the database.

Because the goal of the systematic literature review is to find a method for determining the heat load of a region, work area or enclosure, this search was not limited to the mining industry. There are also many methods in the literature regarding the Heating, Ventilation and Air-conditioning (HVAC) industry and heat load calculations for buildings. Therefore, the findings in the HVAC industry could prove beneficial for this study.

The database used for the systematic literature review is Scopus. Scopus is a scientific database produced by Elsevier, which is an academic publisher. Scopus contains a range of peer-reviewed research in the form of conference proceedings, journals, and books [5]. The keywords and their modifiers entered into the database relate to both the mining and HVAC industries, with a focus on heat. Post modifiers are used to narrow the search to specific regions and types of studies. The keyword combination input into the database is shown in Table 1-1.

Table 1-1: Keyword combination inputs for databases

Pre-modifier	Core keyword	Post modifier 1	Post modifier 2
Mine	Heat	Region	Method
Mining		Production area	Study
Colliery		Production-area	Quantify
Coalery		Production zone	Quantification
HVAC		Production-zone	Evaluate
Heating ventilation and air conditioning		Workplace	Evaluation
Building ventilation		Work place	Determine
		Work-place	Determination

Pre-modifier	Core keyword	Post modifier 1	Post modifier 2
		Workspace	Simulation
		Work space	Analysis
		Work-space	
		Stope	

A total of 297 studies were retrieved from the Scopus database. Of these, 254 studies were related to mining, and 43 studies pertain to HVAC. These studies will move on to the next step, where their titles will be screened, followed by an analysis of their abstracts to determine inclusion.

Step 4: Screen for inclusion

Each of the 297 unique studies retrieved was evaluated based on their titles and abstracts to determine relevance to the study's scope and objectives. From the initial 297 studies, 89 were selected based on their titles; however, a further 60 were excluded after reviewing their abstracts. This process results in 29 studies that will be examined further through their full texts and quality.

Step 5: Assess quality

The full-text review of the 29 studies was conducted to determine their inclusion in the final state-of-the-art matrix. Typically, only recent studies from the past five years are included, and any study published after this period is normally excluded. However, the literature review indicates that little research exists in this field, and due to the small number of relevant studies, the publication date was not a reason for exclusion.

Step 6: Extract data

After completing the full-text reviews, a total of 8 studies were considered valuable for the study. This was done by reading through the whole document of each study. An additional 7 studies were included from backward and forward searches. Backward and forward searches are searches done in other databases to check whether more studies are found and to ensure more studies are included in the study. These research databases are Google Scholar, Researchgate and Science direct.

Step 7: Analyze and synthesize data

To assess the quality of the final studies, it is generally accepted that most should be journal articles; however, the journals should be accredited and industry-approved. An example of a journal article being approved in the study is the VDW method being published in "The mine

ventilation practitioner's book" [28] where it encourages mine ventilation practitioners to use the methods in the book. The pie chart shown in Figure 1-11 indicates that most of the studies (60%) are journal articles.

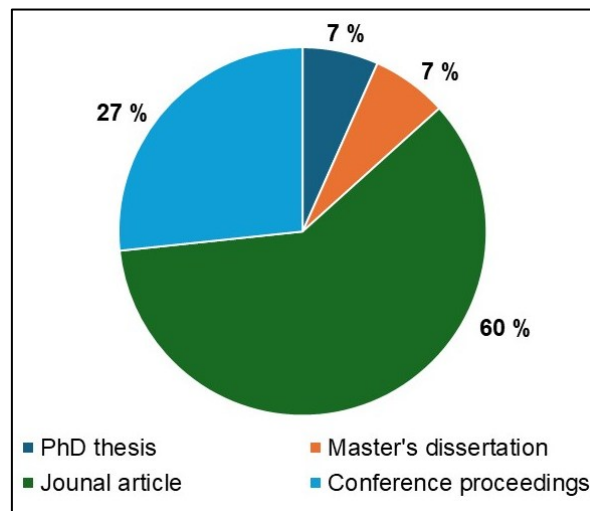


Figure 1-11: Breakdown for type of publication

The systematic literature review also revealed that few studies have been conducted in this field. The process could only identify 4 studies published in the last 5 years. Since the exclusion criteria did not eliminate other studies, it is clear that the remaining 11 studies were published over a longer period, with 4 of them dating before the 1990s. However, despite being older than 5 years, the literature analysis, Section 1.5.1, will show that these are high-quality sources that will significantly contribute to this study. Figure 1-12 displays the publication dates of the final studies over the years.

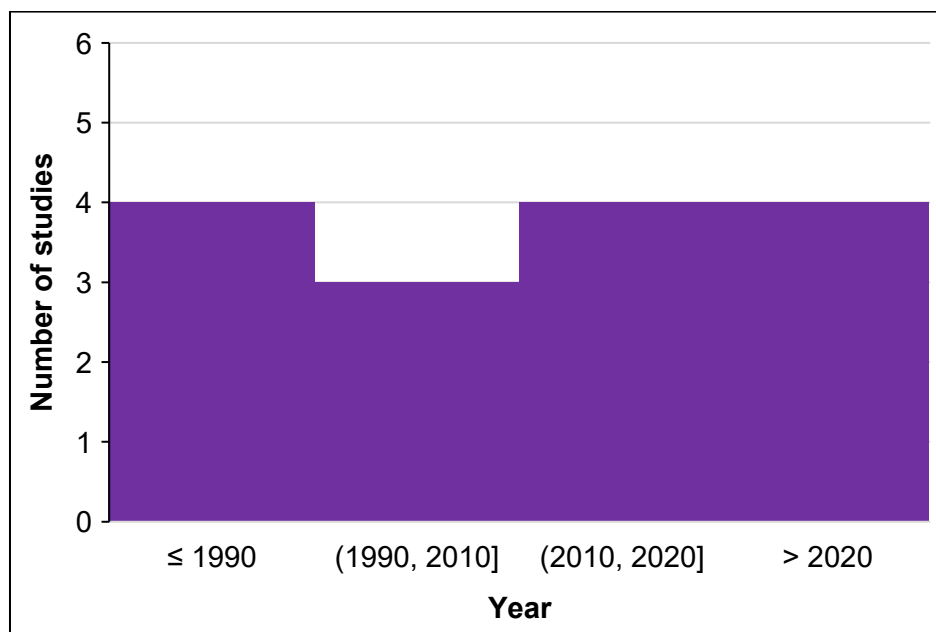


Figure 1-12: Publication dates of the final studies over the years

Step 8: Report findings

The systematic literature review process starts off by retrieving 297 studies from the Scopus database. The studies have undergone several steps so that only the highest quality papers remain to be used in the study. This process resulted in 15 studies that will be examined in the state-of-the-art section. Figure 1-13 summarises the process and results from the systematic literature study.

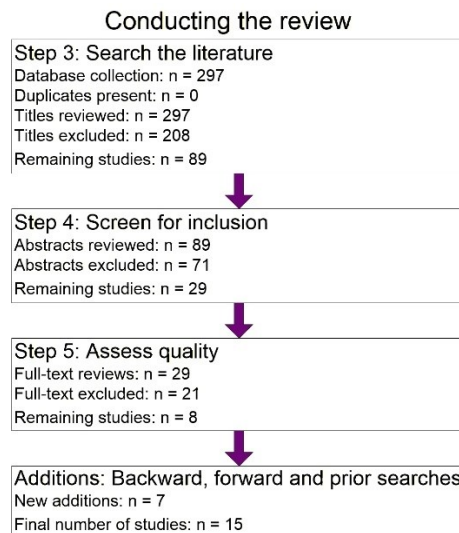


Figure 1-13: Summary of systematic literature review results

1.4.2 Concluding remarks from the systematic literature review findings

This section aims to highlight the type of studies that were retrieved from the systematic literature review but were excluded from the final selection.

Many of the studies also involve drilling boreholes for geothermal heat extraction, with various configurations being explored. These boreholes are drilled underground solely for the purpose of heat extraction and are harnessed on the surface as heat recovery.

Numerous investigations on backfill utilization aim to provide cooling to the stope; however, these primarily focus on quantifying the additional cooling capacity rather than determining the actual cooling requirements to offset deficits within the stope. Additionally, there are studies examining the use of geothermal energy from abandoned stopes for energy recovery, thus contributing to the reduction of fossil fuel consumption in heating the intake shafts.

The HVAC side of things primarily focuses on energy savings by capturing either thermal radiation from the sun or heat recovery from heat pumps to make heating processes more efficient. Studies in the HVAC field have not provided a comprehensive view of how much cooling is needed or

how much heat is generated in the building, and how much of that heat must be offset, apart from two studies which will be discussed in the next section.

1.5 State of the art

The state of the art aims to conduct a thorough review of the existing literature on quantifying stope heat loads. It begins by selecting studies that meet all the criteria from the systematic literature review and then performing a literature analysis that summarizes the main ideas and key findings relevant to this study. Next, the studies are further summarized in the state-of-the-art matrix to evaluate which of the main categories they fall into.

1.5.1 Literature analysis

This section outlines the studies that meet the inclusion criteria for the state of the art. These studies will help shape the chapter, as their findings and methods will be analysed to assess their relevance to this study's objectives. The following sections summarize the key information and results from each study related to heat loads in a stope.

Source 1: Practical determination of heat loads for existing deep level gold mines [8]

Authors D. Nell

Year published 2019

The PhD thesis addresses the problem that the mining industry uses outdated methods to determine their total mine heat loads. Nell's PhD literature review concluded that there are newer and more accurate methods for determining heat loads, but they require extensive numerical and analytical calculations, which are too time-consuming for mine ventilation engineers working in industry. This thesis tackled both issues by developing a novel and practical method for determining total mine heat loads that mine ventilation engineers can easily apply and that is accurate. The thesis compared the current industry approach and simulation method to the new novel method (energy balance method). Another significant contribution of this study is demonstrating how the new method aligns with Industry 4.0 advancements in the mining industry. The thesis also discusses the effects of seasonal changes and the thermal flywheel effect concerning total mine heat loads.

Key findings

The thesis determined the full mine heat loads using a novel energy balance method for two case studies, and compared the results to the current industry approach and simulation. For one of the case studies, although the industry approach predicts the full mine heat within 9.1%, it is clear that its estimate of geothermal energy has a 43% error. In contrast, the simulation method closely matches the heat load within 1.3% and the geothermal energy within 7.3%. Additionally, the industry approach underestimates the heat. Table 1-2 displays these results.

Table 1-2: Heat balances of heat sources and heat sinks [8]

Parameter	Unit	Energy balance	Industry approach	Simulation Model
<i>Total heat</i>	[kW]	14 876	13 519	15 075
<i>Geothermal heat</i>	[kW]	2 602	1 482	2 806
Overall error (Compared to energy balance approach)	%	-	9.1%	1.3%
Geothermal error (Compared to energy balance approach)	%	-	43 %	7.3%

Source 2: The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield [26]

Authors S.J. Bluhm, N.A. Alexander, T.W. March, P. Bottomley, F. von Glehn

Year published 1986

The journal article conducted an empirical study to determine the heat load of a stope. Heat sources and sinks were identified and quantified. The geothermal energy (heat coming from the rock) was measured using an energy balance, because this component was too complex to determine accurately through analytical methods at the time. A total of 19 measurements were taken over two months on a case study stope.

Key findings

The study found that geothermal energy was by far the largest contributor to the heat within the stope, with ventilation air serving as the primary heat sink. It concluded that the heat load of the

stope ranged from 400 kW to 800 kW, averaging 542 kW. The study confirmed the relationship between ore extraction and heat load, stating that 80 W/tonne/month of heat is generated by the stope. Figure 1-14 displays the results of the waterfall heat balance, illustrating the relationship between heat sources and heat sinks.

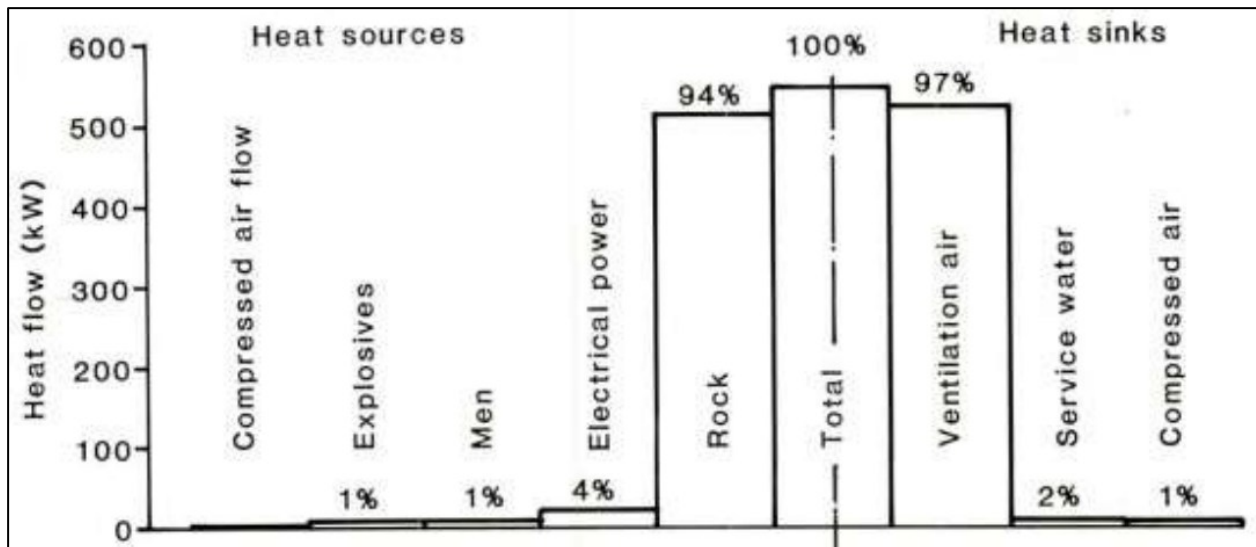


Figure 1-14: Heat balances of heat sources and heat sinks of the Klerksdorp stope[26]

Source 3: Heat load in a ledging stope at Free State Geduld Gold mine [29]

Authors E. de Jager

Year published 1989

This paper is very similar to the article titled “The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield.” The study conducted an empirical investigation to determine the heat load of a production area. The difference with this article is that instead of a stope, the heat load study was performed on a ledging stope. Similar to the above-mentioned article, heat sources and sinks were also identified and quantified, and an energy balance was carried out to determine the geothermal energy.

Key findings

Similar findings were also obtained, with some variations due to differences in the age of the stope. Geothermal energy contributed to 93% of the heat generated, and ventilation air accounted

for 79% of heat sinks. The overall and day shift heat loads were 97.6 kW and 149.9 kW, respectively. Figure 1-16 shows the results of the waterfall heat balance, illustrating the relationship between heat sources and heat sinks.

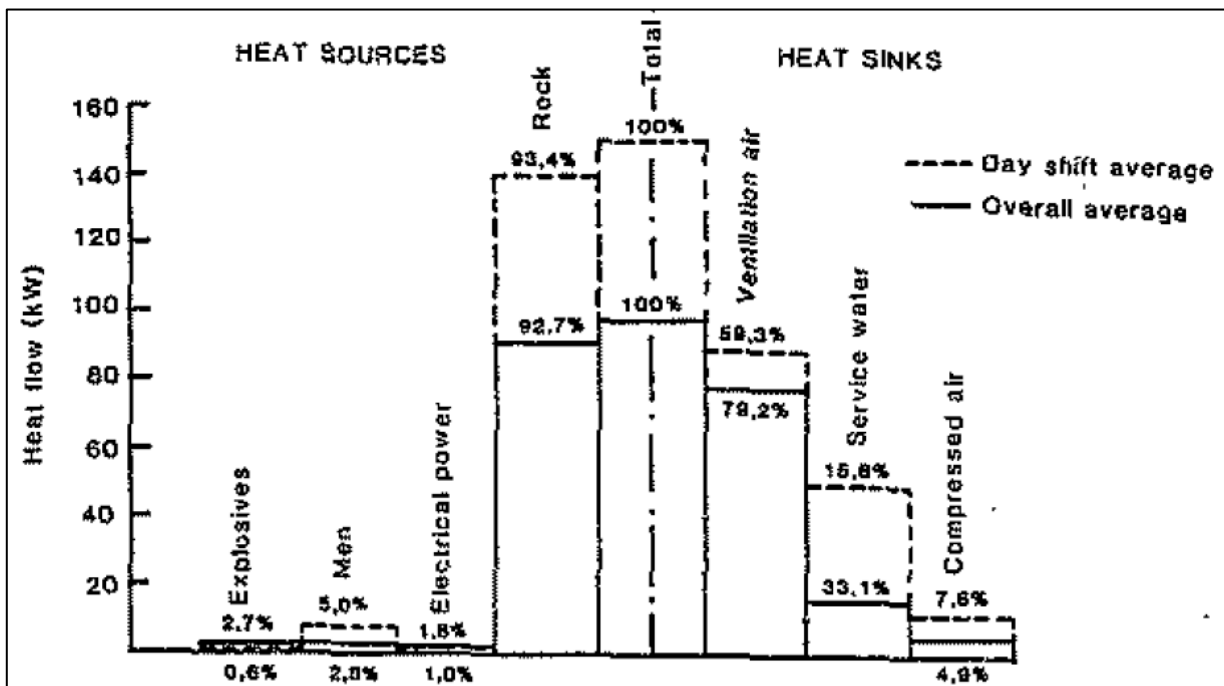


Figure 1-15: Heat balances of heat sources and heat sinks of the Free State ledging stope

Source 4: The analysis of ventilation and cooling requirements for mines [30]

Authors

J. Van der Walt, E.M. De Kock, L.K. Smith

Year published

1983

The paper's goal was to develop an alternative method for mine planning and calculation of mine heat loads. The Van der Walt's method (VDW) is systematic and aimed to break down each mine region to determine its individual heat load. It also explains how to calculate the total cooling supplied by the mine's infrastructure, and suggests ways to improve ventilation and cooling strategies.

Key findings

The method described in this paper separates the heat load of each mining region into temperature-dependent and temperature-independent parts. The temperature-dependent part includes all parameters that rely on air temperature, such as exposed rock, broken rock, and

ground water. The temperature-independent part includes all parameters unaffected by air temperature, like locomotives, dewatering pumps, fans, substations, electrical equipment, diesel equipment, and personnel. The key benefit of this method is that it allows the heat load of the stope to be isolated and calculated specifically for this region.

Source 5: Numerical modelling of heat flow in mines [31]

Authors

F.H. von Glehn, R. Hemp, R.C. Funnell

Year published

2002

This study addresses the complexities of determining the geothermal energy that flows from the rock face. The study tackles these complexities by developing a rock heat model that includes the complexity of different boundary conditions, stope wetting, and fluctuations in ventilation areas flowing through the excavations.

Key findings

To develop the rock heat model, in-field measurements were conducted underground. A key focus of the field measurements is what happens at the newly exposed rock face. To determine this, temperature probes of varying distances were drilled and inserted into the hanging wall, footwall, and advancing faces. The purpose was to track where the VRT in front of the rock was to accurately develop the model. A schematic of the temperature probes and setup is shown in Figure 1-17.

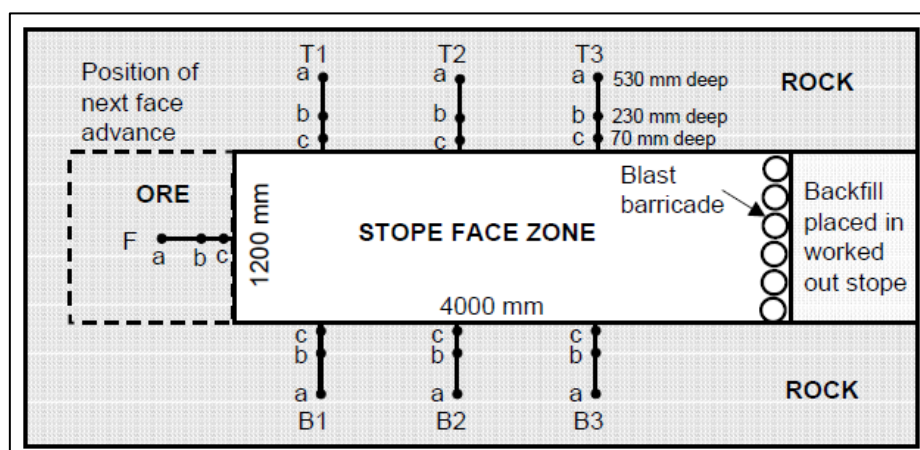


Figure 1-16: Position of temperature probes [31]

The results of the infield measurements are shown in Figure 1-18.

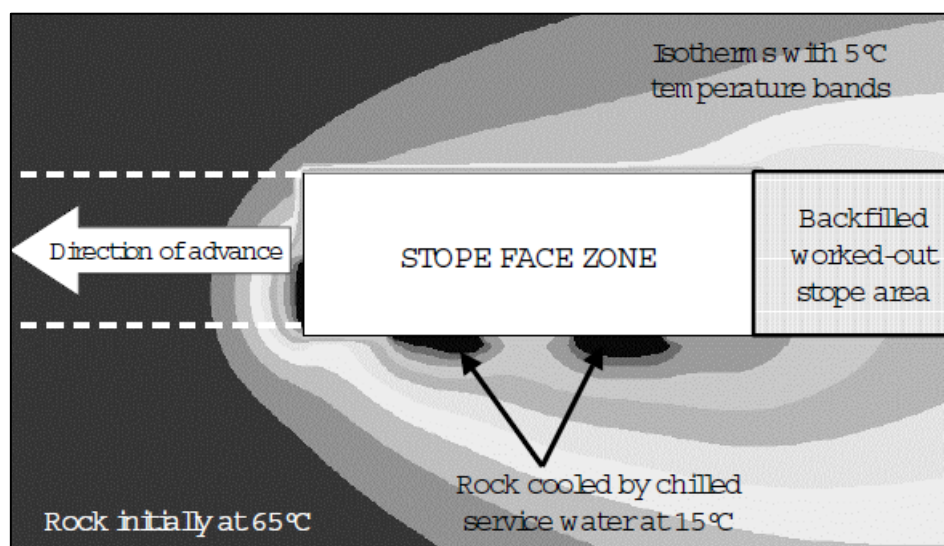


Figure 1-17: Rock temperature profile bands around open stope excavation [31]

It is clear that the rock temperature profile bands are not uniform around the open excavation. The VRT front on the left side, measured at 65°C, is very close to the excavation due to the low number of days exposed. At the footwall, it is observed that the chilled service water significantly cooled the surface and absorbed geothermal energy, causing the VRT front to move deeper into the rock surface in that area. These findings contributed to the development and enhancement of the rock heat model derived from the study.

Source 6: Variations in ultra-deep, narrow reef stoping configurations and the effects on cooling and ventilation [32]

Authors S. Bluhm, M. Biffi

Year published 2001

The paper evaluates different stoping configurations used in the gold mining industry for narrow reef mining in ultra-deep operations, and determines which configurations provide the best thermal conditions. It also discusses the pros and cons of using backfill in the stope.

Key findings

The paper's findings show that the dip pillar underhand and overhand configurations produce the lowest heat load compared to all other configurations, while the down-dip configuration results in the highest heat load. The paper also states that including backfill in the stope reduces the stope's heat load by 30% because the backfill acts to seal off the worked-out area, effectively decreasing

the exposed rock surface. Additionally, the paper mentions a drawback of using backfill: if the slurry reaches the stope at temperatures higher than the air temperature, the pumping process will increase the heat load in the stope. Information regarding the calculation of the stope heat load was not provided. Figure 1-19 depicts the breakdown of heat sources and sinks in a typical stope, based on the paper's findings.

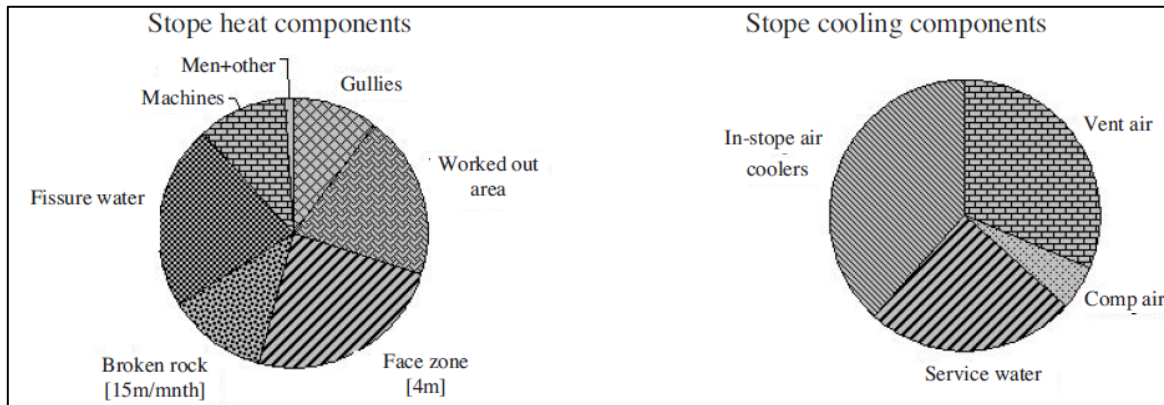


Figure 1-18: Breakdown of the heat sources and sinks in a typical stope [32]

Source 7: Heat Balance Determination Methods for Mining Areas in Underground Mines – A Review [25]

Authors A. Wróblewski, A. Banasiewicz, S. Gola

Year published 2021

The paper reviews current literature on estimating heat loads in underground mines. It states that, because of the complex nature of the underground environment, the best way to estimate heat loads is through energy balances. The paper also highlights the most important heat sources to consider when conducting energy balances. Additionally, the study reviews various methods for determining heat fluxes from the rock face.

Key findings

The study mentions that the procedures found in literature for conducting energy balances were formulated many years ago. This is evident from journal articles such as “Heat load in a ledging stope at Free State Geduld Gold mine” and “The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield,” which were published in the 1980s. The paper notes that because these methods are quite old, there is a risk that they may not be accurate. However, in Nell’s PhD,

the thesis indirectly verified that the energy balance method remains accurate since the thesis results differed from simulation by only 1.3%, as mentioned earlier.

Source 8: An empirical study of heat flow in stopes in South African gold mines [33]

Authors J. de V Lambrechts

Year published 1959

This paper was published as a supplement to Lambrechts' original paper. It presents the technical discussions of Prof T. Boldizar and Mr C. Jones. Lambrechts' paper was an empirical study on how to quantify the changes in air temperatures as it flowed through the stopes.

Key findings

Lambrecht's paper states that the heat from the surrounding rock is the primary heat source in the stope. He also measured how the wet-bulb air temperature increased as it flowed through the stope. The discussions in this paper emphasize ways to improve Lambrecht's findings and approach to the calculations. The technical discussion included that Lambrecht's model does not account for the change in humidity of air as it travels through the stope, nor does it consider any latent heat and evaporation from the wet footwall surfaces. It was also stated that observing only the wet-bulb temperature variations through the stope is insufficient, and it was recommended to instead observe the enthalpy change through the stope.

Source 9: Analysis of Thermal Environment and Its Influencing Factors in Deep Stope of Metal Mine [34]

Authors S. You, J. Sun, H. Ji, Q. Feng

Year published 2022

The purpose of the paper was to better understand the different factors that contribute to the heat load of a stope and why certain factors influence the environmental conditions more than others. The paper is divided into three parts. The first part aims to identify the heat sources and determine how much heat is released by each. The second part uses the entropy weighted method (EWM) to assess each factor's impact on the thermal conditions. The weights are determined by the

degree of uncertainty and the amount of change each factor induces on the conditions. Finally, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method is employed to identify which level has the highest risk of experiencing problems with thermal conditions.

Key findings

The paper findings indicate that the heat from the surrounding rock contributes the most to the levels. However, the EWM showed that the water flow rate of the groundwater has the greatest effect on the thermal conditions. The TOPSIS method is typically used in multi-objective decision-making and in this case study was used to rank the amount of heat generated by each source for each level [35]. The TOPSIS method concluded that level 960 m has the most significant problems regarding thermal conditions. This makes sense, because level 960 m has a substantially higher groundwater heat flow compared to the other levels, while the other parameters remained fairly consistent across the levels. Figure 1-20 shows the percentage contribution of each heat source, and Figure 1-21 provides the breakdown of the weightings.

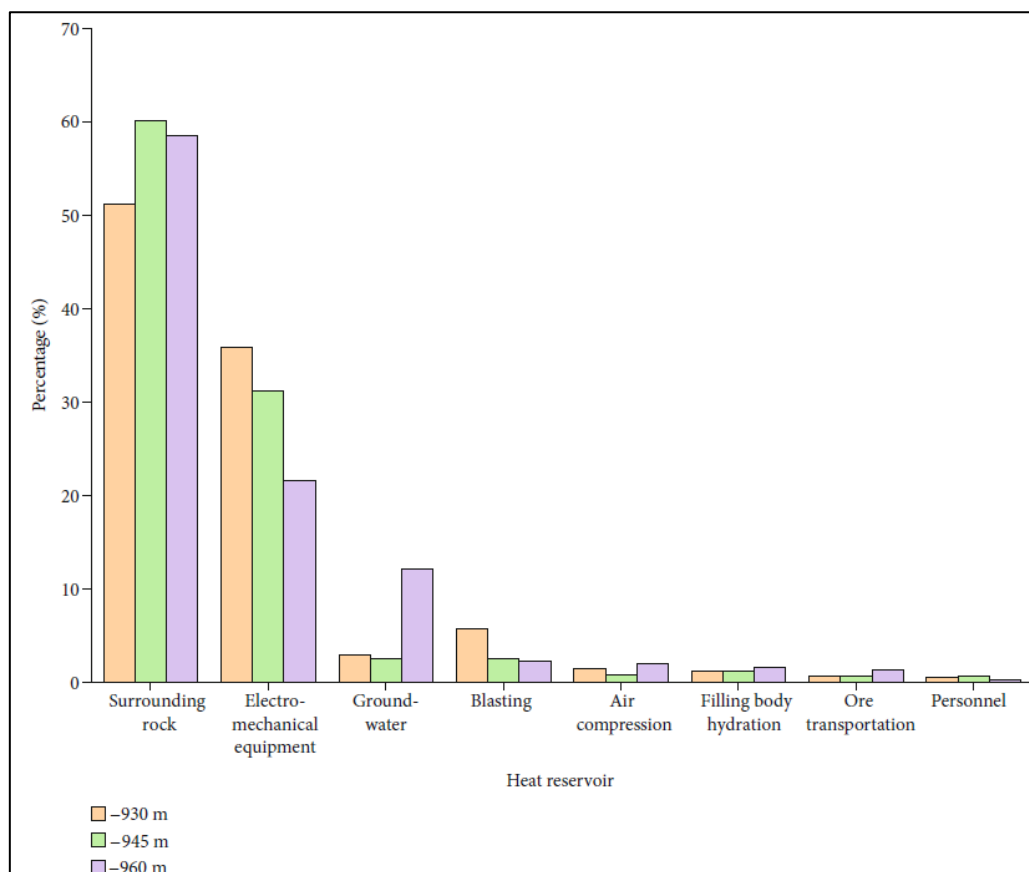


Figure 1-19: Percentage contributed by each heat source [34]

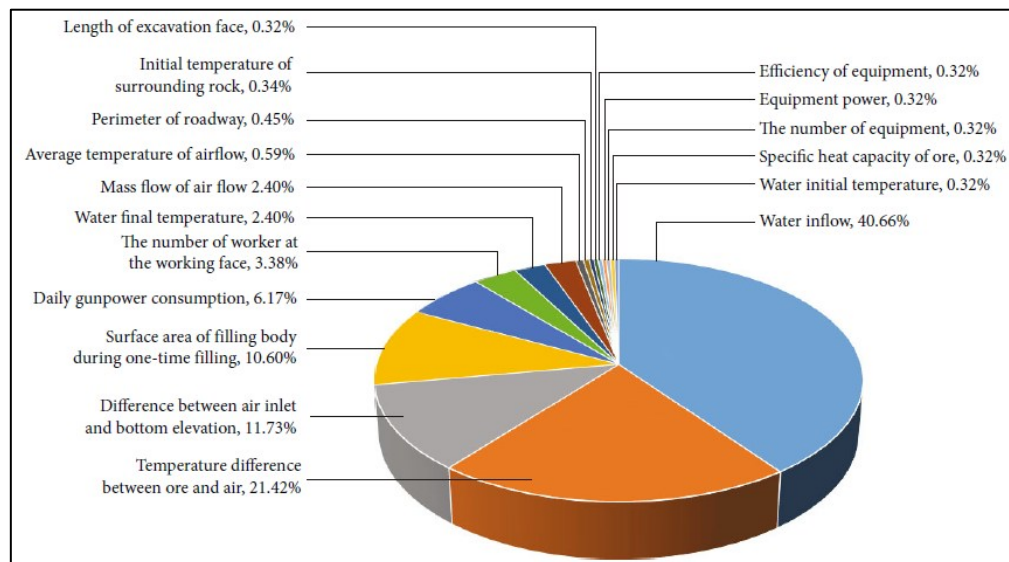


Figure 1-20: Percentage breakdown of parameter weighting on thermal conditions [34]

Source 10: The management of heat flow in deep mines [11]

Authors H. Wagner

Year published 2010

The paper's aim is to find ways to control heat flow in mines. It starts by identifying the different heat sources within the mine and calculating the heat generated by each source analytically. The paper offers recommendations on how to minimize the amount of heat produced in an underground mine.

