

Holistic evaluation of surface cooling plant configurations for different seasons at deep mines

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ABSTRACT

Title: Holistic evaluation of surface cooling plant configurations for different seasons at deep mines.

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Keywords: Deep mine, surface cooling plants, simulations, plant configurations, electricity saving, seasons.

The mining sector consumes a large portion of South Africa's electricity. Deep mining contributes to 15% of the total electricity consumption in South Africa. Mining electricity costs in South Africa have increased by 655% over the last 18 years. The increase in mining electricity costs is 3.6 times more compared to the increase of inflation for the 2021/22 year in South Africa. The electricity costs for a typical deep gold mine account for 18% of all the operating costs. Cooling systems in deep mines consume more than 20% of the electricity used on the mine and it is a big factor to be considered.

Annual reports of deep gold mining companies state that rising mining costs will harm attempts to increase financial margins and growth funding on gold-producing operations with low margins (nearing the end of their operating lives). This may result in increased debt and a loss in the profitability of deep gold mines. The increase in mining electricity cost and the unreliability thereof are in the top 10 risks as identified by gold mining companies and opportunities to mitigate the risk are needed.

Deep mines are influenced by electricity cost increases because deeper mines require more cooling. Research shows that electricity reductions in cooling systems of deep mines are possible. Surface cooling systems and cooling plant configurations of deep mines can typically become integrated and complex, as more cooling is required to go deeper. Changes made to complex and integrated cooling systems can affect the underground conditions of deep mines.

A holistic evaluation was done on a complex and integrated cooling system with plant configurations for different seasons. An integrated, phased electricity saving approach was developed for a deep mine cooling system, maintaining the underground conditions. The electricity saving strategy of deep mine cooling systems will lead to electricity cost reductions in different seasons. The holistic evaluation entails five different steps to reach the desired outcome. This includes investigation and understanding, simulations, calibration and verification, simulated strategies and implementation and

validation. The different phases of the electricity saving strategies on integrated and complex cooling systems were evaluated and implemented and led to electricity cost reductions.

Due to the complexity of the cooling systems of case study Mine A and the uncertainty of the effect on underground conditions, a phased electricity saving approach was developed. The second phase of the implemented electricity savings strategy led to a power reduction of 1.44 MW, resulting in a ZAR 1.73 million cost saving for one winter month and ZAR 5.18 million per annum. More electricity savings can be achieved if the ventilation system of the case study Mine A can be resolved.

The phased electricity saving strategy that was developed through holistically evaluating surface cooling systems and plant configurations of a deep mine can ensure that an electricity reduction is achieved, while also maintaining underground conditions. This will lead to better service delivery on the deep mine cooling systems and lower electricity costs in different seasons. Due to the increase in mining electricity costs, the phased energy saving strategy that was developed for complex and integrated deep mine cooling systems will relieve the pressure on the increased debt and loss in profitability for deep gold mines.

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NOMENCLATURE

Symbol	Description	Units
T_{abs}	Absolute temperature	K
A_k	Actual measured data point	
ρ_a	Air density	kg/m ³
P	Air pressure	kPa
v_a	Air velocity	m/s
T_{DB}	Ambient dry bulb temperature	°C
T_{WB}	Ambient wet bulb temperature	°C
COP	Coefficient of performance for the cooling plant	
I	Current	I
D	Ducting diameter	m
A	Flow area	m ²
h_{fg}	Heat of evaporation at 0 °C	J/kg.K
H	Height	m
R_{air}	Ideal gas constant	J/kg.K
L	Length	m
$\dot{m}_a$	Mass air flow rate	kg/s
$\dot{m}_{water}$	Mass flow rate of water	L/s
P_{motor}	Motor power of the compressor	W
π	Pi	
% Error	Percentage error	%
pf	Power factor	
R_{mol}	Ratio of the molecular mass of water vapour to air	
P_{sat}	Saturated air pressure	kPa
S_k	Simulated data point	

k	Specific data point	
C_{pa}	Specific heat of air	kJ/kg.K
C_{pw}	Specific heat of water	kJ/kg.K
C_{pvap}	Specific heat of water vapour	kJ/kg.K
V	Specific volume of moist air	m ³ /kg
T_{in}	Temperature of the water going into the evaporator cycle of the cooling plant	°C
T_{out}	Temperature of the water going out of the evaporator cycle of the cooling plant	°C
Q_{evap}	Thermal energy absorbed in the evaporator	W
K	Total number of data points	
V	Voltage	V
$\dot{v}_a$	Volumetric air flow	m ³ /s

LIST OF ABBREVIATIONS

ACU	Air cooling unit
ARS	Ammonia-absorption refrigeration cycle
AP	Ammonia plant
AI	Artificial intelligence
BAC	Bulk air cooler
3CPFS	3 Chamber Pump Feeder System
COP	Coefficient of performance
CCT	Condenser cooling tower
DIKW	Data information knowledge wisdom
°C	Degrees Celsius
FP	Fridge plant
UA	Heat transfer coefficient
HMI	Human-Machine Interface
KPI	Key Performance Indicator
kWh	Kilowatt-hour
L	Level
LOM	Life of mine
MW	Megawatt
MCU	Mobile Cooling Unit
PCT	Pre-cooling tower
PRV	Pressure-reducing Valve

PFD	Process Flow Diagram
PTB	Process Toolbox
PLC	Programmable Logic Controller
PI	Proportional and integral
RH	Relative Humidity
ZAR	South African Rand
SCADA	Supervisory Control and Data Acquisition
VCR	Vapour-compression refrigeration cycle
VSD	Variable speed drive
VRT	Virgin rock temperature

CHAPTER 1 INTRODUCTION AND LITERATURE

1.1 Preamble

Chapter 1 discusses the background and literature on surface cooling plants and systems in deep mines. The electricity consumption of cooling in deep mines in South Africa is discussed. More detail on deep surface cooling systems and different types of surface cooling systems is provided. Existing studies and electricity savings strategies for integrated surface cooling systems are discussed. This research led to the need for the study and the objectives of this study. Chapter 1 concludes by describing the dissertation overview in summary.

1.2 Mining electricity in South Africa

Climate change is becoming a worldwide problem, which makes the use of fossil fuels more and more expensive [1], [2]. This has a big effect on energy use and savings in the energy sector [3].

Deep mining contributes to 15% of the total energy consumption in South Africa [4]. Mining electricity costs in South Africa have increased by 655 % over the last 18 years from 2003 to 2021 in South Africa [5]. Figure 1 shows the mining electricity cost increase versus the inflation in South Africa over those 18 years [5], [6].

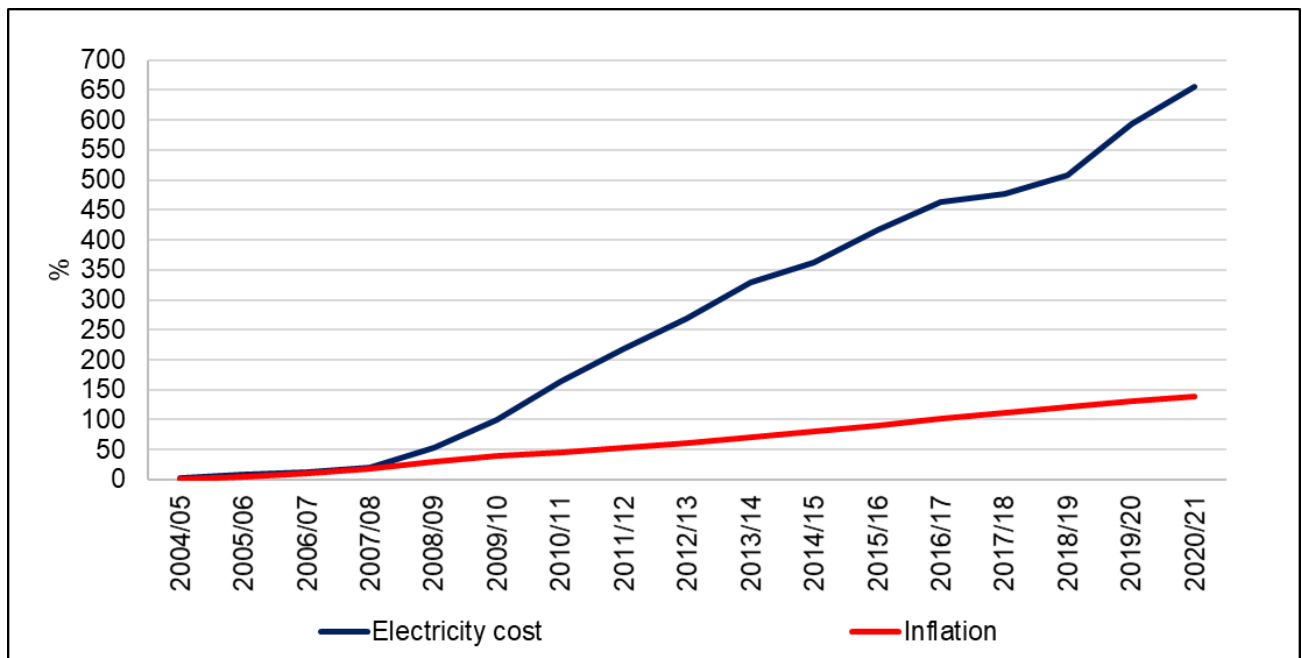


Figure 1: Electricity cost increase vs inflation in South Africa over 15 years, adapted from [5], [6]

When considering Figure 1, the increase in mining electricity costs was 4.7 times more than the increase of inflation in the 2017/18 year in South Africa. It is clear that mining electricity costs were much higher and were increasing much faster compared to inflation. Figure 2 shows the operating costs of a deep gold mine in South Africa [7].

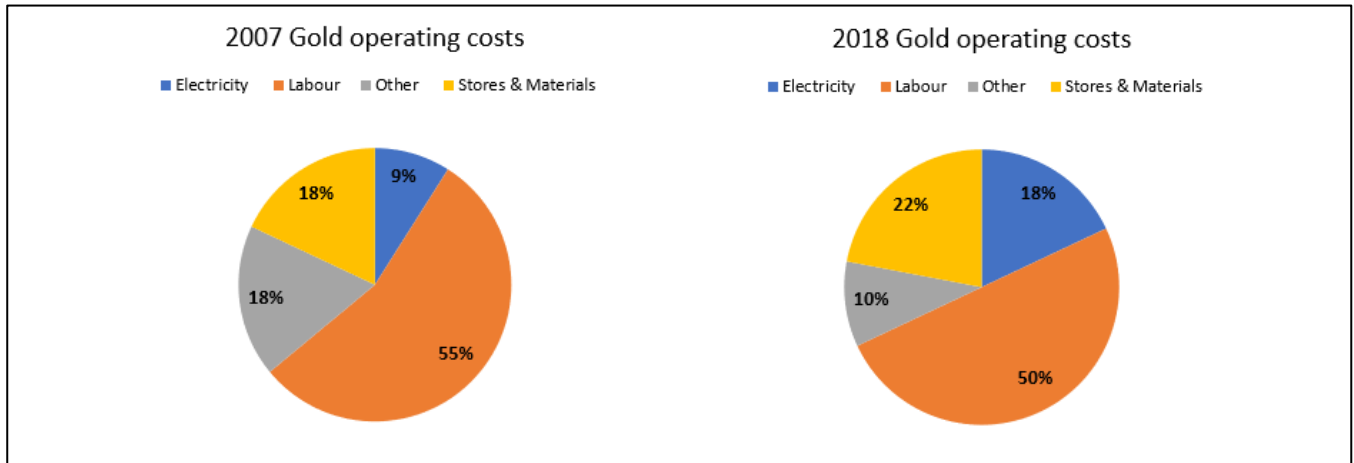


Figure 2: Gold operating costs in 2007 vs 2018, adapted from [7]

The electricity costs for a typical deep gold mine increased from 9% of the operating costs in 2007 to 18% in 2018, as shown in Figure 2 [7]. A large contributor to the increase in electricity costs for deep gold mines is due to Eskom dividing its tariff into low-demand and high-demand seasons [8]. Eskom is the main electricity supplier to all mining operations in South Africa [5]. Table 1 shows the impact of Eskom's seasonal demand tariff

Table 1: Eskom's seasonal Megaflex demand structure for 2021/22, adapted from [5]

	Megaflex active energy tariff (c/kWh)	
	Low-demand season (September 2021 - May 2022)	High-demand season (June 2022 - August 2022)
Peak (VAT incl)	154.09	472.43
Standard (VAT incl)	106.08	143.12
Off-peak (VAT incl)	67.30	77.73

It is evident that Eskom's tariff increase contributes to the increase in the annual working costs of a deep gold mine as the peak tariff is 3 times higher in the high-demand season and the standard and off-peak tariffs are 1.4 times and 1.2 times higher, respectively, compared to the low-demand season.

Due to the large increase in electricity cost for mining and the high contribution of electricity to the operating cost of mining, more and more deep gold mining companies are considering renewable energy projects like solar photovoltaic plants to ensure sustainable operations [9]. Renewable energy

projects can however not be implemented in all the deep mines due to the high initial cost of the projects, especially when the mine is already under pressure and operating on low margins [10].

It can be deduced that the high increase in mining electricity costs will influence the profitability of electricity-intensive industries like deep mines. As time progresses and the current trend is followed, this problem will only worsen, which could implicate the closure of certain unprofitable deep mines [9], [10].

Cooling systems in deep mines consume more than 20% of the electricity and it is a big factor to be considered [11], [12]. It is thus very important to implement electricity management systems on surface cooling systems to ensure that electricity usage is as low as possible. For this study, an investigation was done on the surface cooling and ventilation systems of deep mines.

1.3 Deep mining background

1.3.1 Results of electricity increase in deep mines

According to the RHC Technology Platform, by 2050, the cooling demand for new buildings will be 3 times higher than in 2006 [3]. This shows that climate changes are affecting the cooling of new buildings that have access to natural ventilation.

Deep mines need to go deeper and further away from the shaft barrel to mine the reef ore [13]. These deep mines are known for the fact that they can go to depths of up to 4 km below the surface to extract the ore [14]. The primary temperature of rock mass influences the temperature of underground excavation air [15]. Also, convection and thermal radiation will further increase the air temperature experienced underground as greater depths are reached to acquire the reef ore [14], [15].

Physical exercise and work done under hot conditions cause the human body's performance to decrease regardless of the duration of the exercise or work being done [2], [16]. Hot environments also affect mental performance and cognitive function [16]. Previous studies show that employees must have sufficient cooling and regulations prohibit employees from conducting work underground where the conditions exceed 32.5 °C wet bulb temperature and 37 °C dry bulb temperature [17], [18].

Water spray and air ventilation are cooling techniques that improve exercise and work done in hot conditions [16]. The effectiveness of the cooling intervention is also dependent on the amount of cooling and the extent of the thermal strain experienced [16]. Some deep mines combine water spray and air ventilation cooling techniques by using Bulk air coolers (BACs) to cool down working

conditions [19]. Deep mines thus get influenced by electricity cost increases as deeper mines require more cooling [20], [21]. Electricity cost increases also place pressure on job opportunities in the mining sector [7].

Furthermore, according to annual reports of deep gold mining companies, rising mining costs will harm attempts to increase financial margins and growth funding on gold-producing operations with low margins (nearing the end of their operating lives), which may result in increased debt and a loss in profitability [9], [10]. According to the main deep gold mining companies, the increase in mining electricity costs and the unreliability thereof are in the top 10 risks as identified by the mining companies, and opportunities to mitigate the risk are needed [9], [10], [22].

Therefore, the evaluation and implementation of electricity savings on surface cooling systems and other cost-saving initiatives can increase the life of mine (LOM) of low-margin deep gold mines in South Africa.

1.3.2 Surface cooling systems of deep mines

The main purpose of cooling plants of deep mines is to cool down water that is used to cool down underground working conditions [18]. For this study, a refrigeration plant and all the accompanying equipment and machinery are defined as a cooling plant, and a cooling system is defined as a grouping of all the different cooling plants at a specific location, i.e. on surface or underground.

According to research, cold water is an essential technique to ensure that deep underground working conditions are cooled down [18]. Figure 3 shows a typical deep mine surface cooling system with different functions in the cooling process [23].

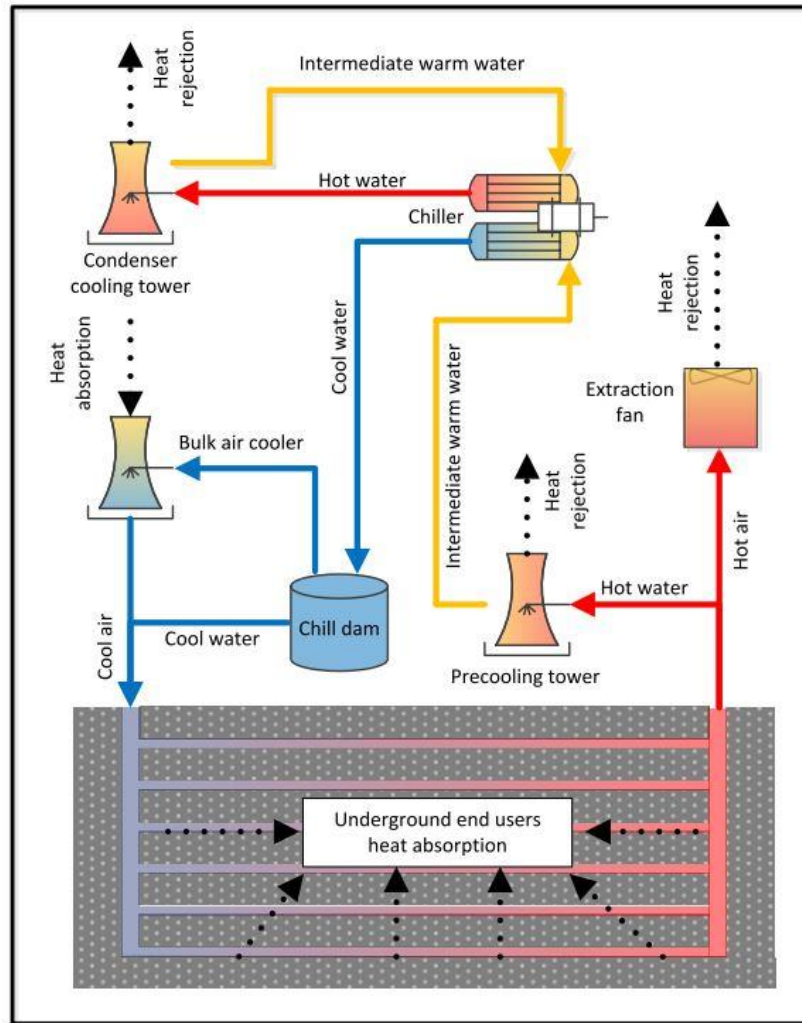


Figure 3: Typical deep mine surface cooling system [23]

Figure 3 shows that deep mine surface cooling systems provide the following different functions [23]:

- **Heat absorption:** The main reason why surface cooling systems exist is to remove heat from the surface and underground ambient conditions [23]. The surface BAC absorbs heat that is found in ambient air, resulting in cooler air that is directed underground [23]. Rock mass temperatures, heat from underground machines and devices, the heat of moisture vaporisation and heat generated through auto-compression are all factors that contribute to heat being absorbed in the underground air and water [15].
- **Heat rejection:** The heat that is absorbed in underground air and water needs to be extracted through extraction fans and dewatering pumps to ensure a safe work environment for mine employees [23]. The surface extraction fans enable the underground hot air to be rejected into the atmosphere [23]. Surface pre-cooling towers and condenser cooling towers reject the heat from underground water into the atmosphere [23].

- **Chillers:** The rejection of heat through the surface cooling towers is determined by the atmospheric conditions [23]. Thus, hot atmospheric conditions prohibit all heat from being rejected, resulting in intermediate warm water. The chillers, also known as cooling plants, cool down the intermediate water so that it can be used to cool down underground working conditions [23].
- **Thermal heat storage:** Different shifts underground cause fluctuations in the usage of the cooling plants and thermal heat storage units are used to overcome the problem of fluctuations [23]. Chill water dams are used to store thermal heat [23].

Bulk air coolers:

Surface and underground BACs are typically used in deep mines to provide additional cooling to working areas and account for approximately 7% of the entire mine cooling system's electricity consumption [19]. Typical spray BAC units consist of a mechanical axial fan, an electrical motor, cold water feed, water spray nozzles, splash packing, ambient air feed, a BAC sump to store the water and a BAC sump pump and motor as seen in Figure 4 and Figure 5 [19]. Vertical forced draft coolers and horizontal forced draft (crossflow) coolers are two typical spray BACs seen on deep mine cooling systems [19], [23]. Figure 4 shows an illustration of a single-stage vertical forced draft BAC [19].

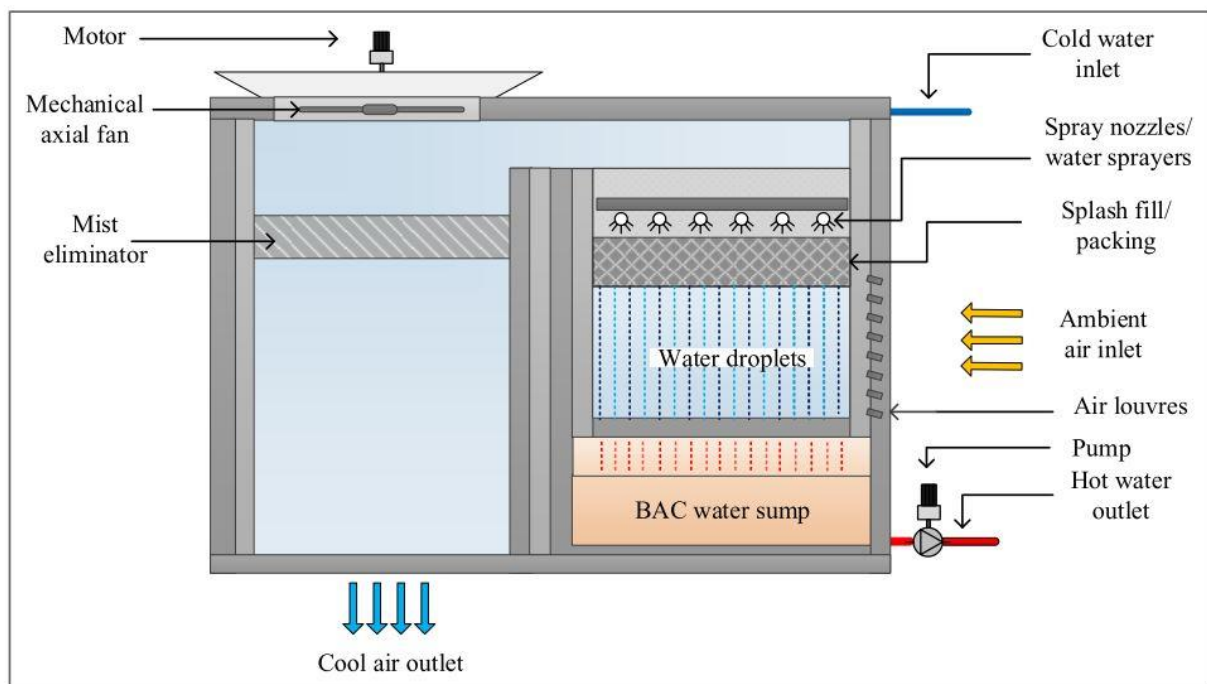


Figure 4: Single-stage vertical forced draft spray BAC [19]

In vertical forced draft spray BACs, cold water (supplied by cooling plants) enters the BAC and is sprayed as a fine mist by using nozzles [19]. The mechanical axial fan further ensures that optimal heat transfer occurs by directing the water flow (mist) and airflow in opposite directions [19]. The mechanical axial fan extracts the cooler air mixture into the shaft's duct [19]. The mist eliminator filter is used to remove any water droplets before the cooled air is sent underground [19]. The water droplets from the mist sprayers are gravity fed into the BAC sump dam and then pumped back to the cooling plants to be cooled again [19]. Some research suggests that vertical draft BACs are recommended due to their low costs and larger cooling capacity [19].

Figure 5 shows an illustration of a multi-stage horizontal forced draft (crossflow) spray BAC [19].

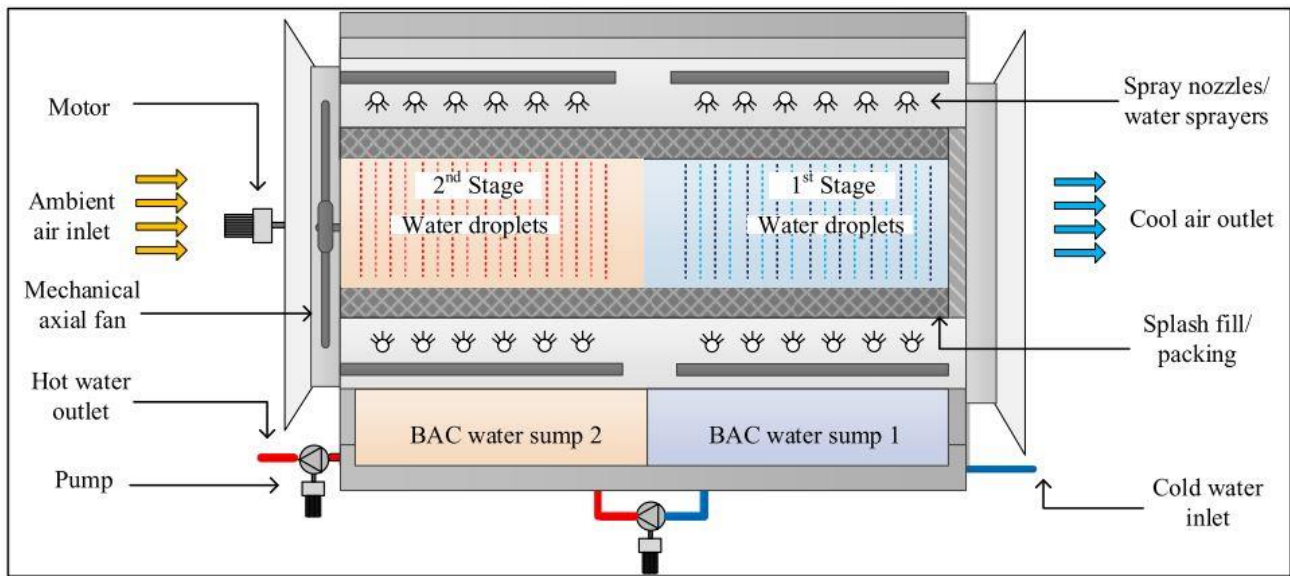


Figure 5: Multi-stage horizontal forced draft spray BAC [19]

In a horizontal forced draft BAC, the mechanical axial fans direct the ambient air through two cooling stages that are designed on the same principle of water nozzles spraying cold water and then accumulating in the BAC sumps [19]. The water nozzles for a horizontal forced draft BAC are installed on top and at the bottom of the BAC [19]. After the first-stage cooling as seen in Figure 5, the air mixture goes through the mist eliminator filter before it is sent underground [19]. The difference between the horizontal and vertical forced draft BAC is that, with the horizontal draft BAC, the chilled water from the first-stage cooling is re-used for the second-stage cooling before it is pumped back to the cooling plants to be used again [19].

Thus, considering the working of a typical forced draft spray BAC and existing research, it can be said that the performance of the BAC is dependent on the inlet air and water temperature of the

BAC [19]. It can therefore be deduced that the BAC delivers no cooling when it is operated in ambient air inlet temperatures lower than the inlet water temperatures of the BAC [19].

Surface extraction fans:

The surface extraction fans are large fans that contribute the most to the total mine airflow [24]. Ventilation networks for deep mines are one of the most important aspects of the mine as this is used to ensure that the minimum environmental conditions are met and mining can take place safely [13], [25]. Figure 6 shows a basic layout of a typical underground ventilation network [24].

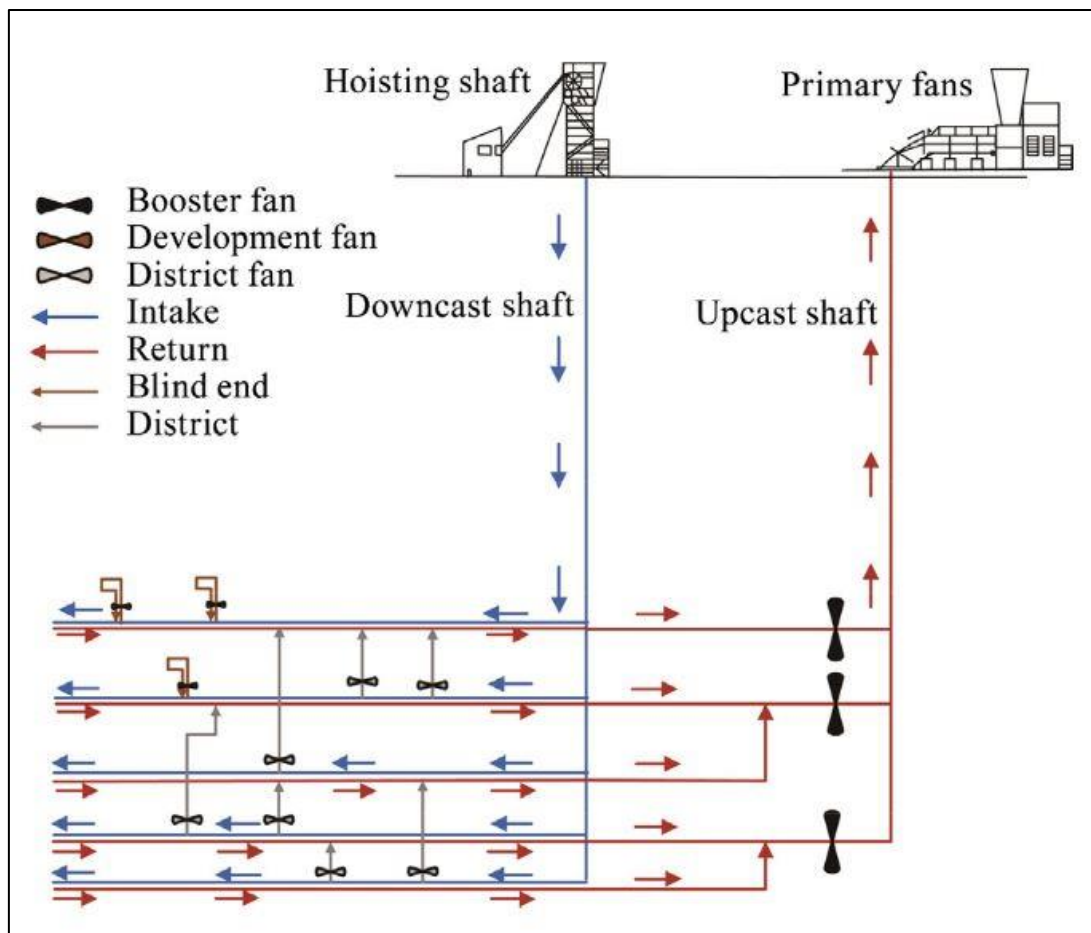


Figure 6: Basic layout of a typical underground ventilation network [24]

Figure 6 shows how the ambient air is directed through the downcast shaft and booster fans are used to ensure that the ventilation air reaches the end of the working areas of deep mines [24]. The hot ventilation air is directed through return airways and extracted through booster fans and primary surface extraction fans as seen in Figure 6 [24].

Cooling towers:

Pre-cooling towers (PCTs) and condenser cooling towers (CCTs) are also seen as heat rejection systems in mine cooling systems and operate in the same manner [23]. Both PCTs and CCTs are typically either mechanical draft or natural draft cooling towers [26]. Cooling towers are mostly used to decrease the water temperature before the water enters the cooling plants [26]. Hot mine water generally has a temperature of between 26 °C and 28 °C when pumped from underground dewatering dams to surface into a surface water mine water storage dam [12]. Figure 7 shows a typical layout and photo of a mechanical draft cooling tower [23].

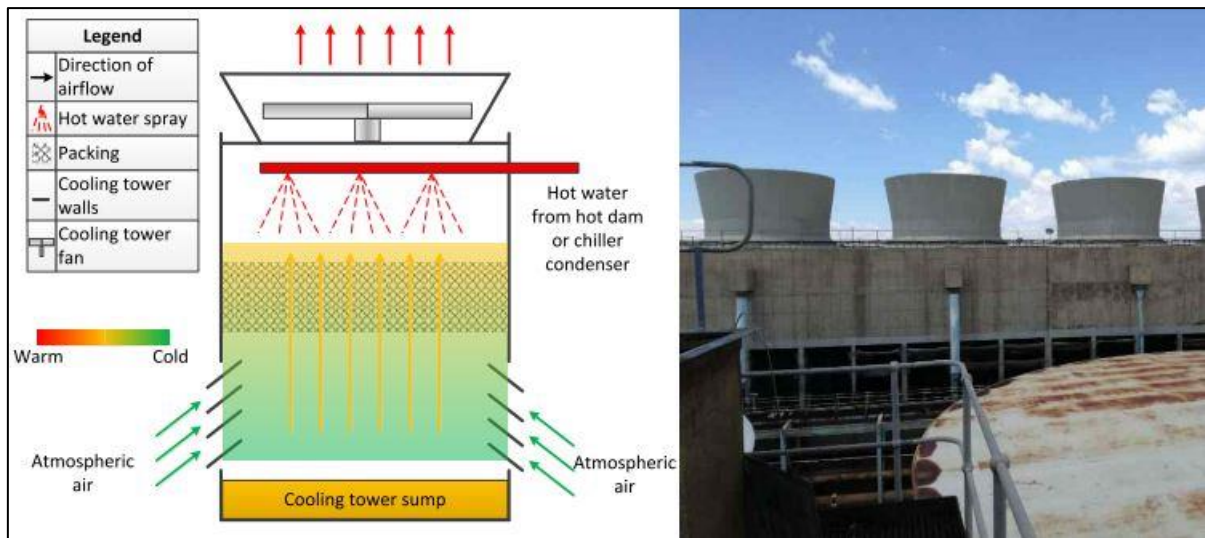


Figure 7: Typical layout and photo of a mechanical draft cooling tower [23]

Typical spray cooling towers consist of a mechanical fan, an electrical motor, hot water spray nozzles, splash packing, ambient air feed, a sump to store the water and a sump pump and motor as seen in Figure 7 [23]. The hot mine water is pumped from the surface mine water storage dam through the pre-cooling towers' spray nozzles that cool down the water adiabatically by making use of the fans, and heat rejection is achieved through the ambient air into the atmosphere [12]. The pre-cooling towers' sumps store the water before it is pumped to the cooling plants with designated evaporator pumps [12].

Condenser cooling towers are used to cool down the condenser circuit water of the refrigeration cycle, which will be discussed later [23]. Cooling towers have a very high coefficient of performance (COP) of 30 [19]. It is very important to note that the performance of the cooling towers is mostly dependent on the operational properties of the ambient air and inlet water temperature [19]. The cold and dry air conditions experienced during the winter season are ideal to guarantee a high COP [19]. Research shows that it is recommended to operate all the available cooling towers in the cooling

systems during cold and dry air conditions to ensure that more heat is extracted from the water (compared to warmer ambient conditions) and less heat extraction is needed from large electricity consumers such as cooling plants [19], [26].

Cooling plants:

Cooling plants are usually installed on surface and underground, depending on the depth and the required cooling of the specific mine [27]. Cooling plants for deep mines typically make use of ammonia absorption (ARS) and vapour-compression (VCR) cycles, depending on the amount of cooling required [19]. Figure 8 shows the typical vapour-compression deep mine cooling plant diagram [19].

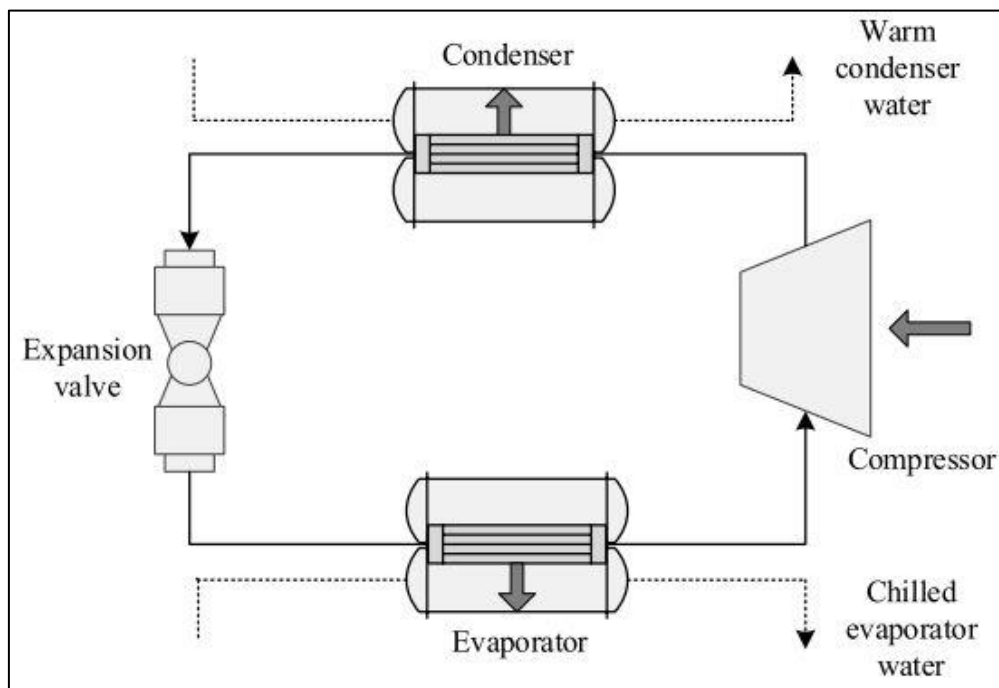


Figure 8: Typical vapour-compression deep mine cooling plant diagram [19]

The refrigeration cycle for both the ARS and VCR is based on the same working principles as shown in Figure 8 [19]. ARS and VCR cycles allow heat transfer to occur from the hot water to the refrigerant [18]. The refrigerant gases used in both ARS and VCR cycles are usually ammonia (R717) and R134a or Freon, respectively [19]. The ammonia found in the ARS cycle is toxic, which makes the VCR a safer refrigeration cycle due to the non-toxicity of its working gases. It is, however, seen that deep cooling systems combine both ammonia and R134a cooling plants to provide the required water temperatures [23]. Existing research shows that the COP of VCR and ARS cooling cycles will typically range between 3 and 6, where a COP value of 6 is considered to be energy efficient and a cooling cycle of 3 or less is considered inefficient [19].

The main components of the VCR cycle shown in Figure 8 are discussed below [19]:

Evaporator: The evaporator cycle cools down the water by using a refrigerant to absorb the heat through vaporisation from the water [18], [19]. Initially in the cycle, the refrigerant is at low pressure and temperature [19]. The refrigerant will absorb the heat within the shell and tube heat exchanger and a picture of a front and side view of a typical evaporator is shown in Figure 9 [19], [23]. The refrigerant exits this cycle as a vapour at low pressure and temperature before moving through the compressor [19].

Compressor: The compressor compresses the vapour refrigerant adiabatically to a superheated vapour [19]. The refrigerant then exits the compressor as a superheated vapour at a higher pressure and is sent to the condenser cycle [19]. The typical compressors used in cooling plants are either centrifugal or screw type [23].

Condenser: During the condenser cycle, the refrigerant is cooled and condensed by removing the heat through a condensing medium such as water or air [19]. The condensing medium gets cooled by extracting heat into the environment by typically making use of CCTs [18], [23]. The condenser typically also uses a shell and tube heat exchanger and a picture of the side and front view of a typical condenser is shown in Figure 9 [23]. The refrigerant exits the cycle as a high-pressure liquid.

Expansion valve: The expansion valve throttles the high-pressure liquid refrigerant to reduce the pressure adiabatically [19]. As the refrigerant moves through the throttled expansion valve, the temperature decreases, which ensures that the mixture of vapour and liquid evaporates to return to the evaporation system in the refrigeration cycle [19].

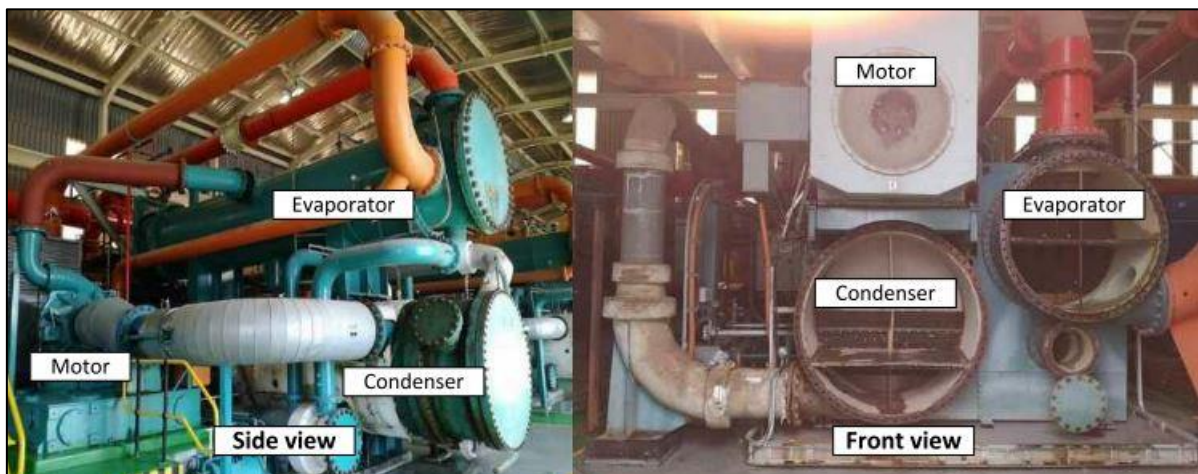


Figure 9: Picture of the shell and tube heat exchanger used in the condenser and evaporator circuit [23]

Cooling plants have complex control philosophies and system configurations to ensure that they operate under optimal efficiencies and COPs [18]. Generally, the control philosophy includes specifically designed operational set points for the different refrigeration cycles and is controlled automatically by a programmable logic controller (PLC) [18]. System configurations are designed by considering the pipelines and connections of the refrigeration cycles, the different pumps used in the cooling plants and the configuration of cooling plants used to achieve the desired cooling in the specific deep mine [18]. Typically, multiple cooling plants are found in deep gold mines and are determined by the amount of cooling that is required for the mine [18]. The main cooling system configurations that are used in deep mines are the series-, cascade-, the series-parallel and parallel configurations, which can be seen in Figure 10 [23].

