# Optimal mine water management to improve ambient conditions

**Shamy Manchala Sithole**

**33601666**

orcid.org/0000-0002-7463-4968

Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Mechanical Engineering* at the Potchefstroom Campus of the North-West University

Supervisor: Dr Hendrik Brand

Graduation: June 2021

# ABSTRACT

Title: Optimal mine water management to improve ambient conditions

Author: SM Sithole

Supervisor: Dr Hendrik Brand

Keywords: South African Mines, Water temperature reduction, heat loads, cooling car, Cooling systems, Water control, Fridge plants.

The local mining industry in South Africa is experiencing a decline in gold production. This is due to unique production challenges faced by the industry. One of the major concerns is the production cost associated with the deepening of mines to retrieve the resources. This comes with added operational costs which forces the mines to increase production to maximise profit. This might lead to the closing down of marginal mines.

The increase in mining depth makes it difficult to maintain acceptable underground environmental conditions for the mine workers. Optimal production and productivity from the mine workers are enhanced by optimal underground conditions. The cost of maintaining good environmental conditions is affected by the increase in depth. This encourages deep-level mines to implement cost saving initiatives and underground cooling initiatives by optimising current systems and using the current infrastructure effectively.

One area offering large optimisation potential is addressing the inefficiencies of the cooling systems of deep-level gold mines. These inefficiencies include low cooling duties supplied by the cooling systems and high outlet temperatures on tertiary cooling systems. The cooling systems use water as a primary cooling medium. The mismanagement of chill water used by the cooling systems adds to the inefficiencies of the cooling systems.

Lower service delivery from the cooling systems results in an increase in underground temperatures. High underground temperatures reduce miners' productivity and production because miners are less productive in high temperatures. The water mismanagement adds additional constraints to the system as unnecessary energy is used to remove the water from underground. This in turn results in additional costs which can be better utilised elsewhere.

Different cooling systems are utilized underground. Because less research has been done on tertiary cooling systems, there is more scope for research on these systems. It was evident that a need existed to optimise the water management of tertiary cooling systems in order to

improve underground conditions and reduce energy use in Mine A. A methodology was then developed to identify, evaluate and solve the inefficiencies found on the tertiary cooling systems. This method involved a step-by-step approach which incorporated a root cause analysis and a reconfiguration strategy to optimise water management on tertiary cooling systems.

An investigation performed on Mine A showed that poor water management and inefficient pipeline configurations contributed to high water usage during the off-peak times when system pressures increase. The average duty of the tertiary cooling system was found to be 177kW compared to the design duty of 500kW per cooling car. The average outlet wet-bulb temperatures on the cooling cars appeared to be 28,5°C, which is more than the recommended outlet temperature of 26°C.

The developed methodology was applied, and inefficiencies were identified. A new configuration was then developed which involved the installation of flow regulating valves and the optimasation of the system by maximizing the flow through the cooling cars. Simulations showed that the suggested configuration could lead to an overall decrease of 3,5°C in wet-bulb temperatures and an increase of 4,4 MW in cooling duty across mine A. The simulation on the installation of pressure regulating valves showed an overall saving of 18 ℓ/s in water usage. A suggestion was also made to remove unnecessary components on the system. This showed an expected saving of R640 000 p.a.

The suggested method was implemented on the cooling cars of mine A. All the cooling cars were reconfigured. The cooling cars on the crosscuts allowed water to be reused at the drilling ends. The cooling cars on the main haulages were subsequently fitted with the pressure regulating valves to limit the flow during off-peak time when the system pressure increases. This resulted in a decrease of 4°C in cooling car outlet wet-bulb temperatures and an increase of 2MW in cooling duty. The overall water usage by the cooling cars was reduced by 20,4 ℓ/s which reduced the pumping costs by R4,8m p.a. All the unnecessary pumps were removed and a total of R640 000 p.a. was saved.

The results were validated against the predictions through simulations. The validation yielded an average error of 14%. The reduction in outlet wet-bulb temperatures were used to calculate the overall increase in workers' productivity. This yielded an overall increase of 17%. However, this value could not be verified quantitatively as it is difficult to measure workers' productivity. The study resulted in a total financial benefit of R5,44m p.a. for the presented case study. The objectives of the study were achieved from the outlined case study.

# ACKNOWLEDGEMENTS

I would like to thank and appreciate the following people whose contributions were important to the success of this study:

- ETA Operations for the funding of the project.
- My family for their continuous support in my decision to further my studies.
- Dr Hendrik Brand and Prof. EH Mathews for the opportunity and guidance to complete this dissertation.
- My mentor Dr Charl Cilliers for continued assistance and guidance.
- Finally, I would like to thank God for the knowledge and strength he has given me to complete this dissertation.

**All information portrayed in this dissertation was done acknowledging sources and referencing published work. Please inform me if any oversights are noticed by the reader so that it can be rectified.**

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# LIST OF ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| BAC | Bulk air cooler |
| C/C | Cooling Car |
| DSM | Demand Side Management |
| KPI | Key Performance Indicator |
| PID | Proportional Integral derivative |
| RAW | Return Air Way |
| RCA | Root Cause Analysis |
| SCADA | Supervisory Control And Data Acquisition |
| X/C | Cross Cut |
| PLC | Programmable Logic Controller |
| kW | Kilowatt |
| LMTD | Log Mean Temperature Difference |

# LIST OF SYMBOLS

| Symbol | Description | Units |
|---|---|---|
| #C | Cooling car number | - |
| UA | Heat transfer coefficient | |
| $p$ | Density | $kg/m^3$ |
| $t$ | Time | Seconds |
| n | Efficiency | % |
| h | Head | m |
| P | Pressure | Bar/kPa |
| Kv | Valve coefficient | - |
| $\sum m_i.$ | Sum of inlet mass flow | Kg/s |
| $\sum m_e.$ | Sum of exit mass flow | Kg/s |
| V | Velocity | m/s |
| $Q.$ | Cooling duty | kW |
| $\dot{m}.$ | mass flow rate | Kg/s |
| $C_{pw}.$ | Specific heat of water | $j/kg \cdot ℃.$ |
| $\Delta T$ | Temperature difference | ℃. |
| H | Enthalpy | $kJ/kg.$ |
| $\dot{v}_a.$ | Air volumetric flow | $m^3/s.$ |
| $A.$ | Cross sectional flow area | $m^2.$ |
| RH | Relative humidity | - |
| $Tw_{in}.$ | Inlet water temperature | ℃. |
| $Tw_{out}.$ | Outlet water temperature | ℃. |
| $Tout_{_db}.$ | Outlet dry bulb temperature | ℃. |

| | | |
|---|---|---|
| $Tout_{_wb}$. | Outlet wet bulb temperature | ℃. |
| $T_{in_wb}$. | Inlet wet bulb temperature | ℃. |
| $T_{in_db}$. | Inlet dry bulb temperature | ℃. |

# GLOSSARY

| | |
|---|---|
| **“Baseline”** | Data reference point used for future comparison |
| **“Cooling car”** | Mobile air cooling units |
| **“Cooling coils”** | Heat exchangers found in cooling cars |
| **“Cooling Duty”** | The measure of a coolings systems capacity to remove heat/ Removed heat by the cooling system. |
| **“Sweeping shift”** | Process of collecting all the blasted rock from the stopes and loading it into hoppers |
| **“Change of shift”** | Period where the sweeping crew give way to the drilling crew for the next drilling period. |
| **“Blasting”** | Process of using explosives to break large rock bodies into smaller pieces for excavation |
| **“Peak drilling period”** | Refers to the mine drilling time |
| **“Service delivery”** | Refers to principles and standards supplied for production purposes |
| **“Haulage”** | Mine main travel way connecting the mine shaft/station to the cross cuts. |
| **“Cross cut”** | travel way connecting stope areas with haulages |
| **“Footwall”** | Surface water channel in the cross cut or haulage |
| **“Validation”** | Process used to ensure the obtained results accurately address the problem statement |

| | |
|---|---|
| **“Verification”** | Process of ensuring the developed solution strategy is accurate and can be used |
| **“Stope”** | Mine site containing the rock face |
| **“Off peak drilling periods”** | periods excluding mine drilling periods |

# 1 INTRODUCTION

## 1.1 SOUTH AFRICAN GOLD MINES

South Africa has been the leading producer of gold in the world until China took over in 2009. According to P. N. Neingo and T. Tholana [1] South Africa is currently ranked fifth in the world, following China, Australia, Russia and the USA. South Africa has a comparative advantage due to its mineral endowment, but it fails to translate the comparative advantage into competitive advantage because of mine industrial challenges. The mining industry strives to address these challenges to remain competitive globally [1].

The gold mining industry plays an important role in the South African economy. It creates employment for over 104 369 of 490 146 people in the mining sector. There has been a significant decrease in employment numbers since 2012. Figure 1 shows that the employment in the mining sector decreased to 21% in 2015 as compared to the 27% in 2012 [2].

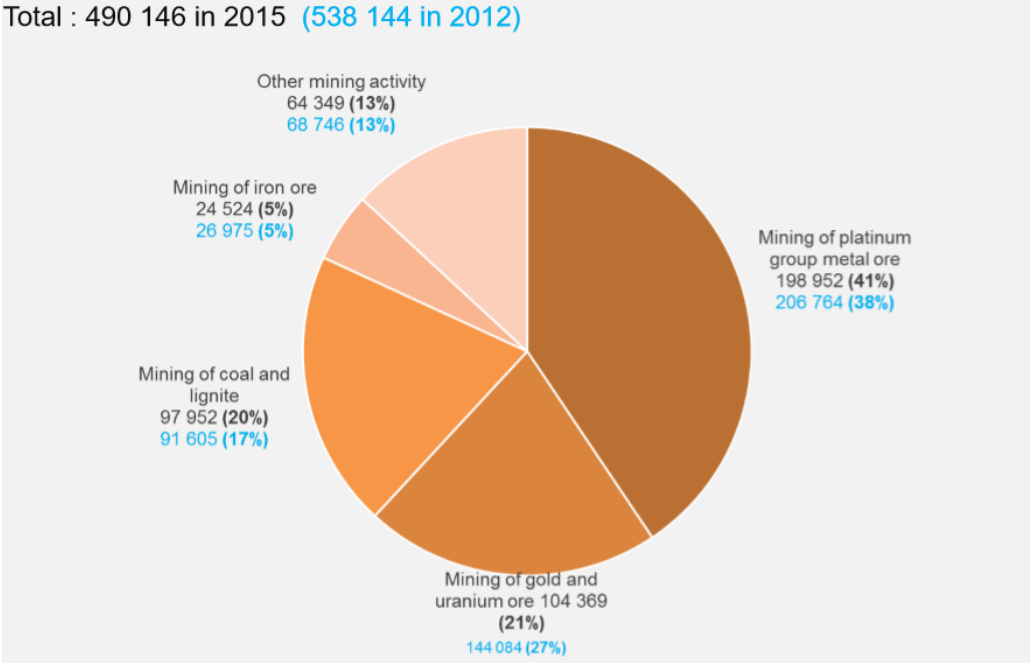



*Figure 1: Employment comparison by activity between 2012 and 2015 [2]*

The gold mining industry has been the largest South African employer between 1995 and 2006, as reported by statistics South Africa [2]. The gold mining industry moved to second place as it was surpassed by the platinum group metals industry as the largest mining employer. The gold mining industry shows a rapid decreasing trend. Figure 2 illustrates the decline in gold mine employment for South Africa from 1995 to 2014 [2].

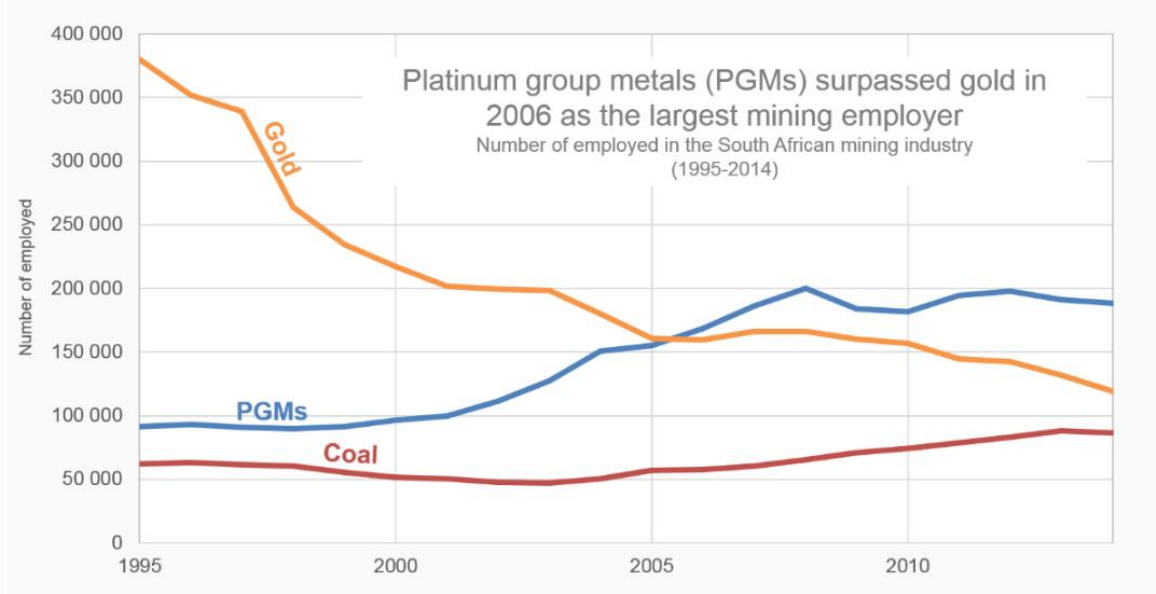
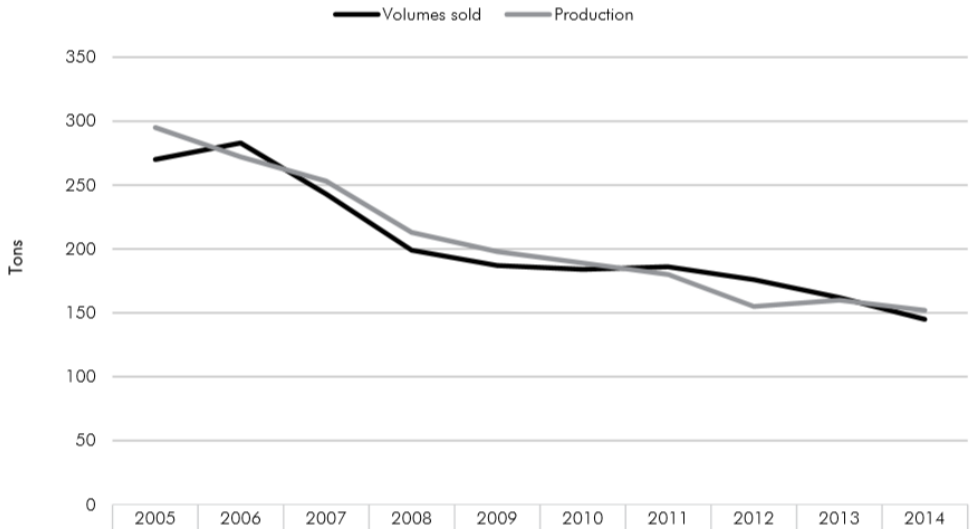



*Figure 2:The decline in gold mine employment from 1995 to 2015 [2]*

Gold production declined from 295 tons in 2005 to 152 tons in 2015, a significant decrease of 48%. A 3,2% increase in 2013 was an exception to the general declining trend. Gold volumes sold followed a similar trend. They decreased by a significant margin of 46,3% from 270 tons in 2005 to 145 tons in 2014 [3]. Gold ore grade has declined from 12 grams per ton (g/ton) in 1970 to approximately 5 g/ton in 2016 [4]. Figure 3 shows the decline in gold production and the gold volumes sold [3].




| | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 |
|---|---|---|---|---|---|---|---|---|---|---|
| Volumes sold | 270 | 283 | 243 | 199 | 187 | 184 | 186 | 176 | 162 | 145 |
| Production | 295 | 272 | 253 | 213 | 198 | 189 | 180 | 155 | 160 | 152 |

*Figure 3:Gold production and volumes sold, 2005-2014 [3]*

Research has indicated that the output of the gold mining industry, and its contributions to the economy of South Africa, is on a decline. The South African mineral council reported that 75% of South African gold mines are unprofitable, or barely making money [5]. There are still massive gold resources in South African gold mines with approximately 39 years before depletion [6][7]. But, to recover these resources, mines need to go deeper [8]. The greater the depth, the more challenges the mines is exposed to.

In 1995, close to 10% of South African gold production came from depths greater than 2 500m [8]. It was projected that by the year 2010 approximately 60% of the gold production will come from a depth greater than 2 000m [9]. It has also been projected that 50% of the production will come at a depth greater than 2 500m in 2015 [8]. A total of seven South African gold mines features in the world's top ten deepest mines. In 2019, the majority of gold mines ranged from depths of 2 500m to 4 000m with close to six mines having a greater depth than 3 000m [10]. As mine depth increases, so do the technical challenges, heat exposure, operating and input costs.

The increase in mining depth makes it very difficult to maintain acceptable underground environmental conditions for the mine workers. It also affects the initial desired operating

design conditions of the underground cooling systems. Good production and productivity from the mine workers are enhanced by good underground environmental conditions. Studies also show that there is a relationship between environmental conditions, productivity and accidents rates [11], [12]. The range of workplace air temperatures is typically 27,5ºC to 29ºC [11]. The cost of maintaining good environmental conditions is affected by the general increase in depth. Figure 4 shows the relationship between the wet-bulb temperatures and the general mine worker's loss in productivity.

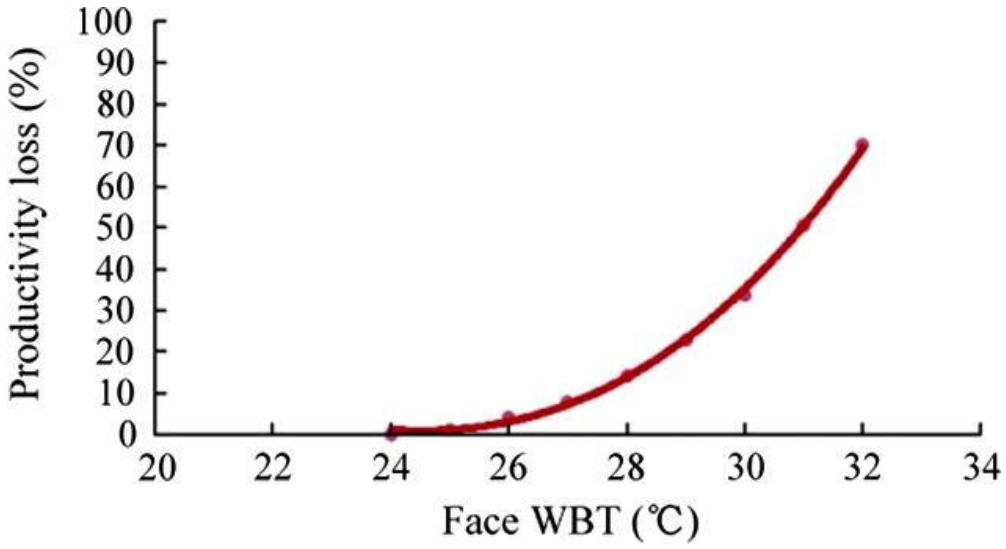



*Figure 4:Face WBT vs productivity loss [12]*

The following equation can be used to calculate the productivity loss experienced by the miners:

$$P_{loss} = AT^3 - BT^2 + CT \quad (1)$$

Where:

$P_{loss}$= Productivity loss

$T$ = Face wet-bulb temperature

$A$ = 0.0383 (Experimental value)

$B$ = 1.8787 (Experimental value)

$C$ = 23.067 (Experimental value)

The hierarchy of cooling systems was established in 1998 in South Africa to provide an outline of a basic structure for different stages of implementation of cooling methods as mine depth increases. The general hierarchy has been previously used in different studies and referenced. For instance, Belle and Biffy [12] used the same hierarchy principle. Figure 5 Depicts the generic hierarchy of the application of mine cooling at depth.

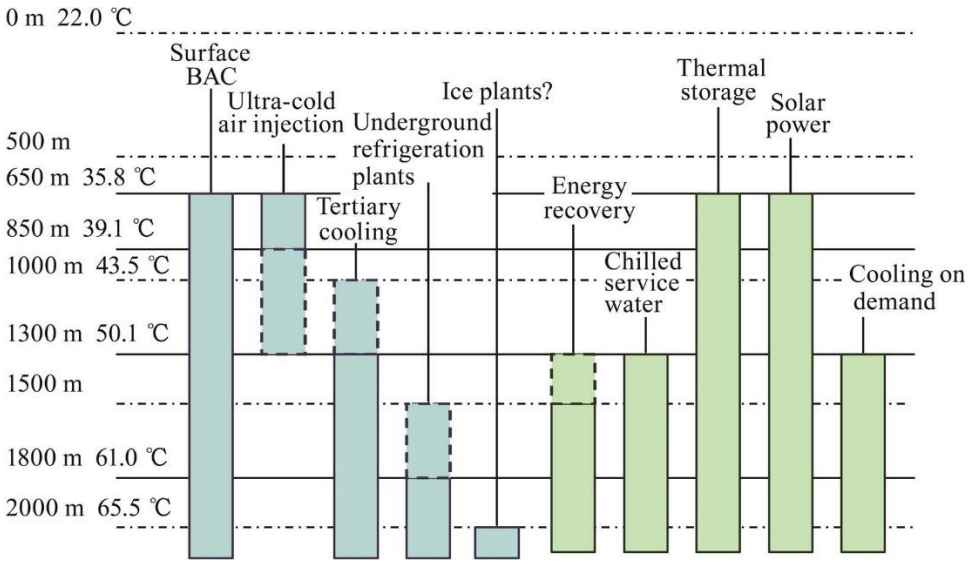



*Figure 5: Platinum mine cooling hierarchy [12]*

Figure 5 outlines the phases of the cooling methods which can be employed as the mining depth increases. The first part of the hierarchy is ventilation. Ventilation is a system used to ensure that the acceptable underground conditions are always maintained. But, below a depth of 1 600m ventilation alone is inadequate to maintain safe underground air temperatures., This is due to the increase in cooling demands from rapid exposure of the virgin rock [13]. Cooling systems, then, becomes a dominant operating cost factor. The cooling systems include surface bulk air cooling, underground primary bulk air cooling, underground secondary and tertiary cooling, cold water from surface and ice from surface.

Cooling systems depend on water as a primary cooling medium. These cooling systems are generally incorporated with ice plants and fridge plants to ensure that the temperatures of the water as a cooling medium is always as low as possible.

There are different factors that affect water temperature as a cooling medium. This results in the water temperatures not meeting the expected demands of the cooling systems, and thus in inefficient cooling. There is a great need in mines to improve underground ambient

conditions in order to satisfy the workers. This can be achieved by optimizing the performance of the cooling systems. The optimal management of the cooling systems' water becomes critical since the water serves as a primary cooling medium.

This study focuses on the optimal management of mine cooling systems' water to improve the cooling performance and mine operation conditions. Different cooling methods are evaluated to study the impact of water on underground cooling.

## 1.2 MINE WATER CONTROL AND COOLING SYSTEMS

Water is an important medium for south African deep mines, since ventilation is inadequate for mines deeper than 1 600m [13]. Temperatures increase as the mining depth increases – the mine is exposed to virgin rock temperatures of 60 ºC at 4 000 m depths [14], and this makes it difficult to maintain acceptable working conditions, which are defined by the mining industry in South Africa as wet-bulb temperatures less than 27,5ºC. It is also important to ensure that machines operate within the manufacturers' design specifications and temperature limits [15], [16]. Figure 6 shows the relationship between the mine depth and the virgin rock temperature (VRT).

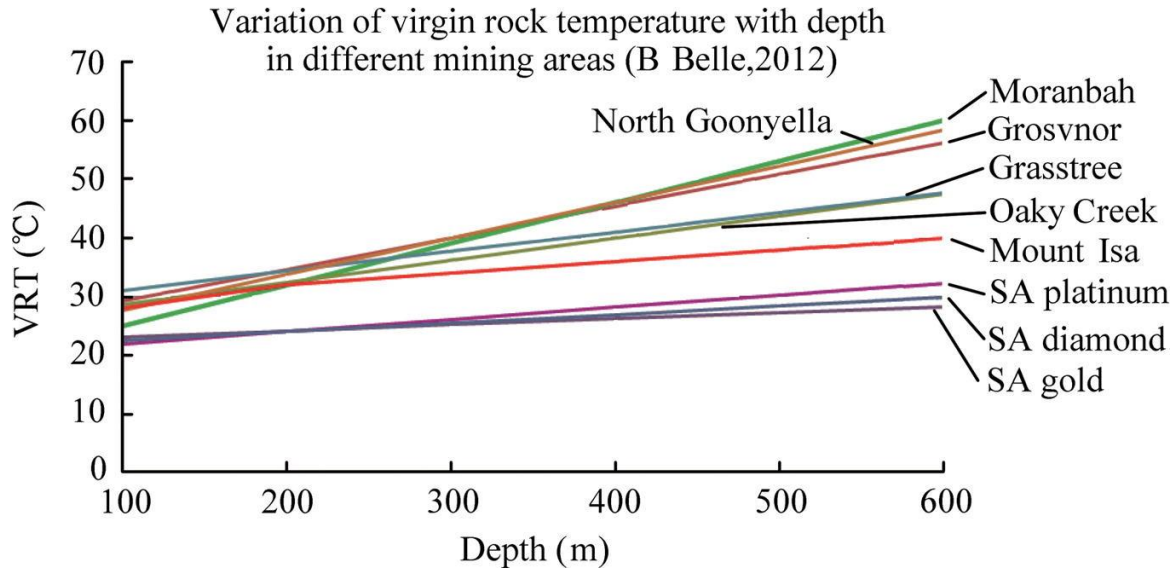



*Figure 6:VRT vs Depth [12]*

This figure illustrates the necessity of secondary and tertiary cooling systems for deep mines with depth greater than 1 600m. However, the secondary and tertiary cooling systems depend greatly on the chill water. Instead of other fluids, water is primarily used because of its cooling

abilities. Studies have shown that sending chilled water underground reduces the wet-bulb temperatures in the working stopes [17], [18]. After being utilised, The water needs to be returned to surface to be cooled.