Key findings

The paper's findings are that the largest source of heat in an underground mine is geothermal energy. It compares the analytical method with an established method developed by Van der Walt and Whillier and finds that they compare well. The paper states that the best way to reduce a mine's heat load is to lower the geothermal energy. The first recommendation is to minimize open tunnels and to focus mining operations on a few faces, while increasing face advances to rapid rates to meet planned production rates. The second recommendation is to insulate the exposed rock surface to increase thermal resistance and reduce the heat transfer coefficient.

Source 11: Effects of rock-airflow conjugated heat transfer in development headings: A numerical study [36]

Authors

S. Xin, W. Wang, C. Zhang, C. Li, H. Li, W. Yang

Year published

2022

The study addresses the problem of how to ventilate development faces with regard to optimising the cooling load to provide the best environmental conditions for workers. The paper considers different tunnel shapes, rock roughness, and Reynolds numbers to determine which options minimize the cooling load. The study employs CFD numerical simulations to calculate the convective heat transfer coefficients, wall temperatures, and the length of the heat transfer region.

Key findings

For the cross-sectional area, the circular shape results in a higher heat transfer coefficient, while the three-centred arch and rectangular cross sections provided similar heat transfer coefficients. The higher the surface roughness of the tunnel, the higher the heat transfer coefficients for all shapes. The higher the Reynolds number, the higher the heat transfer coefficient and the cooler the wall temperature, because a lot of energy is extracted from the face, and the VRT front is pushed deeper into the rock. The higher the Reynolds number, the larger the heat transfer region becomes and the more heat is extracted. Figure 1-22 and Figure 1-23 show the CFD simulation results and summary of the paper's findings.

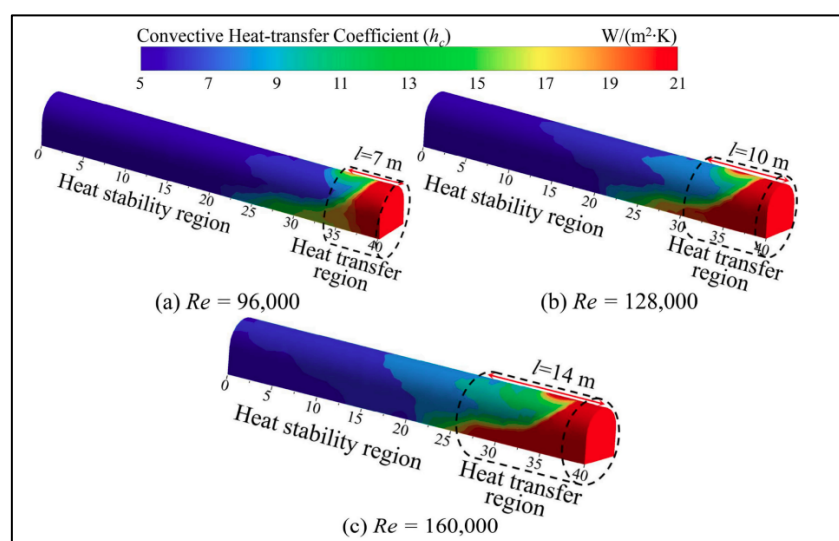


Figure 1-21: CFD simulation results of the different parameters [36]

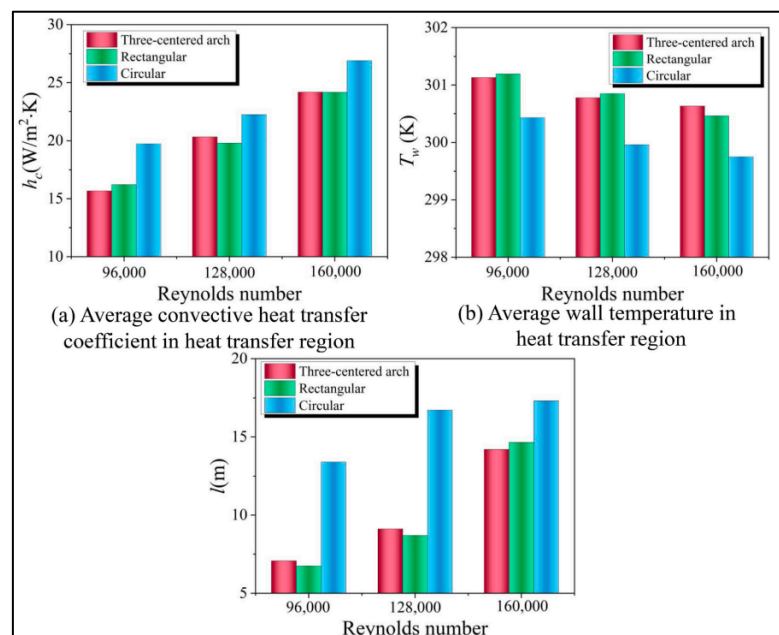


Figure 1-22: Effect of Reynolds number on the heat transfer coefficient, wall temperature and length of the heat transfer region [36]

The study concludes that providing more air to ensure a comfortable environment for the workforce can negatively affect the amount of heat extracted from the rock, which increases the cooling load. It indicates that to minimize geothermal energy extraction, the lowest Reynolds number should be used; however, this also has a negative impact on air temperature, and both parameters need to be optimized for the best outcome.

Source 12: Heat flow assessment in an underground mine: An approach to improve the environmental conditions [37]

Authors M. Bascompta, A.M. Castañón, L. Sanmigue, J. Oliva

Year published 2016

This study focuses on identifying the heat sources within an underground mine and presents a project proposal to improve underground ventilation conditions, which will enhance workers' productivity. The study identifies and breaks down the heat sources relevant to the case study mine. The project proposal is to replace diesel mechanized machinery with an electric fleet.

Key findings

The study analyses the different heat sources in detail. It also concentrates on mechanized machinery, examining the types used, their quantities, and separating their heat into sensible and

latent parts. This study used the simulation programs ClimSim and VNet for its findings. The study shows that replacing diesel machinery with an electric fleet will decrease their heat load contribution from 74% to 52%. Additionally, it compares the contribution of each heat source between the diesel and electric mechanized fleet. It should be noted that, in this case study, the mechanized fleet contributes the most to the heat load, which is usually not the case, as geothermal heat is typically the biggest contributor to heat in a mine [8, 26, 29, 34]. Figure 1-23 shows the breakdown.

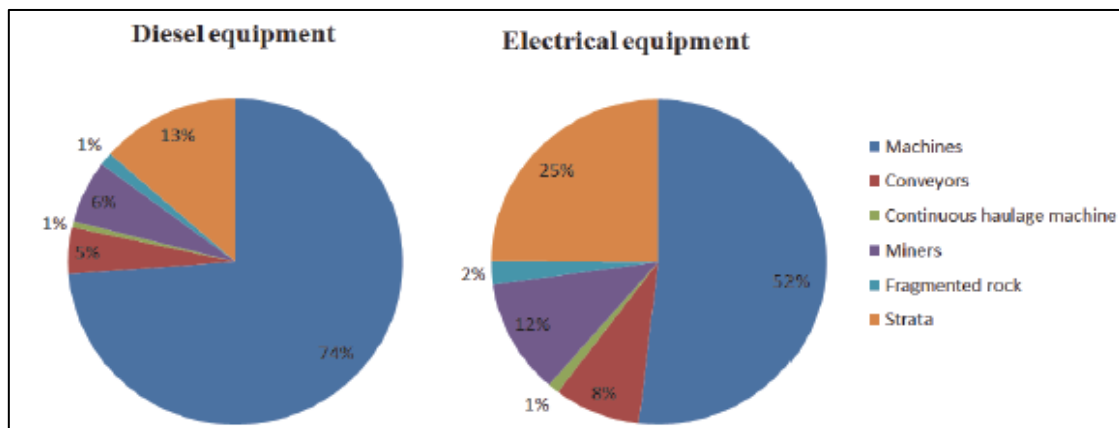


Figure 1-23: Breakdown of heat sources and their contribution when diesel vs electric mechanised machinery is used [37]

Source 13: Heat Balance Analysis of an Office Building with Fully Glazed Façade in Tropical and Temperate Climates in Brazil [38]

Authors M.M. Pinto, F.S. Westphal

Year published 2021

This study examines how window types affect HVAC cooling loads in an office. It hypothesizes that current Insulated Glass Unit windows (IGUs) increase cooling demand at shift start compared to Single-pane Laminated Glass Unit windows (SGULs). IGUs have higher thermal resistance, reducing heat flux during the day and night time. This means that when workers return in the morning, the HVAC system faces a higher cooling load. SGUL windows, with lower thermal resistance, dissipate more heat at night, lowering the morning cooling requirement.

Key findings

The theoretical cooling load of the office buildings was simulated using the EnergyPlus program [39]. Heat inputs included the number of people, outdoor temperature heat fluxes of the

walls, floor, ceiling, and windows, as well as heat generated from office equipment and leakages into the building. A heat balance was performed to determine the cooling load by setting the cooling equal to the heat produced by the above-mentioned sources. The study's hypothesis is proven correct, since the IGU window demonstrates an overall higher cooling load than the SGUL window type. Figure 1-24 shows the results of the heat balances between the two windows for summer across all four sides of the building.

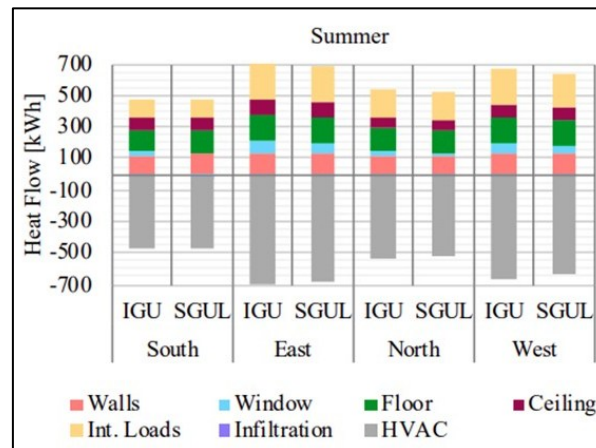


Figure 1-24: Heat balances for the IGU and SGUL window types [38]

Source 14: Numerical Study on Accumulative Effect Owing to Heat Storage by Building Envelopes in HVAC Systems [40]

Authors W. Li, G. Gong, J. Chen

Year published 2020

The study addresses a shortcoming in the current method for determining the cooling and heat loads of buildings. According to the paper, the shortfall lies in how exterior ambient temperature fluctuations affect the heat flux into the building (the accumulation effect), which the current method fails to account for. The new method presented in this paper develops a numerical approach that includes the accumulation effect.

Key findings

A case study was conducted on a building, during which in-field measurements were taken to determine the experimental cooling and heating loads for the building. The new method was

compared to both the in-field measurements and an established simulation program (EnergyPlus). The theoretical cooling and heating loads were simulated using the EnergyPlus program, which omits the accumulation effect, whereas the new method includes this effect. The comparison is indicated in Figure 1-25.

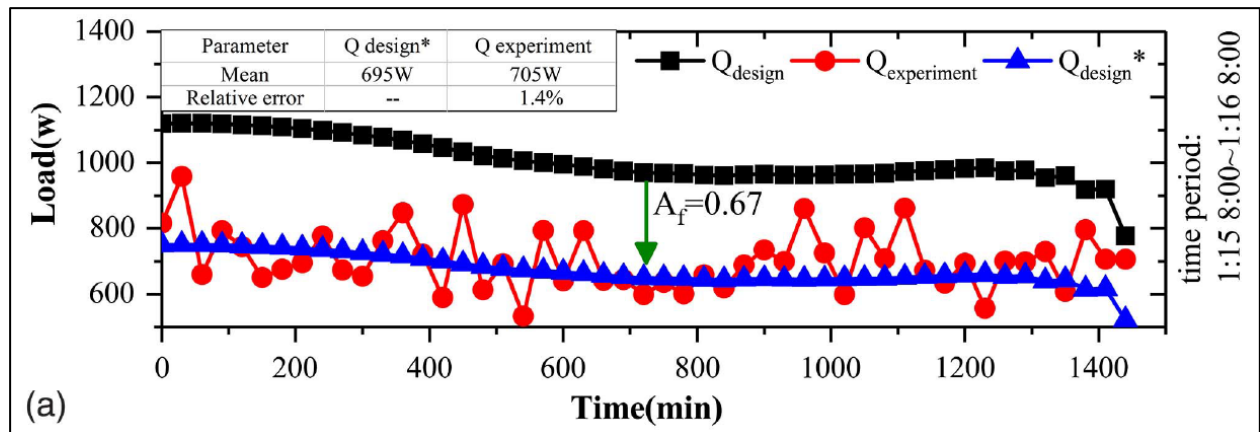


Figure 1-25: Comparison of methods with and without the accumulation effect [40]

What is clear is that the EnergyPlus program overpredicts the heat load (black line and blocks), while the new method (blue triangles), which includes the accumulation effect, more accurately predicts the heat load and matches the in-field measurements within 1.4%.

Source 15: Investigation on the new design method of heat source for reducing the energy consumption in the shaft antifreeze system [41]

Authors Y. Bai, L. Yang, S. Zheng, W. Tang

Year published 2020

The study focuses on determining the heat load of intake shafts and horizontal tunnels to combat extreme cold seasonal ambient temperatures. It addresses a problem where the current practice underestimates the heat load and develops a new method to accurately determine the amount of heat needed by the mine's anti-freeze system.

Key findings

It addresses the issue that the current design heat load is a fixed value for all seasons, and emphasizes the need to consider seasonal changes in ambient conditions. It proposes that the

primary anti-freeze system should be designed for moderate ambient temperatures. When conditions become extreme, a standby anti-freeze system is activated to handle the increased heating demand. The study implements heat load balancing for both the main and standby anti-freeze systems. It explains that, for example, if the actual heat load is 50 kW, the main anti-freeze system can only supply 40 kW. Therefore, the standby units should be designed to cover the remaining 10 kW. This study discusses using some form of heat load method to heat intake tunnels to meet a specific target; however, it does not specify what the heat load method is or provide any formulas or principles. The study also does not use simulation, and in the South African context, the seasonal change that results in downcast shafts freezing is not relevant.

1.5.2 State of the art matrix

The state-of-the-art matrix aims to better summarize the studies that have gone through the literature analysis phase by categorising them accordingly. This categorisation helps identify the specific criteria each study meets or does not meet. The criteria are discussed below:

- **Identification of heat sources and sinks:** Does the study indicate any of the sources and sinks present in the stope that will aid this study when conducting its own in-field case studies?
- **Quantitative method:** Does the study mention any method (analytical, numerical) that will assist in quantifying the heat sources and sinks?
- **Stopes:** Is the focus on a mining stope or production area?
- **Holistic method:** Does the study present a comprehensive approach that encompasses all the sources and sinks to enable heat load calculations relevant to this study?
- **Simulation:** Does the study utilise simulation software to determine its heat load? This is a requirement, because the nature of this study is a simulation approach.

The state-of-the-art matrix is shown in Table 1-3.

Table 1-3: State-of-the-art matrix

Study	Identification	Quantitative method	Stopes	Holistic method	Simulation
[8]					
[26]					
[29]					
[30]					
[31]					
[32]					

Study	Identification	Quantitative method	Stopes	Holistic method	Simulation
[25]					
[33]					
[34]					
[11]					
[36]					
[37]					
[38]					
[40]					
[41]					
Included			Not included		

1.5.3 Summary of the literature review process

What is evident in the state-of-the-art matrix is that not all categories have been satisfied. The first three studies in the matrix indicate that holistic methods have been employed on stopes to determine their heat load, but a gap exists because simulation was not used to either assist the study or compare the findings.

The most comprehensive approach for determining heat loads is through an energy balance. For the “Holistic method” column that 8 out of the 15 studies conducted variations of heat load or energy balance analyses. Journal articles such as “The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield” [26] and the dissertation “Heat load in a ledging stope at Free State Geduld Gold mine” [29] provide in-depth information on how to conduct an energy balance within stopes. Nell’s PhD thesis [8], “Practical determination of heat loads for existing deep level gold mines,” also demonstrates how to perform an energy balance across a full mine, which includes the stope mining region. And also with the article “The analysis of ventilation and cooling requirements for mines” [30] which is one of the ways in which industry calculates its stopes heat loads. These studies will serve as the foundation for this study to achieve its research objectives.

1.6 Problem statement and objectives

The literature clearly covers the identification and measurement of heat sources and sinks in mines. However, it lacks confirmation that simulation can be used to determine a stope's heat load. Such confirmation would allow mine ventilation professionals to use simulation for

determining heat loads. To ensure correctness the results obtained by using simulation as method must be validated.

Thus, the simulation method must be validated by applying it to case studies. This will show that the technique in this study can be used by mine ventilation practitioners to predict expected stope heat loads and compare their own calculations using industry-accepted methods.

Therefore, there is a need to quantify a stope's heat load with an energy balance, develop simulation models, and use the simulation to predict stope heat loads. As well as for all case studies calculate the stope heat load of an industry accepted method which will be compared to the simulation method. This study also aims to fill the gap left by two previous studies ("The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield" [26] and "Heat load in a ledging stope at Free State Geduld Gold mine" [29]) that do not meet the criteria for using simulation to compare their calculated heat load.

The main objects of the study are to:

1. Conduct in-field measurements on three currently active gold mining case study stopes.
2. Determine the heat load of the three case study stopes using the energy balance method.
3. Develop simulation models of the case study stopes and simulate the heat load.
4. Retrieve results and information from the literature case study stopes. These are the stopes from the two journal articles titled "The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield" [26] and "Heat load in a ledging stope at Free State Geduld Gold mine" [29].
5. Develop simulation models of the literature case study stopes and simulate the heat load.
6. Determine the stope heat load of all case studies using an industry accepted method. This method is the VDW method presented in "The analysis of ventilation and cooling requirements for mines" [30].
7. Compare the energy balance method and VDW method to the simulation method.
8. Conclude whether the simulation method has been validated and can compare with the VDW's method.

Sub-objectives include:

1. Develop layouts and procedures for auditors to conduct the in-field measurements on the case study stopes.
2. Measure the temperatures and flows of ventilation air and service water entering and leaving the boundary, and also what happens within the boundary.
3. Break down the findings from the case study stopes.

4. Develop layouts on the results of in-field measurements

1.7 Research methodology

A case study methodology offers advantages because it allows the collection of insights on a specific phenomenon [42]. It can focus on rare or unusual cases and examine them in detail within their unique context, such as with stope heat loads, which are a rare and nuanced aspect of deep-level mine planning. This approach enables comprehensive questioning and flexible insight gathering, providing meaningful understanding [43, 44].

This is why this research methodology is best suited for the outcomes of this study. This aligns with the study objectives, which include conducting in-field measurements on three active gold mining stopes and utilizing information from case studies presented in. "The measurement of heat loads in a deep level stope in the Klerksdorp Goldfield" [26] and "Heat load in a ledging stope at Free State Geduld Gold mine" [29]. Within this real-world context and the simulation and VDW methods being used, the study objectives will be achieved. The case study methodology process that will be employed in the study is shown in Figure 1-26.

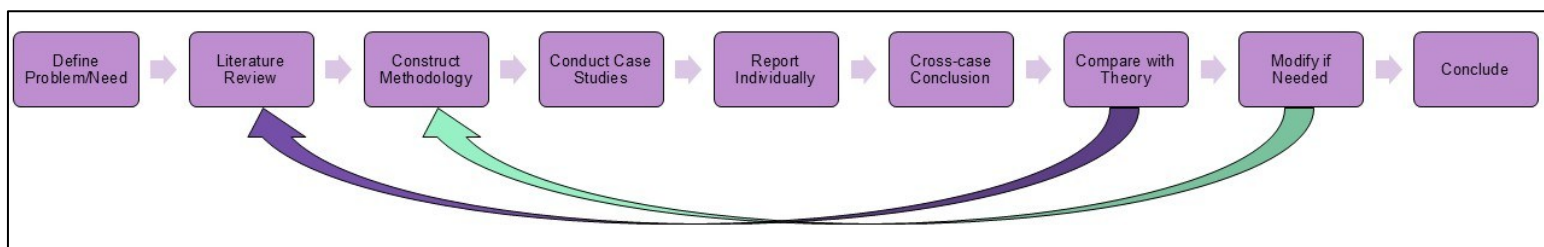


Figure 1-26: Case study methodology process [45]

1.8 Conclusion

This chapter introduces the study's background, literature review, and aims. The mine must plan ahead for mining areas, facing challenges like Eskom's impact on electricity and cooling costs. Simulation software aids ventilation engineers in predicting cooling needs, but questions about their accuracy remain, raising doubts about their reliability.

The systematic literature review revealed that simulation has indeed been used and proven accurate for calculating full mine heat loads and isolated tunnels. However, no literature has verified whether the complex nature of stopes in gold mining allows this tool to be trusted.

Based on these gaps in the literature, this study aims to compare the use of simulation as an approach for predicting heat loads in deep-level gold stopes. This will be achieved by conducting an energy balance on three active gold stopes to determine their heat loads. Simulation models will be developed for these case study stopes based on in-field measurements. Additionally, two

other literature case study models will be created and their heat loads simulated. Finally, a well-established industry method will be employed and compared to the simulation approach. The following chapter outline will be used to execute the study's objectives, aligning with the case study methodology, this is shown in Figure 1-27.

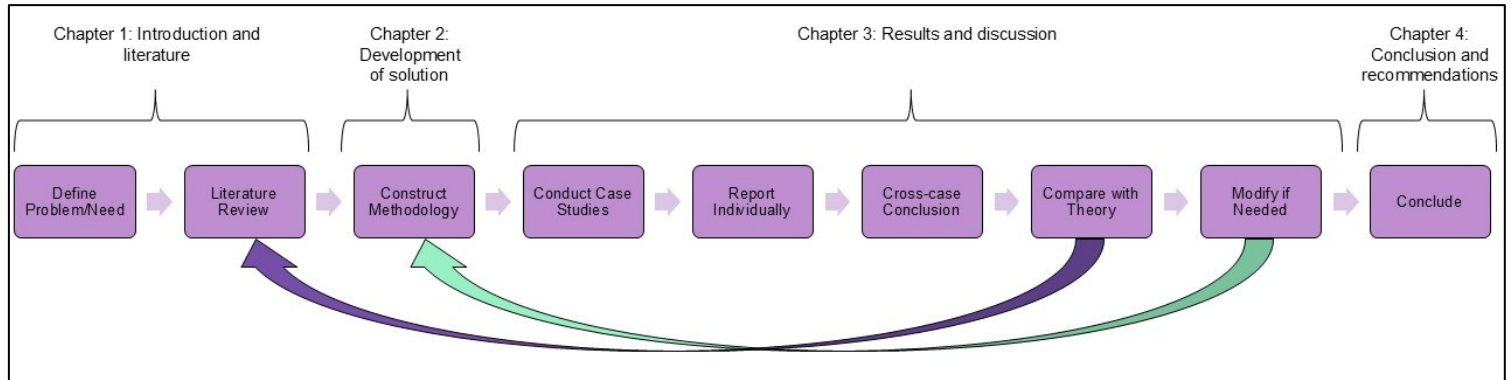


Figure 1-27: Chapter outline [45]

CHAPTER 2: DEVELOPMENT OF SOLUTION

2.1 Preamble

This chapter discusses the rationale and approach of the study. It will discuss the energy balance approach for determining the heat load of a stope, as well as the construction and output of the simulation models for the different case studies. The method is based on established practices in the literature and also aims to fill gaps in the state-of-the-art matrix, which involves developing a solution to identify and quantify heat sources and heat sinks, focusing on the stope/production area, uses a holistic approach such as the energy balance method to quantify heat load and incorporates a simulation method to compare the findings.

2.1.1 Outline of chapter and study

Based on the literature discussion in Chapter 1, it is evident that an energy balance around the physical system eliminates the most uncertainty. Thus, the foundation of this study will be based on this method. A basic outline of the study is given below.

Information gathering, data collection, and analysis will be obtained from a case study mine. Subsequently, in-field measurements will be conducted to capture real-life heat generation and absorption using the energy balance method. The energy balance method has been selected because it is the most common approach found in the literature analysis and provides a comprehensive way to determine stope heat loads. Using the data from these measurements, simulation models will be built to create a model of the stopes, and their heat loads will be simulated. The insights gained will enable the construction of simulation models of literature case study stopes with their recorded information and data. Their heat loads will also be simulated. Finally, the VDW method will be used for verification and comparison of the calculated heat loads. As seen in Chapter 1, there is a need to verify whether the simulation results are accurate and applicable in the mining industry, specifically in the stopes. This chapter aims to develop a method to meet that need. The diagram below outlines the basic approach to be followed in this study.

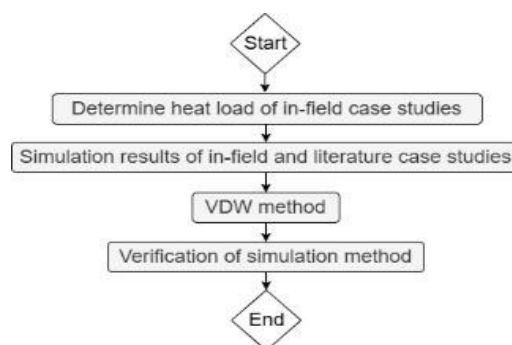


Figure 2-1: The basic method of the study

2.2 Determine heat load of in-field case studies

2.2.1 Fundamental principle

At their core, heat load predictions adhere to the first law of thermodynamics.

$$\Delta U = Q - W \quad (1)$$

where:

ΔU = Internal energy [J/s]

Q = Heat energy [J/s]

W = Work done [J/s]

Where the internal energy, ΔU , within a boundary is equal to the heat transferred, Q , and work done to the system, W , the total energy contained in an isolated system is constant. The first law also encapsulates the law of energy conservation, which states that energy cannot be created or destroyed; energy within a boundary can only be transformed from one form to another. In the context of mining, heat sources found in a stope (geothermal, electricity, metabolic, fuels etc.) are transferred to heat sinks (ventilation air, service water and compressed air) [8].

2.2.2 Define boundary

Continuing from the previous section, the study's starting point is to determine the heat load of a specific region. It is essential to carefully select the appropriate region for analysis to avoid including a region in the mine that is not of concern to the study. The boundary for the different case studies to be employed extends from the intake point to the reject point. Figure 2-2 depicts the study's boundary.

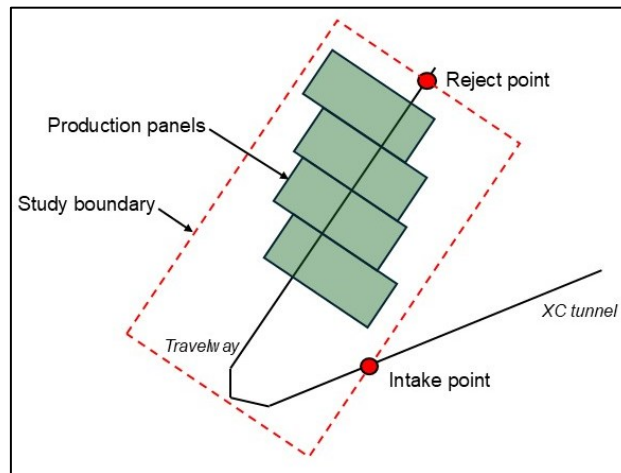


Figure 2-2: Depiction of study boundary

Typical stopes have their intake forced in from the level below and then allowed to travel up the stope to ventilate the working places [32]. The intake air is then rejected out of the stope and ventilated to infrastructure such as booster fans out of the shaft.

2.2.3 Information gathering

Information on stopes needs to be gathered beforehand to plan the type of measurements, how to measure, and to determine whether the measured item is the correct one to measure in the first place. Hence, this section will mention the information to be gathered before infield measurements can be done.

Determine types of heat sources and heat sinks

Section 2.2.1 mentioned that energy within the stope will get transferred from one source to another to achieve thermodynamic equilibrium. Found in the stopes are heat sources and heat sinks. Heat sources are surfaces/items that emit heat into the ambient environment, and heat sinks are also surfaces that absorb the energy emitted by heat sources. Below is a list of typical heat sources and sinks found in stopes [26, 29]:

Heat sources in typical stopes:

- Geothermal heat
- Metabolic heat
- Electrical heat
- Auto-compression heat (if applicable)
- Explosive heat
- Heat from strata movement

Heat sinks in typical stopes:

- Ventilation air
- Service water
- Compressed air

Determine type, phase and location of stoping

Type

Different operations employ various mining techniques to extract gold-bearing ore from the stope panel. Knowing these stope types is crucial because it can alter the behaviour of a particular heat sink. For example, a conventional stope with intake point at the bottom level experiences auto-decompression as the ventilation air travels up and through the panels, lowering the energy content (enthalpy) of the ventilation air [32]. However, if the stope was to be winze, where the intake is at the top of the stope and air feeding to a lower level, the ventilation air experiences auto-compression, altering its energy content.

Phase

Stopes typically undergo three primary phases to extract the rock [32]:

Ledging – This is when the raise line has been joined and connected to an adjacent level to allow the ventilation of air. And the raise starts to extend the face, developing the beginning points of strike gullies and preparing and forming the panels—typical duration 6 – 12 months.

Stoping – This is when fully fledged mining takes place with routine blasts and advancement of panel faces—typical duration 3 – 5 years.

Vamping – The end cycle of the stope where the gold fines and remainder of ore is extracted. Reclamation of mining equipment also takes place during this time. Typical duration 6 – 12 months.

Knowing which phase the stope is in for this study is relevant, as the phases have induced different amounts of heat due to the amount of mining activity and exposed rock surface area.

Location

There are a lot of panels present in the stope, and not all of them are mined at the same time. It is vital to determine where the active panels are within the stope. This will also give an indication of increased localised heat generation in this region because of metabolic and electrical activity in this area, accompanied by high heat flux from the rock. Other panels not mined at that moment

are sometimes sealed off, but not all the time. Thus, consultation with the shift boss before any stope visit is essential to ensure auditors do not enter any area of the stope not declared safe by the shift boss. This information can be found by inspecting stoping reports which indicate current and future panels to be mined, the locations and numbers of panels, and the dimensions of the excavation at measured points. Figure 2-3 shows a basic example of a stoping report.

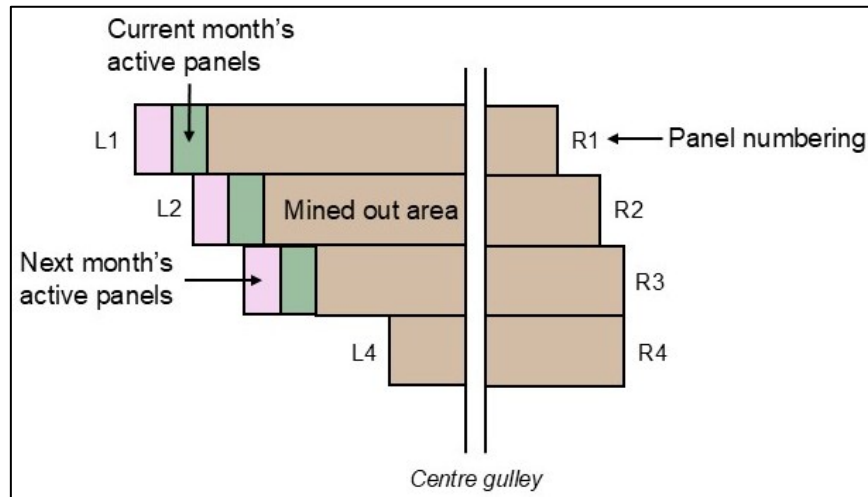


Figure 2-3: Depiction of stope report

The stoping report will indicate the name and location of the panels, with panels on the right marked by “R” followed by their number. Typically, the panels are denoted by their cardinal directions relative to the mine[32]. The stope report also has multicoloured blocks and each colour is representative of the month in which the panel will be active.

2.2.4 Conduct in-field measurements of in-field case studies

Procedure

Audit measurements of the audit stopes were done during the drilling shift. A team of four auditors were split into three teams. The teams were the bottom feed, top feed, stope team. Air measurements were taken and Water flow was continuously recorded with an ultrasonic water flow meter.

Feed stream

This team consisting of one auditor was responsible for measuring intake air stope conditions at the travel way (barometric pressure, WB and DB temperatures and mass flow), inlet stope water conditions (flow and temperature) and outlet water draining from the box fronts (flow and temperature).

Reject stream

This team consisting of one auditor was responsible for measuring reject air stope conditions at the reject point (barometric pressure, Wet-bulb (WB) and Dry-bulb (DB) temperatures and quantity), inlet stope water conditions (flow and temperature).

Stope conditions

This team consisting of two auditors were responsible for measuring air stope conditions as they travelled through the stope (barometric pressure, WB and DB temperatures, and mass flow), stope water conditions of any leakages or open ends, and also recording their location (flow and temperature). The team also took note of the active faces, locations and number of drills, men, electrical equipment and general stope and ventilation conditions. The auditors only visited areas declared safe by the shift boss and miner.

A summary of the procedures and measuring points for the in-field measurements is illustrated in Figure 2-4.