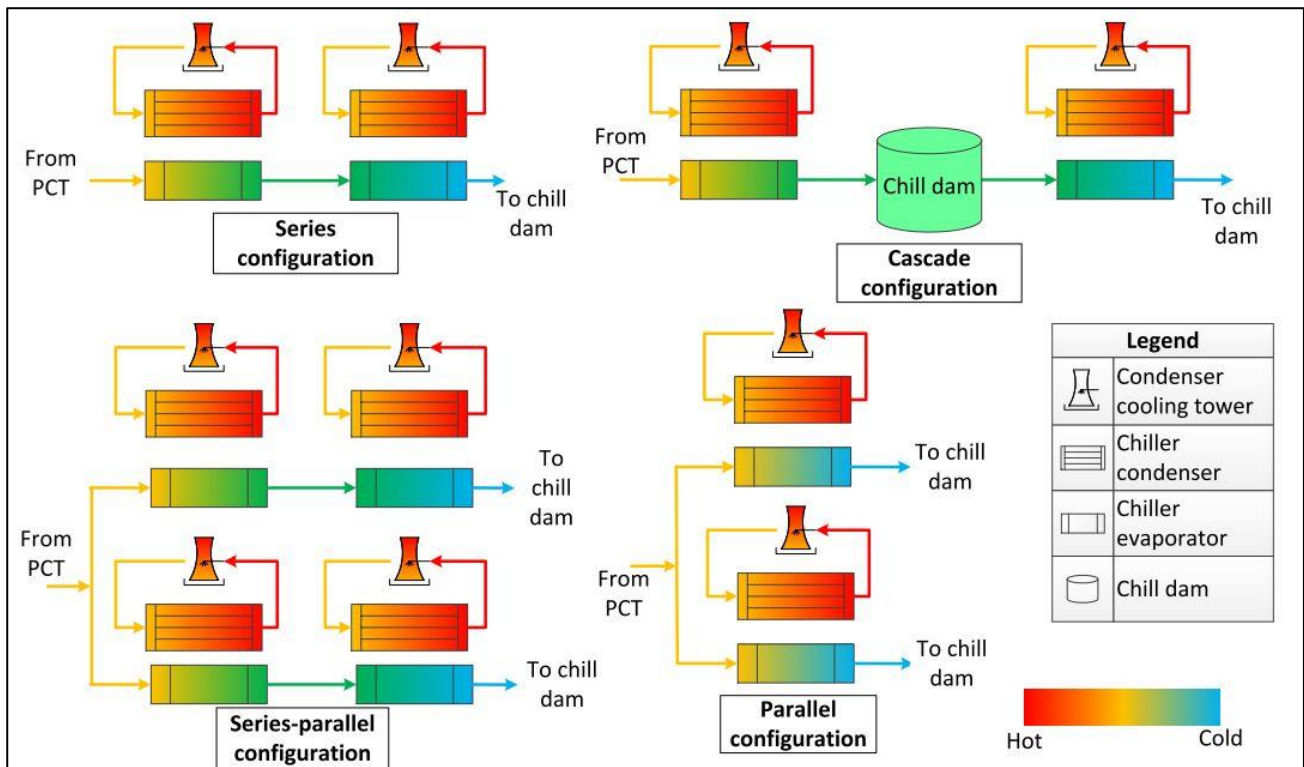


Figure 10: Different mine cooling system configurations [23]

Series configuration:

Series configurations are mostly used when a constant flow and varying temperature of chilled water are required to be sent underground [18], [23]. The series configuration enables the cooling plants to be controlled for different seasons, depending on the ambient conditions [18]. This implies that some cooling plants can be switched off during the winter months, as the cooling duty required is lowered, which leads to electricity savings [18].

Cascade configuration:

Cascade configurations are used to cool down the water in multiple steps and the cooling plants are separated by thermal storage units such as dams [23]. The function of the thermal storage units will be discussed later in this section.

Series-Parallel configuration:

The series-parallel configurations are used where both chilled water temperatures (cooling duty) and flow can be controlled [18], [23]. This ensures that the advantages of both the series- and parallel configurations are utilised [23]. Whenever maintenance is done on these types of cooling plants the cooling duty reduces and additional cooling plants need to be installed to mitigate this problem [18].

Parallel configuration:

Parallel configurations have the advantage that the chilled water flow can be varied with control valves or variable speed drives (VSDs) on the evaporator pumps, while maintaining a constant water temperature [18], [23]. Individual cooling plants can be isolated without affecting the cooling duty of the refrigeration system [18]. This is ideal for scenarios where less water is needed for specific times of the day.

Thermal heat storage (dams):

Large dams are used as thermal heat storage for both cold and hot water used in a deep mine reticulation system [19]. Dams are used to ensure that the cooling plants can supply and keep up with the chilled water demands that are continuously changing, as excess cold water can be stored [19]. Fluctuations in chilled water flow used for cooling underground conditions are mostly attributed to seasonal changes [19]. Cooling plants are used to maintain certain design water temperatures in the dams as water is moved between different dams [19]. Dams are usually thermally insulated to ensure that no thermal losses (to the atmosphere) are experienced in the chilled water [19].

1.3.3 Integrated cooling systems

The required and designed cooling capacity of deep mines is mostly dependent on the depth and size of the mine [12]. According to research, there are various methods and cooling systems such as conventional air coolers (different ventilation fans), cooling plants, air coolers like BACs, air cooling units (ACUs), cooling cars and cooling towers that are used to provide the required cooling for deep mines [12]. Figure 11 shows how the required cooling infrastructure changes and increases as the underground depths and temperatures vary [12].

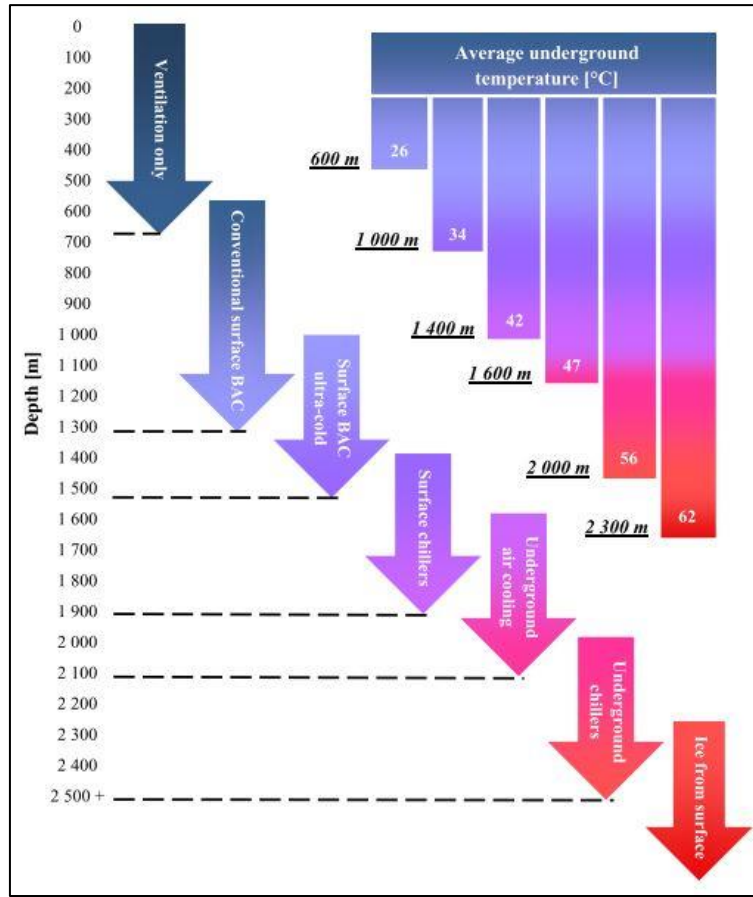


Figure 11: Required cooling infrastructure for varying underground depths and temperatures [12]

As seen in Figure 11, the deeper the underground mine, the more cooling is needed as the virgin rock temperature (VRT) can rise above 62 °C below 2300 m [12]. Thus, it can be seen that as the mine gets deeper, the cooling system becomes more complex and integrated with the ventilation system to ensure that sufficient cooling is achieved in the working areas.

Seasonal demand changes also affect the operational performance of deep mine cooling systems due to colder surface ambient temperatures experienced in the winter and warmer surface ambient temperatures experienced in the summer [19]. This is a very important factor to consider, as winter electricity tariffs are also 3 times higher in peak times than in summer, as shown in Table 1 [5].

Surface mine cooling systems can be classified as open-loop, semi-closed loop and closed-loop systems [28]. These classifications are done based on different pipe and system configurations. It is also important to note that different cooling system configurations can be integrated to ensure that sufficient cooling is supplied to underground working areas [28]. Figure 12 shows the open-loop surface mine cooling configuration [28].

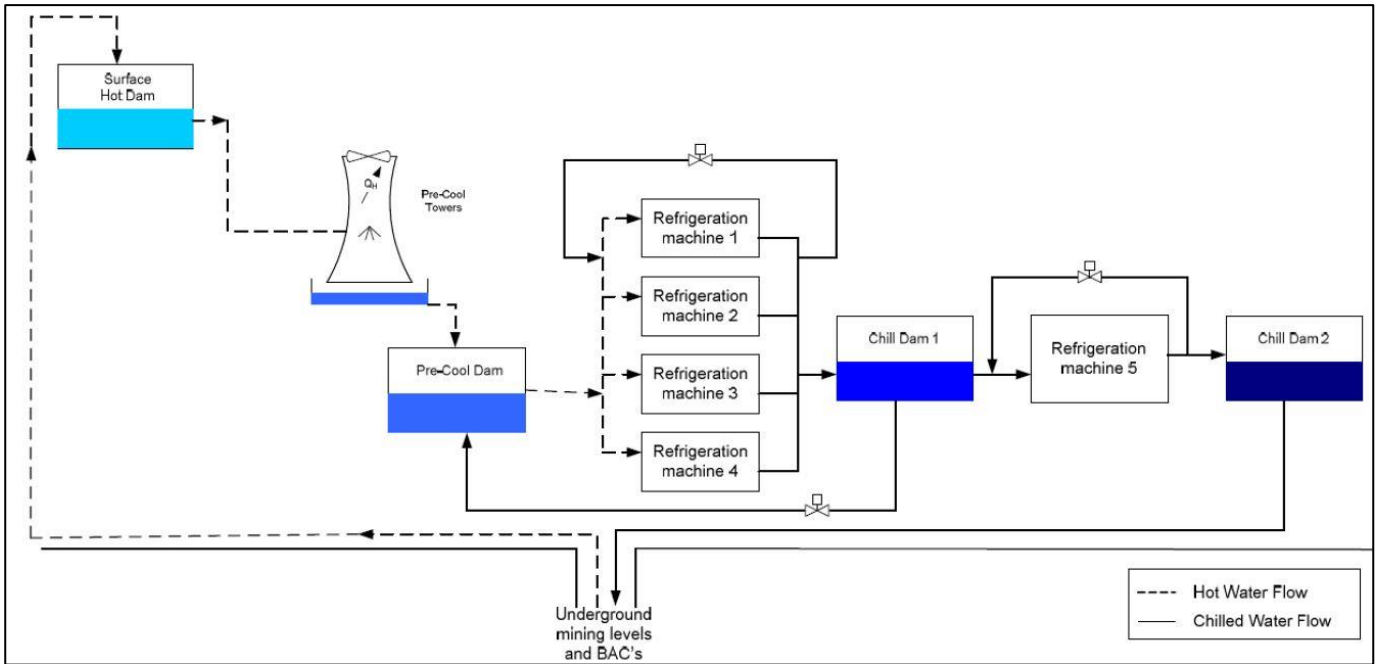


Figure 12: Open-loop mine cooling system [28]

In an open-loop surface mine cooling system, the hot water is pumped from underground and stored in the surface hot dam as seen in Figure 12 [28]. The hot water is then pre-cooled through cooling towers which are also known as the make-up water section because the water re-enters into the refrigeration system during this section [29]. Additional make-up water can also be added to the cooling towers when inefficiencies such as evaporation or leaks are present in the mine cooling system [30], [31], [32]. After the pre-cooling process, the water is cooled using refrigeration plants that can have different stages of cooling as seen in Figure 12 [28]. Figure 13 shows the schematic of a semi-closed loop mine cooling system.

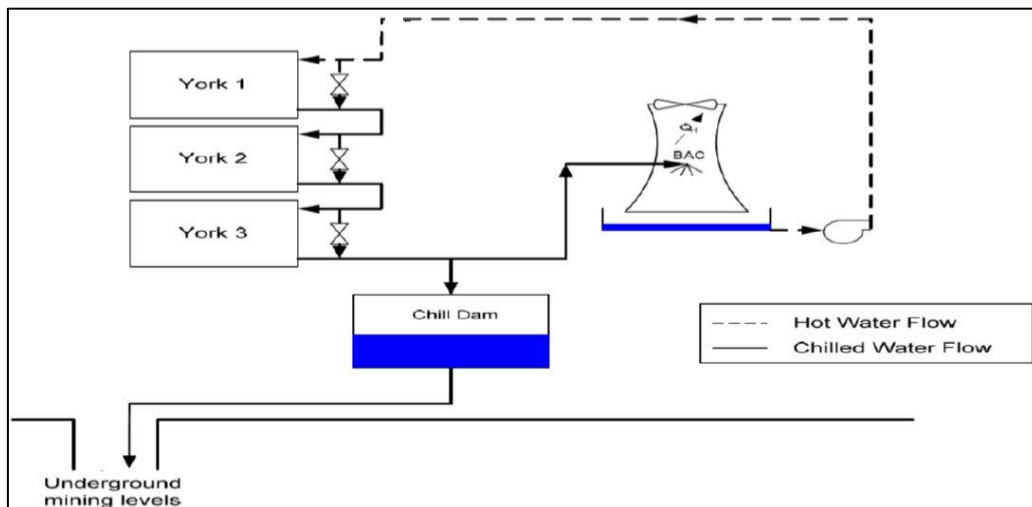


Figure 13: Semi-closed loop mine cooling system [28]

Semi-closed loop mine cooling systems provide cold water for underground use, and use surface air cooling systems (BACs) to cool down the underground conditions of shallow levels [28]. Thus, the cold water is distributed between the surface BAC and water going underground, as seen in Figure 13 [28]. Typically, flow control will be implemented between the cold water going underground and the water that is used by the BAC [23]. After the cold water is used by the surface BAC, it is recirculated to the refrigeration plants to be cooled and used again [28]. The cold water that is sent underground is used and then pumped to the surface hot dam to go through the refrigeration process again. Figure 14 shows the schematic of a closed-loop mine cooling system [28].

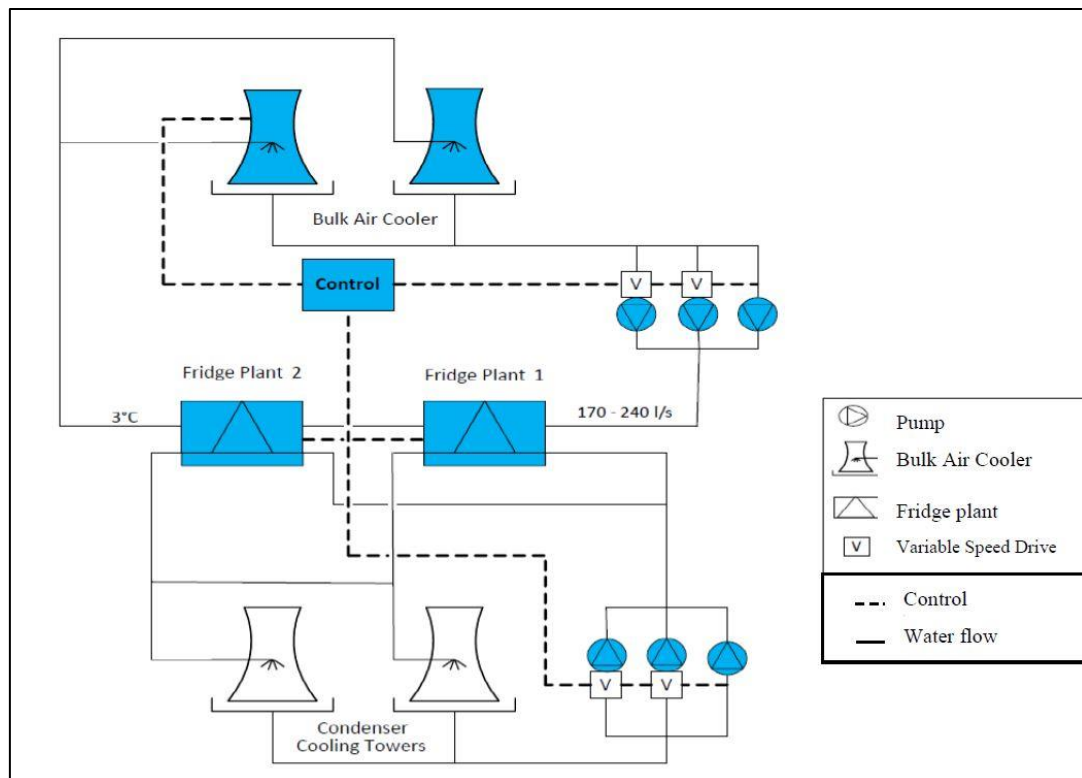


Figure 14: Closed-loop mine cooling system [28]

Closed-loop mine cooling systems provide cooling to surface air cooling systems (mostly surface BACs) [28]. Thus, closed-loop mine cooling systems are used to supply a designated and specific cooling system with cold water and are mostly isolated from the other mine cooling systems [28]. Closed-loop mine cooling systems have potential for energy management strategies, as the systems are energy intensive [28].

Considering Section 1.3, it can be seen that a large number of factors contribute to ensuring that sufficient cooling is provided to deep mine underground working areas. These cooling systems can become very complex and integrated, especially when the mines get deeper as development occurs [28]. The more refrigeration plants are used in different configurations, the more complex it becomes

[33]. This is due to each specific surface cooling system having the potential to influence the underground working conditions and the other surrounding cooling systems. The different surface ambient conditions experienced throughout the year, parallel with increased electricity tariffs during high-demand seasons, have an impact on the working conditions underground. It is, therefore, very important to holistically evaluate deep mine cooling systems when changes need to be made to them.

1.4 Existing electricity management and reduction strategies for cooling systems

The electricity consumption of cooling systems in deep mines contributes to 25% of all electricity costs for deep mines and much research has been done in this field [11]. Different electricity management and reduction strategies have been developed for cooling systems over the years. The main electricity management and reduction strategies include load shifting, load clipping and energy efficiency, which can be seen in Figure 15 [23]. The blue line in Figure 15 shows the baseline and the red line show the load-shaping possibility [23].

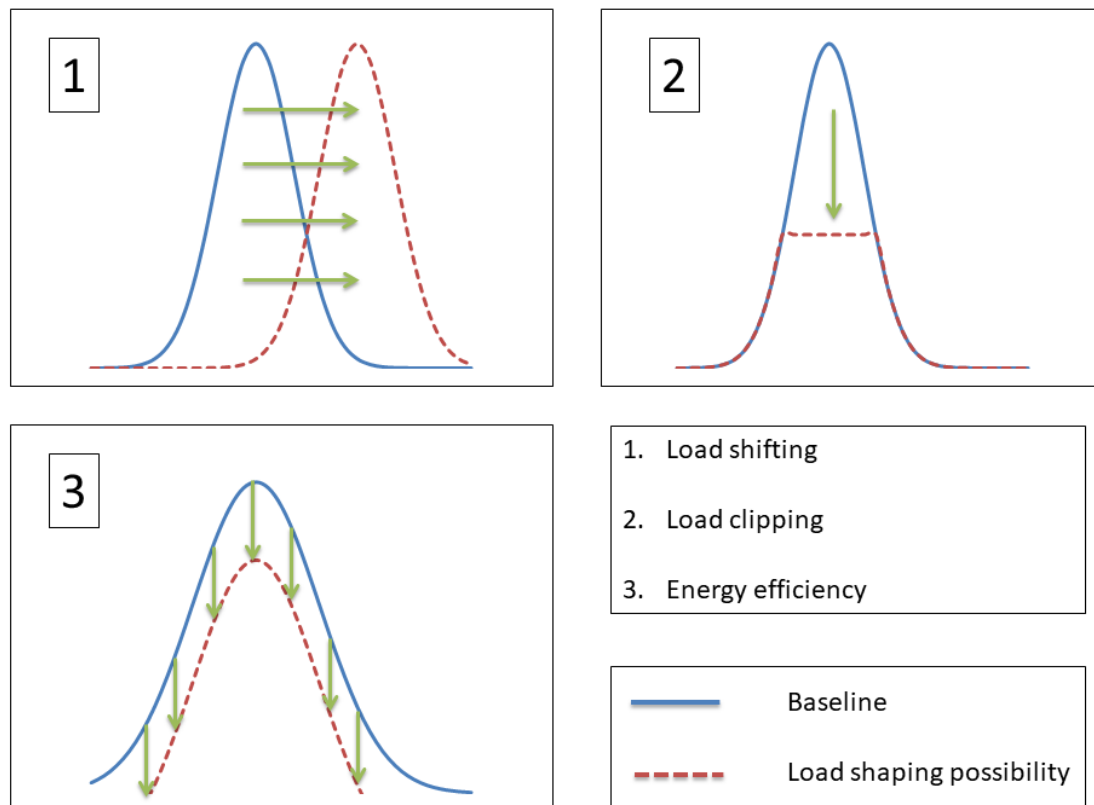


Figure 15: Existing electricity management and reduction strategies [23]

Load shifting:

Eskom implemented time of use (TOU) tariffs for electricity consumers so that the consumers can re-evaluate the use of electricity at specific times of the day [23]. Figure 16 shows the Eskom TOU for low-demand seasons (September to May) and high-demand seasons (June to August) [8].

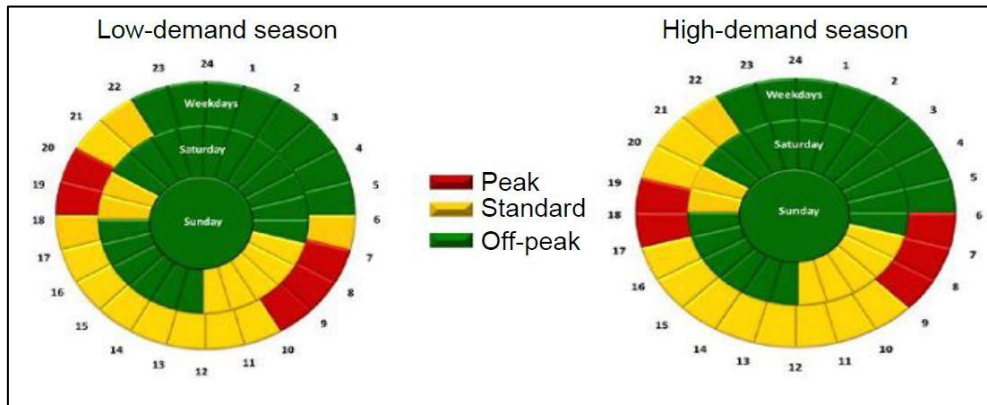


Figure 16: Eskom TOU schedule for different seasons [8]

The load-shifting strategy reduces electricity costs, even though the electricity consumption is not reduced, as seen in Figure 15 [23]. The electricity is “shifted” or moved out of the high peak times to either the standard peak times or off-peak times [23]. Ideally, when considering Table 1, cooling electricity costs can be reduced if electricity consumption is moved from peak times to off-peak times.

Load clipping:

Load clipping reduces the electricity consumption for a specific period of the day as seen in Figure 15 [23]. Load clipping ensures that the overall electricity consumption and cost reduces [23]. Load clipping is usually done in the evenings when no workers are underground and thus less cooling is needed [12], [34].

Energy efficiency:

The energy efficiency strategy modifies cooling systems to use electricity more efficiently [23]. Energy efficiency strategies further reduce electricity consumption and costs as seen in Figure 15 [23]. Energy efficiency strategies enable the cooling systems to be operated more efficiently, with higher COPs [34]. Existing research shows that load reductions on cooling plants and surface BACs can be achieved by reducing the water flow to the units [23].

Existing research shows that saving strategies can also be implemented on cooling systems in different seasons. Studies showed that seasonal control can be implemented at deep mines through

variable flow, varying cooling and inlet cooling plant temperatures that are a function of seasonal ambient wet bulb temperatures [23], [30]. Variable flow can be achieved by typically using control valves or variable speed drives (VSDs) on feed pumps [8], [30]. Research indicates that VSDs are, however, a very expensive technology in South Africa [23], [35].

Existing electricity savings research on cooling systems:

For this study, a literature search was conducted by using ScienceDirect¹, the Academic Journals database², the NWU Publication Finder³, the NWU repository⁴ and general searches in Google Scholar⁵. The following keywords and combinations of these keywords were used in the above-mentioned sources and databases: surface cooling systems, refrigeration systems, deep mine, simulation, ventilation systems, holistic evaluation, seasonal control, bulk air coolers, chilled water, energy savings, integrated and configurations. The research was further filtered to consider studies that had full text available through the NWU portal and were less than 10 years old.

The literature study showed that studies implemented different electricity management and electricity reduction strategies on surface cooling systems with different applications. In this section, some studies from the research are evaluated and the outcome and shortcomings regarding electricity reduction strategies on surface cooling systems are identified. An overview of the study is discussed.

Zietman (2008) developed an identification model for cost-effective electricity savings on a mine cooling system where an integrated method had to identify whether there were electricity saving opportunities on interconnected mine cooling systems [23]. The method included a simulation model to assist the identification model [23]. The simulation model could, however, not simulate what impact the electricity saving initiative would have on the underground working conditions and practical temperature measurements had to be taken [23]. This identification model was developed and implemented on a deep platinum mine bulk air cooler and resulted in a peak-clipping initiative being incorporated with an existing cooling plant load-shift initiative [23]. However, the method developed in the study only considered reducing electricity consumption during peak Eskom tariff periods and did not consider energy efficiency initiatives and performance improvements on mine cooling systems [23].

¹ ScienceDirect. "Journals & Books." <https://www-sciencedirect-com.nwulib.nwu.ac.za/> (accessed 2022).

² Academic Journals. "Journals." <https://academicjournals.org/journal> (accessed 2022).

³ NWU Publication Finder. "Searching: Publication Finder for NWU." <https://publications-ebSCO-com.nwulib.nwu.ac.za/?custId=s8336801&groupId=main&profileId=pfui> (accessed 2022).

⁴ NWU. "Library LibGuides." <https://libguides.nwu.ac.za/> (accessed 2022).

⁵ Google Scholar. "Google Scholar Search." <https://library.nwu.ac.za/google-scholar-search> (accessed 2022).

Crawford (2019) developed an automated dynamic control philosophy for sustainable energy savings on mine cooling systems to optimise the control of mine cooling systems, reduce operational costs and improve system sustainability [19]. A simulation model was used to verify the theoretical impact that the control strategy would have on the surface cooling system and did not include the impact that it might have on the underground conditions [19]. This control strategy was implemented on an integrated cooling system of a South African gold mine and led to a significant electricity cost reduction due to evening load shifts done through inlet guide vane (IGV) control, chiller control and flow control [19]. The implementation of this control strategy also led to improved cooling plant performance [19]. The study, however, only considered electricity cost reductions during the evening peak tariff and did not consider changing cooling plant configurations to achieve energy efficiency on the cooling system [19].

Ashmead (2020) developed a holistic approach to evaluate the feasibility of implementing ice thermal storage on deep mines to prove the feasibility to implement ice thermal storage as an alternative, more effective and cost-saving solution compared to the typical cooling systems of deep mines [12]. A simulation strategy was incorporated with analytical approaches and a feasibility analysis to predict the behaviour of the cooling system and determine whether the project was more effective and had cost-saving capabilities without having capital expenditure [12]. The ice thermal storage project was holistically evaluated before and after implementation and the study achieved electricity cost savings through load shift initiatives [12]. The implementation of the load shift project resulted in a reduction in the performance of the cooling system [12]. The study did, however, not include the impact that the implementation of a load shift has on underground conditions [12].

Maré (2017) developed novel simulations for energy management of mine cooling systems by simulating a transient response model of a complex and integrated mine cooling system [36]. The transient simulation model was implemented on two case study mines and showed that savings can be achieved by reconfiguring cooling plants or installing VSDs or valves to implement flow control [36]. The transient simulation model also considered the operational improvements that can be achieved on an integrated cooling system [36]. The model considered an integrated cooling system that included the surface cooling system, the underground dewatering system, the 3 chamber pump feeder system (3CPFS), booster pumps, drilling, mobile cooling units (MCUs) and pressure-reducing valves (PRVs) [36]. The study did, however, not consider the effect of the cold BAC air that is supplied to the working areas [36].

Cost and energy savings on mine surface cooling systems were achieved by Moropa (2017) by developing a versatile load management strategy that could be implemented on closed- or semi-closed loop mine surface cooling systems [28]. The load management strategy was implemented at

two mines and only evening peak tariff electricity cost reductions were implemented for different seasons [28]. Underground conditions such as temperature and relative humidity (RH) were monitored and evaluated on three critical levels while the load management strategy was implemented [28]. The load management strategy also made use of cooling plant reconfiguration to ensure that electricity savings could be achieved during evening peak tariff periods [28]. The study did, however, not consider and evaluate the effect that surface ambient conditions have on surface cooling systems as the load management strategy did not include a simulation model [28].

Peach (2020) developed a novel approach for improved control processes on ageing mine refrigeration systems that could be used to implement improved control processes on ageing cooling systems in gold mines which also increases performance [34]. The study implemented temperature resets on mine cooling plants, which led to improved cooling performance and a reduction in electricity costs [34]. This study implemented the recycling or bypass-looping of chilled water and it was controlled to achieve colder temperatures, while also improving the system's efficiency [34]. This study evaluated the effect in temperature that the implemented seasonal control process would have on underground working conditions [34]. The study did, however, rely heavily on the practical knowledge that someone has of the cooling system, thus not developing a simulation model [34]. This can be problematic when an inexperienced person implements the control process of this study [34].

Pretorius *et al.* (2019) implemented a DIKW model on a deep mine cooling system to show that simple models such as a data, information, knowledge and wisdom (DIKW) model can help managers in deep mines to improve the mine's cooling system performance [17]. The DIKW model was implemented on a deep mine's underground cooling system that is approximately 2 km underground and the cooling system performance increased [17]. This study considered the effects that the DIKW model had on underground conditions as it was verified with cooling cars in the mining block [17]. Due to the DIKW model being implemented on an underground cooling system, there was no seasonal control [17]. This study did, however, not consider implementing a simulation model in the DIKW model [17].

Optimising mining refrigeration systems through artificial intelligence was achieved by Harmse (2021) by using optimisation techniques as a solution model and applying it to the characteristic model of a cooling system to determine the optimal operating conditions [8]. The AI solution model was implemented in dynamic automated control cooling systems and led to efficient cooling plant selection that resulted in a reduction of electricity costs during peak tariff periods [8]. The study implemented a simulation model to determine the accuracy of the AI solution model [8]. Although

the study implemented the AI solution model on different seasons, it did not consider the effect the AI solution model would have on underground conditions [8].

Peach *et al.* (2018) achieved dynamic optimisation of deep-level mine refrigeration control by developing and implementing control optimisation strategies that can adapt to a dynamic environment [37]. The study implemented the dynamic optimisation strategy on a surface mine cooling system and that resulted in improved overall performance and electricity cost reductions on the cooling system [37]. The study considered the effect of the implemented dynamic optimisation strategy for seasons on the surface cooling system [37]. The effect of the implemented dynamic optimisation strategy on the underground working conditions was not evaluated [37]. No simulation model was implemented as part of the dynamic optimisation control strategy in this study [37].

Wang *et al.* (2018) followed a practical approach to chiller plants optimisation through inspection of the varying profiles of each optimised variable [38]. The study showed that optimisations that are implemented on the condenser water flow rate and condenser water inlet temperature resulted in the greatest electricity cost reduction [38]. This study implemented a simulation model as part of the practical approach to cooling plant optimisation [38]. This approach was only implemented on a cooling plant and a holistic evaluation of the seasonal effect was not considered in this study [38].

Questions and comments arose during the literature study that need to be answered. The following four questions and statements led to the identification of categories to be used in the state-of-the-art matrix shown in Table 2:

1. How can the electricity reduction strategies be verified?
2. Cooling systems of deep mines are very complex and integrated.
3. What are the holistic effect and implications of lowering the cooling systems' electricity cost on the underground working conditions?
4. Are there any other benefits to using a specific electricity reduction strategy?

It was found that several studies considered certain aspects of simulations on the cooling systems as a tool to verify the electricity reduction strategy that was going to be implemented, simulating different electricity reduction scenarios and identifying potential electricity reduction strategies [8], [12], [19], [23], [29], [36], [38-43]. Furthermore, simulations are a cost-effective means to investigate different scenarios [42]. Considering the above-mentioned studies, simulations were seen as an important aspect of this study and could be used to develop an electricity reduction strategy and plant performance improvements for an integrated cooling system.

During the literature study, it was found that multiple studies considered complex and integrated deep mine cooling systems as part of their implementation [8], [12], [17], [19], [23], [28], [29], [34-43].

The research used to develop Table 2, only evaluated the effect and implications on the underground working conditions (regarding temperatures) when seasonal control was implemented on complex deep mine cooling systems but did not consider including the effect on the airflow on the underground working areas.

Existing research showed that electricity reduction strategies could also have the benefit of improved cooling plant performance if a good strategy is implemented [8], [12], [17], [19], [34], [36], [37], [40], [42]. As the refrigeration plant performance improves, the COP increases [11], [39]. Condition monitoring and cooling plant performance monitoring ensure that informed decisions can be made regarding maintenance that needs to be done on the equipment and cooling plants [42]. Table 2 is a summary of the studies that were considered and shows the state-of-the-art matrix that indicates the gaps from past studies. Four categories were developed through the questions and comments that arose during the literature study as can be seen in Table 2. The red blocks indicate that the study did not consider the specific category and green blocks indicate that the study did consider the specific category.

Table 2: State-of-the-art matrix indicating gaps in previous studies regarding the four identified categories

SOURCE	SIMULATED	INTEGRATED COOLING PLANTS CONSIDERED	HOLISTIC EVALUATION ON SEASONAL CONTROL	COOLING PLANT PERFORMANCE IMPROVEMENT	COMMENTS
[8]					AI solution model was implemented on a cooling system to determine optimal operating conditions which led to a peak demand electricity cost saving.
[12]					Load shift initiative was implemented on ice thermal storage system.
[17]					DIKW model was implemented on an underground cooling system and the cooling performance was improved.
[19]					Automated dynamic control load shift implemented on IGVs, chiller plant control and flow control during peak evening demand periods to achieve electricity cost savings.
[23]					Peak clip-in collaboration with a load-shift initiative was implemented on the surface BACs to achieve electricity cost savings.
[28]					Load management strategies were developed and the focus of the study.
[29]					Variable flow control using VSDs was implemented at a platinum mine and resulted in an electricity cost reduction and maintained service delivery temperatures.
[34]					Implemented temperature resets on ageing cooling plants, resulting in improved cooling performance and a reduction in electricity costs.
[35]					Variable flow control using VSDs was implemented and resulted in a reduction in electricity costs.
[36]					The transient simulation model considered all the systems of the mine and implemented electricity cost savings through a plant configuration change or flow control through VSDs or valve control.
[37]					A dynamic control strategy was implemented on a cooling system and a reduction in electricity cost and an improvement in the cooling system performance were achieved.
[38]					A practical approach to cooling plant optimisation through inspection of the various profiles of each optimised variable was implemented which led to an electricity cost saving.
[39]					Converted an ice storage system into a cooling plant and implemented varying flow through the cooling plant using VSDs control for electricity cost reductions.
[40]					Variable flow control using VSDs and reconfigurations of different equipment in the cooling plant was implemented which led to a reduction in electricity costs.
[41]					A peak clip was implemented on a surface BAC and it resulted in a reduction in electricity cost.
[42]					Condition monitoring ensured optimal plant performance and maintenance schedule and resulted in a reduction in electricity costs.
[43]					An evening peak clip was implemented on a surface BAC through a BAC controller and it resulted in a reduction in electricity cost.

When considering Table 2, it is clearly seen that there are gaps in the existing research.

1.5 Need and objectives

When examining all the studies that were considered in Table 2, it was found that no study considered evaluating the holistic effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling systems and whether the implementing of an electricity reduction strategy will improve cooling plant performance.

Thus, a need exists to holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling plant configurations and to determine whether cooling plant performance can be improved if the electricity strategy is implemented.

The objectives of this study are to:

- Identify and implement seasonal electricity reduction strategies on complex and integrated deep mine cooling plant configurations, and
- Develop a method that can holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling plant configurations.

The method will also consider plant performance improvements that will be added to the electricity reduction strategies.

1.6 Dissertation overview

1.6.1 Chapter 1

Chapter 1 consists of an in-depth background on electricity systems in deep mines of South Africa, and more specifically, cooling systems. Chapter 1 also provides details on the operations of cooling systems and existing electricity management and reduction strategies that are used in research. This leads to the identification of a need that exists for the specific problem at hand.

1.6.2 Chapter 2

Chapter 2 describes the development of an in-depth and complete method that can be followed for a holistic evaluation of the impact and effect of the underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine surface cooling plant configurations. This method can then be applied to any two-stage cooling system with an additional cooling plant stage.

1.6.3 Chapter 3

In Chapter 3, the method that was developed in Chapter 2 is applied to a specific deep case study mine in South Africa. Relevant background information on the case study mine is also provided. The results of the simulation model of the applied method is compared to the real-life implementation results to determine the accuracy of the applied method.

1.6.4 Chapter 4

Chapter 4 concludes by providing a summary of the study and describing what the study has achieved. The chapter ends with final remarks and recommendations for future work that can be investigated.

CHAPTER 2 DEVELOPMENT OF METHOD

2.1 Preamble

This chapter describes the research methodology that was used to develop a method to fulfill the need of the study and the study objectives that have been identified and described in Section 1.5. The method used to develop a solution is explained in full detail. This includes considering different cooling plant configurations and case study mines. A method was developed and each step is discussed thoroughly. The impact of this study and how the impact of the study was determined is discussed later in the chapter.

2.2 Method overview

From the literature, it could be seen that research methodology has multiple methods that can be used for conducting research [44]. The research methods are divided up into qualitative and quantitative research methods [44]. For this study, a case study method was used due to the advantages it has [44]. A case study method is typically used to validate a method that was developed in a study [44]. Another benefit to using the case study method is that in this study, it was not possible to control behavioural events [44]. Figure 17 shows the case study method that was used to conduct this study [44].

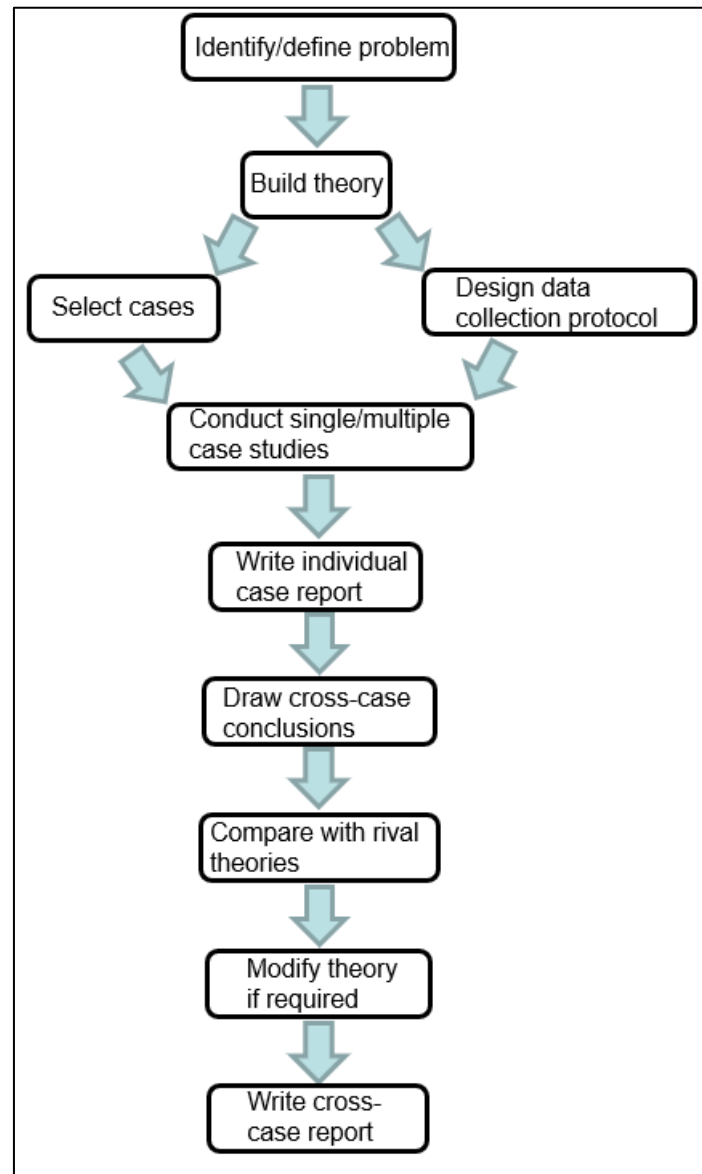


Figure 17: Case study research method [44]

When considering Figure 17, it can be seen that for this study, the problem has already been identified and defined in Section 1.5. The next step was therefore to develop a method that can provide a solution to the problem of this study.