The water reticulation system distributes the water to air cooling systems and mining activities. It is vital to understand the main uses of water underground. Chilled water is utilised underground for the following mining activities [19], [20]:

- At the stopes for air cooling (using cooling systems)
- Rock drilling, where it is used as working fluid and cooling fluid
- Dust suppression, and lastly
- Sweeping after blasting and general cleaning

The underground water demand heavily depends on the mine operating schedule. Different mines have unique schedules, but all mines have adopted the concept of shift for general operation. The mine has a total of 3 shifts which include the morning shift, afternoon shift and night shift.

- Morning–Drilling shift: Holes are drilled into rock surfaces, so that the explosives can be placed into them. As mentioned, the water is used as a working fluid. The water also serves as dust suppression on the stopes and crosscuts. Some mines prefer the working areas to be cleaned in the morning shift for reasons of health.
- Afternoon - Blasting shift: After the holes have been drilled, all workers are cleared from underground and explosives are triggered. Minimal water is used during these hours; most of the water is used for cooling systems.
- Evening – Cleaning shift: After blasting the virgin rock, the ore is cooled and moved to loading boxes for extraction to surface. Water is used for cooling, dust suppression and swiping during this shift.

Mines generally operate for 24 hours per day. Figure 7 shows a typical mine water demand profile for a 24-hour period. The morning is normally between 6:00 and 13:00, the afternoon shift from 13:00 to 20:00 and the evening shift from 20:00 to 6:00 am of the next day.

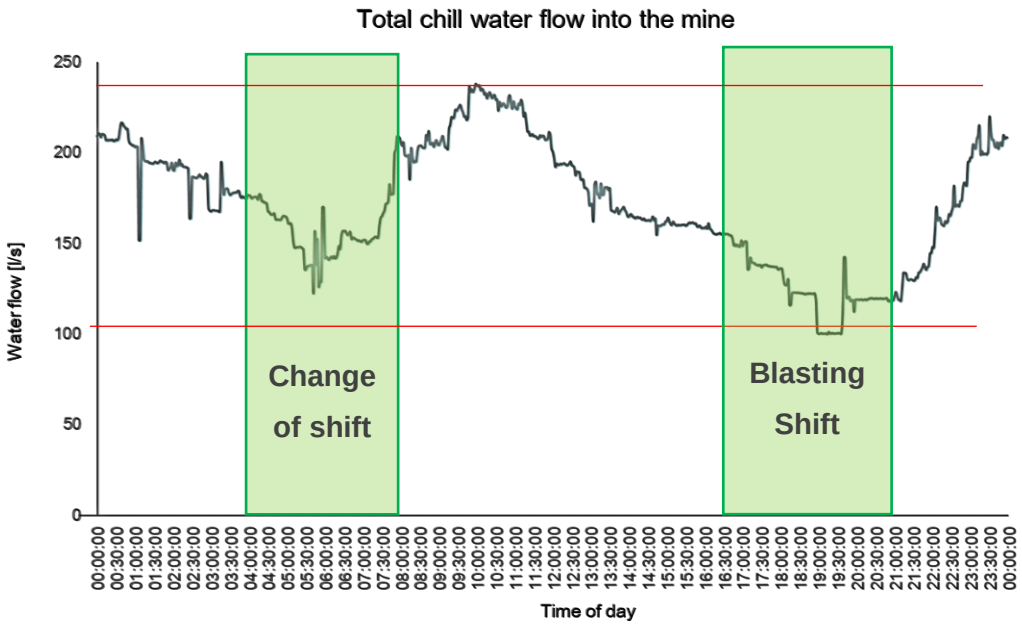



*Figure 7:Chill water sent underground (Harmony gold mine)*

No mining occurs during the blasting shifts. From the graph it can be seen that most of the water consumption during this time went towards usage by cooling systems and the remainder went into water leaks. It is evident from the graph that close to 50% of water consumption goes into either cooling systems or leakage. The maximum amount of water used by the mine is 240 ℓ/s and the minimum is 100 ℓ/s. Activities that consume water include drilling and other mining services.

Two of the main concerns when it comes to water management are the wastage of water, as well as the electricity bills associated with the pumping of water back to surface. The water used for underground systems needs to be circulated throughout the duration of the mine working hours. The system that integrates refrigeration, underground water supply and the general dewatering system is called the water reticulation system. In deep level mines the water reticulation system is the primary consumer of electricity, consuming close to 41,9% of the total energy used at a gold mine [21].

Therefore, there is a great need to continuously decrease the electricity usage in deep mines, especially since the cost of electricity has been increasing constantly since 2008. It should be

clear that the optimization of water management should contribute to large savings on electricity bills.

In order to achieve significant cuts in the electricity bill by optimization of water management, it is essential to understand the basic water reticulation system of a typical deep gold mine as it outlines a clear overview of the general water management in underground mines. The water reticulation system consists of the following integrated systems:

- Mine water control and distribution
- Mine cooling systems

Figure 8, which depicts a simplified layout of the water reticulation system, will assist to further discuss the above-mentioned systems in more detail. Each of these systems contributes to achieve safe working conditions for the underground workers [25], [26], [27]. The cold and hot water channels are indicated by blue (cold) and red (hot) lines respectively, the precooled water is indicated by organed (warm).

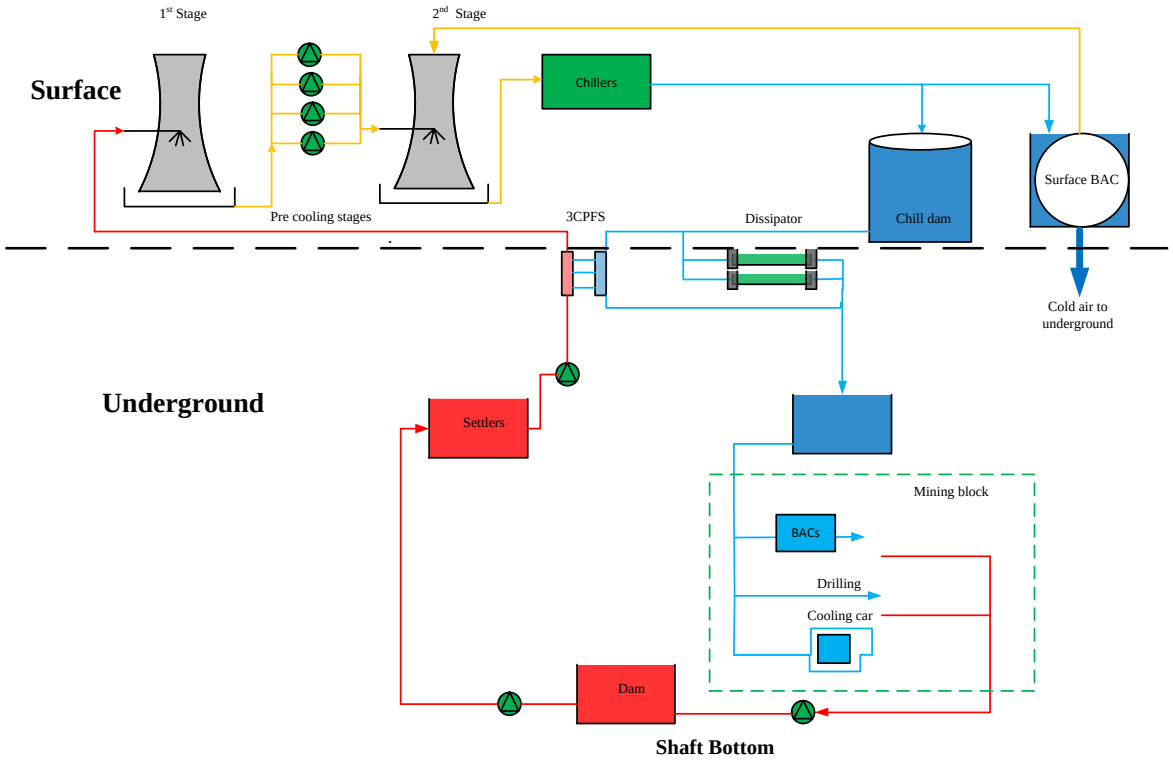



*Figure 8: Simplified mine water reticulation system*

The process of the water reticulation system generally starts with hot water from underground being pumped to the surface. The water is then pumped through the pre-cooling towers. The pre-cooling towers pre-cool the water for the water chillers. The water is normally stored in the hot storage dam to provide a storage capacity for the water to ensure constant supply to the chillers [28].

The chillers cool down the water to a set temperature and send it to the chill water dam or to the surface bulk air coolers. The chill water dam is used as a storage mechanism to ensure that there is continuous and uninterrupted supply of chilled water to the mining operations. The bulk air coolers use chilled water to provide cooling for the underground activities, using air as a cooling medium. The water that flows through the Bulk air coolers is pumped back to the pre-cooling dam.

The chilled water is gravity fed from the surface chill water dam to the underground chill water dam where it is effectively distributed to the mine working areas [29], [30]. The used water from the mining activities is channelled through the settlers to separate mud from the water. The water is then pumped back to the surface to repeat the water reticulation cycle.

Figure 9 depicts a typical mine water reticulation system incorporated with surface ice plants instead of the precooling system and the normal surface chillers.

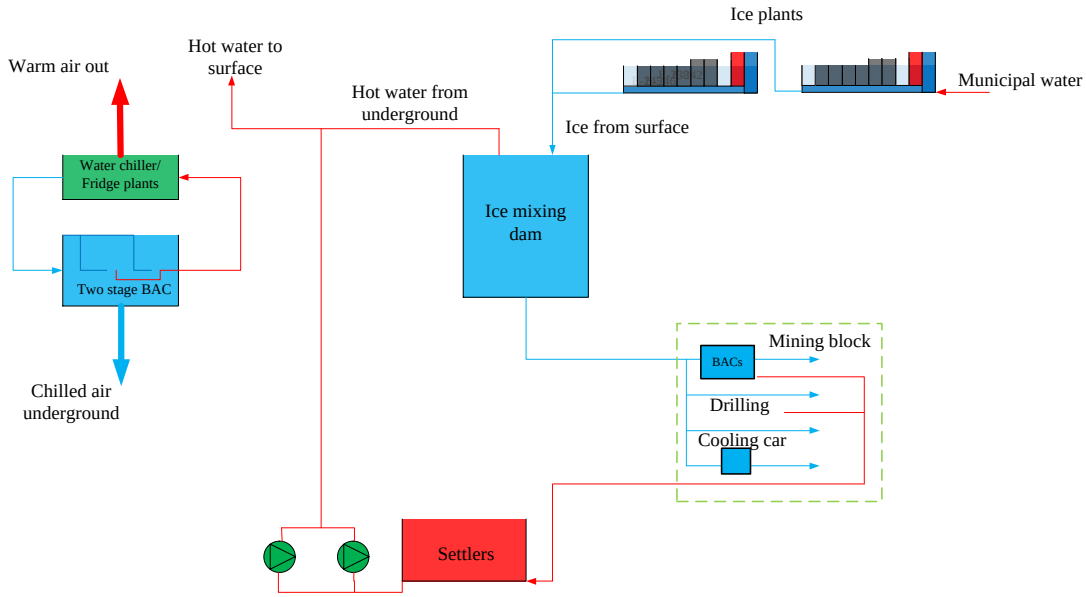



*Figure 9:Deep mine water reticulation system with ice plants*

The water reticulation system for this type of mine is a closed loop where the water is treated underground and reused by being introduced back into the ice dam which will in turn be cooled using the ice from surface.

The process starts with the ice blocks sent from surface to the ice dam. The ice dam receives additional hot water from underground. The ice and the hot water mix to result in chill water which is sent underground to the mining block. The chill water is used for drilling purposes and to provided underground cooling through cooling cars and BACs.

The hot water from the mining block is sent to the settlers where the water gets treated before it gets pumped back to the ice dam. Some mines consist of a closed loop system which includes the water chillers and the multistage bulk air coolers.

The cooling cars and BACs require chilled water at the lowest temperatures possible. Mines are focusing more on the optimisation of the ice dam to ensure that the chill water is cold enough to reach the cooling cars and BACs.

### Mine water control and distribution

There are different processes used to control water to enable safe working environments. The water that goes down to the mine needs to be controlled and channeled properly as it may cause damages on the pipelines, the reason being that water is an incompressible fluid that induces high pressures on the pipelines due to the considerate head. [26], [31]. Water control also assists with the necessary water and energy saving strategies to limit wastages in the system. Valves and pumps form an integral part of water control in underground mines. Actuated valves are commonly used to control the water systems [32].

Valves vary considerably by area of application; these applications can vary from simple flow obstructions to complex structures designed to strict specifications. The general use of valves is opening, closing and partial obstruction of a pipeline with a medium (such as water) flowing through it [33]. The valves commonly used in underground mines are listed below:

- Control valves with actuators
- Throttle valves

### *Control-Butterfly valves*

The butterfly valve depicted in Figure 10 is a stem-mounted disk that, when closed, seats against an O-ring or compliant seal near the pipe surface. A single 90-degree turn opens the valve completely, hence the design is ideal for controllable quick opening and quick closing situations which typically occur in the fire protection industry and the electrical power industry. However, a considerable dynamic torque is needed to close these valves, and losses are high when the valves are nearly closed.[34].

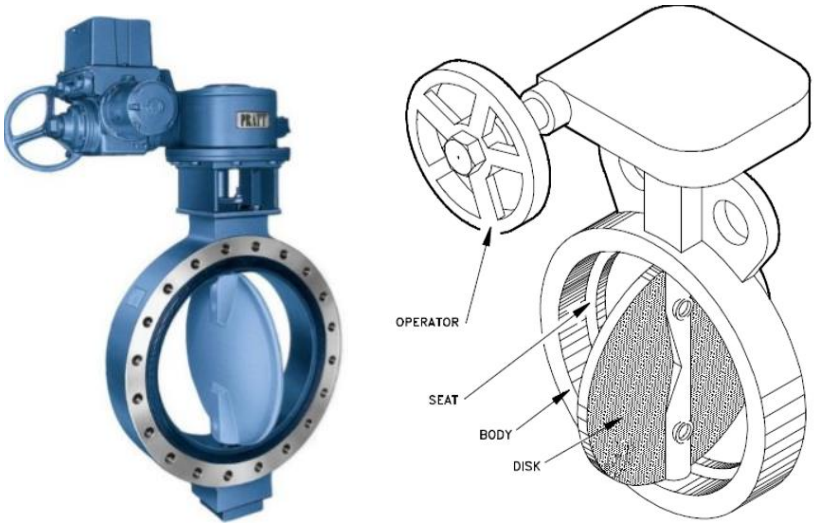



*Figure 10: Butterfly valves*

Butterfly valves consist of a valve body, a seat and a disc. The disc is located directly in the pipe through which the liquid flows. The shaft of the butterfly valve is usually connected to an actuator, where the valve can be automated and controlled. The disc is used to open and close the flow. When the disc is perpendicular to the flow, the valve will close, and the valve will open when the disc is parallel with the flow. The disc also restricts flow even when the valve is completely open, resulting in a pressure drop at all times [33].

Butterfly valves are generally used in water control applications with high pressure ranges and flow rates in large industrial plants [35]. The valve can be easily controlled and throttled since it ensures a low pressure drop at larger valve openings [36]. The pressure drop across the valve dramatically increases as the valve closes; this is caused by the nature of the valve design. This generally causes problems such as cavitation and water hammer [37]. An

advancement in the valve geometry and design can strengthen the usability of the butterfly valve for control purposes [38].

### *Throttle valves.*

A throttle valve is placed in series with the pump making it possible to adjust the duty. The throttling results in a reduction of flow is depicted in Figure 11. The throttle valves add resistance to the system and raise the system curve to a higher position. Without the throttle valve the flow is Q2 and with the throttle valve the flow is reduced to Q1 [39].

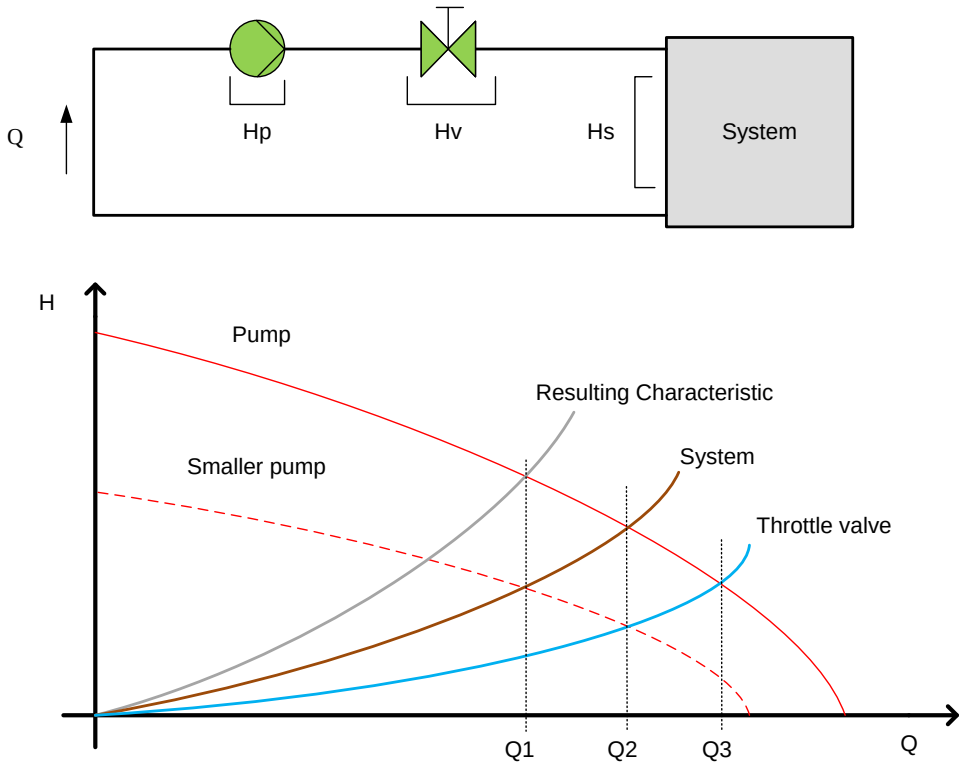



*Figure 11: Throttling control [39]*

Throttle valves can be used to limit the maximum possible flow. Flow generally depends on the pressure or head induced in the system by a pump. Generally, for systems without throttling valves, the flow cannot be regulated as it will always increase when the pressure in the system increases. The throttling valve is used to restrict the flow to a certain value when the pressure increases in the system. The throttling valve is also used to adjust the performance of pumps.

One of the commonly used throttling valves is the Maric flow regulating valve. The Maric flow valves maintain a constant pre-set flow rate of water over a wide pressure range. The valve offers many benefits and valuable protection for the following components:[40]

- Flow rate sensitive pumps
- Filters
- Pump glands
- Water distribution systems

Figure 12 shows a typical Maric flow valve. The technology of the Maric valves is based on a precision molded rubber control ring installed in the body of the valves with an orifice diameter that varies in response to the pressure differential applied to it. The greater the pressure, the smaller the orifice, and vice versa, thereby maintaining a constant flow. The advantage of these valves is that the valves are compact, self-cleaning and maintenance free throughout the life of the valve [40].




*Figure 12: Maric throttling flow valves [40]*

### *Valve sizing and selection*

It is critical that the correct size and type of valve is selected for a particular application. Valves have different losses which are commonly measured experimentally and correlated with the pipe flow parameters. The concept of determining the ability for a valve to obstruct or allow flow is the same for all valves. The difference between valves lies in their specific design by the manufacturer and their ability to restrict flow [38].

The first step required in valve selection includes determining the operating conditions that the valve needs to adhere to. These conditions include [42]:

- Pressure drop
- Flow (minimum and maximum)

- Operating temperature (minimum and maximum)
- Fluid type and properties
- Application environmental conditions and state (e.g. muddy or dusty areas)

The second step includes the calculation of the valve flow factor (K). The valve flow factor (K) indicates the relationship between the pressure difference over the valve and flow through the valve [41]. The higher the valve flow factor, the higher the flow through the valve. It is important that the valve flow factor is calculated correctly, as it outlines the physical capabilities of a valve. The valve flow factor is calculated using Equation 2.

$$K_v = Q(\frac{\Delta P}{S_g}) \quad (2)$$

Where:

$$K_v = Valve\ flow\ factor$$

$$Q\ = Volume\ flow\ (m^3/s\ )$$

$$\Delta P = Pressure\ drop\ (bar)$$

$$S_g = Specific\ gravity\ (Water = 1)$$

Water reticulation systems are complex and large as they run throughout the mine. It has been discussed above that different valves are used to control the water in the system. In order to control these valves, actuators are used to allow the valve to prompt flow obstruction. Automated valves generally use electric or pneumatic actuators that are automatically triggered [43],[44],[45].

Valves such as the Maric flow valves do not require any special instrumentation. These valves are usually preset and are used in areas with limited instrumentation or control systems. The valves are meant to limit the flow to the desired maximum. The technology of these valves makes it easy for the valves to be controlled without a need for additional instrumentation.

### *Water flow to pressure relationship*

In order to be able to analyze the water reticulation system and to understand the relationship between the general pipe losses in the system and the flow characteristics of the chill water, different governing equations need to be analyzed. The Bernoulli steady state energy equation is used to analyze water reticulation systems.

It is important to note that the principle only holds true under the following conditions:

- Steady state conditions
- Constant density evaluation
- Points 1 and 2 lie on the same streamline

One of the driving factors in the pipeline system is the pressure difference. The pressure difference in the system is induced by different pipeline losses. These pipeline losses are inherent in any system where fluid is involved [34]. Most fluid dynamic simulation software use the concept of the Bernoulli steady state energy equation for analysis. The simulation uses Darcy-Weisbach equations for iterating to fluid dynamic solutions.

There are major and minor head losses. The theorical calculations for these categories are outlined in **Appendix A**. It is important to select software that has proven to simulate these theoretical concepts accurately.

### *Water reticulation pumps*

Pressure serves as a main driving factor for the water flow rate in the water reticulation system. It is always necessary for the water reticulation system to have enough pressure to overcome all the head losses for the water to reach the desired destination. The overall pressure on the water reticulation system is lowest when reaching the stopes. Mines generally use pumps to boost the water to the stopes. After use, the service water needs to be removed from underground; pumps are used to pump the water back to surface.

Electrical energy (in kWh) is required to pump water. The required energy depends on the required flow and head that the pump needs to overcome. Figure 13 shows the relationship between the head (m) and the flow ($m^3/s$) in parallel pumps. The theoretical energy at a given head, flow and time can be calculated using Equation 3 [46].

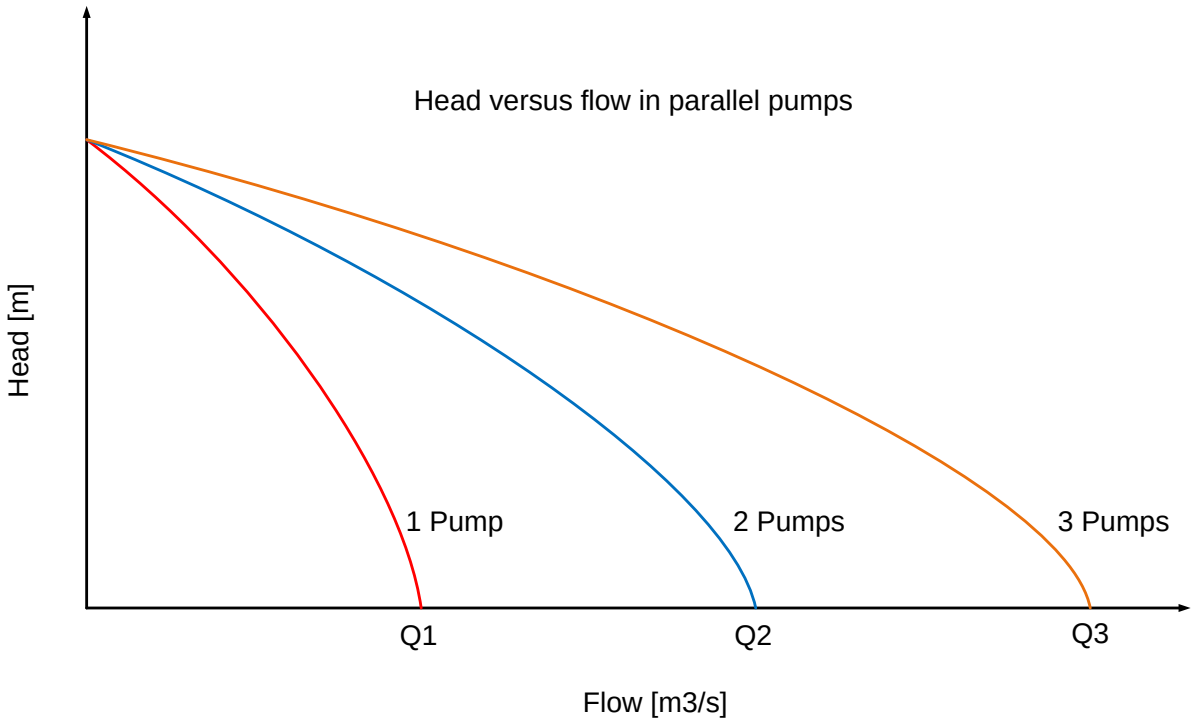



*Figure 13: Head versus flow in parallel pumps [46]*

$$E = \left(\frac{\rho \times g \times Q \times h}{\eta}\right) \times t \quad (3)$$

Where:

$E$ = Energy (kWh)

$P$ = Density of fluid $(kg/m^3)$

$g$ = Gravitational constant $(m/s^2)$

$Q$ = Flow in $(m^3/s)$

$h$ = Head in $m$

$\eta$ = Pump overall efficiency

$t$ = Time (hours)

It is important to note that the required energy is directly proportional to the head, the flow and the time. The higher the head and flow and the longer the time, the higher the energy required

to pump the water. If the flow and the system head losses are not optimized, more energy will be used, thus leading to wastage.