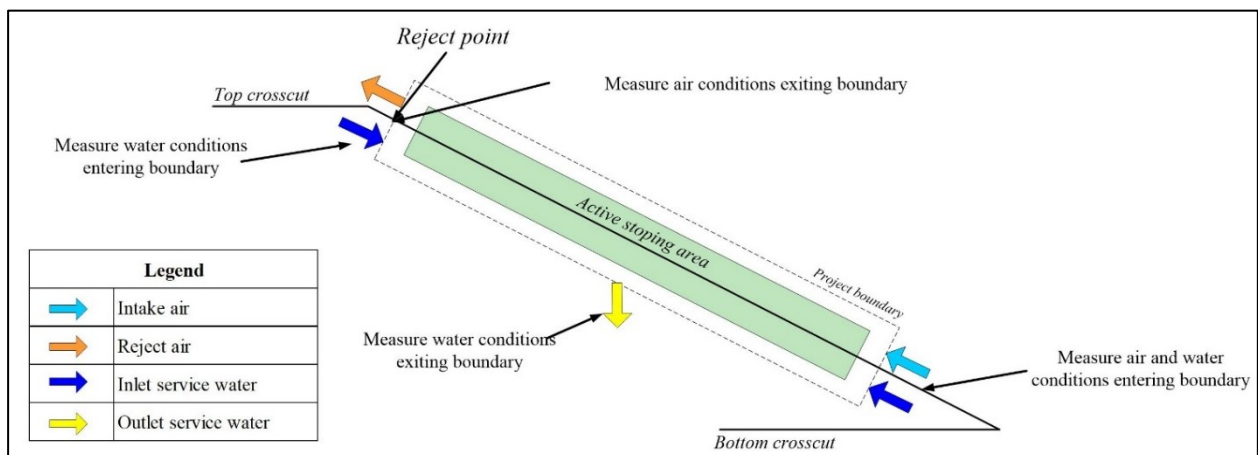


Figure 2-4: Summary of measurement procedure

2.2.5 Quantify heat load (energy balance method)

As outlined in Section 2.2.1, with the fundamental principle, the heat of the stope will be quantified by determining the amount of heat energy transferred to the heat sinks. This will be equated to the heat energy released by the stope during the measured period.

$$\text{Heat load of stope} = \text{Heat sources} = \text{Heat sinks} \quad (2)$$

Where the heat sinks in the stope comprise mainly ventilation air and service water.

$$\text{Heat sinks} = \text{Ventilation air duty} + \text{water duty} \quad (3)$$

The effect of compressed air has been omitted from the study, as it is predetermined to have a relatively low contribution to the heat sinks. It was calculated that the cooling provided by the depressurisation of compressed air amounted to 30 kW, which will later be seen to only accounts for 4% of the heat sinks. This air is ultimately combined with the ventilation air stream and is thus accounted for in the ventilation air duty side of the equation.

Ventilation air

Ventilation air duty is calculated as the difference between the specific enthalpy of the inlet and outlet flows (determined by psychrometry) multiplied by the mass flow of ventilation air.

$$\text{Ventilation air duty} = \dot{m}_{air}(h_{out} - h_{in})_{air} \quad (4)$$

where:

$\dot{m}_{air}$ = Mass flow of ventilation air [kg/s]

h = Specific enthalpy of ventilation air [J/kg]

Water duty

Water duty is calculated as the difference between the inlet and outlet temperature, multiplied by the specific heat and mass flow of water.

$$\text{Water duty} = \dot{m}_{water}C_{p_{water}}(T_{out} - T_{in})_{water} \quad (5)$$

where:

$\dot{m}_{water}$ = Mass flow of service water [kg/s]

$C_{p_{water}}$ = Specific heat of water [J/kg°C]

T = Temperature of service water [°C]

Similar to the point where compressed air joins the ventilation air stream and is accounted for in the ventilation air duty, any fissure water present in the stope will contribute to the temperature gain of the service water being measured at the reject point. Thus, any amount of fissure water

needs to be measured and determined, which will ultimately need to be subtracted from the calculated water duty.

2.3 Simulation modelling of in-field and literature case studies

2.3.1 Selection of simulation package

Numerous simulation packages are employed globally throughout the mining industry. The purpose of these simulations is to mathematically model real-world mines and solve problems that different mines face. With the context of this study, simulation packages can help understand the various driving forces of heat in the stopes and thus calculate their heat loads. The information from this can be used to critically evaluate a mine's LOM heat and determine whether the cooling infrastructure will be able to handle the heat demand, providing safe working conditions for mine employees.

Three simulation packages were considered to model the different case study heat loads: Process Toolbox (PTB), Ventsim and Vuma. These simulation packages offer different simulation and numerical methods to solve ventilation-related problems. **Error! Reference source not found.** shows the different parameters that the simulation packages are used to compute.

Table 2-1: Comparison of simulation packages

<u>Modelling parameter</u>	<u>Process Toolbox (PTB) [46]</u>	<u>Ventsim [47]</u>	<u>Vuma [48]</u>
VRT	✓	✓	✓
Days exposed	✓	✓	✓
Rock thermal conductivity	✓	✓	✓
Rock density	✓	✓	✓
Rock specific heat	✓	✓	✓
Thermal diffusivity	✓	✓	✓

<u>Modelling parameter</u>	<u>Process Toolbox (PTB) [46]</u>	<u>Ventsim [47]</u>	<u>Vuma [48]</u>
Air moisture	✓	✓	
Sensible and latent heat	✓	✓	✓
Integration of ventilation and air components	✓		

For the most part, the three simulation packages can simulate stope heat loads. However, the stopes are equipped with water pipes and watering equipment that continuously introduce water into the system, which only one simulation package can model. PTB has been chosen for use in this study because of its ability to integrate ventilation air and water components governed by an overall heat transfer coefficient to determine how well heat transfer occurs between these two mediums. This simulation package is also readily available to the study's author.

2.3.2 Method for constructing the simulation models

A method needs to be developed and meticulously followed when constructing the simulation models of the various case studies. Since PTB can integrate both ventilation air and water components, the method needs to incorporate the separate process flow methods and integrate them at the end. This can be seen in Figure 2-5.

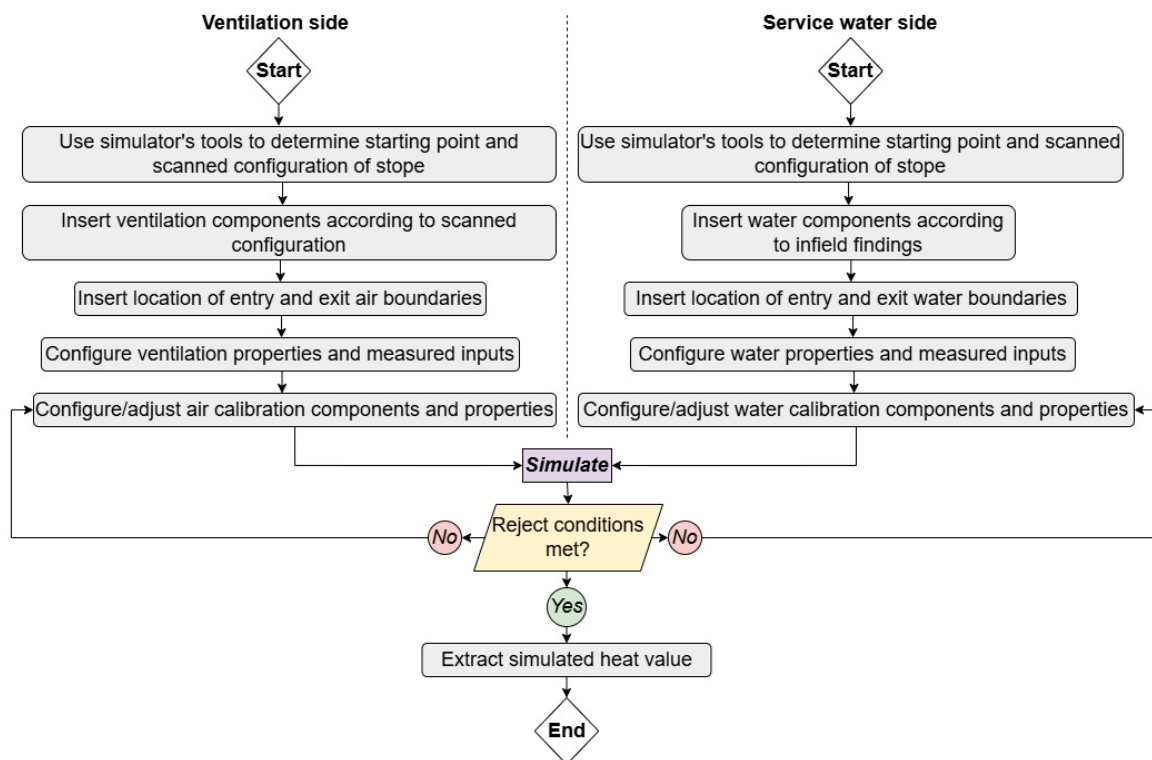


Figure 2-5: Method flowchart of constructing the simulation models

Both process flow methods start with the location. The location is a crucial input for the ventilation side because it affects the VRT of the stope, which is the primary driving force in stope heat. Likewise, for the water side, the locations of heat exchange between ventilation air and service water directly affect the amount of heat emitted from the rock downstream, which in turn affects environmental conditions, which then influence geothermal heat, and so on. The method continues by inputting the correct configurations and properties in the simulation.

Once the model has been constructed and simulated, the IF statements are followed. If the reject conditions (specifically, the air and water enthalpies) are not met according to the reported data, the calibration components are adjusted (wet area fraction, UA of the water heat exchangers, etc.) and then simulated again. Once the reject conditions have been met, the stope heat value is extracted, and the END state is reached.

2.3.3 Description of simulation components

The purpose of any simulation tool is to match the real-world system closely. Thus, specific simulation tools have certain goals to match the real-world system. Table 2-2 describes all the simulation components to be used in the models, along with their real-world representations.

Table 2-2: Description of simulation components with the real-world system

<u>Component</u>	<u>Description</u>	<u>Representation in real-world system</u>
Air side		
Air pressure boundary	- Constant conditions	- Inlet and outlet points of air into and out of the boundary
Air nodes	- Calculation points for airstreams (perfect mixing)	- Mixing points in stope - Measurement points
Air tunnel	- Pathways constructed for airflow - Resistance calibration - Wet area fraction	- The different areas of the stope - Ventilation infrastructure (brattices, wooden planks, backfill support, wooden support) - Pondered footwall surfaces, water evaporating into the air
Water side		
Water pressure boundary	- Constant conditions	- Inlet and outlet points of air into and out of the boundary
Water nodes	- Calculation points for airstreams (perfect mixing)	- Mixing points in stope - Measurement points
Water pipe	- Piping constructed for water flow	- Pipeline of water
Water mass flow	- Specifying water flow rate through pipeline	- Amount of water measured at entrance of boundary, estimated at leak
Water and air component		
Water-air cooling tower	- Heat exchanger between air and water	- Leaks identified, i.e. open ends (water hoses, leaks of pipes) - Water users (drills, water jets)

2.3.4 Construction of simulation model

This section presents the findings generated by the simulation models, following the methods outlined in Section 2.4.

To begin constructing the simulation models, the location of the stope needs to be determined. Mine surveyors routinely scan the tunnels, and these scans are converted into Drawing Exchange Format (DXF) files. The scans take into account the geometry and distances of the tunnels relative to the datum. By importing the DXF file into the model, the precise starting point of the stopes can be identified. Figure 2-6 displays the imported DXF file within the simulation model.

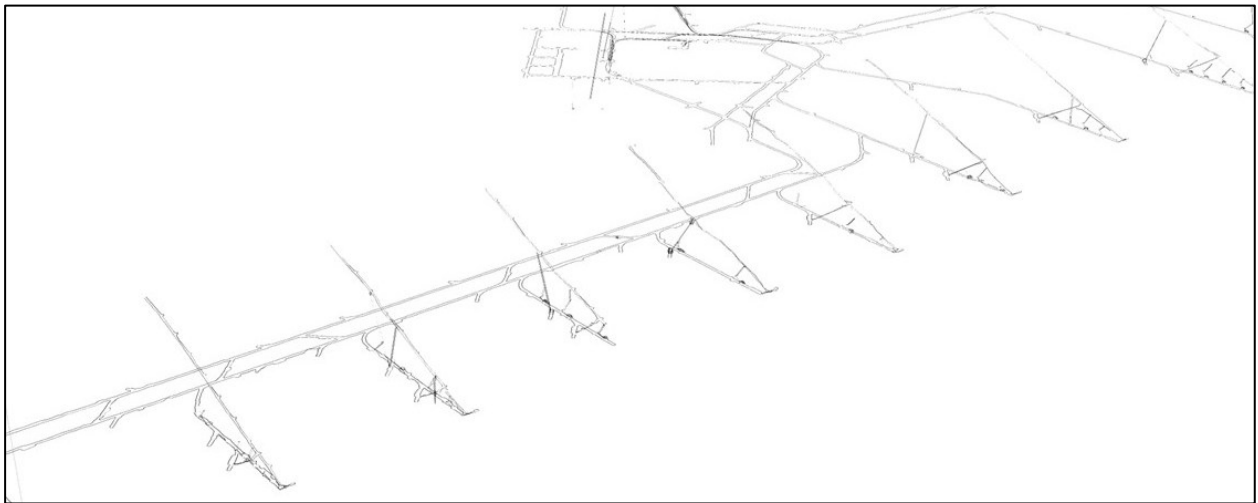


Figure 2-6: DXF file imported into model

A critical piece of information in the DXF file is the exact depth below the datum, which helps to determine the depth below the shaft collar (the starting point of the rock). This information allows the simulation program to calculate the correct VRT temperature for the model. The DXF file also enables the operator to locate the crosscut (XC) to be modelled.

Using both the stoping report and the DXF file, the stope can be modelled on a 1:1 scale. The stoping report is tilted at the specific dip angle and scaled up so that the central gully shown in the DXF file perfectly aligns with the central gully of the stoping report. Figure 2-7 illustrates how this alignment was achieved in the simulation model.

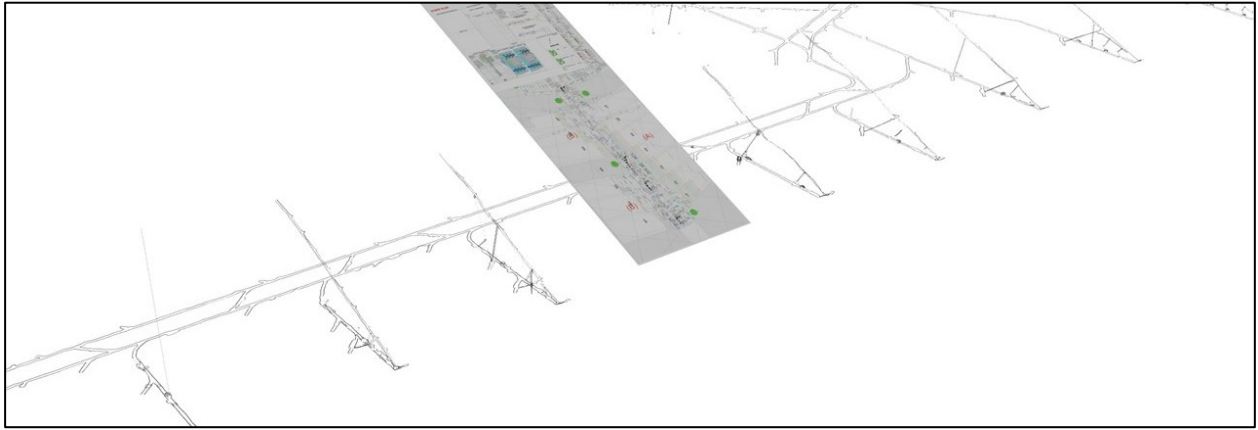


Figure 2-7: Stopping report joined onto the DXF file

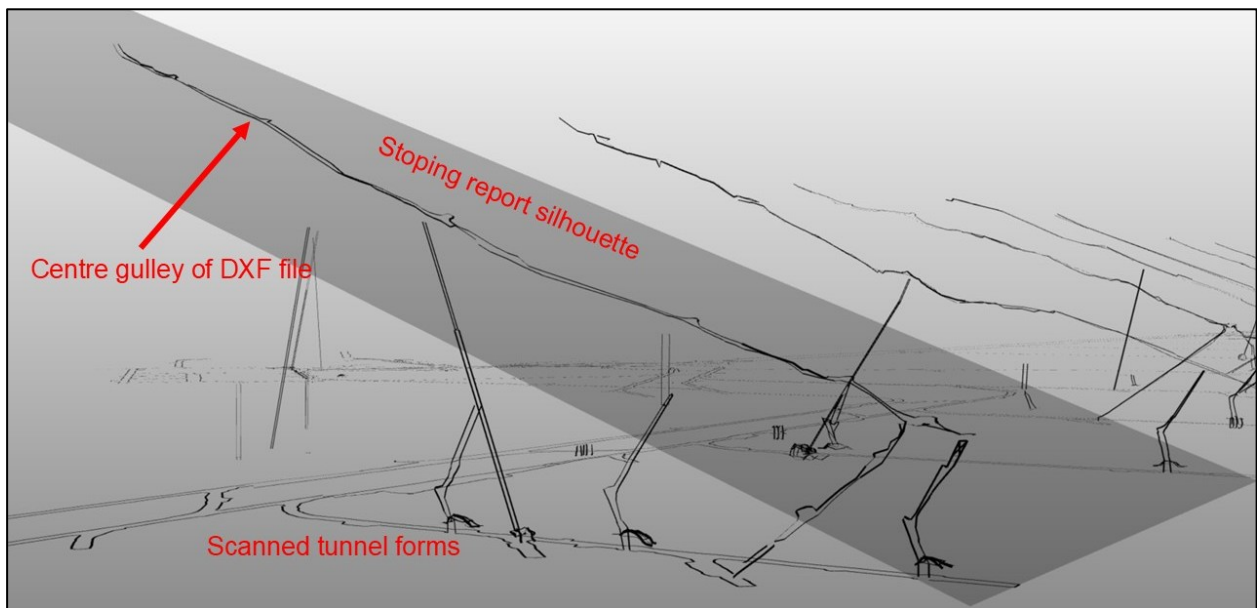


Figure 2-8: Stopping report tilted, shifted and scaled to match 1:1 with DXF's centre gully

The tilting, shifting, and scaling of the stopping report allow the operator to accurately position ventilation components within the simulation model, as the report includes the scanned rock geometry for that stope. This ensures that the model reflects the true tunnel lengths necessary for determining air and heat flows. Figure 2-9 shows how the simulation components are placed relative to the stopping report.



Figure 2-9: Simulation components placed relative to stoping report

Figure 2-9 demonstrates how the simulation components are positioned according to the contours and lines indicated by the stoping report, which depicts the rock's location. The parameters for the ventilation tunnel and pipe components are configured according to their thermal hydraulic properties. The "planned outlook" region provides additional information on how the stope will extend in future blasts.

Once the simulation components are positioned according to the rock geometry, the inlet and reject components need to be modelled, completing the boundary of the simulation model. Figure 2-10 below illustrates the inlet portion of the stope and its boundary.

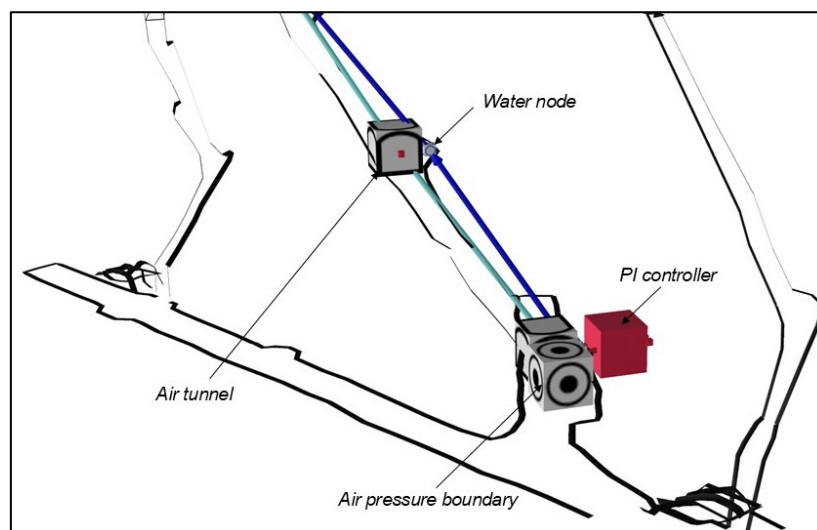


Figure 2-10: Simulation components showing inlet point of stope

Figure 2-10 indicates the air and water pressure boundaries (with the water pressure boundary located behind the air pressure boundary) where ventilation air and service water are introduced. The parameters for the air and water pressure boundaries, such as ambient pressure and WB and DB temperatures, as well as water pressure and temperature, are configured accordingly. The Proportional-integral (PI) controller displayed in the figure regulates the amount of water supplied to the stope to a setpoint, as recorded by the in-field case studies. Inputting the measured water pressures in the simulation water pipeline results in more water being supplied to the stope, as an "ideal" pipe (without fouling and rust on the inner walls) is being simulated. The PI controller accounts for this by adding resistance to the pipeline network to meet the setpoint of the measured values. The flow of ventilation air is driven by the differential pressure measured at the inlet and reject points of the stope.

Interaction of service water and rock face

Field measurements indicate that the stopes have high service water consumption. One reason for this is that miners use service water to remove geothermal heat energy from the rock by wetting the face or leaving the ends of water pipes open [31]. This interaction between service water and the rock face has been the subject of past studies, which focused on the heat conduction aspects of the rock face and service water in stopes [26, 29, 31, 33]. These studies concluded that service water rapidly cools the surface of the rock face, transferring the heat energy contained within the rock to the service water. As a result, the heat flux from the rock is pushed deeper, and the ventilation air passing over the rock face has a smaller temperature difference, allowing it to perform less work in cooling the workplace. At the same time, service water absorbs most of the geothermal energy.

The heat transfer flow path of face wetting means that geothermal energy is directly transferred to the service water. However, the available simulation software cannot directly model this interaction; instead, it employs an indirect approach. This approach involves transferring geothermal energy to the ventilation air, which is then used to heat the service water. This method is valid, as it adheres to the principle of conservation of energy. Thus, this indirect modelling effectively represents the heat transfer from the rock face to the service water by using ventilation air as an intermediary. The difference in heat transfer flow paths between real-life interaction and simulated interaction is illustrated in Figure 2-11.

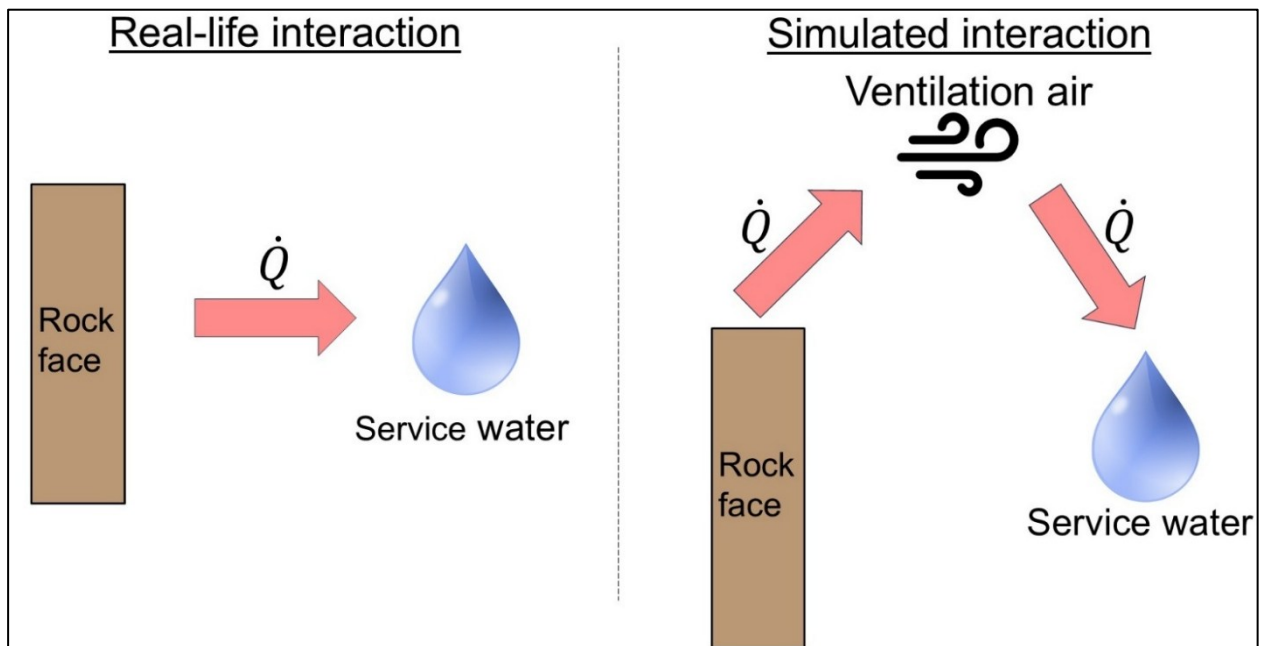


Figure 2-11: Heat transfer flow path difference between the real-life and simulated interaction

At locations where water leakages have been recorded, a direct contact heat exchanger (DCHE) component has been modelled. Figure 2-12 provides an example of the DCHE in the simulation model.

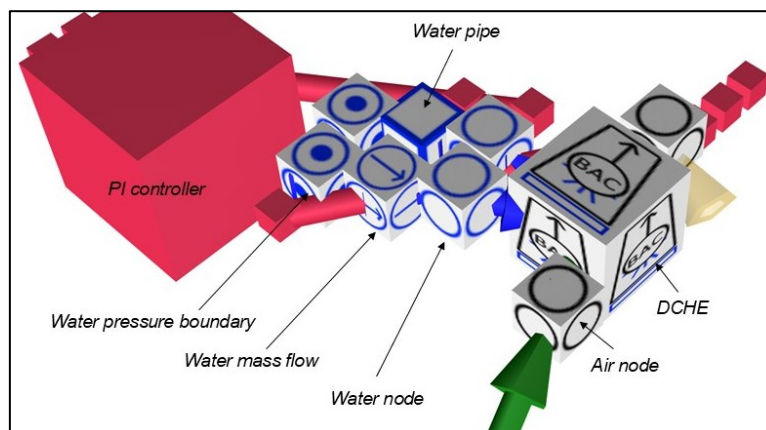


Figure 2-12: Modelling of DCHE in stope

The DCHE includes inlets and outlets for ventilation air and service water, and its performance is determined by a calibrated UA. This coefficient dictates the amount of energy transferred between the service water and chilled water. The water mass flow is estimated based on the inputs provided by the stope team. The PI controller, in this case, allows for the calibration of the DCHE by adjusting the UA value. This is accomplished by linking the PI controller to the outlet water temperature node and the DCHE-controlled UA node. The controller modifies the UA value to achieve the target temperature, continuously adjusting this value to stabilise at the desired setpoint. The amount of heat gained by the service water stream translates to the cooling energy applied to the ventilation air side.

Mass balances were performed on the measured inlet water, and the amounts of sources found in the stope do not balance. This discrepancy indicates that not all sources were identified by the auditors. The remaining water is distributed evenly to every active panel in the stope. Figure 2-13 shows the final version of the simulation, including the positioning and close-up of the DCHEs in the simulation model.

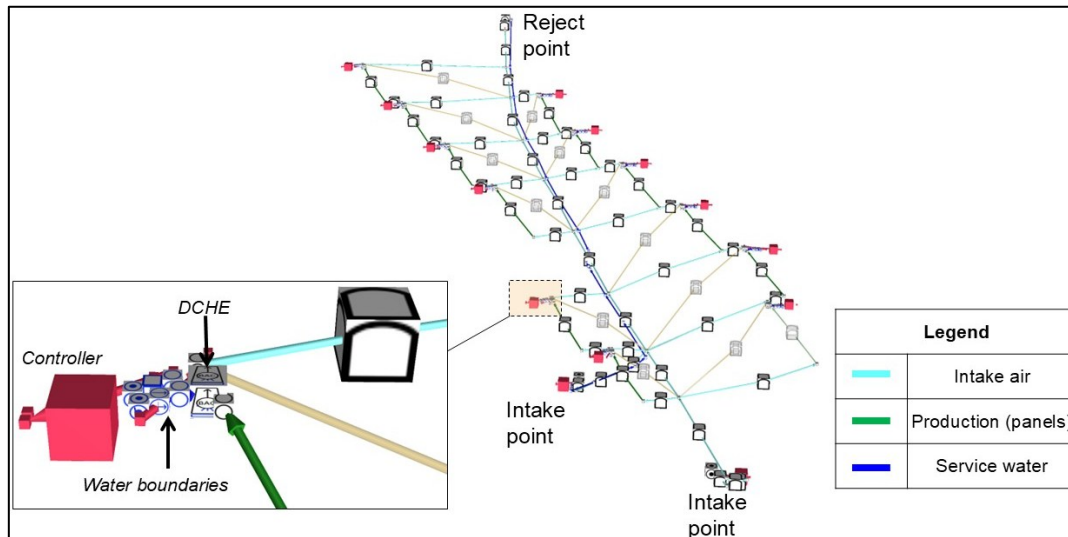


Figure 2-13: Positions of the DCHEs in the simulation model

Backfill modelling

In-field measurements indicated that ventilation air arriving in the strike gully would bypass the panels through the backfill and timber packs. To simplify this interaction, the backfill was modelled as a tunnel with properties similar to those of the strike gully. This assumption enables us to consider the energy removed from the backfill as equivalent to that of the ventilation air that bypasses the panel. Resistance calibration was performed on this component to ensure that only the measured amount of bypass air can flow through this region. Figure 2-14 illustrates how the backfill component was modelled in the simulation. From the in-field case studies, the backfill being pumped into the stope was measured as 32°C.

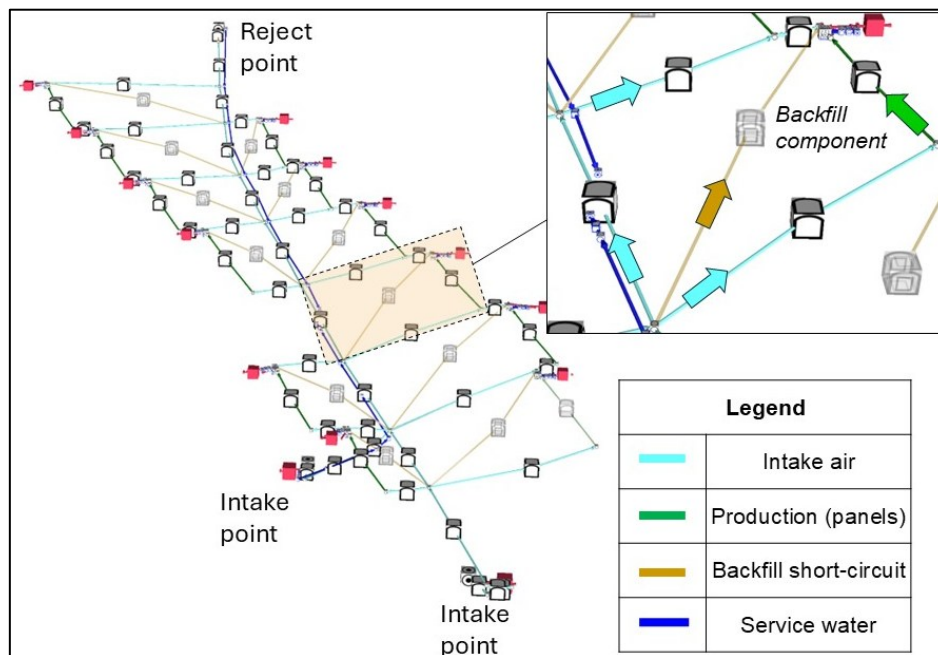


Figure 2-14: Backfill component in the simulation model

2.3.5 Simulation of heat maps and mass flows

A comparison of the simulated in-stope conditions against the in-field measurements needs to be made to determine the accuracy of the simulation models. To do this, the locations where the measurements were taken in the in-field measurements will be identified and replicated in the simulation models. The PTB simulation package has a mode that allows heat maps to be viewed, displaying a colour gradient throughout the model (with dark blue indicating low values and red indicating high values). This comparison is necessary to assess whether the simulation can accurately determine in-stope conditions. Figure 2-15 shows a schematic of the heat map result.

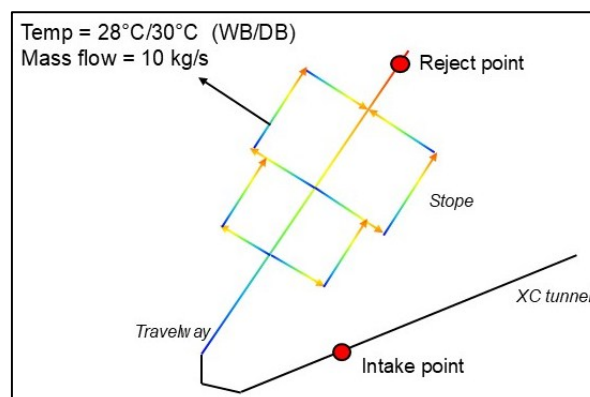


Figure 2-15: Schematic of simulated heat map

2.3.6 Simulation of heat loads

To determine the heat load of the stope, it is important to decide the time interval for data extraction. The simulations to be conducted are steady state, as the goal of this study is to find

the overall heat load of the stope. Different mining cycles affect the heat load differently, as discussed in Chapter 1. However, this study focuses on determining the stope heat load during the drilling shift. The drilling shift was chosen because, according to literature, this is generally the shift with the most mining and human activity [26].