The method to holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling plant configurations was developed by considering a normal two-stage cooling plant system (open loop system) and an existing case study gold mine in South Africa (semi-closed loop system) [8], [42]. A typical two-stage cooling system has an intermediate dam between the first-stage cooling

units and second-stage cooling units, which ensures versatility as variations in water flow between the two series of cooling plants can be achieved [8]. Figure 18 shows a typical two-stage open-loop cooling system [8].

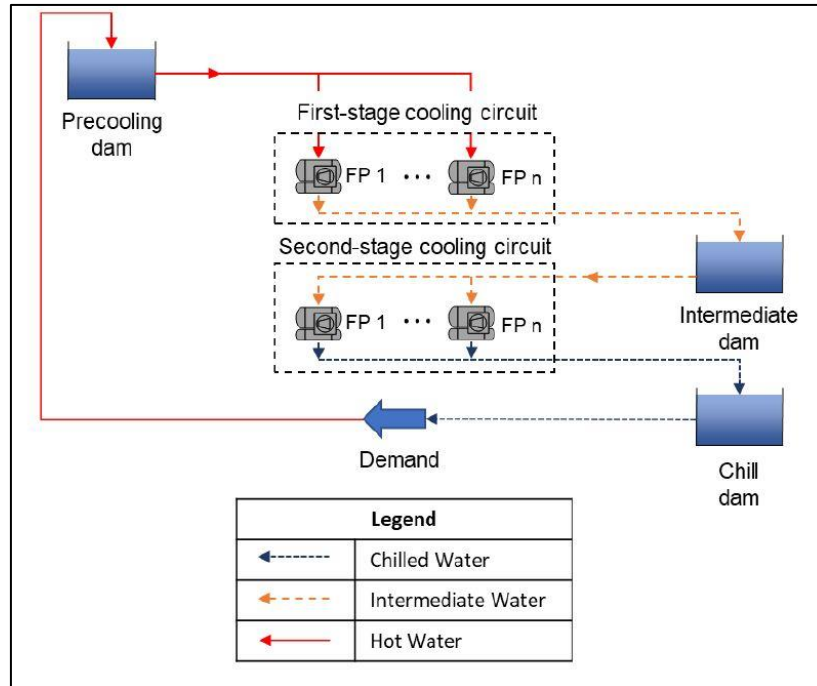


Figure 18: Typical two-stage cooling system [8]

As seen in Figure 18, the water for the first-stage cooling circuit is received from the precooling dam and heat is extracted [8]. After the first-stage cooling circuit, the water is sent to the intermediate dam, whereafter the second-stage cooling circuit extracts more heat from the water before it is sent to the chill dam to be used for underground cooling and mining services [8]. Figure 19 shows the case study gold mine cooling system layout that was also considered to develop the cooling system layout used to develop the method [42].

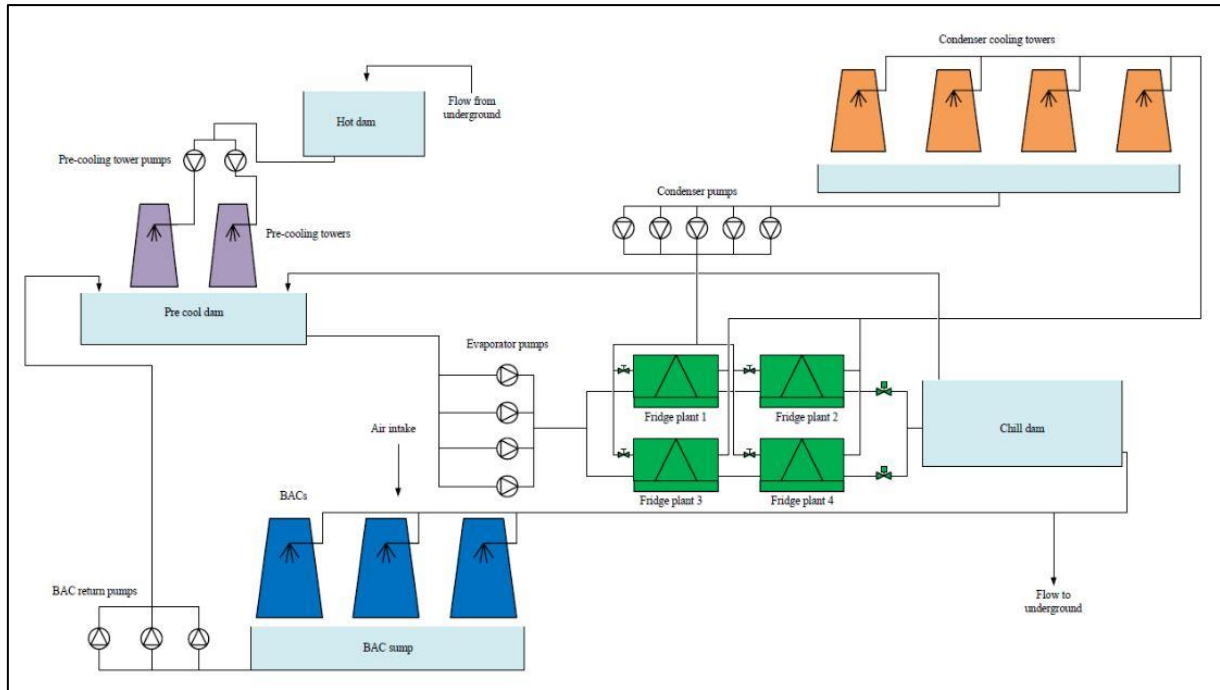


Figure 19: Existing case study gold mine cooling system [42]

As seen in Figure 19, the cooling system of the case study gold mine can be identified as a semi-closed loop system [42]. The heat in the water from the precooling dam is extracted by using a combination of cooling plants and is sent to the chill dam [42]. The cooling system in Figure 19 can be defined as a semi-closed loop system, as the water in the chill dam is used for both surface cooling using a BAC and underground cooling and mining services [42]. The water used by the BAC is then sent back to the precooling dam [42].

The cooling system layout used to develop the method was developed by adapting and combining the two different cooling systems shown in Figure 18 and Figure 19, and can be seen in Figure 20 [8], [42].

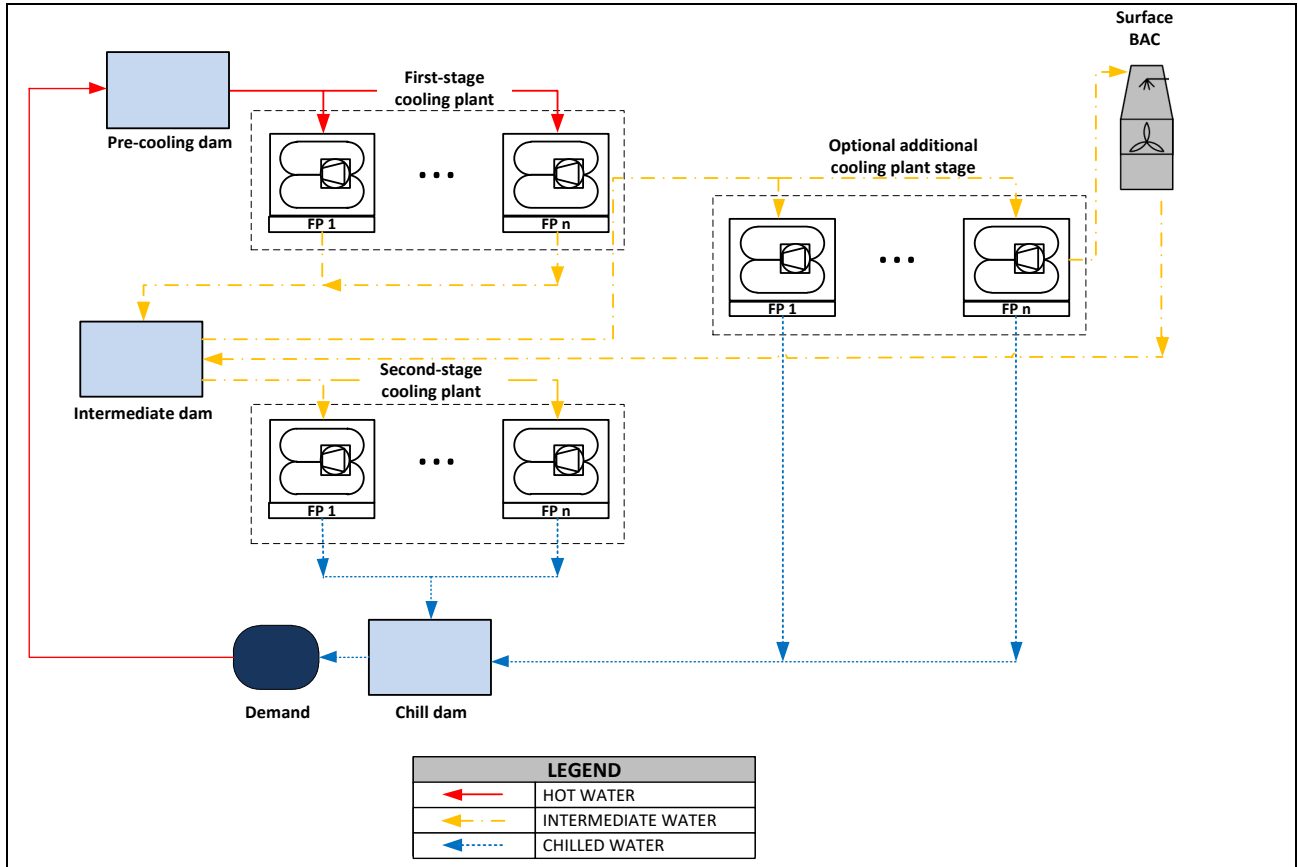


Figure 20: Two-stage cooling plant layout with optional cooling plants, adapted from [8], [42]

Figure 20 illustrates a two-stage cooling plant system with an optional additional cooling plant stage that could be used either to supply a surface BAC or to assist the main cooling system that supplies cold water to underground deep mines.

Figure 20 shows a combination of an open-loop and semi-closed loop cooling system pipe configuration as described in Section 1.3.3. As seen in Figure 20, the two-stage cooling plant system consists of a series of first-stage cooling plants that extract heat from the water and then feed it to the intermediate dam. Thereafter, more heat is extracted from the water through a series of second-stage cooling plants before it is fed to the chill dam. The chill dam supplies water to the underground cooling and mining services. After the water is used for services, it is pumped from underground into a pre-cooling dam and the heat exchange process is repeated.

Furthermore, Figure 20 also shows an optional additional series of cooling plants that can be used to supply cold water to the surface BAC of a deep mine. Due to the specific pipe configuration, the additional series of cooling plants can also supply cold water to either the chill dam or the intermediate dam.

The complexity of the combined pipe configurations and cooling systems enables a deep mine to have more operating options in terms of water and air cooling. There are numerous benefits to having the optional additional cooling plants, such as auxiliary cooling when breakdowns occur on a specific stage cooling plant and the availability to supply more chilled water when there is an increase in demand. Figure 21 shows the method of Mathews [45] that was adapted to develop a method to holistically evaluate the effect that implemented seasonal control has on integrated cooling plant configurations and provide a solution.

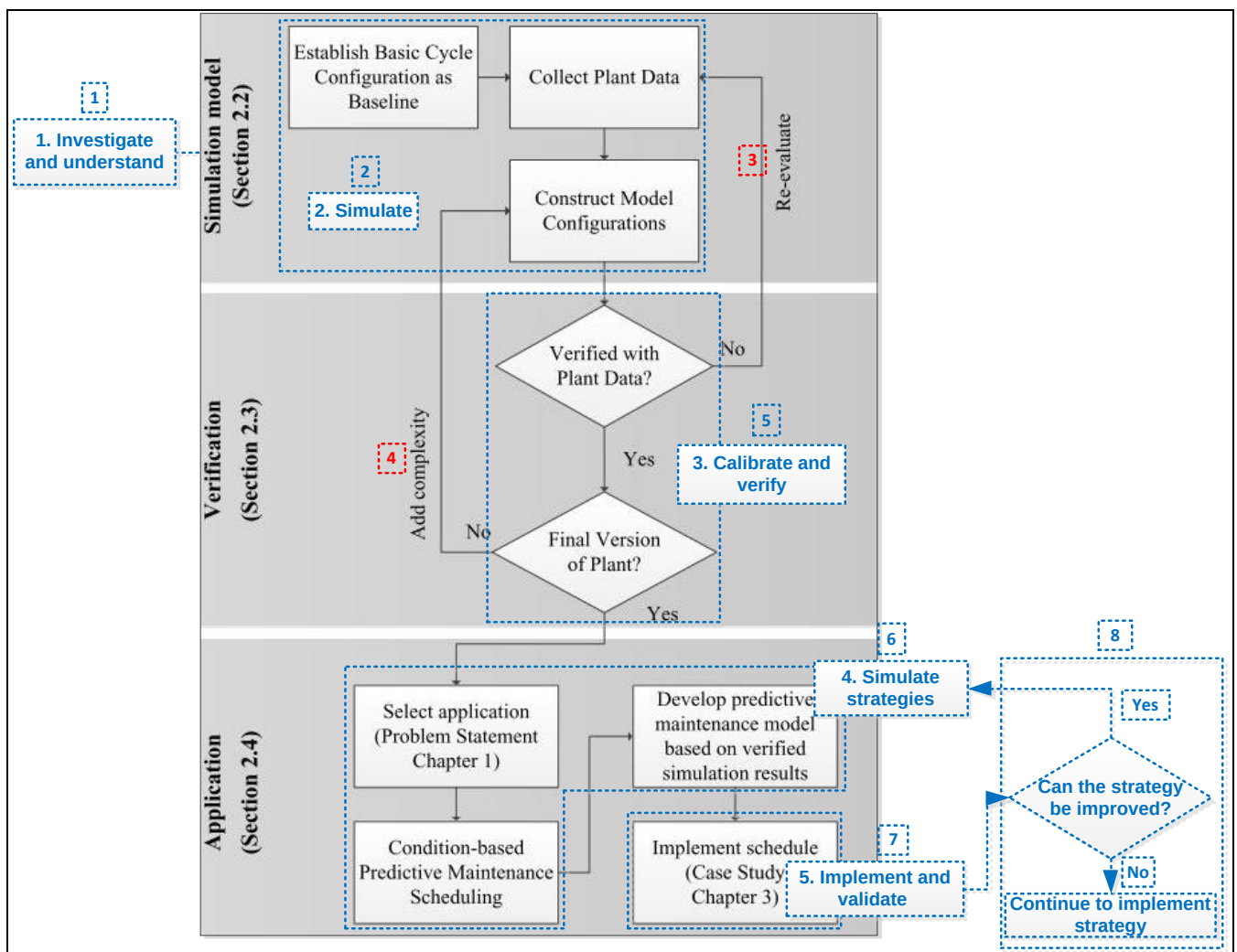


Figure 21: Existing method by Mathews [45] and adjustments made for this study

During the method development process, certain exclusions and adjustments had to be made to the existing method to provide a solution to the need and study objectives of this study, as shown in Figure 21 [45]. The adjustments to the existing method are indicated in blue and the exclusions are indicated in red in Figure 21.

The following reasoning was used to adjust the method illustrated in Figure 21 to achieve the method to provide a solution to this study:

1. For this study, Step 1: 'Investigate and understand' needed to be added to the existing method due to the holistic evaluation approach that was followed and the complexity of the cooling plant configuration as shown in Figure 20. It is thus important to first investigate and understand the complex and integrated cooling plant configuration of a case study mine with a configuration similar to the one in Figure 20 as this will ensure that a good solution is provided. According to the study that was used to develop the method for this study, it is important to have prior knowledge of the specific system's parameters when the modelling of systems is required [45]. Furthermore, additional studies also included the investigation of specific systems as part of one of the first steps in the method [12], [19].
2. Step 2 in the adapted method is 'Simulate'. For this step, three different steps in Mathews' study method [45] were combined into one step with two sub-sections that are discussed later. Other studies also indicated that simulation modelling was considered one of the crucial steps in the method [8], [11], [46], [47].
3. For this study, the specific re-evaluation step in the Mathews' method [45] was not needed, as it was included in this developed method's Step 3: 'Calibrate and verify' which is discussed later in this section. The plant data do not have to be re-evaluated, because, in Step 3 of the adapted and developed method, the simulation model is calibrated and verified.
4. In the method developed for this study, the addition of complexity as seen in Mathews' study [45] was excluded. The adapted method accommodates complexity, as the simulation model was built according to the complex cooling plant configuration similar to that which is seen in Figure 20 and the holistic approach was used.
5. Step 3 in the adapted method used in this study is 'Calibrate and verify'. Two steps from Mathews' method [45] were combined into one step with two sub-sections for the developed method. Existing studies showed that a simulation model needs to be calibrated and verified to improve its accuracy and represent real-life operations of cooling systems [18], [45], [47].
6. Step 4 in the adapted method is the 'Simulate strategies'. When Mathews' study method is examined [45], it can be seen that three steps were combined into the new 'Simulate strategies' step, which was divided into two sub-sections. According to the existing method, the simulation model is applied to the problem at hand and a solution can then be achieved [45]. Previous studies show that simulating different strategies is a key factor in the method due to the immediate feedback the simulation model provides to a real-life system when a strategy is simulated [12], [19], [45-47].

7. Step 5 in the adapted method is the 'Implement and validate' of the proposed strategy to the real-life complex cooling plant configuration. The existing method implements the simulation model in a real-life system [45]. Existing studies show that it is important to evaluate (validate) the solution once it is implemented to determine the performance of the solution in a real-life system [8],[18], [46], [47].
8. A last step was added to the existing study's method shown in Figure 21 [45]. This step was added to account for improvements that can be made to the strategy if more information is brought to the table or cooling requirements are changed. If no new information regarding improvements is provided, the current saving strategy can be implemented until new information arrives. Existing studies show that it is important to re-analyse project constraints after implementation for the best possible solution to the project [12], [47].

Figure 22 shows the simplified method that was developed and adapted from an existing method in a previous study [45]. The method can be used to develop a solution to the need and the study objectives mentioned in Chapter 1.

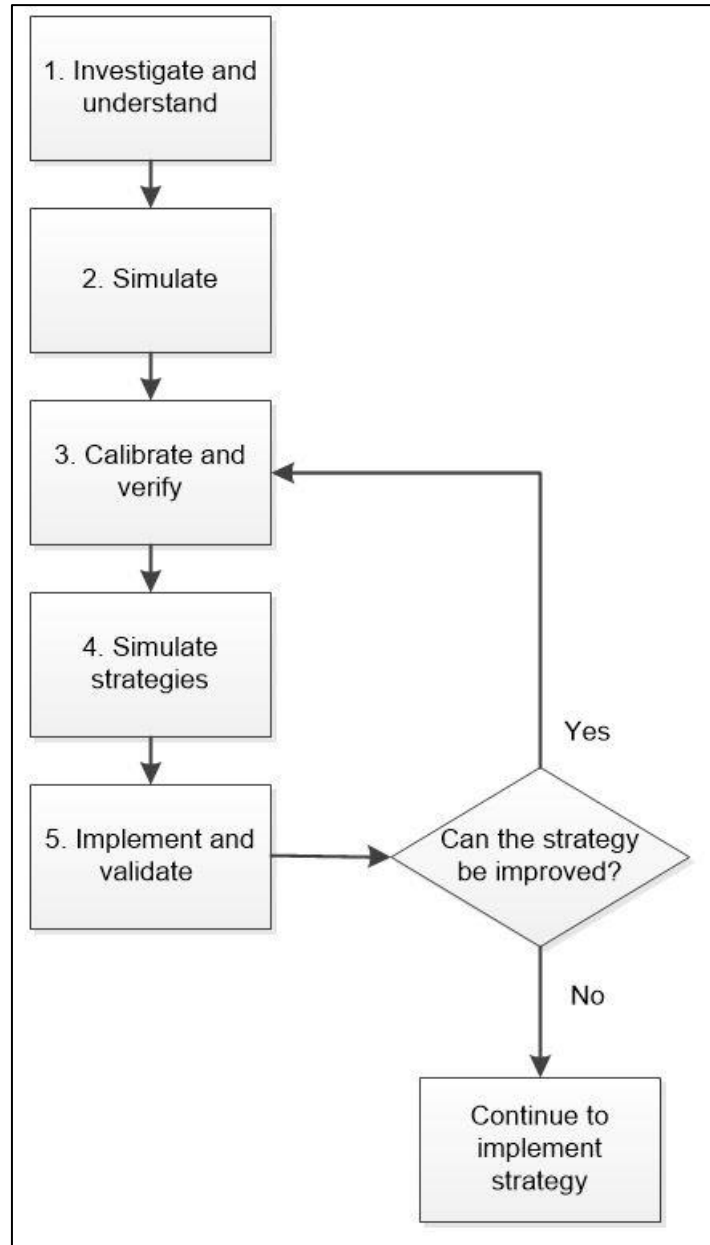


Figure 22: Simplified developed method, adapted from [45]

As seen in Figure 22, the first step in the method used to develop a solution was to investigate and understand the complex and integrated cooling system in the environment in which it was found. After the investigation of the complex and integrated cooling system, a simulation model could be built. Data and information on the complex cooling system needed to be collected so that a simulation with the specific pipe configurations of the cooling plants could be built. The simulation model could then be calibrated by adding real-time data to the cooling parameters. The real-time data were used to verify the accuracy of the simulation model. Different control and electricity saving strategies could be investigated and simulated to determine what the impact of it would be on the cooling system and the underground working conditions. The result of the best possible electricity saving strategy that

was simulated could then be implemented and validated to determine the actual results and success of the strategy. The method also accounts for improvements in the implemented strategy by revising it and reverting it to the third step if needed.

2.3 Components in method

The method shown in Section 2.2 could be applied and revised until the desired strategy is achieved. Figure 23 shows the detailed method that was used to provide a solution to the need and objective of this study as stated in Chapter 1. It is important to note that a generic method is shown in Figure 22 and Figure 23 and that the method was applied to a real-world case study deep mine as described in Chapter 3.

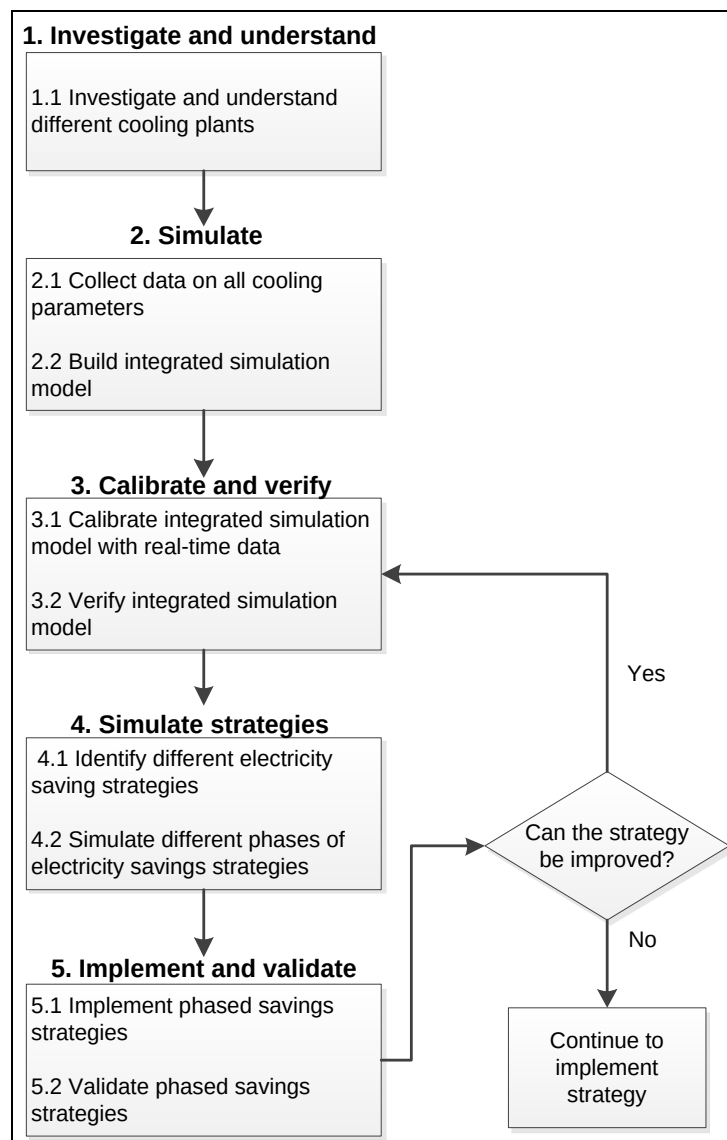


Figure 23: Detailed developed method for this study, adapted from [45]

Figure 23 shows that each component of the method can be broken up into sub-sections which are discussed thoroughly in Section 2.3.

2.3.1 Investigate and understand

2.3.1.1 Investigate and understand different cooling plants

This step in the developed method considers the holistic investigation of surface cooling plant configurations for deep mines with similar configurations as shown in Figure 20. According to existing studies, this step of the method is important, as it can influence the success of a study, and the more time is spent on this section, the easier it will be to identify the best possible solution to holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling plant configurations [12], [47]. It is also recommended that, whenever a need and study objective similar to what was described in Chapter 1 are found, the working of the specific surface cooling and ventilation systems should be examined and understood thoroughly [12], [19], [45]. This ensures that a good understanding of the specific case study deep mine cooling and ventilation system is achieved. Further, an existing study shows that an intensive investigation assists with the identification of system boundary conditions and operational parameters [19]. During the investigation, questions arise, which could lead to more information being discovered regarding the need and study objective.

The next step in this section is to do a general site-specific investigation. During this investigation, it is important to collect as much information as possible to ensure that the process in the method can be followed thoroughly and an accurate simulation model can be built [47]. It is further useful to take photographs, inspect and write down notes of the cooling plant specifications, auxiliary machinery, equipment specifications, and valves, as some of the information might be forgotten over time due to the complexity of the cooling plant configurations [12], [36]. A pipe configuration layout of the cooling plants can be obtained from the mine (if available) or compiled, as this assists in determining the exact locations of the infrastructure of the cooling plants [36].

The checklist given in Table 3 can be used to make sure that all the high-level cooling plants and surface BAC plants information is collected. A check mark (“√”) can be used if the information for the specific entry is available and a cross (“X”) can be used if the information is not available. All deviations should be noted and comments should be made in the checklist to ensure that informed assumptions are made in the next step of the developed method. This method can be applied for the lists in Table 3, Table 4, and Table 5.

The checklists shown in Table 3, Table 4 and Table 5 are divided into two sections, namely essential and desirable. The essential section contains the minimum information needed for the holistic evaluation of the cooling plant configurations to be successful. The desirable section includes information that will make it easier to follow the method, as certain calculations can then be neglected due to available measuring equipment.

Table 3: High-level Inspections done on the cooling plants and surface BAC plants, adapted from [8], [24], [36]

General inspections- Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
SCADA historian data available [8]?				
PLC controlled or manually controlled [8]?				
Refrigerant used for specific cooling plants [36]?				
Current meters available on all equipment [36]?				
Voltage meters available on all equipment [36]?				
Level percentage sensor for the pre-cooling dam available [8]?			N/A	
Level percentage sensor for the intermediate dam available [8]?				
Level percentage sensor for the chill dam available [8]?				
General inspections- Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Power consumption meters available [8]?				
Guide vane angle feedback of the compressor available [8]?				
Air velocity sensor for the intake air of BAC available [36]?	N/A			
Barometric pressure sensor of ambient surface air available [24]?				
Temperature sensor inspections- Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Inlet evaporator temperature sensor available[36]?				
Outlet evaporator temperature sensor available [36]?				
Inlet condenser temperature sensor available [36]?				
Outlet condenser temperature sensor available [36]?				
Outlet pre-cooling system temperature sensor available [36]?			N/A	
Intermediate dam temperature sensor available [36]?				
Hot dam temperature sensor available [36]?				
Chill dam temperature sensor available [36]?				
BAC inlet water temperature sensor available [36]?	N/A			
Air inlet (ambient dry bulb) temperature sensor of BAC available [36]?				
Air inlet (ambient wet bulb) temperature sensor of BAC available [36]?				
Air outlet (wet bulb) temperature sensor of BAC available [36]?				
Temperature sensor inspections- Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Inlet pre-cooling system temperature sensor available [36]?			N/A	
BAC outlet water temperature sensor available [36]?	N/A			
Water flow rate inspections- Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Inlet evaporator flow rate available [36]?				
Inlet condenser flow rate available [36]?				
Chilled water flow rate to underground demand available [8]?			N/A	
BAC water flow rate available [36]?	N/A			
Water flow rate inspections- Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Outlet evaporator flow rate available [36]?				
Outlet condenser flow rate available [36]?				

According to existing research, the Supervisory Control and Data Acquisition system (SCADA) is a network used by mines to collect and communicate data to a central location for supervision and access [8], [47]. The SCADA system can also manage and control complex mine systems and has a historian to collect and store the data [8], [47].

After all the instrumentation of the cooling plants and surface BAC plants has been inspected at a high level and all the relevant information has been obtained, a high-level investigation is done on the infrastructure properties of the cooling plants and surface BAC plants. This inspection includes water storage systems and pre-cooling water systems according to Table 4. It is important to note all deviations in the list and comment on them to ensure that informed assumptions can be made in the next step of the developed method.

Table 4: High-level inspections done on infrastructure properties of cooling systems, adapted from [8], [23], [24], [34], [36]

Inspection of infrastructure properties of cooling system -Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Number of cooling plants available and operational [36]?				
Number of evaporator pumps per cooling plant [36]?				
Number of condenser pumps per cooling plant [36]?				
Number of pre-cooling pumps [36]?			N/A	
Pre-cooling pumps: motor and pump specification plate available [36]?				
Number of BAC return water pumps [36]?	N/A			
Return BAC pumps: motor and pump specification plate available [36]?				
Evaporator pumps: motor and pump specification plate available [36]?				
Condenser pumps: motor and pump specification plate available [36]?				
Compressor: motor and compressor specification plate available [36]?				
Valve sizes and position of valve available [23]?				
Cladding on pipes [34]?				
Bends on the evaporator and condenser pipes [24]?				
Constraints in the system (i.e., throttling of valves, broken pumps, leaks in the cooling system) [34]?				
Capacity of hot dam [36]?			N/A	
Location of the pre-cooling tower (elevation difference) [34]?				
Capacity of pre-cooling dam [8]?				
Number of pre-cooling towers [36]?				
Pre-cooling fans: motor and fan specification plate available [36]?				
Number of condenser towers [36]?				
Condenser fans: motor and fan specification plate available [36]?				
Location of evaporator pumps [34]?				
Location of condenser pumps [34]?				
Location of the intermediate dam (elevation difference) [34]?			N/A	
Capacity of the intermediate dam [8]?				
Location of the chill dam (elevation difference) [34]?				
Capacity of the chill dam [8]?				
Location of the surface BAC [34]?	N/A			
Number of BAC fans [36]?				
BAC fans: motor and fan specification plate available [36]?				
Pipe sizes and lengths for the evaporator circuit available [34]?				
Pipe sizes and lengths for the condenser circuit available [34]?				
Pipe sizes and lengths between the intermediate dam and chill dam available [34]?			N/A	
Pipe sizes and lengths for the surface BAC available [34]?	N/A			
Infrastructure properties of cooling system-Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Location of cooling plants (inside a building/ outside) [34]?				

After a high-level investigation has been done on the infrastructure properties of the cooling system, a high-level investigation is done on the surface ventilation fans and underground working areas by using Table 5. The surface ventilation system is also included in the investigation, as the method was designed to holistically evaluate cooling plants and the effect that they have on the deep mine. It is important to note all deviations in the list and comment on them for informed assumptions to be made in the next step of the method.

Table 5: High-level inspections done on ventilation system, adapted from [8], [18], [24], [36], [47]

General inspections- Essential		
	Surface Ventilation	Comments/ Deviations
PLC historian data available [8]?		
PLC controlled or manually controlled [8]?		
Current meters available on all equipment [36]?		
Voltage meters available on all equipment [36]?		
Frequency meters for ventilation fan motors available [24]?		
Air velocity sensor of surface ambient air available [24]?		
Air velocity sensor of underground ambient air available [18]?		
Deep mine ventilation layouts and elevations available [47]?		
General inspections- Desirable		
	Surface Ventilation	Comments/ Deviations
Power consumption meters available [8]?		
Barometric pressure sensor of the fan available [24]?		
Barometric pressure sensor of the underground working area available [18]?		
Temperature sensor inspections- Essential		
	Surface Ventilation	Comments/ Deviations
Air (ambient underground dry bulb) temperature sensor available [36]?		
Air (ambient underground) relative humidity sensor available [36]?		

As seen in Table 3, Table 4, and Table 5, an intensive high-level investigation must be done to obtain all the information. As this information is attained, a better understanding of the operation of the specific cooling system will also be achieved. This initial comprehensive high-level investigation assists with the identification of possible solutions to the problem. The information collected in Table 3 and Table 4 can be used to compile a pipe configuration layout of the cooling system of a deep mine if the mine does not have one available.

2.3.2 Simulate

Simulations are an integral part of providing solutions to current problems. Research shows that simulation models enable different strategies and tests to be run, without physically impacting the cooling systems [42]. Complicated surface cooling plant configurations can also be simulated to determine the full impact of the tests done on the system [45]. Simulations also have the advantage that the effect of adjustments made to single or multiple components can be visualised [45]. A holistic simulation model for a complex and integrated surface cooling plant configuration and ventilation system will further ensure a more accurate representation compared to real-life operations [45].

There is a large range of different simulation software packages available for different applications [45], [48]. According to previous studies, the following software packages had been considered and evaluated and as summarised in Table 6 [45], [48]. Note that Table 6 is adapted to this current study.

Table 6: Current simulation software package evaluation, adapted from [45], [48]

No.	Simulation software package	Selection criterion	
		Dynamic analysis	Scenario investigations
1	EES ⁶	X	✓
2	Excel (IF97) ⁷	X	✓
3	FlowNex ⁸	✓	✓
4	AFT ⁹	✓	✓
5	PTB ¹⁰	✓	✓
6	EPANET ¹¹	✓	✓

As shown in Table 6, four of the software packages could be used in this study's application. Furthermore, the availability of and access to those four software packages were also considered to determine which software package to use. For this study, Process Toolbox (PTB) was used due to the availability and accessibility thereof, as well as all the built-in features that had been specifically designed for applications on deep mine cooling systems [48]. Furthermore, existing studies show that good results (simulation results versus actual results) can be achieved by making use of the PTB simulation software package to simulate mine cooling systems [12], [19], [26], [36], [49]. Additionally, PTB can also be used on deep mine ventilation systems with high accuracies (simulation results versus actual results) [47], [50]. Table 7 shows existing studies that made use of PTB software to simulate different real-life mine cooling and ventilation systems [12], [19], [26], [36], [47], [49], [50].

⁶ F-Chart Software. "Engineering Equation Solver: Overview." <https://fchartsoftware.com/ees/> (accessed 2022).

⁷ The Editors of Encyclopaedia Britannica. "Microsoft Excel software." <https://www.britannica.com/technology/Microsoft-Excel> (accessed 2022).

⁸ Flownex. "About Flownex." <https://flownex.com/about/> (accessed 2022).

⁹ Applied Flow Technology. "AFT Fathom 12." https://www.aft.com/products/fathom?utm_source=EmpoweringPumps (accessed 2022).

¹⁰ I. Mathews, "A simulation-based prediction model for coal fired power station condenser maintenance," North-West University (South Africa), 2020.

¹¹ EPA. "EPANET." <https://www.epa.gov/water-research/epanet> (accessed 2022).

Table 7: PTB software simulation accuracies on existing studies [12], [19], [26], [36], [47], [49], [50]

Author	System simulated with PTB software	Percentage accuracy (simulation results vs actual results) [%]
Ashmead [12]	Ice thermal storage (mine cooling system)	93.5
Crawford [19]	Various mine cooling systems	97
Jerling [26]	Mine cooling system	91.6
Maré [36]	Mine cooling system (Case study mine 1)	97
Maré [36]	Mine cooling system (Case study mine 2)	94
Rouan [47]	Mine ventilation system	96.9
Nel [49]	Mine cooling system	96.3
Mulder [50]	Various mine ventilation systems	89.9

PTB is an in-house three-dimensional (3D) modelling software package that makes use of a semi-empirical thermohydraulic platform to simulate surface cooling plants and ventilation systems for deep mines [45], [48].

2.3.2.1 Collect data on all cooling parameters

As shown in the case study research method used in Figure 17, the design data collection protocol is part of this step of the method that was developed According to a study by Rouan (2021), data collection can be divided into three different sections, namely low-, intermediate- and high-level data [47]. Low-level data ensures that the most accurate simulation models can be developed and includes data obtained from airflow quantities, temperature, and barometric pressure (for key measuring ventilation characteristics). [47]. Typically, low-level data will be found on a deep mine's SCADA system if the mine is equipped with measuring instrumentation [47]. It is important to note that the data from the SCADA has been proven to produce accurate simulation models due to the functionality of the system to produce and recall large amounts of data [47].

Intermediate-level data is defined by the same study to be data that can be used to construct mass balances for mines [47]. This is mostly data that provides information on the status of a subsection in the mine [47].

Furthermore, according to Rouan, high-level data only characterises key performance indicators (KPIs) of specific deep mine systems [47]. Research indicates that a KPI is a quantifiable measure used to compare strategic and operational goal performance [47]. Examples of high-level data used for KPIs on surface cooling plants of deep mines are temperatures and water flow rates of cold water being sent underground. It is also important to note that the literature claimed that simulation models built using only high-level data will not produce a high accuracy [47].

For the next step in the developed method, the information that has been gathered through the inspections done using Table 3, Table 4, and Table 5 is used to develop an accurate simulation model [47]. The data for a complex surface cooling system and ventilation system need to be accumulated for a simulation model to be built. Thus, Table 3, and Table 5 were adapted so that the data can be collected from the high-level inspection information of the first step.

Table 8 shows a list of the data that need to be collected on the cooling system of a deep mine for the simulation to be built [17], [18], [24], [33], [51]. The form provides two different methods to collect the required data. The first method is by using the SCADA historian tag and provides a description of the tag being used. It is often difficult to pinpoint different measuring instrumentation by looking at the tag names, especially when the tag names are not used regularly. It is recommended that a description is added to each tag name as this will also assist in fault finding. The second method of collecting data is by doing practical measurements. This method is included as some deep mines do not have access to measuring instrumentation that is connected to the SCADA.

Table 8: Data collection to be done on cooling systems [17], [18], [24], [33], [51]

General data collection- Essential				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Current meters on all equipment		• Analogue current meter or • Digital Multimeter		• Analogue current meter or • Digital Multimeter
Voltage meters on all equipment		• Analogue volt meter or • Digital Multimeter		• Analogue volt meter or • Digital Multimeter
Level percentage sensor for the pre-cooling dam		N/A		
Level percentage sensor for the intermediate dam				
Level percentage sensor for the chill dam				
General data collection- Desirable				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Power consumption meters [24], [51]		• Analogue current and voltage meters or • Digital clamp-multimeter or • Digital power meter		• Analogue current and voltage meters or • Digital multimeter or • Digital power meter
Guide vane angle feedback of compressor		N/A		N/A
Air velocity sensor for the intake air of BAC [18], [24], [33]	N/A			• Digital manometer & pitot tube (if fan curve available) or • Laser distance meter and • Whirling hygrometer or temperature logger and • Barometer and • Analogue vane-anemometer or • Digital vane-anemometer
Barometric pressure sensor of ambient surface air [18], [24]				• Barometer
Temperature sensor data collection- Essential				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet evaporator temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)		• Digital thermometer or • Temperature gun (uninsulated pipes)
Outlet evaporator temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)		• Digital thermometer or • Temperature gun (uninsulated pipes)
Inlet condenser temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)		• Digital thermometer or • Temperature gun (uninsulated pipes)
Outlet condenser temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)		• Digital thermometer or • Temperature gun (uninsulated pipes)

	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Outlet pre-cooling system temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)	N/A	
Intermediate dam temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)		
Chill dam temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)		
Air inlet (ambient dry bulb) temperature sensor of BAC [18], [24], [33]	N/A			• Whirling hygrometer or • Temperature logger
Air inlet (ambient wet bulb) temperature sensor of BAC [18], [24], [33]				• Whirling hygrometer or • Temperature logger
Air outlet temperature sensor of BAC [18], [24], [33]				• Whirling hygrometer or • Temperature logger
Temperature sensor data collection- Desirable				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet pre-cooling system temperature sensor [17], [18]		• Digital thermometer or • Temperature gun (uninsulated pipes)	N/A	
BAC outlet water temperature sensor [17], [18]	N/A			• Digital thermometer or • Temperature gun (uninsulated pipes)
Water flow rate data collection- Essential				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet evaporator flow rate [18]		• Ultrasonic water flow meter		• Ultrasonic water flow meter
Inlet condenser flow rate [18]		• Ultrasonic water flow meter		• Ultrasonic water flow meter
Cold water flow rate to underground demand [18]		• Ultrasonic water flow meter	N/A	
Water flow rate data collection- Desirable				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Outlet evaporator flow rate [18]		• Ultrasonic water flow meter		• Ultrasonic water flow meter
Outlet condenser flow rate [18]		• Ultrasonic water flow meter		• Ultrasonic water flow meter

Table 9 gives a list of the data that need to be collected on the ventilation system of a deep mine for the simulation to be developed [18], [24], [33], [51]. The same two methods as in Table 8 will be used for the data collection on the ventilation system.