Eskom uses time of use structures (TOU) to bill consumers for electricity usage according to certain times of the day. The structure was introduced due to high electricity usage of industrial and mining companies. Consumers who uses a notified demand of more than 1 MVA fall within the Megaflex tariff structures category. Mining and industrial companies fall within this category. [47]

The Megaflex tariff structure bill consumers according to their time of use in 3 different periods; namely peak, standard and off-peak times. The electrical cost (Charged as c/kWh) changes daily and seasonally [47]. Megaflex tariff structures for a typical gold mine within 300 km of Johannesburg, South Africa is depicted on Figure 14.

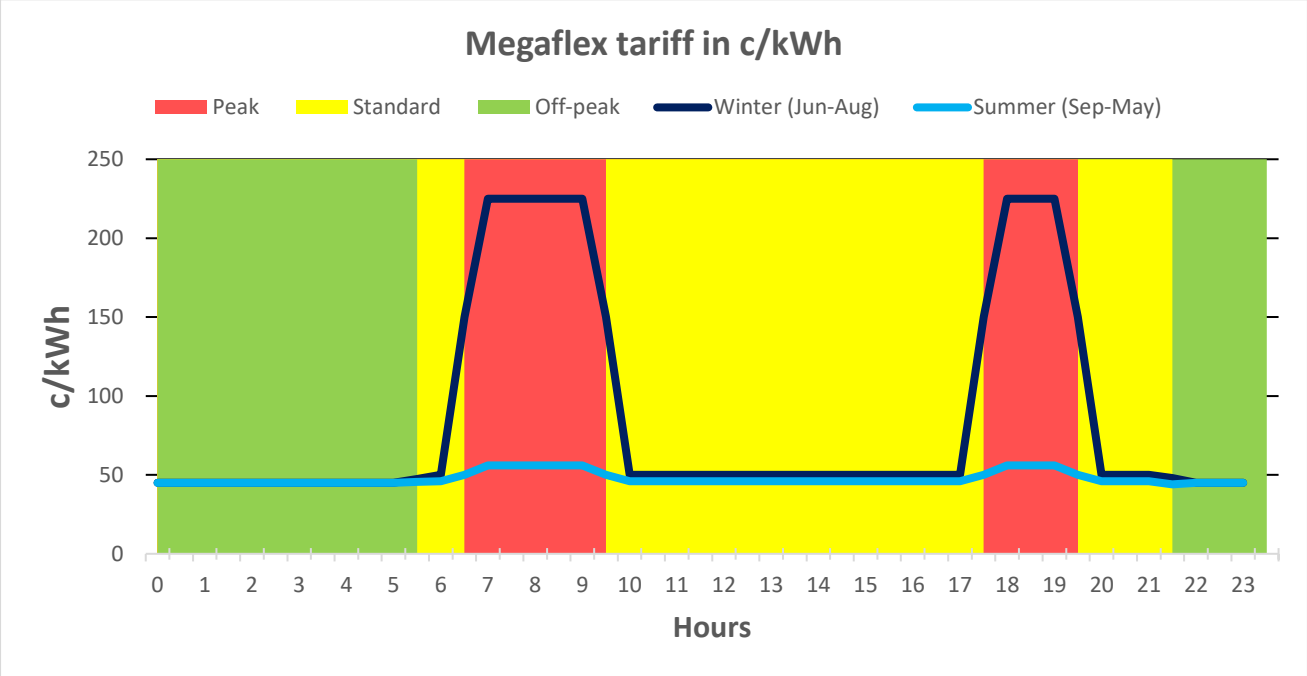



*Figure 14: Eskom Megaflex tariffs [47]*

It can be seen from Figure 14 that the tariffs increase drastically in winter times during the peak times. The Megaflex tariff structure can be used to quantify the total energy used by different mining components which consume electricity. Proper management of component use can lead to energy savings.

## Mine Cooling systems.

The Mine Health and Safety Act 29 of 1996 requires the mine to maintain underground wet-bulb temperatures below 27,5ºC [48]. There is a direct relationship between the mine workers' effectiveness and the underground wet-bulb temperatures. As soon as the temperatures on the stopes rise above 28ºC, the effectiveness drops drastically [48]. The human body starts absorbing heat as soon as the underground temperatures go beyond 37ºC. The underground dry-bulb temperatures need to be kept below 37ºC [49]. The effect of wet-bulb temperatures on the effectiveness of mine workers is illustrated in Table 1.

*Table 1: Effects of wet-bulb temperatures on work efficiency [50]*

| Wet-Bulb temperatures | Workers' efficiency |
|---|---|
| Wet-bulb temperatures < 27 ºC | 100 % efficient |
| 27 ºC < Wet-bulb temperatures < 29 ºC | Economic efficiency |
| 29 ºC < Wet-bulb temperatures < 33 ºC | Corrective action required |
| 33 ºC < Wet-bulb temperatures | Worker can be exposed for short periods |

Chilled water is required in deep level gold mines to cool the underground environment. Air coolers consume chilled water to cool underground environments. Chill water coolers are used to cool down water coming from underground. Mines generally use ice plants and fridge plants to cool down underground water to meet the desired mine requirements. Water cooled by the ice plants and fridge plants ranges between 2ºC and 6ºC [51],[52].[53].

The mine's cooling system ensures that the underground working environment temperatures are maintained under crucial conditions and that the workers' productivity and safety is ensured. The cooling systems also ensure that the underground mining equipment functions properly with limited breakdowns as a result of heat [54]. An improvement in ambient temperatures results in an increase in the general mine production and profit increase [55].

## Mine water cooling systems

Mine water cooling systems are used to cool underground service water to allow for underground air-cooling systems to meet minimum cooling requirements. Deep mines use fridge plants and ice plants to cool down the water. These components are discussed in detail below.

### Fridge plants

Fridge plants are generally used to cool down underground hot water. Fridge plants consume close to 66% of the cooling system's total power [56]. The refrigeration process works on the principle of the vapour compression cycle to lower the water temperatures [57]. The vapour compression cycle is generally used in cooling systems found in automotive industry, malls' HVAC cooling systems and households [58]. Mines utilize the vapour compression cycle due to its low operational cost and simplicity as compared to other existing cycles.

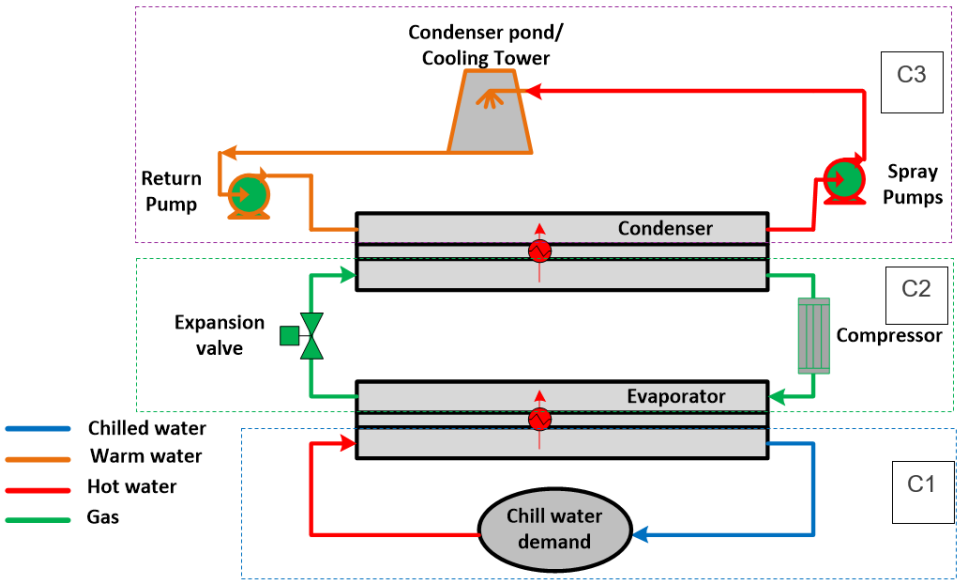



Figure 15 shows the refrigeration cycle and different components found in the refrigeration cycle.

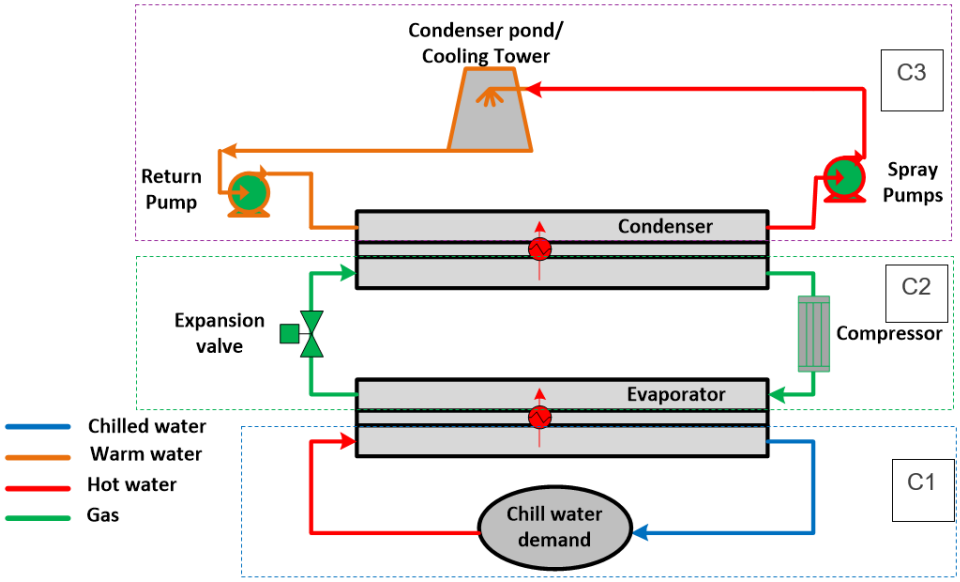



*Figure 15:Refrigeration cycle*

The refrigeration system is made up of three cycles: The refrigeration water cooling cycle, which is cooled down by the refrigerant and discharges heat to the refrigerant cycle; the refrigerant gas cycle that extracts heat from the water in the evaporator and discharges it into the condenser; and lastly the condenser water cycle which extracts heat from the system to the external environment. The cycles are illustrated in

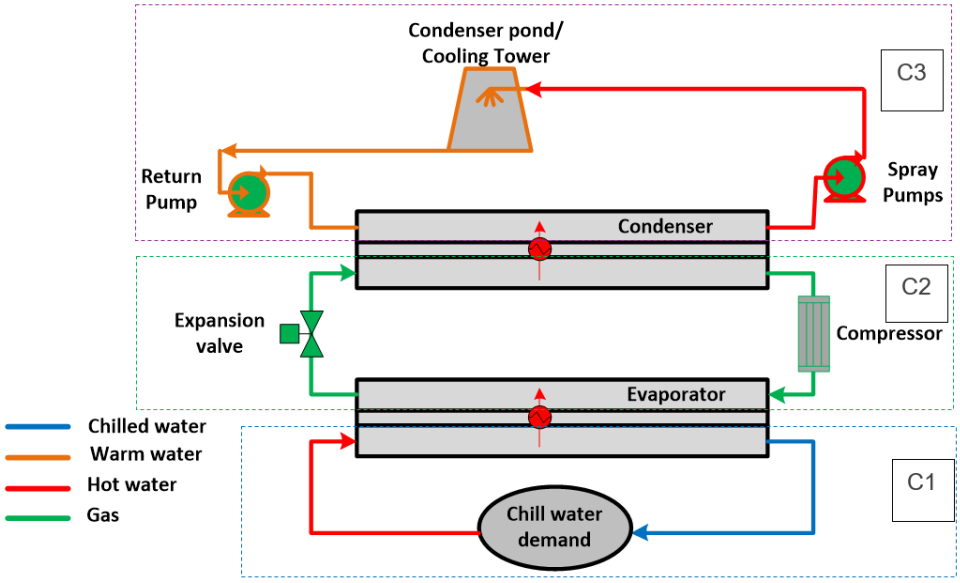



Figure 15 as C1, C2 and C3 respectively.

Figure 16 depicts the vapour compression cycle.

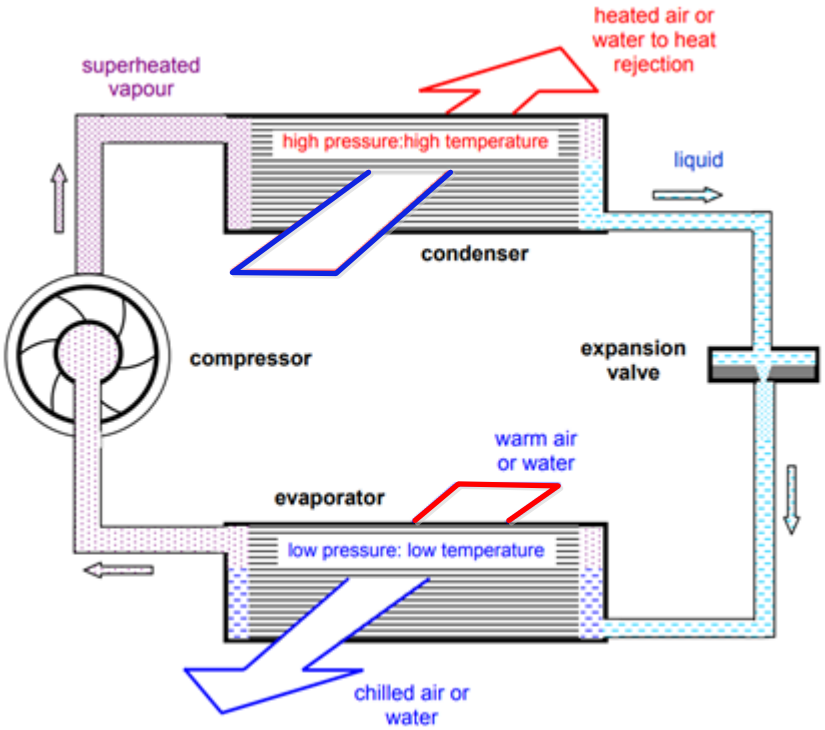



*Figure 16:Vapour compression cycle [57]*

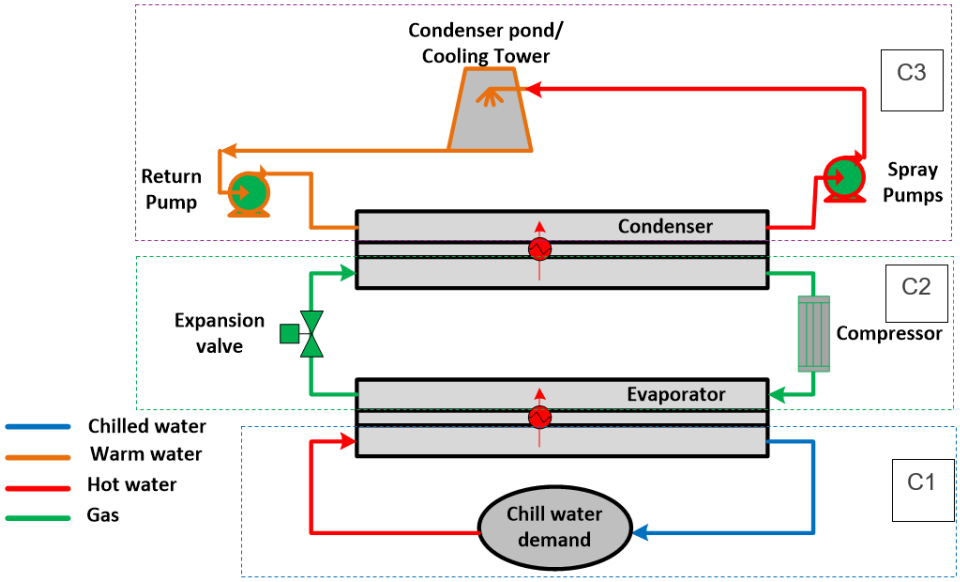



Figure 15) is a heat exchanger that transfers heat from the hot fluid to the cold fluid. It uses a refrigerant as a cooling medium. The refrigerant flows inside the finned tubes of a shell and

tube heat exchanger while the hot water flows through the outside shell. Heat is transferred from the hot water to the refrigerant. The warmed-up refrigerant enters the compressors which regulate the cooling duty through its speed – the flow rate of the refrigerant through the compressor controls the heat transfer rate of the evaporator via the inlet guide vanes. The refrigerant exits the compressor and enters the condenser.

The condenser resembles a shell and tube heat exchanger. Heat is transferred from the refrigerant to the water source which is warmer than the refrigerant. The condensed refrigerant is then passed through the expansion valve. The valve ensures that the pressure of the refrigerant is increased at the expected level prior to entering the evaporator, and the cycle continues.

With fridge plants operating at the same principle, the differentiating factor of most of the fridge plants is the control philosophy and the general system configuration. The optimal control and system configuration ensure that the fridge plants operate at maximum efficiencies. The control philosophy of fridge plants relates to the general operation and general set points, especially because most fridge plants are automated. Control philosophies are mostly programmed on the PLC.

Normally fridge plants are operated in multiple units. The configuration generally refers to the pipeline connection of the fridge plants, the set-up of the pumps, as well as the arrangement of the units of the fridge plants. A variety of fridge plant configurations are found on deep level gold mines. The number of units and the temperature outlets from the units depend on the depth of the mine, as this determines the overall cooling requirements.

Deep mines use different configurations to arrange fridge plants. Figure 17 depicts a schematic representation of 3 different configurations found in deep level mines.

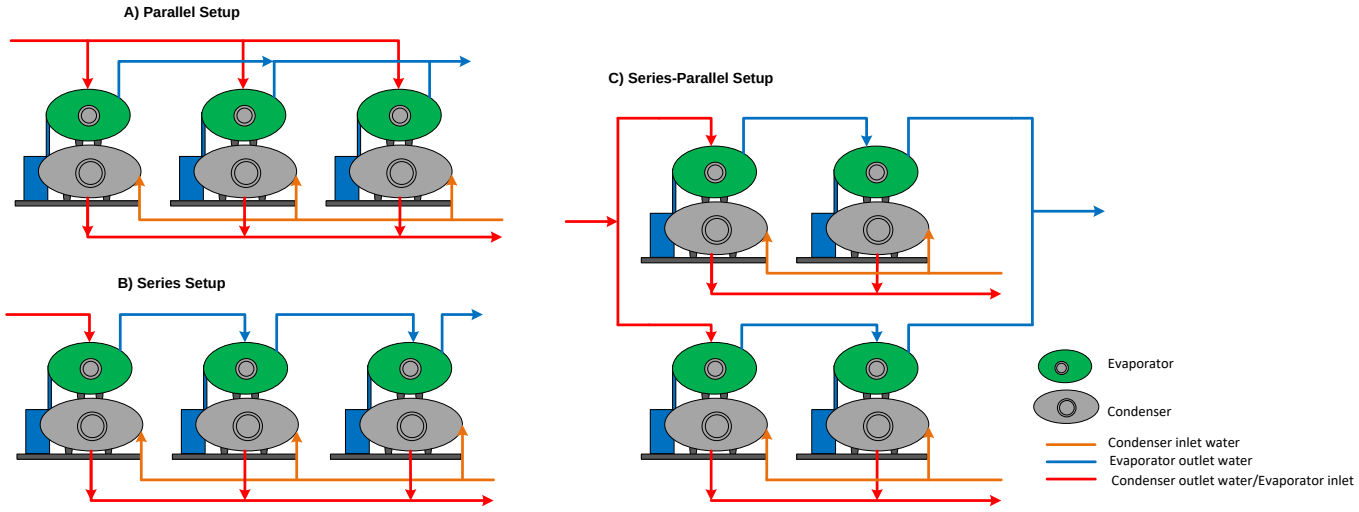



*Figure 17: Configuration of fridge plants*

Figure 17A - Parallel configuration ensures that the cooling load remains the same throughout the operation of the fridge plants. The collective outlet evaporator control remains constant, depending on the efficiency on of the individual plants. The configuration allows for individual plants to be isolated completely and the collective water flow can be varied with control valves. One of the drawbacks is that the inefficiencies experienced at one plant can be seen on the collective performance of the plants [53],[59].

Figure 17B -Series configuration is generally used when constant flow is required throughout the plants. The configuration allows for the cooling duty to be controlled. In the series configuration the condenser side still follows the parallel configuration for the optimization of the heat reject of the plants. The series configuration allows for seasonal operations. During summer days the duty demand is high, and this allows for maximum duty to be generated. In winter days where the duty requirements are minimal due to low ambient conditions, some of the fridge plants can be switched off to achieve energy savings in the system [53],[59].

Figure 17C – The last configuration is the hybrid configuration that combines the parallel and the series configurations. The configuration allows for both cooling duty and water flow rate to be controlled. The cooling duty can be increased when it is needed and reduced depending on the demand. The main challenge associated with the hybrid configuration is the maintenance, as duty will be lost when one plant is being maintained. Mines generally install more plants than required to accommodate any maintenance requirements [53],[59].

### *Ice plants*

As mines become deeper and deeper, the surface fridge plants become ineffective as the positional efficiency decreases. Normally underground fridge plants are considered, but due to lack of space available underground and the costs associated with the fridge plants, ice plants are introduced. Ice plants are usually considered when mine depth reaches 2400m [60]. Ice plants are put on surface, allowing for more space during the construction process. Figure 18 depicts typical ice plants constructed at one of the South African gold mines.




*Figure 18 Ice plants [62]*

Independent ice plants can produce close to 800 tons of ice and more per day with close to 27ºC water in feed. The ice plants rely on ammonia as the main refrigerant. The ice is generated on several vertical non-rotating stainless-steel evaporators. The capital cost to produce at least 220 tons of ice is below R9 000 per kilowatt, which is far lower than the alternative cooling systems [61], [62]. Ice plants have proven to be highly efficient and environmentally friendly. They can operate non-stop for 24 hours per day. There are different types of ice plants. Some plants form slurry or snow crystal ice, while others form solid blocks.

The ice is normally introduced into a dam where it is mixed with warm water from underground which has been treated on surface or underground by the settlers. The general control of the water circulation through the ice dam and the ice to water ration in the dam determines how cold the outlet water sent to underground will be. The ice dam water outlet temperatures range from 2ºC to 15ºC depending on the amount of ice introduced, the water flow and the

temperature of water returning from underground. Figure 19 shows the general configuration and flow circulation of the ice plants' circle.

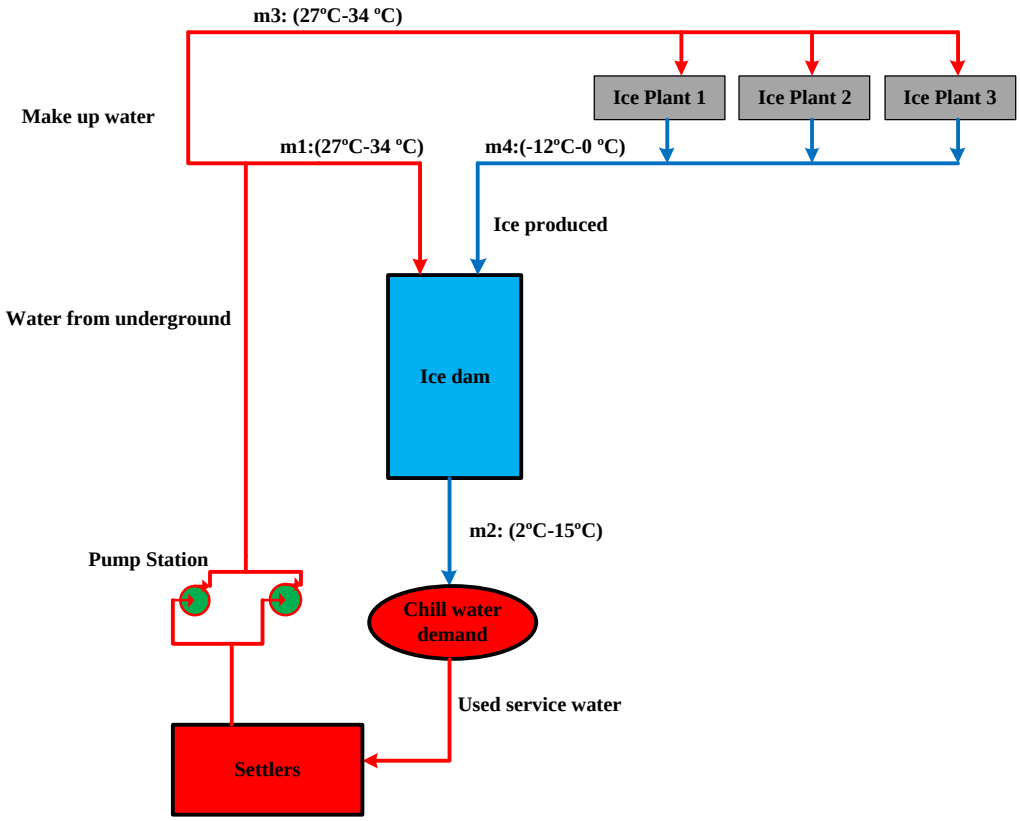



*Figure 19 : Ice plants mine configuration*

The return underground temperatures range from 27ºC to 34ºC, depending on the season. The water from the ice dam is usually provided to the underground bulk air coolers and other mining services. There are currently only limited numbers of studies relating to the ice dam, since it is still a new initiative. The conservation of mass needs to hold at all times to avoid flooding of the ice dam and the mine in general. Equation 4 needs to be conserved:

$$\sum m_i = \sum m_e \qquad (4)$$

Where:

$\sum m_i$ = sum of the water sent underground from the ice dam

$\sum m_e$= sum of the water from underground to the ice dam and the ice plants

## *Air cooling Systems (BAC and Cooling cars)*

Water chillers and ice plants are responsible for the temperature optimization of the water sent underground. Water optimization focuses strictly on the general flow of the water which is affected by the general pressures in the system and the control. The second focus is the temperature control, since the water needs to be at a set temperature when reaching underground working areas.

The second part of the cooling system includes components which transfer the cooling duty from the water which was cooled down by the water chiller and the ice plants to air. The cooling systems generally use the concept of heat exchangers.