All thermo-hydraulic simulations have an initialisation point when the calculations begin [46]. It is after some time that all the iterations in the simulation reach a steady state. It is important to always export the simulated heat once the simulation has reached steady state. Figure 2-16 displays the temperature and mass flow results for nodes and tunnels from the initial point to when they reach steady state.

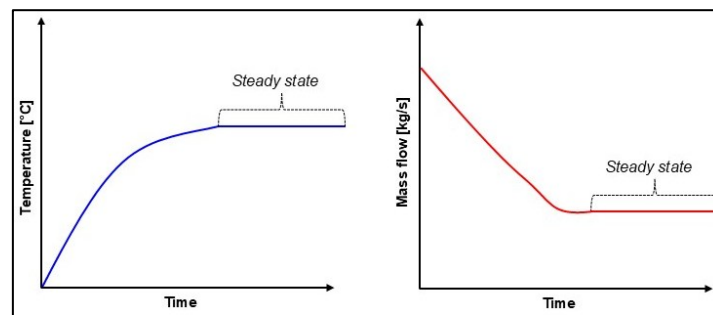


Figure 2-16: Schematic of steady state point reached [46]

2.3.7 Waterfall heat loads

To determine the breakdown of heat sources and sinks in the simulation model, a waterfall heat flow diagram will be generated. This diagram adheres to the conservation principle, as all the heat sinks will sum up to the heat sources [8]. This step is necessary to analyse the heat sources side of the energy balance method, since the in-field measurement results break down the heat sinks side, and the total of that is equal to the heat sources side. The waterfall graphs will show how much the heat sources are broken down relative to the heat sinks. Figure 2-17 shows the schematic of how the heat sink's side (left with blue blocks) relates to the heat sources' side (right with yellow blocks).

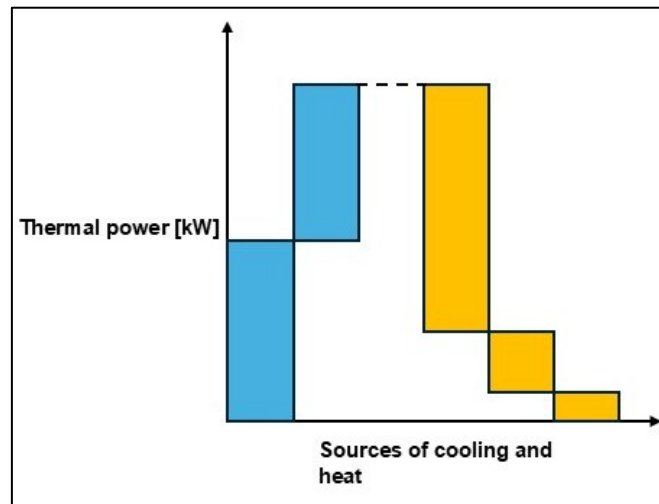


Figure 2-17: Schematic of waterfall heat load [8]

2.4 Van der Walt's method (VDW)

As discussed in the literature analysis section of Chapter 1, the paper “The analysis of ventilation and cooling requirements for mines” is a method which can determine the heat load of existing and future planned mines [30]. A key advantage and relevance to the VDW and its application in this study is that it can isolate the stoping region of the mine, and the heat load can be calculated only for that region. This method will be employed in this study as an additional comparison between the energy balance and simulation methods which determines the heat load of the stoping region.

A fundamental principal of the VDW method is that it uses Fourier transforms to determine the heat generation by cylindrical tunnel excavations. Since the heat from the rock decays over time because of the VRT front being pushed back deeper in the rock surface, the Fourier transform is able to accurately determine this phenomena. In the development of the method, Van der Walt simplified the calculations into analytical equations that could be used by mine ventilation practitioners. This subsection will outline the approach and formulae used to calculate the stope heat loads for the VDW's method [28, 49]. The foundation of the principal is explained below:

Firstly, the foundation starts with the heat equation:

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2} \quad (6)$$

Equation 6 shows the partial differential equation of how temperature changes over a distance and over time [50, 51].

Where:

$u(x,t)$ = the temperature at a distance x and time t ($^{\circ}\text{C}$)

α = Thermal diffusivity (m^2/s)

This explains the rate of change of heat over space (or distance) over time, with the α dictating how fast the heat dissipates.

The second foundation is the Fourier transform. The Fourier transform in the context of heat is able to represent any temperature distribution onto sine and cosine functions into what is called a Fourier series. The Fourier transform converts functions of distance into the frequency domain, making the equations easier to solve. Once the equations are solved, the Fourier transform is converted back into the distance domain [51].

To simplify the concept within the mining industry, Fourier transforms can model heat from any source as a decaying function, like how geothermal heat initially emits a lot of energy, but over time the rate of heat release diminishes [52]. Figure 2-18 below shows an illustration of heat dissipation over time.

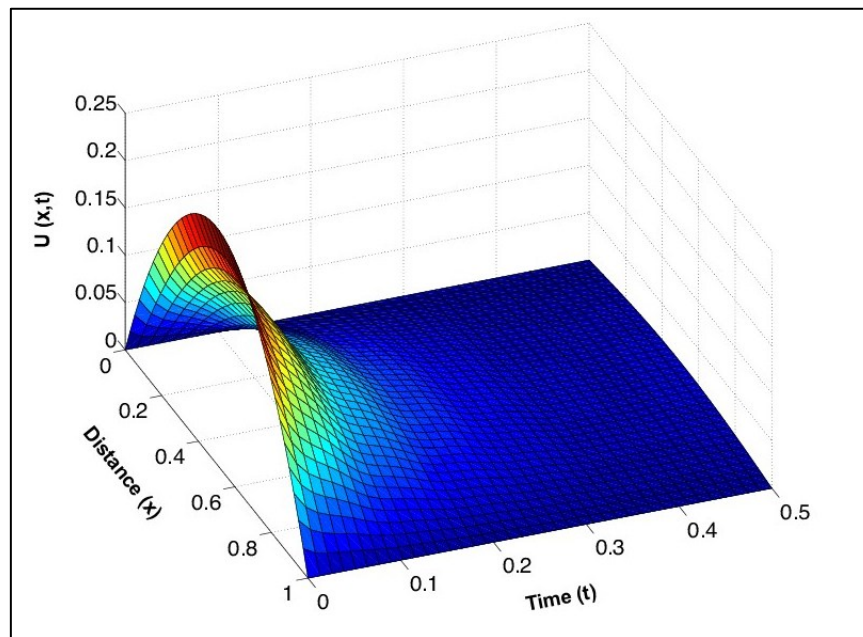


Figure 2-18: Illustration of heat dissipation over time [52]

The figure shows how the temperature of the surface $u(x,t)$ is highest at $t = 0$, and gradually decreases at $t = 4$.

Below are the Fourier functions for the VDW method [30]:

$$F(\tau) = 0.1854\tau - 0.6497\tau^{0.9} + 2.79199\tau^{0.8} - 3.07286\tau^{0.7} + 1.43615\tau^{0.6} + 0.87729\tau^{0.5} \quad (7)$$

$$F'(\tau) = 0.1854 - \frac{0.58474}{\tau^{0.1}} + \frac{2.23359}{\tau^{0.2}} - \frac{2.151}{\tau^{0.3}} + \frac{0.86169}{\tau^{0.4}} + \frac{0.43865}{\tau^{0.5}} \quad (8)$$

where:

τ = Time constant of the Fourier function [-]

Below is the supporting equation of the time constant:

$$\tau = 4\left(\frac{k}{\rho C_{p_{rock}}}\right) \quad (9)$$

where:

k = Thermal conductivity [kW/mK]

ρ = Density [kg/m³]

$C_{p_{rock}}$ = Specific heat of the rock [kJ/kgK]

The method is simplified into two parts. Firstly, the temperature-dependent part includes all parameters that rely on air temperature, such as exposed rock, broken rock, and ground water. And secondly, the temperature-independent part includes all parameters unaffected by air temperature, like locomotives, dewatering pumps, fans, substations, electrical equipment, diesel equipment, and personnel.

The equations for the supporting temperature-dependent parts are shown below:

Heat generated from the exposed rock surfaces:

$$Q_{SR} = 4 \sqrt{\frac{k\rho C_{p_{rock}} A_m A_s}{\pi \times 30 \times 24 \times 3600}} (T_V - T_R) \quad (10)$$

where:

Q_{SR} = Heat generated from the exposed rock surfaces [kW]

A_M = Area mined per month [m²/month]

A_S = Stopped-out area that is ventilated [m^2/month]

T_V = Average VRT [$^{\circ}\text{C}$]

T_R = Temperature of air [$^{\circ}\text{C}$]

Heat generated from the broken rock:

$$Q_{BR} = \frac{P_S(T_V - T_R)C_{p_{rock}}}{30 \times 24 \times 3.6} \quad (11)$$

where:

Q_{BR} = Heat generated from the broken rock [kW]

P_S = Rock broken in stopes [tonne/month]

Heat generated from both the exposed rock surfaces and broken rock

$$Q_{SB} = Q_{SR} + Q_{BR} \quad (12)$$

Heat generated from ground water:

$$Q_{SW} = L_g C_{p_{water}} (T_V - T_R) \quad (13)$$

where:

Q_{SW} = Heat from the ground water [kW]

L_g = Ground water inflow rate [l/s]

$C_{p_{water}}$ = Specific heat of water [kJ/kgK]

The VDW method is concluded by adding both the temperature-dependent and independent parts to obtain the VDW stope heat load.

$$VDW_{Stope\ heat} = temperature_{dependent} + temperature_{independent} \quad (14)$$

2.5 Validation of correctness of simulation method

The goal of the study is to validate whether simulation can be used to predict stope heat loads and in-stope conditions. No model in the world is 100% accurate. However, the goal of any model is to try to achieve results that are as close as possible to the real-world system [53].

The simulation method will be validated by applying it to case studies. This will show that the technique in this study can be used by mine ventilation practitioners to predict expected stope heat loads and compare their own calculations using industry-accepted methods, such as the VDW method.

There is no general equation or form to determine whether a simulation is verified [54-56]. It is highly dependent on the context in which the simulation occurs. In most cases, the decision rests with the person performing the validation [54, 55]. The simulation method aims to produce outputs of stope heat loads, which are highly dynamic and complex. In this study, these outputs will be compared to the energy balance method, which was validated in Nell's PhD thesis [8]. Therefore, it is appropriate to assess the error of the simulation method relative to the energy balance method. This will be done by calculating the mean absolute error, and if it is less than 15%, the simulation method is considered validated [54, 55]. The VDW method will also be compared to the simulation method. The equation for the mean absolute error is shown below [57].

$$\text{Mean absolute error} = \frac{1}{n} \sum_{i=1}^n |x_i - x| \quad (15)$$

where:

n = number of observations

x_i = actual value of the i^{th} observation (energy balance method result)

x = predicted value of the i^{th} observation (simulation or VDW method results)

2.6 Conclusion

This chapter expanded on the method to be followed by the study. This method will be applied to several in-field case studies, as well as studies found in the literature. Figure 2-19 shows the complete flowchart of the method to be employed in the study. Remembering back to the state-of-art matrix where the study aims to calculate stope heat loads through existing calculation methods, calculate by using a simulation method and validating the correctness of the simulation method against existing methods.

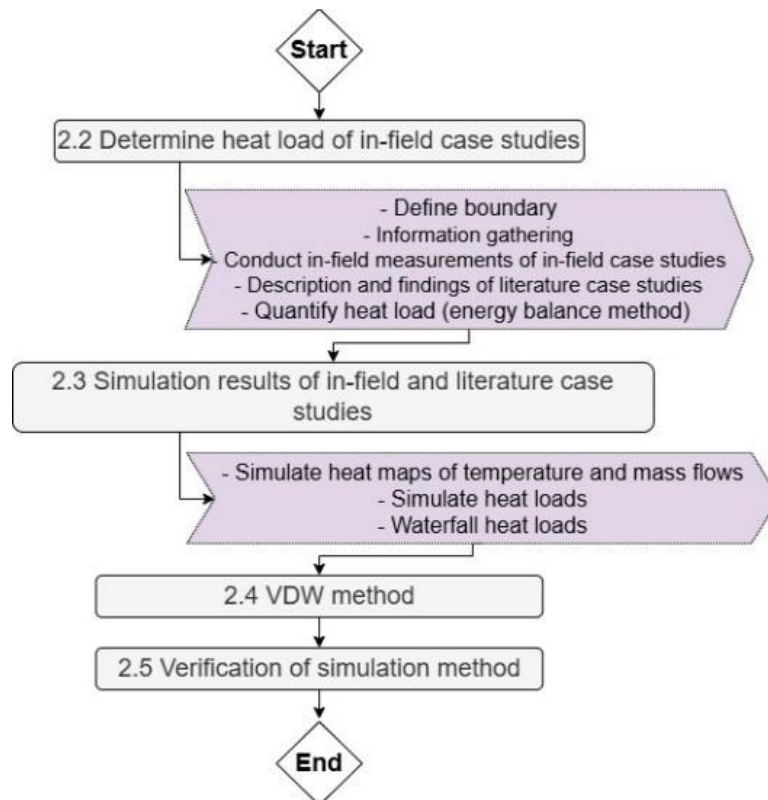


Figure 2-19: Detailed method for the study

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Preamble

This chapter presents the results of the methods described in Chapter 2, applied in an active deep-level mine in RSA. The in-field measurements and energy balance method were used for various case studies, leading to the development of simulation models based on these findings. Subsequently, the VDW method was used to compare in-field measurement results and the simulation outcomes.

To avoid repetitive reporting, some information is provided in the Appendix A and B. Detailed results for XC-A are reported in this chapter. Only summaries of XC-B and XC-C are reported in this chapter, but the details are captured in the Appendix. For the literature case studies, some results are discussed in detail in this chapter, with the rest of the details available in the Appendix. The outline of Chapter 3 is provided in Figure 3-1.

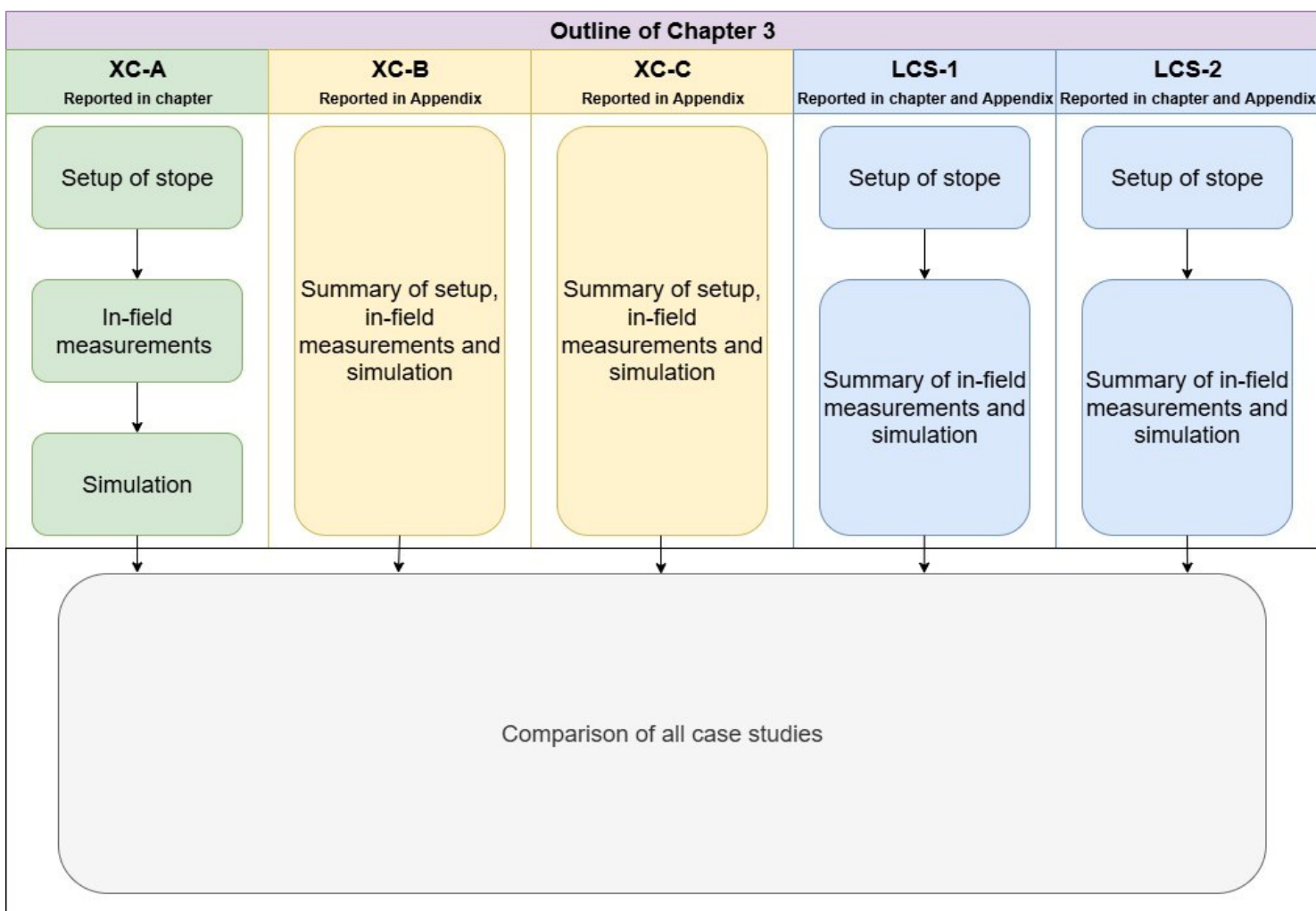


Figure 3-1: Outline of Chapter 3

3.2 Determine heat load of in-field case studies

3.2.1 Define boundary

The case study mine's stopes have two main entrances. Typically, workers enter the stope from the lower entrance (bottom XC) to reach their assigned panel, while the upper entrance (Top XC) serves as a secondary escape route. Ventilation air is introduced at the bottom of the stope and directed upward through the panels, exiting the stope and entering the return network. The boundary of the production zone is defined by the area where ventilation air enters and exits the stope, as illustrated in Figure 3-2.

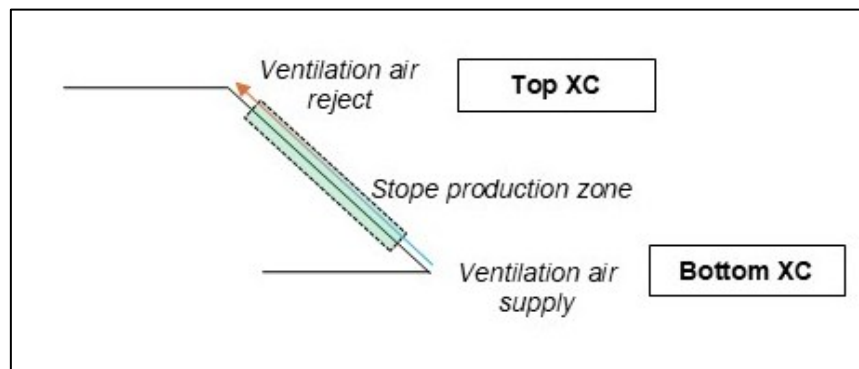


Figure 3-2: Ventilation air boundary

Service water enters the production stope through two main inlets: the bottom feed and the top feed. The terms "bottom feed" and "top feed" refer to the locations where the service water is supplied. The top feed supplies the panels at the top of the stope, whereas the bottom feed supplies the panels at the bottom. Service water pipes run through the central gully and are fitted with manifolds that distribute water to different panels. Excess water forms small ponds, which can overflow into the box holes and drain out of the stope. The boundary of the service water is visible in Figure 3-3.

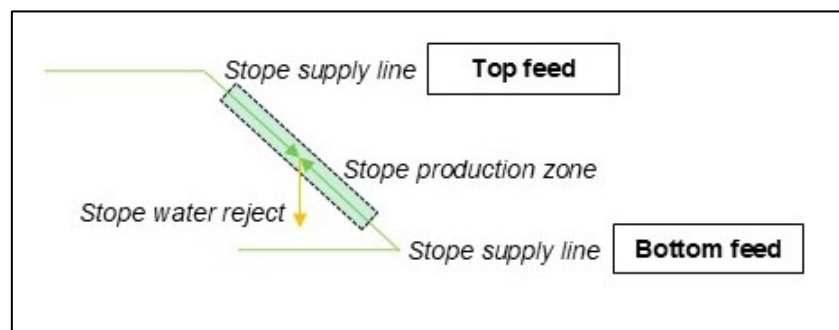


Figure 3-3: Service water boundary

The final boundary is a combination of the ventilation and service water boundaries. The final boundary for all case study stopes is shown in Figure 3-4.

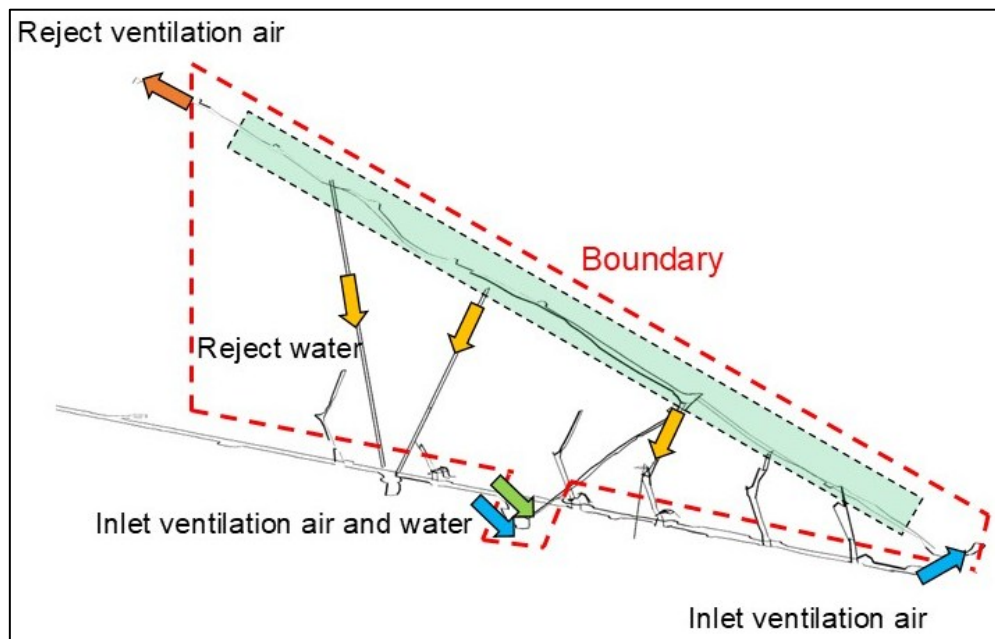


Figure 3-4: Final case study boundary

3.2.2 Information gathering

The mine utilises a U-tube system in which chilled water and ice are supplied from the surface. Chilled water is sourced from the chilled water dam and transported to cooling units in the XCs to cool the ventilation air. Figure 3-5 illustrates the mine's basic chilled water reticulation system.

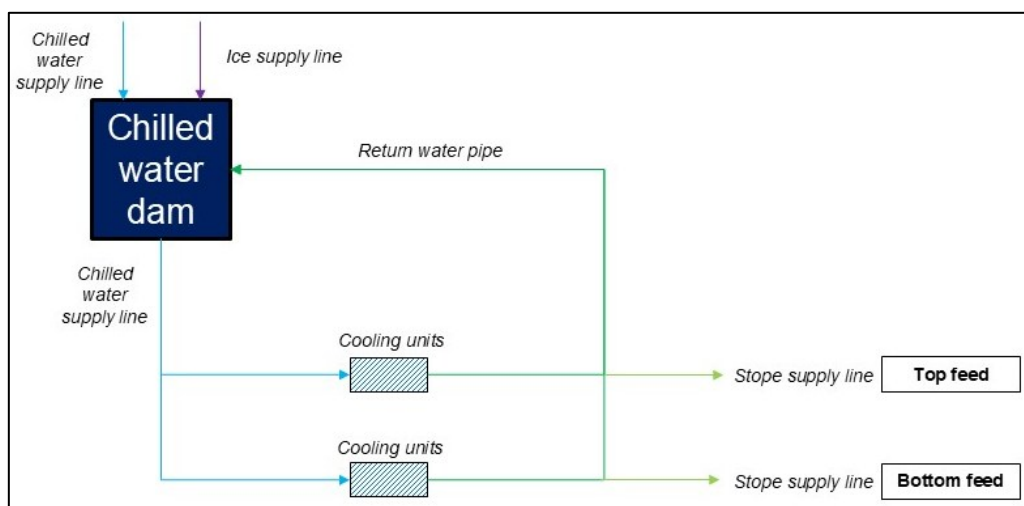


Figure 3-5: The case study mine's basic chilled water reticulation diagram

Chilled water from the XC is supplied through the haulage and into the cooling units. These units transfer heat from the ventilation air to the chilled water, enhancing the environmental conditions for workers in the XC and stopes. The water that exits the cooling units is distributed to the stopes as service water, while the excess is returned to the ice dam. Figure 3-6 provides a more detailed view of the water reticulation system in the XC.

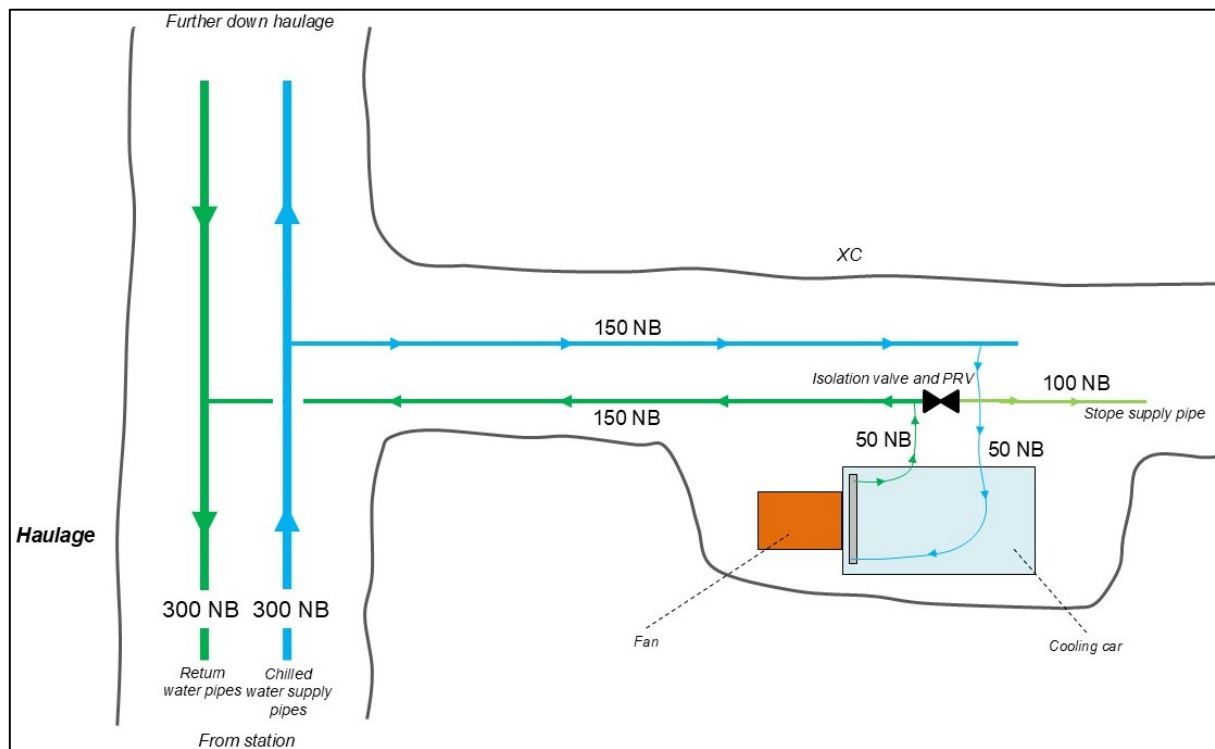


Figure 3-6: Chilled water reticulation system in XC

The in-field case study mine is located in the Witwatersrand region, employing conventional double-sided mining on two production levels.

Three stopes were selected based on their relatively high production rates, along with some unique attributes. XC-A is a relatively “young” stope, with panels that do not extend far from the centre gully. It was chosen because it has only one access travelway, which increases air resistance; thus, the airflow cannot balance with a second travelway to alleviate pressure. As a result, the air mass (kg/s) entering XC-A is lower than that of the other stopes. Additionally, XC-A is located on the lower production level, which experiences higher VRT.

In contrast, XC-B and XC-C are relatively “older” stopes with long strike gulleys that extend far from the centre gully. These stopes are situated on the upper active production level but on opposite sides of the mining production area. XC-B is located in a region with high mining activity, and it receives re-used air from another raise line, leading to higher intake temperatures compared to the other stopes. Table 3-1 summarises the information on the in-field case study stopes.

Table 3-1: Information of in-field case study stopes

ID	Region	Depth below surface m	Average VRT °C	Rock production rate Tonnes/month	Mining method
XC-A	Witwatersrand	3 559	60.4	6 728	Double-sided breast
XC-B	Witwatersrand	3 454	59.1	6 702	Double-sided breast
XC-C	Witwatersrand	3 454	59.1	6 730	Double-sided breast



Figure 3-7: XC-A panel lengths and locations of drilling and supporting panels

Table 3-2: Total centre gully, strike gully and panel lengths of in-field case study stopes

ID	Centre gully length m	Strike gully length m	Panel length m	Total length of airways m
XC-A	222	260	303	785
XC-B	269	568	351	1188
XC-C	299	840	423	1562

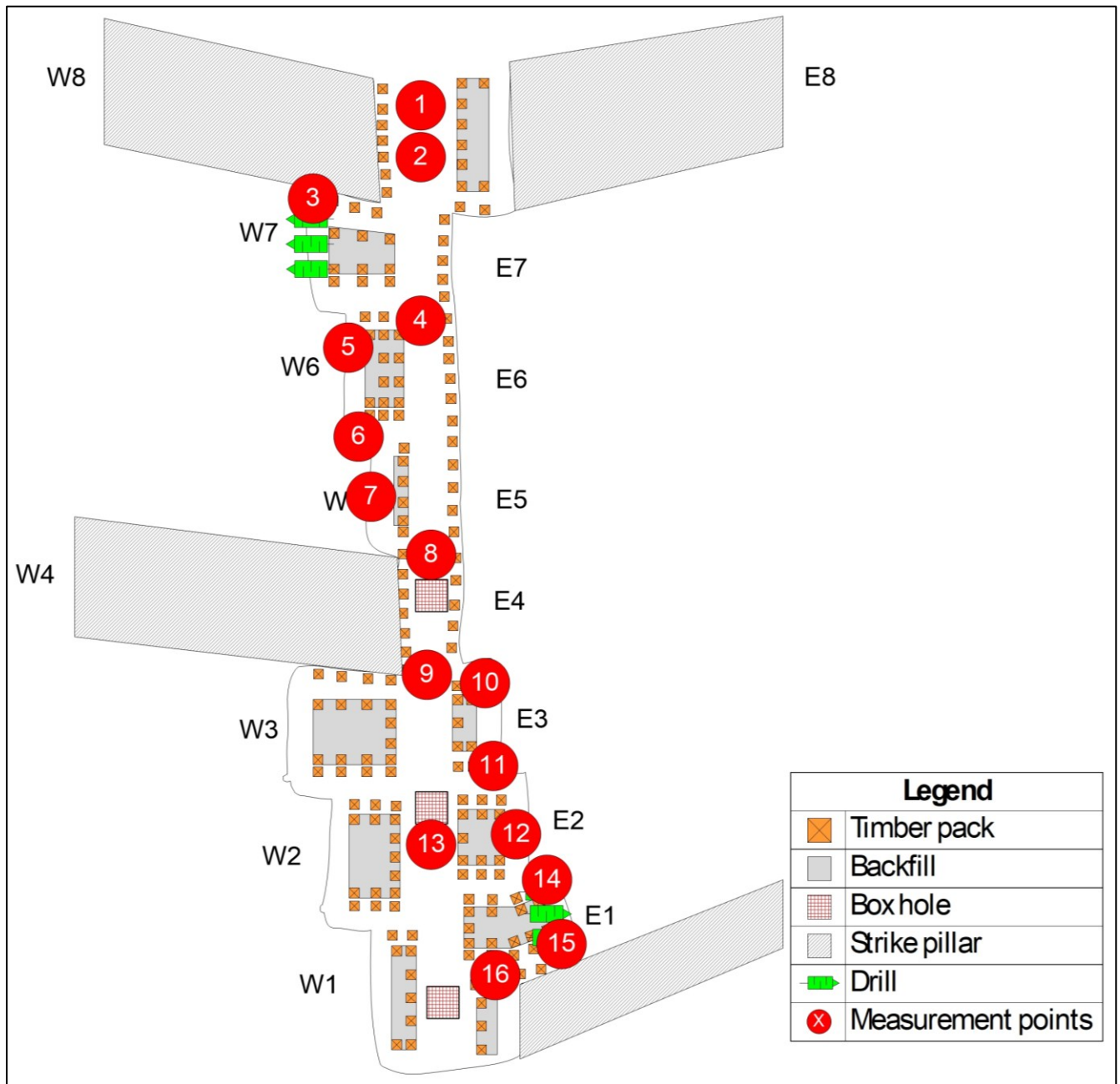


Figure 3-8: Measurement locations of XC-A

3.2.3 Conduct in-field measurements

This section presents the measurements taken from in-field case studies. The in-field case study measurements were conducted at an active gold mining operation during the drilling shift. The IDs of the stopes have been anonymised to protect sensitive information about the specific operation and XC number. Following the method presented in Chapter 2, the findings will be reported.