Table 9: Data collection to be done on the ventilation system [18], [24], [33], [51]

	Description & tag name	Practical measurement
Current meters on all equipment		• Analogue current meter or • Digital Multimeter
Voltage meters on all equipment		• Analogue volt meter or • Digital Multimeter
Frequency meters for ventilation fan motor		N/A
Air velocity sensor of surface ambient air [18], [24], [33]?		• Digital manometer & pitot tube (if fan curve available) or • Laser distance meter and • Whirling hygrometer or temperature logger and • Barometer and • Analogue vane-anemometer or • Digital vane-anemometer
Air velocity sensor of underground ambient air [18], [24], [33]?		• Laser distance meter and • Whirling hygrometer or temperature logger and • Barometer and • Analogue vane-anemometer or • Digital vane-anemometer
General data collection- Desirable		
	Description & tag name	Practical measurement
Power consumption meters [24], [51]		• Analogue current and voltage meters or • Digital clamp-multimeter or • Digital power meter
Static pressure sensor of fan [18], [24]		• Barometer or • Digital manometer & pitot tube (if fan curve is available)
Barometric pressure sensor of underground working area [18], [24]		• Barometer
Temperature sensor data collection		
	Description & tag name	Practical measurement
Air (ambient underground dry bulb) temperature sensor [18], [24], [33]		• Whirling hygrometer or • Temperature logger
Air (ambient underground) relative humidity sensor [18], [24], [33]		• Whirling hygrometer or • Temperature logger

Table 10 shows the equipment needed to do the practical measurements for Table 8 and Table 9 and gives a short description of the measuring equipment [17], [18], [24], [33], [48], [51]. Detailed information and steps on how the measuring equipment is used can be seen in other studies and tutorial videos and will not be discussed in this study, as it is not part of the scope of this study.

Table 10: Equipment to be used to do practical measurements [17], [18], [24], [33], [48], [51]

Name of measuring instrument	System measured	Unit	Description	Example of a product that can be used	Possible data storage capability available
Analogue current meter	Current (electricity)	Ampere [A]	Can be connected to the electrical circuit to measure the current through a specific circuit. This can be used to calculate the power consumption of a component.	Basic analogue current meter	No
Analogue voltage meter	Voltage (electricity)	Volt [V]	Can be connected to the electrical circuit to measure the voltage over a component in a specific circuit. This can be used to calculate the power consumption of a component.	Basic analogue voltage meter	No
Digital Multimeter	• Current (electricity) • Voltage (electricity)	• Ampere [A] • Volt [V]	Has a current meter and voltage meter that can be connected to the electrical circuit to measure the current through a component or voltage over a component in a specific circuit, respectively. This can be used to calculate the power consumption of a component.	Basic digital multimeter	No
Digital clamp-multimeter	Electrical power consumption	kW	Can be used to measure the power consumption of a component in a specific circuit.	UNI-T UT204A [24]	Yes
Digital power meter	Electrical power consumption	kW	Can be used to measure the power consumption of a component in a specific circuit [51].	Schneider-Electric Powerlogic ION7330 [51]	Yes
Digital manometer & pitot tube	Static air pressure	kPa	Can be used to measure static air pressure. When fan curves for the specific fan are available, the air velocity of the fan can be calculated by using the measured static air pressure.	Delta Ohm HD2134P.2 [24]	No
Laser distance meter	Area	m ²	Can be used to measure distances (area) through which the air is flowing [18, 33].	Bosch PLR-25 [18]	No
Whirling hygrometer	• Dry bulb air temperature • Wet bulb air temperature	°C	Can be used to measure the dry bulb and wet bulb temperature if the fabric over the thermometer is soaked with water at room temperature.	Basic whirling hygrometer [18], [24], [33]	No
Temperature logger	• Dry bulb air temperature • Wet bulb air temperature	°C	Can be used to measure the dry bulb and wet bulb temperature. The temperature logger has a relative humidity sensor which can be used to calculate the wet bulb temperature.	Gemini Tinytag view 2 [18]	Yes
Barometer	Barometric air pressure	kPa	Can be used to measure the barometric air pressure.	Tenmar 404 [18], [24]	No
Analogue vane-anemometer	Air velocity	m/s	Can be used to measure the air velocity of the air flowing through a specific area.	Basic analogue vane-anemometer [33]	No
Digital vane-anemometer	Air velocity	m/s	Can be used to measure the air velocity of the air flowing through a specific area.	Tenmar-404 [18], [24]	No
Digital thermometer	Water temperature	°C	Can be used to measure the water temperature if there is a thermowell (probe pocket) available [17].	Gemini Tinytag view 2 with thermistor probe [18]	Yes
Temperature gun	Water temperature	°C	Can be used to measure the water temperature if there is no thermowell (probe pocket) available. The temperature gun can be directed at the pipe that is uninsulated [17].	Basic temperature gun [17]	No
Ultrasonic water flow meter	Water flow rate	L/s	Can be used as a non-intrusive water flow meter to measure the water flow rate [17, 48]. It is suggested that the outside of the pipe is thoroughly cleaned before measurements are done.	Basic portable water flow meter [18]	Yes

As seen in Table 10, not all of the practical measuring equipment has data storage capacity available, and in some cases only instantaneous data measurements will be available. When using practical measuring equipment, it is important to measure at critical times to ensure that the data is reliable. For example, erroneous data will be collected if water flow is measured without any pump being operational.

It is evident from existing studies that low-level data will ensure that the most accurate simulation model is developed [47]. The following process from a previous study is used to obtain low-level data for cooling systems as shown in Figure 24 [8].

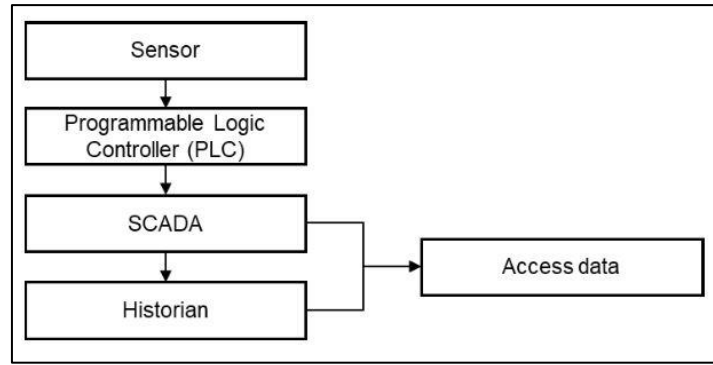


Figure 24: Data flow diagram according to [8]

Figure 24 shows that the data from cooling systems are generated continuously by sensors that measure specific parameters [8]. The measured data are transferred through a communication cable to a PLC [8]. The PLC is used as an interface between the measured data of the sensor and the SCADA [8]. Live data can be seen by using a Human-Machine Interface (HMI) that is connected to the SCADA and stores data for a temporary period [8]. The historian is used to store the data for longer periods when data investigations are required [8]. A tag name is allocated to each parameter that a specific instrumentation sensor measures [27], [48].

Another important factor that needs to be considered during data collection for this method is the quality of the data. Raw data gathered from the historian need to be processed into the desired format to be used in the simulation model. For this study, raw data are defined as data gathered from the historian or SCADA, without any changes made to it. The quality of the data needs to be evaluated to ensure that there are no errors or faulty data in the dataset. Evaluating the quality of the dataset contributes to high accuracy in the simulation model [48]. Different approaches can be used to evaluate the quality of the data, but for this study, the existing method [48] as illustrated in Figure 25 was used.

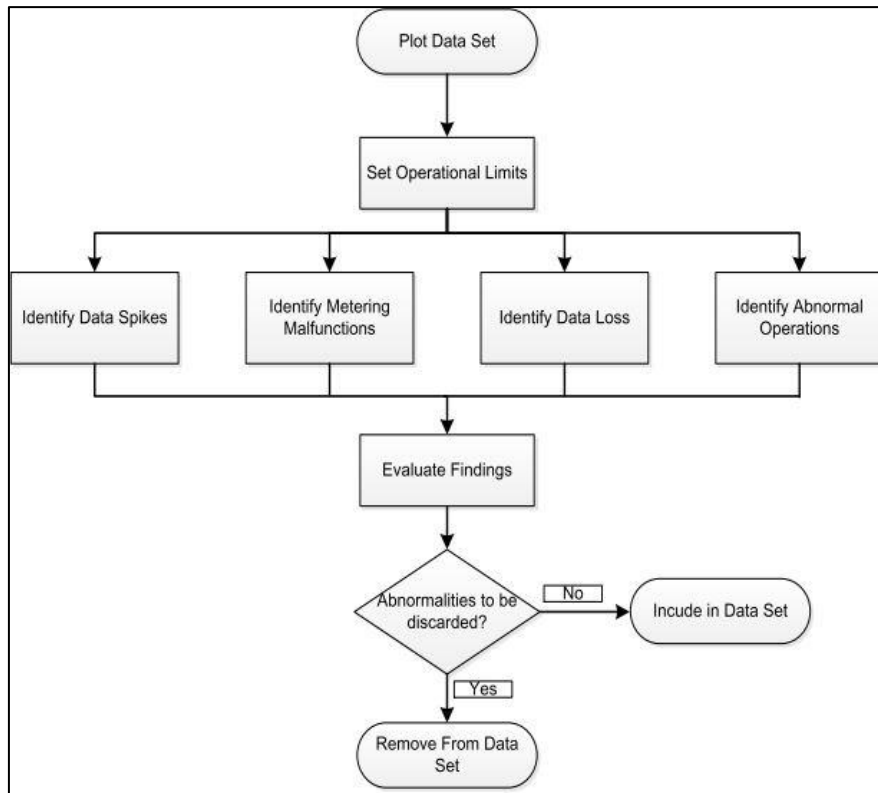


Figure 25: Method to evaluate data quality [48]

The first step in this method to evaluate the quality of the data is to plot the raw data [48]. From a previous study, it can be seen that Microsoft® Excel is popular software that can be used to plot raw data [48]. An example of a plotted data set from a previous study where the data quality method was applied, can be seen in Figure 26 [48].

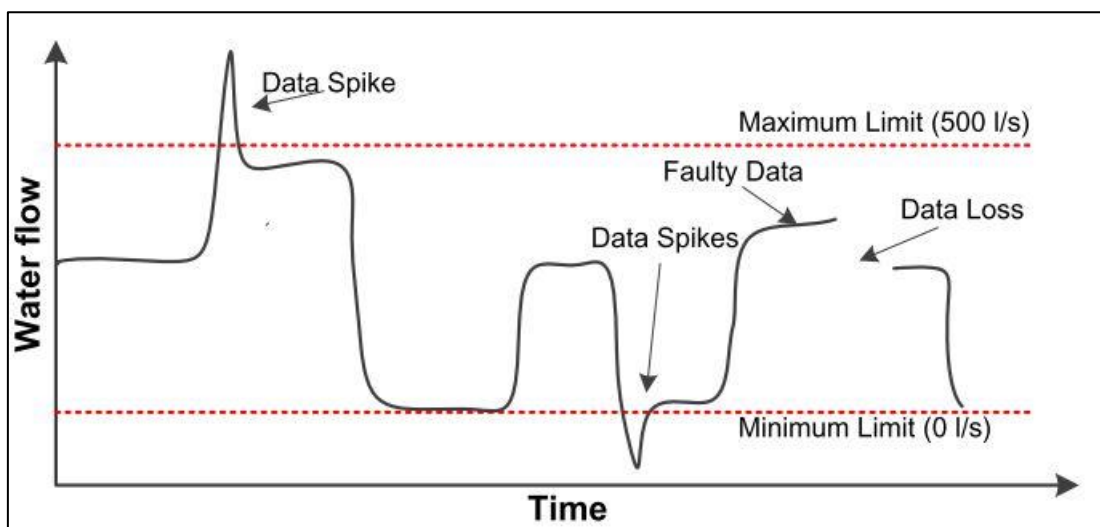


Figure 26: Dataset quality process [48]

After the raw data has been plotted, the processing of the data can commence by identifying and defining operational limits for the specific cooling data [48]. Set points are defined by considering the operational values of the measuring instrumentation used to generate the data [48]. Set points can be defined by examining the design specifications of different sections in the cooling systems. An example of a set point for an instrument measuring the water flow rate could be a maximum flow that the specific pipe can achieve as a maximum set point and a minimum limit of zero due to one-way valves that are installed in the cooling system [48]. Thus, any data outside the limits can be seen as data spikes as shown in Figure 26 [48].

More factors such as malfunctioning measuring instrumentation, data loss, or irregular mining activities could impact the validity of a data set, as shown in Figure 25 [48]. According to an existing study, it was found that malfunctioning measuring instrumentation is often seen in mines [52]. Malfunctioning measuring instrumentation will result in faulty or inaccurate data or data loss in a dataset, as shown in Figure 26 [48]. Irregular mining activities can be identified as abnormal measurements during specific times when mining activities are not expected, such as during blasting shifts, and can be neglected if it is not essential to the future design of the mine [48].

After all the data irregularities have been evaluated and processed, the data quality process shown in Figure 25 is complete [48]. For this study, it was also important to consider intermediate- and high-level data collection methods, as some deep mines do not have access to measuring instrumentation that is connected to the SCADA [47]. Thus, the same data quality process needs to be followed for the data collected from practical measuring equipment with/ without data storage capabilities.

An existing study further shows that data validation processes ensure that the data are trustworthy and accurate, which will assist in the implementation and validation step (Step 5) of the developed method of this study [8]. The following tests which apply to this study can be implemented on all the data gathered to ensure data integrity [8]:

1. **Constant value check:** Measuring instrumentation showing constant values for long periods can be seen as faulty flow meters and must be excluded from the data set [8].
2. **Measurement unit check:** The unit in which the data are stored needs to be constant throughout the data collection and simulation development phase and a previous study proposes that the units be converted to Système Internationale (SI) units [8]. An example is converting water flows that were measured as L/h to L/s [8].
3. **Redundancy check:** Redundant measuring instrumentation can be used so that a comparison between two data points can be made [8]. The data from measuring

instrumentation that shows a large discrepancy between similar measurement instrumentation will be excluded from the data set [8].

4. **Correlation check:** The data from measuring equipment of a specific cooling plant need to correlate with one another [8]. Thus, the cooling duty cannot be achieved when a cooling plant is not operational and that data will be excluded from the data set [8].
5. **Mass balance check:** The sum of the mass flow rates entering and exiting a point needs to be equal [8]. According to a previous study, a 5% deviation can be ascribed to measurement and instrumentation accuracy deviations [45].

After the data quality and validation processes have been applied to the data set, the data set can be used for calculations and the development of the simulation model. Due to the unavailability of smart measuring instrumentation in deep mines, certain important parameters need to be calculated as discussed below.

Calculating the COP of a cooling plant:

The COP of a cooling plant can be calculated by using Equation 1 [19], [36]:

$$COP = \frac{Q_{evap}}{P_{motor}} \quad (1)$$

where:

- COP is the coefficient of performance for the cooling plant,
- Q_{evap} is the thermal energy absorbed in the evaporator in Watt (W), and
- P_{motor} is the motor power of the compressor in Watt (W).

The thermal energy absorbed in the evaporator can be calculated by using Equation 2 [36]:

$$Q_{evap} = \dot{m}_{water} C_{pw} (T_{out} - T_{in}) \quad (2)$$

where:

- Q_{evap} is the thermal energy absorbed in the evaporator in Watt (W),
- $\dot{m}_{water}$ is the mass flow rate of water in L/s,
- C_{pw} is the specific heat of water, which is 4.18 and is measured in kJ/kg.K [36],

- T_{out} is the temperature of the water going out of the evaporator cycle of the cooling plant in °C, and
- T_{in} is the temperature of the water going into the evaporator cycle of the cooling plant in °C.

According to existing research

The density of water is assumed as 1000 kg/m³, thus L/s can be used for the mass flow rate of water [46]. Furthermore, the temperatures of the water going into and leaving the evaporator cycle of the cooling plant can be used in °C due to the equation considering the change in temperature and the same answer will be achieved regardless of the unit used.

Equation 3 can be used to calculate the power consumption of a three-phase electrical motor [36]:

$$P_{motor} = \sqrt{3}VIpf \quad (3)$$

where:

- P_{motor} is the motor power in Watts (W),
- V is the voltage in volts (V),
- I is the current in ampere (I), and
- pf is the power factor.

Calculating the mass air flow rate:

According to existing research, the mass air flow rate can be calculated by using Equation 4 [18]:

$$\dot{m}_a = \rho_a \dot{v}_a \quad (4)$$

where:

- $\dot{m}_a$ is the mass air flow rate in kg/s,
- ρ_a is the air density in kg/m³, and
- $\dot{v}_a$ is the volumetric air flow in m³/s.

Equation 5 can be used to calculate the volumetric airflow [18]:

$$\dot{v}_a = v_a A \quad (5)$$

where:

- $\dot{v}_a$ is the volumetric air flow rate in m³/s,
- v_a is the air velocity in m/s, and
- A is the flow area in m².

The flow area can be calculated by using Equation 6 [18]:

$$A = \frac{\pi}{4} D^2 \text{ or } A = L \times H \quad (6)$$

where D is the ducting diameter used for round areas, L is the length and H is the height that is used in squared areas, measured in m.

According to existing research, the density of air can be calculated by using Equation 7 [18]:

$$\rho_a = \frac{1 + RH}{V} \quad (7)$$

where:

- ρ_a is the air density in kg/m³,
- RH is the relative humidity of the airflow and can be measured by using a temperature logger with a relative humidity sensor or by calculating it, and
- V is the specific volume of moist air in m³/kg.

The specific volume of moist air can be calculated by using Equation 8 [18]:

$$V = \frac{R_{air}(T_{DB} + T_{abs})}{P \times P_{sat} \times RH} \quad (8)$$

where:

- R_{air} is the ideal gas constant which is 287.05 J/kg.K [18],

- T_{DB} is the ambient dry bulb temperature in K,
- T_{abs} is the absolute temperature, which is 273.15 K [18],
- P is the air pressure in kPa,
- P_{sat} is the saturated air pressure in kPa, and
- RH is the relative humidity of the airflow and can be measured by using a temperature logger with a relative humidity sensor or by calculating it.

Equation 9 shows how the saturated air pressure can be calculated [18]:

$$P_{sat} = e^{\left(\frac{C_1}{T} + C_2 + TC_3 + T^2C_4 + T^3C_5 + C_6 \log T\right)} \quad (9)$$

where the constants ($C_{1...6}$) were extracted from the Hyland and Wexler correlation and are defined as [18]:

$$C_1 = -5\,800.2206$$

$$C_2 = -5.516256$$

$$C_3 = -0.048640239$$

$$C_4 = 0.000041764768$$

$$C_5 = -0.000000014452093$$

$$C_6 = 6.5449673$$

Further, Equation 10 shows the temperature (T) in Kelvin (K) below [18]:

$$T = T_{DB} + T_{abs} \quad (10)$$

According to existing research, the relative humidity (RH) of air can be calculated by using Equation 11 [18]:

$$RH = \frac{P \times W}{P_{satDB}(R_{mol} + W)} \quad (11)$$

And W is given by Equation 12 [18]:

$$W = \frac{\left(\frac{R_{mol} P_{satWB}}{P - P_{satWB}}\right) (h_{fg} - T_{WB}(C_{pw} - C_{pvap})) - C_{pa}(T_{DB} - T_{WB})}{h_{fg} + C_{pvap}T_{DB} - C_{pw}T_{WB}} \quad (12)$$

where:

- R_{mol} is the ratio of the molecular mass of water vapour to air, which is typically 0.62198 [18],
- h_{fg} is the heat of evaporation at 0 °C, which is typically 2 501 000 J/kg.K [18],
- C_{pa} is the specific heat of air, which is 1.006 kJ/kg.K [18],
- C_{pvap} is the specific heat of water vapour, which is 1.805 kJ/kg.K [18], and
- T_{WB} is the ambient wet bulb temperature in K.

The ambient wet bulb temperature (T_{WB}) can be calculated by using Equation 11 and Equation 12 if the relative humidity (RH) can be measured or measured by using a whirling hygrometer [18].

Once all the data are collected, processed for data quality and validation, and the appropriate calculations are done, the data are ready to be used to build a calibrated simulation model of an integrated cooling system of a deep mine.

2.3.2.2 Build integrated simulation model

Different characteristics need to be considered in the simulation model due to the complexity and holistic evaluation done on the surface cooling plant configurations of deep mines for different seasons. As previously mentioned, PTB was used to model the complex cooling plant configurations for different seasons. PTB is a powerful simulation package and the following capabilities of the simulation software were used:

- Cooling plant and cold water distribution on surface [12], [19], [26], [36], [49],
- High-level surface and underground ventilation systems [47], [50], and
- Power consumption of the whole surface cooling system [53].

For an accurate complex and integrated simulation to be developed, an understanding of a basic cooling plant and a basic ventilation simulation model must first be developed in PTB. Figure 27 shows a basic cooling plant (with all auxiliary components) simulation model that was developed in PTB.

Table 11: Process Toolbox (PTB) components used in basic cooling plant simulation [53]

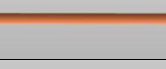
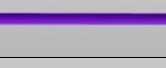
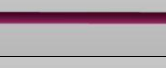
Main components		
Component	PTB Name	Description
	Water Chiller	The water chiller removes heat from the water circuit connected to the evaporator [53]. This heat and the compressor's heat are then transferred to the water circuit connected to the condenser and cooling water is needed to cool down the condenser [53].
	Water Dam Round	The dam is a thermal-hydraulic system break with variable thermal storage available with inlet and outlet flows that are not functions of one another [53].
	Water Air Cooling Tower	A counter flow direct contact heat exchanger where mass and heat are transferred through air and water simultaneously [53]. The air can be cooled and humidified or dehumidified or heated and humidified with direct contact with water [53].
	Air Fan	Generates a pressure difference in an airflow network to induce airflow [53]. This component also generates heat in the fluid due to inefficiencies and adiabatic compression [53].
	Water Pump	Generates a pressure difference in a water flow network to induce water flow [53]. This component also generates heat in the fluid due to inefficiencies [53].
	Energy Tariff	Used to specify energy rates (R/kWh) for all electrical energy-consuming thermal-hydraulic components used in the system [53].
	Water Node	Water network properties such as pressure, enthalpy, temperature, etc. are calculated in the water node component [53].
	Water Pipe	Water network flow pressure losses are calculated in the pipe component and include a variable valve fraction to control pressure or flow [53].
	Pipe properties: Hot water	The hot water pipe is displayed in this colour in the PFD view of PTB.
	Pipe properties: Pre-cooled water	The pre-cooled water pipe is displayed in this colour in the PFD view of PTB.
	Pipe properties: Condenser inlet water	The condenser inlet water pipe is displayed in this colour in the PFD view of PTB.
	Pipe properties: Condenser outlet water	The condenser outlet water pipe is displayed in this colour in the PFD view of PTB.
	Pipe properties: Chilled water	The chilled water pipe is displayed in this colour in the PFD view of PTB.
	Air Pressure Boundary	User-specified temperatures, pressures, and humidities have constant values for time periods [53]. Used to connect networks to other systems or sources [53].
Control components		
	Valve	User-specified valves can be imported with valve fractions.
	PI Control	A proportional and integral controller is used to control a specific system and has two control input signals [53]. A PI controller is mostly used if specific parameters of a deep-mine cooling system are controlled by a PLC [8].
Instrumentation components		
	Instrumentation Current Transducer	Instrumentation transducer used to measure the current of a specific system.
	Instrumentation Flow Transducer	Instrumentation transducer used to measure the water flow of a specific system.
	Instrumentation Level Transducer	Instrumentation transducer used to measure the level of a specific system.
	Instrumentation Position Transducer	Instrumentation transducer used to measure the position of a specific system.
	Instrumentation Temperature Transducer	Instrumentation transducer used to measure the temperature of a specific system.

Figure 28 shows a basic ventilation system simulation model in PTB.

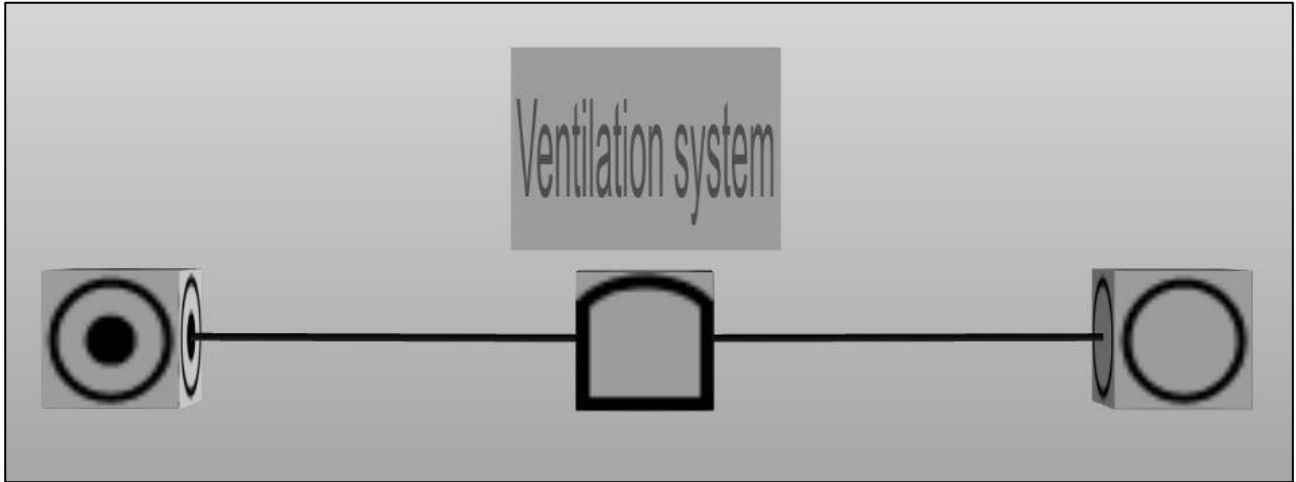


Figure 28: Basic ventilation system PTB simulation model

A PFD view of a basic ventilation simulation is shown in Figure 28 to show the different temperatures of the air in the ventilation system. This basic ventilation simulation model was developed by using the basic components needed in a ventilation system as discussed in Section 1.3.2. The basic ventilation system does not include the large extraction fans as it was not within the scope of this study and Figure 28 is based on the principle of mass air balances and pressure differences to simulate the airflow through a tunnel. Table 12 discusses a breakdown of all the components needed to develop a basic ventilation simulation model similar to the one shown in Figure 28 [53].

Table 12: Process Toolbox (PTB) components used in basic ventilation simulation [40]

Main components		
Component	PTB Name	Description
	Air Pressure Boundary	User-specified temperatures, pressures, and humidities have constant values for time periods [53]. Used to connect networks to other systems or sources [53].
	Air Tunnel	Used to simulate thermal-hydraulic fundamentals of underground shafts, stopes, and mine haulages [53]. Rock heat transfer and air pressure losses are also included by using Atkinson's friction factors [53].
	Air Node	Air network properties such as pressure, density, temperature, etc. are calculated in the air node component [53].

After a basic understanding of the development of the ventilation system and cooling plant simulation models on PTB has been developed, the basic PTB simulation models can be expanded to develop complex and integrated cooling system and ventilation system simulation models. For this step in the developed method, the complex cooling plant and ventilation system simulation model must be developed in such a way that a digital blueprint of the surface cooling system and ventilation is realised. This can be achieved by using the pipe configuration layouts obtained from Step 1 in the developed method for this study and expanding it from the basic simulation model.

During this step, it is only necessary to build the essential infrastructure of the systems, without importing any data that was collected into the various components of the simulation model. Thus, at this stage in the developed method, no components have been specified to represent the same component in real-life and all have default specifications. It is, however, important to include the appropriate elevations in the blueprint simulation models by using the information gathered in Step 1 of the developed method for both the cooling system and ventilation system model. This will become important in the following steps in the method, as PTB uses elevations to calculate different properties for the air and water used [53].

2.3.3 Calibrate and verify

The calibration and verification step in the developed method is an important part of the method used in this study. It establishes whether the simulation models that have been built are comparable to what is seen in real-life deep mine operations and conditions. According to existing research, an accuracy of 95% when comparing simulated measurements and real-life measurements is deemed sufficient, as measuring equipment can deviate by 5% [45]. The information and data that were gathered during the first two steps of the developed method are now used to calibrate and verify the simulation models that were developed for the cooling system and ventilation system of a deep mine.

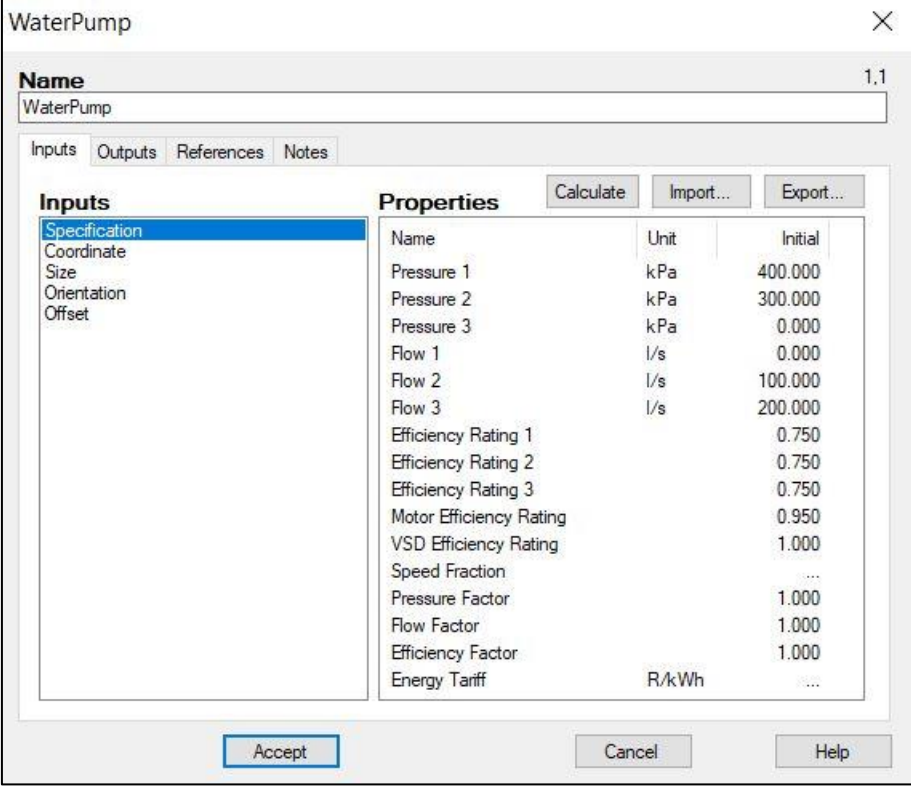
2.3.3.1 Calibrate integrated simulation model with real-time data

During the calibration step of the method, all the information that has been gathered in Step 1 and all the data that have been collected and processed are used to update the blueprint simulation models that were developed for a complex and integrated cooling system and ventilation system of a deep mine. Calibrating the model ensures that the simulation model is an accurate representation of the actual cooling and ventilation system [45]. The outcome of the calibration phase should deliver simulation models that are digital replicas of the real-life deep mine cooling and ventilation system. This might imply that the design specifications of certain components and machinery need to be changed or adapted (de-rated). This might be due to modifications made to the machinery or no maintenance being done to the machinery resulting in the machinery not operating within the design specifications [24], [30], [34]. Research shows that thermal efficiencies of cooling equipment can be reduced from design specifications due to fouling, corrosion and scale build-up [30].

It is important to make well-informed assumptions and make notes of all the assumptions that were made during the calibration of the cooling system and ventilation system simulation models. This ensures that assumptions that were made can be revisited whenever the simulation is not within the specified accuracy of 95% as mentioned earlier [45].

Calibration of a complex and integrated cooling system:

The calibration of a complex and integrated cooling system can become complicated, especially if the cooling system simulation model is large. PTB makes use of specific inputs that are required to calibrate and characterise the component [53]. Figure 29 shows an example of the specific inputs needed in PTB for a water pump.



WaterPump 1.1

Name: WaterPump

Inputs: Outputs: References: Notes:

Inputs

- Specification
- Coordinate
- Size
- Orientation
- Offset

Properties

Name	Unit	Initial
Pressure 1	kPa	400.000
Pressure 2	kPa	300.000
Pressure 3	kPa	0.000
Flow 1	l/s	0.000
Flow 2	l/s	100.000
Flow 3	l/s	200.000
Efficiency Rating 1		0.750
Efficiency Rating 2		0.750
Efficiency Rating 3		0.750
Motor Efficiency Rating		0.950
VSD Efficiency Rating		1.000
Speed Fraction		...
Pressure Factor		1.000
Flow Factor		1.000
Efficiency Factor		1.000
Energy Tariff	R/kWh	...

Buttons: Calculate, Import..., Export..., Accept, Cancel, Help

Figure 29: Water pump specification inputs in PTB

According to existing research, the information and data that were gathered can be summarised as an input table [36], [40]. PTB further also has a calculate function that can be used to calibrate the component where inputs that are more easily obtainable are used and the software then calculates the required inputs [53]. Figure 30 shows an example of the inputs needed for a water pump on PTB when the calculate function is used.

The image shows a 'WaterPump Calculator' dialog box. It has two tabs: 'Inputs' and 'Outputs'. The 'Inputs' tab is active. On the left, there is a list box containing the word 'Inputs'. On the right, there is a table titled 'Properties' with three columns: 'Name', 'Unit', and 'Initial'. The table contains five rows of data. Above the table are three buttons: 'Calculate', 'Import...', and 'Export...'. At the bottom of the dialog are two buttons: 'Accept' and 'Cancel'.

Name	Unit	Initial
Pump Motor Power	kW	0.000
Pump Flow	l/s	0.000
Pump Motor Efficiency		0.000
Pump Efficiency		0.000
Pumping Elevation	m	0.000

Figure 30: Water pump calculate function inputs in PTB

Table 13 shows a summary of the required information and data that were gathered during Step 1 and Step 2 of the method, used as input specifications in a basic cooling plant PTB simulation model. Table 13 also shows the inputs that are needed when the calculate function on PTB is used.

Table 13: Component specifications used for cooling system calibration in PTB, adapted from [36], [40], [53]

Cooling plant						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
PI controllers	-		Inlet evaporator temperature	°C		
Refrigerant used	-		Outlet evaporator temperature	°C		
Cooling capacity	kW		Evaporator water flow rate	L/s		
COP	-		Inlet condenser temperature	°C		
Inlet evaporator temperature	°C		Outlet condenser temperature	°C		
Outlet evaporator temperature	°C		Compressor motor power	kW		
Inlet condenser temperature	°C					
Outlet condenser temperature	°C					
Water pump						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Pump curve (pressures)	kPa		Pump motor power	kW		
Pump curve (flows)	L/s		Pump flow	L/s		
Pump efficiency rating	%		Pump efficiency rating	%		
Motor efficiency rating	%		Motor efficiency rating	%		
Dam						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Barometric pressure	kPa		Inlet temperature	°C		
Dam temperature	°C		Outlet temperature	°C		
Dam volume	m³		Flow rate	kg/s		
Dam level	%					
Cooling tower						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
UA (heat transfer coefficient)	kW/kJ/kg		Barometric pressure	kPa		
Water flow rate	L/s		Water inlet temperature	°C		
Air flow rate	kg/s		Water outlet temperature	°C		
			Water flow rate	L/s		
			Air inlet temperature	°C		
			Air inlet relative humidity	%		
			Air flow rate	kg/s		
Air fan						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Fan curve (pressures)	kPa		Fan motor power	kW		
Fan curve (flows)	m³/s		Fan flow	kg/s		
Fan efficiency rating	%		Fan efficiency rating	%		
Motor efficiency rating	%		Motor efficiency rating	%		
Inlet air density	kg/ m³		Fan inlet pressure	kPa		
			Fan inlet temperature	°C		

Table 13 can now be used to summarise the inputs that are needed for the specific components to be used to develop the complex integrated cooling system simulation.

According to research, PTB's optimisation solver can solve steady-state or transient (dynamic) systems [47]. PTB further allows any number of time periods to be specified for the simulation model [53]. Table 14 shows the descriptions and the time intervals used in PTB [53].

Table 14: Defining time intervals in PTB, adapted from [53]

Time interval name	Description
Number of time periods	Any number of time period schedules can be specified for all components.
Number of time steps	The number of times the simulation will be executed per time period can be specified. It is recommended to use at least 60-time steps for a transient model.
Time period size	The time period size in seconds (s) for each specific time period can be specified.

When considering Table 14, the following transient time intervals were used in this study, due to the holistic evaluation that was done on the surface cooling plant configurations at deep mines for different seasons:

- Number of time periods: 192
- Number of time steps: 60
- Time period size: 3600 seconds (s).

The number of time periods is defined as in Table 15

Table 15: Number of time periods defined in PTB for this study

Time period	Number of periods
Summer weekday	48
Summer Saturday	24
Summer Sunday	24
Winter weekday	48
Winter Saturday	24
Winter Sunday	24
Total	192

The summer weekday and winter weekday used in Table 15 represent the average weekday (24 hours) for summer and winter, executed twice. The summer and winter Saturday and Sunday time periods represent the average Saturday (24 hours) and Sunday (24 hours) for the respective seasons. This approach ensures that all different types of typical days on deep mines with varying loads are included in the simulation model.

According to research, one of the most effective ways to calibrate a simulation model is by isolating specific systems in the complex and integrated cooling system simulation model [36], [54]. Figure 31 shows how this method is implemented where a specific water chiller is removed and isolated from the existing complex and integrated cooling system to calibrate the water chiller.

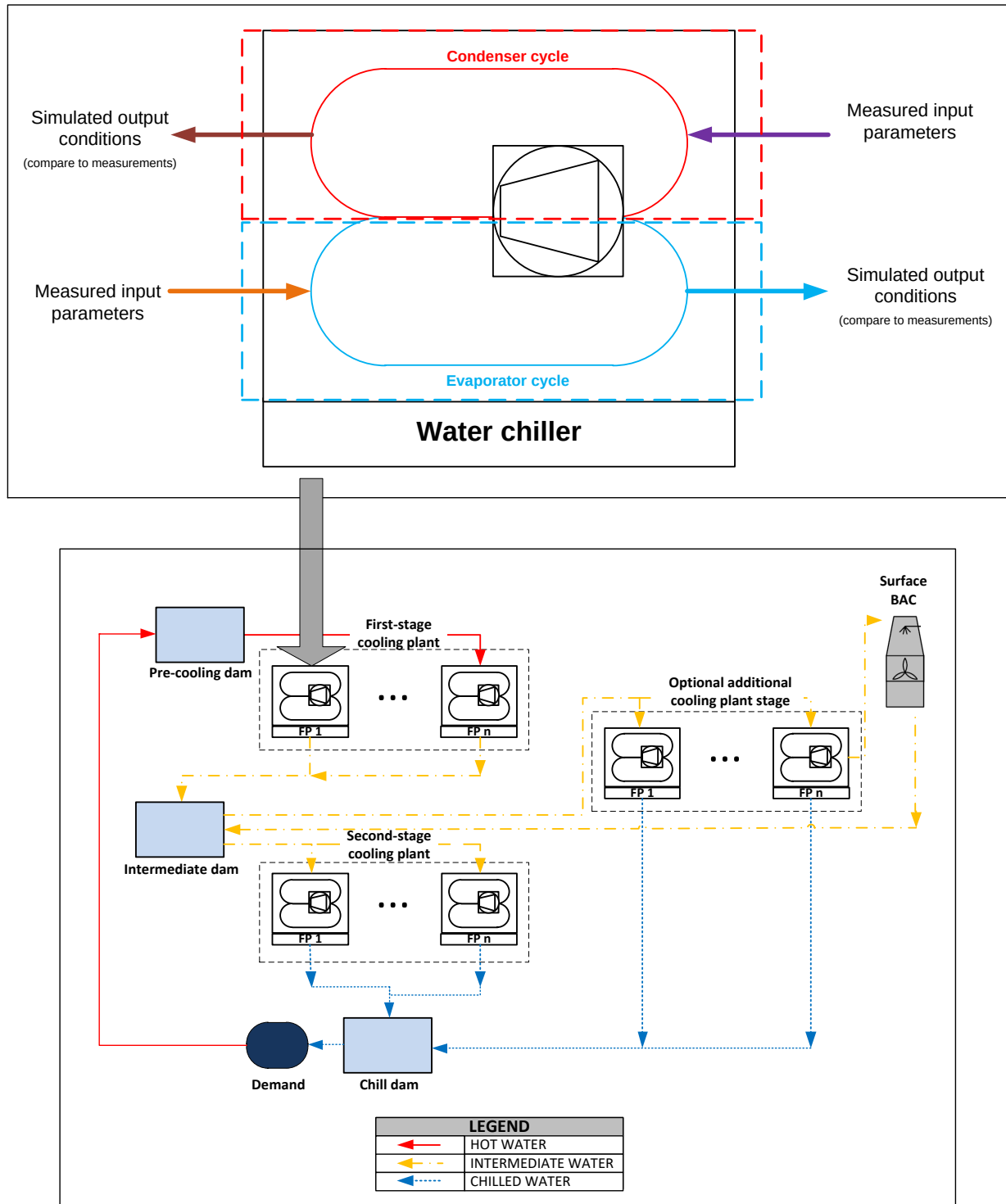


Figure 31: Isolating a water chiller for calibration in PTB

A water chiller can be calibrated by isolating it from the rest of the complex and integrated cooling system and specifying conditional boundaries for the input and output conditions, as shown in Figure 31. Thus, the condenser and evaporator cycle of the water chiller is calibrated by using the measured input parameters similar to the parameters needed in Table 13 and then comparing the simulated output conditions to the measured output conditions of that specific water chiller to determine whether it was calibrated correctly. As mentioned previously, for this study a deviation of less than 5% between the measured and simulated conditions needed to be met [45]. The same calibration process is then followed with all the components of the integrated and complex cooling system simulation.

It is important to note that the input air pressure boundary (barometric pressure, temperature, and relative humidity) and water pressure boundary (pressure and temperature) need to be dynamically calibrated by using the same number of periods as for the simulation as these are the inputs needed for the complex and integrated simulation model.