Underground heat exchangers are well known as cooling coils. Cooling coils allow heat energy in one process fluid to be transferred to another fluid in a controlled manner with an end goal of either to remove heat from a fluid (cooling) or to add heat to the system by heating up the fluid. The heat energy transferred can be in the form of sensible heat as in the coolers and typical heaters or latent heat for boilers and condensers [57].

Cooling coils are used in various systems, environments and processes that involve the transfer of heat energy. Cooling coils are generally used for temperature profile control, steam generation and phase separation. The mining industry uses cooling coils strictly for underground cooling. Cooling coils are generally designed to work at set conditions to allow for the mine to be cooler, according to desired temperatures [63].

Improper design and poor maintenance of cooling coils may lead to the degradation of system performance and increased operational cost. Cooling coils depend on fluid flows and temperatures. The deviation of operational conditions from the design operating conditions may lead to a decrease in the performance of the cooling coil.

The major contributing factor in cooling coil performance reduction is the effect of fouling. Fouling is a general term referring to any kind of deposit of extraneous materials that build up on the heat transfer surface during the operation of the cooling coil [64]. Typical fouling deposits in the mining sector include the buildup of silica on the external surfaces, and the mud build-up on the internal surfaces of the coils. This happens typically when the service

water is used as a cooling medium. The internal lining of the pipeline tends to rust, and this will form internal fouling which will affect the performance of the cooling coil/heat exchanger. Figure 20 shows internal fouling on pipes.



*Figure 20: Internal fouling in pipes and cooling coils [65],[66]*

Internal fouling affects the overall flow rates of the cooling coils. Extreme cases of internal fouling include a total blockage of tube surfaces by deposits of ash, soot, dirt and scales. Internal fouling increases the pressure drop required to maintain the flow rate through the cooling coils. The formation of internal fouling depends on several variables. These include:

- The flow regime (fluid flow rate, temperature, pressure and concentration of components)
- The geometry and pipeline configuration as it affects the formation of deposits

### *Bulk air coolers*

Bulk air coolers consist of several cooling banks which are connected to the same line. Uniform distribution of water in this system is of paramount importance since it is necessary for the increased efficiency and reliability of the equipment. To allow for uniform distributions, manifolds are generally used on the BAC. However, due to challenges faced in the mining industry, the manifolds are often altered and operate differently from the initial design of the system. This leads to maldistribution in the system. Figure 21 illustrates a general manifold which operates based on the standard Bernoulli equation as expressed in equation 1.

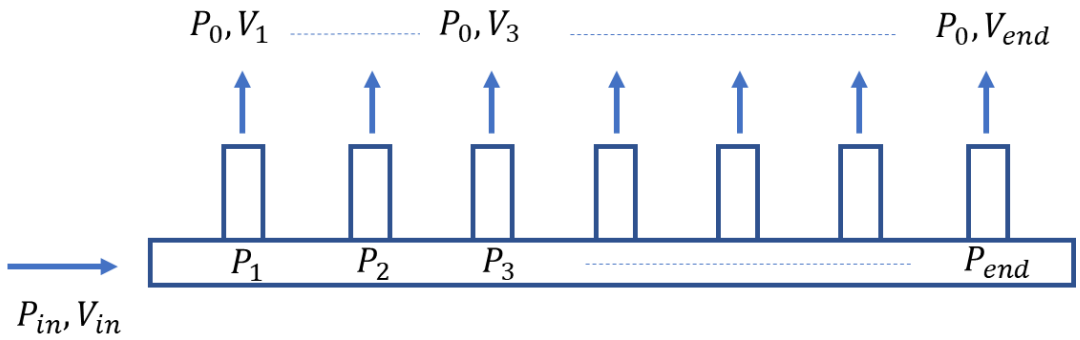



*Figure 21: Flow distribution manifold [67]*

The water mass flow rate through each opening is proportional to the driving force which is the pressure difference between the pressure in the pipeline (P1) and the pressure (P0) outside of the system. Mass flow is at its maximum at the entrance, and decreases towards the closed end of the distributor. Figure 22 depicts a typical profile along the length of the manifold.

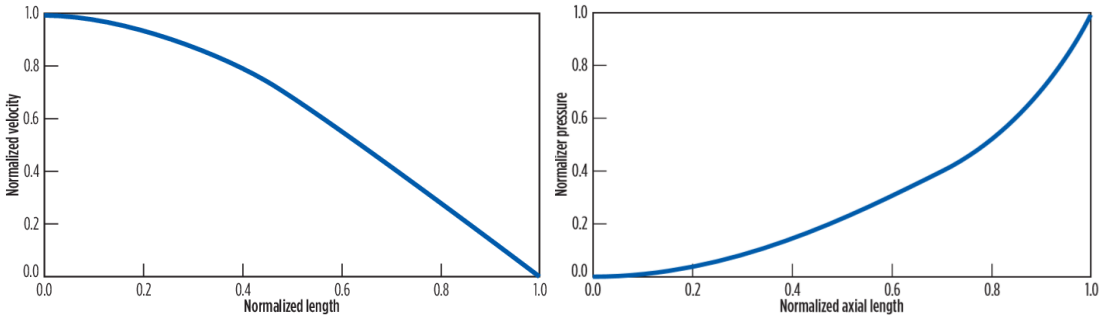



*Figure 22: Normalized velocity and pressure profiles [67]*

The most common method used to achieve uniform distribution over manifolds is that of changing the flow area of the outlet pipes. Valves are generally used to balance the pressure distribution over the manifolds and thus the total flow distribution of the system. Figure 23 shows a typical BAC connected on a manifold with valves installed. The valves are circled in yellow. The general distribution of the water differs from mine to mine, depending on the manifold configuration.



*Figure 23: BAC U-bend manifold*

The optimization of a manifold allows for the optimization of the mine water management and can successfully affect the overall cooling performance of the BAC. Figure 24 shows a BAC connected on a different manifold. All the banks are connected on a single pipeline. The manifold also contains control valves to balance the overall flow through each bank.

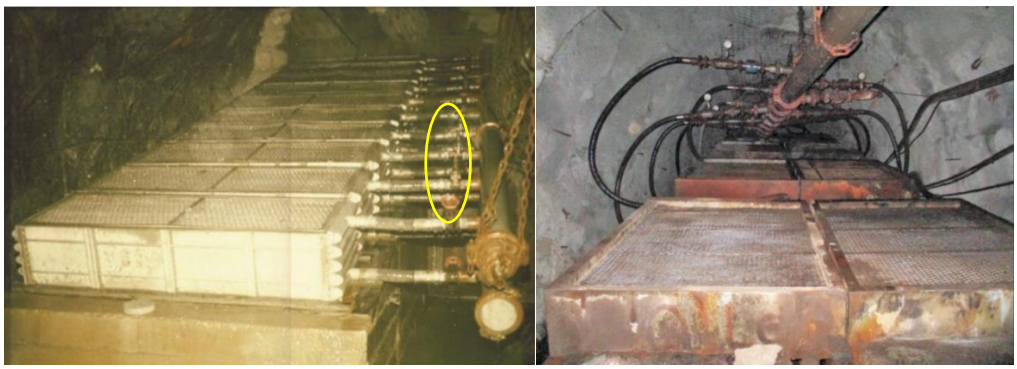


*Figure 24: Single pipeline manifold*

Cooling systems use about 50% of the water sent underground. The overall configuration of the cooling systems determines how the water can be managed underground. BACs can be operated in a closed loop system with fridge plants, but for other mines, they are connected on the mine water reticulation system.  Bulk air coolers are generally installed on surface, due to positional efficiency. The cooling from the BAC becomes ineffective for mines deeper than 1600m.

### *Cooling cars*

In instances where primary cooling and secondary cooling from surface BACs and underground BACs cannot reach the working faces respectively, tertiary cooling is applied. Tertiary cooling involves the use of cooling cars. Cooling cars also known as spot coolers have been used in Anglo American gold and platinum mines since the early 1950s. The capacity of the spot coolers varies from 100 to 500 kWR [68]. Cooling cars consist of an indirect-contact heat exchanger also known as cooling coils. Figure 25 depicts a schematic of the cooling car working principle.

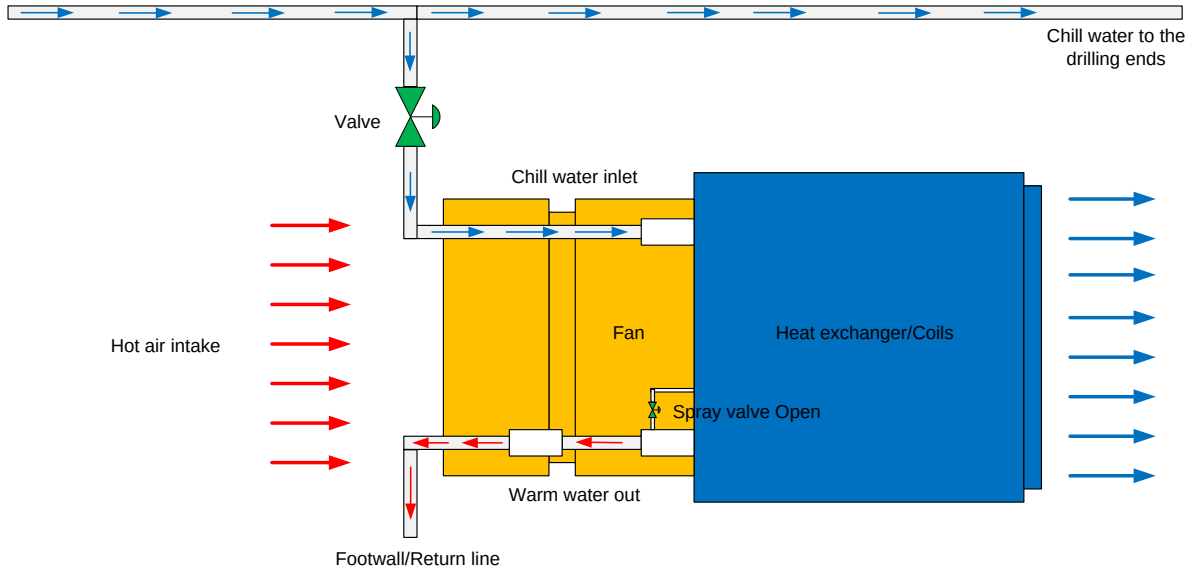



*Figure 25: Cooling car working principle*

The heat exchanger/ cooling coils is supplied with chilled water from the refrigeration plants. Cooling cars are connected directly to the mine water reticulation system where it receives chilled water. Hot air is forced through the cooling car using a fan. The hot air exchanges heat with the chilled water and the air leaves the cooling car at a lower temperature and proceed to the working faces.

Hot water leaving the cooling car is dumped onto the footwell, the accumulated water on the footwall is pumped to the dewatering dams on the shaft bottom using spindle pumps. The water is then pumped back to surface or the refrigeration plants using dewatering pumps.

A reduction in chilled water flow through the cooling cars will reduce the electrical energy consumption of the pumps and chillers. An added benefit is reduced maintenance requirement on all components related to the system.

The simplest method to reduce the flow through the cooling cars is through the installation of either flow restricting or flow regulating valves. The valve needs to be robust such that to regulate the flow through the cooling car irrespective of the supply pressure. Figure 26 depicts an example of the valves which was used by Mare to reduce the flow through the cooling cars.



*Figure 26: Maric flow regulating valve [69]*

Depending on the mine, for some cooling cars, the outlet water of the cooling cars is still chilled to be reused for other mining activities such as drilling. In such a case, the mine prefers reusing the water from the cooling cars on the stopes. This would mean that the overall water used would decrease and the energy would be reduced.

Cooling cars are generally used for direct face cooling to minimize the effect of thermal layering due to freshly exposed rock wit VTR ranging from 44-54°C [70]. Cooling cars are generally used at a depth of 1300 m with the face VRT of 57°C and an average daily production of 5000 t/day. The cooling cars are required to maintain an effective temperature below 29°C [71].

Cooling cars are beneficial in deep stopes where it is difficult for the primary and secondary cooling to reach. However, the use of cooling cars or spot coolers requires chilled water to be

available and for the piping reticulation to be available and maintained at a reasonably close distance to the working faces [72].

Cooling cars are often exposed to corrosion, high ambient temperatures, insufficient supply-water temperature and flow, and large ducting distances. Owing to these harsh conditions, cooling cars require intensive maintenance to prevent it from becoming inefficient.

Inefficient cooling cars negatively affect the ambient conditions for which they should positively impacting/ contributing. Inefficient cooling cars also lead to water and electricity wastage through the needless use of fans and excessive water consumption.

It is important to optimally manage the water flow through the cooling cars while ensuring that the efficiency of the cooling car unit is not affected. Cooling cars are typically designed to supply set conditions for the service delivery, if the conditions are over supplied, this would mean that the services are abused. Mines are considering systems in place to allow for cooling cars to use the resources for exactly the required cooling and ambient conditions.

The optimal operating cooling car is critical for adequate mine service delivery, sustainability and prevention of excessive electricity consumption. Therefore, a method is required to optimally manage the water used by cooling cars to ensure optimal performance of the cooling cars.

## *Cooling coil performance evaluation*

Cooling coils contain two different or similar fluids, one cold and the other warmer. The cooling coils at the mines are generally air to water heat exchangers where the air is warmer/hotter than the water side. In order to evaluate the actual performance of the cooling coils, the water and the air duties as well as the UA product of the cooling coils need to be evaluated. The governing equations for the calculation of the cooling coil performance are outlined below.

***Water duty***

The water duty, $Q_w$ in kilowatt is calculated as follows [73],[74]:

$$Q_w = C_{pw}\dot{m}_w\Delta T \tag{5}$$

Where:

$Q_w$ = Water duty in kW

$C_{pw}$ = Specific heat of water at constant pressure ($4.187\ j/kg \cdot ℃$)

$\dot{m}_w$ = Water mass flow rate in ($kg/s$)

$\Delta T$ = Temperature difference between the inlet ($T_{wi}$) and outlet ($T_{wo}$) water temperatures.

***Air duty***

Enthalpy enables air duty calculations for both direct and indirect contact heat exchangers. Mines generally use sigma energies for air duty calculations, especially for direct contact heat exchangers. This section will outline the calculation of air duty using the enthalpy change method. The air duty in kilowatt is calculated as follows [75]:

$$Q_a = \dot{m}_a(H_o - H_i) \tag{6}$$

Where:

$Q_a$ = The air duty in kW

$\dot{m}_a$ = Air mass flow rate in ($kg/s$)

$H_O\ and\ H_i$ = The outlet and inlet enthalpy respectively in ($kJ/kg$)

The air mass flow rate can be calculated by:

$$\dot{m}_a = \rho_a \dot{v}_a \tag{7}$$

Where:

$\rho_a$ = Air density in ($kg/m^3$)

$\dot{v}_a$ = Air volumetric flow in ($m^3/s$)

The volumetric flow rate can further be calculated as follows:

$$\dot{v}_a = v_a A \tag{8}$$

Where:

$v_a$ = Air velocity in ($m/s$)

$A$ Is the flow area in ($m^2$) calculated by $A = \frac{\pi}{2}\emptyset$ and $\emptyset$ as the ducting diameter in ($m$)

The air density, $\rho_a$, is calculated as follows:

$$\rho_a = \frac{1 + RH}{V} \tag{9}$$

Where:

$V$ = Specific volume of moist air in ($m^3/kg$)

$RH$ = Relative humidity of the air

The specific volume of moist air can be calculated by:

$$V = \frac{R_{air}(T_{adb} + K_t)}{P \cdot P_{sat} \cdot RH} \tag{10}$$

Where:

$R_{air}$ = Ideal gas constant ($287.05\ J/kg \cdot K$)

$T_{adb}$ = Air dry-bulb temperature in (°C)

$P$ is the pressure in ($kPa$) and $P_{sat}$ is the saturated pressure of the air in ($kPa$)

The saturated pressure of air can be calculated by:

$$P_{sat} = e^{(\frac{C_1}{T} + C_2 + TC_3 + T^2C_4 + T^3C_5 + C_6 logT)} \tag{11}$$

Where:

*The constants* ($C_x$) *extracted from the Hyland and Wexler correlation are defined as follows:*

$$C_1 = -5800.2206$$

$$C_2 = -5.516256$$

$$C_3 = -0.048640239$$

$$C_4 = 0.000041764768$$

$$C_5 = -000000014452093$$

$$C_6 = 6.5449673$$

$T$ = Temperature in Kelvin calculated by: $T = T_{adb} + K_t$

$K_t$.= Absolute temperature in Kelvin ($273.15\ K$)

The equation that enables the calculation of the relative humidity RH is as follows:

$$RH = \frac{P \times W}{\left(P_{sat(db)}(R_{mol} + W)\right)} \tag{12}$$

Where W is given by the following equation:

$$W = \frac{\left(\frac{R_{mol}P_{sat(wb)}}{P - P_{sat(wb)}}\right)\left(h_{fg} - T_{wb}\left(C_{pw} - C_{Pvap}\right)\right) - C_{pa}(T_{db} - T_{wb})}{h_{fg} + C_{Pvap}T_{db} - C_{pw}T_{wb}} \tag{13}$$

Where:

$R_{mol}$ = The ratio of molecular mass of water vapor to air $(0.62198)$

$h_{fg}$ = Heat of evaporation at 0 ℃ $(2501000\ J/kg \cdot K)$

$C_{pa}$ = Specific heat of air $(1.006\ kJ/kg \cdot K)$

$C_{Pvap}$ = Specific heat of water vapor $(1.805\ kJ/kg \cdot K)$

Finally, the enthalpy (H) of air in kJ/kg entering and leaving the cooling coils can be calculated as follows, as depicted by Equation 18:

$$H = C_{pa}T_{db} + (\frac{R_{mol}P_{sat(db)}RH}{P - P_{sat(db)}RH})(h_{fg} + C_{Pvap}T_{db}) \tag{14}$$

*Calculating the UA Product:*

The log mean temperature difference (LMTD) and the water duty are used to determine the UA product. The overall heat transfer coefficient, UA in kW/℃ can be defined by [73],[74],[76]:

$$UA = Q_w \times LMTD = Q_w \times \left(\frac{In\left(\frac{\Delta T_1}{\Delta T_2}\right)}{\Delta T_1 - \Delta T_2}\right) \tag{15}$$

$Q_w$ represents the water duty and LMTD for log mean temperature difference. The equation is further expanded with the inclusion of the log mean temperature difference equation with $In$ the natural logarithm, $\Delta T_1$ and $\Delta T_2$ the temperature differences of the fluids at each of the cooling coils calculated by:

$$\Delta T_1 = T_{air}In_{wb} - T_{water}Out \tag{16}$$

A clean coil generally has a UA value that ranges between 10-25 $kW/\ °C$ [73]. The method

$$\Delta T_2 = T_{air}Out_{wb} - T_{water}\,In \tag{17}$$

used to calculate the LMTD is suitable for parallel-flow and counter-flow heat exchangers [76]. The cooling coils used in the mining industry use the cross-flow configuration [77],[73]. The flow conditions in the cross-flow configuration are complex. This results in complicated UA value calculation for this specific case. The correction factor *(F)* is a suitable alternative to use, and this can be obtained from one shell pass and even number correction factor chart [76],[78],

$$R_F = \frac{T_{air}in_{wb} - T_{air}Out_{wb}}{T_{water}Out - T_{water}\,in} \tag{18}$$

$$P_F = \frac{T_{water}Out - T_{water}\,in}{T_{air}in_{wb} - T_{water}\,in} \tag{19}$$

The correction factor (*F*) can also be calculated using the following numerical calculation method [79].

$$F_{1,2} = \begin{cases} \dfrac{\frac{\sqrt{1+R^2}}{(R-1)}\log_{10}\left(\frac{1-P}{1-PR}\right)}{\log_{10}\left(\frac{\frac{2}{P}-1-R+\sqrt{1+R^2}}{\frac{2}{P}-1-R-\sqrt{1+R^2}}\right)}, R<1 \\ \dfrac{\frac{P\sqrt{1+R^2}}{2.3(1-P)}}{\log_{10}\left(\frac{\frac{2}{P}-1-R+\sqrt{1+R^2}}{\frac{2}{P}-1-R-\sqrt{1+R^2}}\right)}, R=1 \end{cases} \tag{20}$$

R and P represent $R_F$ and $P_F$ from equation 18 and 19 respectively.

**Fouling factor**

The fouling factor is the reciprocal of the heat transfer coefficient of the used cooling coil/heat exchanger minus the reciprocal of the heat transfer coefficient of the newly designed cooling coil. The higher the factor, the lesser will be the overall heat transfer coefficient and the higher the foulant accumulation in the system. It is expressed as follows [80]:

$$F_f = \frac{1}{UA} - \frac{1}{UA_{Design}} \tag{21}$$

Where UA is the overall heat transfer coefficient calculated from the measured data of the cooling coils and $UA_{Design}$ is the design overall heat transfer coefficient.

The water duty, air duty and UA product are all evaluation parameters for actual performance. These values provide valuable information regarding the condition of the cooling coil. Normally the overall duty of the cooling coil is compared with the design duty to calculate the performance of the cooling coil.

**Cooling coil measurements**

The functions of the cooling cars and the bulk air coolers are the same. The minimum measurements required to evaluate the performance of the cooling coils in both cooling cars and BACs are listed in Table 2 below. Table 2 also shows the necessary instruments required for measurements together with their operational characteristics [73],[74].

*Table 2: Cooling coil measurements points and accuracy*

| Description | Unit | Instrument | Accuracy within | Resolution | Range |
|---|---|---|---|---|---|
| Inlet and outlet water Temperature | ℃. | Gemini Tinytag view 2 with Thermistor Probe | 0,25% | 0,02 | -40,0~125,0 |
| Inlet and Outlet Air Temperature | $℃_{wb}/℃_{db}$ | Whirling Hygrometer | 2% | 0,5 | -5,0~50,0 |
| Inlet and outlet air pressure | kPa | Tenmar-404 Anemometer | +-2 | 0,1 | 0,35~110,0 |
| Water Mass flow | kg/s | Portable water flow meter | 5% | 0,25 | 0,0~14,0 |
| Air velocity into the cooling coils. | m/s | Tenmar-404 Anemometer | +-2%+0.2 | 0,1 | 0,4~20,0 |

| | | | | | |
|---|---|---|---|---|---|
| Inlet fan/Ducting diameter | m | Bosch PLR-25 lase distance meter | 2,0 % | 0,001 | 0,05~25,0 |

Figure 27 depicts the measuring points of the cooling car. Bulk air coolers and cooling cars serve the same primary purpose and their primary operational concepts are similar, but their general configuration and design differ. The points of measurement are standard and follow the same procedure. The cooling car is used as an example.

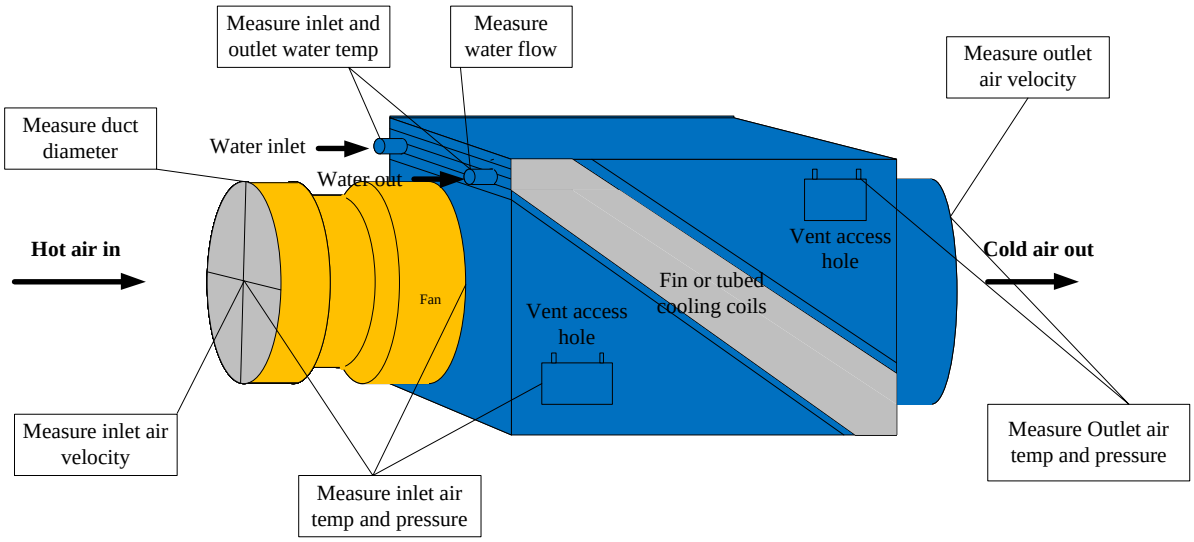



*Figure 27: Cooling car measuring points*

### *Inlet and outlet water temperatures*

Cooling cars usually have probe pockets, also known as thermowells, located on the inlets and the outlet water columns. The probe pockets allow for non-invasive water temperature measurements with a Tiny Tag or a thermometer. In the case where probe pockets are absent, an alternative solution is to measure the inlet water temperatures( $T_{water} in\ in$ ℃.) on the main supply column closer to the cooling coil, and the return water temperature ($T_{water} Out\ in$ ℃) at the water discharge onto the footwall or into the drain.

***Inlet and outlet air temperature***

Cooling cars have small access doors on both sides of the heat exchanger as depicted in Figure 27 above. The doors serve as a suitable area to take inlet and outlet air temperature measurements. In certain cases, the access doors may have rusted shut or can't open due to other circumstances. Therefore, the locations before and after the ventilation ducts can be used for measurements. In the case where the fan is attached to the cooling coils, the inlet air measurement is done before the fan and the fan induced air temperature needs to be accounted for. The mining industry widely uses whirling hygrometers for air temperature measurements [73],[81]. A typical whirling hygrometer that is calibrated provides wet-bulb and dry-bulb air temperatures and it is suitable to measure the inlet and outlet air conditions of the cooling car illustrated in Figure 27

***Inlet and outlet air pressure***

There is usually an air pressure reduction over the cooling coils. The reduction ( $\Delta P_a \; in \; kPa$) in pressure is obtained by measuring the inlet and outlet air pressure with a barometer, utilizing a manometer or using specification sheets of the cooling coils from the manufacturer. Figure 27 shows the areas to measure the air pressure.