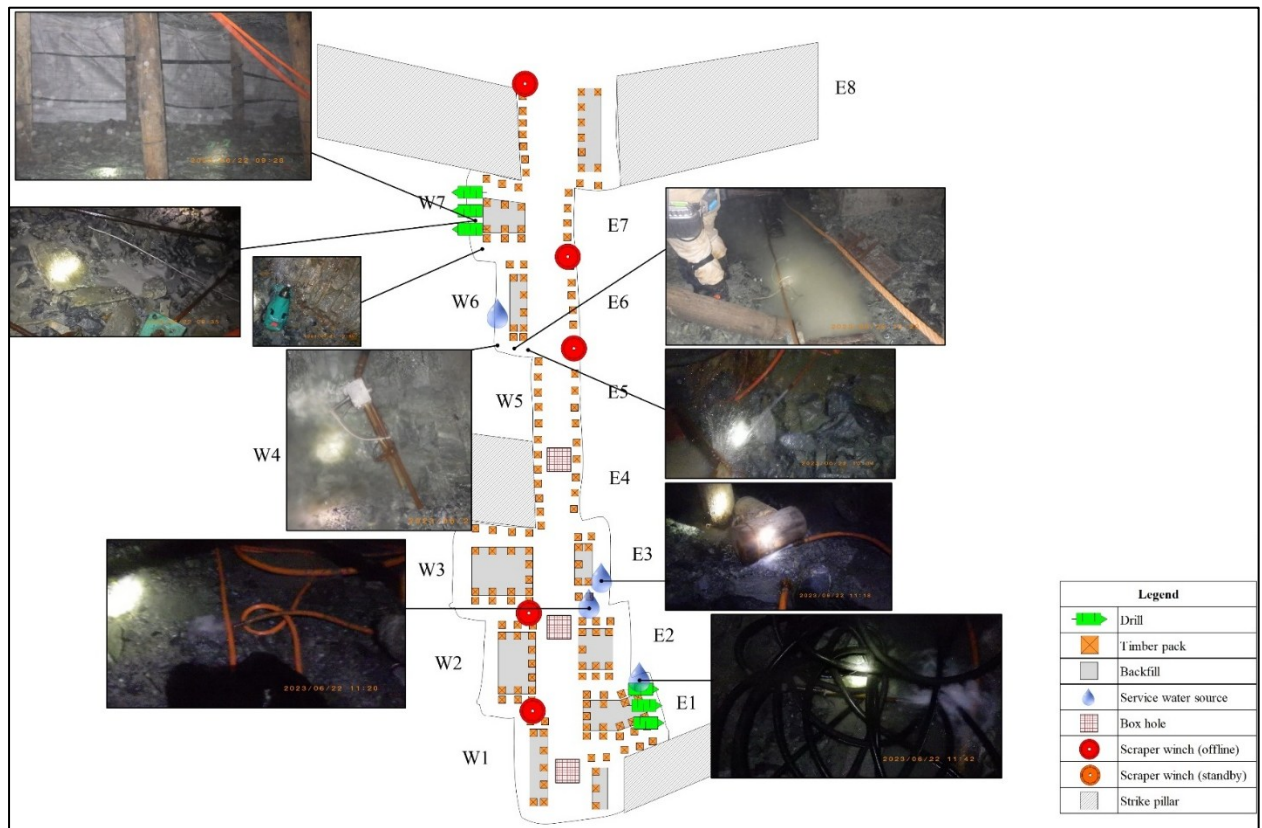


Figure 3-9: Supporting images of XC-A findings

Figure 3-9 provides an overview of the conditions within the stope and examples of water usage.

The most notable finding from the study is the significant amount of water usage in the stopes. Typical water usage values are about half of what the ultrasonic flowmeters recorded [26]. The figures below provide an overview of the water usage observed during the in-field measurements.



Figure 3-10: Close-up of water flowing in strike gully

Figure 3-10 depicts water flowing down one of the strike gullies due to open hoses and leaks from water pipes. This water does not originate from the drills, which typically exhibit low water flows.

Most, if not all, of the excessive water misuse arises from open ends, leakages, and water jets, rather than from the equipment used for drilling.

The consequences of this water misuse are illustrated in Figure 3-11. For all in-field case study stopes, water was flowing out of the box fronts and onto the footwall of the XC.



Figure 3-11: Water flowing out of box fronts and XC conditions

This situation creates a direct heat exchange between the incoming XC air and the water being expelled from the stope, thereby raising the intake temperature of the stope and adversely affecting working conditions within it. All findings from the audits are summarised and shown in Table 3-3 and Table 3-4.

First, the intake conditions of the case study stopes were measured, as shown in Table 3-3.

Table 3-3: Intake conditions of in-field case study stopes

ID	Air temperature (WB) °C	Air temperature (DB) °C	Barometric pressure kPa	Air mass kg/s	Water temperature °C	Water mass kg/s
XC-A	26.0	26.7	125.4	14.1	20.3	12.5
XC-B	28.3	29.6	123.7	25.3	20.2	15.0
XC-C	26.8	27.0	124.4	24.4	21.2	12.4

XC-B has approximately a 2°C higher intake WB and DB temperature compared to XC-A and XC-C. This difference is attributed to the mining activity and the re-use of air from another raise line,

as mentioned earlier. XC-A has a noticeably lower intake air mass due to its single travel way, which increases resistance in the raise line. Water temperature and flow are relatively constant across all in-field case study stopes.

The results from the ventilation Tinytags, which monitor intake and reject air in the stope, are shown below. Only the data recorded between 09:00 and 13:30 is relevant, as this represents the actual duration of the in-field measurement. Data outside this range pertain to the sensor traveling to and from the measuring area.

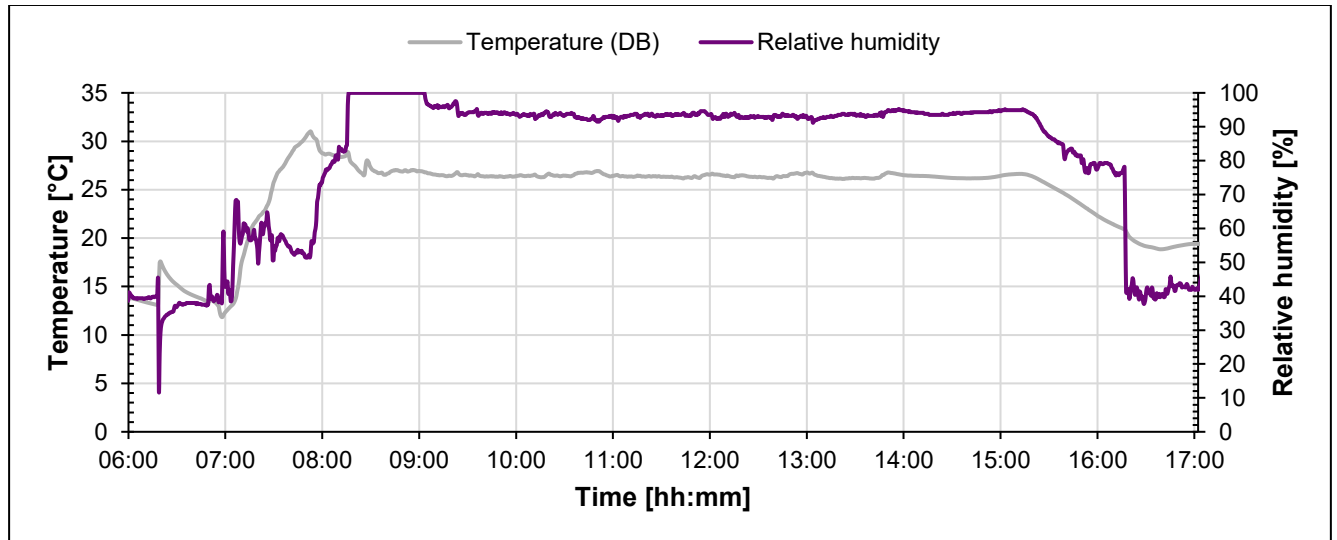


Figure 3-12: XC-A intake profile of ambient conditions

The results of the ultrasonic water flow meter are displayed in Figure 3-13 below. Unfortunately, the sensor experienced data loss; however, the available data still provides insight into the amount of water used by XC-A during the drilling shift.

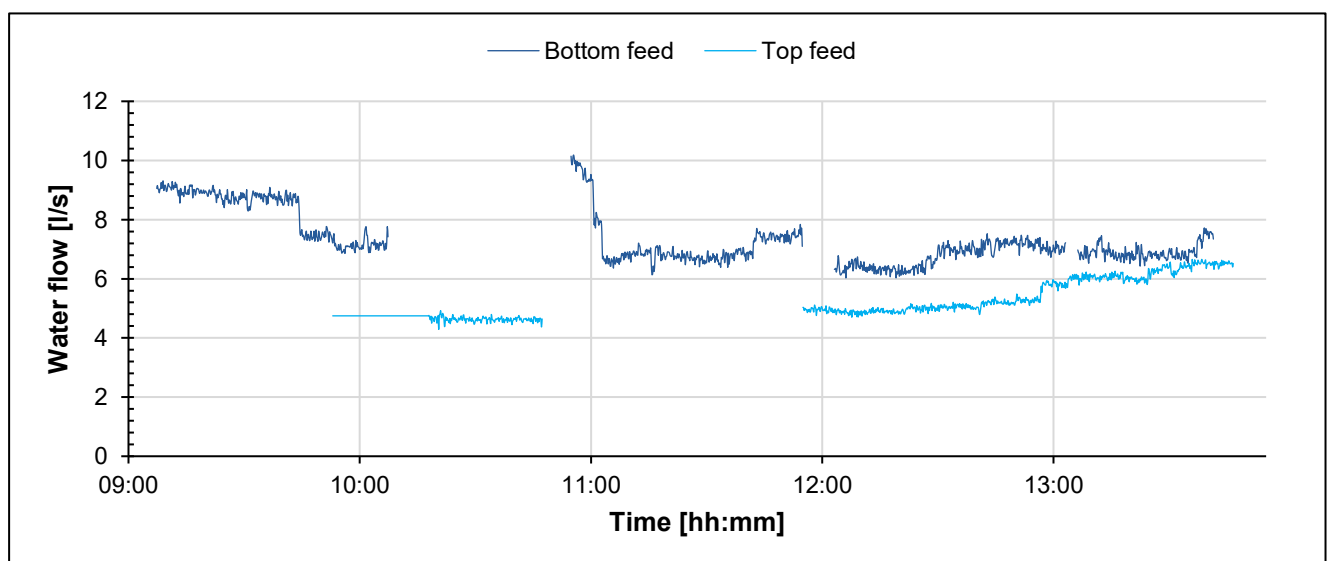


Figure 3-13: Water flow profile for XC-A

The reject conditions measured by the stope and top entrance teams are summarised in Table 3-4.

Table 3-4: Reject conditions of in-field case study stopes

ID	Air temperature (WB) °C	Air temperature (DB) °C	Air enthalpy kJ/kg	Water temperature °C
XC-A	30.0	31.0	86.4	28.7
XC-B	30.0	31.2	87.0	28.4
XC-C	30.0	30.0	86.5	28.2

An interesting finding is that regardless of the differing intake conditions, all the stopes exhibited similar reject conditions. Additionally, the amount of water used across the stopes was consistent. This high volume of water saturates the air, maximising heat transfer between the air and the rock surface. As a result, significant amounts of heat are extracted, allowing heat flux from the rock to dissipate to the surface at roughly the same distance for all the case study stopes.

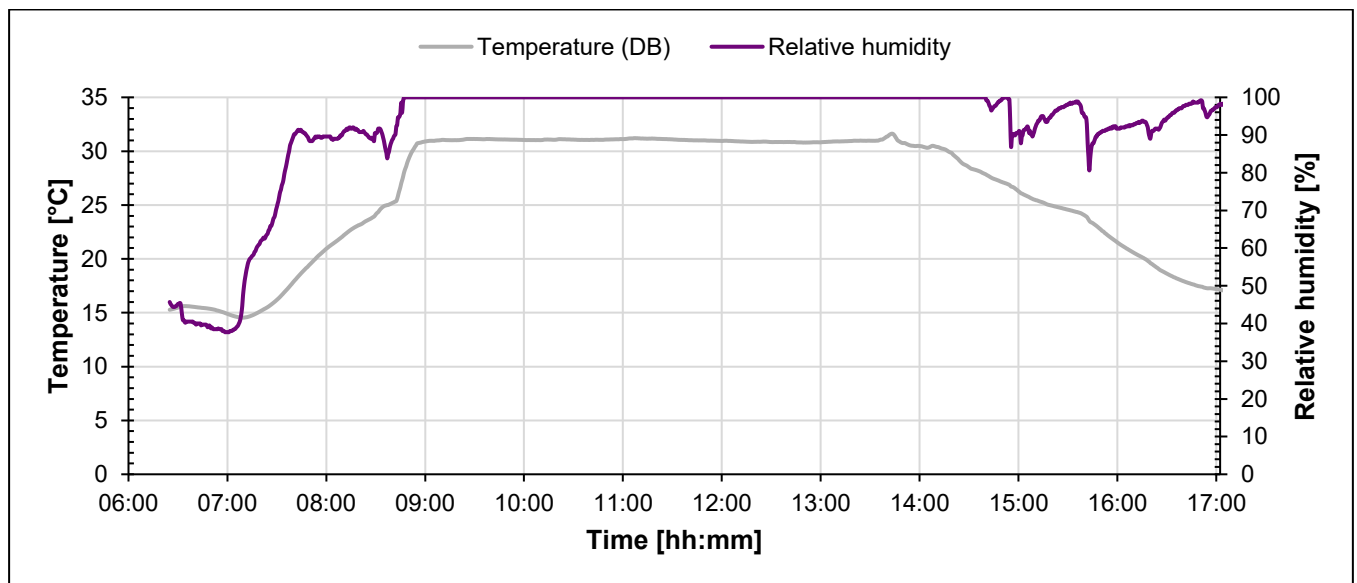


Figure 3-14: XC-A reject profile of ambient conditions

Figure 3-12 and Figure 3-14 indicate minimal fluctuation in the intake and reject temperatures recorded by the ventilation Tinytags, reinforcing the idea that heat load calculations conducted during the drilling shift are consistent. The ultrasonic water flow and ventilation Tinytag recorded data for the other in-field case study stopes are given in the Appendix.

Table 3-5: Measured conditions of XC-A

No.	Air temperature (WB) °C	Air temperature (DB) °C	Pressure kPa	Relative humidity %	Density kg/m ³	Width m	Height m	Area m ²	Velocity m/s	Volume flow m ³ /s	Mass flow kg/s
1	30.3	31.0	124.06	94.5%	1.40	1.7	2.4	4.1	0.4	1.7	2.3
2	31.8	32.0	124.01	98.2%	1.40	2.2	1.8	4.0	0.4	1.6	2.2
3	31.0	31.0	123.94	100.0%	1.40	3.2	1.2	3.9	0.4	1.6	2.2
4	29.5	30.0	123.94	96.2%	1.41	2.9	3.4	9.9	0.7	6.9	9.7
5	32.0	32.0	123.94	100.0%	1.39	3.5	1.5	5.3	0.4	2.1	2.9
6	31.0	31.0	-	-	-	-	-	-	0.3	-	-
7	31.0	32.0	124.36	92.8%	1.40	3.5	1.5	5.3	1.1	5.8	8.1
8	29.8	30.3	123.94	96.2%	1.41	2.9	3.4	9.9	0.9	8.9	12.5
9	29.0	29.5	124.46	96.2%	1.42	1.6	2.7	4.3	0.9	3.9	5.5
10	31.0	31.5	124.46	96.3%	1.40	3.5	1.5	5.3	0.4	2.1	2.9
11	30.8	31.0	-	-	-	-	-	-	0.5	-	-
12	30.0	30.5	124.46	96.3%	1.41	3.5	1.5	5.3	0.6	2.9	4.1
13	28.0	29.0	124.46	92.4%	1.42	3.5	1.5	5.3	0.9	4.7	6.7
14	29.0	30.0	123.77	92.5%	1.41	2.5	2.8	7.1	0.4	2.8	4.0
15	29.0	29.0	123.77	100.0%	1.41	2.1	1.8	3.9	0.4	1.6	2.2
16	29.0	29.5	-	-	-	-	-	-	-	-	-

Inquiries were conducted to determine the reasons behind the high levels of water usage in the stopes. The problem appears to be three-fold. Firstly, the cooling provided by the ventilation air is insufficient to counteract the heat generated in the stope (this will be proven later). In some cases, miners have resorted to constructing makeshift BACs to cool both the broken rock and the ventilation air, as discussed earlier. The auditors also noted that, while temperatures did not exceed legal limits, the environmental conditions were at times unbearable because of the high relative humidity of the air.

Secondly, the Pressure Relief Valves (PRVs), responsible for reducing the water pressure supplied to the stopes, were not functioning correctly. As a result, rock drills malfunction due to water pressure exceeding their operational range. To address this, miners open as many hoses as possible and create numerous open ends to reduce the water pressure, allowing the drills to

operate. Many of these open ends were not intended for cooling ventilation air and were simply left open. One example observed was an open water jet left unattended with auto shutoff handle damaged in open position, as illustrated in Figure 3-15.



Figure 3-15: Open water jet left unattended

Lastly, negligence also plays a role; miners sometimes forget to close hoses and water jets after use.

3.2.4 Description and findings of literature case studies

As previously discussed in Chapter 1, two case studies were identified from literature that measured the heat load of stopes. These case studies were conducted to address the concern that most assessments of heat loads within mines were based solely on theoretical models, and that these theories needed to be validated by empirical data gathered from actual mining operations. The two case studies originate from different regions and exhibit varying VRT compared to the in-field case studies. Additional information about these literature case studies can be found in Table 3-6.

Table 3-6: Information on literature case study stopes

ID	Region	Depth below surface m	Average VRT °C	Rock production rate Tonnes/month	Mining method
FS-GD	Free State	1 539	42.5	2 070	Ledging
KL-HF	Klerksdorp	1 930	43.0	6 702	Double-sided breast

These studies were conducted over an extended period to determine whether the heat loads in the stope varied over time. Measurements were obtained through data recorders and manual observations. The key findings from the literature case studies are summarised in Table 3-7 and Table 3-8.

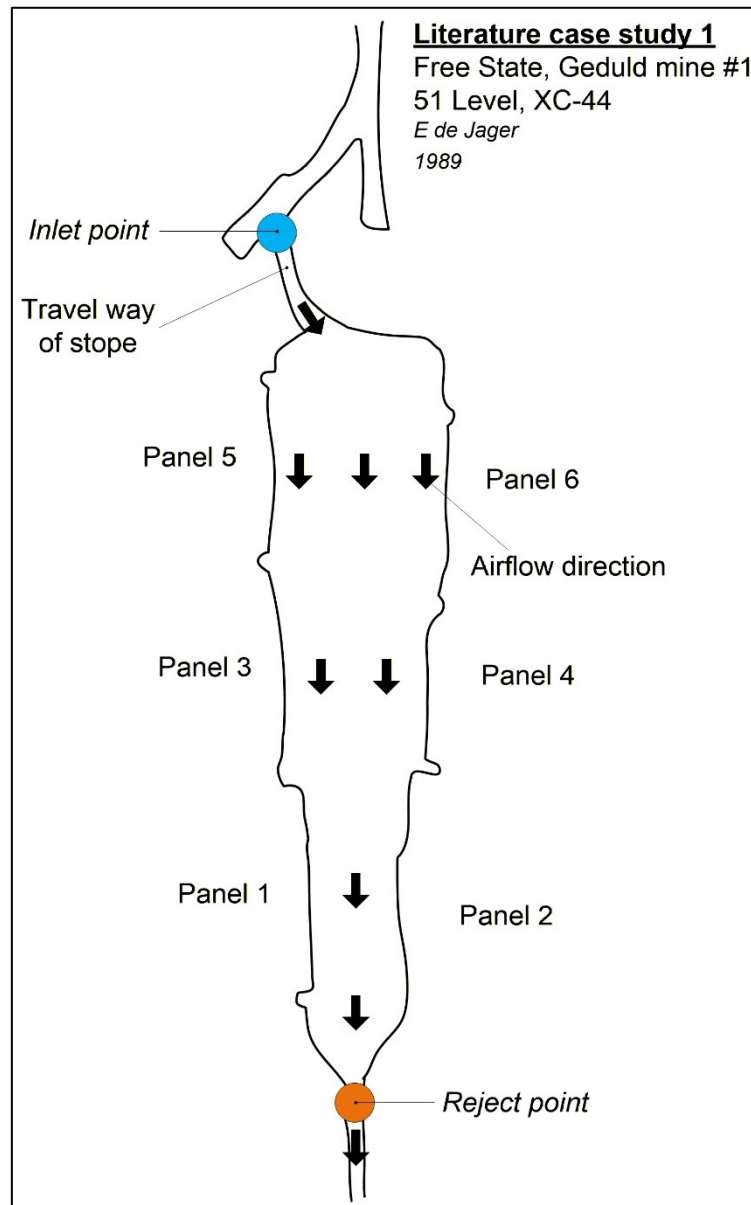


Figure 3-16: Layout of LCS-1

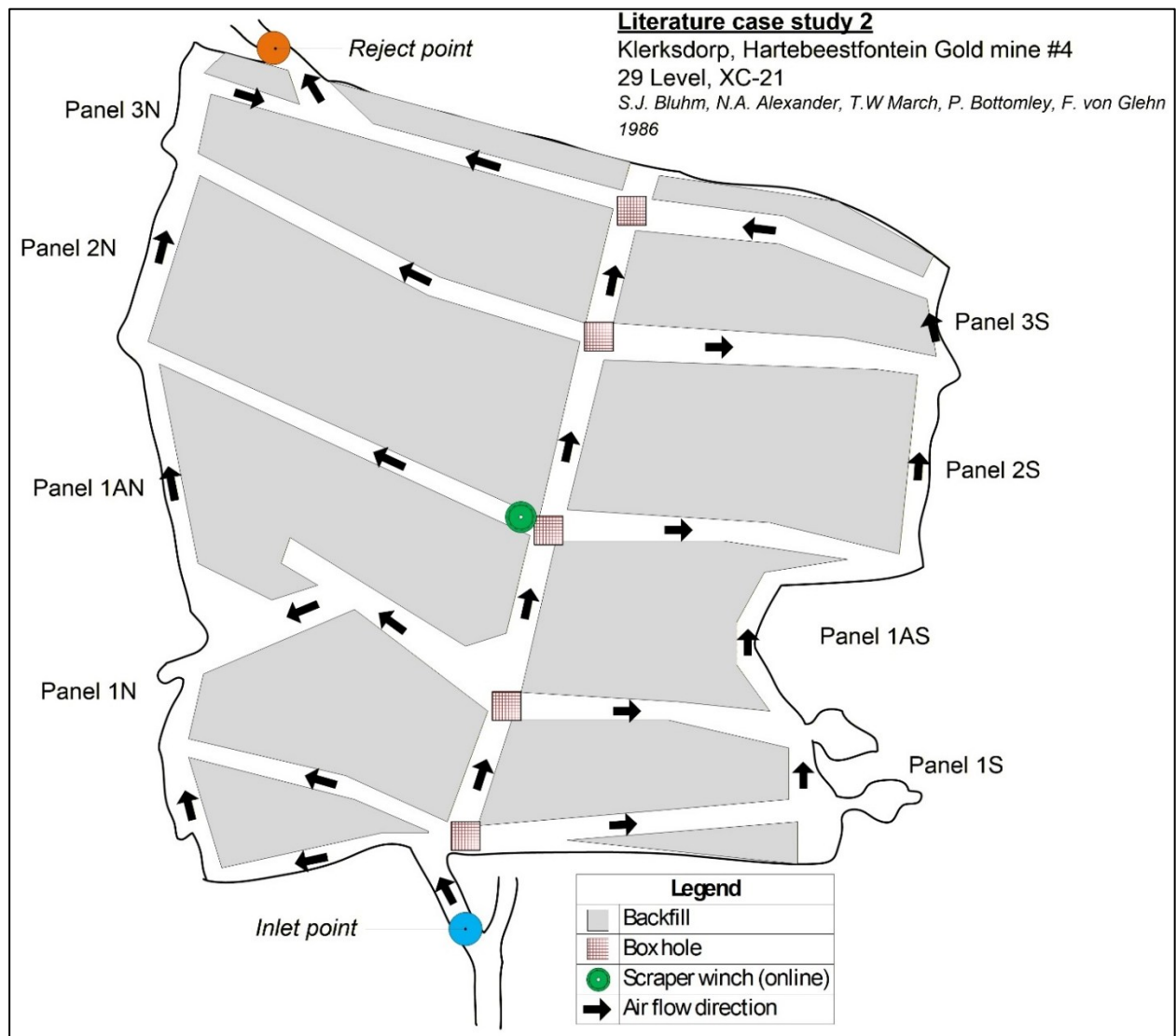


Figure 3-17: Layout of LCS-2

Table 3-7: Intake conditions of literature case study stopes

ID	Air temperature (WB) °C	Air temperature (DB) °C	Air mass kg/s	Water temperature °C	Water mass kg/s
FS-GD	28.8	32.5	10.1	18.6	0.9
KL-HF	24.6	26.5	30.8	26.0	0.8

Table 3-8: Reject conditions of literature case study stopes

ID	Air temperature (WB) °C	Air temperature (DB) °C	Water temperature °C
FS-GD	30.2	32.0	29.9
KL-HF	28.0	30.0	28.0

A notable difference in the findings compared to in-field case studies is the significantly lower amount of water used in the stopes. Despite this reduction, the case studies reported instances of ponded water, which would eventually flow to the box holes and be drained away. Although the volume of water is less, it still helps mitigate the geothermal energy from the rock, as evidenced by the relatively high reject temperatures of the service water. In terms of ventilation air, the conditions are similar to those of the in-field case studies, with the exception of the FS-GD stope, which received cooler air but with a lower air mass flow rate.

The heat loads from the case studies were analysed using the energy balance method, which will be discussed in the next section.

3.2.5 Quantify heat load (energy balance method)

Utilising the method outlined in Chapter 2, the energy balance method was applied to all case studies. The energy absorbed by the heat sinks is equivalent to the total heat energy dissipated by the stope under the given feed conditions. The results from the energy balance method are presented in Table 3-9 and Figure 3-16.

Table 3-9: Energy balance method heat loads

ID	Air cooling kW	Water cooling kW	Heat load kW
XC-A	234 (35%)	444 (65%)	678
XC-B	194 (27%)	516 (73%)	710
XC-C	335 (48%)	362 (52%)	697
FS-GD*	100 (67%)	50 (33%)	150
KL-HF*	578 (96%)	24 (4%)	602

**As reported by case study*

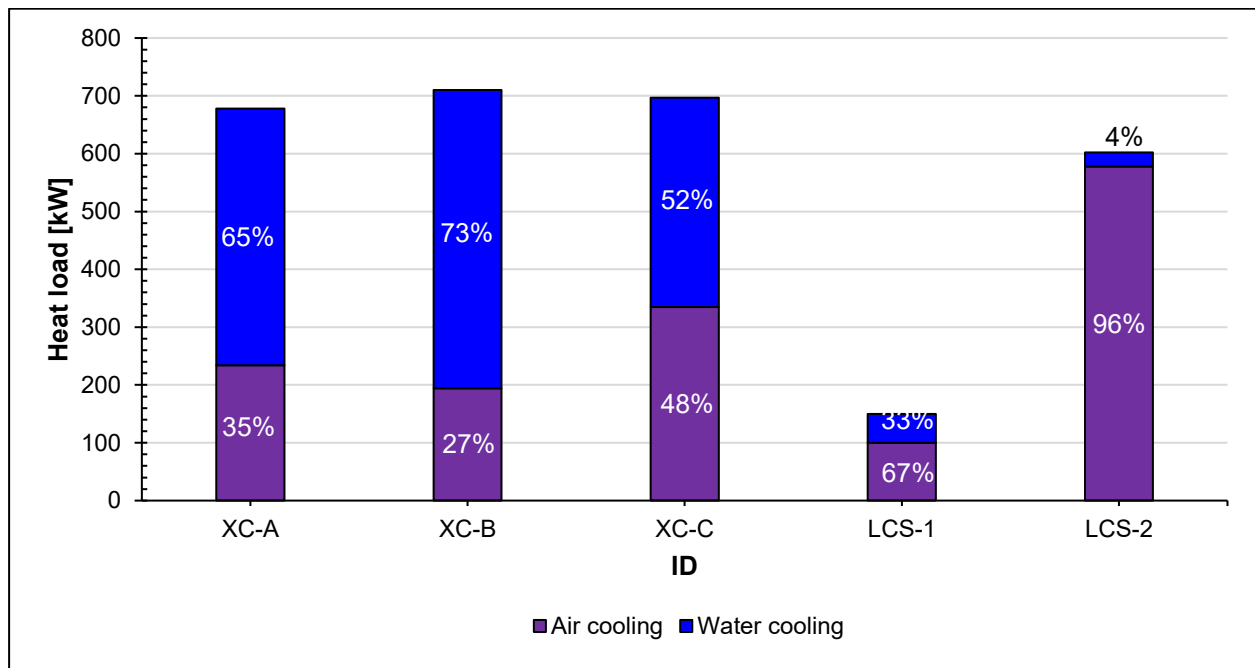


Figure 3-18: Energy balance method stope heat loads

The results indicate that the in-field case studies closely align with one another, despite variations in exposed rock surface areas, especially when comparing XC-B and XC-C to XC-A. A consistent observation among the in-field stopes was the high-water consumption, which occasionally saturated the ventilation air in the stope. This saturation enhances the heat release from the exposed rock surface. Consequently, the saturation of ventilation air across all in-field case studies resulted in comparable heat loads.

The FS-GD stope reported a significantly lower heat load than the other case studies, confirming the hypothesis that stope heat loads vary depending on the mining phase. This is primarily attributed to the amount of exposed rock surface area. The FS-GD stope, being in the ledging phase, corresponds to the pre-stoping phase.

The findings also highlight the type of heat sink used to manage heat loads. In the literature case studies from the 1980s, the primary cooling medium was ventilation air, accounting for roughly two-thirds of the cooling supplied. In contrast, data from the in-field case studies show a reversal of this trend, with service water becoming the predominant source of cooling. This proves that the ventilation air supplied to the stopes is not sufficient by itself to combat the heat load; thus, the workers use service water to provide additional cooling. This shift in trend negatively affects workers in the stopes, because the relative humidity of the saturated ventilation air reduces productivity and can increase the risk of workplace injuries [58, 59]. The uncomfortable conditions prompt workers to open service water outlets to create makeshift coolers, which can adversely impact workers downstream.

3.3 Simulated heat load of simulation models

Known parameters were established based on real-world knowledge, such as the age of exposed rock faces and thermal conductivities. Unknown parameters were adjusted to match real-world measurements as closely as possible, particularly regarding the complex interaction of backfill. Once the model was developed, it was calibrated by adding moisture to the environment to increase air enthalpy at the reject point. The simulated heat load values and their comparisons are presented Figure 3-19 and Figure 3-20.