Once all the individual components have been calibrated and returned to the complex and integrated cooling system simulation model, the main integrated system needs to be calibrated. This is done by specifying the heat transfer that is going to be gained by the environment through the dams and pipes. According to existing research, heat transfer in the main integrated system can be neglected if the pipes and dams are insulated [19], [39].

Calibration of a ventilation system:

The same process followed to calibrate the complex and integrated cooling system simulation model was used to calibrate the ventilation system simulation model for this study. Figure 32 shows an example of the specific inputs needed in PTB for an air pressure boundary.

The **AirPressureBoundary** dialog box has a title bar with a close button. It features a **Name** field with the value "AirPressureBoundary" and a version number "7,3" in the top right corner. Below the name field are four tabs: **Inputs**, **Outputs**, **References**, and **Notes**. The **Inputs** tab is active, showing a list of input categories: **Specification** (highlighted), **Coordinate**, **Size**, **Orientation**, and **Offset**. To the right of this list is a **Properties** section with a table of parameters. Above the table are three buttons: **Calculate**, **Import...**, and **Export...**. At the bottom of the dialog are three buttons: **Accept**, **Cancel**, and **Help**.

Name	Unit	Initial
Pressure	kPa	...
Temperature	°C	...
Relative Humidity	%	...
Elevation	m	0.000
Reference Pressure	kPa	100.000
CO2	ppm	...

Figure 32: Air pressure boundary specification inputs in PTB

The PTB calculate function mentioned above can be used in this case too. [53]. Figure 33 shows an example of the inputs needed for an air pressure boundary on PTB when the calculate function is used.

The **AirPressureBoundary Calculator** dialog box has a title bar with a close button. It features a **Inputs** tab at the top left. Below the tab is a list of input categories: **Inputs** (highlighted). To the right of this list is a **Properties** section with a table of parameters. Above the table are three buttons: **Calculate**, **Import...**, and **Export...**. At the bottom of the dialog are two buttons: **Accept** and **Cancel**.

Name	Unit	Initial
Altitude	m	0.000

Figure 33: Air pressure boundary calculate function inputs in PTB

As mentioned earlier, the ventilation system simulation model does not include large extraction fans and is based on the principle of mass air balances and pressure differences. Table 16 shows a summary of the required information and data gathered during Step 1 and Step 2 of the method used as input specifications in a basic ventilation system PTB simulation model. Table 16 further shows the inputs needed when the calculate function on PTB is used.

Table 16: Component specifications used for ventilation calibration in PTB, adapted from [53]

Air pressure boundary						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Barometric pressure	kPa		Altitude	m		
Air inlet temperature	°C					
Air inlet relative humidity	%					
Air tunnel						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Flow area	m²		Days exposed	-		
Flow perimeter	m		Rock thermal conductivity	kW/m/°C		
			Rock density	kg/m³		
			Rock specific heat	kJ/kg/°C		

Table 16 can now be used to summarise the inputs needed for the specific components to be used to develop the ventilation system simulation. A transient system with the same number of time periods is used for the complex ventilation system simulation model. Each component in the ventilation system simulation model is removed and calibrated from the main ventilation system and returned to the main simulation model.

2.3.3.2 Verify integrated simulation model

After the calibration process has been followed, the verification of the complex and integrated cooling system simulation model and ventilation system simulation model must be done. This is where the simulation models are compared to real-life operations with a seasonal approach. Thus, the simulation models need to be verified for both summer and winter conditions. This determines how accurate the complex simulation models are compared to real-life operations.

According to existing research that was examined, simulation models can become very complex with many dynamic inputs and outputs and it is important to determine which conditions need to be verified to determine the accuracy of the complex and integrated simulation models [36]. For this study, it was recommended that the verification conditions of the simulation models be determined by using a KPI system. The KPIs used to determine the success and accuracy of the cooling system

simulation model were adapted from an existing study [34] and the need for the study as discussed in Section 1.5, and can be seen in Table 17.

Table 17: KPIs used for verification of cooling systems, adapted from [34]

Objective	Component	Measurement	Unit	Actual value	Simulated value	Percentage error	Coefficient
Performance	Cooling plant	Inlet water temperature	°C				
		Outlet water temperature	°C				
		Inlet/outlet water flow rate	L/s				
		Cooling duty	kW				
		Compressor power	kW				
	Chilled dam	Outlet water flow rate	L/s				
		Level	%				
		Temperature	°C				
	Surface BAC	Outlet air temperature	°C				
		Inlet water temperature	°C				
		Inlet water flow rate	L/s				
Reduced operating cost	Cooling system	Overall power consumption	kW				

A sensitivity analysis can be done to determine the uncertainties of the chosen KPIs shown in Table 17. Due to the need for the study, only the uncertainty for the overall power consumption of a cooling system will be analysed. Equation 1 and Equation 2 can be rewritten to form Equation 13 to determine the uncertainty of the overall power consumption of the cooling system:

$$P = \frac{\dot{m}_{water} C_{pw} (T_{out} - T_{in})}{COP} \quad (13)$$

As shown in Equation 13, the overall power consumption is linearly dependent on the water flow and difference in temperature. According to existing research, the measurement accuracy of a digital thermometer is 0.25% and 5% of the portable water flow meter respectively [18]. Thus, when considering Equation 13, it can be deduced that the overall power consumption KPI shown in Table 17, will have an uncertainty of 5%. This will also apply to an electricity reduction strategy that is implemented in different phases.

The KPIs used to determine the success and accuracy of the ventilation simulation model were adapted from an existing study [34] and the need for the study that is discussed in Section 1.5, and are given in Table 18.

Table 18: KPIs used for verification of ventilation systems, adapted from [34]

Objective	Component	Measurement	Unit	Actual value	Simulated value	Percentage error	Coefficient
Performance	Surface BAC	Air temperature (wet bulb)	°C				
		Mass airflow	kg/s				
	Underground: Ventilation system	Air temperature (wet bulb)	°C				
		Air temperature (dry bulb)	°C				
		Mass airflow	kg/s				

Thus, when considering Table 17 and Table 18, it is clear to see the reason why the KPIs of these components were chosen, as a need exists to holistically evaluate the effect of seasonal control on complex cooling plant configurations for deep mines. Table 17 and Table 18 can be further developed to account for both seasons that were being evaluated in this study. Some of the KPIs used in Table 17 and Table 18 were also used later to validate the success of the study after it was implemented.

As shown in Table 17 and Table 18, a coefficient between the actual value and the simulated value can also be used to determine the ratio between the actual and simulated value.

According to research, the percentage error of any specific parameter can be calculated by using Equation 14 [47]:

$$\% Error = \frac{1}{K} \sum_{k=1}^K \left| \frac{A_k - S_k}{A_k} \right| \times 100\% \quad (14)$$

where:

- $\% Error$ is the percentage error in %,
- K is the total number of data points,
- k is a specific data point,
- A_k is the actual measured data point, and
- S_k is the simulated data point.

Due to the dynamic execution of the simulation models, the average values over the specific time periods are compared to each other as shown in Table 17 and Table 18. The accuracy of the main simulation models is expected to be 95%, as previously mentioned [45]. In the verification process,

the actual parameters and the simulated parameters can also be compared to one another using a graphical representation as shown in Figure 34 [36].

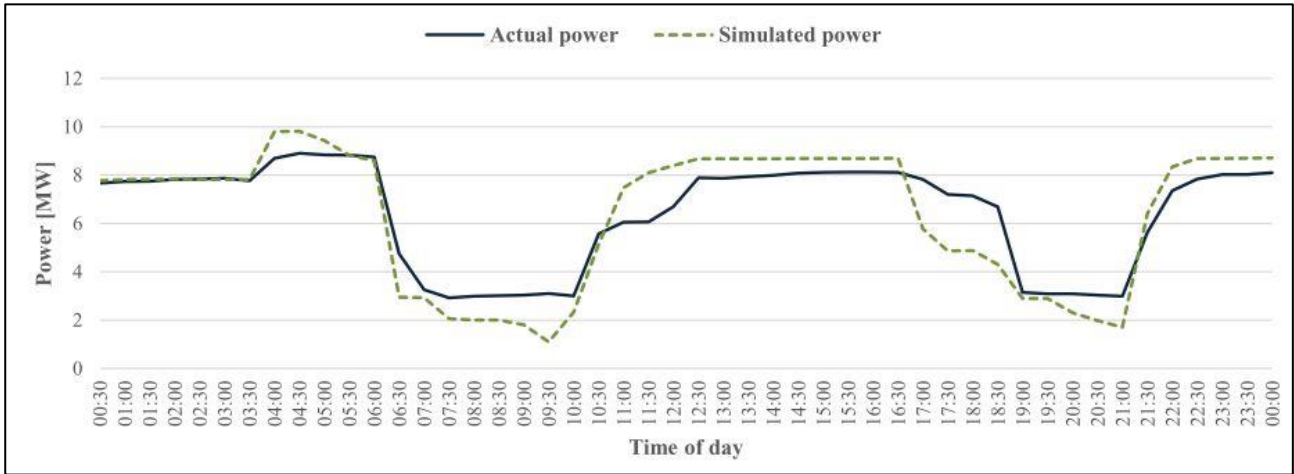


Figure 34: Example of simulated vs actual power consumption [36]

A percentage error of 1.17 % was achieved for the average power consumption in the example shown in Figure 34 [36].

2.3.4 Simulate strategies

During Step 4 of the developed method in this study, different strategies can be simulated, as real-life digital simulation models for complex and integrated cooling systems and ventilation system with high accuracy were developed. This step simulates different strategies to predict how the system might react [42], [45]. The holistic effect of the different strategies on the integrated and complex cooling system can also be shown. The benefit of simulating different strategies is that the effects can be seen instantaneously [40].

2.3.4.1 Identify different electricity savings strategies

Due to the large electricity tariff increases over the past 18 years, strategies must be developed to lower power consumption, while maintaining the same underground conditions in deep mines [5], [6], [12]. During this step, electricity saving strategies for different seasons must be identified, keeping the status quo underground. Existing saving strategies from research shown in Section 1.4 can be used to identify energy savings strategies for cooling systems for different seasons. It is also important to note whether capital expenditures are available to reduce the electricity cost or not [23], [35].

Existing research shows that different seasonal control strategies were implemented at case study mines, which are summarised below:

- Variable flow control on surface cooling plants on surface BACs [23], [29], [30], [36],
- Switch off surface BAC and cooling plants in cold ambient conditions [12], [30], [36],
- Recycling or bypass-looping of chilled water [34], and
- Peak-clipping initiative implemented on surface BAC [23].

The above-mentioned seasonal control saving strategies can be used and adapted to identify saving strategies for the desired case study mine.

It is further recommended that a phased electricity saving approach at deep mines with complex and integrated surface cooling plant configurations is used whenever seasonal control has not previously been implemented there. This will remove the uncertainty of the effect that the electricity saving strategy has on underground conditions and ensure that workers' safety is always considered [34].

2.3.4.2 Simulate different phases of electricity saving strategies

During this step of the method, different phases of electricity saving strategies developed in the previous step are simulated. PTB allows the different strategies to be simulated to determine the viability of that electricity saving strategy [19]. After all the different identified strategies have been simulated, the best-performing strategies in terms of electricity savings while maintaining the underground conditions can be determined. PTB can also be used to compile procedures on how the different strategies can be implemented (e.g. which valves should be opened and which pumps should be operational), as the same procedure will be presented when it is implemented at a deep mine [28].

2.3.5 Implement and validate

The implementation and validation step in the developed method determines the success of the study and the application of the method and this is where the actual electricity savings are achieved.

According to existing research, the implemented electricity saving projects that change the underground conditions of deep mines might have a risk of production loss and safety concerns [23]. Site-specific health and safety risk assessments must be completed before any tests or electricity saving projects are implemented to ensure that all possible risks related to the implementation are considered and mitigated, if possible [18]. The site-specific health and safety risk assessment can be obtained from the health and safety department of a deep mine [23].

Thorough procedures need to be compiled if a test of a saving initiative is done to ensure that the mine personnel knows exactly what to do and that the proposed initiative or test is implemented exactly as it should be [12], [31].

Due to the safety risks and production losses accompanying electricity saving initiatives, additional support to the simulation might be requested from the mine personnel, especially if it is a first-time electricity saving project on surface cooling systems [23]. The following tests, shown in Table 18, can be proposed and implemented to provide additional support to the simulation model. Note that research, however, also proved that the surface BAC does not assist the surface extraction fans with ventilation airflow and underground working conditions can be maintained during winter months when the surface BACs are switched off [23], [40].

Table 19: Supporting tests on first-time electricity saving projects on surface cooling systems

Possible question/ concern	Measurement	Proposed test description
Does the surface BAC assist the surface extraction fans with the ventilation air flow of the mine?	Static pressure measurements	Measure the static pressure of the surface extraction fans before and after the surface BAC fans are switched off. Measure the static pressure inside the surface extraction fans and the barometric pressure underground [24].
	Air flow measurements	Measure the airflow on all the underground intake levels of the main shaft barrel before and after the BAC fans are switched off [18], [24], [33].
Can the required underground working conditions be maintained in colder seasons if the surface BAC fans are switched off?	Temperature measurements	Install portable temperature loggers on underground levels where temperature problems are experienced and do spot measurements when the temperature loggers are exchanged [23].

The results obtained from the above-mentioned tests can then be presented to the mine personnel to provide additional support to the simulation model. Seasonal control is very dependent on ambient conditions and the installation of surface and underground weather stations and weekly weather forecast reports will ensure that the project runs smoothly [28].

2.3.5.1 Implement phased saving strategies

It is recommended that the same phased approach is used as in Step 4 of the method if seasonal control is implemented for the first time on a complex and integrated deep mine. After all the phases of the electricity savings strategies have been implemented, the results of the KPIs shown in Table 17 and Table 18 must be collected. These data are used to validate the success of the project.

2.3.5.2 Validate phased saving strategies

During this step of the method, the success of the project is determined. The actual savings achieved are compared to the simulated or proposed savings of the KPIs mentioned in Table 17 and Table 18.

To determine the actual impact of the implemented saving strategies, they need to be compared to a baseline power consumption profile [23], [55]. Research indicates that a baseline provides a reference point to be used and the electricity saving impact is calculated by subtracting the actual power consumption (after the saving strategy has been implemented) from the baseline power consumption [55]. Research further states that a baseline power consumption must be a true representation of what the power consumption would have been in the absence of any electricity saving implementations [55].

An appropriate baseline period from historic data needs to be selected for the impact of the implemented electricity savings to be determined [23]. Figure 35 shows an example from an existing study where a baseline power consumption was compared to the actual power consumption of a savings initiative for a seasonal control project [23].

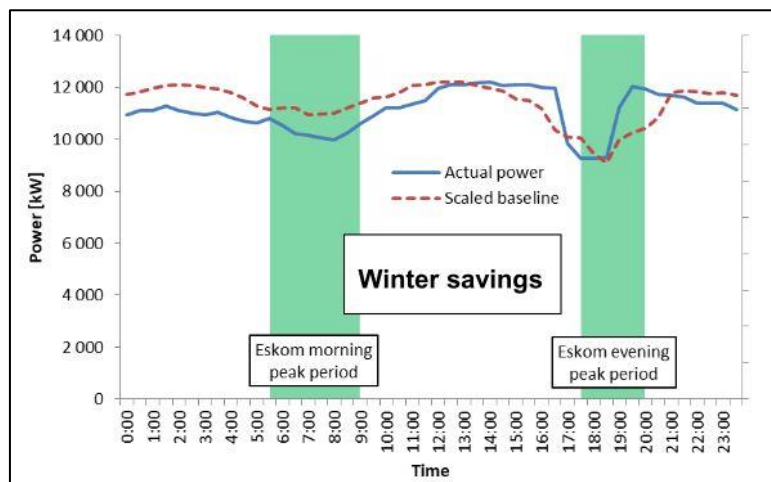


Figure 35: Example of a power consumption baseline vs actual power consumption of a saving initiative [23]

In this example, a power reduction of 6700 kWh was seen as shown in Figure 35 and it resulted in an average electricity cost reduction of ZAR 110 000 over that specific winter month [23].

2.3.6 Revise

After the electricity saving strategies have been implemented and validated, the developed method can be revised. An important question needs to be asked and that is whether the strategy can be

improved or not. If the electricity saving strategy can be improved, revert to Step 3 of the method. An improved strategy can usually be identified after a major change occurs in the surface cooling system configuration or the cooling requirements of a deep mine have changed [34]. Research also indicates that it is necessary to continuously revise the process to accommodate dynamic changes in the system [19]. It is, therefore, necessary to re-calibrate the surface cooling system simulation model and follow Steps 3, 4, and 5 whenever any system changes occur. If the saving strategy cannot be improved further, continue to implement the current electricity saving strategy.

2.4 Determining the impact of the study

Due to increased debt and a loss in the profitability of deep gold mines, the impact of this study needed to be determined [9], [10]. The impact of the study can be seen through the validation step of the method. The impact of the study further needed to be aligned with the objective of the study.

The impact of the study could therefore be established by assessing the results of the holistic evaluation of the surface cooling plant configurations for different seasons at deep mines that was done in this study. The results of the holistic evaluation done in this study needed to reduce the power consumption of the surface cooling systems and maintain the required underground conditions. The power consumption reduction typically equates to a monetary value which is especially expensive in the winter seasons, thus resulting in an operational cost saving [5].

2.5 Conclusion

Chapter 2 shows an in-depth holistic evaluation method that was developed and can be used on integrated surface cooling systems of a deep mine. This holistic evaluation can be done by applying the method that was developed as described in Chapter 2. This method can be applied to any surface two-stage cooling plant system with an additional optional cooling plant stage in a deep mine, as shown in Figure 20. The developed method consists of 5 steps and a revision step to ensure that the best possible electricity saving strategy is achieved.

This chapter also includes methods to collect and process data from surface cooling systems and ventilation systems. This ensures that the simulation models are accurate after the calibration step and represent the real-time operations of the surface cooling systems and ventilation system of a deep mine. This allows for different electricity saving strategies to be simulated without any changes made to the real-life cooling system of a deep mine. After the electricity saving strategies have been implemented in a phased approach, the impact of the study can also be determined by considering the results achieved from the implementation of the saving strategies.

CHAPTER 3 RESULTS AND DISCUSSION

3.1 Preamble

This chapter includes an example of where the developed method (Chapter 2) was applied to a complex and integrated surface cooling system case study mine that is similar to a two-stage cooling system with an additional optional cooling stage. Background information related to this study is described. The case study mine's surface cooling and ventilation system, as well as the effect that a phased seasonal electricity saving strategy had on the underground working conditions, was evaluated holistically. The results obtained from the simulation model of the applied method were compared to the real-life implementation results and the accuracy of the method was established. The impact of the study is also noted.

3.2 Case study background

When considering the case study research method shown in Figure 17, the next step is to select cases. For this study, only one case study was used. Mine A was identified as the case study mine to which the developed method as described in Chapter 2 would be applied. Mine A is a deep mine and is located in South Africa, with the deepest working level being at a depth of 3 700 m. Due to the extreme depth of this mine, high VRTs are experienced underground, which require a large cooling system [12]. Figure 36 shows a general level layout of mine A, which consists of the main shaft and a sub-shaft.

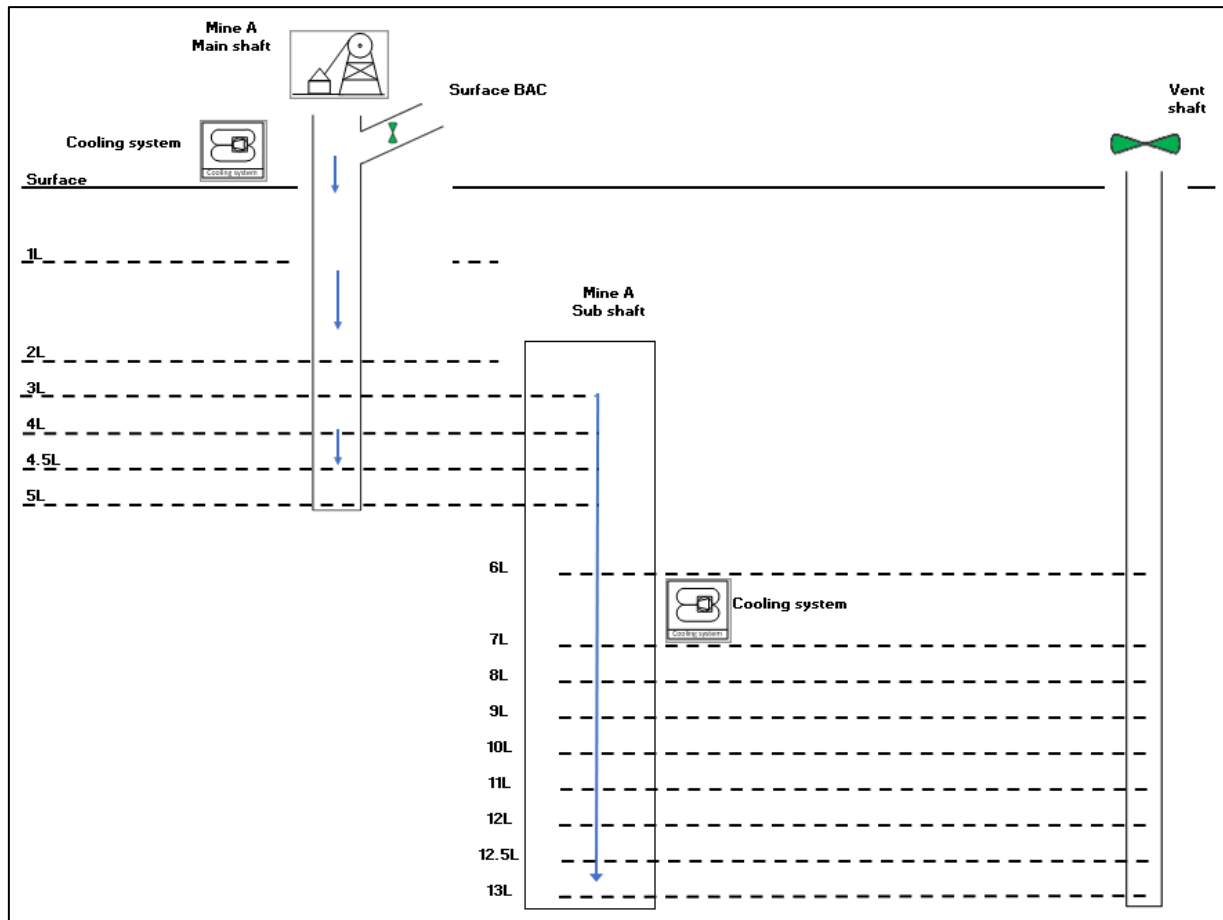


Figure 36: General level layout of Mine A

Mine A has 15 working levels (including 2 half-levels) with a surface BAC and cooling systems on surface and on Level 7 (L), as seen in Figure 36. Thus, the water is cooled on surface and then sent underground to be used for cooling and mining. Due to the extreme depth of mine A, the water is cooled once again before the lower levels use the water for cooling and mining. Mine A makes use of underground BACs, cooling cars, and ACUs to reduce the temperature of underground working areas.

In this study, a holistic evaluation of the surface cooling system of Mine A was done, and a general surface cooling layout is shown in Figure 37.

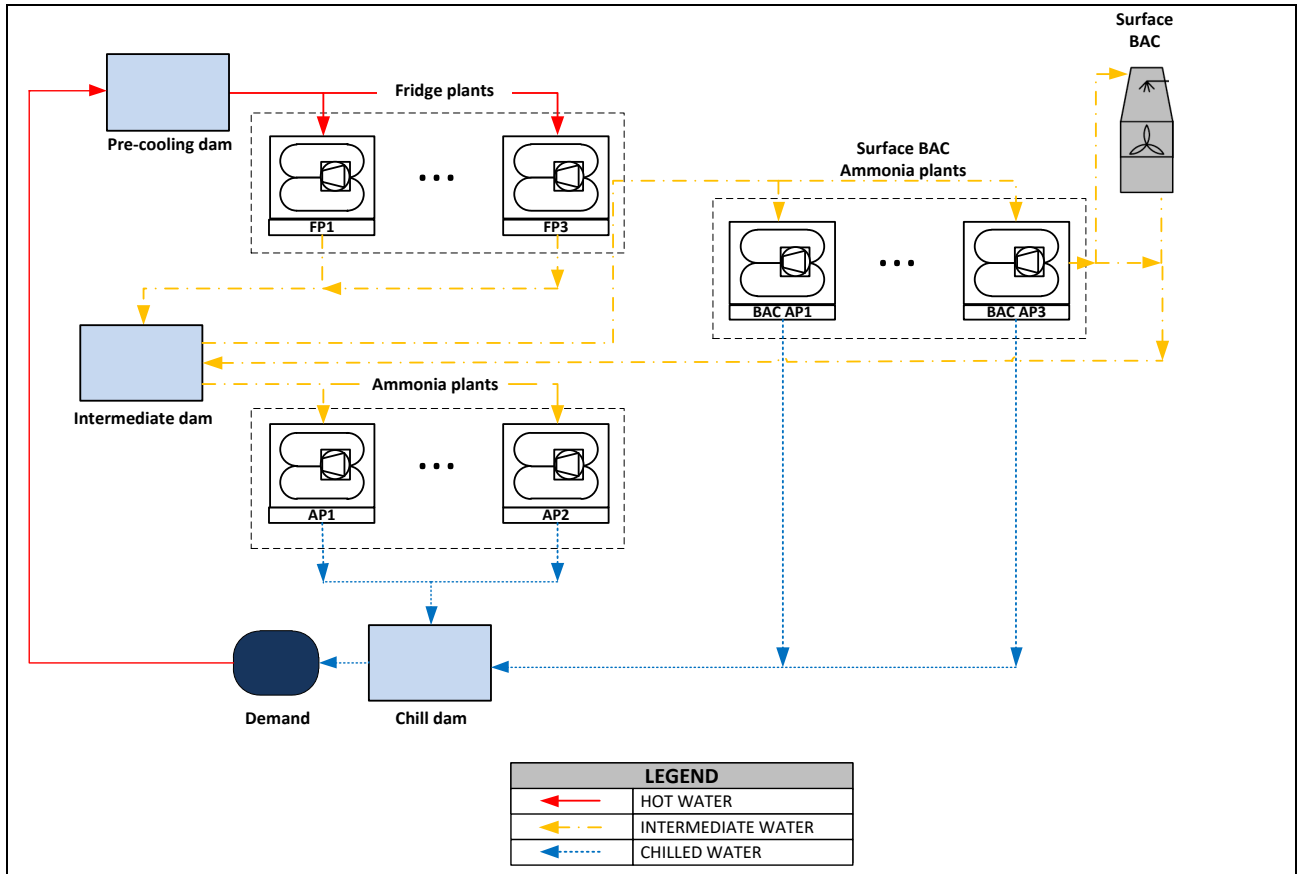


Figure 37: General surface cooling system layout of Mine A

The surface cooling system of Mine A consists of first-stage cooling plants, second-stage cooling plants and additional optional cooling plants which are three fridge plants (FPs), two ammonia plants (APs) and three surface BAC ammonia plants (BAC APs), respectively, as shown in Figure 37. When examining Figure 37, it can be seen that the hot water is pumped from underground into a hot dam. The hot mine water is pre-cooled through PCTs and pumped into the FPs to be cooled. The intermediate water is then pumped into the intermediate dam. The APs receive water from the intermediate dam and cool the water. The BAC APs recirculate the water from the intermediate dam by cooling the water, pumping it to the surface BAC and pumping it back to the intermediate dam.

Mine A's cooling system consists of a combination of an open-loop and semi-closed loop cooling system pipe configuration as described in Section 1.3.3. The cooling plant configurations of the three FPs are parallel and the two APs and the three BAC APs are in series. The cooling system of Mine A consists of eight cooling plants, a pre-cooling dam, an intermediate dam, a chill dam and a surface BAC, as seen in Figure 37. Mine A's pipe configuration enables the AP BAC plants to either supply the BAC, bypass the BAC and supply the intermediated dam, or supply the chill dam with water, as

seen in Figure 37. Due to Mine A having a large, complex and integrated cooling system, there was potential for electricity reduction strategies to be implemented on Mine A.

3.3 Investigation and simulation of case study mine

During the next step of the case study research method used for this study and shown in Figure 17, the developed method was implemented on the case study mine discussed in Section 3.2.

Site-specific investigation

A general site-specific investigation was conducted on the surface cooling system of Mine A. The investigation was conducted in 2019 with two skilled people over two days, working 8.5 hours per day. During this investigation, photographs of all the important cooling system equipment and machinery were taken. As the photographs were taken, notes were made and the photographs were labelled according to the notes that were made. Figure 38 shows an example of a photograph that was taken of the specification plate of one of the compressor motors used in the BAC AP.

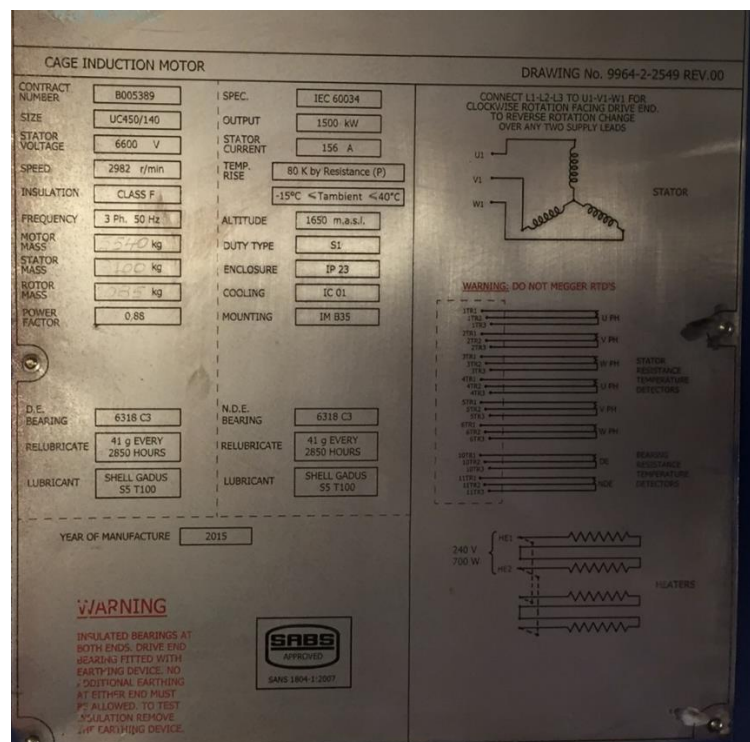


Figure 38: Photograph of the specification plate of a compressor motor of Mine A¹²

¹² J. Lodewyk, personal photograph. "Compressor motor specification plate", South Africa, 2019.

A pipe configuration layout of the surface cooling system was requested from the personnel of Mine A before the general site-specific investigation, but it was not available. During the general site-specific investigation, rough drawings of the complex and integrated pipe configuration of Mine A's complete cooling system were made. After the site-specific investigation, the complex and integrated pipe configuration layout was drawn using available computer software, as can be seen in Figure 39.

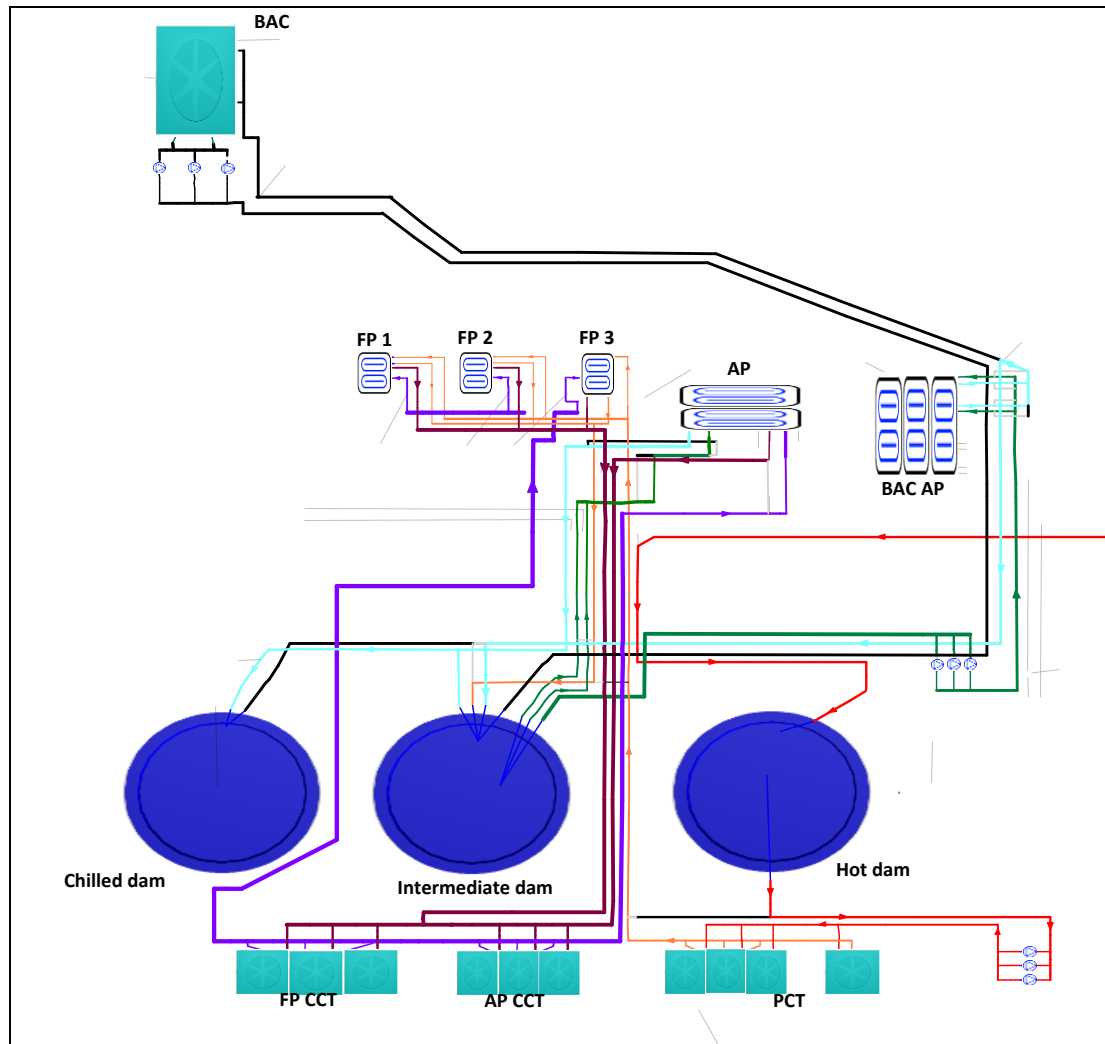


Figure 39: Complete pipe configuration layout of Mine A's surface cooling system

The pipe configuration layout was compiled using the same colour scheme as that used in the PFD view of PTB shown in Table 11. During the general site-specific investigation, it was noted that Mine A has pipe configurations available that enable the cooling plants to be reconfigured when maintenance is done. Table 3, Table 4 and Table 5 were completed during the investigation to ensure that all the high-level information was collected. The completed high-level inspection checklists can be seen in Table 20, Table 21 and Table 22.

Table 20: High-level Inspections done on the cooling plants and surface BAC plants of Mine A

General inspections- Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
SCADA historian data available?	✓	Some not available: Pumps, fans and valves	✓	Some not available: Pumps, fans and valves
PLC controlled or manually controlled?	✓	PLC controlled	✓	PLC controlled
Refrigerant used for specific cooling plants?	✓	FPS: R134a APs: Ammonia	✓	BAC APs: Ammonia
Current meters available on all equipment?	✓	Some analogue meters	✓	Some analogue meters
Voltage meters available on all equipment?	✓	Some analogue meters	✓	Some analogue meters
Level percentage sensor for the pre-cooling dam available?	✓		N/A	N/A
Level percentage sensor for the intermediate dam available?	✓			
Level percentage sensor for the chill dam available?	✓			
General inspections- Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Power consumption meters available?	✓	Feeder meters	✓	Feeder meters
Guide vane angle feedback of the compressor available?	✓		✓	
Air velocity sensor for the intake air of BAC available?	N/A		✗	
Barometric pressure sensor of ambient surface air available?			✗	
Temperature sensor inspections- Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Inlet evaporator temperature sensor available?	✓	FPS: Parallel APs: Series	✓	BAC APs: Series
Outlet evaporator temperature sensor available?	✓	FPS: Parallel APs: Series	✓	BAC APs: Series
Inlet condenser temperature sensor available?	✓	FPS: Parallel APs: Series	✓	BAC APs: Series
Outlet condenser temperature sensor available?	✓	FPS: Parallel APs: Series	✓	BAC APs: Series
Outlet pre-cooling system temperature sensor available?	✓		N/A	N/A
Intermediate dam temperature sensor available?	✓			
Hot dam temperature sensor available?	✓	Assume inlet PCT temperature		
Chill dam temperature sensor available?	✓			
BAC inlet water temperature sensor available?	N/A		✓	Assume outlet evaporator temp of BAC APs
Air inlet (ambient dry bulb) temperature sensor of BAC available?			✓	Questionable due to the location (directly in sun)
Air inlet (ambient wet bulb) temperature sensor of BAC available?			✗	
Air outlet (wet bulb) temperature sensor of BAC available?			✓	Assume 100% humid air
Temperature sensor inspections- Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Inlet pre-cooling system temperature sensor available?	✗		N/A	
BAC outlet water temperature sensor available?	N/A		✗	
Water flow rate inspections- Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Inlet evaporator flow rate available?	✓	FPS: Assume outlet evaporator flow APs: Assume outlet evaporator flow	✓	Assume outlet evaporator flow
Inlet condenser flow rate available?	✓	FPS: Assume outlet condenser flow APs: Not available	✗	Not available
Chilled water flow rate to underground demand available?	✓	2 pipe columns	N/A	
BAC water flow rate available?	N/A		✓	Assume outlet evaporator flow
Water flow rate inspections- Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Outlet evaporator flow rate available?	✓		✓	
Outlet condenser flow rate available?	✓	FPS: Assume outlet condenser flow APs: Not available	✗	

As seen in Table 20, some information was not available and thus needed to be accounted for through measurements. Table 21 shows the high-level inspections done on the infrastructure of Mine A's cooling system.

Table 21: High-level inspections done on infrastructure properties of Mine A's cooling system

Inspection of infrastructure properties of cooling system -Essential				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Number of cooling plants available and operational?	✓	FPs: 3 APs: 2	✓	BAC APs: 3
Number of evaporator pumps per cooling plant?	✓	FPs: 3 APs: 2	✓	BAC APs: 3
Number of condenser pumps per cooling plant?	✓	FPs: 3 APs: 2	✓	BAC APs: 3
Number of pre-cooling pumps?	✓	3 Pre-cooling pumps	N/A	
Pre-cooling pumps: motor and pump specification plate available?	✓	Photograph taken		
Number of BAC return water pumps?	N/A		✓	3 BAC return pumps
Return BAC pumps: motor and pump specification plate available?			✓	Analogue amp meter available
Evaporator pumps: motor and pump specification plate available?	✓	Photograph taken	✓	Analogue amp meter available
Condenser pumps: motor and pump specification plate available?	✓	Photograph taken	✓	Analogue amp meter available
Compressor: motor and compressor specification plate available?	✓	Photograph taken	✓	Photograph taken
Valve sizes and position of valves available?	✓	Photograph taken of main valves	✓	Photograph taken of main valves
Cladding on pipes?	✓		✓	
Bends on the evaporator and condenser pipes?	✓	Noted	✓	Noted
Constraints in the system (i.e., throttling of valves, broken pumps, leaks in the cooling system)?	✗		✗	
Capacity of hot dam?	✓		N/A	
Location of the pre-cooling tower (elevation difference)?	✓	+7m (FPs is zero point)		
Capacity of pre-cooling dam?	✓			
Number of pre-cooling towers?	✓	PCTs: 4		
Pre-cooling fans: motor and fan specification plate available?	✓	Analogue amp meter available		
Number of condenser towers?	✓	FPs: 3 APs: 3	✓	BAC APs: 2
Condenser fans: motor and fan specification plate available?	✓	Analogue amp meter available	✓	Analogue amp meter available
Location of evaporator pumps?	✓	Noted	✓	Noted
Location of condenser pumps?	✓	Noted	✓	Noted
Location of the intermediate dam (elevation difference)?	✓	+5m (FPs is zero point)	N/A	
Capacity of the intermediate dam?	✓			
Location of the chill dam (elevation difference)?	✓	+5m (FPs is zero point)		
Capacity of the chill dam?	✓			
Location of the surface BAC?	N/A		✓	Noted
Number of BAC fans?			✓	2
BAC fans: motor and fan specification plate available?			✓	Analogue amp meter available
Pipe sizes and lengths for the evaporator circuit available?	✓	Noted	✓	Noted
Pipe sizes and lengths for the condenser circuit available?	✓	Noted	✓	Noted
Pipe sizes and lengths between the intermediate dam and chill dam available?	✓	Noted	N/A	
Pipe sizes and lengths for the surface BAC available?	N/A		✓	Noted
Infrastructure properties of cooling system-Desirable				
	Cooling plant	Comments/ Deviations	Surface BAC cooling plant	Comments/ Deviations
Location of cooling plants (inside a building/ outside)?	✓	Inside	✓	Inside

As seen in Table 21, all of the infrastructure information was available, while some of the information that needed to be calculated. Table 22 shows the high-level inspections done on the ventilation system of Mine A.