***Water mass flow***

A portable ultrasonic water flow meter makes non-intrusive methods to determine the water flow rate of the cooling coils possible. In the case where the ultrasonic flow meter cannot be used or is not available, a bucket method is also a practical method to measure the flow rate of the cooling car. The method involves measuring the time it takes to fill up a bucket. The bucket volume is thereafter divided by the time lapsed to calculate the mass flow rate. The bucket method is not feasible and safe to be used/performed in the case of high-pressure cooling coils and very high flow rates, typically greater than 10 ℓ/s. The bucket method is also not suitable for bulk air coolers.

***Air velocity into the cooling coils***

The air velocity is typically measured inside the ducting or on the fan intake before the cooling car. In the case of the bulk air cooler, the measurement is taken on the intake of the coils as shown in Figure 27. The measurement of the air velocity ($v_a \; in \; m/s$ ) into the cooling coil

requires an air velocity meter such as a vane anemometer. It is important to measure the ducting diameter and the parameters of the cooling car and BAC inlet respectively. A distance meter or a measuring tape can be used. The distance can be used to calculate the volumetric flow ($\dot{v}_a \ in \ m^3/s$) through the cooling coils.

***Chill water management problems***

Cooling systems require chilled water to provide cooling underground. Cooling systems generally operate under specific conditions. The conditions of the chill water serve as the main driving factor when it comes to the performance of the cooling systems. Typically, chilled water is produced in surface water chillers at 2-3 °C, to reach the work faces at 7-10°C, depending on the depth of the mine or distance to the work faces [82].

It is important to optimally manage chill water to ensure that the desired conditions are met. Because of high pressures and flows encountered within the mine water reticulation system as well as the underground operating conditions, various problems may arise in the supply of the chilled water to the cooling systems.

Pressure increases in the system as the chill water moves down the column in a mine. The Joule-Thomson effect occurs where the water molecules move closer to each other causing internal friction within the water [82]. A general increase in temperature of up to 2,33℃ for every 1 000m of head can be noticed in the water reticulation system [83]. Normally mines use steel pipes to transfer the chilled water to the working areas. The heat transfer of the steel pipes is generally high, allowing heat to be exchanged with the surrounding environment. Most of the deep level mines use cladding to reduce the heat transfer rate between the chill water and the surrounding environment [84].

Pipe leaks are one of the common problems occurring in this environment. They may be caused by high pressures in the system and the lack of proper maintenance. Water leaks are generally found between the pipe flanges, especially if the gaskets are worn out. Because the chill water, if chilled by water cooling systems which use a significant amount of energy, large amounts of energy is lost through leaks.

The leaks also reduce the overall pressure in the system and as a result, the water ends up with too little force to get to the working areas at the desired flow.

***Mine health and safety***

Health and safety form an integral part of the measuring procedures. It is therefore important to always ensure that the required health and safety standards are adhered to. Cooling cars and bulk air coolers are generally found underground, and the following personal protective clothing is always required when going underground:

- Toe steel gumboots
- Hardhat
- Overalls
- Eye protection glasses
- Earmuffs
- Nose musk

Both the cooling cars and the bulk air coolers contain draft fans that emit sound frequencies ranging from 90 to 130 db. As per health and safety recommendation, frequencies which exceed 85 decibels are dangerous and can lead to hearing loss. It is always of great importance to wear earmuffs when working with cooling cars and bulk air coolers. A health and safety risk assessment form need to be completed before going underground to ensure that all possible risks related to the components at hand are well taken care of. Figure 28 below depicts the human threshold and the draft fan dB respectively.




*Figure 28: (a) Human Db limit and (b) Cooling car fan threshold*

## 1.3 SIMULATION PACKAGES

Gold mine water reticulation and cooling systems are complex systems. A wide variety of simulation software exists today. This software aims to simplify the complexities of underground mine systems and assists with accurate simulations of different flow scenarios. The main advantage of simulation software is allowing for users to perform several analyses of a complex system accurately and quickly. Simulation software can solve problems and enhance the performance of different cooling subsystems and the water reticulation networks. It is important to select validated simulation software to avoid occasional, costly and dangerous physical testing.

The selection of simulation software is driven by the requirements of the analysis and the model complexities. The simulation software needs to include all the components of physical and physiological properties. These include: Temperatures, mass flow rates, thermal capacities, dam capacities, pipe sizes, friction losses and all the system inefficiencies. The simulation software needs to be able to provide the possible expected results based on the provided data and calibrated model built. This includes providing solutions and improvements on cooling systems when water systems are properly managed. Some of these software programs are discussed below.

***KYPipe [85]***

KYPipe uses energy equations and mass continuity to solve problems within various parameters. The software generally solves steady state flows and pressure in pipe network systems. One of the main assumptions of the program is constant density for different liquid applications. The KYPipe software is a better approach for pipe hydraulic applications where liquid densities can be assumed to be a constant.

***Process Toolbox (PTB) [86]***

Process Toolbox is a transient thermal hydraulic system simulation and optimisation tool that enables the user to design, analyse and optimise system performance. It is generally used to simulate systems such as water reticulation systems, cooling and refrigeration systems, ventilation systems and compressed air networks. This simulation software can accurately incorporate and simulate all the components of the water reticulation system and the refrigeration system into a single model.

The model can be used to identify system inefficiencies and evaluate the potential impact of different solution strategies. The software is based on first principle equations and the water management and flow pipe calculations are approached similarly to that which was discussed under the line friction losses section.

***SolidWorks flow simulator [87]***

SolidWorks flow simulator uses the Navier-Stokes equation for solving the flow characteristic for specific scenarios. The simulation requires the building of components before constructing the flow simulation. The simulation can give virtual presentation of flows and characteristics. It can be categorised as internal or external flow scenarios depending on the user's requirements. The simulation cannot simulate large networks such as the water reticulation system. It is advantageous when dealing with component specific simulation. The software simulators come as an add-in to SolidWorks.

## Simulation software selection

The simulation software for this study is selected based on the pros and cons of the different programs. The most important advantage needs to be the availably of the software, as well as its simplicity. It also needs to be relevant to the current study. The advantages and disadvantages of each simulation software package can be seen in Table 3.

*Table 3:Simulation software advantages and disadvantages*

| Simulation Package | Advantages | Disadvantages |
|---|---|---|
| KYPipe | • Fairly accurate<br>• Applicable for hydraulic applications<br>• Easy to use | • Limited to constant density fluids<br>• Requires subscription |
| Process Toolbox (PTB) | • Accurate for mining applications<br>• Easily accessible<br>• User friendly | • Fairly new on the market<br>• 2-dimetional |

| | | |
|---|---|---|
| | • Available studies conducted using the software | |
| SolidWorks flow simulator | • Detained solution for specific components<br>• Evaluates many additional parameters<br>• High accuracy<br>• Enough studies based on the software | • Time consuming to build individual components<br>• Expensive and requires full solid work package<br>• Not popular for mining applications |

From Table 3 it should be clear why Process Toolbox was selected as the simulation software for this specific study. The selection was based on its availability, user friendliness and accuracy on mining applications. As outlined in the table above, the simulation software has been used and proven to be accurate in various mining related studies. The simulation uses fundamental principles used to analyse different systems outlined for the study [86],[88],[89].

## 1.4 RESEARCH DONE PREVIOUSLY ON COOLING SYSTEMS.

This section consists of a literature review in which the most important research concerning underground cooling systems used in deep level mining will be discussed. The study seeks to outline the current contribution of literature on water management including how water is utilized and optimized to ensure that cooling is optimized. Additionally, the study will look into the benefit that comes with an efficient water management system which adds to energy savings.

The literature discussed in each category has been arranged chronologically and was evaluated based on the following guideline questions:

- What's was the aim of the research?
- Why was the research conducted?

- How was the research conducted?
- What are the most important results that have been obtained?
- What conclusions were drawn from the research?

The guideline questions will also assist in obtaining the shortcomings of the reviewed literature, because it has not, in all instances, been possible to obtain answers to all the above questions.

The importance of previously implemented studies, particularly on optimal water management and improvement of underground cooling systems is relevant to the study in many ways. It is important to understand what has been accomplished in this field of research, as well as to critically analyse the shortcomings in terms of optimal management and improvement. The specific focus is on managing water systems to effectively improve underground cooling systems.

The studies will be analysed based on the following criteria:

A-Research focus

B-Outcomes of the research

C-Shortcomings of the research

**Schoeman, W. [90]**

The objective of the study was to achieve energy savings on the deep mine water reticulation system through the reduction of peak load, specifically, the dewatering side. This was achieved by automating pumps, optimizing scheduling and load shifting. The study implemented monitoring instrumentation, communication networks and control software to develop a control philosophy that will allow for the starting and stopping of the dewatering pumps at predetermined dam levels.

The study resulted in an increase of 26,6 MWh electrical usage in the system. This shows that, as a load shifting project, the study was unsuccessful in shifting the load to result in energy reductions and savings. The study only evaluated the negative impact on the energy, but could not link the study to the overall cooling impact on the mine, although it also focused on the optimization of the clear water dams and chill water dams.

**Vosloo, J. [46]**

Vosloo's [46] research focused on the mine water reticulation optimization and the broader range of mine water reticulation components which include turbines, fridge plants and dewatering pumps. These components were integrated into a control system to result in a reduction in peak load demand and electrical energy usage.

The study used a Real-time Energy management system for pumping in order to monitor conditions throughout the system and to optimally control the system. The method ensured that the supply of chilled water was not impacted. This was achieved by using fridge plants to build up chilled water capacity before peak times. Dewatering load shifting was achieved through pump scheduling and turbine utilization with minimal impact on the chill water sent underground and thus the underground cooling.

This method achieved an overall electrical energy saving of 4,8 MWh per day through the optimization of the water-cooling system and its auxiliaries, as well as to shift a total load of 7.7MW from the morning and the evening shift.

The study focused only on the energy savings and very little to no information was provided in terms of the service delivery improvement and cooling optimization. No correlation was drawn to depict the impact of water optimization and energy saving on the overall underground cooling. Load shifting for water supply might result in the water mass flow shifting of the cooling systems, thus affecting the cooling energy balance of the mine.

**Buys, JL [91]**

The study was conducted on platinum mine cooling systems by executing a DSM energy efficiency project. The study incorporated the installation of variable speed drives (VSDs) on the cooling auxiliaries and BAC pumps to intensify the efficiency. Power saving on the cooling systems was achieved as a result of adding new apparatus for improved control. The study did not outline the impact of the implemented method on the service delivery of the cooling systems. The improvements on the overall cooling were not outlined.

**Du Plessis, GE [92]**

The focus of this study was on the development of an energy efficient cooling model. The model was implemented as a DSM project, focusing on gold mines. The model necessitates managing the cooling auxiliaries with VSDs by complying with water and temperature demands specified by the mine, whilst operating with reduced power. The precooling towers were replaced, and more equipment was added onto the system to enhance the cooling auxiliaries' control. PTB was used for simulations and the study managed to achieve power savings of approximately 35,4%. Though the study was referenced about 280 times, it proved to be of limited value to the current study, because the method was not applied on the mobile cooling cars and spot coolers. However, the study managed to focus both on the energy and service delivery side of the system.

**Uys, DC [93].**

The objective of Uys's [93] study was to focus on the reconfiguration of components within the mine's cooling system. The main focal point was converting surface ice plants to fridge plants. The replacement of the ice plants with fridge plants led to a total power saving of 2,5 MW. The fridge plants were then used as a backup plant. The reconfiguration led to an availability of a high volume of chill water storage capacity. This enabled the mine to achieve a morning and evening load shifting. Power savings of 2,2 MW and 3,4 MW were noticed. The research only focused on reconfiguring fridge plants and achieving energy savings and did not outline the impact of the conversion on the service delivery side, nor did it evaluate the overall water management to improve underground cooling.

**Schutte, AJ [94]**

Schutte [94] evaluated the practicality of applying load shifting on the surface BACs and the impact on underground temperatures. It also focused on the overall improvement of the cooling system efficiency. The research was carried out as a DSM project on gold mines which found that the 2-hour load shifting on surface BACs did not affect underground temperatures. In order to improve the cooling system efficiency, the study focused on the adjustment of the systems control philosophy by adding new equipment to the cooling system of the mine. The water through the BAC was reduced, because it was in excess of what was allowed for by the design. The study achieved energy savings on the water flow reduction and illustrated that load shifting of the surface BACs was feasible. However, the

reconfiguration of secondary and tertiary cooling systems were not covered, and the efficiency improvement on cooling coils was not outlined; nor was the impact of water flow reduction on the Surface BACs accounted for.

**Mare, P [95]**

This research focused on DSM project implementation strategies to improve the sustainability of energy efficiency. The strategy was validated by implementing it on two different gold mines. It was conducted on a new project which lasted for 7 months in order to save power. Moreover, the strategy was validated for about 17 months on an old project where power savings were disregarded. The case study only focused on the addition of new equipment to improve the mine's control capabilities. PTB simulation software was used in order to prove the reliability of other case studies. The study did not include the reconfiguration of cooling systems and the improvement of service delivery efficiency.

**Lambrechts, JV [96]**

This study investigated the underground stations and stope ambient temperature by imperial formula derivation. The empirical formula was subject to dissimilar variables. It was found that the underground temperatures can be predicted during the BAC load shifting. The study did not include any physical changes to the mine cooling equipment.

**Kukard, WC [97].**

Kukard's [97] study proved the feasibility of load shifting and energy efficient projects on the underground auxiliary and main surface fans of a gold mine. By load shifting the fans at two of South Africa's most advanced mines, a possible load shifting saving of about 2,25 MW and 3,5 MW was achieved. The study only focused on the fans, and did not outline other cooling auxiliaries. Nor did it outline the reconfiguration of underground systems to realize further energy savings and cooling improvements or chill water management optimization.

**Greyling, J [98]**

Greyling [98] conducted a study based on simulation to determine the optimal location of cooling equipment for deep level gold mining. Vuma simulation estimated the level temperatures, whereas Flownex software was used to simulate dam capacities, pipe and pumps sizes. In conclusion, Greyling stated that optimal cooling for mines mining at 4 000 m below surface is ice plants located on surface and underground, closed loop chillers and

BACs. The study did not outline the reconfiguration of the system to investigate different configurations which would improve the cooling efficiency through water management optimization. The study illustrated the value of simulation software and its applicability.

**Kamyar, A *et al.* [99]**

The research outlined an overview of the latest techniques used by the experts to address issues relating to underground ventilation and cooling. It also outlines novel ventilation strategies and mine refrigeration methods. The specific focus on these strategies was mainly on identifying their ultimate effect on efficiency and mining costs. Finally, future developments were outlined in the area of mine cooling.

The main objective of the research was to reduce the energy consumption of mine cooling with the aid of technologies such as Variable Speed Drives (VSD), control valves and other Demand-Side Management (DSM) methods.

The research focused on the latest automation strategies which can implement accurate monitoring and control techniques to observe the conditions of air temperatures and velocities, containments and water flow rates. The research included a few studies that implemented the automation strategies. Table 4 below illustrates the outcomes of the studies.

*Table 4: Cooling systems optimisation studies[99]*

| Study | Place of application | Monitoring section | Outcome |
|---|---|---|---|
| Pelzer et al (2010) | 3 south African mines | Monitoring and optimizing the inlet chiller temperatures | 32 416MWh electricity reduction due to increase in Coefficient of performance |
| Vosloo et al. (2012) | Kopanong Mine South Africa | Water reticulation system | 2% reduction in overall power consumption. Close to R8 971 426,26 cost savings |
| Du Plessis et al (2013a) | Kusasalethu mine South Africa | BAC flow control using VSD. BAC control using | 31% saving of the total plant power consumption. |

| | | | |
|---|---|---|---|
| | | valves and retrofitting of old pre-cooling towers | Considered the ventilation and cooling side, conditions were met |
| Du Plessis et al (2013b) | Cooling systems of 20 South African mines | VSD installation on chiller compressor motors and all pumps | Range of 168 633 to 144 721 MWh/year power savings |
| Mare et al. (2015) | 2 mines case studies | VSD on evaporators, compressors and BAC pump motors | Evaporator- dam level control. Condenser -fixed temperature difference. Constant Wet-Bulb temperatures for the BAC (8 degrees) |

Du Plessis *et al.* (2013a) presented the general improvements and differences after implementing the techniques. Figure 29 shows the Cooling Loads vs Coefficient of Performance of cooling systems. The COP improved after the implementation per unit cooling load.

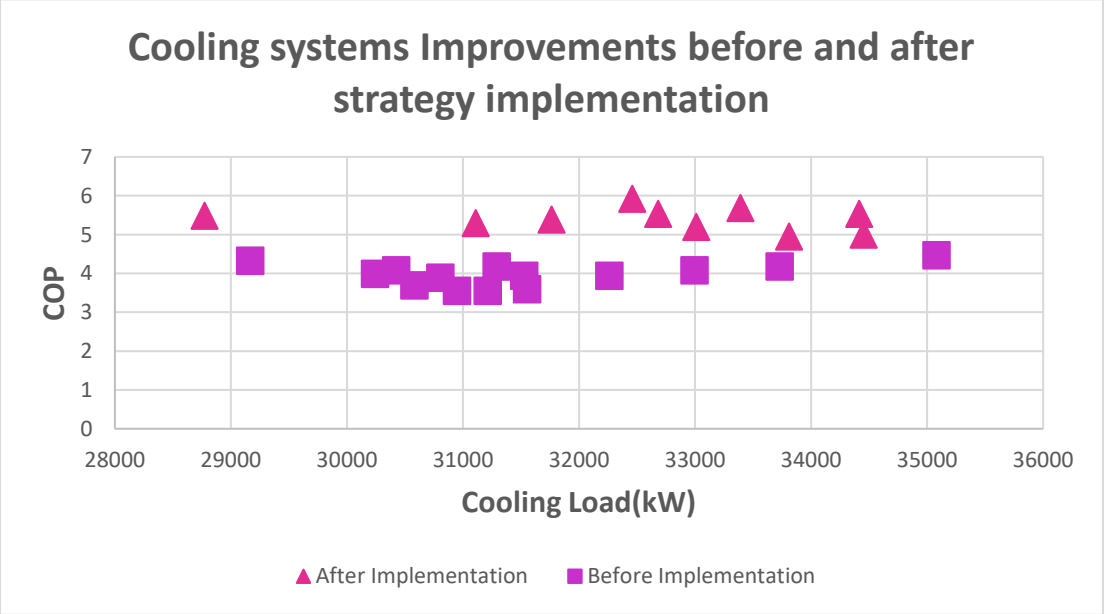



*Figure 29:Cooling systems improvement before and after implementation [99]*

The paper concluded that there are large financial benefits from the optimization of underground cooling systems. It also outlined the fact that the following factors can assist in addressing the energy efficiency and the cost-effectiveness from the management point of view.

- Introduction of novel monitoring systems
- Implementing control strategies to obtain cooling-on-demand
- Thermal energy recovery from available resources
- Improving the performance of the current cooling systems

**Botha, A. [100]**

This paper focused on the optimization of underground mine water supply. The mine water optimization was achieved by controlling supply valves on various mining levels. The main objective of the study was to minimize the usage of water when there is less water demand. The periods where less water is required, include the blasting shifts. The secondary objective of the study was to achieve energy savings from the reduction of water, with the goal of saving costs. The study used the fact that less pumping is required when less water is used.

Costs savings were achieved by the reduction of electricity consumption for the dewatering system. This results from the decrease in pump operation time and load. EMS was used to monitor and evaluate the control valve data; this includes pressures and water flow rates. A PID control system was used to control and adjust the valve to the desired location or set point.

The paper considered two case studies. The first case study resulted in an average power reduction of about 400 kW per day; the total energy savings equated to 9.6 MWh per day. The second case study evaluated and identified the water leaks on the water reticulation network. This included the repair of the leakage. As a result, a total decrease of 7 ML was achieved per day. The total energy savings reported by this case study was 73 MWh per day.

One of the main limitations of the study includes the fact that the savings can only be achieved during limited periods of the day. Savings were only observed during peak periods and winter.

The implemented methods only decrease the supply for limited periods of 5-8 hours. In reality, there is a great need to decrease water demand for the water reticulation system during all hours of the day. The study did not outline the impact of water savings on the cooling systems. The cooling systems were not reconfigured for improved cooling and adjusted to the new control philosophy of water demand reduction.

**Conradie, W. [101]**

The paper focused on the stope isolation control, and a brief background on stope isolation control is provided. The objective of the study was to reduce water usage during different mining shifts. The mining shifts consist of the drilling shift, blasting shift and the cleaning shift. The listed shifts are the morning, the afternoon and the evening shifts respectively.

It was reported that cold water is only used during the drilling and cleaning shifts. This means that the chill water sent to the stopes can be discontinued during the blasting shift, when no chill water is needed in the stopes. However, the paper emphasised the importance of *not* cutting the water supply to the cooling systems during the blasting period, since cooling is always significant for the mine because the supply of cold air needs to be maintained to avoid heat pickups during these times.

The paper investigated two different types of stope isolation methods, namely the manual and the automated valve stope isolation method. The manual isolation method depends on the miners as the main operators. This means that the miners would open and close the valve when there is a need for water in the stopes. The limitation of this method is the fact that people tend to forget tasks and that the operation might not be consistently undertaken every day, depending upon the discipline of the miners. The cost implications of this method were proven to be minimal as there would not be any need for additional actuators on the valves. The manual method was not recommended.

The automatic methods require an additional installation of actuators on the valves. It also includes additional control instrumentation to regulate the flow and the valves. The automatic system/method can operate on times used for the shift scheduled or for the mine's centralized blasting system. Due to the inconsistencies of the shift time schedule, a predetermined time schedule for the valves would cause problems for the mine. The centralized blasting system of the mine works in such a way that when the working section has been cleared up, the shift boss inserts a key into a clearance box. The key can be used as a valve switch.

It was concluded that the automated stope isolation method was the best option, and that the stope isolation system results in a significant water supply reduction during the blasting shift. The method resulted in a total of 8 hours of water saving during the blasting shift.

In conclusion, the research demonstrated the importance of not discontinuing the chill water to the cooling systems when applying stope isolation methods, but could not outline the chill water optimization on the cooling systems and possible energy savings. No control was implemented to achieve optimal performance on the cooling systems.

**Lebele-Alawa, B.T. & I.O Ohia (2014) [80]**

The aim of this study was to evaluate the effects of fouling on three heat exchanger units (pump around cooler, first stage condenser and preheater) in a polyethylene plant. The study utilized direct measurements and steady state monitoring programs to obtain data. The overall heat transfer coefficient, heat duties, temperature and pressure range of fluids, capacity ratio and effectiveness were evaluated. The KPIs were used to calculate the fouling factor of the system.

It was concluded that the calculated heat transfer coefficient (UA) value for the pump around cooler was 51,60% less than the design value and 86,39% for the first stage condenser.

The external fouling was calculated. and the study proved in which different ways it affected the performance of the heat exchanger, although it did not present any results on how the internal fouling affects the flow distribution as well as the pressure drop on the system. This will in turn be related to the performance, as the mass flow affects the duty of the cooling coil.

**Jain, S *et al.* (2018) [102]**

Jain, S *et al.* [102] studied the impact of air distribution on the combustor in a sulfuric acid ($H_2SO_4$) regeneration (SAR) unit. The study involved the analysis of air distribution to burners in a commercial SAR furnace. The air is distributed to three burners through a manifold pipe with three outlet ducts. Computational fluid dynamics (CFD) simulations were used to build and simulate the structure in order to evaluate the air distribution on the system. Figure 30 illustrates the unit built on the CFD simulation.

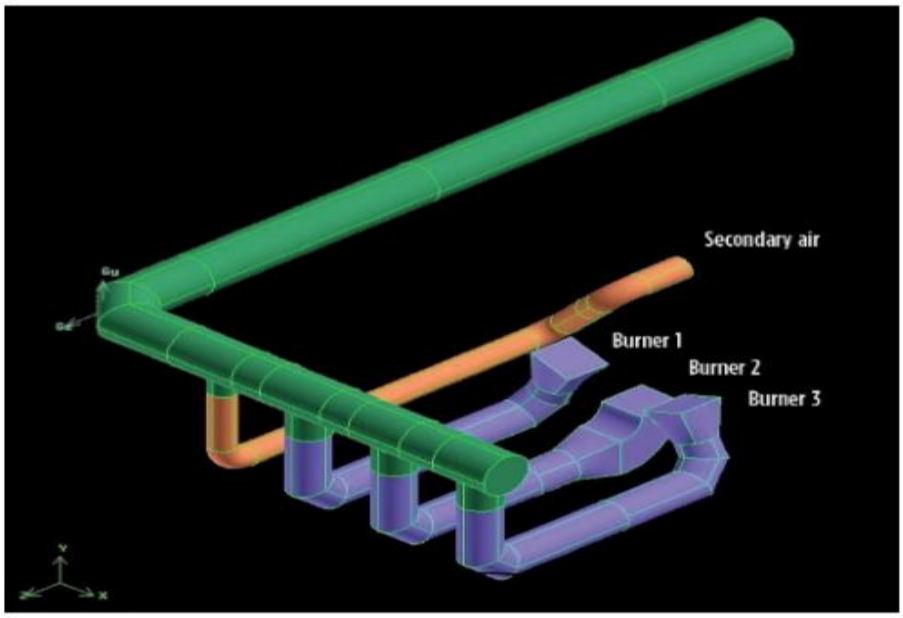



*Figure 30: Manifolds [102]*

The expected air distribution to the three burners was 33,33% per burner. The results showed an overall distribution of 27,6% for burner 1, and 36,2% for both burner 2 and burner 3. This proved that the air was not equally distributed, as it could be seen that burner 1 received less air flow. The study reconfigured the design by installing restricting orifices in burners 2 and 3 and the new results were 33,2% for burner 1, and 33,4% for burners 2 and 3.

The research focused exclusively on the reconfiguration of the design by only installing an orifice, and did not evaluate the impact on the change of the pipeline connection and its geometry and the general locations. The study was not based on cooling systems and water management, but rather on air flow. In conclusion, the authors were unable to supply the impact of flow configuration on the performance of the burners. In cooling systems the cooling performance would have to be evaluated after the reconfiguration of the manifold.