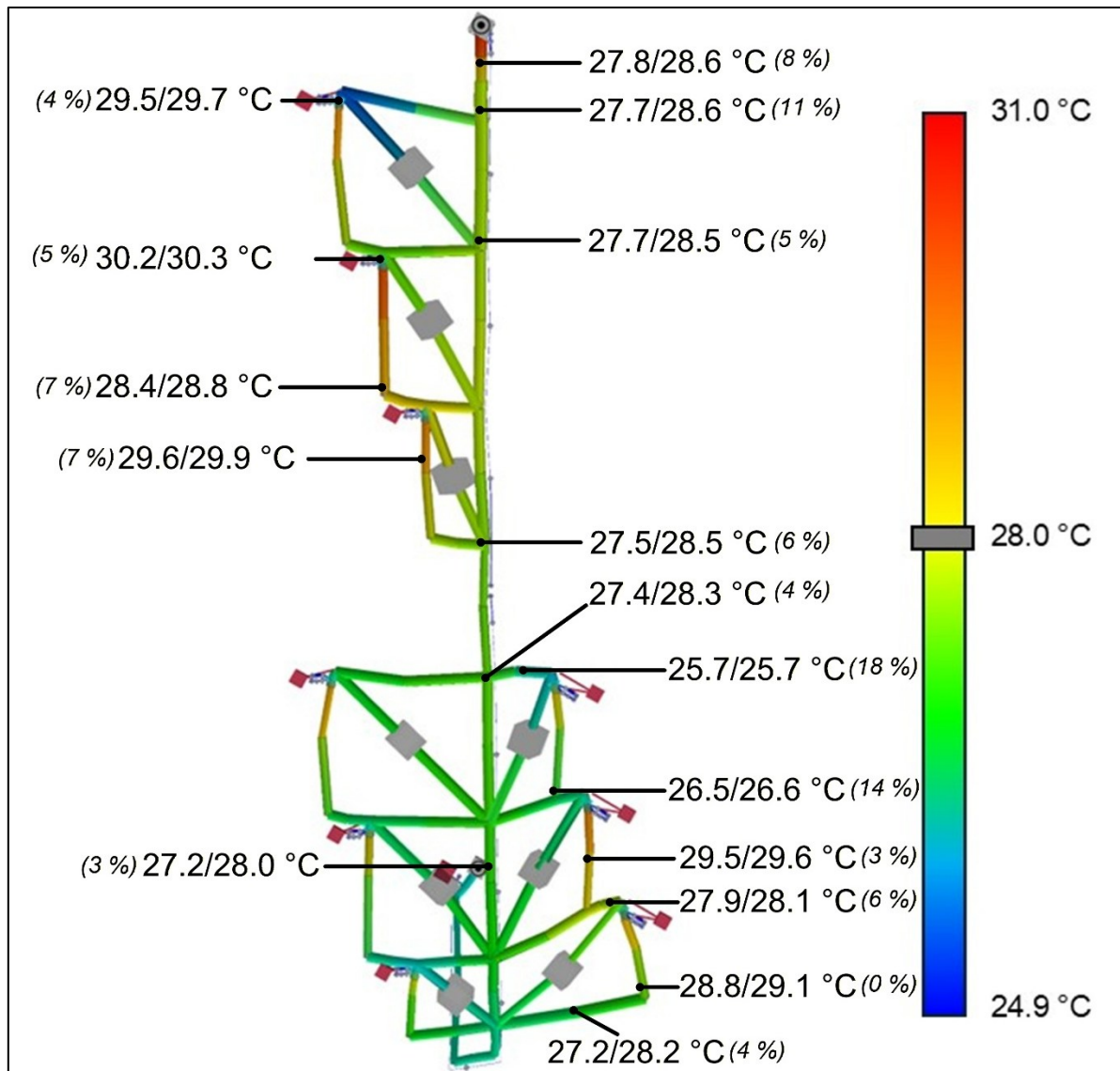


Figure 3-19: Heat map of simulated WB and DB temperatures with errors of XC-A

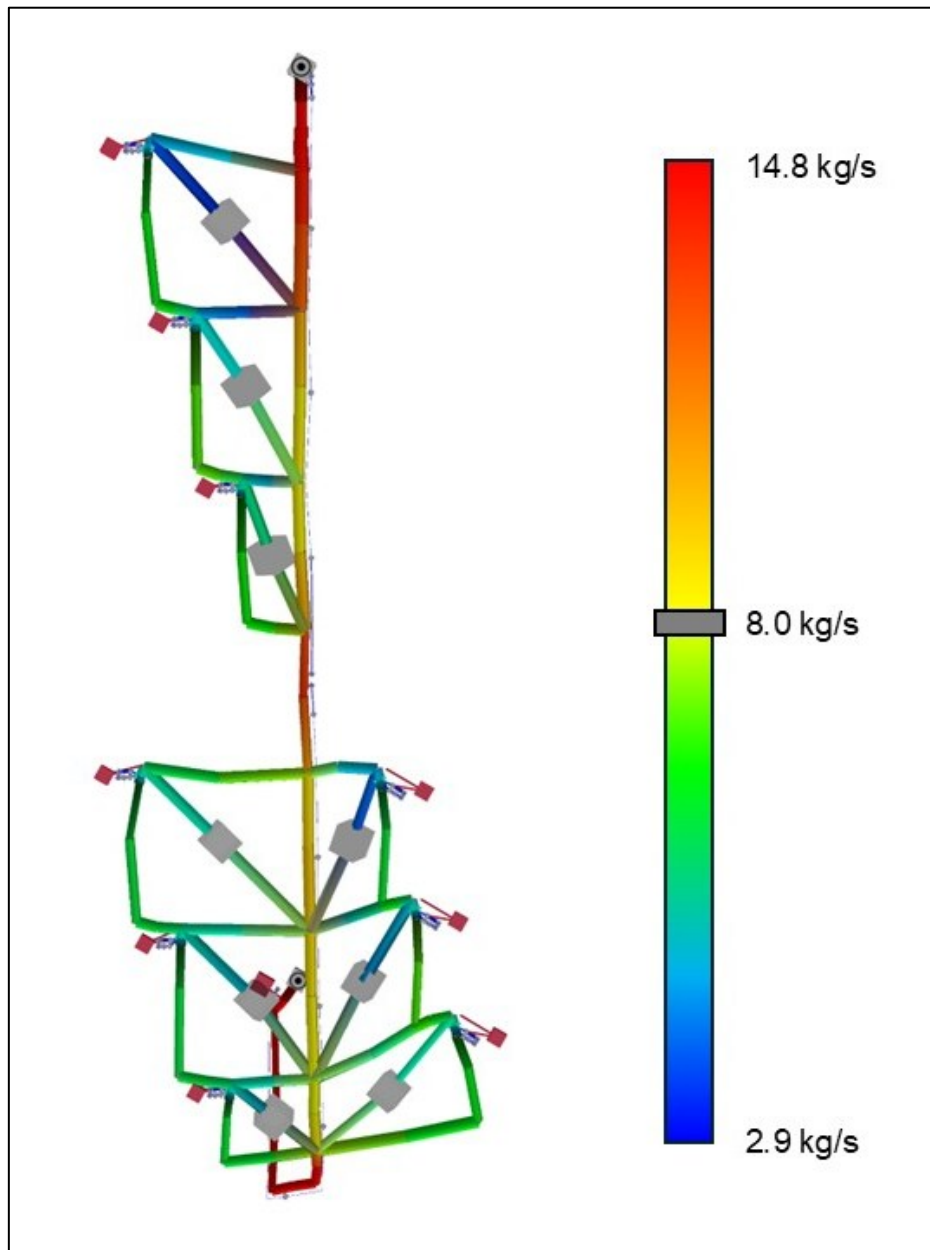


Figure 3-20: Heat map of simulated air mass flow of XC-A

Table 3-10: Values of simulated heat loads

ID	Heat load [kW]
XC-A	554
XC-B	702
XC-C	711
FS-GD	133
KL-HF	517

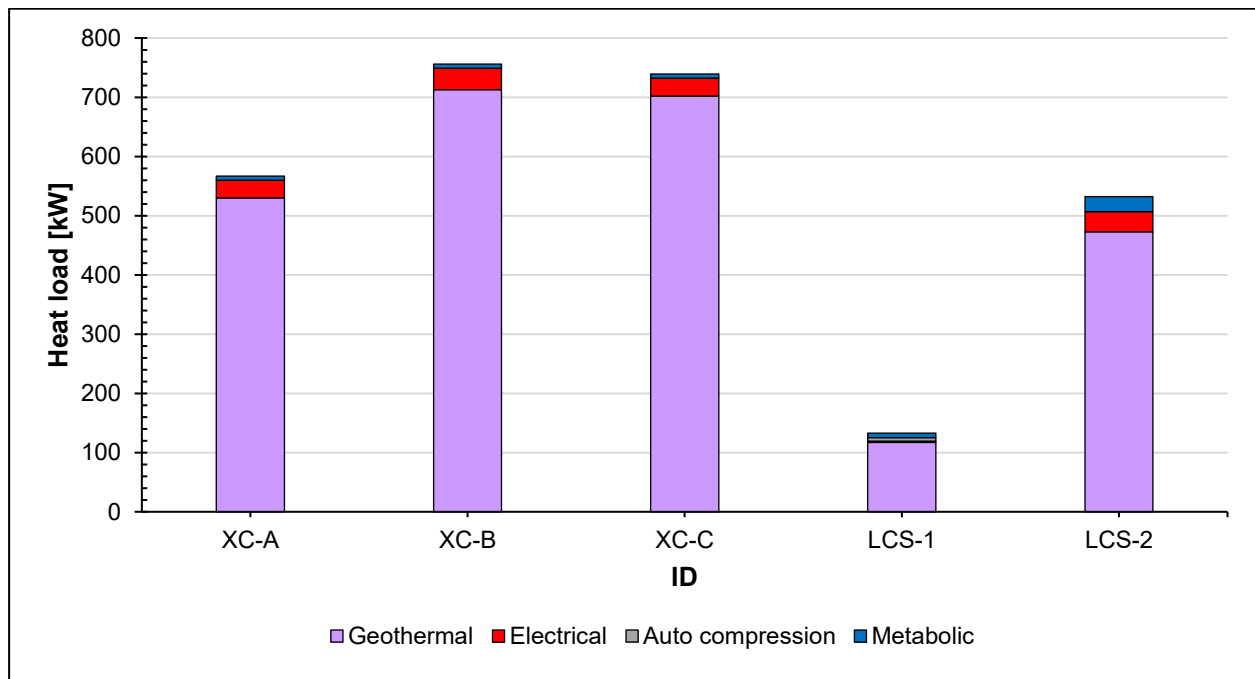


Figure 3-21: Graph showing comparison of simulated heat loads

Similar to the in-field measurements, the simulated heat loads are aligned with the energy balance method. XC-A exhibits a lower heat load compared to the other in-field case studies due to a lower mass flow of air through the stope and a significantly smaller exposed rock surface area. The FS-GD stope shows the lowest simulated heat load, which aligns with its reduced exposed rock surface area and low VRT. The trends in simulated heat loads are justifiable and consistent.

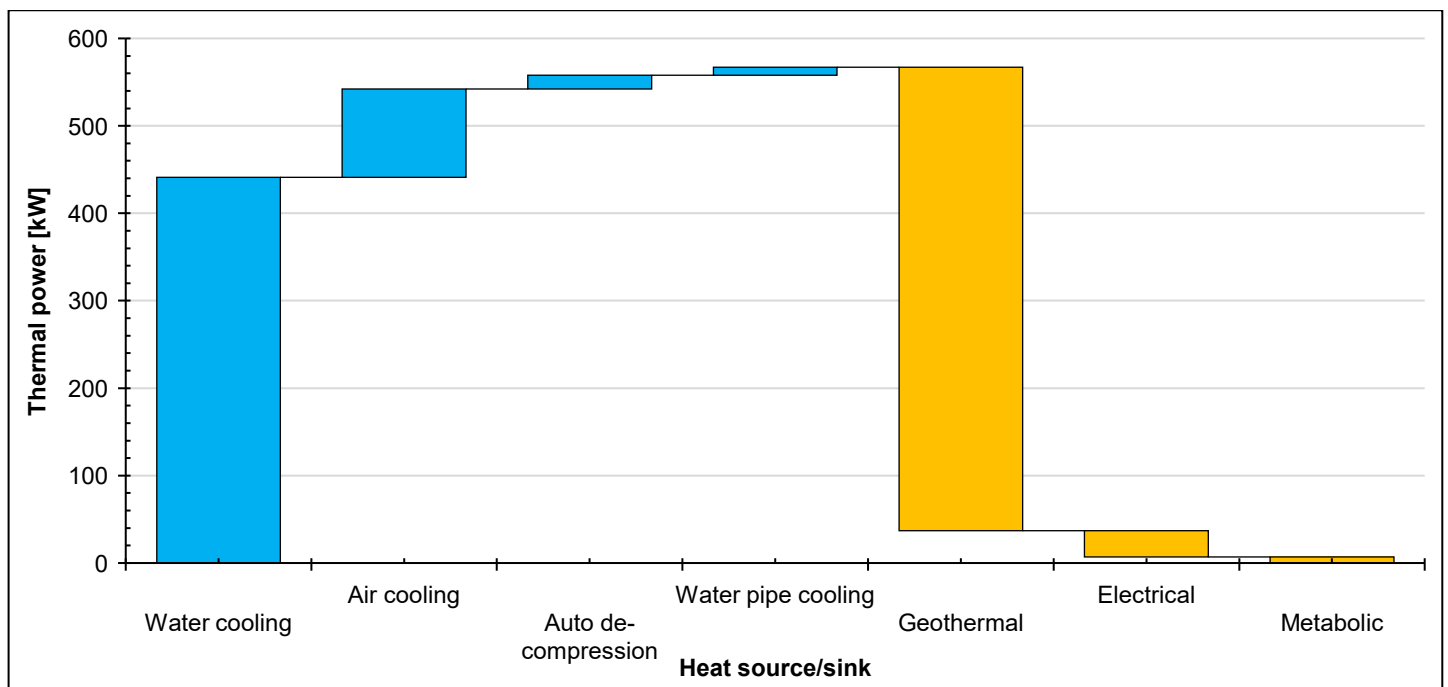


Figure 3-22: Waterfall heat load of XC-A

3.4 VDW method

The VDW method will be calculated and compared to the energy balance and simulation methods. The procedure outlined in Section 2.5 will be used to compute the VDW heat load for both in-field and literature case studies. The first set of calculations will support the final calculation of the VDW stope heat load. Table 3-11 presents the output of these supporting calculations.

Table 3-11: Supporting calculations

Supporting Stope calcs		XC-A	XC-B	XC-C	FS-GD	KL-HF
Heat walls (Q_{SR})	kW	615	739	970	179	310
Heat broken rock (Q_{BR})	kW	66	63	63	8	33
Heat ground water (Q_{SW})	kW	0	0	0	0	0

Among all the case studies, XC-C generates the highest heat from the walls of the stope. This is attributed to XC-C having the largest mined-out area, thereby making it the "oldest" stope in the study. This result is consistent with the notion that a larger surface area enhances heat transfer with the heat sinks. Notably, there is no contribution to the heat load from fissure water. Table 3-12 utilises the outputs from Table 3-11 to calculate the final stope heat loads.

Table 3-12: Output of VDW method

		XC-A	XC-B	XC-C	LCS-1	LCS-2
Temperature dependent heat load						
Rock broken in stopes (P_s)	tonne/month	6728	6702	6730	2070	6840
Area mined out per month (A_M)	m ² /month	4050	4950	5400	1564	4000
Stoped-out area that is ventilated (A_s)	m ²	4133	5326	8414	4539	5902
Average VRT (T_v)	°C	60.4	59.1	59.1	42.5	43.0
Fissure water inflow rate (L_G)	l/s	0	0	0	0	0
Heat from the walls and broken rock (Q_{SRB})	kW	681	802	1033	187	343
Heat from fissure water (Q_{SW})	kW	0	0	0	0	0
Temperature dependent heat load (Q_{SD})	kW	681	802	1033	187	343
Temperature independent heat load						
Scrapers	kW	0	6	0	-	-
Fans	kW	0	0	0		
Water jet pumps	kW	30	30	30		
Temperature independent heat load (Q_{HI})	kW	30	36	30	1	27
Total heat load	kW	711	838	1063	188	370

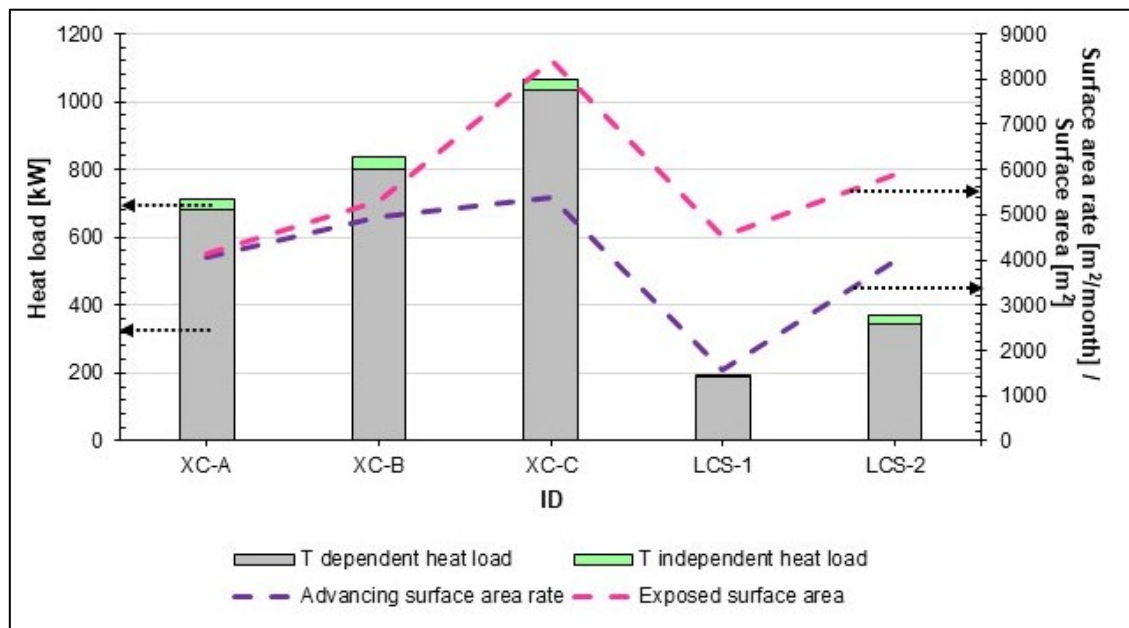


Figure 3-23: Result breakdown of the VDW's method

The area that has been mined and the ventilated stoped area is highest for XC-C, resulting in the stope having the highest heat load at 1 063 kW. The VDW method emphasises the exposed surface area of the rock and the amount of surface area being mined each month. Nevertheless, the VDW method indicates that the in-field stopes have the highest heat load, followed by the KL-HF stope (which has the highest broken tonnes), and the FS-GD ledging stope, which has the lowest mined area per month.

3.5 Validation of correctness of simulation method

When comparing the outputs from all methods and case studies, the results generally correlate with each other, with only a few exceptions. This is encouraging, as it suggests that none of the methods produced outputs that would significantly undermine their validity or indicate calculation errors. Below, in Figure 3-24, we compare the results from all methods and case studies with those from the energy balance method.

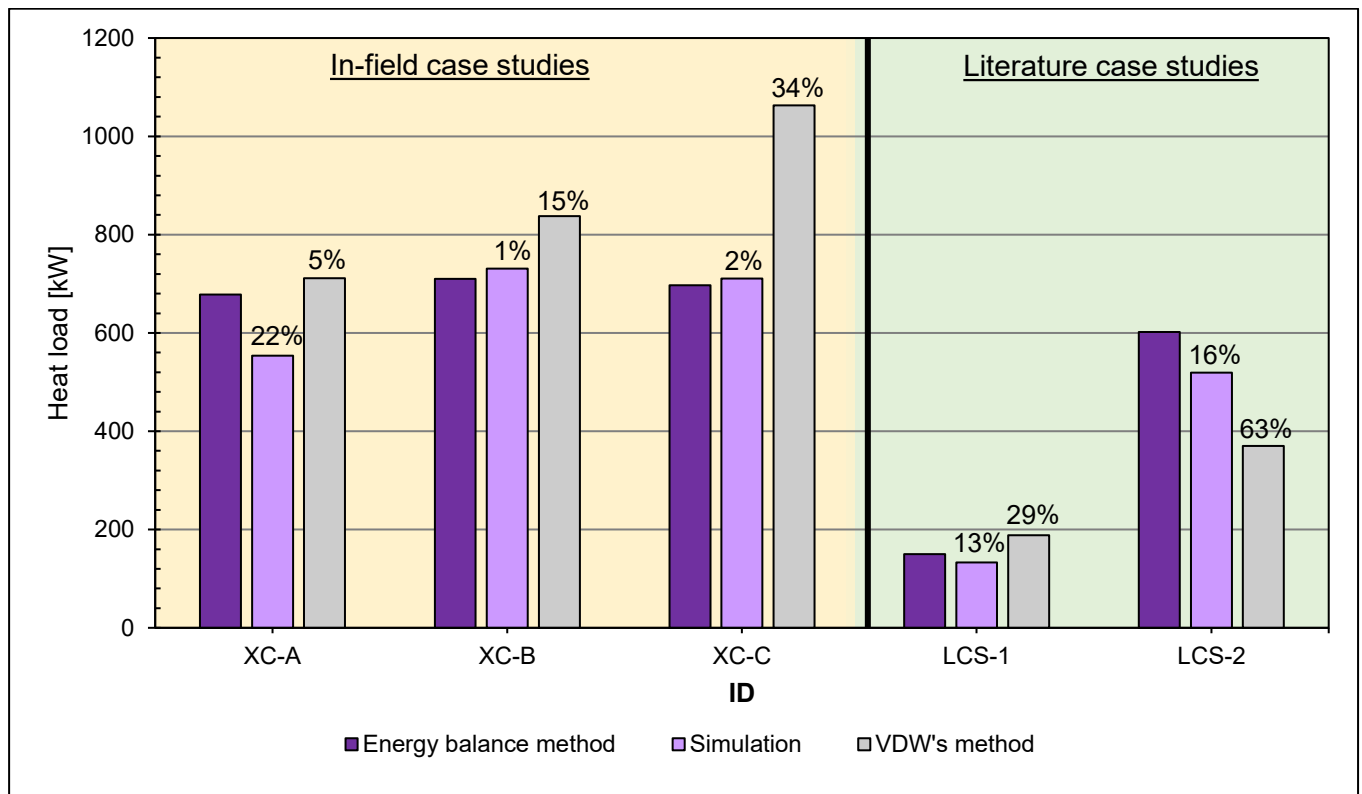


Figure 3-24: Comparison of method outputs for all case studies

For the in-field measurements, there is a good correlation between the energy balance method and the simulation, particularly with cases XC-B and C. Additionally, there is a strong correlation with the literature case studies, where the simulation model predicts a slightly lesser heat load compared to the energy balance method. However, it is notable that the VDW method, except for KL-HF, consistently overshoots the energy balance benchmark.

The reason for this is that the original intent of the VDW method (at its inception) was to calculate the total heat load for the entire mine. And it could be that during the development of the method, the method result for some sections of the mine produced less heat compared to the empirical data, and that the additional heat needed to be added in the stope heat section of this method. However, the overall heat load for the entire mine was validated for the method. Another reason for the difference could be that the main heat source in the VDW method is geothermal heat, and the instruments and methods previously used to determine the VRT often inaccurately modelled higher VRT temperatures and geothermal rock properties. However, over the years, these methods and instruments have improved and can now accurately measure the VRT and geothermal rock properties, and this precise data is used in the simulation model.

Additionally, the figure shows that the in-field case studies have significantly higher heat loads for all methods compared to the literature case studies. This difference is because measurements in literature case studies were conducted at a time when the RSA was not mining at deep-level depths. The main difference is the significantly higher VRT temperature RSA gold mines currently

operate at. The average absolute error for the simulation is 10.9%, while for the VDW method, it is 29.6%.

The primary objective of this study was to investigate whether simulation models can be effectively utilised to predict stope heat loads—the outputs of the simulation model needed to be relatively close to the benchmark established by previous methods. The results indicate that the simulation output closely matches the energy balance method and even predicts stope heat more accurately than the VDW method. Therefore, this study successfully demonstrates that simulation models can indeed be used to determine stope heat loads.

3.6 Implications of the results for the mining industry

The findings of this study clearly demonstrate that an integrated, interdisciplinary approach is indispensable when planning heat loads in production areas. It is necessary to gather and process information from various departments, as the simulation output is highly dependent on the input data. Furthermore, the results of the simulation have implications for those departments. For example, increased cooling requirements impact capital expenditure budgets within engineering departments. Another method to enhance thermal conditions involves reducing the exposed surface area, which entails decreasing the number of production areas; however, this solution adversely affects the mining and financial departments due to reduced production yields. Nevertheless, as Wagner [11] recommends, this issue can be mitigated by adopting more aggressive production advance rates.

Simulation remains a vital component of the Industry 4.0 framework, where real-time monitoring tools are integrated into simulation models to constantly optimise heat loads in production zones [8]. This study shows that simulation can more precisely forecast heat loads and in-stope conditions. Linking this with Industry 4.0 will improve heat load control in production areas, leading to increased workplace safety by reducing thermal overexposure.

This study aimed to improve the operational planning stage within the larger mining planning cycle, which all mines follow to stay profitable and ensure worker safety. This phase is crucial, as its success directly affects the longevity of a mine's production. The primary goal is to prevent early mine closures resulting from flawed operational planning.

Considering the findings from Nell's thesis [8], the heat load analysis for one of the case studies concluded that the production area (entire mine levels in this thesis) necessitates an additional cooling supply of 3.6 MW. The annual operational expenditure (OPEX) cost associated with implementing the refrigeration systems to provide this cooling is calculated using a general Coefficient of Performance (COP) of 3 [8], and based on Eskom's effective annual tariff of approximately R2.2 per kWh³, resulting in an expenditure of R23 million p.a. By applying the

³ 3: <https://www.eskom.co.za/distribution/wp-content/uploads/2025/07/Tariff-booklet2.pdf> (accessed October 2025)

errors derived from the simulation and VDW method to estimate the potential inaccuracies in the OPEX budget, it is observed that the simulation approach yields a budget estimate that is approximately R4.3 million p.a. more precise compared to VDW's method for the production area. This cost mitigation, demonstrated by the simulation method, will prevent mines from overspending on cooling costs, which is critical when the mine operates near profitability margins and could otherwise lead to financial strain or premature closure. Overspending on cooling cost might not always be negative. However, there is a point where if the workplace becomes too cold, workers' productivity will decline, as can be seen in many Northern Hemisphere gold mines during winter, when efforts are made to add heat into the intake shaft to increase workplace temperatures [41, 60, 61]. The simulation approach facilitates more accurate planning and budgeting regarding operational expenses.

Significant time has been dedicated to the development of simulation models for the studies. A balance must be established between the time invested in these models and the extent of additional cooling implemented based on the findings. Further studies may be initiated to determine this optimal balance.

3.7 Validation of study

To determine whether the study has been successful overall, it must be assessed if the study's objectives have been met. Referring to the objectives outlined in section 1.6, the study will be compared against them. The points discussed below:

1. The study has conducted in-field measurements on three active gold mining stopes in RSA. The layout and tables related to the information collected are included in the study.
2. The study has determined the stope heat loads of the in-field case studies using the energy balance method. The average heat load for the in-field stopes was 695 kW.
3. The method for constructing simulations was presented, along with the simulated heat loads for the in-field case studies.
4. Information from the literature case study stopes was broken down and simplified into meaningful data that could be used in the simulation and VDW methods.
5. Similar to 3, the simulated heat loads for the literature case studies were also presented.
6. Using the industry accepted standard method, the VDW method, the stope heat loads for all case studies were determined.
7. The simulation method and VDW method was compared to the energy balance method using the mean average error method. The mean absolute error for the simulation and VDW method is 10.9% and 29.6%, respectively.
8. Lastly, the simulation method was validated for correctness in the study as the mean absolute error remained within 15% (as was the target defined in section **Error!**

Reference source not found.). The simulation proved to be more accurate than the VDW method for determining stope heat loads and can be used to verify the VDW method's findings.

In conclusion, the simulation method was validated through external case studies. Overall, it demonstrated how this method in this study can be used by mines to predict expected stope heats and verify their calculations.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

4.1 Summary

The literature has established that there is not a lot of research on identifying heat sources and sinks in stopes, as well as determining their stope heat loads. However, no evidence has been presented in the literature on whether simulations can be used to predict stope heat loads and can be used to verify methods being used in industry.

The main objective of the study was to determine whether the simulation can be used as a tool to predict stope heat loads and to verify calculations from industry standard methods. However, the simulation method must first be validated by applying it to case studies.

Three in-field case studies of an operational gold mine were conducted. Significantly high service water usage was observed both entering and within the stope. The average heat load is 695 kW, with service water and ventilation air contributing 441 kW and 254 kW, respectively. The heat loads and findings from the literature case study, which involved different mining depths and regions, were noted.

Thermo-hydraulic models was configured and simulated with certain parameters based on real-world knowledge, while unknown parameters were adjusted to match real-world measurements as closely as possible. Simulation models were developed for the three in-field case studies as well as the two literature case studies. The VDW's method was used as an alternative comparison to the energy balance and simulation methods.

The mean absolute error of the simulation is 10.9%, while VDW's method has resulted in 29.6% compared to the energy balance method. The simulation method was validated using external case studies. Overall, it showed how this method can help mines predict stope heat loads and verify calculations done using industry-accepted methods.

The results and findings presented in this study give mine ventilation practitioners the confidence to trust the simulation predictions of stope heat loads, allowing them to improve planning to protect the workforce against the risk of thermal overexposure in the workplace, along with a few other benefits such as over budgeting.

4.2 Limitations of study

- The study's limitations include its focus on a specific point in time. The stope measurements and the case studies were only conducted during the drilling shift. Hence, the study did not consider the transient effects of the mining cycle and its fluctuation of

heat load. The measurement of compressed air for the measured stopes was excluded, as its contribution as a heat sink is relatively small compared to ventilation air and service water.

- The modelling of service water in the in-field simulation models proved to be a difficult task, as it was not obvious to locate the exact source of the service water stream.
- The real-life interaction of the heat exchange between the rock and the service model could not be modelled directly; however, making use of the principle of conservation of energy, this was overcome by the heat transfer from the rock via the ventilation air and then the rock.
- Measuring the reject service water temperature included accounting for the heat of the ore stored in the box fronts and ore passes. This was done because measuring at the boxhole (in the stope – the entrance of the ore pass) was considered too unsafe; the grizzly (steel bars) has a grid large enough for a person to fall through, and the area around the box hole was slippery and had low traction. However, measurements taken close to the boxhole were close to the temperatures measured at the box front.

4.3 Recommendations for future study

- Investigation into the other mining shifts, especially the cleaning shift (transient effects).
 - Immediately after the blasting shift, the stope will experience the highest heat load, since the broken rock has more surface area transferring heat and a new layer into the unbroken is also exposed to the ventilation air.
- In-depth investigation into the backfill interaction of the stope. As the backfill was being pumped into the bags, the auditors measured 32°C of the backfill temperature. Future researchers can explore whether there is an opportunity to supply backfill as a heat sink to the stope to combat heat loads.
- Investigation of the effect of neighbouring stopes and their impact on the heat load.
- In-field measurements to be taken over longer intervals, potentially over months, to determine if there are significant fluctuations in heat load and to obtain more accurate averaged values.
- Explore the sensitivity of other stope configurations and the effect of ventilation controls on the environmental conditions.
- Explore heat loads of production areas with trackless machinery.