Table 22: High-level inspections done on the ventilation system of Mine A

General inspections- Essential		
	Surface Ventilation	Comments/ Deviations
PLC historian data available?	✓	
PLC controlled or manually controlled?	✓	
Current meters available on all equipment?	✓	
Voltage meters available on all equipment?	✓	
Frequency meters for ventilation fan motors available?	✓	
Air velocity sensor of surface ambient air?	X	
Air velocity sensor of underground ambient air?	X	
Deep mine ventilation layouts and elevations available?	✓	
General inspections- Desirable		
	Surface Ventilation	Comments/ Deviations
Power consumption meters available?	✓	Feeder meters
Barometric pressure sensor of the fan available?	X	
Barometric pressure sensor of the underground working area?	X	
Temperature sensor inspections- Essential		
	Surface Ventilation	Comments/ Deviations
Air (ambient underground dry bulb) temperature sensor available?	✓	
Air (ambient underground) relative humidity sensor available?	X	

As seen in Table 22, a large amount of information was not available and thus needed to be obtained through measurements.

Simulation model – data collection and processing

All the information that was collected from the general site-specific investigation was used to build an accurate, complex and integrated cooling system simulation model and an accurate ventilation system simulation model for Mine A. As stated in Chapter 2, it was decided that, for this study, PTB was used as the simulation software package as it met all the criteria for this study.

For Mine A, it was beneficial that low-level data could be collected and used to develop the simulation models due to the good accuracy that could be achieved. It is important to note that Mine A has access to a relatively large SCADA system that monitors and controls a certain section of the surface cooling system. Thus, as far as possible, low-level data was used for the case study Mine A.

The complexity and size of the cooling system, shown in Figure 39, results in large amounts of data and tags that are connected to it. Therefore, Table 42 in Annexure A shows a list of all the tag names and practical measurements that needed to be collected on the integrated and complex surface cooling system of Mine A for the simulation model to be built. The tag names were shortened to protect the confidentiality of the case study Mine A. Comments were also made on which practical measurements needed to be made on specific equipment and machinery to collect the data.

The same approach that was followed for the cooling system of Mine A was followed for the ventilation system of Mine A and a list of SCADA tags and practical measurements that were required was compiled and can be seen in Table 43 of Annexure A.

The raw data for the SCADA tags which are listed in Table 42 and Table 43 were collected for seasonal periods in 2018 and 2019. Due to faulty instrumentation which led to data invalidity and poor data quality, the required practical measurements were taken from 2019 onwards.

Once all the data had been gathered and plotted for the integrated and complex cooling system, the quality of the data was evaluated by implementing the data quality method discussed in Section 2.3.2. After the data quality method had been implemented, the data validation process discussed in Section 2.3.2 was implemented on the data. As seen in Table 42 and Table 43, Mine A does not have all the smart measuring instrumentation available that was required for this study and some of the parameters needed to be calculated by using some measuring instrumentation that is connected to the SCADA or data from practical measurements. Equations 1 to 12 shown in Section 2.3.2 were then used to calculate the specific parameters that were required in the calibration step of the method for this study.

Building integrated simulation model

Due to the complexity of Mine A, the basic cooling plant and ventilation system PTB simulation model shown in Figure 27 and Figure 28 of Section 2.3.2 needed to be expanded for the cooling simulation model to be similar to the pipe configuration layout seen in Figure 39. The expanded ventilation model had to also include the underground working levels. A complex and integrated cooling system simulation model of Mine A was built and the PFD view in PTB can be seen in Figure 40.

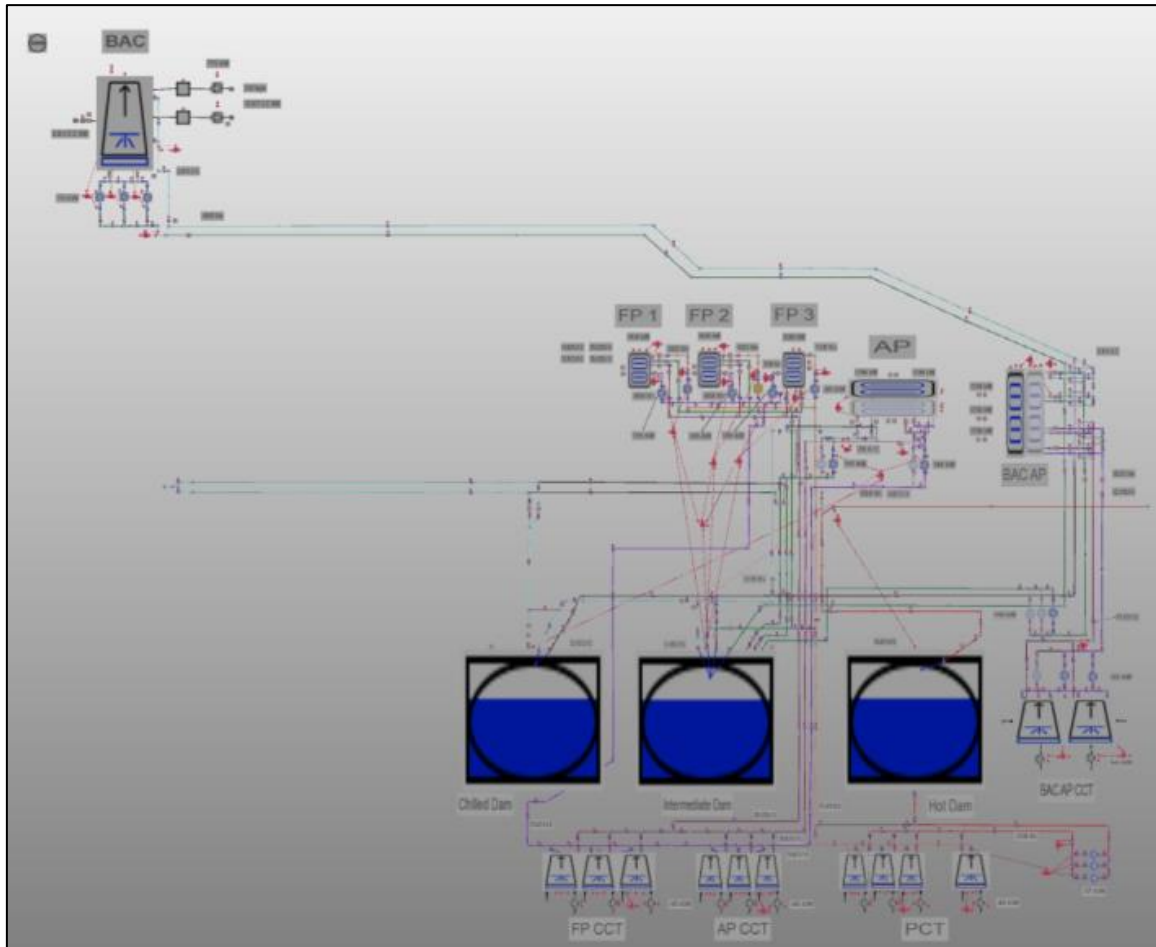


Figure 40: Complex and integrated cooling system simulation model of Mine A

The complexity of the cooling system simulation model of Mine A can be seen through a snapshot of an enlarged section of the cooling plants and their configurations as shown in Figure 41.

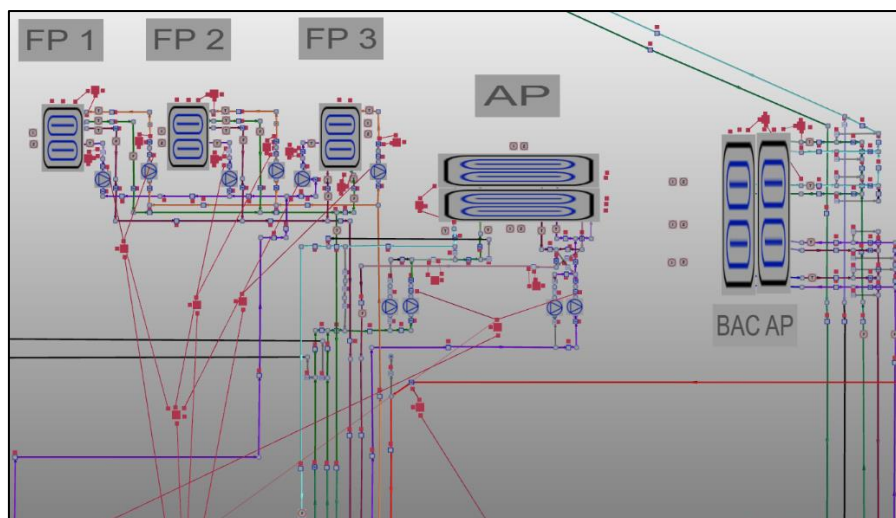


Figure 41: Enlarged complex and integrated cooling system simulation model of Mine A

As seen in Figure 40 and Figure 41, the complex and integrated cooling system simulation model was a digital blueprint of the surface cooling system of Mine A. This simulation model included the appropriate elevations in the different sections of the cooling system. The same approach was followed for the ventilation simulation model and the expanded ventilation system simulation model can be seen in Figure 42.



Figure 42: Expanded ventilation system simulation model for Mine A

Figure 43 shows a snapshot of the underground working section (2L and Main shaft) in the ventilation system simulation model for Mine A.

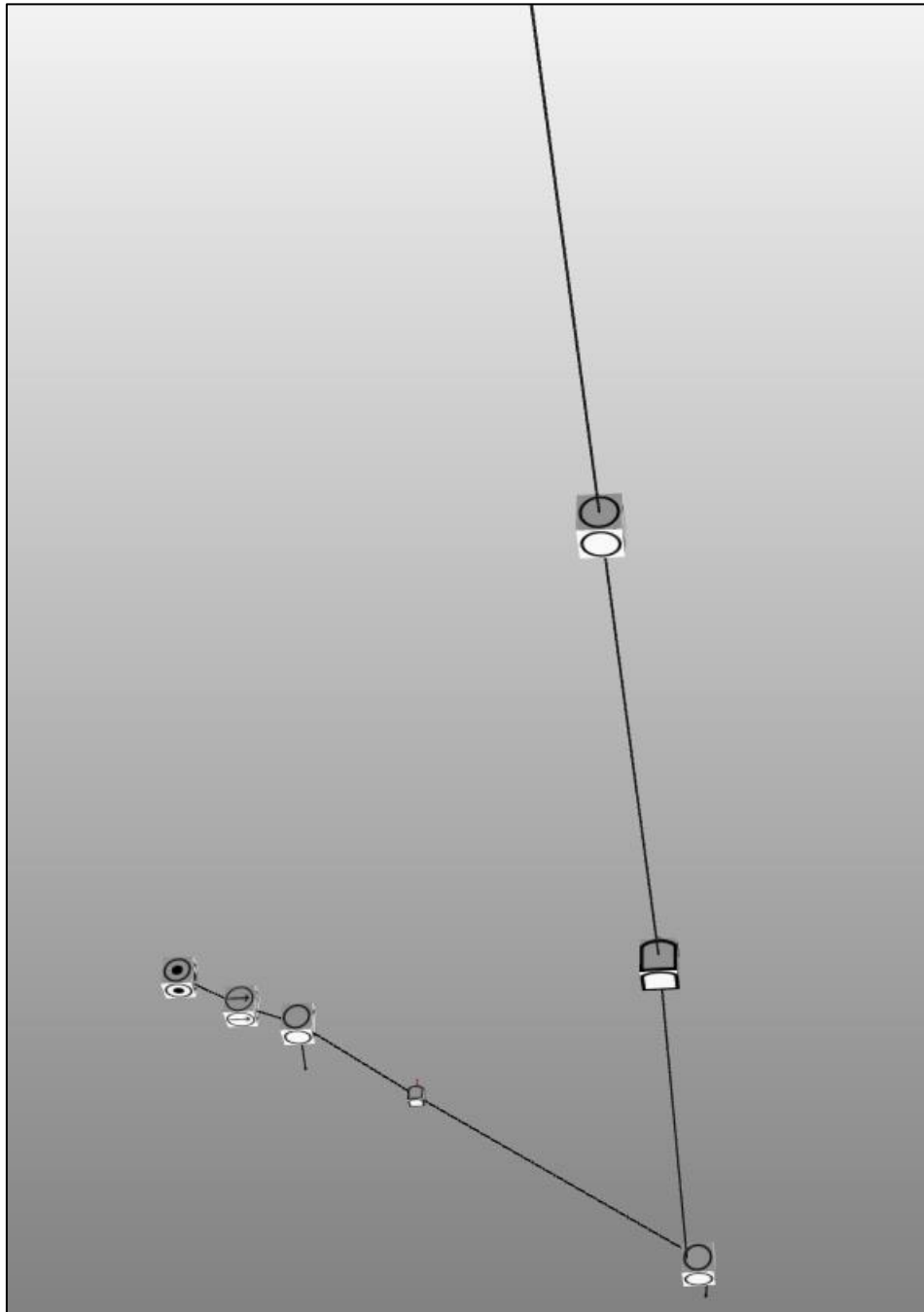


Figure 43: Enlarged section of underground working area in ventilation simulation model for Mine A

When considering the expanded ventilation system simulation model for Mine A, shown in Figure 42 and Figure 43, it can be seen that a digital blueprint of the ventilation system for Mine A was built, which also included the underground working level depths.

Simulation model – calibration and verification

After the expanded simulation models were developed for both the integrated and complex cooling system and ventilation system of Mine A, the simulation models had to be calibrated and verified to ensure that the simulation models had an accuracy of 95%, as this would ensure that the simulation models could be compared to the real-life operations of Mine A [45]. The same transient time intervals described in Section 2.3.3 were used for both the simulation models due to the holistic evaluation that was being done on the surface cooling system and ventilation system of Mine A.

The complex and integrated cooling system of Mine A was calibrated by following the method discussed in Section 2.3.3, where each of the components was removed, isolated and calibrated, and then returned to the complex and integrated cooling system simulation model. Table 23 shows an example of one cooling plant component's input specifications for Mine A that was required to do the calibration of the cooling system. The whole complex and integrated cooling system of Mine A was calibrated by using the same approach.

Table 23: Component specifications used for cooling system calibration of Mine A

FP1 cooling plant							
PTB input requirements			PTB calculate function input requirements			Notes	
	Unit	Value		Unit	Value		
PI controller	-	4	Inlet evaporator temperature	°C	Not needed		
Refrigerant used	-	R134a	Outlet evaporator temperature	°C			
Cooling capacity	kW	5900	Evaporator water flow rate	L/s			
COP	-	5.7	Inlet condenser temperature	°C			
Inlet evaporator temperature	°C	20.5	Outlet condenser temperature	°C			
Outlet evaporator temperature	°C	7.5	Compressor motor power	kW			
Inlet condenser temperature	°C	25					
Outlet condenser temperature	°C	29					
Evaporator water pump							
PTB input requirements			PTB calculate function input requirements			Notes	
	Unit	Value		Unit	Value		
Pump curve (pressures)	kPa	Not needed	Pump motor power	kW	43		
Pump curve (flows)	L/s		Pump flow	L/s	105		
Pump efficiency rating	%		Pump efficiency rating	%	0.9		
Motor efficiency rating	%		Motor efficiency rating	%	0.94		
Condenser water pump							
PTB input requirements			PTB calculate function input requirements			Notes	
	Unit	Value		Unit	Value		
Pump curve (pressures)	kPa	Not needed	Pump motor power	kW	155		
Pump curve (flows)	L/s		Pump flow	L/s	400		
Pump efficiency rating	%		Pump efficiency rating	%	0.75		
Motor efficiency rating	%		Motor efficiency rating	%	0.94		
Chill dam							
PTB input requirements			PTB calculate function input requirements			Notes	
	Unit	Value		Unit	Value		
Barometric pressure	kPa	84	Inlet temperature	°C	Not needed		
Dam temperature	°C	3.1	Outlet temperature	°C			
Dam volume	m³	5000	Flow rate	kg/s			
Dam level	%	70					
FP1 CCT1							
PTB input requirements			PTB calculate function input requirements			Notes	
	Unit	Value		Unit	Value		
UA	kW/kJ/kg	130	Barometric pressure	kPa	Not needed		
Water flow rate	L/s	271	Water inlet temperature	°C			
Air flow rate	kg/s	271	Water outlet temperature	°C			
			Water flow rate	L/s			
			Air inlet temperature	°C			
			Air inlet relative humidity	%			
			Air flow rate	kg/s			
FP1 CCT1 air fan							
PTB input requirements			PTB calculate function input requirements			Notes	
	Unit	Value		Unit	Value		
Fan curve (pressures)	kPa	Not needed	Fan motor power	kW	39		
Fan curve (flows)	m³/s		Fan flow	kg/s	300		
Fan efficiency rating	%		Fan efficiency rating	%	0.65		
Motor efficiency rating	%		Motor efficiency rating	%	0.94		
Inlet air density	kg/ m³		Fan inlet pressure	kPa	84		
			Fan inlet temperature	°C	19		

The data that were collected, processed and validated were used to provide the simulation values with input specifications for the different machinery as shown in Table 23. The data for a large

number of tags were used either in the PTB input requirements window or the PTB calculate function input requirements, depending on what data were available, as seen in Table 23.

The input air pressure boundary, which included barometric pressure, temperature and relative humidity, as well as the water pressure boundary, which included pressure and temperature, were used as input specifications in the complex and integrated cooling system of Mine A. It is important to note that the same number of periods (192 time periods) were used for the input specifications of the air pressure and water pressure boundaries.

For this case study, it was not necessary to calibrate the main integrated cooling system of Mine A after all the individual components were calibrated, as the pipes of the cooling system were insulated and the heat transfer gained by the environment could thus be neglected [19], [39].

The same method was used as with the cooling system, where an individual component was removed from the main ventilation system, calibrated and then returned to the main system to calibrate the ventilation system simulation model of Mine A, also using the same number of time periods (192 time periods) to do a dynamic transient evaluation of the ventilation system. An example of the specific input specifications for the different components used in the ventilation system simulation model to do the calibration is shown in Table 24.

Table 24: Component specifications used for ventilation system calibration of Mine A

Surface extraction - air pressure boundary						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Barometric pressure	kPa	84	Altitude	m	Not needed	
Air inlet temperature	°C	19.3				Average summer temperature over the specified time period
Air inlet relative humidity	%	71.0				Average summer RH over the specified time period
Surface extraction - air tunnel						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Flow area	m²	26	Days exposed	-	Not needed	
Flow perimeter	m	30	Rock thermal conductivity	kW/m/°C		
			Rock density	kg/m³		
			Rock specific heat	kJ/kg/°C		
Surface BAC - air pressure boundary						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Barometric pressure	kPa	84.25	Altitude	m	Not needed	
Air inlet temperature	°C	6.9				Average summer temperature over the specified time period
Air inlet relative humidity	%	100.0				Assume 100% RH due to saturated air from spray BAC
Surface BAC - air tunnel						
PTB input requirements			PTB calculate function input requirements			Notes
	Unit	Value		Unit	Value	
Flow area	m²	18	Days exposed	-	Not needed	
Flow perimeter	m	17.5	Rock thermal conductivity	kW/m/°C		
			Rock density	kg/m³		
			Rock specific heat	kJ/kg/°C		

The method that was developed to holistically evaluate the effect that seasonal control on complex and integrated cooling systems has on underground working conditions makes use of a collaboration between the surface cooling system simulation model and the ventilation system simulation model. The simulated outlet air temperature that the BAC delivers is used as an input value for the air pressure boundary of the BAC section of the ventilation system simulation model. The whole ventilation system was calibrated by following the same approach. The data of the tags and practical measurements were used in the PTB input requirements window. For this case study, it was not necessary to use the PTB calculate function input requirements, as seen in Table 24.

After the calibration process, both the integrated cooling system and the ventilation system of Mine A were verified by comparing the simulation models to real-life operations for the different seasons. According to research, a deviation of 5% between the simulation model and the real-life operations is deemed acceptable [45]. Table 25 shows the verification results of the integrated and complex

surface cooling system of Mine A during summer conditions. Note that the simulation model accounted for a dynamic and transient approach, but due to the number of data points that had to be compared, Table 25 only shows a simplified comparison with the average values over the summer period for both the actual measurements and the simulation model.

Table 25: Average values of verification KPIs used for Mine A's cooling system in summer

Objective	Component	Measurement	Unit	Actual value	Simulated value	Percentage error [%]	Coefficient
Performance	FP1	Inlet water temperature	°C	20.6	20.7	0.16	1.00
		Outlet water temperature	°C	7.8	8.2	4.81	0.95
		Inlet/ outlet water flow rate	L/s	99.0	94.5	4.56	1.05
		Cooling duty	kW	5079.8	4941.0	2.73	1.03
		Compressor power	kW	893.5	859.3	3.82	1.05
	Chilled dam	Outlet water flow rate	L/s	267.3	269.8	0.96	0.99
		Level	%	77.9	78.3	0.52	0.99
		Temperature	°C	2.4	2.4	0.17	1.00
	Surface BAC	Outlet air temperature	°C	6.9	7.1	2.92	0.97
		Inlet water temperature	°C	2.0	1.9	2.51	1.03
		Inlet water flow rate	L/s	407.0	404.1	0.70	1.01
Reduced operating cost	Cooling system	Overall power consumption	kW	8465.4	8667.8	2.39	0.99

When comparing the integrated and complex cooling system simulation model with the real-life operations of Mine A, it can be seen that the simulation model was very accurate, as shown in Table 25. The overall power consumption of the entire cooling simulation model differed by 2.39 % when compared to real-life operations. The same verification process was also followed for the rest of the components in the cooling system during the summer period, maintaining an accuracy of 95% or above. Table 26 shows the simplified verification results of the integrated and complex surface cooling system of Mine A during the winter period. The average simulated values over the winter period were compared with the average actual values over the same period for simplicity.

Table 26: Average values of verification KPIs used for Mine A's cooling system in winter

Objective	Component	Measurement	Unit	Actual value	Simulated value	Percentage error [%]	Coefficient
Performance	FP1	Inlet water temperature	°C	19.9	20.4	2.5	0.97
		Outlet water temperature	°C	8.1	8.2	1.3	0.96
		Inlet/ outlet water flow rate	L/s	97.4	96.4	1.0	1.03
		Cooling duty	kW	4634.1	4836.6	4.4	0.99
		Compressor power	kW	883.7	861.9	2.5	0.99
	Chilled dam	Outlet water flow rate	L/s	269.1	268.1	0.4	1.00
		Level	%	77.7	78.9	1.6	0.99
		Temperature	°C	2.2	2.2	2.7	1.02
	Surface BAC	Outlet air temperature	°C	4.5	4.6	2.0	0.92
		Inlet water temperature	°C	2.0	1.9	0.6	0.94
		Inlet water flow rate	L/s	413.7	404.1	2.3	1.02
Reduced operating cost	Cooling system	Overall power consumption	kW	6471.4	6500.6	0.5	1.01

Table 26 shows the accuracy of the complex cooling system simulation model compared to the real-life operations during the winter period. When comparing the integrated and complex system simulation model with the real-life operations of Mine A, it can be seen that the accuracy of the simulation model is within the desired range of deviation. The overall power consumption of the entire cooling simulation model differed by 0.5 % when compared to real-life operations during the winter period. The same verification process was also followed for the rest of the components in the cooling system during the winter period, maintaining an accuracy of 95% or above.

For the verification of the ventilation system of Mine A, the same approach and the same number of time periods as for the complex surface cooling system were applied for the summer period and can be seen in Table 27.

Table 27: Average values of verification KPIs used for Mine A's ventilation system in summer

Objective	Component	Measurement	Unit	Actual value	Simulated value	Percentage error [%]	Coefficient
Performance	Surface BAC	Air temperature (wet bulb)	°C	7.1	6.9	2.2	1.02
		Mass airflow	kg/s	342.0	354.8	3.8	0.96
	Underground: Ventilation system 2L	Air temperature (wet bulb)	°C	20.5	21.2	3.5	0.97
		Air temperature (dry bulb)	°C	26.5	26.8	1.3	0.99
		Mass airflow	kg/s	167.6	162.4	3.1	1.03
	Underground: Ventilation system 12L	Air temperature (wet bulb)	°C	26.5	27.4	3.2	0.97
		Air temperature (dry bulb)	°C	34.6	33.8	2.5	1.03
		Mass airflow	kg/s	145.0	141.1	2.7	1.03

As seen in Table 27, the accuracy of the ventilation simulation model of Mine A in the summer was within the desired range of deviation. The same approach was followed to calibrate the rest of the underground levels during the summer period. Table 28 shows the verification for the ventilation simulation model during the winter period.

Table 28: Average values of verification KPIs used for Mine A's ventilation system in winter

Objective	Component	Measurement	Unit	Actual value	Simulated value	Percentage error [%]	Coefficient
Performance	Surface BAC	Air temperature (wet bulb)	°C	4.5	4.6	2.0	0.98
		Mass airflow	kg/s	342.0	353.9	3.5	0.97
	Underground: Ventilation system 2L	Air temperature (wet bulb)	°C	17.5	18.2	4.0	0.96
		Air temperature (dry bulb)	°C	24.0	24.8	3.4	0.97
		Mass airflow	kg/s	167.6	161.7	3.5	1.04
	Underground: Ventilation system 12L	Air temperature (wet bulb)	°C	23.5	24.4	3.8	0.96
		Air temperature (dry bulb)	°C	31.4	32.5	3.6	0.97
		Mass airflow	kg/s	145.0	141.1	2.7	1.03

The ventilation simulation model of Mine A was within the range of deviation when comparing the real-life conditions and the simulation model, as seen in Table 28. The same verification process

was also followed for the rest of the components in the ventilation system during the winter period, maintaining an accuracy of 95% or above.

The simulated power consumption can also be compared to the actual power consumption in a graphical illustration, as mentioned in Section 2.3.3. Figure 44 shows the transient simulated power consumption compared to the actual power consumption of the complex cooling system of Mine A for the summer period. The simulated power consumption is represented by a dashed green line and the actual power consumption is represented by a solid blue line.

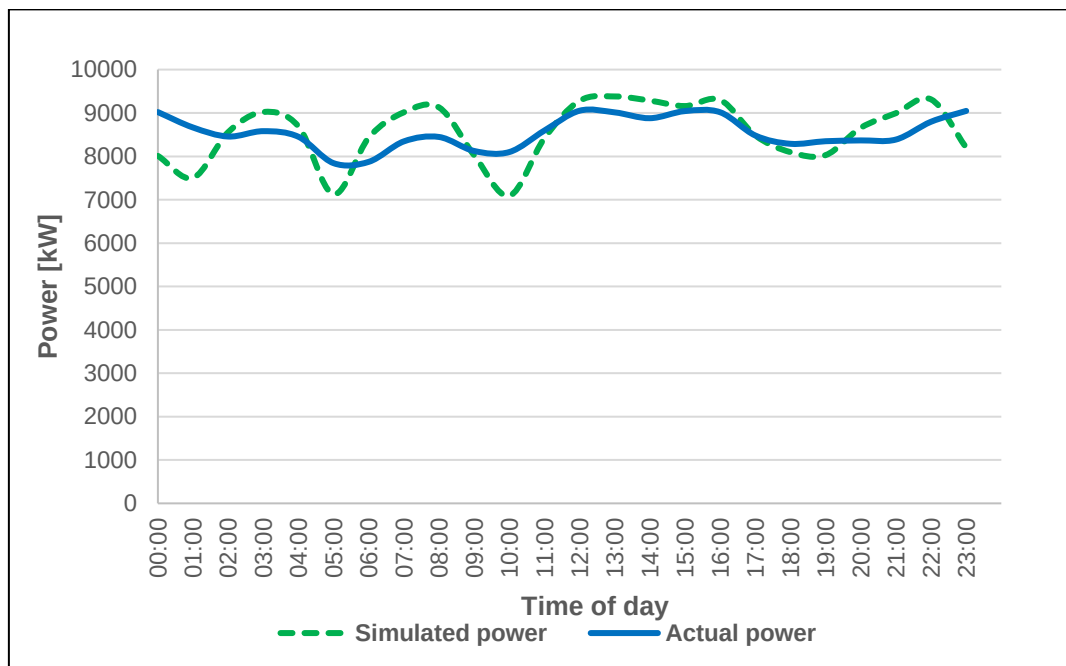


Figure 44: Simulated vs actual power consumption for the surface cooling system of Mine A in summer

As shown in Figure 44, the 24-hour simulated power consumption profile correlates with the actual power consumption with a percentage error of 5.39 % for the dynamic transient response. The reason for the deviation is that the simulation model of the complex and integrated cooling system reacted too aggressively during the mornings of the summer periods and behaved better during the afternoon and evening periods. Mine A experiences fluctuations in water demands due to varying daily mining activities that occur during the mornings of the summer period. The deviation can be improved by continuing with the tedious process to calibrate the complex and integrated cooling simulation model.

Figure 45 shows the transient simulated power consumption compared to the actual power consumption of the complex cooling system of Mine A for the winter period. The simulated power

consumption is represented by a dashed green line and the actual power consumption is represented by a solid blue line.

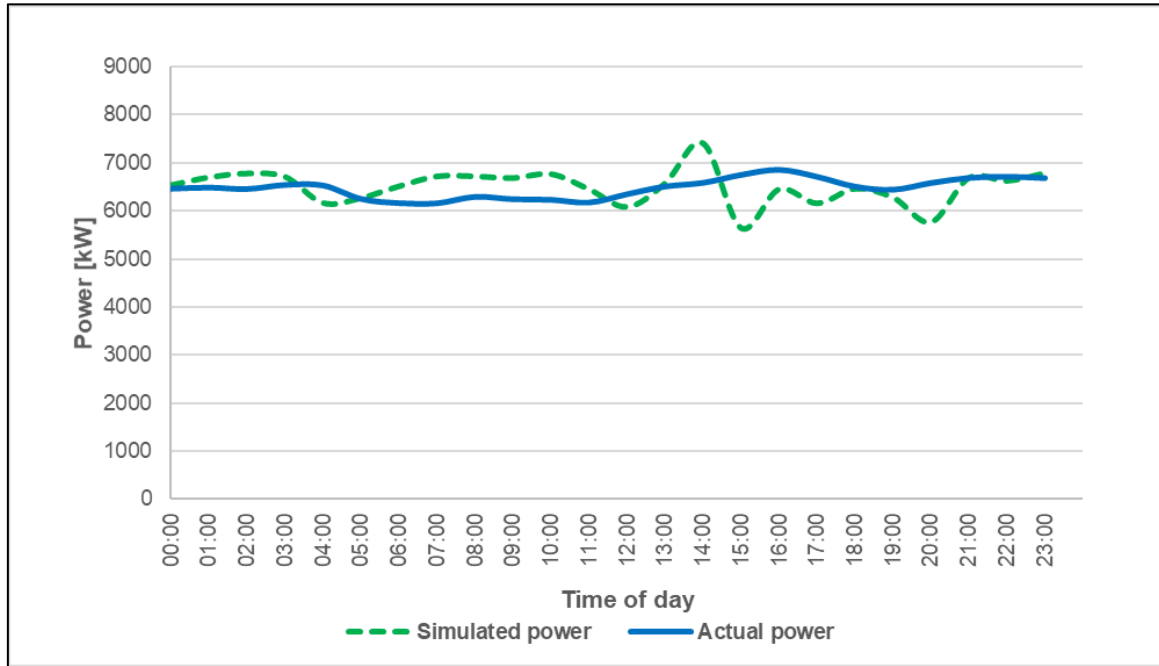


Figure 45: Simulated vs actual power consumption for the surface cooling system of Mine A in winter

Figure 45 shows the 24-hour simulated power consumption profile compared to the actual power consumption with a percentage error of 5.38 %. The deviation is due to the complex and integrated cooling system simulation model that is reacting too aggressively to small cooling demand fluctuations during certain periods in the winter. Mine A experiences fluctuations in cooling demands due to varying daily ambient conditions that affect the required cooling during the afternoons in the winter [19], [26]. The deviation can be improved by continuing with the tedious process to calibrate the complex and integrated cooling simulation model.

Therefore, it can be seen that the simulation models for both the complex and integrated surface cooling system and the ventilation system of Mine A for both summer and winter periods were calibrated and verified within an acceptable deviation range, as expected.

3.4 Simulation strategy results

During this step in the developed method, different electricity saving initiatives for different seasons were identified and investigated by using the calibrated complex cooling system simulation model of Mine A. Mine A had not previously implemented seasonal control electricity saving initiatives and it was decided to implement the identified electricity saving initiatives in a phased approach due to the uncertainty of the effect that the initiative could have on the health and safety of the underground

mining employees. After investigating the different saving initiatives that were identified for the complex and integrated cooling system of Mine A, the best initiative was chosen and the phased approach was divided into three sections to further ensure that the initiatives were implemented in a controlled manner.

During the development of the cooling system simulation model, it was seen that Mine A has pipe configurations on the different cooling plants that can be reconfigured to provide cooling when maintenance is done on cooling plants.

From the complex and integrated cooling simulation and ventilation simulation model that was developed for Mine A, it was seen that the average wet bulb temperature of the mixed air going down the main shaft of Mine A during the summer period was 10.6 °C, as can be seen in Table 29.

Table 29: Average summer wet bulb temperature of mixed air going down Main shaft of Mine A

Description	Average summer conditions	
	Simulated wet bulb air temperature [°C]	Simulated airflow [kg/s]
Surface BAC	6.9	355
Surface air bypassing BAC	15.6	209
Mixed air going underground	10.6	564

During the identification of the new electricity saving initiatives, the simulation showed that, when the surface ambient temperature goes below 7 °C wet bulb, the surface BAC will provide cooler air temperatures than what is required. Thus, the complete electricity saving initiative that was simulated was dependent on the surface ambient conditions and based on the principle to maintain the summer period cooling requirements.

3.4.1 Phase 1

The strategy of Phase 1 was developed to reduce the unnecessary cooling that occurs during periods where the surface ambient wet bulb temperature goes below 7 °C. The data showed that this occurs typically in the winter months when the Eskom peak demand tariffs are very high, thus also increasing the electricity cost. Figure 46 shows the pipe configuration layout of the cooling system on Mine A with the electricity savings strategy Phase 1 implemented on the system.

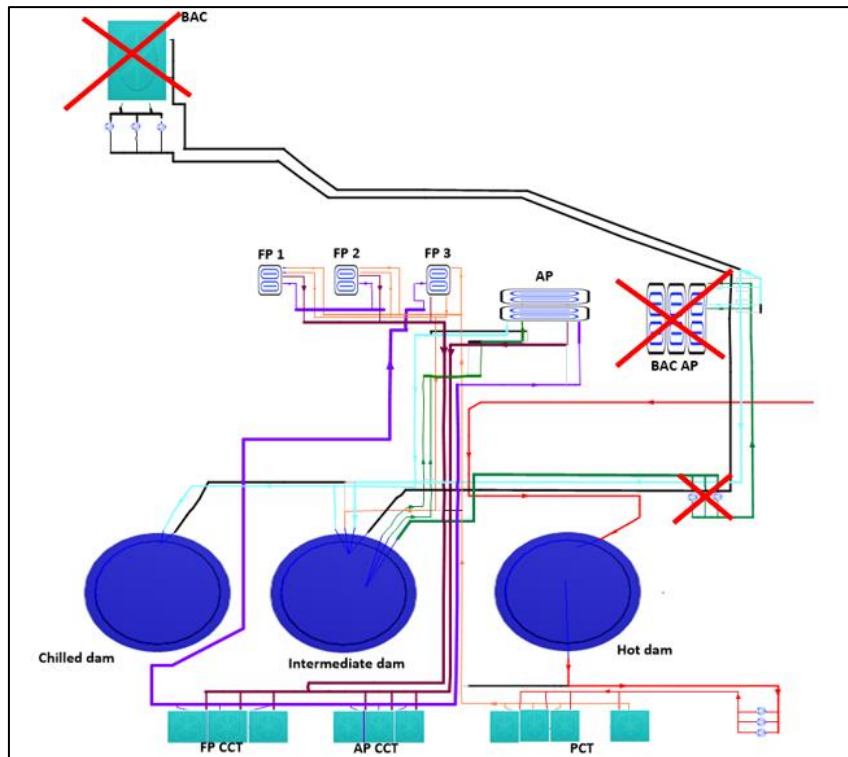


Figure 46: Electricity reduction strategy of phase 1 on Mine A

Figure 47 shows a simplified layout of Figure 46 and contains all the surface cooling system components needed to implement Phase 1 of the electricity reduction strategy. Note that the grey colour indicates that there is no flow.

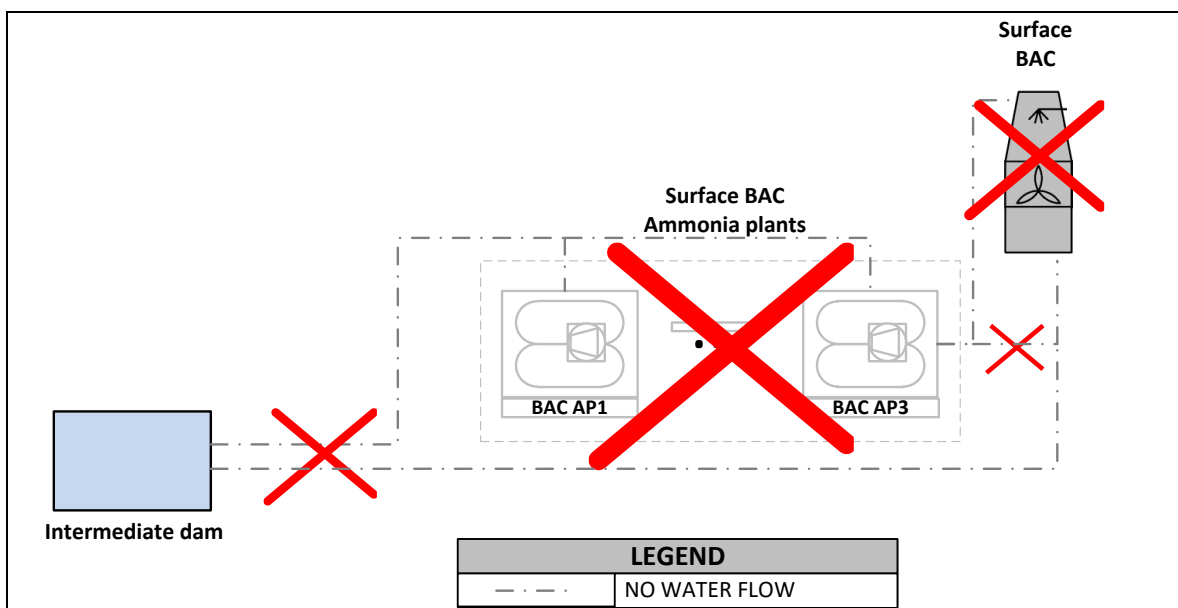


Figure 47: Simplified layout of electricity reduction strategy of Phase 1 on Mine A

Therefore, for Phase 1, the AP BAC plants and all auxiliary equipment (which includes the pumps and BAC fans) were switched off during the coldest times of the day in winter, between 16:00 and 10:00 the following day. Figure 48 shows the operating strategy for phase 1.

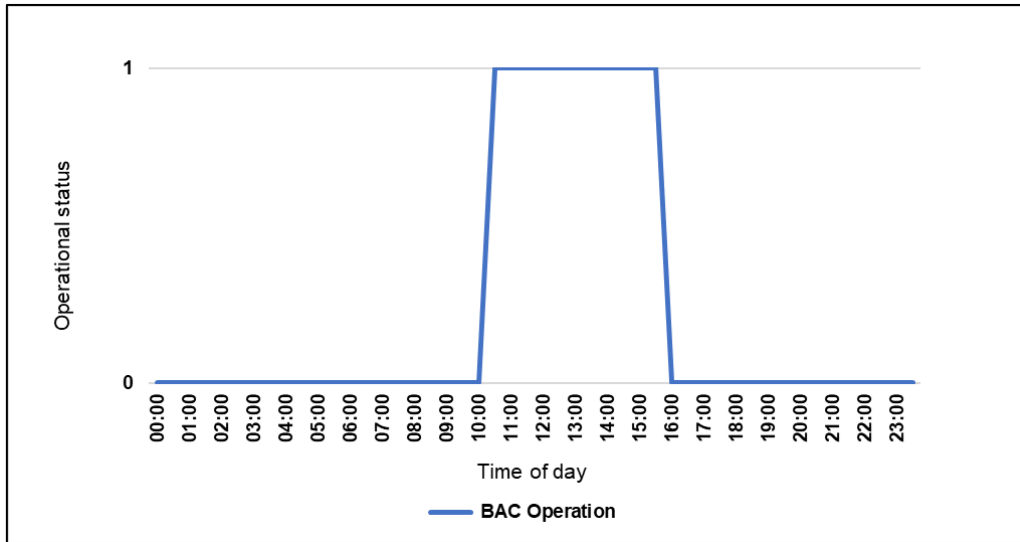


Figure 48: Phase 1 operating strategy

The simplified operating strategy shown in Figure 48 provided a graphical illustration to the mine personnel to ensure that the electricity saving strategy was implemented correctly.

Table 30 shows the simulated results when Phase 1 were implemented on the cooling system of Mine A compared to the actual summer baseline values. Due to the complex and integrated cooling system of Mine A being evaluated holistically, important parameters were identified to determine what effect seasonal control would have on the cooling system compared to the actual summer baseline. Table 30 also shows the reduction in overall power consumption that can be achieved when comparing it to the winter simulated baseline value.

Table 30: Simulated results of Phase 1 for Mine A's cooling system

Component	Measurement	Unit	Actual summer baseline value	Phase 1 simulated value	Difference [Simulated-Actual]
Chilled dam	Outlet water flow rate	L/s	267.3	268.2	0.89
	Level	%	77.9	78.9	1.03
	Temperature	°C	2.4	2.2	-0.26
Surface BAC	Outlet air temperature	°C	6.9	5.8	-1.08
Cooling system	Measurement	Unit	Simulated winter baseline value	Phase 1 simulated value	Difference [Simulated baseline -Actual]
	Overall power consumption	kW	6500.6	5580.1	-920.40

When examining Table 30, it can be seen that the same water flow rate can be sent underground, while maintaining the chilled dam level as during summer periods. Furthermore, it can be seen that both the average chilled dam temperature and the outlet BAC air temperature would decrease compared to the summer period with Phase 1 implemented.