**Khamis Mansour, M & M. Hassab (2012) [103]**

This study focused on the design of different cooling coils. Two different types of coils were considered, namely the direct-expansion coils and chilled water coils. The authors evaluated a new method used to design the above-mentioned cooling coils. Instead of using the method based on log mean enthalpy or log equivalent dry-bulb temperature difference where the cooling coil is treated as a single zone/region, and hence the required surface area required,

the study focused on numerical calculations using a discrete technique “row-by-row method” to calculate the detail design of the cooling coil in order to enhance the calculation accuracy and trace the air and coil surface temperature locally. The challenge with the log-mean method is that it does not give accurate results when the cooling coil is partially wet.

The methodology is useful to evaluate the construction and geometry of the coils, the fin patterns on the coils and lastly to solve the heat and mass transfer equations simultaneously. All governing equations and the methodology were outlined. The method was applied on 2 different cases, both on the Dx-coils and partially dry chilled-water coils. It was found that the use of the numerical discrete method was by far better than treating the coils as a single zone; an average of 12% difference was observed.

The above mentioned method can simply be used to evaluate the performance of the cooling coils. This will require the measurements of the temperatures for each row of the coil. Also, most of the underground cooling coils are already assembled underground which makes it difficult to strip and isolate the coils to count the rows and to measure temperatures per row. For the method to be applicable on the cooling coils in order to calculate the performance of the cooling coils, the coils need to be restructured and a new specific mathematical model needs to be developed. This makes it difficult to apply the method directly in underground surroundings.

The shortfalls of the study include that no simulation tool was used to predict the results and that the case study was only based on theoretical results. No actual measurements were considered in order to prove the practical use of the method in real-life situations. Also, the calculations were based on the design calculation and not on practical/actual conditions.

**Tatara, R.A. & G.M. Lupia (2011) [104]**

The aim of this research was to assess the performance data of heat exchangers, considering the possible errors in temperature measurements. The study evaluates the methodology used to calculate the performance of heat exchangers and considers possible uncertainties/errors in measurements to obtain the data used to calculate the performance. The authors evaluate other statistical methods, but realized that those methods were complex and are not easily applicable to heat exchangers, especially those that are used in the industry where data is limited and difficult to obtain. The study developed an effective method that focusses on

temperature measurements and fluid flow in the heat exchanger and is based on standard deviation and t-distribution values within a 95% confidence level.

The study reviews a range of temperature instrumentation for various measurement techniques to prove the expected inaccuracies in temperature measurements. Calculations were done in order to illustrate the significant effect of decreasing the sample frequency. The study concluded that in any system with sensors, any reduction in sensors leads to an increase in uncertainties. The study realized a total of 11,6% in overall heat load uncertainty due to flow and temperature measurements. It was applied on a sample water to water cooler, using steady state field data.

In this study it is demonstrated that the performance of heat exchangers has at least a percentage error of 11,6% due to uncertainties in temperature and flow measurements. It is therefore important for this potential error to be considered when evaluating the performance of heat exchangers. However, no simulation was undertaken to support some of the statements made by the authors. The conclusion was only based on firsthand calculations. The heat exchanger was also only based on the design conditions and not on the normalized operation conditions. The error in evaluation thus includes the error of not evaluating the heat exchanger in terms of its design conditions. The impact of the methodology is important, especially when it comes to ensuring that the obtained data is accurate, but if the same measuring instrument is used for all measurements, these uncertainties will be eliminated by a mere consistency from measurements. This will also not affect the basic goal, which is to demonstrate that the change in flow configuration will typically affect the performance of the cooling coils.

**Mare et al. (2014) [105]**

Mare et al conducted a study on the use of specialized valves on cooling cars to reduce water consumption. The water consumption for one cooling car unit was reduced by 237 kl/day. This is equivalent to a total saving of 37,5 kW per unit. The projected saving on a total of 26 cooling car units was approximately 1 MW, which amounts to an annual saving of R2,8 million. It was concluded that the Maric valves were more effective, but need special maintenance.

The study did not optimize the water management through the cooling cars, it only focused on the installation of the Maric valves on the cooling cars to reduce water consumption. The study did not do an in-depth optimization study where the outlet temperatures of the cooling cars

were considered as well as the overall duty. The main objective of the study did not include the general improvement of the ambient conditions, it only maintained them. No pipeline reconfiguration was done to optimise or maximise the flow through the cooling cars.

**Greyling. J, (2008) [106]**

Greyling (106) conducted a study where different configurations of the air cooling units (ACU) developed by Van Eldik [107] were investigated. The study found that cooing coils supplied with ice are more economical. It was also outlined that a potential exists in using the Air Cooling Units for additional cooling by using the hot outlet water of the cooling cars as potential heat sink. This showed that the water outlet water from the cooling cars still has some cooling duty and can be reused underground if the water is at the recommended temperature.

Table 5 summarizes all the research applicable to the water managements and the cooling of the study.

*Table 5: Research summary*

| SOURCE | Water Management | Optimisation | Energy Management | Fridge Plants | Cooling Towers | Cooling Coils | System reconfiguration | Service delivery | Ambient conditions |
|---|---|---|---|---|---|---|---|---|---|
| Schoeman, W. [90] | | | | | | | | | |
| Vosloo, J. [46] | | | | | | | | | |
| Buys, JL [91] | | | | | | | | | |
| Du Plessis, GE [92] | | | | | | | | | |
| Uys, DC[93] | | | | | | | | | |
| Schutte, AJ [94] | | | | | | | | | |
| Mare, P [95] | | | | | | | | | |
| Lambrechts, JV [96] | | | | | | | | | |
| Kukard, WC [97] | | | | | | | | | |
| Greyling, J [106] | | | | | | | | | |
| Kamyar, A *et al.* [99] | | | | | | | | | |
| Botha, A. [100] | | | | | | | | | |
| Conradie, W. [101] | | | | | | | | | |
| Lebele-Alawa, B.T. & I.O Ohia [80] | | | | | | | | | |
| Jain, S *et al.* [102] | | | | | | | | | |
| Khamis Mansour, M & M. Hassab [103] | | | | | | | | | |
| Tatara, R.A. & G.M. Lupia [104] | | | | | | | | | |
| Mare et al. [105] | | | | | | | | | |

| | |
|---|---|
| | Not within previous scope of study |
| | Included in the previous scope of the study |

## 1.5 NEED FOR THE STUDY AND STUDY OBJECTIVES

A mine water reticulation system has different components. Cooling systems serve the primary purpose of cooling in underground mines and they consume close to 50% of the energy used in the mining industry. Water that has been chilled by fridge plants and ice plants from surface is sent underground to various mining levels.One of the objectives of sending chilled water underground is to cool down ambient temperatures.

Previous studies focused on the optimisation of water usage and outlined the importance of optimal usage to achieve electricity savings. Different cooling systems have been optimised to achieve optimal cooling systems. Some of the studies which were considered in the previous main point were conclusive on the aim of electricity reduction. There have also been studies which focused on the optimisation of methods used to evaluate the performance of cooling systems. These studies supplied a broad analysis of underground cooling systems. Another object of several studies has been to supply an outline of how the reconfiguration of cooling systems can further improve the efficiency of the systems.

Research also stressed the importance of integrating water management strategies with optimal cooling performance, since water is the primary cooling medium for underground cooling systems. Little research has been done on the integration of water management strategies with tertiary cooling systems such as cooling coils (BACs and cooling cars). Most mines still don’t have a set control strategy for bulk air coolers and cooling cars to achieve optimal water usage and cooling performance.

Therefore it should be clear that there exists a need to study the way water is utilised in cooling systems to reduce the consumption, improve the efficiency and increase the cooling of tertiary cooling systems.The objective of this study is to improve underground cooling conditions through an optimisation of water flow in mine cooling systems. The study focuses on cooling coils where the pipelines and the reticulation system of the cooling coils is reconfigured for optimised flow. The study further evaluates possible savings in the optimisation of water flow.

The study objectives therefore are:

- Cooling car outlet ambient temperature reduction
- Cooling car duty improvement
- Reduction on overall water usage and increasing water through the cooling car.

- Energy usage reduction leading to financial savings

# 2 METHODOLOGY

## 2.1 FOREWORD

The objective of this study is to improve underground cooling conditions through an optimization of water flow in mine cooling systems. The study focuses on cooling coils where the pipelines and the reticulation system of the cooling coils is reconfigured for optimized flow. The study further evaluates possible savings in the optimization of water flow. This chapter focuses on the development of the methodology to accomplish the desired results.

## 2.2 METHODOLOGY

A step-by-step method was developed to achieve the study objective. The method takes all aspects related to the focused studies mentioned in the literature review (see previous chapter) into consideration, as well as the knowledge gained through a more general literature review.

Existing flow optimization projects mainly focus on the possible flow reductions and general cost savings from flow reduction strategies. Some of the studies focus on optimization of the cooling systems through possible efficiency improvements of the cooling system. The short fall of most of the studies is the evaluation of possible water optimization in order to improve underground cooling. Most studies do not detect a link between the water management side and the cooling side of the cooling system, and no physical changes were suggested to improve underground cooling.

The model this study aims to use in order to evaluate water management optimization and cooling improvements in various cooling systems in deep level mines can be summarized in Figure 31 below.

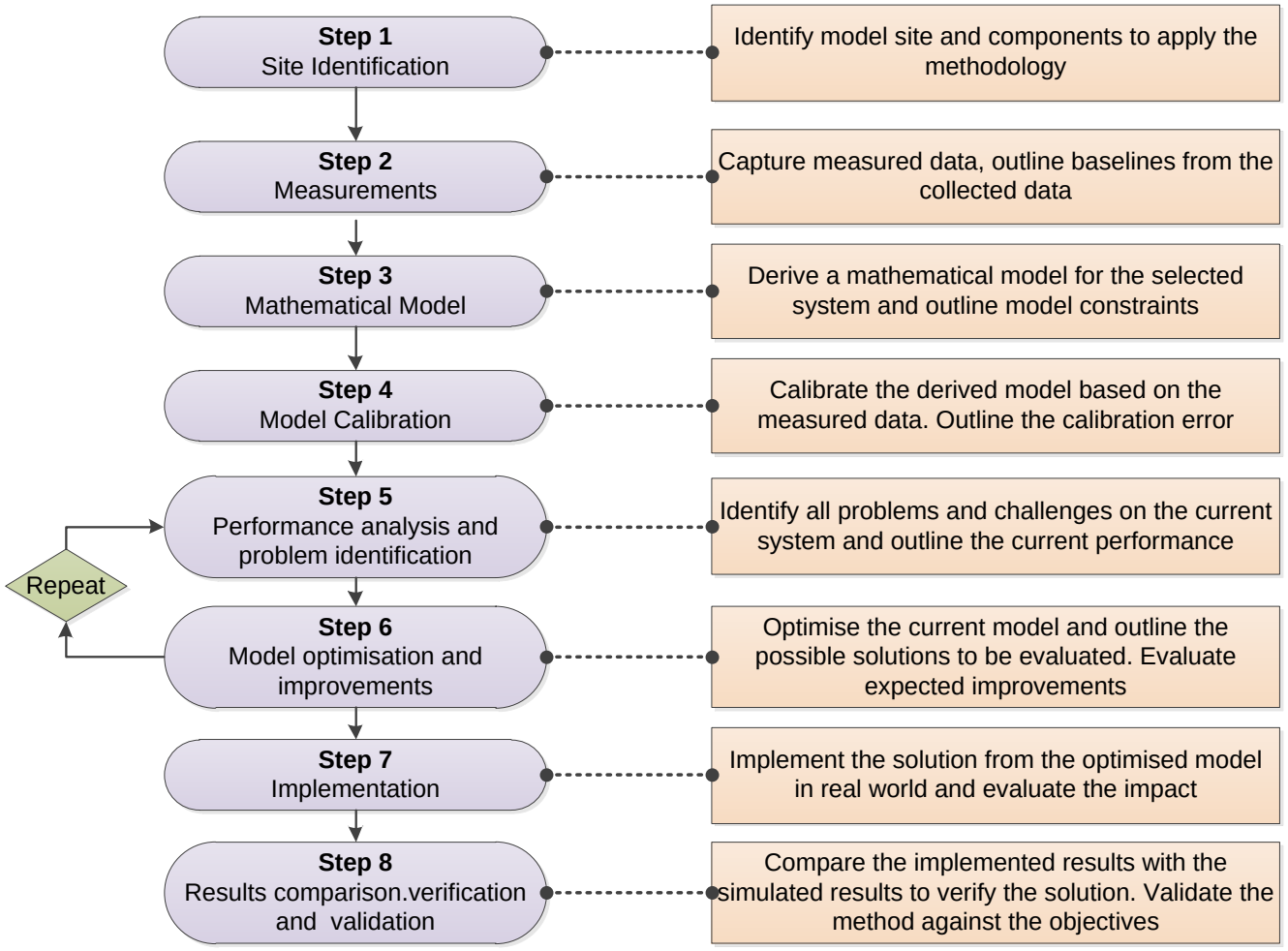



*Figure 31:Methodology flow chart*

In order to achieve optimal water flow through the cooling systems, proper preparations are necessary. Step 1 towards achieving the study objective will be to identify sites which use underground cooling systems, including cooling coils in the form of cooling cars or bulk air coolers which utilize water as a primary cooling medium. There is also the need to achieve savings in water usage and to determine where there is a need for cooling improvements. Step one will also show the general overview of the mine's system.

It is important to identify the baseline and the initial performance of the current cooling systems. Step 2 will be to identify the performance of the cooling systems as well as categorizing and identifying the current challenges/problems relating to the cooling systems. This includes relating the cooling to the water management initiatives which are directly proportional to the cooling systems. The identification process will involve physical inspections

and the application of the root cause analysis (RCA) method. Site personnel will be interviewed and asked relevant questions relating to the cooling systems at the specific mine. This step includes collecting data through measurements or through existing data of the mines. The data needs to be easily processed and analysed. The goal of this study is to evaluate the possible improvements of the cooling systems through improved or optimized water management systems. The data will focus on the water circulation, cooling performance and potential saving indicators.

With the collected data, a mathematical model will be developed in order to simulate the current underground systems. Step 3 will focus on creating relevant mathematical models to quantify and evaluate the impact of possible changes to the systems in order to achieve improvements. The mathematical models to be evaluated include those of the cooling coils in the form of cooling cars or bulk air coolers. The model will strive to evaluate the cooling side and the water optimization side and will be evaluated based on the measured results to ensure that it is a true representation of the underground components.

Step 4 will focus on the calibration of the models using the existing data, and requires the dependent and independent variables to be identified. These variables can be used to determine if the current model holds for the current systems. This section will include relevant simulation models using the relevant simulation tools. The mathematical model will have to meet the simulation model standards in order to be successful. This will include the evaluation of the day. Data will be fed into the model as an input and the results from the model will be compared to the actual results recorded on the specific day. Key performance indicators will also be used as output values to calibrate the model. Calculations will be done from first principles to develop a mathematical model which will be compared to the simulation model.

Step 5 includes identifying all the main causes of the identified problems from the model. The key performance indicators outlined in step 5 will be used to guide the decision towards problem identification. For example, the cooling duty indicates poor inlet conditions; this depends directly on the water flow rates; the low water flow rates relate to the water supply challenge or pipeline configuration; duty is also affected by the air inlet conditions. The low heat transfer coefficients represent external or internal fouling. This indicates that there is poor maintenance on the cooling coils. The key performance indicators will also guide the researcher on which areas need improvements.

Step 6 includes integrating the existing model with the possible solution to achieve the goal of the study, meaning that the current systems will be optimized to achieve improved savings or cooling underground. The improved model will be simulated and will be compared with the current data. Step 6 will also quantify the value of the improvements; this will include the calculation of possible savings and cooling improvements. This section will focus on the expected data from the changes made to the current systems. The section will therefore evaluate all positive and negative impacts of the suggested solution.

Step 7 involves the implementation of the current suggested solution to the system. The actual building of the configuration will take place, where all necessary measurements will be taken after implementation to evaluate the improvements.

Step 8, which is the last step, involves evaluating the results obtained from step 7 to be compared with the simulation results and those obtained from the mathematical model. This will verify the proposed solution. In this section the actual savings and cooling improvements are evaluated, this will be done through comparing the baseline results with the newly evaluated results. Finally, the output of the solution will be analysed to determine if the objective of the study has been met.

## 2.3 STEP 1&2 – SITE IDENTIFICATION, MEASUREMENTS AND DATA ANALYSIS

Underground mine cooling improvements projects and water saving projects on South African mines have become more and more common as the depth of South African mines have increased and the need for extensive underground cooling is critical due to safety concerns. Most of the cooling systems use water as a primary medium, but there is a need to achieve water savings due to the increase in water usage tariffs. Mine cooling improvements and water management (saving) system projects can basically be done on any site/mine that utilizes water as a primary cooling medium and has primary, secondary and tertiary cooling systems.

Table 6 Illustrates an example of a mine selection matrix. Such a matrix assists to ensure that there is scope on the selected mine. Several points need to be checked for a specific mine to be selected as an experimental site for the implementation of this study. In the example, mine X meets all the minimum requirements for the study to be performed. In the case of mines Y and Z only 4 points were checked, meaning the study could not have been conducted on those mines.

*Table 6: Site identification and selection rating*

| | Sites | | |
|---|---|---|---|
| **Minimum requirements** | **Mine X** | **Mine Y** | **Mine Z** |
| The mine is easily accessible to perform measurements and capture required data | 1 | 0 | 1 |
| The mine is a deep level mine > 1 600 m | 1 | 1 | 1 |
| The mine uses BACs and cooling cars as primary and secondary cooling systems | 1 | 1 | 0 |
| The cooling systems of the mine use water as cooling medium | 1 | 1 | 1 |
| There exists a need for water and energy saving | 1 | 1 | 1 |
| **Total Rating** | **5** | **4** | **4** |

The objective of this study is to optimally manage water to improve underground ambient conditions and to effectively achieve savings in mine water management processes. After identifying a site with the components which relate to the study, further investigations need to be outlined on the specific mine. Such an investigation involves identifying problems relating to the cooling components on the specific mine. The identification process commenced by interviewing mine personnel to determine if service delivery projects are required to achieve cooling improvements and optimal water management.

The first step in the identification of a problem is to ensure that the focus is placed on the correct area of concern. This is commonly done by applying the root cause analysis which refers to a process followed to identify the root cause of a problem [108]. Typical problems in the industry usually have underlying challenges which need to be investigated in full. Root cause analysis is usually defined hierarchically at a high-level and investigated in depth in order to clearly outline the problem breakdown.

The most common strategy of applying the RCA method is the “5 whys” [109]. The method aims to eliminate mere repercussions of the problem by asking the “why” question repeatedly. The method ensures that the focus remains on the root cause of the problem and assists with

limiting possible scope creep. Figure 32 illustrates a simplified process flow of the RCA technique using the “5 whys” approach.

In many instances the root cause might not be something which can be addressed directly due to time constraints or financial feasibility. Focus should then be diverted to the immediate repercussions caused by the root cause, and minimise the effect thereof. Although this will not directly address the problem at its source, it will assist in alleviating the affects to a point where operations can commence normally [110]. The method will be applied throughout the initial stages of the study.

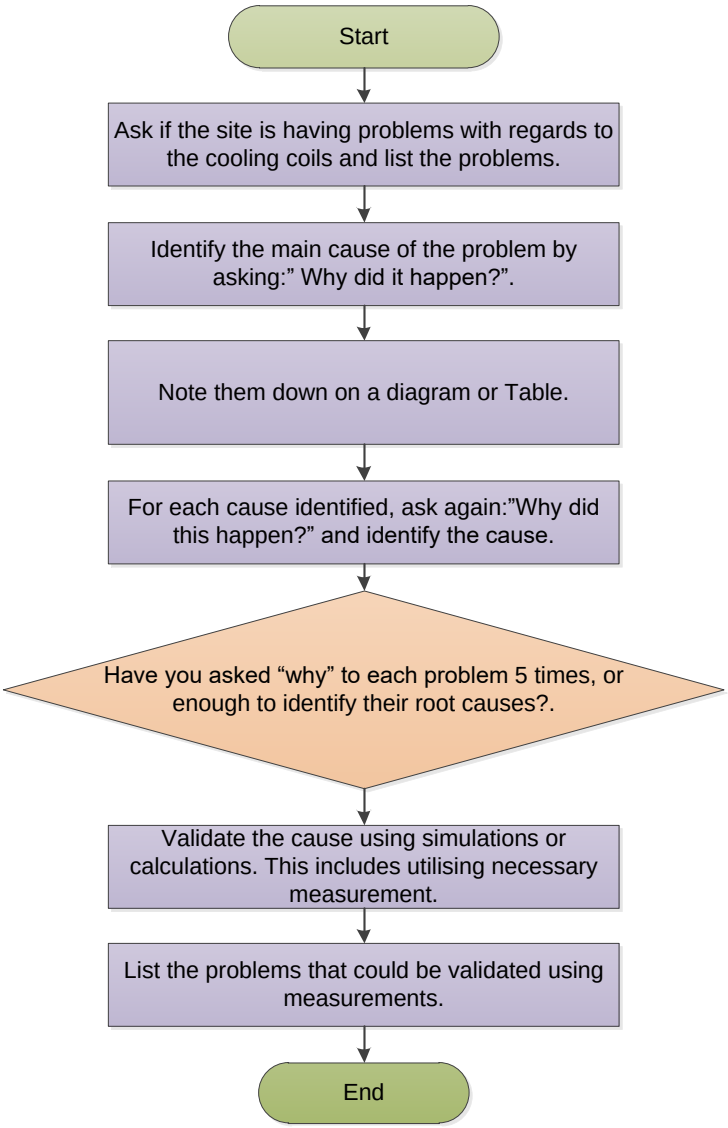



*Figure 32:Root cause analysis*

## MEASUREMENTS

The root cause needs to be validated by use of measurements and calculations. This will assist in identifying inefficiencies in the system. After a mine has confirmed that there exists a need for service delivery projects in cooling systems and water management processes and that a problem exists, data needs to be collected to identify the current performance of the systems compared to the initial design performance thereof. This will be used to create a baseline with which general improvements can be compared. If historical data exists on the mine's SCADA system (database of recorded data), digital data may be collected for the required period to be analysed. If no SCADA or historical data exists on the mine, manual measurements or feedback from mining personnel can be collected to obtain the same data.

J.G Pretorius [112] Outlined the cooling car measuring procedure. This includes the required instruments for the audit, the measurement points as well as the strategies to be followed when certain measuring points are not available. The procedure needs to be followed in detain to ensure that the highest order of accuracy is achieved.

It is important to ensure that the measurements are done safely and that all mine health and safety acts are followed at all time. The critical mine health and safety requirements for the measurements have been outline on the literature sections and they need to be followed.

### Cooling components location

Majority of tertiary cooling systems are located underground. It is required for one to physically go underground to perform audits. It is important to plan the audit well in advance to ensure that the audit is done safely and successfully. The cooling car identification procedure needs to be followed; this involves identifying the locations of the systems before going underground. Figure 33 shows an example that can be followed to identify the location of cooling cars underground

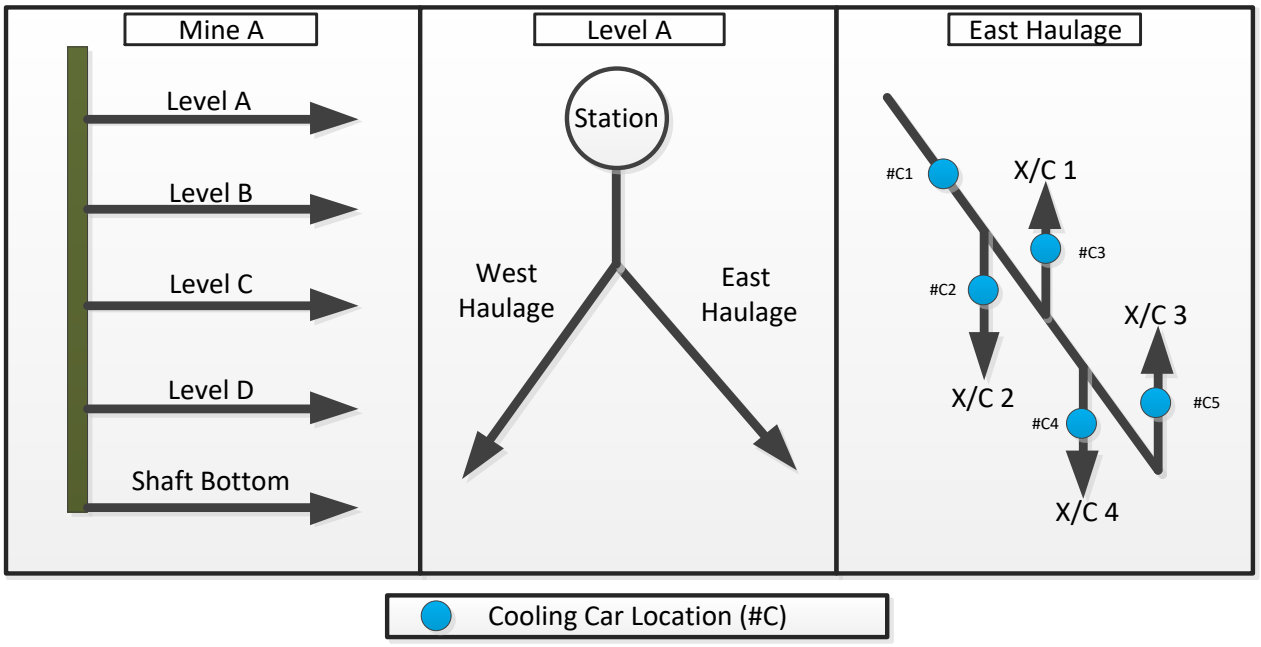



*Figure 33: Cooling car location procedure*

Deeps mines consists of several levels from surface to the deep end of the mine. The mine level further divides into different haulages as depicted on the Figure 33 the haulages further splits into different cross cuts (X/C). The cooling cars are normally located on the main haulages, the cross cuts (X/C) or RAWs.

***Mine health and safety***

Health and safety form an integral part of the measuring procedures. It is therefore important to always ensure that the health and safety standards are adhered to. The procedure outline in the introduction section under mine health and safety will be followed when measurements are taken.