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APPENDIX A: INFIELD CASE STUDY ADDITIONAL INFORMATION

Stope layouts

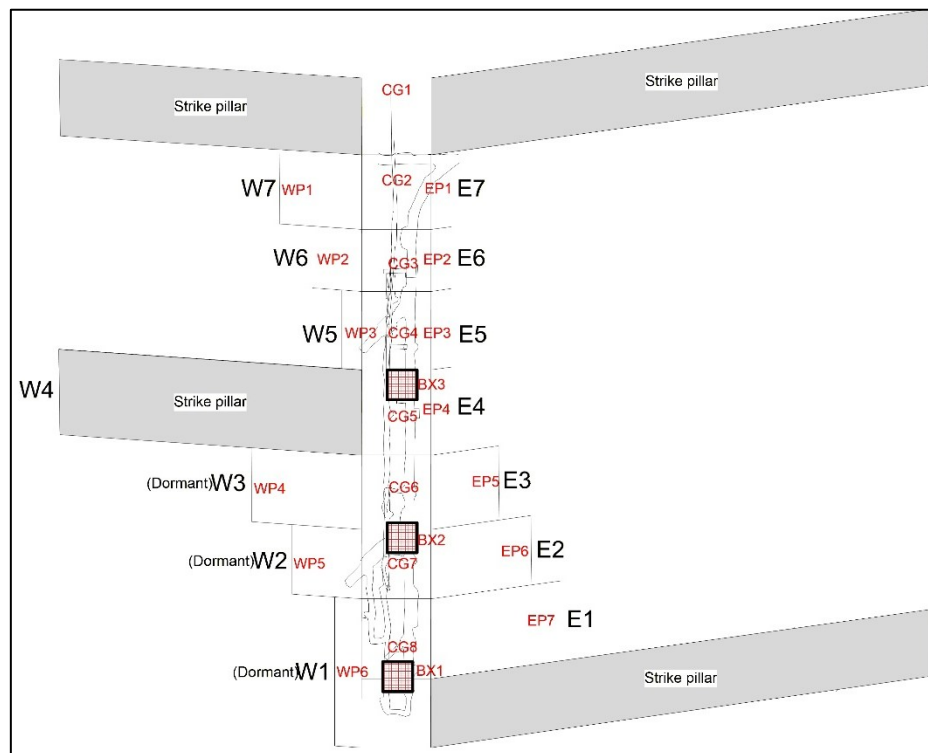


Figure A - 1: In-field stope layout of XC-A

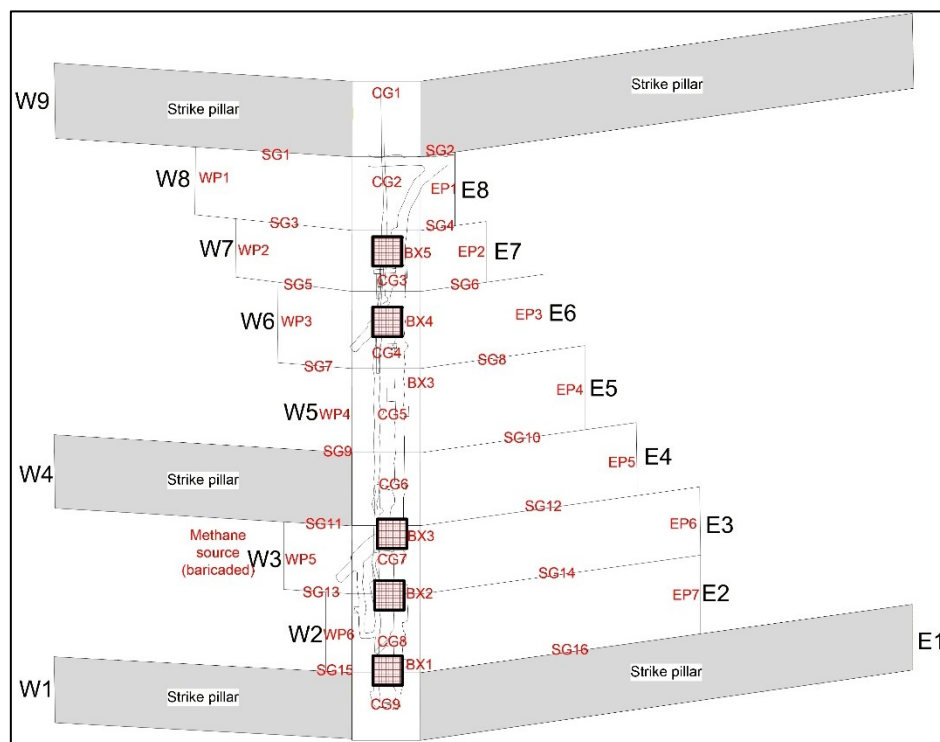


Figure A - 2: In-field stope layout of XC-B

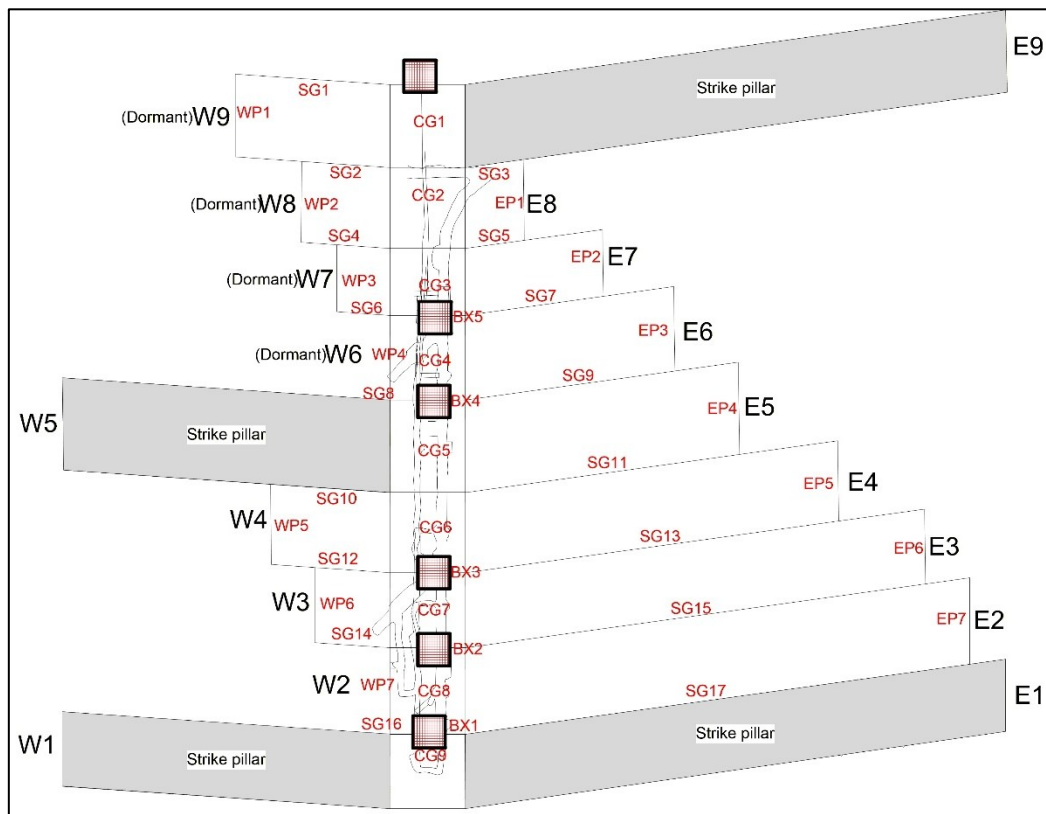


Figure A - 3: In-field stope layout of XC-C

Ventilation tiny tag data

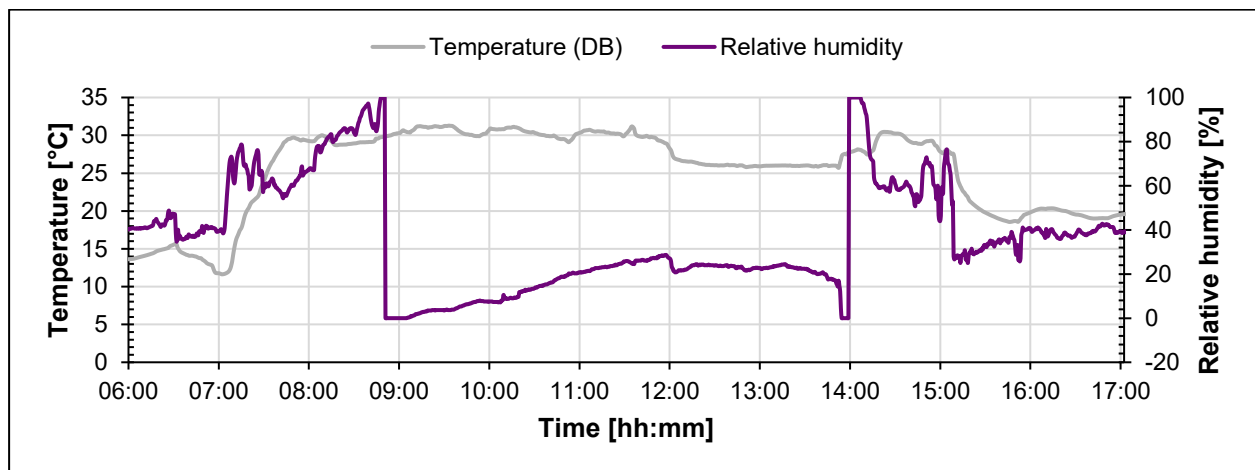
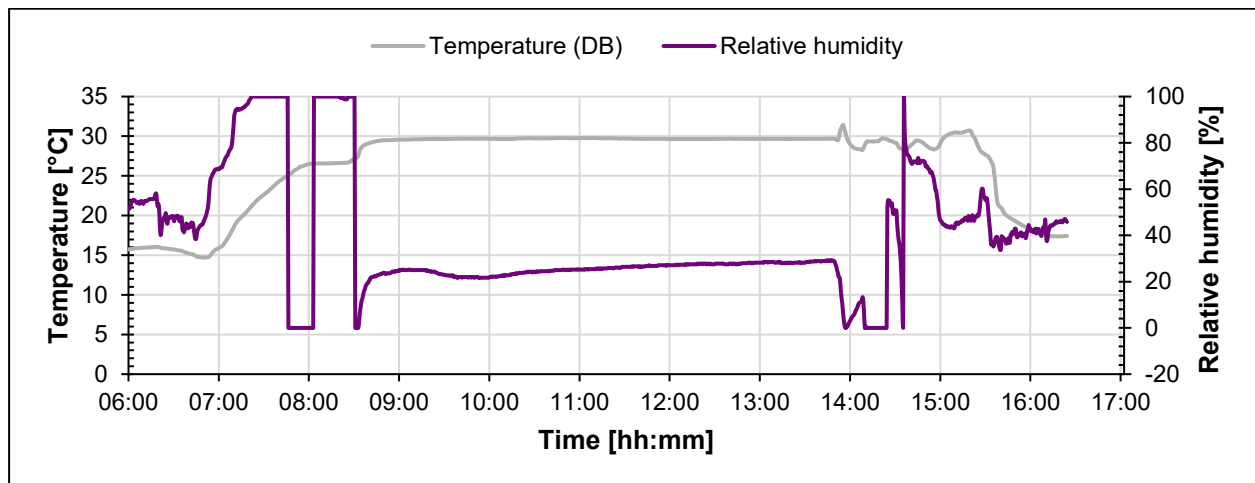
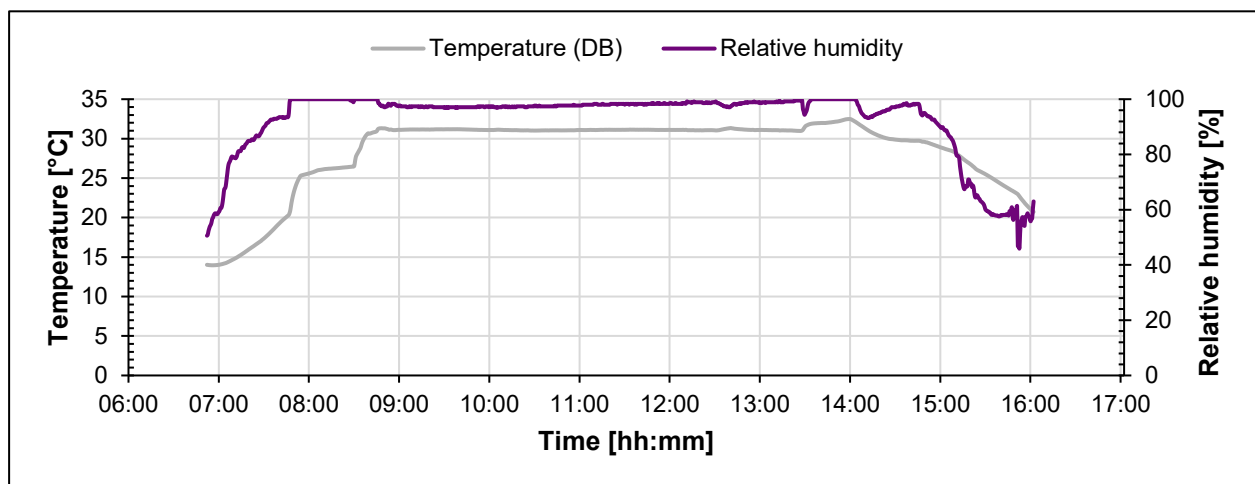
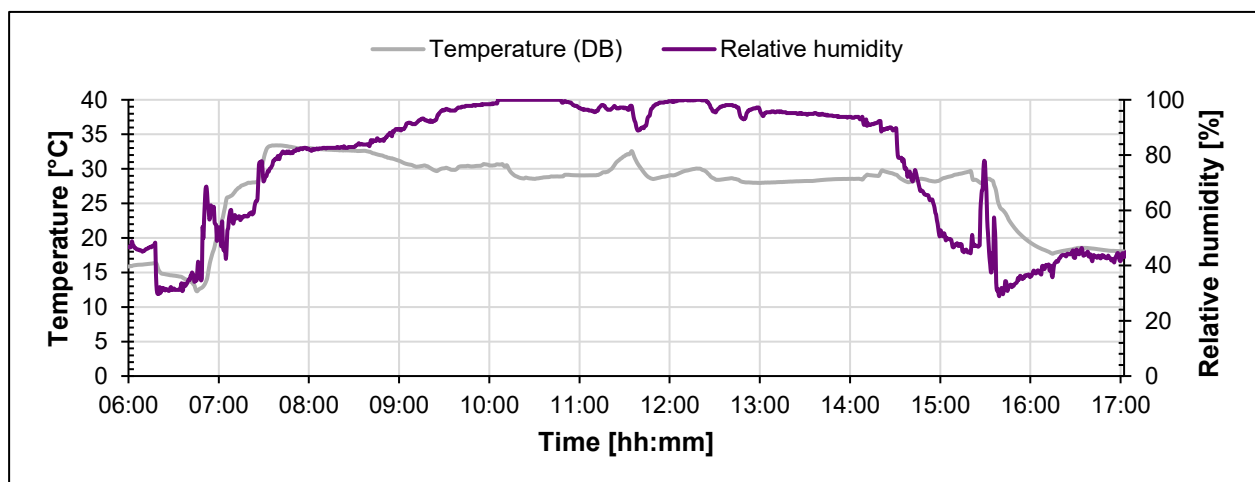


Figure A - 4: XC-A stope profile of ambient conditions

**Figure A - 5: XC-B intake profile of ambient conditions****Figure A - 6: XC-B reject profile of ambient conditions****Figure A - 7: XC-B stope profile of ambient conditions**

Water flow profiles for in-field case studies

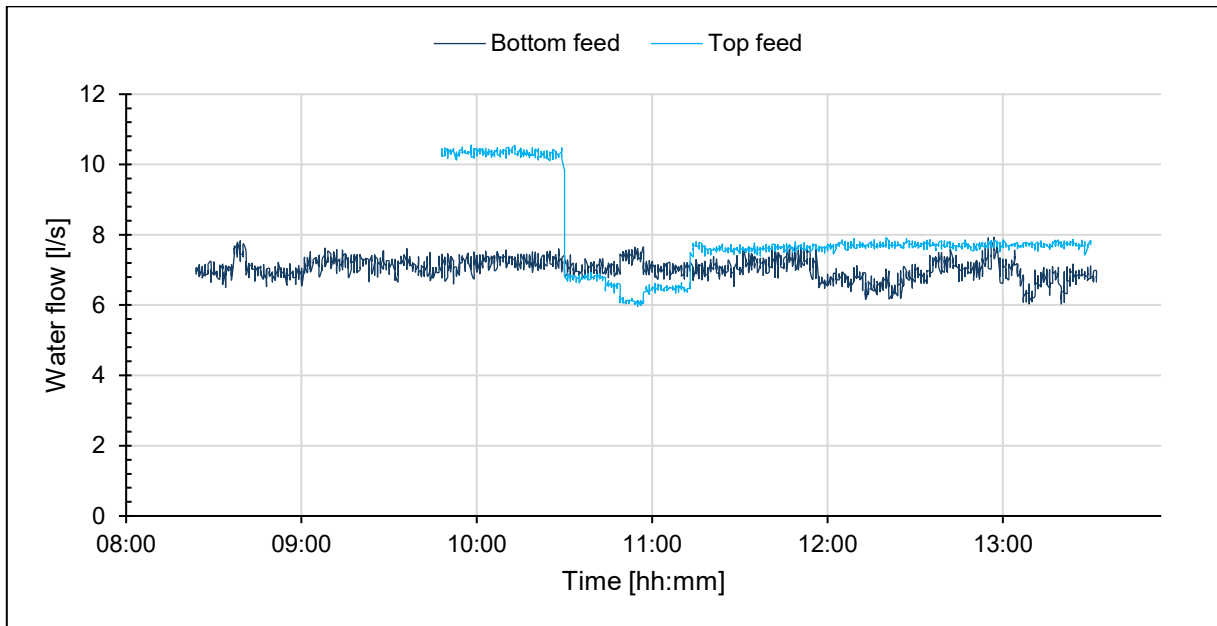


Figure A - 8: Water flow profile for XC-B

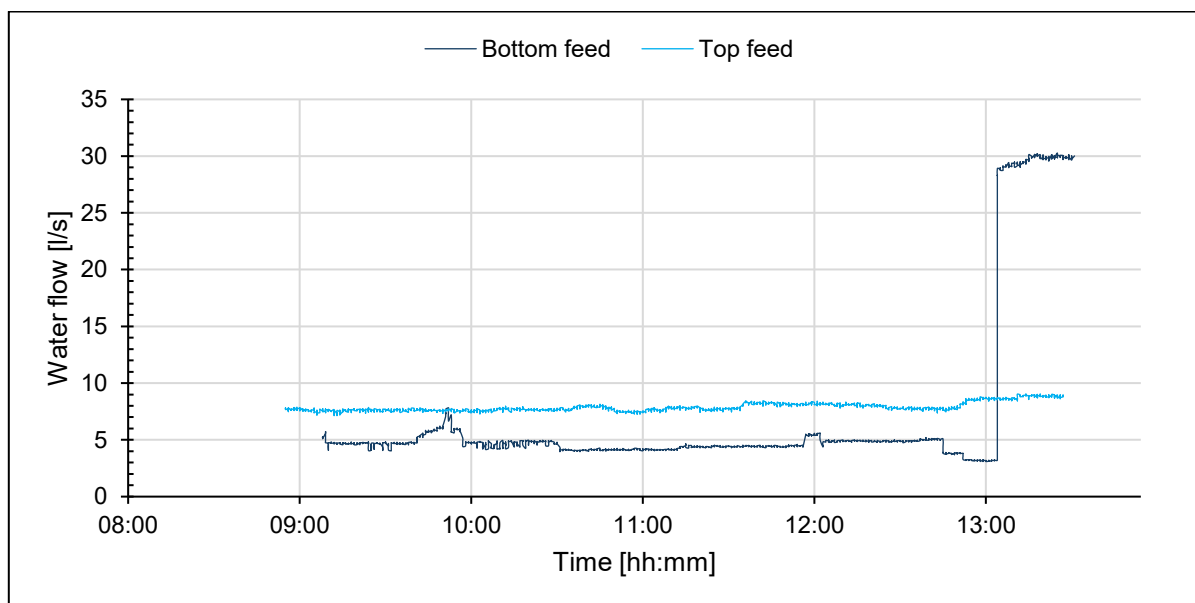


Figure A - 9: Water flow profile for XC-C

Panel lengths and locations of drilling and supporting panels

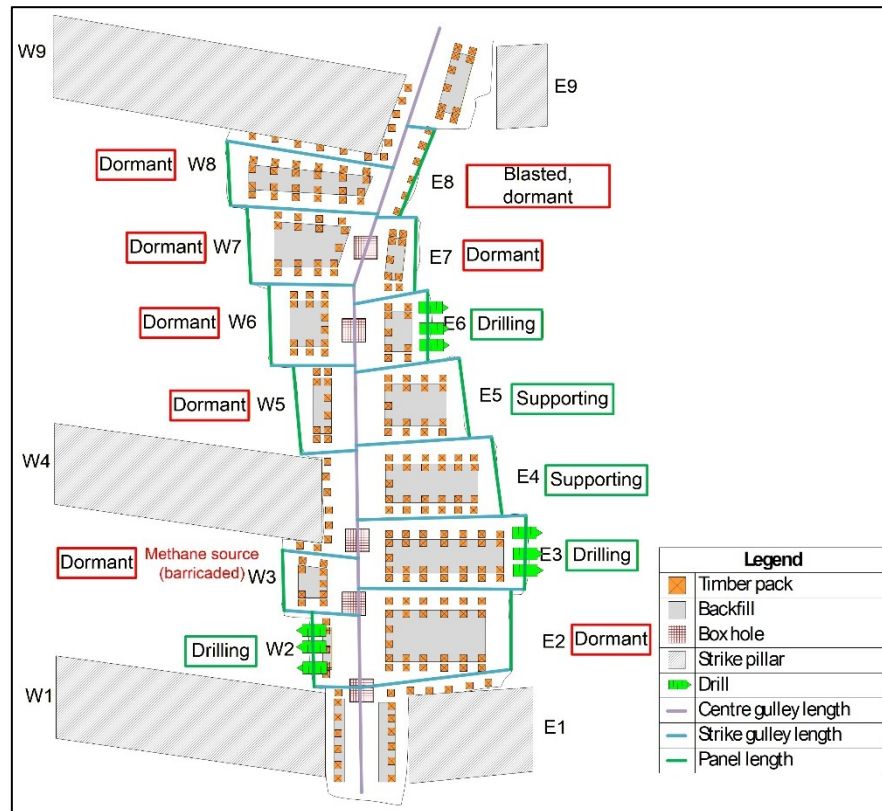


Figure A - 10: Panel lengths and locations of drilling and supporting panels of XC-B



Figure A - 11: Panel lengths and locations of drilling and supporting panels of XC-C

Measurement locations

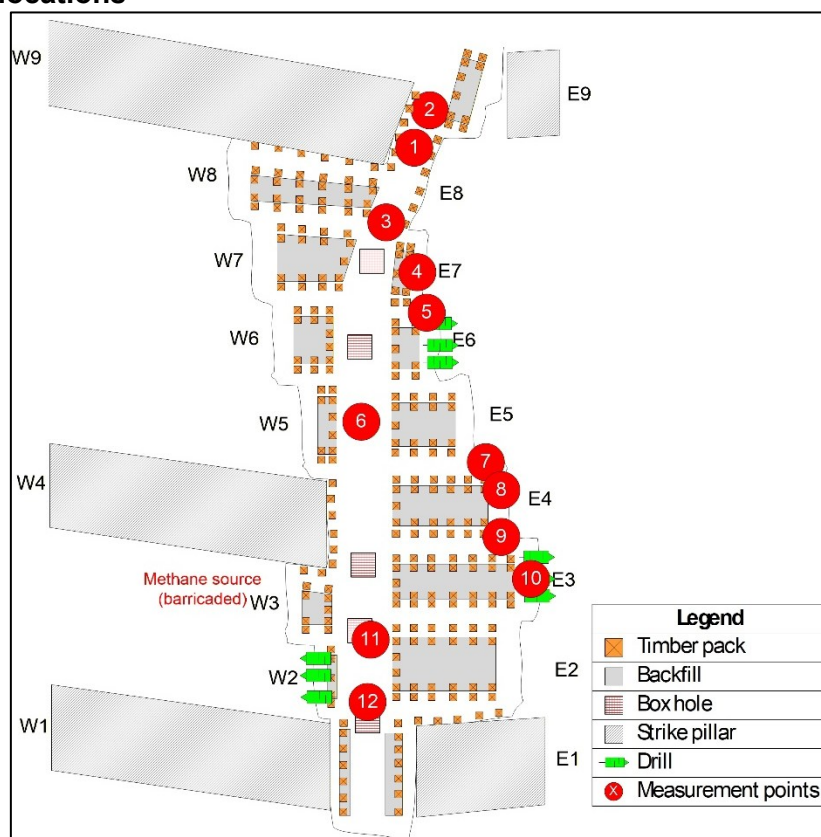


Figure A - 12: Measurement location of XC-B

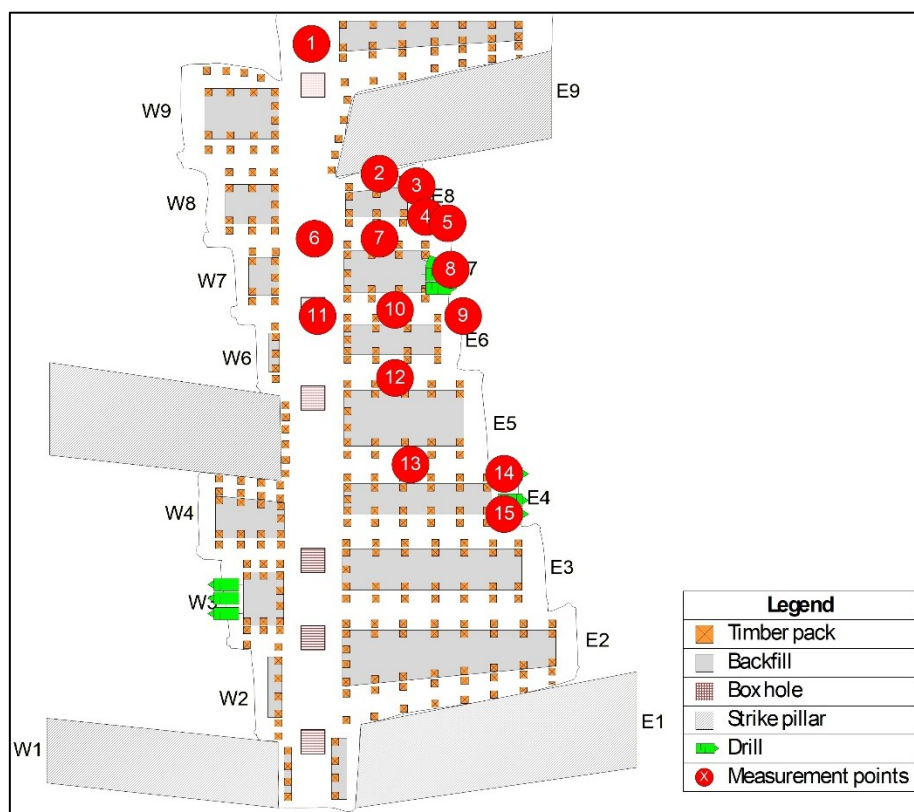


Figure A - 13: Measurement location of XC-C

Supporting Images of In-field findings

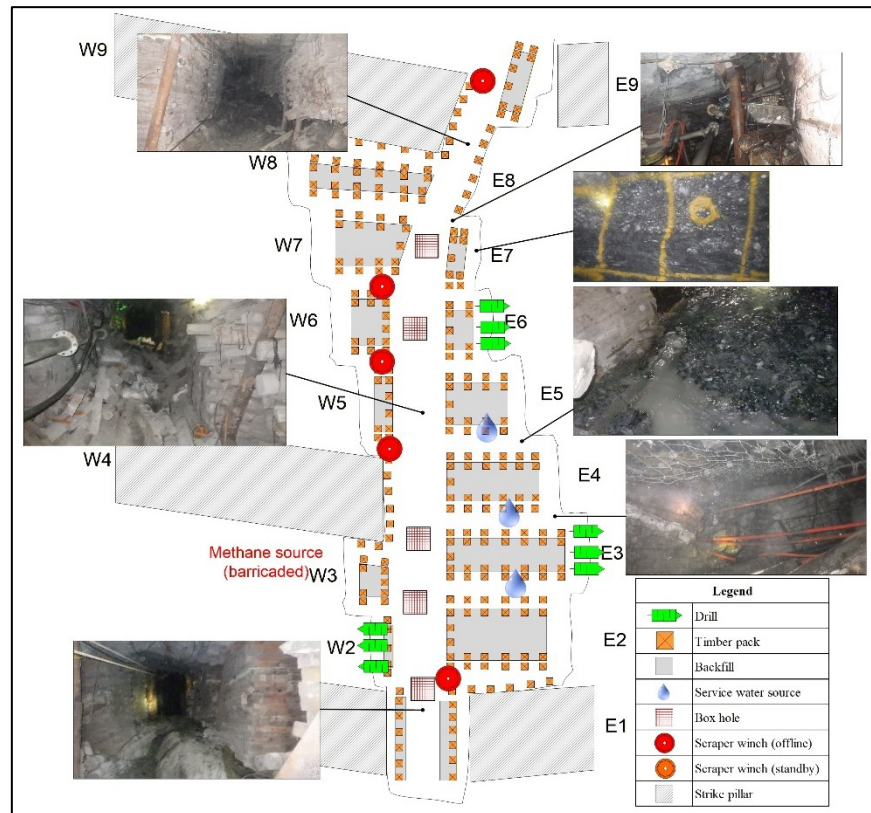


Figure A - 14: Supporting images of XC-B

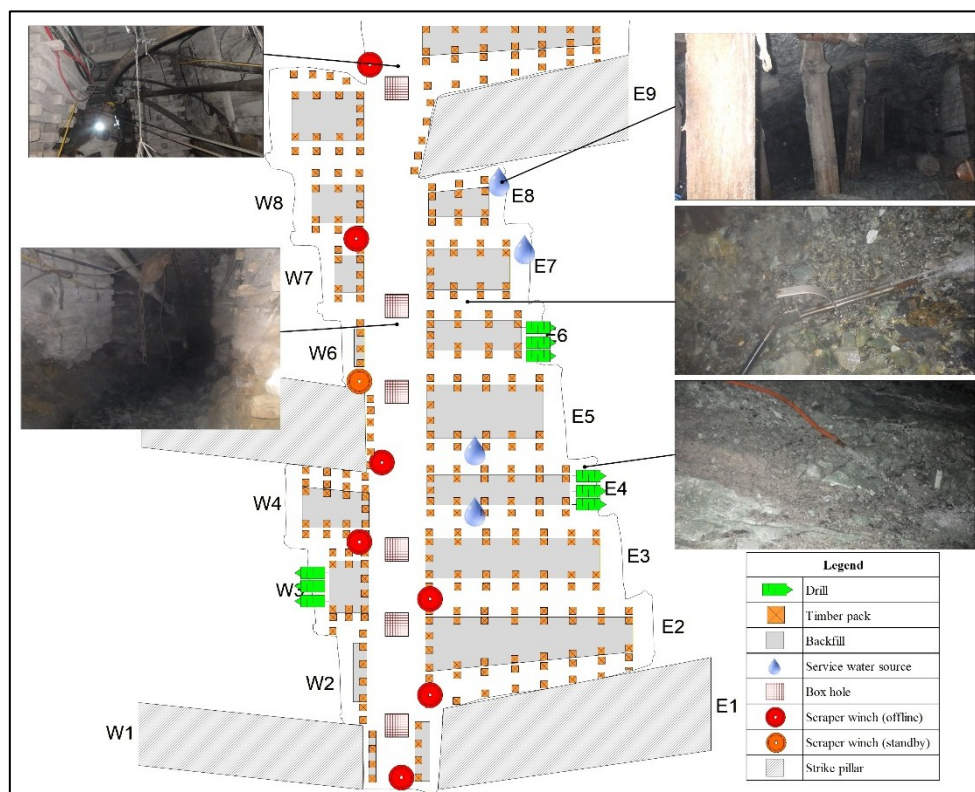


Figure A - 15: Supporting images of XC-C

Measurement data of in-field findings

Table A - 1: Measured conditions of XC-B

No.	Air temperature (WB) °C	Air temperature (DB) °C	Pressure kPa	Relative humidity %	Air Density kg/m ³	Width m	Height m	Area m ²	Velocity m/s	Volume flow m ³ /s	Mass flow kg/s
1	-	-	122.77	-	-	4.09	3.49	14.27	-	-	-
2	29.3	29.5	122.77	98.1%	1.4	1.98	2.71	5.37	-	-	-
3	30.0	30.0	-	-	-	2.19	2.08	4.54	-	-	-
4	31.0	31.0	-	-	-	-	-	-	0.60	-	-
5	30.5	30.5	123.16	100.0%	1.4	-	-	-	1.05	0.0	0.0
6	28.5	29.0	124.37	96.0%	1.4	2.06	2.40	4.95	1.30	6.4	9.1
7	29.5	30.0	-	-	-	-	-	-	<i>Drift</i>	-	-
8	31.0	31.5	123.37	96.3%	1.4	1.82	1.43	2.60	1.00	2.6	3.6
9	31.0	32.5	123.54	89.4%	1.4	4.09	3.49	14.27	1.40	20.0	27.8
10	29.0	29.0	-	-	-	1.74	2.23	3.86	1.20	4.6	-
11	29.5	29.5	123.78	100%	1.4	2.22	2.32	5.16	0.70	3.6	5.1
12	29.3	29.8	123.78	96.2%	1.4	2.22	2.32	5.16	0.70	3.6	5.1

Table A - 2: Measured conditions of XC-C

No.	Air temperature (WB) °C	Air temperature (DB) °C	Pressure kPa	Relative humidity %	Air Density kg/m ³	Width m	Height m	Area m ²	Velocity m/s	Volume flow m ³ /s	Mass flow kg/s
1	30.0	30.0	123.32	100%	1.40	2.1	2.4	5.0	1.5	7.3	10.2
2	31.0	31.0	123.38	100%	1.39	1.8	1.9	3.5	1.1	3.9	5.4
3	30.5	30.5	123.43	100%	1.40	3.7	1.7	6.5	0.8	5.2	7.2
4	31.0	31.0	-	-	-	-	-	-	-	-	-
5	31.0	31.0	123.43	100%	1.39	-	-	-	-	-	-
6	28.0	28.5	123.32	96%	1.41	2.0	2.2	4.4	1.1	4.9	6.9
7	29.3	29.5	123.32	98%	1.40	3.7	1.7	6.5	<i>drift</i>	-	-
8	31.5	31.5	123.52	100%	1.39	2.7	1.2	3.3	1.5	4.9	6.9
9	31.5	31.5	123.52	100%	1.39	4.4	1.3	5.8	0.7	4.0	5.6
10	30.8	30.8	123.52	100%	1.40	1.8	2.0	3.5	<i>drift</i>	-	-
11	28.5	28.5	123.54	100%	1.41	2.0	2.6	5.1	1.4	7.1	10.0
12	28.0	28.0	123.64	100%	1.41	1.3	2.3	2.9	<i>drift</i>	-	-
13	30.5	30.5	123.77	100%	1.40	2.1	1.8	3.9	<i>drift</i>	-	-
14	32.5	32.5	123.69	100%	1.39	3.2	1.5	4.8	0.9	4.3	6.0
15	32.5	33.5	123.69	93%	1.38	-	-	-	-	-	-