Table 31 shows the simulated results of Phase 1 for Mine A's ventilation system when compared to the actual summer baseline value.

Table 31: Simulated results of phase 1 for Mine A's ventilation system

Component	Measurement	Unit	Actual summer baseline value	Phase 1 simulated value	Difference [Simulated-actual baseline]
Underground: Ventilation system 2L	Air temperature (wet bulb)	°C	20.5	18.4	-2.1
	Air temperature (dry bulb)	°C	26.5	25.0	-1.5
	Mass airflow	kg/s	167.6	161.8	-5.8
Underground: Ventilation system 12L	Air temperature (wet bulb)	°C	26.5	24.5	-2.0
	Air temperature (dry bulb)	°C	34.6	32.6	-2.0
	Mass airflow	kg/s	145.0	141.1	-3.9

Therefore, Table 31 shows that the underground working conditions would improve (when compared to the summer actual baseline values) with Phase 1 of the electricity reduction strategy being implemented.

The simulation proved that an overall cooling system power reduction of 0.92 MW compared to the normal winter cooling system operations could be achieved when this strategy would be applied.

This would have an electricity cost reduction of ZAR 1.1 million per winter month when using the Eskom tariffs for 2021/22 described in Table 1.

3.4.2 Phase 2

Phase 2 of the electricity saving strategy builds on Phase 1, seen in Figure 47, with the addition that the AP BAC plants and all auxiliary equipment are switched off during the entire day in winter when the ambient surface wet bulb temperature is below 7 °C. Thus, the operating strategy implies that the AP BAC plants and all auxiliaries are not switched on during the winter months.

Table 32 shows the simulated results when Phase 2 were implemented on the cooling system of Mine A compared to the actual summer baseline values. Due to the complex and integrated cooling system of Mine A being evaluated holistically, the same important parameters were identified as seen in Table 30, to determine what effect seasonal control would have on the cooling system compared to the actual summer baseline. Table 32 also shows the reduction in overall power consumption that could be achieved when comparing it to the winter simulated baseline value.

Table 32: Simulated results of phase 2 for Mine A's cooling system

Component	Measurement	Unit	Actual summer baseline value	Phase 2 simulated value	Difference [Simulated-Actual]
Chilled dam	Outlet water flow rate	L/s	267.3	268.1	0.89
	Level	%	77.9	79.0	1.06
	Temperature	°C	2.4	2.3	-0.08
Surface BAC	Outlet air temperature	°C	6.9	7.0	0.16
Cooling system	Measurement	Unit	Simulated winter baseline value	Phase 2 simulated value	Difference [Simulated baseline -Actual]
	Overall power consumption	kW	6500.6	5142.1	-1358.49

When examining Table 32, it can be seen that the same water flow rate could be sent underground, while maintaining the chilled dam level as during summer periods. Furthermore, it can be seen that both the average chilled dam temperature as well as the outlet BAC air temperature were equal to the summer period when Phase 2 would be implemented.

Table 33 shows the simulated results of Phase 2 for Mine A's ventilation system when compared to the actual summer baseline value.

Table 33: Simulated results of Phase 2 for Mine A's ventilation system

Component	Measurement	Unit	Actual summer baseline value	Phase 2 simulated value	Difference [Simulated-actual baseline]
Underground: Ventilation system 2L	Air temperature (wet bulb)	°C	20.5	18.3	-2.2
	Air temperature (dry bulb)	°C	26.5	25.1	-1.4
	Mass airflow	kg/s	167.6	161.9	-5.8
Underground: Ventilation system 12L	Air temperature (wet bulb)	°C	26.5	24.5	-2.0
	Air temperature (dry bulb)	°C	34.6	32.6	-2.0
	Mass airflow	kg/s	145.0	141.1	-3.9

Therefore, Table 33 shows that the underground working conditions would improve (compared to the summer actual baseline values) if Phase 2 of the electricity reduction strategy was implemented.

The simulation proved that an overall cooling system power reduction of 1.2 MW compared to normal winter cooling system operations could be achieved when this strategy were applied. This would have an electricity cost reduction of ZAR 1.4 million per winter month when using the Eskom tariffs for 2021/22 described in Table 1.

3.4.3 Phase 3

Figure 49 shows the pipe configuration layout of the cooling system on Mine A with the electricity savings strategy Phase 3 implemented on the system.

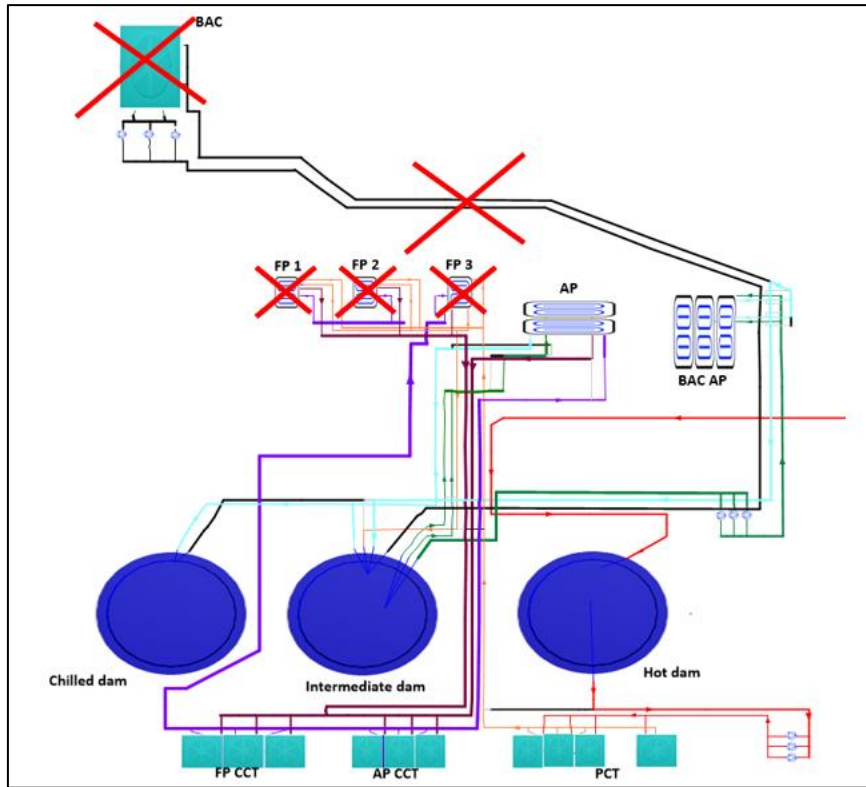


Figure 49: Electricity reduction strategy of Phase 3 on Mine A

Figure 50 shows a simplified layout of Figure 49 and contains all the surface cooling system components needed to implement Phase 3 of the electricity reduction strategy. Note that the grey colour indicates that there is no flow.

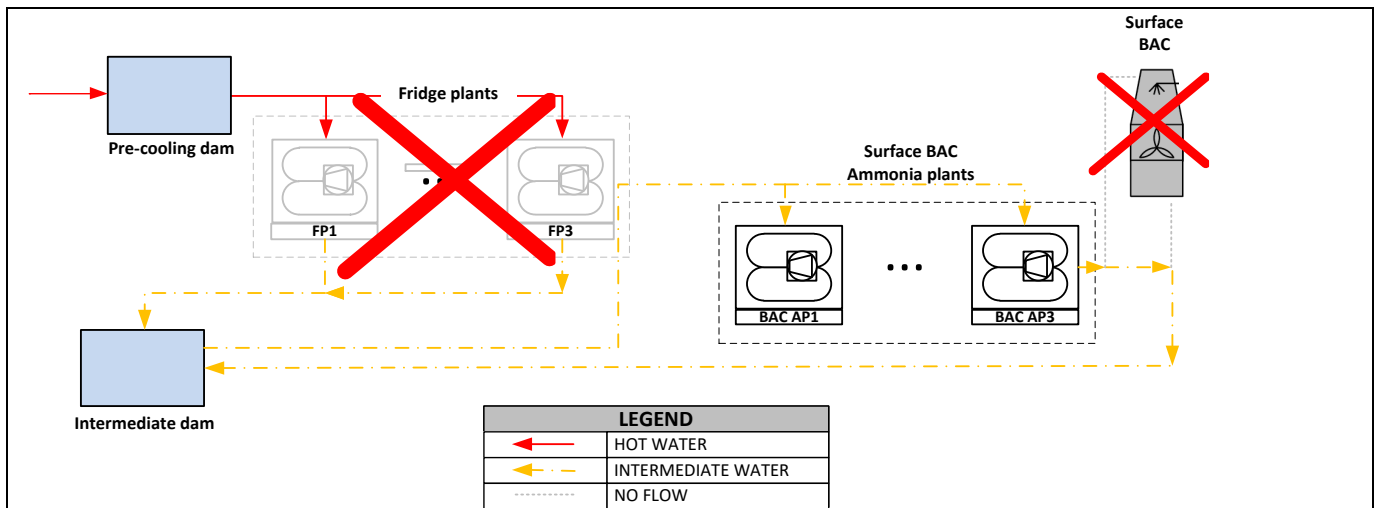


Figure 50: Simplified layout of electricity reduction strategy of Phase 3 on Mine A

The simulation proved that when a reconfiguration were done on the cooling plants, the best electricity reduction would be achieved. Figure 50 shows that the BAC fans are bypassed and the AP BAC plants are used to reduce the water temperature of the intermediate dam. FP1, FP2 and FP3 could then be switched off to achieve more electricity reductions. The simulation model proved that the AP BAC plants have higher COPs compared to the FPs during the colder months and thus provide better cooling. It is important to note that the surface ambient wet bulb temperature needs to be below 7 °C and the BAC fans need to be switched off for the entire day. A full control procedure of how Phase 3 should be implemented can be seen in Table 44 and Table 45 of Annexure B.

Table 34 shows the simulated results when Phase 3 were implemented on the cooling system of Mine A compared to the actual summer baseline values. Due to the complex and integrated cooling system of Mine A being evaluated holistically, important parameters were identified to determine what effect seasonal control would have on the cooling system compared to the actual summer baseline. Table 34 also shows the reduction in overall power consumption that could be achieved when comparing it to the winter simulated baseline value.

Table 34: Simulated results of Phase 3 for Mine A's cooling system

Component	Measurement	Unit	Actual summer baseline value	Phase 3 simulated value	Difference [Simulated-Actual]
Chilled dam	Outlet water flow rate	L/s	267.3	268.1	0.88
	Level	%	77.9	79.0	1.10
	Temperature	°C	2.4	1.8	-0.66
Surface BAC	Outlet air temperature	°C	6.9	6.1	-0.71
Cooling system	Measurement	Unit	Simulated winter baseline value	Phase 3 simulated value	Difference [Simulated baseline -Actual]
	Overall power consumption	kW	6500.6	4813.4	-1687.15

When examining Table 34, it can be seen that the same water flow rate could be sent underground, while maintaining the chilled dam level as during summer periods. The outlet BAC air temperature is equal compared to the summer period with Phase 3 being implemented.

The same simulated results as Phase 2, which is shown in Table 33, would be achieved for Phase 3, as the surface BAC would also be off for the entire day during the winter period according to the operational strategy as with Phase 2.

The simulation proved that an overall cooling system power reduction of 1.69 MW compared to normal winter cooling system operations could be achieved when this strategy were applied. This would have an electricity cost reduction of ZAR 2 million per winter month when using the Eskom tariffs for 2021/22 described in Table 1. Furthermore, the simulation model also proved that cooling plant performance improvements could be achieved when Phase 3 of the electricity reduction strategy were implemented during winter months. Table 35 shows the summary of the simulated savings that can be achieved if the electricity savings strategies were implemented on Mine A.

Table 35: Summary of simulated electricity savings for different phases

Component	Measurement	Unit	Simulated winter baseline value	Phase simulated value	Difference [Simulated baseline - Simulated Phases]
Cooling system: Phase 1	Overall power consumption	kW	6500.6	5580.1	-920.40
Cooling system: Phase 2	Overall power consumption	kW	6500.6	5142.1	-1358.49
Cooling system: Phase 3	Overall power consumption	kW	6500.6	4813.4	-1687.15

From Table 35, the complex and integrated simulation model of the cooling system of Mine A shows that electricity savings were achieved.

3.5 Implementation of strategies

Test results

Additional support to the simulation model was requested by the mine personnel of Mine A to limit the health and safety risks as this is the first time that seasonal control electricity savings initiatives were implemented there. These requests resulted in a long delay in implementing the electricity saving strategies. The following practical tests were done to provide the additional support that was requested.

Static pressure measurements

A static pressure test was done to determine whether the surface BAC assists the surface extraction fans with the ventilation airflow of Mine A. The static pressure was measured inside the surface extraction fans and barometric pressure measurements were taken underground to determine whether the surface BAC is assisting with the airflow of the ventilation system. Measurements were taken before the surface BAC fans were switched off and after the fans were switched off both on surface and underground.

The test procedure was as follows:

- Measure the suction pressure on the main surface ventilation fans when both BAC fans are running.
- Measure the suction pressure on the main surface ventilation fans when both BAC fans are off (3.5 hours after the BAC fans were switched-off).

The results of the test can be seen in Table 36.

Table 36: Suction static pressure test results

Main surface fans suction static pressure (kPa)		
	BAC Fans On (07:00)	BAC Fans Off (10:30)
Fan 1	Off	Off
Fan 2	-4.554	-4.568
Fan 3	-4.616	-4.623

Table 36 shows a marginal change of 0.014 kPa on Fan 2 and 0.007 kPa on Fan 3 on the static suction pressures when the surface BAC fans were switched off. Thus the total airflow through Mine A remained constant. This implies that the BAC fans can be switched off when the BAC is not required.

The results from the underground barometric pressure readings measured on 4L of Mine A yielded no change in pressure when the surface BAC fans were switched off. Thus it was proven through practical measurements that the surface BAC fans do not contribute to the airflow of Mine A's ventilation system.

Air flow measurements

The ventilation department from Mine A was still not convinced that the surface BAC does not assist the surface extraction fans with the ventilation airflow and a test was done where airflow measurements were taken on all the working levels of Mine A's Main shaft before and after the surface BAC fans were stopped. Table 37 shows the airflow measurements that were taken on all the Main shaft working levels of Mine A, while the surface BAC fans were operational and when the BAC fans were stopped.

Table 37: Airflow measurements with surface BAC fans operational and stopped on Mine A

Level	BAC fans operational [kg/s]	BAC fans stopped [kg/s]	Difference	%Difference
2L	116.8	114.3	-2.5	2.1
3L	97.3	100.6	3.3	3.4
4L	280.8	241.7	-39.1	13.9
4.5L	63.8	62.8	-1.0	1.5
5L	7.8	9.5	1.7	21.9
Total	566.4	528.9	37.5	6.6

When considering Table 37, it can be seen that there is a 6.6 % difference between the mass airflow before and after the surface BAC fans of Mine A were stopped. Thus, 37.5 kg/s less airflow was measured while the BAC fans were stopped. Air flow measurements were constant on all the levels, except on 4L, which could be caused by different ventilation doors that were opened or closed during the two test days.

Figure 51 shows a ventilation layout of Mine A with the airflow measurements for the different working levels on Main shaft before and after the surface BAC fans were stopped. Note that the black represents the surface BAC fans being operational and the red represents the BAC fans being stopped.

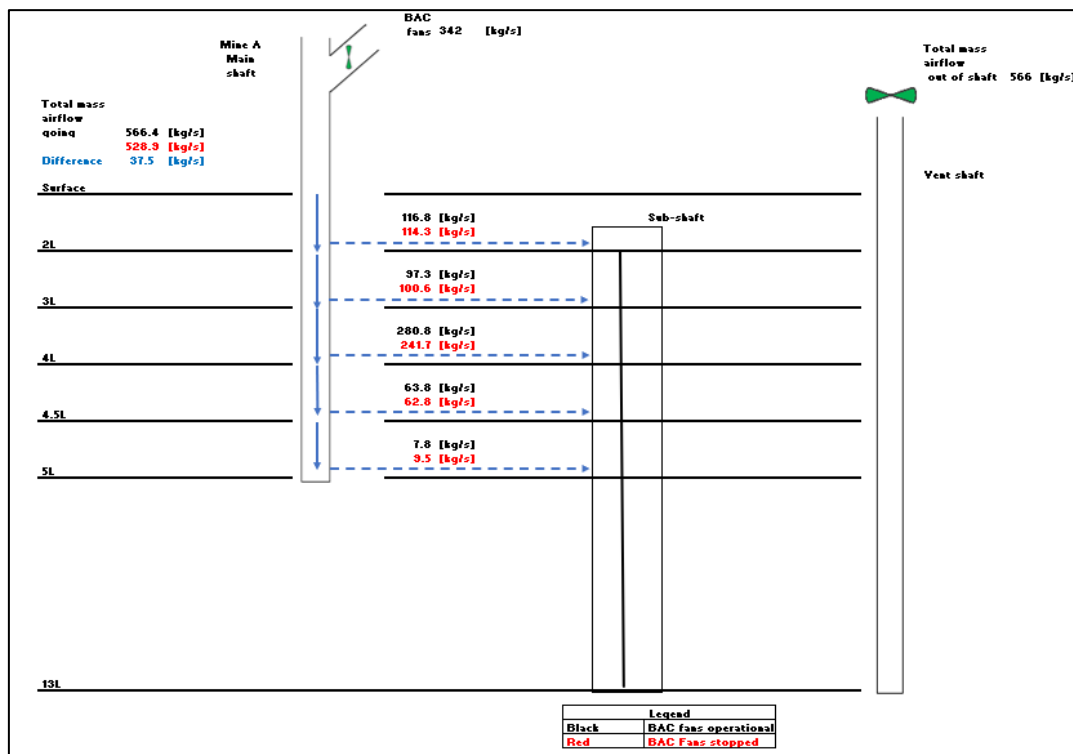


Figure 51: Airflow measurements with surface BAC fans operational and stopped on Mine A

Thus, it was proven through practical measurements that the surface BAC fans do not contribute to the airflow of Mine A's ventilation system as only 4L had a large deviation between the two airflow measurements due to a possibility of different combinations of ventilation doors that was opened on the different tests. The simulation models and temperature measurements (discussed later in Section 3.5) further proves that colder temperatures will be experienced if the electricity saving strategies are implemented in the winter.

Temperature measurements

During the implementation of Phase 1 of the electricity reduction strategy, portable temperature loggers were installed on underground working levels to determine whether the underground working conditions could be maintained during winter conditions. Spot measurements were also made underground when the temperature loggers were exchanged. Figure 52 shows the underground temperatures of 2L while Phase 1 of the electricity reduction strategy was implemented. The temperature was also compared to typical summer conditions with the surface BAC fans being operational. The solid lines represent the average temperature during winter periods while Phase 1 was implemented and the dotted line represents the average temperature during summer periods when the surface BAC fans were operating normally.

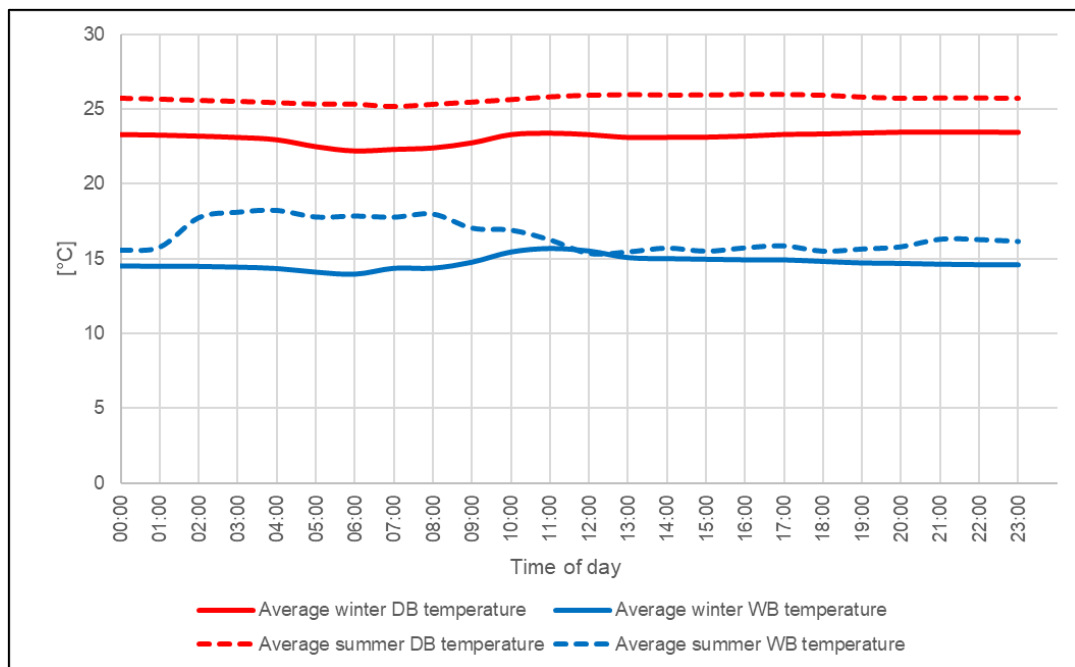


Figure 52: Underground temperatures during Phase 1 of implementation on 2L

When considering Figure 52, it can be seen that the average wet bulb and dry bulb temperatures were well below the average summer temperatures while Phase 1 was implemented. Thus,

considering these results, it can be confirmed that underground conditions can be maintained during colder seasons with seasonal control implemented.

3.5.1 Phase 1

Due to the health and safety risks involved and it being the first time that a seasonal control electricity reduction strategy was proposed to be implemented, a method was developed where a holistic evaluation was done on the complex and integrated surface cooling system of Mine A to determine the effect it might have on underground conditions. After all the supporting information and test results were provided to the mine personnel, Phase 1 of the electricity reduction strategy was implemented on Mine A during a winter month. The same operating strategy for Phase 1 was followed as discussed in Section 3.4.1.

Table 38 shows the actual results of Phase 1, which was implemented during a winter month on the cooling system of Mine A, compared to the simulation values of Phase 1. Due to the complex and integrated cooling system of Mine A being evaluated holistically, the same important parameters were identified as seen in Table 30 to determine what effect seasonal control has on the cooling system compared to the actual summer baseline.

Table 38: Results of implemented Phase 1 on the cooling system of Mine A

Component	Measurement	Unit	Phase 1 actual value	Phase 1 simulated value	Percentage error [%]
Chilled dam	Outlet water flow rate	L/s	274.2	268.2	2.21
	Level	%	80.0	78.9	1.37
	Temperature	°C	2.8	2.2	22.82
Surface BAC	Outlet air temperature	°C	6.5	5.8	10.87
Cooling system	Overall power consumption	kW	5433.2	5580.1	2.70

When examining Table 38, it can be seen that the chilled dam temperature and the outlet air temperature from the BAC deviate by more than 5%. When considering the values, the chill dam is only 0.4 °C over the actual summer baseline temperature and the outlet air temperature of the BAC is well below the summer baseline temperature.

Figure 53 shows the average baseline summer temperatures compared to the average implemented Phase 1 temperatures on Level 12 of Mine A. The solid lines represent the average temperature

during winter periods while Phase 1 was implemented and the dotted line represents the average temperature during summer periods when the surface BAC fans were operating normally

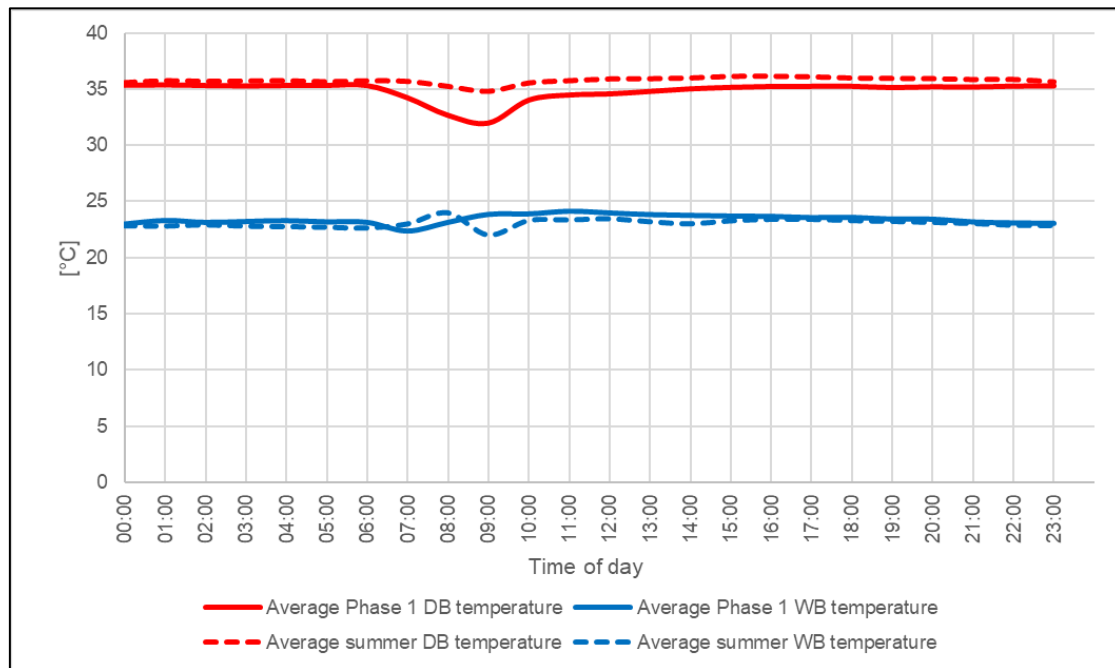


Figure 53: Average baseline summer temperatures vs average implemented Phase 1 temperatures on 12L

Thus, when considering Figure 52 and Figure 53, it can be seen that Phase 1 of the electricity saving strategy was successfully implemented while maintaining the underground conditions that are experienced in the summer when the BAC fans are operational.

Figure 54 shows the actual power consumption of the surface cooling system of Mine A after Phase 1 was implemented compared to the simulated power consumption of Phase 1. The simulated power consumption is represented by a dashed green line and the actual power consumption is represented by a solid blue line.

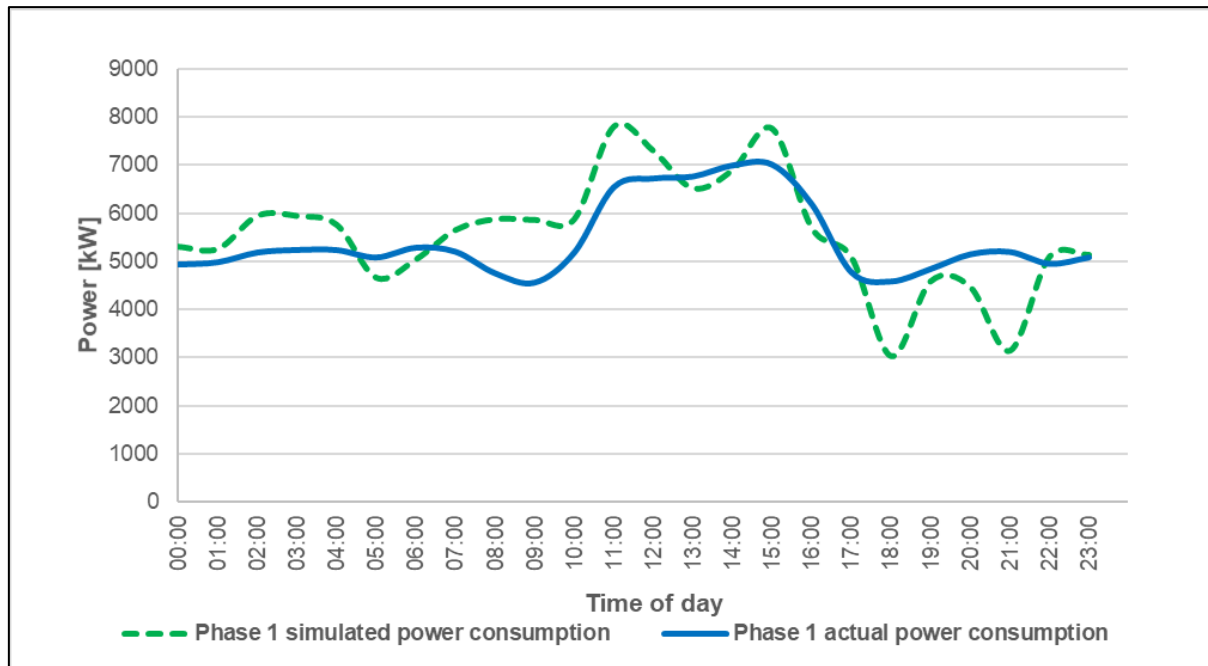


Figure 54: Phase 1 actual power consumption vs simulated surface cooling system on Mine A

Figure 54 shows that the simulation model of Phase 1 follows the profile of the actual power consumption after Phase 1 was implemented, but reacts too aggressively as previously mentioned. Due to this, the accuracy of the simulation model compared to the 24-hour actual power consumption reduced to 87 %.

The actual implementation of Phase 1 on Mine A proved that an overall cooling system power reduction compared to the normal winter cooling system operations can be achieved when this strategy is applied. This would have an electricity reduction of 0.7 GWh equivalent to ZAR 1.24 million per winter month. Thus, when Phase 1 were implemented for the duration of the winter months, it would have an electricity cost reduction of ZAR 3.72 million per annum using the 2021/22 Eskom tariffs described in Table 1.

3.5.2 Phase 2

After implementing Phase 1 successfully on the surface cooling system of Mine A, the mine personnel agreed to the implementation of Phase 2. The electricity reduction strategy of Phase 2 was implemented on Mine A during a winter month. The same operating strategy for Phase 2 was followed as discussed in Section 3.4.2.

Table 39 shows the actual results of Phase 2, implemented during a winter month, on the cooling system of Mine A compared to the simulation values. Due to the complex and integrated cooling system of Mine A being evaluated holistically, the same important parameters were identified, as in

Table 30, to determine what effect seasonal control has on the cooling system compared to the actual summer baseline.

Table 39: Results of implemented Phase 2 on the cooling system of Mine A

Component	Measurement	Unit	Phase 2 actual value	Phase 2 simulated value	Percentage error [%]
Chilled dam	Outlet water flow rate	L/s	277.8	268.1	3.47
	Level	%	80.2	79.0	1.49
	Temperature	°C	1.9	2.3	19.80
Surface BAC	Outlet air temperature	°C	7.9	7.0	11.19
Cooling system	Overall power consumption	kW	5025.9	5142.1	2.31

When examining Table 39, it can once again be seen that the chilled dam temperature and outlet air temperature of the surface BAC deviate by more than 5 % when compared to the actual measurements. In the case of the chilled dam temperature, colder temperatures were experienced during the implementation of Phase 2, than what was simulated, which is beneficial. The outlet air temperature of the BAC were 0.9 °C higher compared to the simulation and is still well below the average wet bulb temperature of the mixed air going down the main shaft during summer.

Figure 55 shows the average baseline summer temperatures compared to the average implemented Phase 2 temperatures on Level 2 of Mine A. The solid lines represent the average temperature during winter periods while Phase 2 was implemented and the dotted line represents the average temperature during summer periods when the surface BAC fans were operating normally.

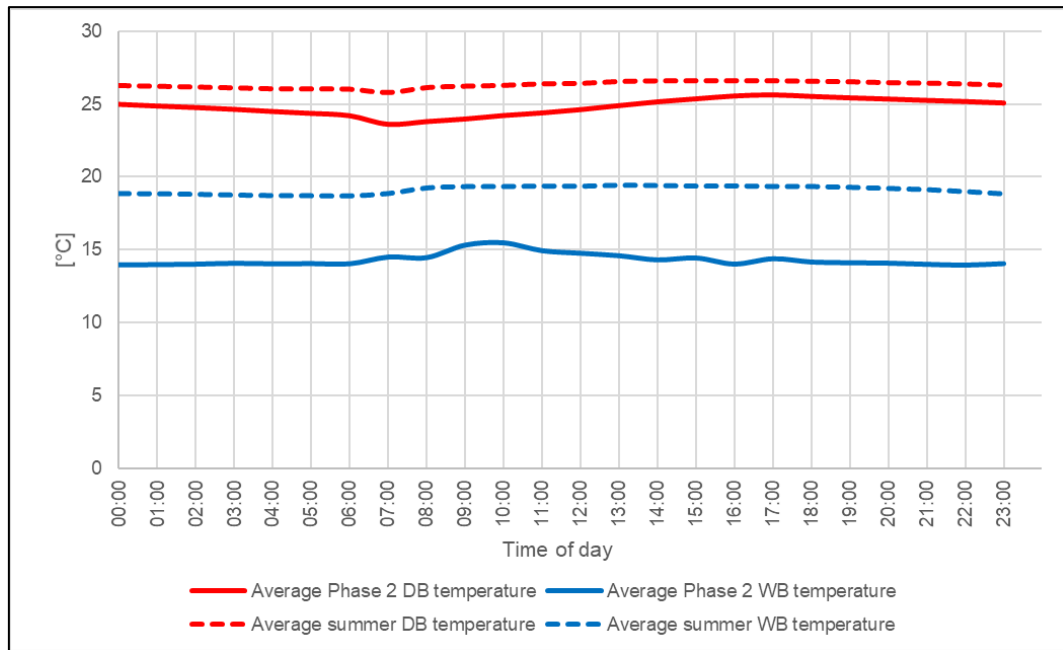


Figure 55: Average baseline summer temperatures vs average implemented Phase 2 temperatures on 2L

Figure 55 shows the temperatures after the implementation of Phase 2, which are below the average actual summer conditions experienced on Level 2.

Figure 56 shows the average baseline summer temperatures compared to the average implemented Phase 2 temperatures on Level 2 of Mine A. Note that the same colour scheme was used in Figure 55.

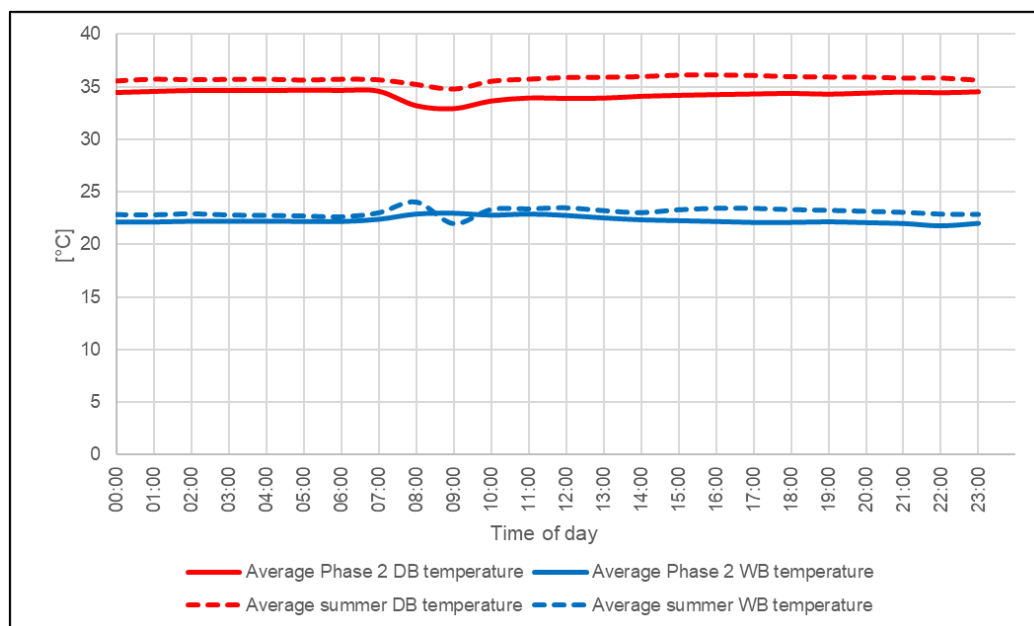


Figure 56: Average baseline summer temperatures vs average implemented Phase 2 temperatures on 12L

Thus, when considering Figure 55 and Figure 56, it can be seen that Phase 2 of the electricity saving strategy was successfully implemented while also maintaining the underground conditions that are experienced in the summer when the BAC fans are operational.

Figure 57 shows the actual power consumption of the surface cooling system of Mine A after Phase 2 was implemented compared to the simulated power consumption of Phase 2. The simulated power consumption is represented by a dashed green line and the actual power consumption is represented by a solid blue line.

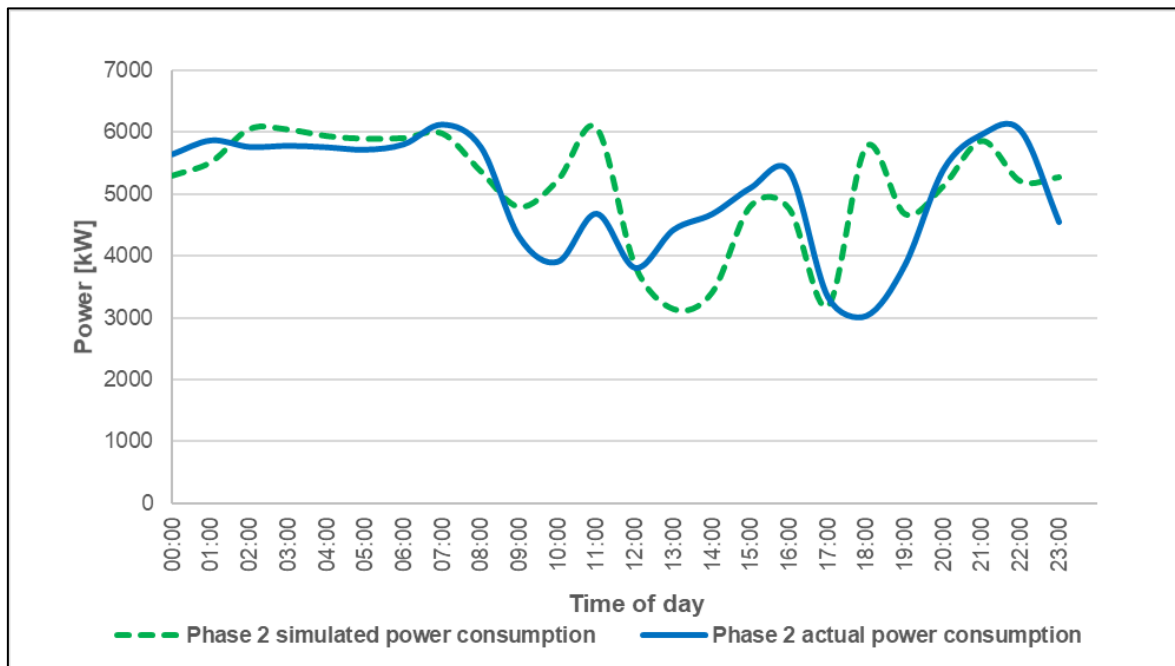


Figure 57: Phase 2 actual power consumption vs simulated surface cooling system on Mine A

Figure 57 shows that the simulation model of Phase 2 follows the profile of the actual power consumption after Phase 2 was implemented, but reacts too aggressively as previously mentioned. Due to this, the accuracy of the simulation model compared to the 24-hour actual power consumption reduced to 88 %.

The actual implementation of Phase 2 on Mine A proved that an overall cooling system power reduction of 1.44 MW compared to the normal winter cooling system operations can be achieved when this strategy is applied. This would have an electricity reduction of 1 GWh equivalent to ZAR 1.73 million per winter month. Thus, when Phase 2 were implemented for the duration of the winter months, it would have an electricity cost reduction of ZAR 5.18 million per annum using the 2021/22 Eskom tariffs described in Table 1.

3.5.3 Phase 3

After implementing Phase 2 successfully on the surface cooling system of Mine A, the mine personnel agreed to a test implementation of Phase 3. The electricity reduction strategy of Phase 3 was implemented on Mine A during a winter month. The same operating strategy for Phase 3 was followed as discussed in Section 3.4.3.

Table 40 shows the actual results of Phase 3, which was expanded to account for a winter month, on the cooling system of Mine A compared to the simulation values. This method was used due to the test of Phase 3 being stopped after one day. Due to the complex and integrated cooling system of Mine A being evaluated holistically, the same important parameters were identified, as in Table 30, to determine what effect seasonal control has on the cooling system compared it the actual summer baseline. Table 40 also shows the reduction in overall power consumption that can be achieved when comparing it to the winter simulated baseline value.

Table 40: Results of implemented phase 3 on the cooling system of Mine A

Measurement	Unit	Phase 3 actual value	Phase 3 simulated value	Percentage error [%]
Outlet water flow rate	L/s	287.5	268.1	6.73
Level	%	77.8	79.0	1.55
Temperature	°C	2.6	1.8	31.79
Outlet air temperature	°C	5.8	6.1	5.59
Overall power consumption	kW	5053.1	4813.4	4.74

When examining Table 40, it can be seen that the chilled dam temperature and outlet air temperature of the surface BAC deviate by more than 5 % when compared to the actual measurements. This is due to a test that was done for one day and the temperatures did not have time to stabilise. Furthermore, the tests were stopped after 1 day due to the control philosophy of the surface cooling system, more specifically the AP BAC plants being in a state of 'trip' after the water bypasses the BAC fans. This meant that the PLC had to be reprogrammed by the mine personnel to account for this electricity saving strategy. The outlet air temperature of the BAC was below the simulated value.

As mentioned previously, the underground conditions when Phase 3 are implemented during a winter month on Mine A, will be the same as for Phase 2 shown in Figure 55 and Figure 56 on Level 2 and Level 12 respectively. This is due to the surface BAC fans that would not be operational for

entire the day. However, due to the test of Phase 3 being stopped, the temperatures could not be validated.

Figure 55 shows the average baseline summer temperatures compared to the average implemented Phase 2 temperatures on Level 2 of Mine A. The solid lines represent the average temperature during winter periods while Phase 2 was implemented and the dotted line represents the average temperature during summer periods when the surface BAC fans were operating normally.