## CONFIGURATION INSPECTION

The current configuration of the cooling cars needs to be confirmed with the specific mine. Water flow through the cooling car is generally affected by the pipeline configuration leading to the cooling car. Cooling cars consume high volumes of water, resulting in mines coming up with creative methods to save water and to increase the flow through the cooling cars with minimal water wastage.

The standard configuration of the cooling cars involves connecting the cooling car to the incoming chill water line. Depending on the flow, the water is then dumped on the footwall or back into the drainage system. Figure 34 shows a typical standard configuration cooling car.

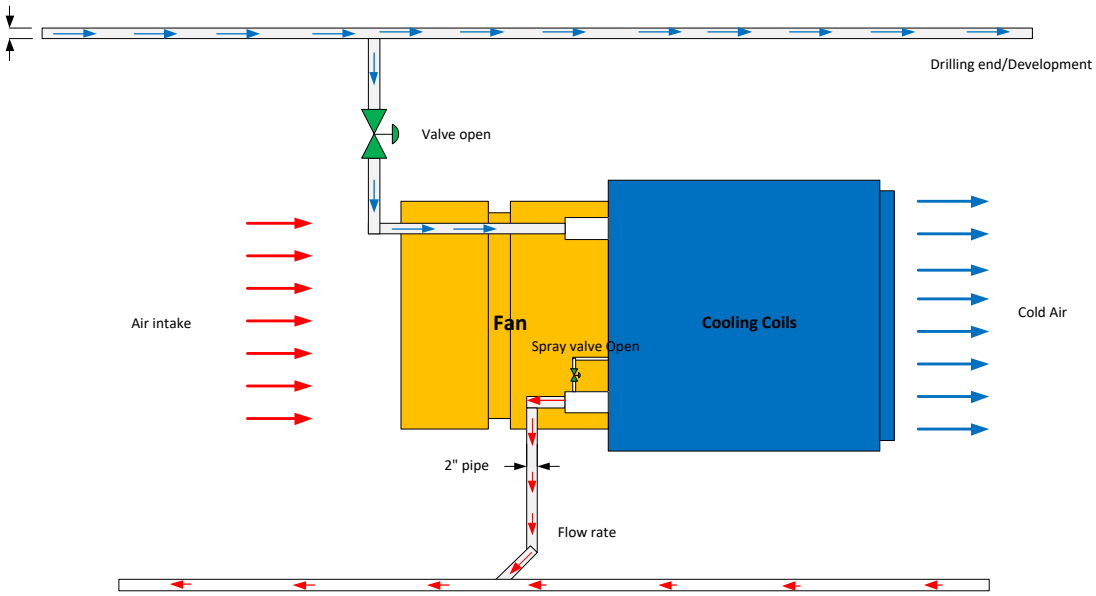



*Figure 34: Cooling car standard configuration*

The inspection of the configuration includes identifying any additional components which might be reducing the effectiveness of the cooling car. Water wastage is one of the major concerns in mines; it is important to make sure if the configuration needs further optimization to reduce mine water wastage.

The configurations have to be outlined and all the expected operations of the configuration need to be outlined. All the drawbacks with the current operation are outlined and explained. This study will focus on improving the cooling car configuration to increase cooling car performances and potentially saving energy.

Table 7 shows an example of a cooling car inspection sheet. The sheet normally includes all the components which are expected on the cooling car. This would mean that the cooling car would not operate according to plan if any of the components is missing.

*Table 7:Cooling car inspection sheet*

| Location | Components | | | | |
|---|---|---|---|---|---|
| | Inlet pipe | Outlet pipe | Cooling coil | Cooling car fan | Dumping method |
| NN X/C HH | ✓ | ✓ | ✓ | ✓ | Drain/Footwall |

The outlined components are only for the standard cooling cars which generally dump the water on the footwall or back into the drain line. The components can always be updated depending on the mine's specific configuration.

## 2.4 STEP 3 – SIMULATION MODELS

After the data collection, analysis and processing is required in order to determine the baselines and primary key performance indicators of the systems. Using appropriate equations, spreadsheets, programs and simulations if necessary, raw data should be processed and analysed for accuracy.

A simulation model will be built and calibrated based on the measured data. The simulation will represent the mathematical model of the actual cooling car underground which will allow for further analysis and evaluations of the cooling car and will assist with outlining its performance. Figure 35 outlines the process that will be followed to build a simulation model.

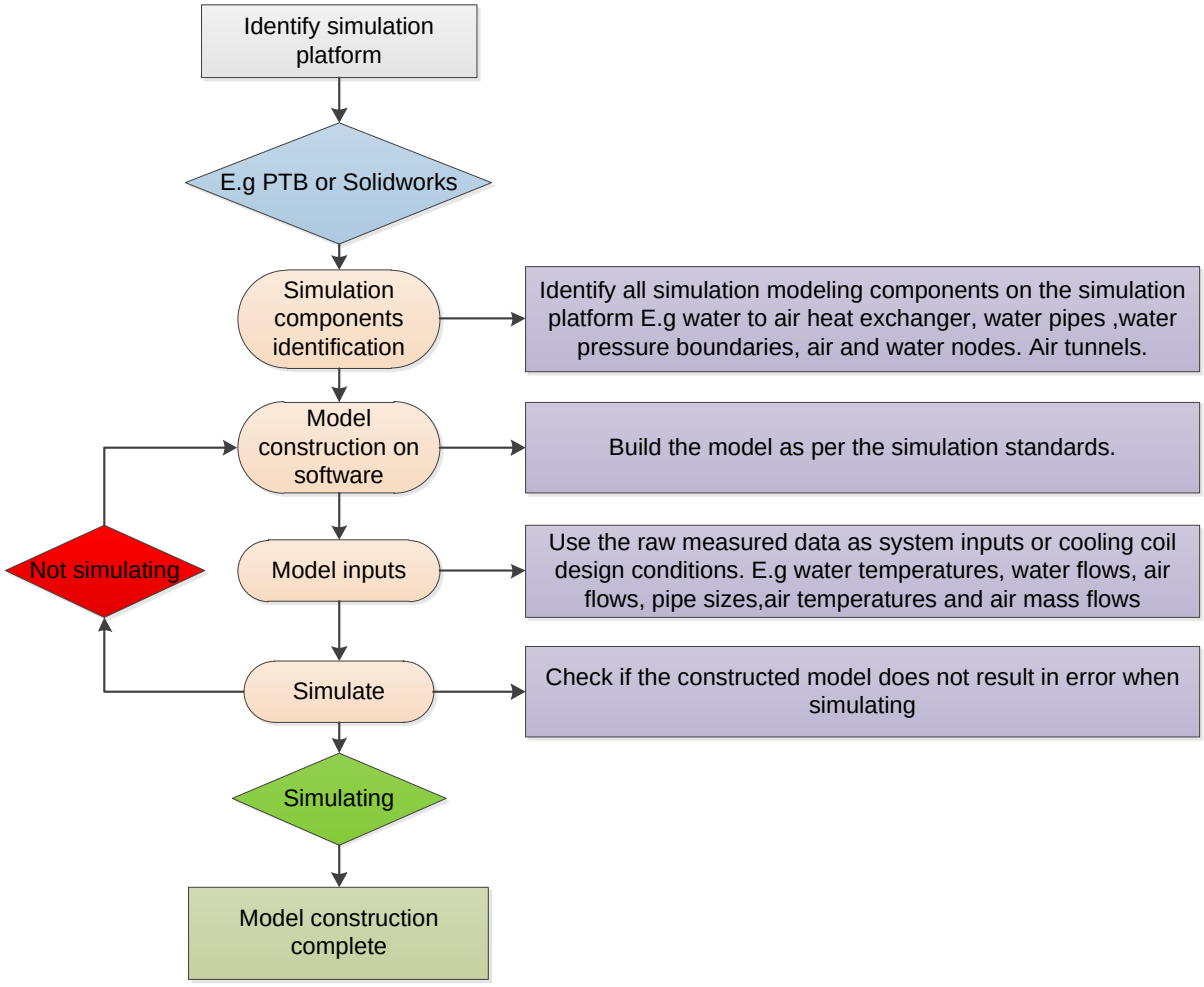



*Figure 35: Model construction process*

The first stage of constructing a simulation model is to identify a simulation platform. The platform needs to allow for an exact prototype of the real-life case to be built. Every simulation software consists of a user manual, the steps can be followed to identify all the relevant components and understanding how to use the software. The built model need to be able to simulate. When the model is successfully built, it needs to be calibrated.

Process toolbox was selected as the best simulation platform on literature due to its accessibility and previous application on cooling system calculations. A summary of all the required components is provided on Table 8 below.

*Table 8: PTB simulation components*

| Component | Name |
|---|---|
|  | Water pressure boundary |
|  | Water pipe |
|  | Water node |
|  | Water mass flow |
|  | Water to air heat exchanger |
|  | Water pump |
|  | Air pressure boundary |
|  | Air tunnel |
|  | Air node |
|  | Air mass flow |
|  | Air fan |

The components outlined on Table 8 are used to build a simplified cooling car for simulations. Figure 36 shows a basic cooling car built on PTB.

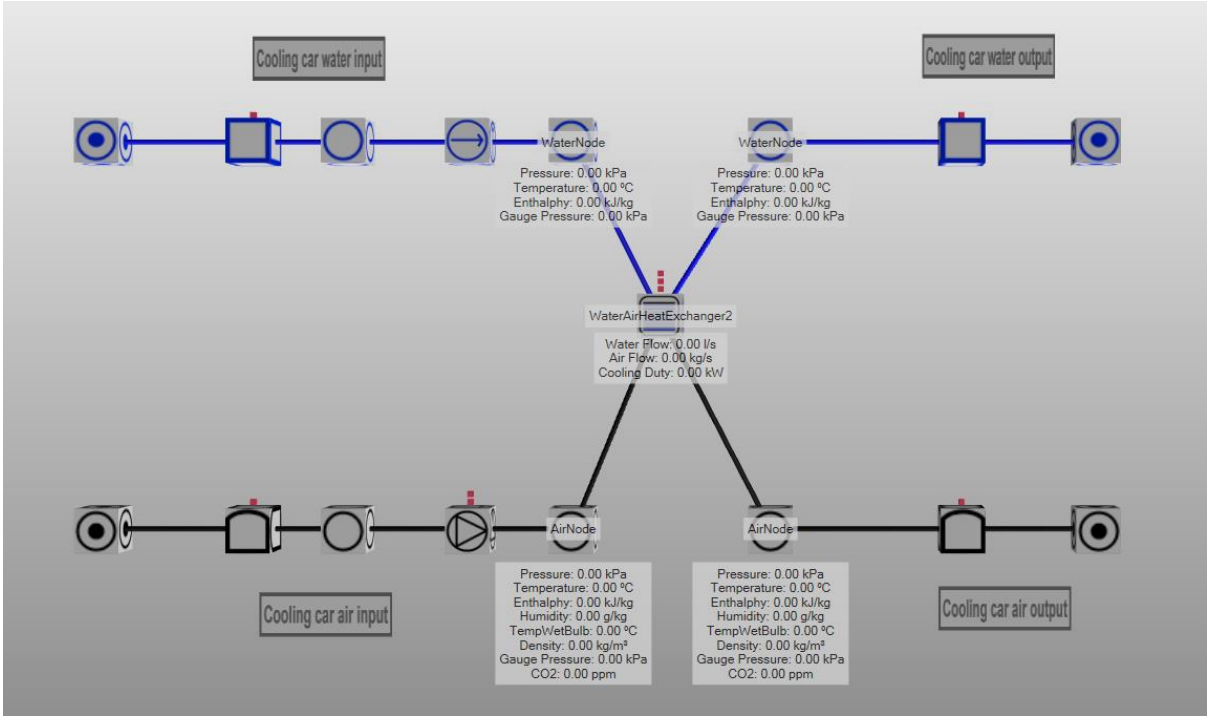



*Figure 36: Cooling car model construction example*

The water to air heat exchanger represents the cooling coils of the cooling car. The section labelled the cooling car water input shows the water inlet of the cooling car with the specified mass flow. The cooling car air input shows the air inlet side of the cooling with an air fan. The simulation manual consists of different examples which can assist with the construction of different configurations in cases where additional components are required.

## 2.5 STEP 4 – MODEL CALIBRATION

In order to calibrate the simulation model, a manual calculation will be done from first principle to determine some of the results expected from the simulation model. The calculated output together with the measured data will be compared with the simulation data. The variation between the data sets will provide the standard accuracy of the model. Figure 37 outlines the calibration process for the model.

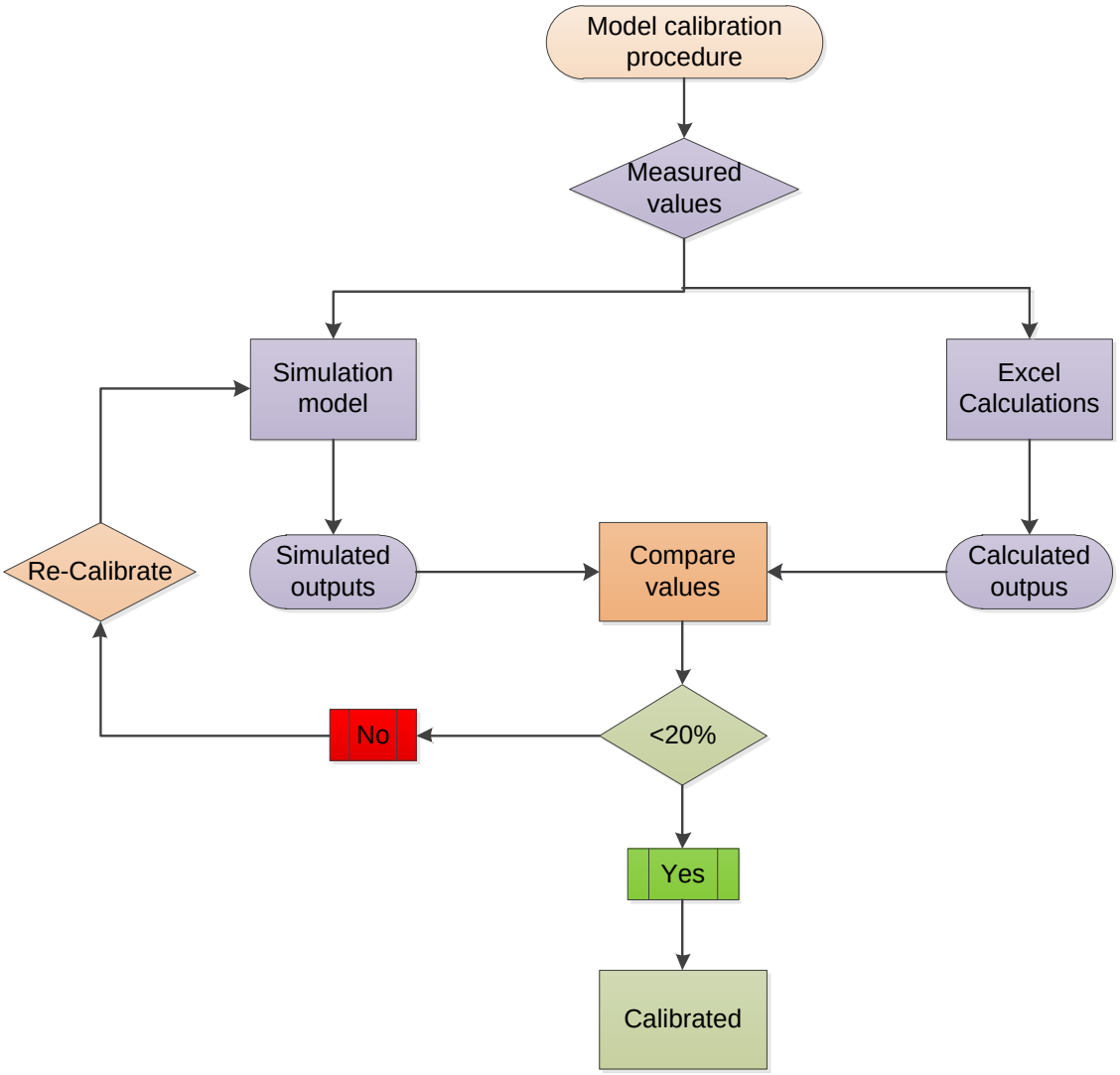



*Figure 37:Model validation process*

Most of the studies which used simulation tools to build models achieved a percentage error that ranges between 0% and 20%. It can be concluded that a fully calibrated model should fall within the specified accuracy bandwidth.

## PERFORMANCE EVALUATION AND ANALYSIS (KEY PERFORMANCE INDICATORS)

Equations 5-21 outlined in the introduction are used to determine the baselines as well as key performance indicators of the cooling coils. The calculations form part of the validation process as all the key performance indicators will be compared to the outcome of the model. The overall efficiency of the cooling coil will have to be determined. This will assist with the evaluation of the overall improvement of the cooling coil.

The efficiency of the cooling coils has generally been calculated by comparing the actual performance of the cooling coils with the design performance of the cooling coils, which is typically 300 kW or 500 kW, depending on the cooling coils under consideration. The drawback of this method is that the design conditions of the cooling coils no longer hold, since the cooling coils are generally operating at off-design conditions underground. Another simple way to calculate the performance or the efficiency of the cooling coils is to use the heat transfer effectiveness, which is obtained by dividing the actual heat transfer rate by the maximum possible heat transfer rate. The challenges associated with the given method is the presence of ventilation, water leaks and open water spray circuits in the system [111].

J.G Pretorius [112] studied the application of the normalized performance of the cooling coils. He postulated that the normalized performance of the cooling coil evaluates the performance of the cooling coils expected at off-design conditions. He found that this yields a more accurate calculation of the efficiency. In this study the following steps will be followed to evaluate the normalized performance:

1. Obtain the performance curves or design specifications from the manufacturer. The cooling coils are designed to operate on a specific curve. If no specifications are acquirable, then use the best-case UA product of 25 kW/°C from literature [113],[114].
2. Build a simulation model of an indirect heat exchanger with the air and the water side calibrated according to the actual measurements.
3. The heat exchanger outputs will then be verified against the actual measurements. Step 2 will have to be repeated until the verification yields more accurate results.

4. The UA product of the coil will have to be changed to that of the design specifications or the best-case UA value of 25 kW/°C .
5. Finally simulate and solve the thermodynamic problem to attain the normalized performance results at the actual operating conditions.

The expected normalized performance is then compared to the actual performance of the cooling coil to attain a more accurate efficiency of the cooling coil.

## 2.6 Step 5– Performance analysis and Problem identification

Cooling coils are affected by different constraints. These directly affect the overall performance of the coils. The following causes are usually identified from literature:

- Water management challenges including low water flow rates, high inlet temperatures and general discipline on mine water management, excessive dumping of water resulting in poor working environments and a wet mine. (Poor water distribution.)
- Increase in cooling coil external and internal fouling due to poor maintenance and bad environmental conditions.
- Cooling car location and positional efficiency. This becomes problematic when the cooling car is not placed at the required position. Mines often position the cooling cars where underground ambient conditions are extremely high.

The results from steps 1-4 are discussed and clearly defined. In this section the performance of the current systems will be evaluated and the drawbacks and inefficiencies are clearly identified. As this study focuses on optimal mine water management to improve ambient conditions, this relates directly to the first point. The identified problems will guide improvements of the systems and the solution will be derived to address the outlined problems.

The problems will be outlined in a check list format to ensure that the suggested solution aims to solve the problems at hand.

## 2.7 STEP 6 – MODEL OPTIMIZATION & EXPECTED IMPROVEMENTS

The cooling car water management is further divided into the following categories: increasing water flow through the cooling car and reducing water flow to achieve water savings while ensuring that the minimum targets are achieved; implementing water management control with a set control philosophy which will ensure that water is optimally managed; decreasing water inlet temperatures through the cooling car.

The water management problems generally relate to the configuration of the cooling car pipeline. In the instances where the cooling car pipelines are inefficient, reconfiguration of the pipelines will be necessary for the optimal water management. The reconfiguration includes the installation of new components and using the old to optimize water flow through the cooling car. To ensure that the optimal reconfiguration is selected, the process diagram as displayed on Figure 38 will be followed. After each step, the solution will be analysed to determine the feasibility. If the solution is not feasible after each step, the process is repeated until the optimal solution is obtained.

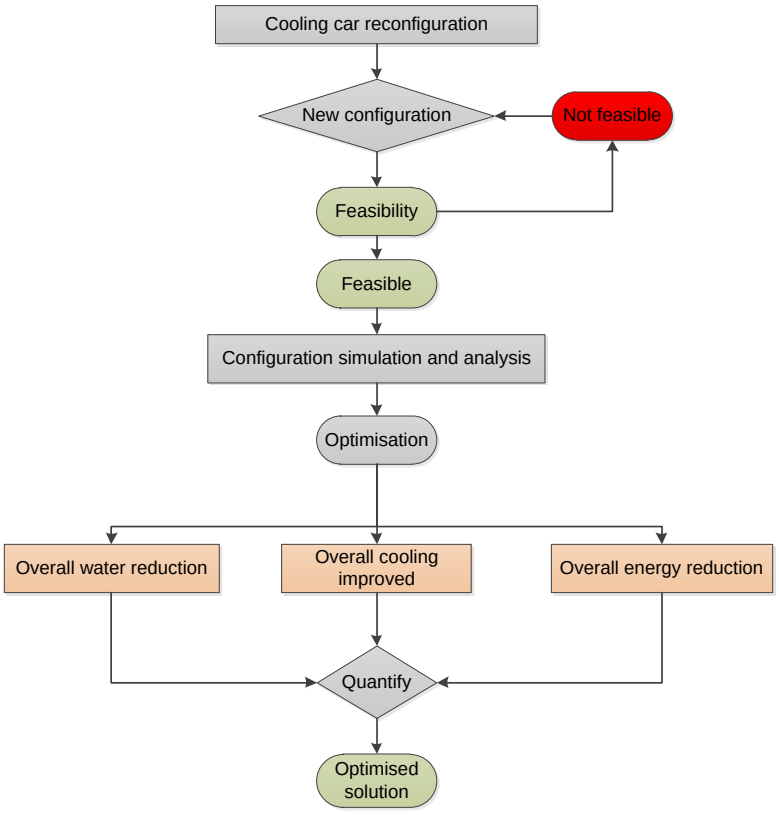



*Figure 38: Cooling coil optimization process*

Figure 38 depicts the reconfiguration process for cooling cars. The PTB simulation will be used to simulate the effect of reconfiguration of the environment and the cooling system. It would be redundant to reconfigure a cooling car and negatively affect the service delivery of the entire system. This will also depend on the mine in the case where water saving and reduced cooling decisions need to be made. The main baseline and expected operation conditions will be used for decision making. The reconfiguration with an improved efficiency should result in improved water savings, overall energy saving and improved service delivery.

## 2.8 STEP 7– IMPLEMENTATION

The developed solution needs to be implemented in order to verify it. Several steps need to be followed to ensure that the implementation is successful. Figure 39 outlines the implementation procedure.

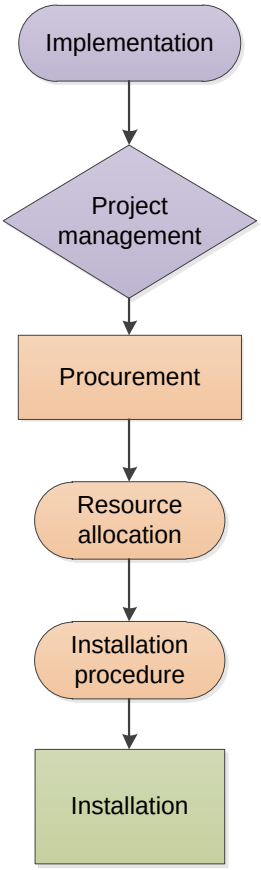



*Figure 39: Installation procedure*

The steps are summarized as follows:

***Project Management***

Proper project management principles need to be followed. This includes outlining the project initiation where a business case will be compiled for the task to be implemented. The goals and objectives as outlined in the need for the study will have to be evaluated for project implementation purposes.

A detailed project plan needs to be followed, where the deliverables are clearly outlined. The deliverables will be further divided into sub deliverables. A work breakdown structure (WBS) will be constructed to ensure that all deliverables are monitored. Key role players will have to be identified. A critical path is usually followed to limit the risk of the project. The risk analysis will be outlined to determine the life of the project

***Procurement***

The required infrastructure, parts, and skilled resources need to be procured well in advance. This will be based on the design requirements and the selected components. The lead time for some specialized components can take several months. It is important that the sourcing of these components is done timeously through local suppliers to avoid delays.

***Installation procedures***

Proper installation procedures have to be put in place. The right people who are qualified to undertake different installations have to be notified of the work that needs to be done. The installation procedure must be accompanied by the inspection procedure to ensure that the quality of the work meets the highest standards.

Incorrect installation procedures may lead to deviations from the original design and this might in turn result in poor performance and deviations from the expected results.

## 2.9 STEP 8– QUANTIFYING IMPROVEMENTS, VERIFICATION AND VALIDATION

The optimal solution strategy that has been implemented has to be validated and the improvements have to be quantified. The validation process involves comparing the evaluated improvements from the implementation with the main objective of the study, in other words verifying the measurement against the simulated results to ensure that the deviations from the initial baseline inlet condition is minimal. The process to be followed for quantifying improvements is outlined below in Figure 40.