APPENDIX B: SIMULATION METHOD ADDITIONAL FINDINGS

Waterfall heat loads of all case studies

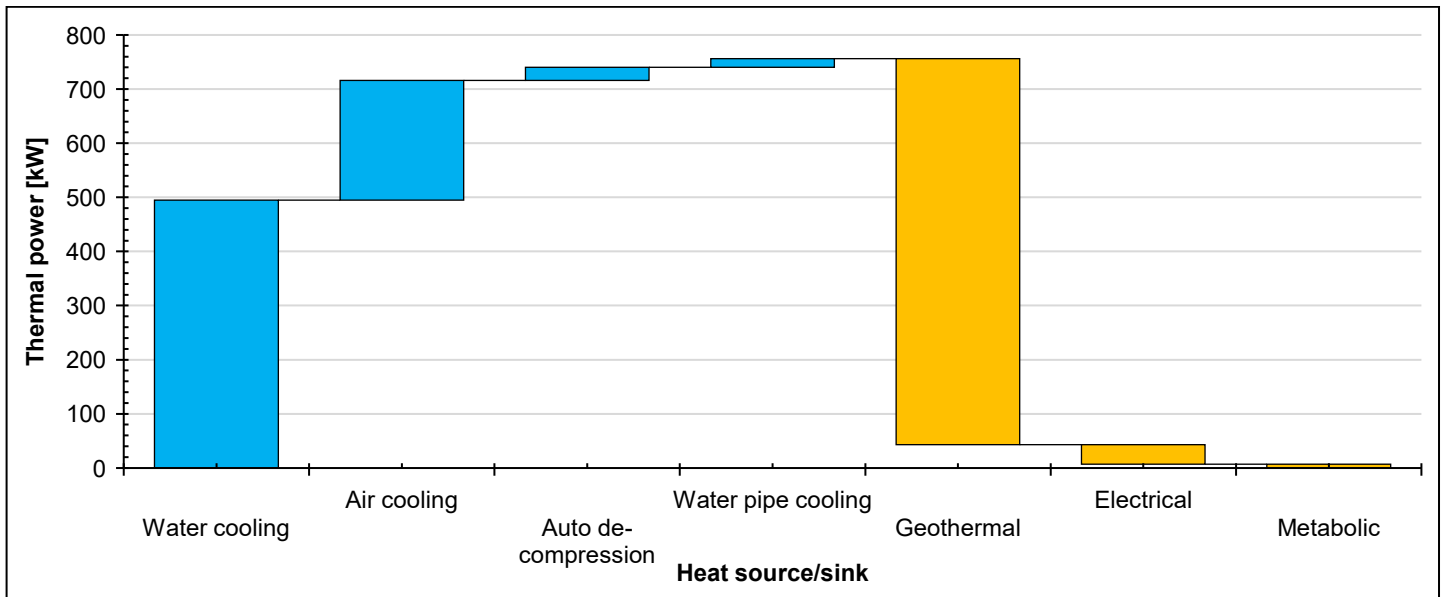


Figure B - 1: Waterfall heat load of XC-B

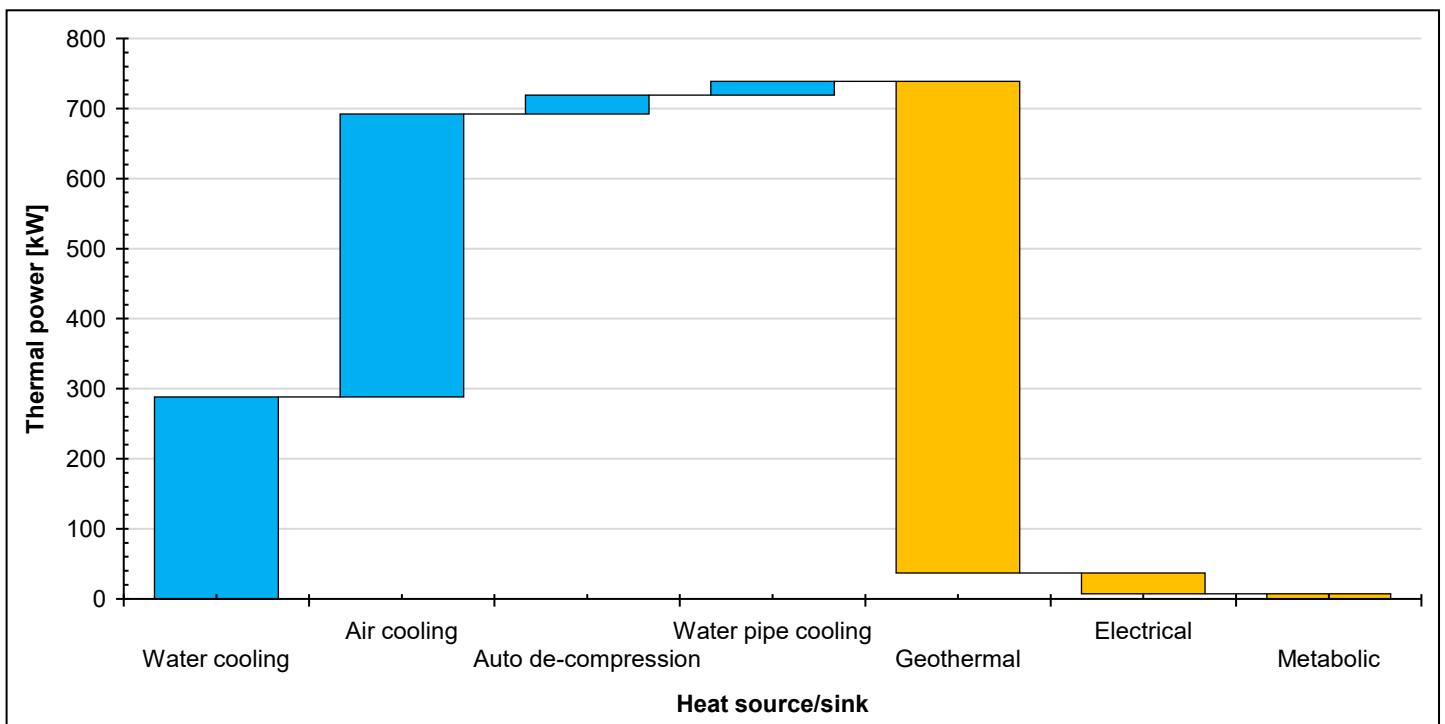


Figure B - 2: Waterfall heat load of XC-C

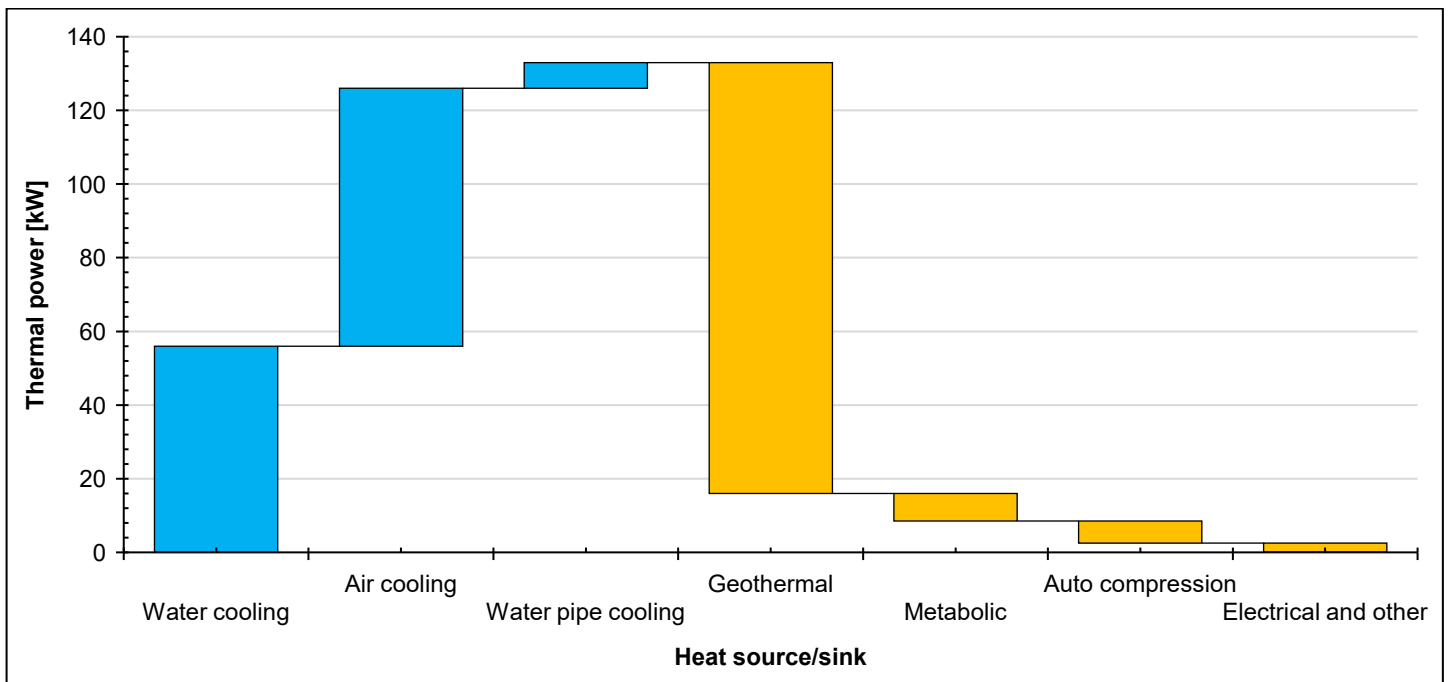


Figure B - 3: Waterfall heat load of LSC-1

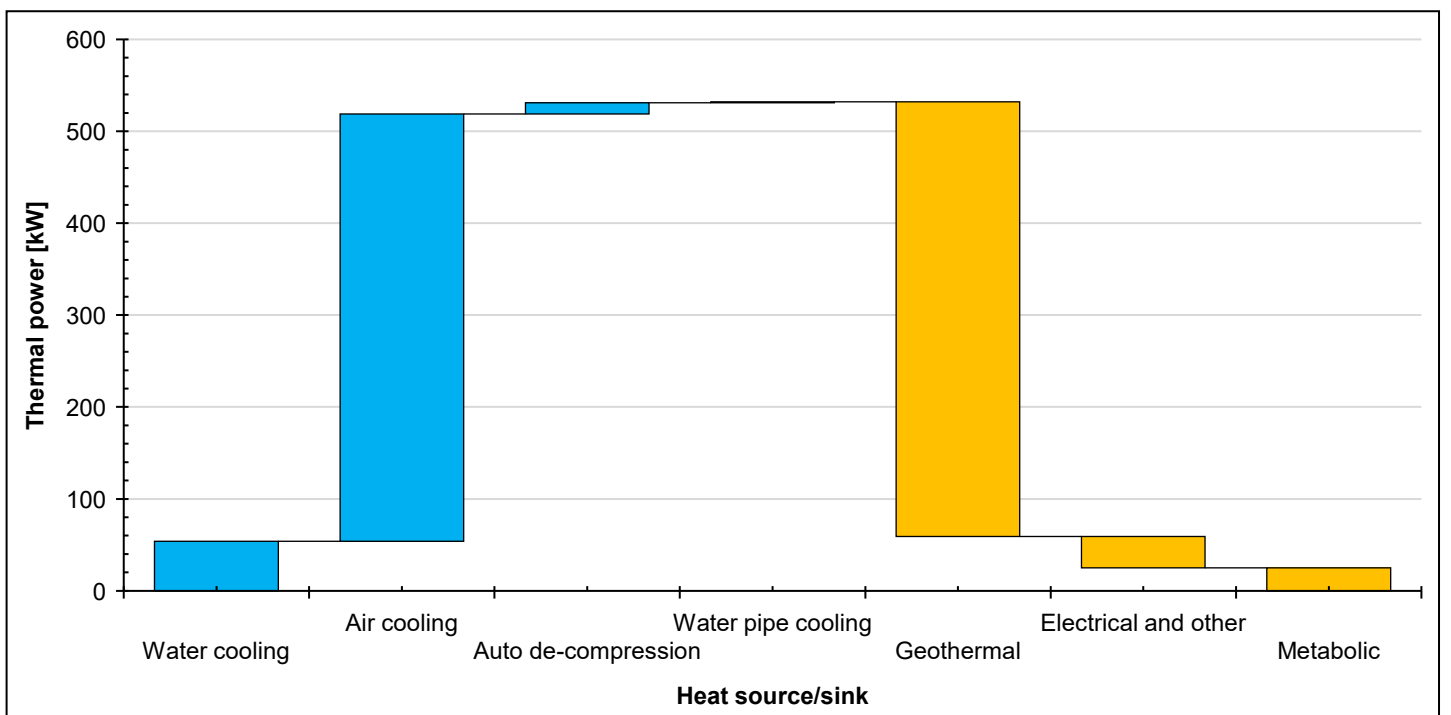


Figure B - 4: Waterfall heat load of LSC-2

APPENDIX C: MINE VENTILATION SOCIETY OF SOUTH AFRICA JOURNAL ARTICLE PUBLICATION

Journal article published in Volume 77 Number 2, April-June 2024

Journal article received the **Best Technical Note award** at the Society's Annual General Meeting

Simulation-based verification of stope heat loads in deep-level gold mines

P.A. Galamadien, North-West University, South Africa and ETA Operations (Pty) Ltd.
D. Labuschagne, Harmony Gold

ABSTRACT

As gold mines continually increase their mining depths and distances from shafts, the difficulty of providing effective cooling also increases. This increases the need for effective planning, which requires accurate knowledge of the contributions of different areas to the mine's total heat load, especially the production areas (stopes). Few heat load quantification methods isolate the heat of production areas. A simulation-based approach can be used, but such a method's accuracy must be verified. In this study, the heat loads of three stopes of an operational mine were quantified by considering their energy balances. Focus was placed on the main heat sinks – ventilation air and service water. Thermo-hydraulic simulations were set up to duplicate the real-world setting as closely as possible. Certain simulation parameters were fixed based on real-world knowledge, while unknown parameters were adjusted to match real-world measurements as best as possible. The simulated heat loads were compared to the energy balances done. The Van der Walt's analytical method was employed for a final comparison. The entire process was repeated for two case studies from literature to verify the results at different mining depths and regions. For the measured stopes, the total stope heat generated was approximately 700 kW at a depth of about 3.6 km. The heat removed by the ventilation air and service water was 254 kW and 441 kW, respectively. Overall (including both the measured stopes and case studies), the average absolute errors produced by the simulation and Van der Walt's method were 10.9% and 29.6%, respectively.

1. INTRODUCTION

Gold mining operations are continually extending to deeper depths. Challenges experienced due to these depth extensions include increasing heat loads as higher virgin rock temperatures (VRTs) and distances from shafts increase, which places strain on environmental conditions (Nell, 2019).

Most gold mines still employ conventional mining methods, which require a human workforce to extract the ore from the stopes. Hotter workplace temperatures decrease human productivity and increase the number of errors/mistakes (Mine Ventilation Society of South Africa, 2014).

Furthermore, the Mine Health and Safety Act No. 29 of 1996 states that the workforce must be evacuated if workplace temperatures exceed certain environmental limits, resulting in a loss of production (Mine Health and Safety Council, 2018). The

abovementioned challenges increase the need for effective cooling supply planning, which requires accurate knowledge of heat contributions from different areas, and especially the production areas.

The mining industry typically estimates cooling requirements through heat load estimations (Nell, 2019). This is done by identifying all the heat sources and the heat sinks present underground. Using an energy balance, the mine's operational cooling need is then determined to quantify the current cooling surplus or deficit (Nell, 2019). The literature on in-stope heat quantification has recently lagged, while the need for improved planning has increased. One focus of heat load estimations is the heat pickup of ventilation air through the workplace.

The temperature at which ventilation air leaves the workplace is referred to as the reject temperature. The relationship between reject temperatures and heat generation within the production area allow mines to plan for a target reject temperature to provide safe and habitable conditions for mine personnel.

Extensive empirical studies were conducted in the 20th century. One of the first studies considering in-stope heat quantification conducted routine observations of 2296 stopes to determine ventilation air heat pickup as it flows through the stopes based on certain characteristic parameters (Lambrechts, 1959). Two studies followed several years later to determine the heat load of specific stopes by measuring different mediums entering and rejecting from the stope for a duration of two months. This was done on a fully developed stope (Bluhm et al. 1986) and a ledging stope (de Jager, 1989). After quantifying the contributions of known heat sources and sinks, an energy balance was used to calculate the remaining heat contribution of the rock (geothermal energy). Any unknown heat contributions for these studies were included in the geothermal heat. A novel approach to practically determine full mine heat loads using an energy balance was published in 2019 (Nell, 2019). It included a roll-out strategy for Industry 4.0. The Ventilation and Occupational Environment Engineering in Mines book (commonly referred to as the "black book") and the Mine Ventilation Practitioner's data book enables ventilation engineers to determine their mine heat loads through various methods developed over the years. Global methods presented in these books are Stroh's method, Barenburg's methods 1 and 2, Whillier's method, and Van der Walt's method. The methods use the overall heat balance equation to determine heat load.

$$\text{Heat load} + \text{auto compression} = \text{cooling load} + \text{air cooling power} \quad (1)$$

Auto compression is heat gained by the ventilation air as it travels down the downcast shaft. The enthalpy of air increases with increasing depth due to the increase of barometric pressure.

The heat load component is based on production tonnes and an intensity value expressed as kW/kT/month. Air cooling power

Original paper presented at the June 2024 MTSSA Conference

is energy removed by the ventilation air relative to a target reject temperature. Enthalpy gained above the reject conditions is not deemed as useful cooling and is not included. Cooling load is the cooling duty of plants within a specified boundary that adds cooling to ventilation air by means of bulk air cooling or by cooling service water (Mine Ventilation Society of South Africa, 2014).

A limitation of this approach is that heat from inactive areas is potentially omitted since these methods were established during an era of high-intensity mining in South Africa.

Furthermore, simulation can be used as a tool that can be set up by anyone with computer knowledge based on planned parameters without physical measurements. Simulation can quantify the contributions of each specific area. However, simulations cannot be implemented blindly, and the accuracy that can be obtained with a simulation-based approach for heat load quantification must be verified. This is the aim of this study.

This communication discusses results from three in-person stope measurements of an operational mine and determines their heat load using an energy balance. Simulation models and Van der Walt's method are compared to the energy balance results.

Two case studies from literature are used to verify the findings for different mining depths and regions. The absolute error between the simulation and Van der Walt's method is compared to the energy balance method. The study focuses only on the drilling shift for a single day, and the transient effects due to the mining cycle are excluded from the scope.

2. METHODS AND MODELLING PHILOSOPHY

In this section, the methods that were used to determine stope heat loads will be discussed as well as the modelling philosophy employed for the simulation models.

2.1 Location and description of stopes considered

A case study mine with three stopes was selected where stope measurements were recorded. The case study mine is situated in the Witwatersrand area. The case study mine has two production

levels: XC-A is situated at the lowest production level, and XC-B and C are situated on the level above. The case study mine supplies service water to the upper and bottom panels through the upper and lower crosscuts. Compressed air drills were used with explosives to advance the face. Backfill was employed to provide support for mined-out areas. No fissure water was present at the time of the measurements. Additional information on the audit stopes is given in Table 1.

The first case study stope was a ledging stope in the Free State area at the Geduld Gold mine. The second was a fully developed stope at the Hartebeestfontein Gold mine in the Klerksdorp area. Table 2 provides additional information on the case study stopes.

2.2 Stope measurements

Audit measurements of the audit stopes were done during the drilling shift. Ventilation air and service water entering and leaving the production area (project boundary) were measured. Air measurements were taken in 30-minute intervals.

Water flow was continuously recorded with an ultrasonic water flow meter. Figure 1 shows the project boundary and the measurement points of the ventilation air and service water entering and leaving the boundary.

Three sections were measured simultaneously by three audit teams: the bottom crosscut, the top crosscut and the stope. The bottom crosscut team measured intake air and water stope conditions at the travel ways and outlet stope water conditions draining from the box fronts.

The top crosscut team measured reject air stope conditions and inlet stope water conditions (flow and temperature). The stope team measured air stope conditions as they travelled and stope water conditions of any leakages or open ends and recorded their location.

The team also took note of the active faces, locations, number of drills, men, electrical equipment, and ventilation conditions. Not all the areas of the stope were visited, only areas declared safe by the Shift boss and Miner were entered.

Table 1: Description of measured stopes

ID	Region	Depth below surface m	Average VRT °C	Rock production rate Tonnes/month	Mining method
XC-A	Witwatersrand	3559	60.4	6728	Double-sided breast
XC-B	Witwatersrand	3454	58.1	6702	Double-sided breast
XC-C	Witwatersrand	3454	58.1	6730	Double-sided breast

Table 2: Description of case study stopes

ID	Region	Depth below surface m	Average VRT °C	Rock production rate Tonnes/month	Mining method
FS-GD	Free State	1 539	42.5	2 070	Ledging
KL-HF	Klerksdorp	1 830	43.0	6 702	Double-sided breast

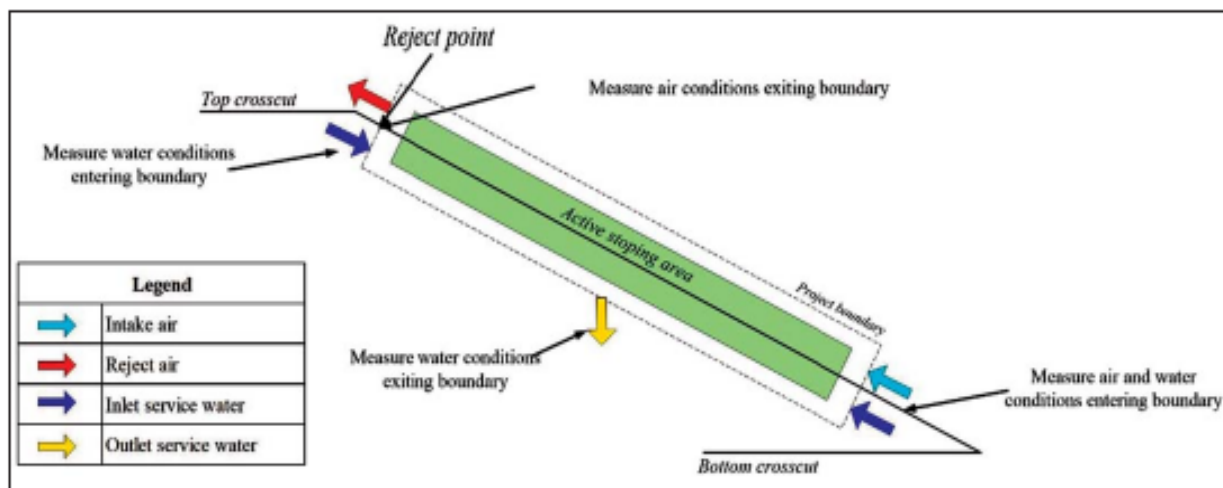


Figure 1: Project boundary of the measured stopes

2.3 The energy balance method

At their core, heat load predictions adhere to the first law of thermodynamics.

$$\Delta U = Q - W \quad (2)$$

Where the internal energy, ΔU , within a boundary is equal to the heat transferred, Q , and work done to the system, W , the total energy contained in an isolated system is constant. The first law also encapsulates the law of energy conservation, which states that energy cannot be created or destroyed, and the energy within a boundary can only be transformed from one form to another. In the context of mining, heat sources found in a stope (geothermal, electricity, metabolic, fuels etc.) are transferred to heat sinks (ventilation air, service water and compressed air) (Nell, 2019).

2.4 Simulation modelling

The simulation software selected for the analysis is Process Toolbox (PTB), a 1-D thermohydraulic software capable of simulating interactions between ventilation air, service water and rock. Steady-state simulation models were developed to focus on the constant heat generation of heat within the stope.

The modelling process started by modelling the ventilation configuration of the stope. This was done by using current DXF files and stope surveys. The stope surveys, indicating the panel face and geology profile, were received from the mine's planning department and were imported and adjusted to a 1:1 scale so that the exact face, strike and centre gully distances were modelled. The flow area and perimeter were modelled as it was measured in the stope measurements. Known parameters were fixed based on real-world knowledge, such as the age of exposed rock faces, thermal conductivities etc. Unknown parameters were adjusted to match real-world measurements as best as possible, such as the complex nature of the backfill interaction. Once the model was developed it was calibrated by adding moisture into the environment to increase air enthalpy at the reject point.

2.4.1 Interaction of service water and rock face

One of the uses of service water in the measured stopes was to remove the geothermal energy of the rock by means of face wetting or leaving water pipe ends open. The interaction of service water and the rock face has been studied in the past. The study focused on the heat conduction aspect of the rock face and service water in stopes. The study concluded that service water rapidly cooled the surface of the rock face, and the heat energy contained within the rock was transferred to the service water (von Glehn et al. 2002).

To simplify the model, ventilation air was simulated to interact with the rock to remove the geothermal heat. This resulted in the air enthalpy being higher than the measured values. To reduce the air enthalpy, direct contact heat exchangers (DCHE) were inserted into the model at the points where open water hoses and water jets were located. This resulted in the water removing the geothermal energy from the ventilation air. Recalling the first law of thermodynamics: this approach indirectly models the heat transfer of the rock face to the service water by using ventilation air as an intermediate medium. This method gives the simulation operator more control in the calibration of water behaviour. However, the flaw with this approach is that the DCHEs are limited by inlet WB temperature which results in some cases where outlet water temperatures of the DCHE do not reach measured outlet water temperatures. To minimise this flaw, DCHE were placed at the rejects of the panels where the inlet WB temperature would be at its highest.

2.4.2 Backfill

Studies have indicated that pumping backfill into the stope is a heat source, but over time, it becomes a heat sink as the backfill absorbs energy. One study published the heat profile of the area surrounding backfill and showed that the backfill was absorbing the heat from the hanging wall and footwall (von Glehn et al. 2002). What was noticed in the stope measurements was that ventilation air arriving in the strike gully would bypass the panels through the backfill and timber packs.

To simplify the air bypass and conduction interaction of the backfill with the rock, backfill was modelled as a tunnel with properties like those of the strike gully and therefore assuming that the energy removed from backfill is the equivalent to that of the ventilation air removing the heat. Resistance calibration was performed on this component to only allow for the bypass air to flow this region to limit the removal of geothermal energy.

2.4.3 Compressed air

Compressed air is seen as both a heat source and a sink. The aspect of it being a source is the energy utilised by the rock drill and transferred into the rock. The cooling aspect is the compressed air arriving into the stope and de-pressurising and mixing with ventilation air (Bluhm et al. 1986).

Although compressed air was not measured during the audits, its contribution as a heat sink is expected to be minimal relative

to ventilation air and service water. Compressed air is estimated to supply 30 kW of cooling to the stope; however, the energy balance with respect to ventilation air accounts for this cooling.

2.4.4 Van der Walt's method

Van der Walt's method breaks mine heat loads into their respective regions. The method uses Fourier numbers and functions to determine the heat flow of cylindrical excavations with high surface heat transfer coefficients. This method is useful to the study as the method can specifically determine the heat load of the stoping sections. The method divides its heat load into temperature dependent and independent parts. The dependent part calculates the geothermal energy released into the environment and the independent part is the heat released by the electrical equipment (The Mine Ventilation Society of South Africa, 1999).

3. RESULTS AND DISCUSSION

In this section, the methodology will be applied to each of the case study stopes. The results of each case study stope will be discussed.

3.1 Measured stope results

Figure 2 shows a layout of XC-A showing the environmental conditions and infrastructure in the stope.

Figure 2 shows some of the measurement points that were recorded. Large amounts of service water wastage were noted. This is contrary to the empirical studies, where minimal amounts of service water usage was reported. For all the measured stopes, many water hoses and waterjets were left open and were lying on the footwall, creating large pools where they were located.

All this water would drain into the strike gullies, where it would dam up and eventually flow to the centre gully and down into the box hole. Also prevalent was the lack of ventilation curtains and brattices to channel the air to the faces. The center gullies had significant amounts of support restricting the tunnel. Ventilation air arriving in the strike gully would bypass the panels through the backfill and timber packs.

The inlet and reject conditions of the audit stopes are shown in Table 3 and Table 4.

From these results, the amount of cooling supplied by each heat sink can be determined, ultimately resulting in the stope heat load using the energy balance method. The energy balance result is shown in Table 5.

The results for all three measured stopes are similar. Despite XC-A being a relatively "young" relative to XC-B and C it's heat load is comparable. This can be attributed to XC-A being one level lower than XC-B and C and having a slightly higher average VRT. Service water has a higher contribution to stope cooling than ventilation air, on average service water provides 441 kW (63%) and ventilation air provides 254 kW (37%) to stope cooling. The average heat load, for the measured stopes, using the energy balance method is 695 kW.

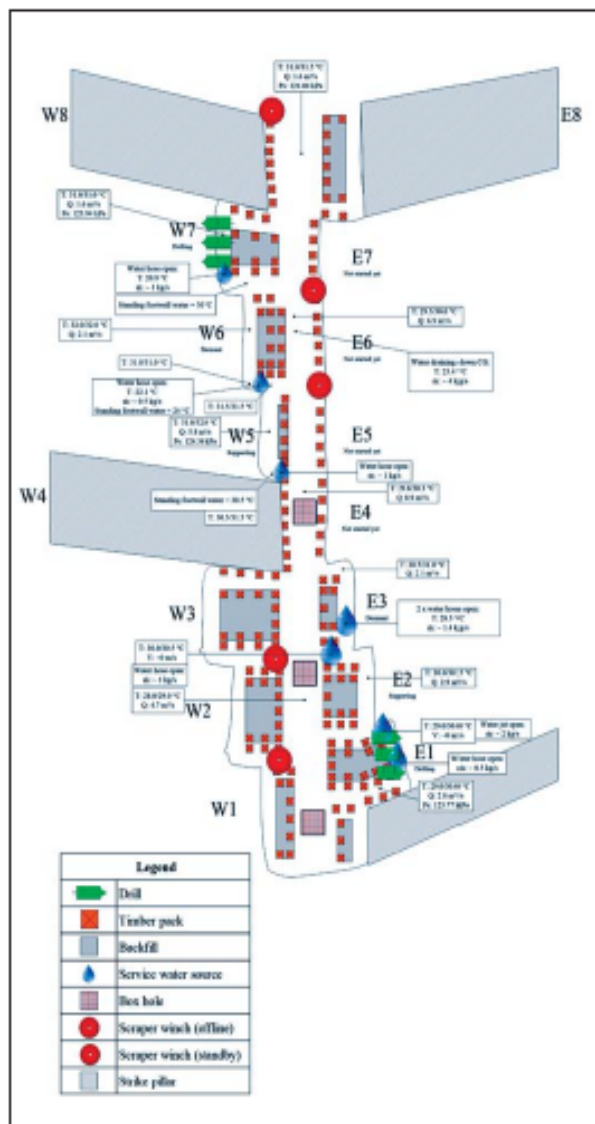


Figure 2: XC-A stope audit layout

Table 3: Intake conditions of measured stopes

ID	Air temperature (WB) °C	Air temperature (DB) °C	Barometric pressure kPa	Air mass kg/s	Water temperature °C	Water mass kg/s
XC-A	26.0	26.7	125.4	14.1	20.3	12.5
XC-B	26.3	26.6	123.7	25.3	20.2	15.0
XC-C	26.8	27.0	124.4	24.4	21.2	12.4

Table 4: Reject conditions of measured stopes

ID	Air temperature (WB) °C	Air temperature (DB) °C	Air enthalpy kJ/kg	Water temperature °C
XC-A	30.0	31.0	86.4	28.7
XC-B	30.0	31.2	87.0	28.4
XC-C	30.0	30.0	86.5	28.2

Table 5: Energy balance result of measured stopes

ID	Air cooling kW	Service water cooling kW	Heat load kW
XC-A	234	444	678
XC-B	194	516	710
XC-C	335	382	697

Table 6: Comparison between methods for the case study stopes

ID	Energy balance method kW	Simulation kW	Van der Walt's method kW
XC-A	678	554 (22.4%)	711 (4.8%)
XC-B	710	702 (1.1%)	836 (15.3%)
XC-C	697	711 (2.0%)	1083 (34.4%)
FS-GD	150*	133 (12.8%)	188 (26.3%)
KL-HF	602*	517 (16.4%)	370 (82.7%)

* Day-shift heat load reported by the case studies

The simulation and Van der Walt's methods were compared to the energy balance method. The absolute error of the two methods based on the energy balance also is shown alongside the results. The average absolute error of simulation is 10.9% and for the Van der Walt's method is 29.6%.

4. CONCLUSION

Three stopes of an operational gold mine were measured, and an energy balance was calculated to determine their heat loads. The average heat load amounts to 695 kW with service water and ventilation air contributing 441 kW and 254 kW, respectively. Relatively simplistic thermo-hydraulic simulations were modelled with certain parameters that were based on real-world knowledge, while unknown parameters were adjusted to match realworld measurements as best as possible.

Simulations and the Van der Walt's methods were used to determine stope heat loads of the measured stopes and two

case studies of different mining depths and regions were compared to verify the results. The average absolute error of simulation is 10.9% and for the Van der Walt's method is 29.6%.

The study's limitations are that it only focuses on a certain point in time. The stope measurements and the case studies were only conducted during the drilling shift. Hence, the study did not consider the transient effects of the mining cycle and its fluctuation of heat load.

The measurement of compressed air for the measured stopes was excluded as its contribution as a heat sink is relatively small compared to ventilation air and service water.

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