Figure 58 shows the actual power consumption of the surface cooling system of Mine A after Phase 3 was implemented compared to the simulated power consumption of Phase 3. Note that the power consumption of the actual value after Phase 3 was implemented was enlarged to account for the test that was stopped after one day. The simulated power consumption is represented by a dashed green line and the actual power consumption is represented by a solid blue line.

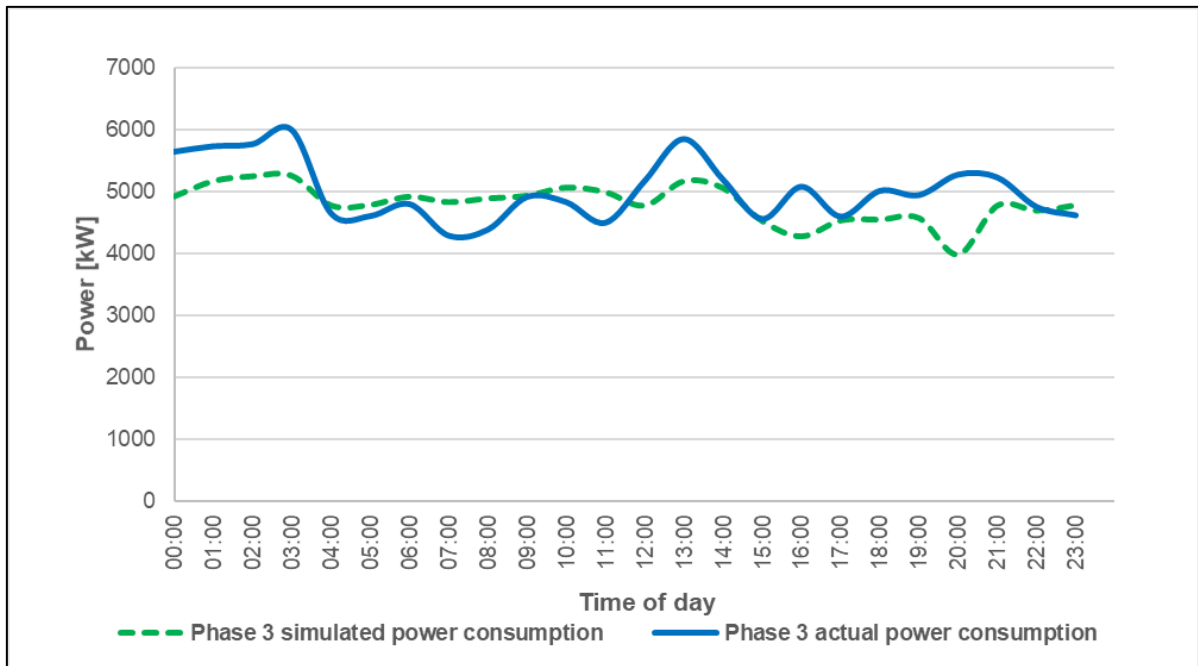


Figure 58: Phase 3 actual power consumption vs simulated surface cooling system on Mine A

Figure 58 shows that the simulation model of Phase 3 follows the profile of the actual power consumption after Phase 3 was implemented, and reacts better than Phase 1 and Phase 2. The reason for this is due to Phase 3 being implemented for only one day. Due to this, the accuracy of the simulation model compared to the 24-hour actual power consumption increased to 91 % when comparing the results from Phases 1 and 2.

The actual implementation of Phase 3 on Mine A can be enlarged and an overall cooling system power reduction of 1.42 MW compared to the normal winter cooling system operations can be

achieved when this strategy is applied. This would have an electricity reduction of 1 GWh equivalent to ZAR 1.69 million per winter month. Thus, when Phase 3 were implemented for the duration of the winter months, it would have an electricity cost reduction of ZAR 5.08 million per annum using the 2021/22 Eskom tariffs described in Table 1.

Furthermore, if the control philosophy of the mine's surface cooling system can be updated to accommodate for the electricity saving operating procedure and Phase 3 is implemented for a full winter month, it is expected that the electricity reduction could be 1.2 GWh (1.66 MW) equivalent to ZAR 1.92 million per winter month according to the simulation model.

3.6 Discussion of results and conclusion

When considering the case study research method shown in Figure 17, the next step is to discuss the results that were achieved from implementing the developed method on the case study mine. Due to this developed method only being implemented on one case study mine, there will be no cross-case conclusions as shown in Figure 17. Furthermore, this study will also not include the last three steps in the method of the case study research method shown in Figure 17, as an in-depth literature study was done in Section 1.4 to compare the method that needs to be developed to the existing research. The developed method also includes a step where modifications can be done if more information is obtained or the cooling system changes, as discussed in Section 2.3.6. The last step in the case study research method, as shown in Figure 17, is to write a cross-case report, which will also not be included in this study due to only one case study being considered.

As part of the method that was developed during this study, an in-depth investigation was done on complex and integrated surface cooling plant configurations of a deep case study mine cooling system. This led to the development of digital simulation models for the complex and integrated surface cooling system and ventilation system of the case study mine. The simulation models were used to identify and simulate seasonal electricity reduction strategies on the case study mine. The simulation models were calibrated and verified by comparing them to real-life operational data of the cooling plants and additional cooling system equipment. No seasonal electricity reduction strategies were implemented previously on the case study mine and it was decided that a phased approach be implemented to reduce the electricity of the complex and integrated deep mine cooling system. The electricity reduction strategies that were identified and simulated were verified by comparing them to the actual results that were achieved through the implementation of the strategies.

The method that was developed and implemented to holistically evaluate the effect that seasonal control of complex and integrated surface cooling systems has on underground conditions while

reducing electricity costs needed to be validated. For the validation of this study, the actual power consumption was compared to the baseline actual power consumption to determine whether the method can be seen as valid. Table 41 shows the actual power consumption of the implemented Phase 1, 2 and 3 electricity reduction strategies compared to the baseline power consumption of a typical winter month to determine whether an electricity reduction was achieved on the complex and integrated cooling system of Mine A.

Table 41: Actual power consumption of Phases 1, 2 and 3 vs baseline power consumption of Mine A

Component	Measurement	Unit	Actual winter baseline value	Actual Phase value	Difference [Actual Phases-Actual baseline]
Cooling system: Phase 1	Overall power consumption	kW	6471.4	5433.2	-1038.19
Cooling system: Phase 2	Overall power consumption	kW	6471.4	5025.9	-1445.47
Cooling system: Phase 3	Overall power consumption	kW	6471.4	5053.1	-1418.32

Thus, from Table 41 it can be seen that electricity savings were achieved by implementing Phases 1, 2 and 3 on the complex and integrated cooling system of Mine A.

According to existing research, the sustainability of electricity saving initiatives and strategies has become a high priority after Eskom's IDM model update in 2015 [34]. Therefore, a sustainability plan was compiled for the phased electricity saving strategy in this study which includes daily monitoring, reporting and annual maintenance sections. The daily monitoring section also includes conditions that need to be met for the electricity savings strategy to be implemented which can be seen in Figure 59.

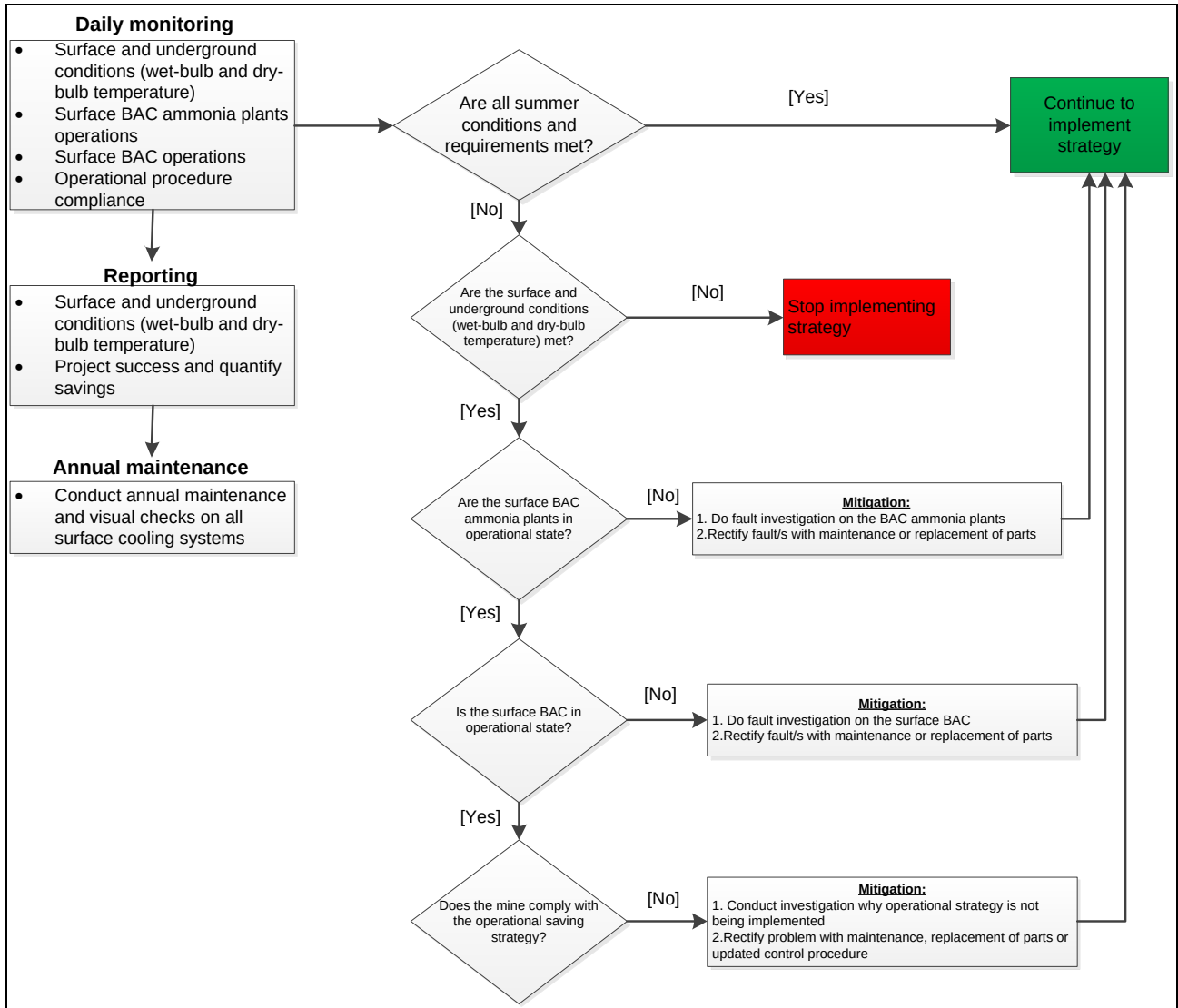


Figure 59: Sustainability plan for the phased electricity saving strategy

The sustainability plan shown in Figure 59 will assist the mine to achieve electricity savings for a longer duration. An example of the feedback reports that can be sent out to the mine as part of the sustainability plan can be seen in Annexure C.

Figure 60 shows a graphical representation of the actual implemented power reduction phases on the complex and integrated surface cooling system of Mine A, compared to the baseline power consumption. The solid red line represents the baseline winter power consumption, the dotted blue line represents Phase 1, the dotted green line represents Phase 2 and the dotted black line represents Phase 3.

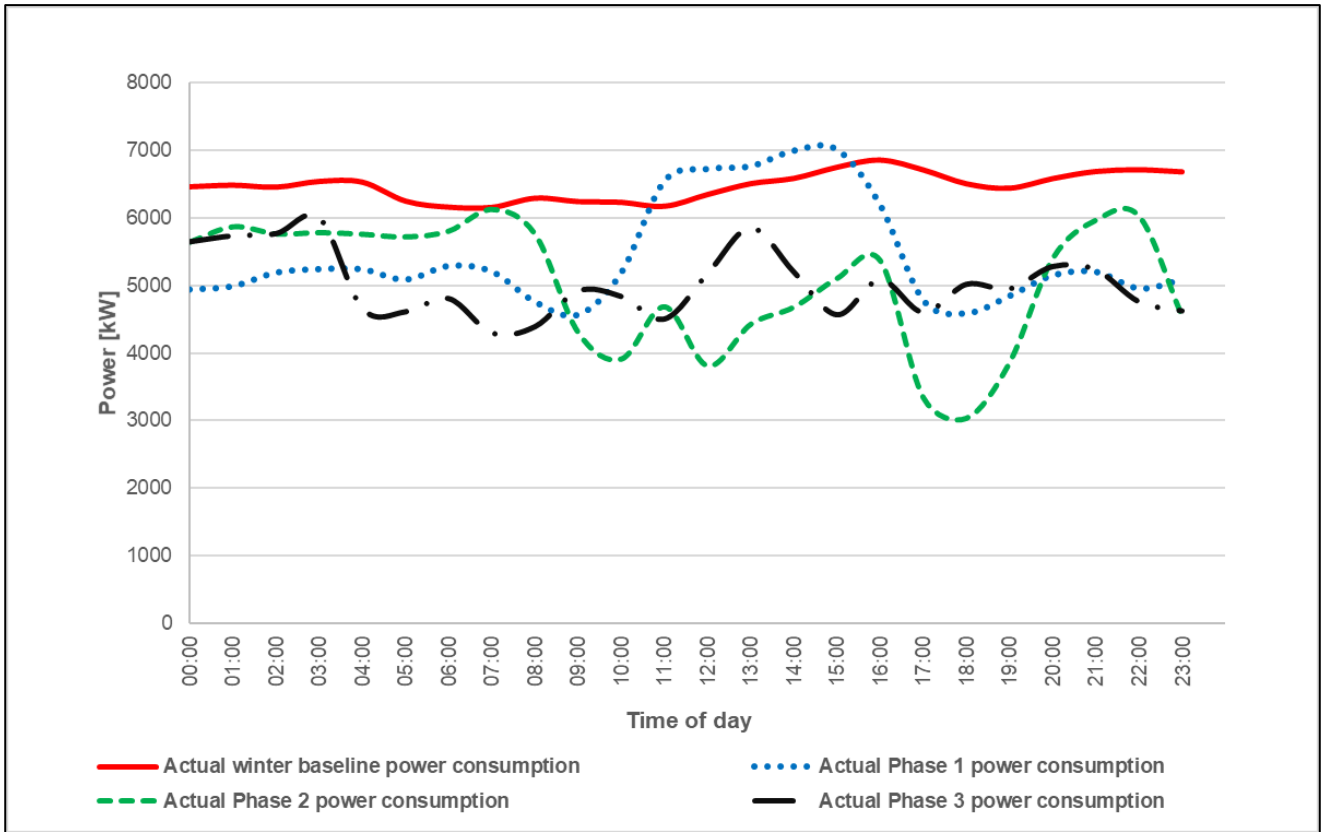


Figure 60: Actual power consumption of Phases 1, 2 and 3 vs baseline power consumption of Mine A

When considering the results that are shown in Figure 60 and Table 41, it can be seen that the implemented electricity reduction strategy led to a reduction of 1.04 MW, 1.44 MW and 1.42 MW, respectively, for the three phases of the surface cooling system of the case study mine. According to the simulation model, a reduction of 1.66 MW can be achieved if the control philosophy of the surface cooling system of Mine A is updated and Phase 3 is implemented for a full winter month. Figure 61 shows the electricity reduction for each phase after implementation and the expected implementation of the surface cooling system for Mine A.

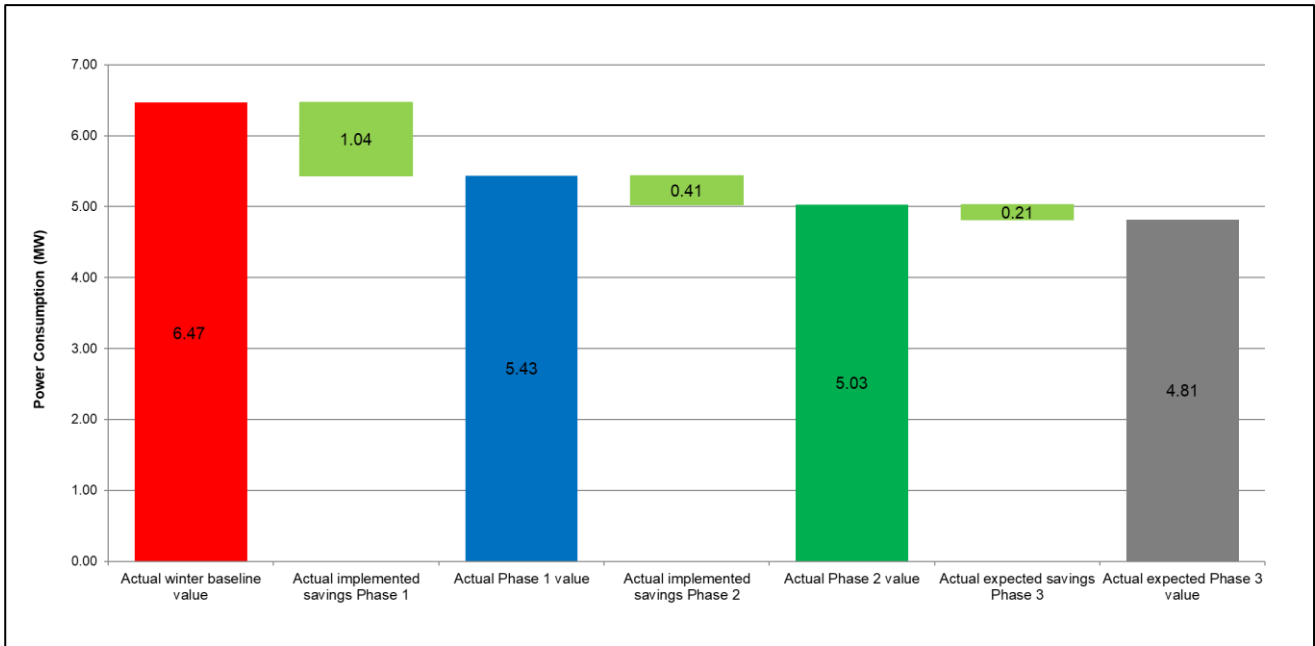


Figure 61: Impact on power consumption for Phases 1, 2, and 3 vs baseline power consumption of Mine A

Further, the results shown in Section 3.5 show that the holistic evaluation that was done on the effect of the electricity reduction strategies on the underground working conditions proved that the phased approach can be implemented safely while also maintaining the same underground conditions as experienced during the summer periods.

Therefore, it can be said that a valid solution was provided for the specific case study mine by implementing the developed method of this study. It is proven that the implemented method led to electricity reductions on a complex and integrated surface cooling system as it was validated through a case study.

From the results that are shown in Sections 3.5 and 3.6 and the rest of the study, it can be seen that the following study objectives were met:

- ✓ Identify and implement seasonal electricity reduction strategies on complex and integrated deep mine cooling plant configurations.
- ✓ Develop a method that can holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling plant configurations.

The study could therefore be seen as a success as a method was developed to identify and implement a seasonal electricity reduction strategy on complex and integrated deep mine cooling

plant configurations while holistically evaluating the effect and implications that the electricity reduction strategies have on the underground working conditions.

The method that was implemented on the case study mine surface cooling system led to a power reduction of 1.04 MW (0.7 GWh), 1.44 MW (1 GWh) and 1.42 MW (1 GWh) for the three phases. This power reduction can lead to an electricity cost reduction of ZAR 3.72 million, ZAR 5.18 million and ZAR 5.08 million per annum respectively for the different phases using the 2021/22 Eskom tariffs described in Table 1.

CHAPTER 4 CONCLUSION

4.1 Summary

Mining electricity costs in South Africa have increased drastically over the last 15 years, being 3 times higher than the inflation of South Africa. Renewable energy projects can, however, not be implemented on deep mines that are under pressure due to low operating margins and high initial costs of these projects.

It was found that the cooling systems of deep mines consume a large percentage of the electricity used on these mines. Research showed that the cooling and ventilation systems of deep mines can become integrated and complex as the mines get deeper.

A study was done on the implementation of load management and electricity reduction strategies on surface cooling and ventilation systems of deep mines. During the study, it was found that a need exists to holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated surface cooling plant configurations.

The following objectives were identified to provide a solution to the need of the study:

- Identify and implement seasonal electricity reduction strategies on complex and integrated deep mine cooling plant configurations, and
- Develop a method that can holistically evaluate the effect and implications on underground working conditions if seasonal electricity reduction strategies are implemented on complex and integrated deep mine cooling plant configurations.

A method with six steps was developed to identify and implement seasonal electricity reduction strategies on a typical deep mine with a two-stage cooling system with an additional cooling stage while evaluating the effect that the reduction strategies have on the underground working conditions. The six steps of the method include investigating and understanding the ventilation and cooling system and configurations, developing a simulation model of the cooling and ventilation system, calibrating and verifying the accuracy of the simulation models compared to real-life operations (with a 5% deviation), identifying and simulating seasonal electricity reduction strategies, implementing and validating the electricity reduction strategies, and revising the strategies if needed.

A case study mine with no prior seasonal electricity reduction strategies implemented on the complex and integrated surface cooling system was identified. Due to no seasonal electricity reduction

strategies being implemented previously, the seasonal electricity reduction strategy identified when the developed method of this study was applied was implemented in a phased approach to the case study mine, which resulted in an electricity cost reduction of ZAR 3.72 million, ZAR 5.18 million and ZAR 5.08 million per annum, respectively, for the different phases. The seasonal electricity reduction strategy includes a sustainability plan to ensure that electricity savings can be achieved for long periods. The method further holistically evaluated the effect of the seasonal electricity reduction strategy on the underground working conditions of the case study mine and it was found that the strategies could be implemented safely through the phased approach, while maintaining the required summer conditions in the working areas.

4.2 Concluding remarks and recommendations

The following remarks and recommendations can be made after the developed method was implemented on a case study mine:

- Due to the uncertainty that occurs when any changes are made to a complex and integrated surface cooling system of a deep mine, it is recommended to install underground weather stations that are connected to the SCADA at vital underground working areas to ensure that the effect of the changes can be determined instantly. This will also lead to seasonal electricity reduction strategies that can be implemented for longer periods of time as ambient conditions also fluctuate before and after the Eskom winter months, which implies that more savings can be achieved.
- An overall sensitivity analysis can be done to determine what is the holistic measurement and KPI uncertainty of the cooling and ventilation system.
- It is also recommended to consider including maintenance and cleaning schedules on the cooling towers and cooling plants as part of the developed method in this study to optimise the COP of the integrated and complex cooling system.
- The electricity reduction feedback reports that are part of the sustainability plan can be compiled in such a manner that they are generated automatically.
- The method that was developed in this study can also be easily adjusted to a single-stage cooling plant with an additional optional cooling stage cooling system if required.
- An investigation can be done to determine whether more electricity cost savings could be achieved if automated valves and VSDs were combined with the method that was developed for this study

- A better approach can be investigated to develop a simulation model that responds to multiple fluctuations in water demands of complex and integrated surface cooling systems and results in a less tedious process to calibrate the simulation.

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ANNEXURE A

As seen in Table 42, the complexity and size of the cooling system of Mine A resulted in using a large amount of data with more than 50 SCADA tags in combination with practical measurements. Table 42 shows the complete list of all the tag names and practical measurements that needed to be collected on the integrated and complex surface cooling system of Mine A for the simulation model to be built, as seen in Section 3.3.

Table 42: Data collection done on the cooling system of Mine A

General data collection- Essential				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Current meters on all equipment	AP1 compressor current: 00RFP04_00IIT#100.FA_PV AP2 compressor current: 00RFP05_00IIT#100.FA_PV FP1 compressor current: 00RFP01_00IIT#100.FA_PV FP2 compressor current: 00RFP02_00IIT#100.FA_PV FP3 compressor current: 00RFP03_00IIT#100.FA_PV	To be measured: PCT pumps 1-3 PCT fans 1-4 AP condenser pumps 1-2 AP evaporator pumps 1-2 AP CCT fan 1-3 FP evaporator pumps 1-3 FP condenser pumps 1-3 FP CCT fan 1-3	BAC AP1 compressor current: 00RFP06_00IIT#100.FA_PV BAC AP2 compressor current: 00RFP07_00IIT#100.FA_PV BAC AP3 compressor current: 00RFP08_00IIT#100.FA_PV	To be measured: BAC AP return pumps 1-3 BAC AP condenser pumps 1-3 BAC AP evaporator pumps 1-3 BAC AP CCT fans 1-2 BAC Fans 1-2
Voltage meters on all equipment	Not available	Voltage on specification plates of machinery	Not available	Voltage on specification plates of machinery
Level percentage sensor for the pre-cooling dam	Pre-cooling towers sump dam level percentage: 00RFP00_00ILT#506.FA_PV	N/A		
Level percentage sensor for the intermediate dam	Intermediate water dam level: 00RFP00_00ILT#501.FA_PV			
Level percentage sensor for the chill dam	Cold water dam level: 00RFP00_00ILT#502.FA_PV			
General data collection- Desirable				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Power consumption meters	AP feeder + Auxiliaries: 0567 AMONIA PLANT FDR FP feeder 1 + Auxiliaries: 0101 Surface York fplant fdr 1P Net FP feeder 2 + Auxiliaries: 0102 Surface York fplant fdr 2 P Net	Not needed	BAC AP feeder + Auxiliaries: 0458 BAC PLANT P Net	Not needed
Guide vane angle feedback of compressor	AP1 compressor guide vane position: 00RFP04_00IZT#120.FA_PV AP2 compressor guide vane position: 00RFP05_00IZT#120.FA_PV FP1 compressor guide vane position: 00RFP01_00IZT#120.FA_PV FP2 compressor guide vane position: 00RFP02_00IZT#120.FA_PV FP3 compressor guide vane position: 00RFP03_00IZT#120.FA_PV	N/A	AP BAC1 compressor guide vane position: 00RFP06_00IZT#120.FA_PV AP BAC2 compressor guide vane position: 00RFP07_00IZT#120.FA_PV AP BAC3 compressor guide vane position: 00RFP08_00IZT#120.FA_PV	N/A
Air velocity sensor for the intake air of BAC	N/A		Not available	To be measured: Air velocity of surface BAC fans
Barometric pressure sensor of ambient surface air			Not available	To be measured: Surface barometric pressure
Temperature sensor data collection- Essential				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet evaporator temperature sensor	AP water temperature inlet: 00RFP00_01ITT#202.FA_PV FP1 inlet evaporator water temperature: 00RFP01_00ITT#202.FA_PV FP2 inlet evaporator water temperature: 00RFP02_00ITT#202.FA_PV FP3 inlet evaporator water temperature: 00RFP03_00ITT#202.FA_PV	Not needed	AP BAC plant inlet: 00RFP00_02ITT#202.FA_PV	Not needed

	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Outlet evaporator temperature sensor	AP water temperature outlet: 00RFP00_01ITT#203.FA_PV FP1 outlet evaporator water temperature: 00RFP01_00ITT#203.FA_PV FP2 outlet evaporator water temperature: 00RFP02_00ITT#203.FA_PV FP3 outlet evaporator water temperature: 00RFP03_00ITT#203.FA_PV	Not needed	AP BAC plant water outlet: 00RFP00_02ITT#203.FA_PV	Not needed
Inlet condenser temperature sensor	AP condenser inlet temperature: 00RFP00_01ITT#182.FA_PV FP1 inlet condenser water temperature: 00RFP01_00ITT#182.FA_PV FP2 inlet condenser water temperature: 00RFP02_00ITT#182.FA_PV FP3 inlet condenser water temperature: 00RFP03_00ITT#182.FA_PV	Not needed	AP BAC condenser inlet temperature: 00RFP00_02ITT#182.FA_PV	Not needed
Outlet condenser temperature sensor	AP condenser outlet temperature: 00RFP00_01ITT#183.FA_PV FP1 outlet condenser water temperature: 00RFP01_00ITT#183.FA_PV FP2 outlet condenser water temperature: 00RFP02_00ITT#183.FA_PV FP3 outlet condenser water temperature: 00RFP03_00ITT#183.FA_PV	Not needed	AP BAC condenser outlet temperature: 00RFP00_02ITT#183.FA_PV	Not needed
Outlet pre-cooling system temperature sensor	Not needed		N/A	
Intermediate dam temperature sensor	Intermediate dam temperature: 00RFP00_01ITT#501.FA_PV	Not needed		
Chill dam temperature sensor	Chill dam temperature: 00RFP00_00ITT#506.FA_PV	Not needed		
Air inlet (ambient dry-bulb) temperature sensor of BAC	N/A		-BAC inlet air temperature (dry-bulb temperature): 00RFP00_00ITT#504.FA_PV	Not needed
Air inlet (ambient wet-bulb) temperature sensor of BAC			Not available	To be measured: Surface wet bulb temperature
Air outlet temperature sensor of BAC			BAC outlet air temperature (wet bulb temperature): 00RFP00_00ITT#505.FA_PV	
Temperature sensor data collection- Desirable				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet pre-cooling system temperature sensor	Not available	To be measured: Inlet pre-cooling system temperature	N/A	
BAC outlet water temperature sensor	N/A		Not available	To be measured: BAC outlet water temperature
Water flow rate data collection- Essential				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet evaporator flow rate	AP plant inlet water flow: 00RFP00_01IFT#200.FA_PV FP1 outlet evaporator water flow: 00RFP01_00IFT#200.FA_PV FP2 outlet evaporator water flow: 00RFP02_00IFT#200.FA_PV FP3 outlet evaporator water flow: 00RFP03_00IFT#200.FA_PV	Not needed	AP BAC water flow outlet: 00RFP00_02IFT#200.FA_PV	Not needed

	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Inlet condenser flow rate	FP1 outlet condenser water flow: 00RFP01_00IFT#180.FA_PV FP2 outlet condenser water flow: 00RFP02_00IFT#180.FA_PV FP3 outlet condenser water flow: 00RFP03_00IFT#180.FA_PV	To be measured: AP condenser water flow	Not available	To be measured: BAC AP condenser water flow
Cold water flow rate to underground demand	Water to underground -Column A: 00RFP00_00IFT#504.FA_PV Water to underground -Column B: 00RFP00_00IFT#505.FA_PV	Not needed	N/A	
Water flow rate data collection- Desirable				
	Cooling plant		Surface BAC cooling plant	
	Description & tag name	Practical measurement equipment	Description & tag name	Practical measurement equipment
Outlet evaporator flow rate	Not needed			
Outlet condenser flow rate				

The same approach that was followed for the cooling system of Mine A was also followed for the ventilation system of Mine A and a list of SCADA tags and practical measurements required were compiled and can be seen in Table 43.

Table 43: Data collection done on the ventilation system of Mine A

	Description & tag name	Practical measurement
Current meters on all equipment	Vent fan 1 current: 00VF#01_00IIT#100.FA_PV Vent fan 2 current: 00VF#02_00IIT#100.FA_PV Vent fan 3 current: 00VF#03_00IIT#100.FA_PV	Not needed
Voltage meters on all equipment	Not available	Voltage on specification plates of machinery
Frequency meters for ventilation fan motor	Vent fan 1 frequency: 00VF#01_00IST#260.FA_PV Vent fan 2 frequency: 00VF#02_00IST#260.FA_PV Vent fan 3 frequency: 00VF#03_00IST#260.FA_PV	N/A
Air velocity sensor of surface ambient air	Not available	To be measured: Total ventilation airflow
Air velocity sensor of underground ambient air	Not available	To be measured: Total underground ventilation airflow
General data collection- Desirable		
	Description & tag name	Practical measurement
Power consumption meters	Ventilation feeder 1: 0563 VENT SHAFT FDR NO. 1 Ventilation feeder 2: 0564 VENT SHAFT FDR NO. 2 Ventilation feeder 3: 0565 VENT SHAFT FDR NO. 3	Not needed
Barometric pressure sensor of fan	Not available	To be measured: Measure static pressure of fans
Barometric pressure sensor of underground working area	Not available	To be measured: Measure the barometric pressure of underground working area
Temperature sensor data collection		
	Description & tag name	Practical measurement
Air (ambient underground dry bulb) temperature sensor	BAC inlet air temperature (dry bulb temperature): 00RFP00_00ITT#504.FA_PV	Not needed
Air (ambient underground) relative humidity sensor	Not available	To be measured: Measure ambient relative humidity

ANNEXURE B

The proposed operating procedure for Phase 3 in the electricity reduction strategy of the complex and integrated cooling system of Mine A can be seen below:

- Stop both surface BAC fans when the surface ambient T_{WBD} or T_{WB} drops below 7°C, using PLC control.
- Start both surface BAC fans when the surface ambient T_{WBD} and T_{WB} exceeds 8°C, using PLC control.
- Always run 4 PCT fans.
- Let the FPs stop when the inlet evaporator water temperature drops below 16°C (do not switch off pre-cooling tower fans). The BAC APs will provide enough cooling (2 compressors). The full procedure can be seen in Table 44
- Start the FPs when the evaporator inlet water temperature exceeds 16°C as required (one plant during winter). The full procedure can be seen in Table 45.

Table 44: Strategy to switching off the FPs of Mine A

Procedure
1.1 Surface Refrigeration Plant running as normal: 1.1.1 Ensure that the APs operate as normal. 1.1.2 Ensure that FPs operate as normal. 1.1.3 Ensure that BAC APs operate as normal. 1.1.4 Ensure that all 4 PCT fans are operational for maximum pre-cooling.
1.2 Stopping Fridge Plant operations: 1.2.1 Stop FP compressors when the inlet evaporator water temperature drops below 16 °C. 1.2.2 Stop FP condenser pumps. 1.2.3 Start/stop FP evaporator pumps to maintain the required intermediate dam level.

Table 45: Strategy to start up the FPs of Mine A

Procedure
1.1 Starting Fridge Plant Operations 1.1.1 Start FPs when the inlet evaporator water temperature exceeds 16°C (only one FP is required to be operational during the winter). 1.1.2 Ensure that the APs operate as normal. 1.1.3 Ensure that the FPs operate as normal. 1.1.4 Ensure that the AP BACs operate as normal. 1.1.5 Ensure that all 4 PCT fans are operational for maximum pre-cooling.

ANNEXURE C

An example of a feedback report of the electricity savings initiative (Phase 1) that can be sent to the mine can be seen below. The feedback report was generated manually and includes project savings, load reductions, the control procedure of the phase, surface and underground temperature measurements.

SURFACE BAC ENERGY SAVINGS PROJECT

Generated for:

Mine A

Intervention Feedback

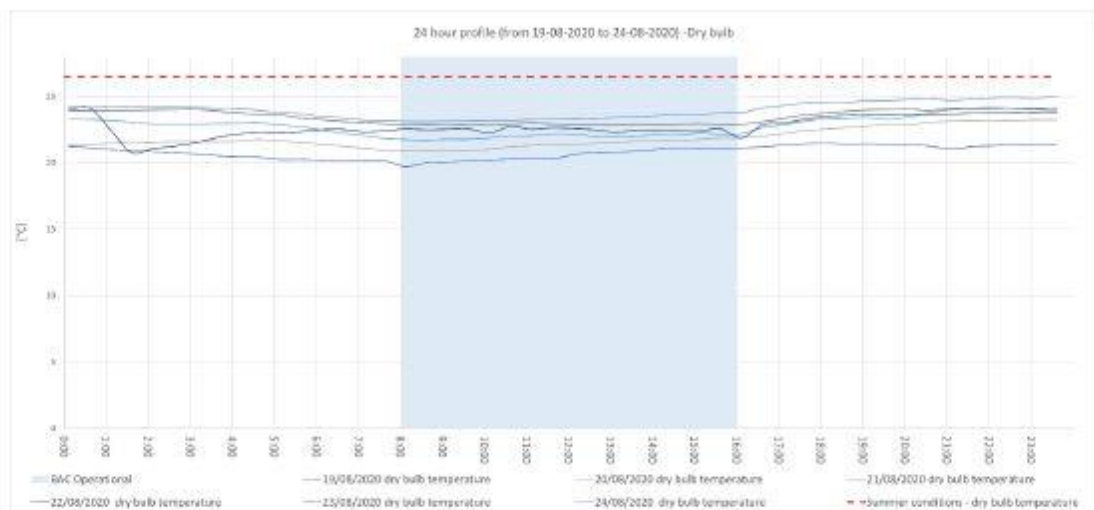
Mine A personnel made significant efforts to reduce electrical demand at Mine A. The surface BAC project was implemented on 01/06/2020. A summary of specific details regarding the project for the week of 19/08/2020 to 24/08/2020 is discussed below.

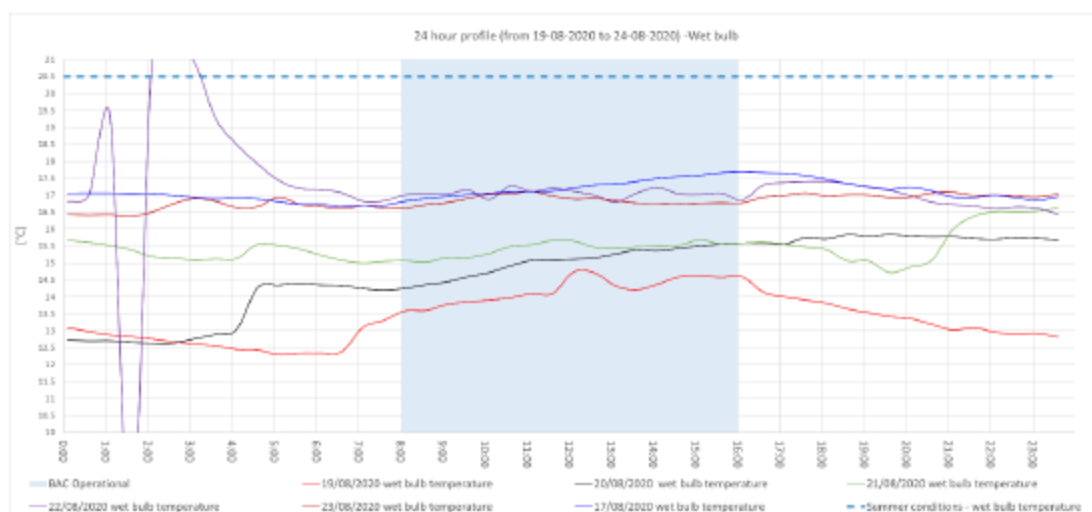
- The savings since this project was partially implemented on 01/06/2020 (until 24/08/2020) is R3 262 000 with an average load reduction of 1.44 MW.
- Note that **ONLY** the surface BAC fans are switched off between 16:00 to 04:00 the following day due to maintenance being done on the Fridge plant machines.
- The transient cooling and ventilation system simulation model was completed on PTB. The **simulation model** showed that the wet bulb and dry bulb temperatures will be below the summer conditions at 2L and 12L as expected. Please let me know if you would like us to discuss the results of the simulation with you.
- The weather station is commissioned, and the temperatures can be seen on the SCADA at the top left of Mine A's Refrigeration tab.
- The temperature probe with the relative humidity sensor was **exchanged** at the 2L station on Tuesday (25/08/2020) and is planned to be exchanged again on Tuesday (01/09/2020).
- The operation of the cooling system is continuously being monitored.
- The table below indicates the underground conditions measured by hand (Note that the green highlighted temperatures indicate that the BAC was operational):

Mine A: Temperatures taken by hand								
Day	Location	Time	Wet bulb	Summer conditions	Difference	Dry bulb	Summer conditions	Difference
01/06/2020	2L	07:35	17.0	20.5	-3.5	21.5	26.5	-5.0
05/06/2020	2L	08:40	18.0		-2.5	24.0		-2.5
05/06/2020	2L	09:10	18.0		-2.5	24.5		-2.0
05/06/2020	2L	09:45	18.0		-2.5	24.5		-2.0
05/06/2020	2L	10:25	18.0		-2.5	25.0		-1.5
11/06/2020	2L	12:58	17.5		-3.0	24.5		-2.0
11/06/2020	12L	07:23	23.5			31.0		
18/06/2020	12L	07:00	23.0			32.0		
18/06/2020	2L	07:30	15.5	20.5	-5.0	20.5	26.5	-6.0
25/06/2020	2L	07:00	16.5		-4.0	23.0		-3.5
25/06/2020	12L	06:15	23.5			30.5		
02/07/2020	12L	06:45	22.5			31.0		
02/07/2020	2L	07:15	16.5	20.5	-4.0	21.0	26.5	-5.5
10/07/2020	2L	06:17	17.5		-3.0	23.0		-3.5
17/07/2020	2L	06:35	12.5		-8.0	20.5		-6.0
23/07/2020	2L	06:35	17.5		-3.0	22.5		-4.0
03/08/2020	2L	07:10	17.0		-3.5	24.0		-2.5
11/08/2020	2L	08:21	17.0		-3.5	21.0		-5.5
18/08/2020	2L	08:17	17.0		-3.5	20.5		-6.0
25/08/2020	2L	07:29	17.0		-3.5	22.0		-4.5

As seen in the table above, the temperatures measured are below the temperatures recorded for the summer conditions (measured on 23/01/2020 while the BAC were operational).

- The figures below show the wet bulb temperatures logged on 2L during the period that the BAC test was implemented and is below the summer conditions:





As seen in the figures below, the temperatures are below the conditions experienced in the summer.

- The table below provides the forecasted average dry bulb and wet bulb temperatures for a town close by to Mine A according to Weather SA:

Date	Forecasted average wet bulb temperature [°C]	Forecasted maximum wet bulb temperature [°C]	Forecasted average dry bulb temperature [°C]	Forecasted maximum dry bulb temperature [°C]
25/08/2020	8.8	14.9	19.5	28.0
26/08/2020	11.7	18.1	17.0	24.0
27/08/2020	11.3	20.4	16.0	26.0
28/08/2020	9.4	16.9	18.0	28.0
29/08/2020	11.1	18.3	16.5	25.0
30/08/2020	11.5	16.5	15.0	22.0

As seen in the table above, the average wet bulb and dry bulb temperatures are still below the agreed temperatures for the project to be implemented.