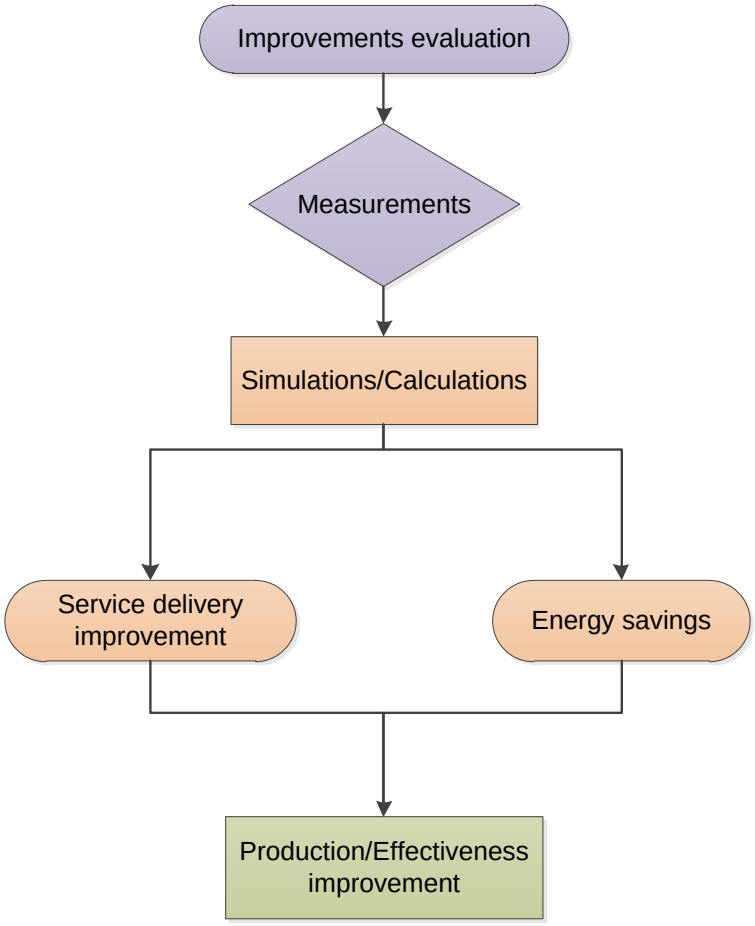



*Figure 40: improvement evaluation process*

## MEASUREMENTS

The same procedure followed on the baseline evaluation needs to be followed. The measuring points might change depending on the new pipeline configuration.

## CALCULATIONS

The data obtained after implementation should be evaluated similarly to the baseline data. The data has to be compared to the baseline to quantify the improvements on the system. The quantification involves calculating the average duty improvements, increase in water flow through the cooling car, decrease in wet-bulb temperatures and overall reduction in the water usage by the cooling cars.

## VERIFICATION OF RESULTS

The results obtained after implementation should be compared to the simulated results. This will allow for the verification of the results. The simulated results will have to be normalized to the current conditions; the normalizing process is outlined below.

### *Inlet air and water conditions*

The verification of the service delivery improvements such as the outlet air conditions, and overall heat transfer should account for changes on the cooling car inlet conditions. These include any inlet water temperatures as well as the air inlets. The condition of the cooling coil needs to be normalized. The recent heat transfer coefficient of the cooling coils has to be determined and adjusted according to the comparison.

### *Inlet pressures and mine water usage*

The verification of the overall water savings and water flow improvements through the cooling car should account for changes in the overall inlet pressures in the system and the mine water usage during the time of measurement. Changes can be implemented by updating the simulation model with recent conditions as outlined. This will ensure that “you compare apples with apples”.

## METHOD OF VALIDATION

After verifying the improvements, they should be translated to production benefits and financial benefits. It has to be proven that there is a correlation between service delivery or cooling condition underground and production figures. There is a correlation between the wet-bulb temperature improvement and the production figures. Figure 41 depicts the correlation.

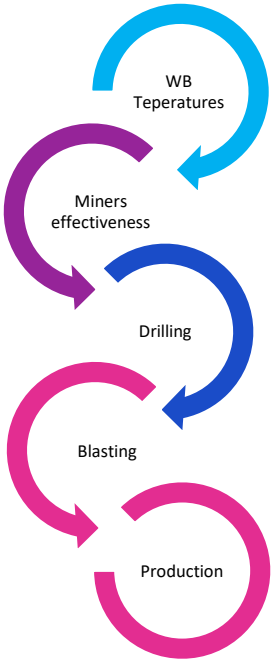



*Figure 41:Correlation process*

The decrease in wet-bulb temperatures results in an increase in the effectiveness of miners. In practice this means that the miner will be able to drill more holes than under higher temperatures. A given number of blast holes are required before blasting can commence. An increase in miners' effectiveness will increase the drilling rate and thus the number of blast holes. The direct effect will be that more tonnes of ore can be mined. There are different scenarios used to quantify the production improvements:

- Drilling time improvement (amount of saved drilling time). This is a result of less fatigue in miners
- Additional ore to be mined when effectiveness increases
- Increase in blast hole targets

The first step will include quantifying the reduction in wet-bulb temperatures, and then will follow the expected increase in the miners' effectiveness. Increase in the miners' effectiveness will be extracted from literature. The relationship between the effectiveness of miners and the increase in wet-bulb temperature was discussed in chapter 1.

The governing equation can be used to calculate the improvement in the general productivity of miners. The increase in productivity can be easily related to the increase in production. In order to validate the calculated results, production data will have to be evaluated. There are different contributing factors affecting the production, including labour issues, new mining sites, tonnes' recording accuracy, decrease in ore deposits and increase in mining distances.

The water saved from the reconfiguration process can be easily translated into energy savings. Usage water needs to be pumped back to surface and this requires electrical energy from the pumps. Utilized energy can be easily translated into financial savings. The first step would be to evaluate the total amount of water saved. Equation 2 in Chapter 1 outlines the energy required to pump water to surface. An average depth will be used for simplicity purposes.

The evaluated parameters need to be compared to the initial objective of the study. Each parameter can be rated between 0 and 1; 0 indicating that the objective was not met and 1 indicating the objective was met successfully.

## 2.10 Conclusion

A methodology has been developed to optimize the mine water management to improve cooling and to achieve potential savings on cooling coils. The first and second step involved site identification and measurements where the necessary data to evaluate the performance of the components was collected. It also entailed a root cause analysis to clearly understand main component challenges through interviews.

The third step involved utilizing the information obtained from step 1 and 2 to develop a model. The model was calibrated based on the measured values and was then again validated by assessing key performance indicators. Calculations were preformed and compared with the simulated values. Performance indicators were used as guidance towards identifying the main areas of improvement.

With the identified areas of improvement the model was optimised, and the optimal model was selected. Expected improvements were quantified. The final steps involved the implementation of the developed solution. The developed solution was also verified and the impact on the mine's production and cooling was quantified. The overall financial benefit of the improvements was then outlined and quantified. Chapter 3 outlines the application of the suggested methodology on a case study.

Before the performance analysis can be completed, the data need to be analysed to ensure that all the required data is available to perform the calculations in order to obtain more meaningful and accurate results. This includes drawing up trends and relationships to identify similarities in data in order to assume data. This section elaborates possible ways to relate data, for example, if we want to interpolate data for 24hours it will be outlined here.

After obtaining all the relevant data, the performance of the current configuration and measurements have to be obtained. In this section of the methodology, the best method used to evaluate the performance of the cooling car is outlined. The "how" part needs to be outlined and described in detail and lastly the possible achievements have to be illustrated clearly. All formulas to be used have to be outlined.

# 3 METHOD APPLICATION AND RESULTS

## 3.1 PREAMBLE/FOREWORD

In order to verify the proposed methodology as outlined in methodology section , the proposed methodology will be applied on a case study. The developed methodology will be followed step by step where the first step of the verification process will be to perform real-world accurate simulations to identify problems and possible improvements on the mine water management systems such as cooling coils. The simulated results will then be compared with the implemented results to validate the methodology. The case study was conducted on a South African gold mine, referred to as Mine A.

## 3.2 STEP 1&2 – MEASUREMENTS, SITE IDENTIFICATION AND DATA ANALYSIS

### SITE IDENTIFICATION

Site identification was based on the scope that relates to the topic at hand. The first step of identifying Mine A as the potential site was to investigate the availability of the cooling coils. The investigation was not done in depth., It included checking the general background of the mine. Three different mines were evaluated, and Mine A was selected.

Table 9 outlines the checklist that was followed for the site identification. Mine A checked all the required points for the investigation.

*Table 9:Mine identification table*

| | Sites | | |
|---|---|---|---|
| **Minimum requirements** | **Mine A** | **Mine B** | **Mine C** |
| The mine is easily accessible to perform measurements and capture required data. | 1 | 1 | 1 |
| The mine is a deep level mine > 1600 m and a gold mine. | 1 | 0 | 1 |

| | | | |
|---|---|---|---|
| The mine uses BACs and cooling cars as primary and secondary cooling systems. | 1 | 0 | 1 |
| The mine cooling systems use water as cooling medium. | 1 | 1 | 1 |
| There exists a need for water and energy saving. | 1 | 1 | 1 |
| **Total Rating** | **5** | **3** | **5** |

Mine A and Mine C had an equal number of points. Mine A was selected as a potential site since it had more cooling coils than Mine C. Mine C makes use of a bulk air cooler consisting of 10 coils. Mine A makes use of a total of 20 cooling coils.

## MEASUREMENTS AND COOLING CAR CONFIGURATIONS

An investigation was carried out on the selected mines to determine the current state of the cooling coils at the mine. The investigation included the evaluation of the current configuration of the cooling coils and taking the measurements of the coils in order to determine their current performance. This section outlines the results obtained from the investigation.

## COOLING COILS CONFIGURATIONS

This section evaluates the general configurations of the cooling components, and the measurements of the components. The section will also confirm the information obtained from the interviews performed with the occupational hygienist and the mine engineers. Finally, the challenges posed by the current configurations and the inefficiencies observed from the measurements will be discussed. The measurements will also include the general layout of the pipeline configuration of the cooling cars. As discussed in the methodology section, the paper will focus on the cooling coils which are mainly divided into two types i.e., cooling cars and bulk air coolers.

## COOLING CAR CONFIGURATIONS

The cooling cars in mine A had two different configurations. The configurations depend on the location of the cooling cars. Type A configurations are for cooling cars located in the crosscuts and type B for the cooling cars located in main haulages and RAWs. The configurations are discussed in detail below. The cooling car location procedure was followed for Mine A. The locations of the cooling cars are outline on **Appendix B**

## TYPE A CONFIGURATION

Type A configuration includes all the cooling cars that are located on the crosscuts (X/C). The configuration was developed by the mine. The initial standard configuration of dumping the water on the footwall resulted in flooding of the crosscuts. The main objective of the connection as per the interview with the mine personnel, was to ensure that the water used by the cooling car is reused by feeding it back into the system. This would ensure that there is minimal or no dumping during the running period of the cooling car. Figure 42 depicts the cooling car configuration.

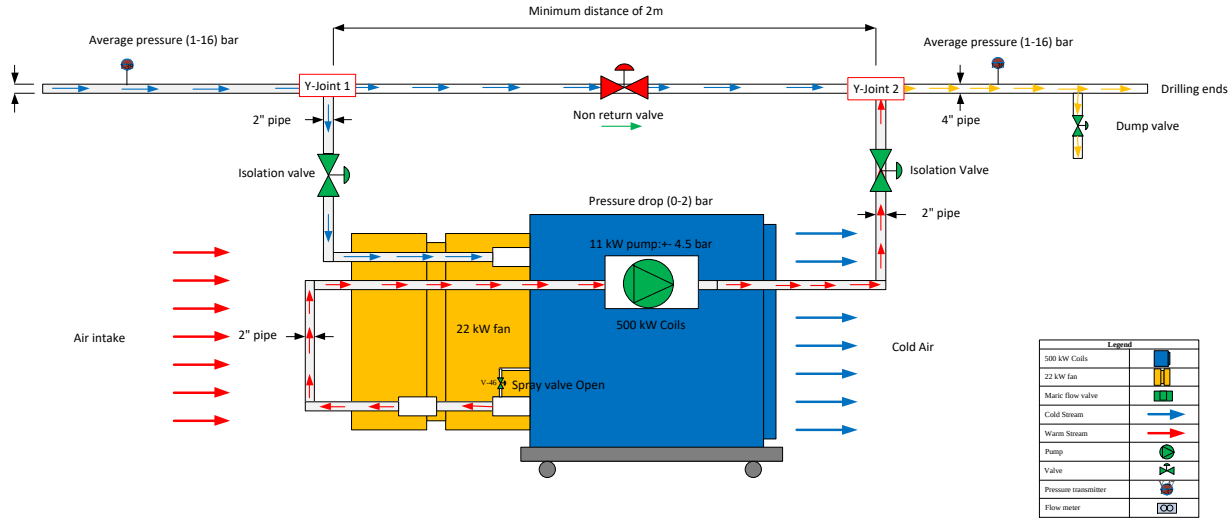



*Figure 42: Mine's cooling car pipeline configuration*

The cooling car receives chill water from the 4-inch pipe; the two isolation valves are put in place to isolate the cooling car from the system. The chill water exchanges heat with the warm ambient air through the cooling car coils; the warm water then exits the cooling car where it is fed through an 11-kW pump that adds a total pressure of 4,5 bar to the system. The pump is

put in place to force the stream back into the system. The sum of the initial pressure leaving joint 1 and that of the pump needs to balance the pressure on the 4 inch pipeline for the water to get back into the system via joint 2.

A dumping valve regulates the flow based on pressure on the main line downstream to allow for the cooling car to operate when the miners are not working and there is no flow downstream. The valve completely closes when the pressure setting is too low and opens when the pressure on the system increases.

General inspections were done on the installed cooling cars. The cooling cars needed to have certain components in place to operate as per the mine's expectations. Type A configuration suggests that the following components have to be present on the system:

- Pump on the cooling car water outlet
- Non-return valve on the chill water line
- Dumping valve where the exit pipe joins the chill water line, and
- Butterfly valve on the chill water line before the non-return valve

Table 10 shows the audit report for the availability of components.

*Table 10: Cooling car components inspection*

| **Location** | **Components** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Inlet pipe | Outlet pipe | Cooling coil | Cooling car fan | Inline Pump | Dump valve | Non-return valve | Recirculation | Dumping |
| 66L X/C 38 | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 69L X/C 71 | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | ✓ | Chill Line |
| 69L X/C 75 | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 71L X/C 73 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | NO | ✓ | Chill Line |
| 71L X/C 36 | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 73L X/C 38 | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 73L X/C 40 | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | ✓ | Chill Line |
| 73L South Dev | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 75L X/C 38 | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | Chill Line |
| 75L X/C 40 | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | ✓ | Chill Line |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 75L X/C 41 | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | N/A | Chill Line |
| 75L X/C 43 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | Chill Line |
| 75L X/C 44 | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | NO | NO | Drain |
| 75L RAW South Left | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 75L RAW South Right | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 75L RAW North Left | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |
| 75L RAW North Right | ✓ | ✓ | ✓ | ✓ | NO | NO | NO | NO | Drain |

It can be seen from the audit report that not all the components were available for the suggested configuration. This would mean that the cooling car on the cross cuts were not operating up to the initial design specifications. For some of the cooling cars, water recirculation was seen, this meant that there was no continuous flow through the cooling car resulting in the cooling car not achieving the cooling purpose.

### TYPE B CONFIGURATION

Type B configuration represents the cooling cars located on the main haulages. This type of configuration is located on two different places, namely the crosscuts and the main haulage of the mine. Crosscuts generally have low pressures as compared to the main haulage pipelines. The pipe sizes on the crosscuts and haulages are typically 4 and 6 inches respectively. Figure 43 indicates the schematic layout of the configuration which the mine uses.

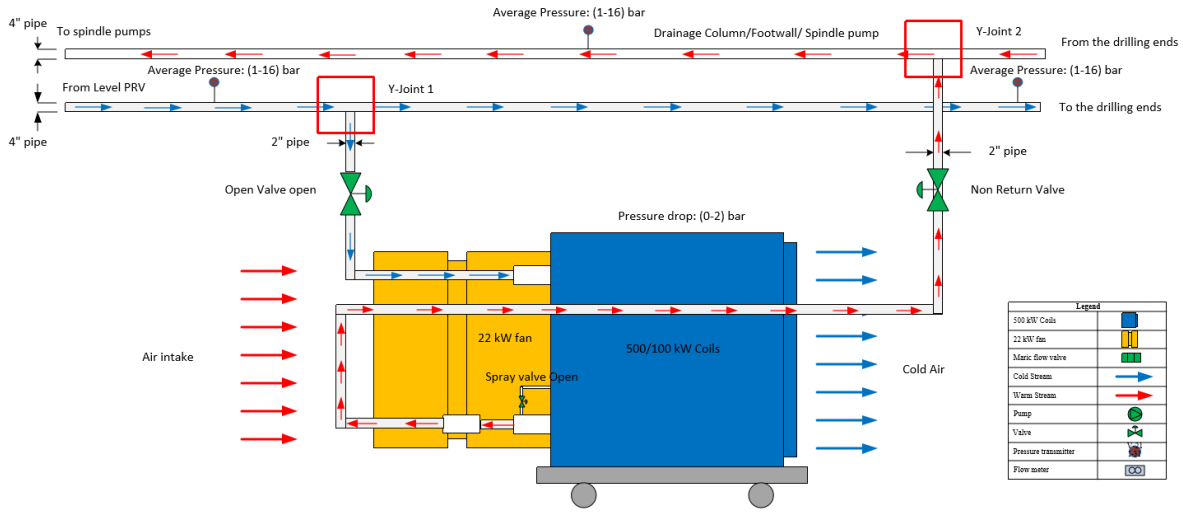



*Figure 43:Type B cooling car configuration*

The cooling car inlet water pipeline is connected to crosscut 4 in the service water pipeline. The water used by the cooling car is then duped directly on the footwall or on the drain pipeline that dewaters the water from the system.

## ACTUAL MEASUREMENTS

All the cooling car locations were identified – A total of 17. Eight cooling cars were located on the mine crosscuts, six of them had type A cooling car configurations and two had type B configurations, dumping directly on the footwall. Nine cooling cars were located on the main haulages or RAWs with type B cooling car configuration. **Appendix** C: Cooling car measurements

**Appendix C** indicates the minimum required measurements to calculate the actual and the normalized performances. The measurements were taken on mine A. All cooling cars were rated 500 kW.

## COOLING CAR PERFORMANCE

The actual performance based on the instantaneous measured values is calculated using the equations discussed in the introduction section. The equations were programmed into a Microsoft Excel worksheet to allow for multiple measurement inputs. The worksheet was used

as a template to calculate the important outputs in order to evaluate the performance of the cooling cars. Table 11 depicts the results calculations for the measurements.

*Table 11:Cooling car performance table*

| Cooling car | $Tw_{in}$ (°C) | Flow(l/s) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | Flow (kg/s) | $Tw_{out}$ (°C) | $Tout_{_db}$ (°C) | $Tout_{_wb}$ (°C) | Duty (kW) | UA kW/°C |
|---|---|---|---|---|---|---|---|---|---|---|
| #C1 | 26.5 | 3 | 31 | 28.5 | 14.41 | 28 | 28.5 | 28 | 33 | 21 |
| #C2 | 28.7 | 15 | 34.5 | 34 | 15.06 | 33.2 | 34 | 33 | 90 | 136 |
| #C3 | 21.3 | 7.8 | 36 | 34 | 16.13 | 27.1 | 31 | 31 | 263 | 23 |
| #C4 | 27.3 | 0.2 | 30.5 | 30 | 12.24 | 31 | 30.5 | 30.5 | -31 | #NUM! |
| #C5 | 19.1 | 20 | 35.5 | 32 | 13.99 | 26.7 | 25.5 | 25.5 | 417 | 109 |
| #C6 | 19.6 | 6.5 | 30.5 | 29.5 | 13.49 | 26.7 | 27 | 27 | 151 | 41 |
| #C7 | 22.9 | 2.4 | 33.5 | 33 | 13.93 | 33.2 | 32 | 32 | 75 | #NUM! |
| #C8 | 19.2 | 10 | 32 | 32 | 13.3 | 25.3 | 27.5 | 27.5 | 286 | 34 |
| #C9 | 20.5 | 4 | 32.5 | 30 | 15.35 | 29.5 | 27 | 27 | 206 | 64 |
| #C10 | 31.2 | 9.7 | 32.5 | 31 | 13.01 | 33 | 32 | 32 | -68 | #NUM! |
| #C11 | 21.6 | 0 | 34 | 31 | 13.99 | 34 | 34 | 30 | 69 | #NUM! |
| #C12 | 16.8 | 2.3 | 32.5 | 29.5 | 15.58 | 30 | 30 | 30 | -39 | #NUM! |
| #C13 | 14.3 | 1.9 | 32 | 30 | 18.02 | 29.5 | 29.5 | 29.5 | 41 | 28 |
| #C14 | 22.5 | 6.2 | 31.5 | 29.5 | 15.2 | 25.1 | 27 | 27 | 167 | 15 |
| #C15 | 22.5 | 6.1 | 34.5 | 31 | 14.67 | 30.1 | 29.5 | 29.5 | **104** | 65 |
| #C16 | 19 | 7.4 | 31.5 | 30 | 15.06 | 24.1 | 25.1 | 25.1 | **317** | 26 |
| #C17 | 19 | 7.4 | 32 | 30 | 14.81 | 24.5 | 24 | 24 | 373 | 32 |
| Average | **22** | **6** | **33** | **31** | **15** | **29** | **29** | **29** | **144** | **#NUM!** |
| Total | | 110 | | | | | | | 2456 | |

It can be deducted from Table 11 that most of the cooling cars were underperforming, this was seen from low cooling car duties. The calculated UA values were questionable because the theoretical UA value suggested by the literature was found to be 25 kW/°C [113],[114]. An error was found when calculating the UA values of #C4, #C7, #C10, #C11 and #C12, indicating that the results measurements did not follow the first principle of thermodynamics. It was incorrectly assumed that there is no heat transfer possible on these cooling cars. All the relevant cooling cars followed the type A cooling car configuration.

Cooling cars #C2 and #C5 had UA values greater than 100 kW/°C. These results were questionable because the UA values were way higher than the one obtained from literature.

All other remaining cooling cars followed type B cooling configurations and were located on the main haulages and the RAW's.

## ROOT CAUSE ANALYSIS

Step 1 of the measurements, site identification and data analysis process includes identifying the challenges relating to the specific mine and their root cause. Mine A experienced chill water management challenges on their cooling cars and active crosscuts. This directly influenced their performance. The cooling cars are expected to have a flow of 10 ℓ/s with an inlet temperature of 11 °C in order to perform optimally. The cooling cars are located on crosscuts and haulages. The following points can be deduced regarding the challenges relating to cooling cars:

- Cooling cars which dump water on the footwall pose the wet mine problem and mud accumulation on the crosscuts.
- The excessive dumping of water from the cooling cars lead to water wastages. This is caused by the lack of water flow control on the cooling cars.
- The cooling cars on the haulages are exposed to high pressures. Since the cooling cars are connected directly to the high-pressure line, this results in the fact that cooling cars use more chilled water than expected.
- Mine A is already experiencing water supply challenges and cannot afford to supply 10 ℓ/s to the cooling cars, especially if the water is dumped directly into the dewatering system. There is an additional need to identify the optimal operating flow that will allow for water savings and enough cooling.
- The mismanagement of water leads to cooling inefficiencies and high underground temperature.

  The high-water usage is energy intensive and leads to high electricity usage. This is due to the pumping and additional pumping infrastructure on the system.

The above-mentioned points were identified using the root cause analysis. The method was applied through asking the “why” question consecutively. The investigation included actual underground inspection and interviews with site personnel.

## 3.3 STEP3– COOLING CAR SIMULATION MODEL

In order to evaluate the impact of the cooling car configuration, a model was build using Process Toolbox, a thermal and hydraulic simulation software package. The cooling coils were modelled as an indirect heat exchanger with all the necessary water pipelines. The model was built to, additionally, confirm the drawbacks of the model as well as the general contribution of the configuration to the performance of the cooling coils. The measurement values and the daily data were used as general input of the model to form a basis for all calculations.

The measured values were used to calibrate the model to be as accurate as possible. Figure 44 depicts the type A simulation model.

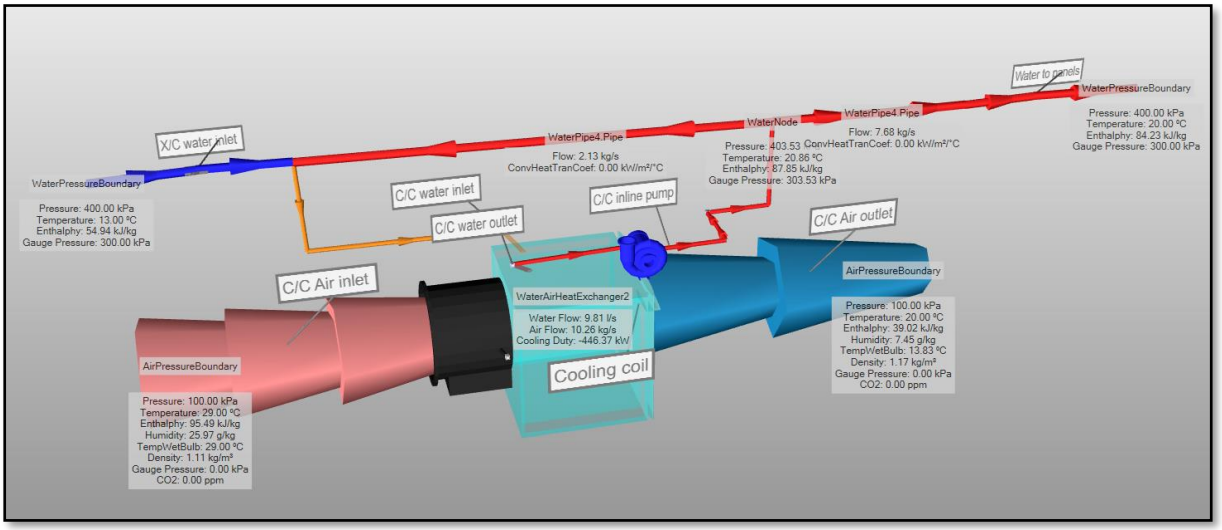



*Figure 44:Type A cooling car simulation model*

The water demand on the mine panels as well as the cooling car demand were incorporated into the model. Some of the cooling cars on the crosscuts could not be calibrated and modelled because of questionable data which could not be verified with the model. In such a case only the water flow was analysed and basic thermodynamics principles were applied. It was fouund that energy was not conserved on the cooling cars. The cooling cars were labelled completely nonoperational.

Figure 45 depicts the cooling car configuration model built for cooling cars located on the haulages (Type B). The measured data was inserted into the cooling car model and used to calibrate the model to allow for possible changes and improvements.

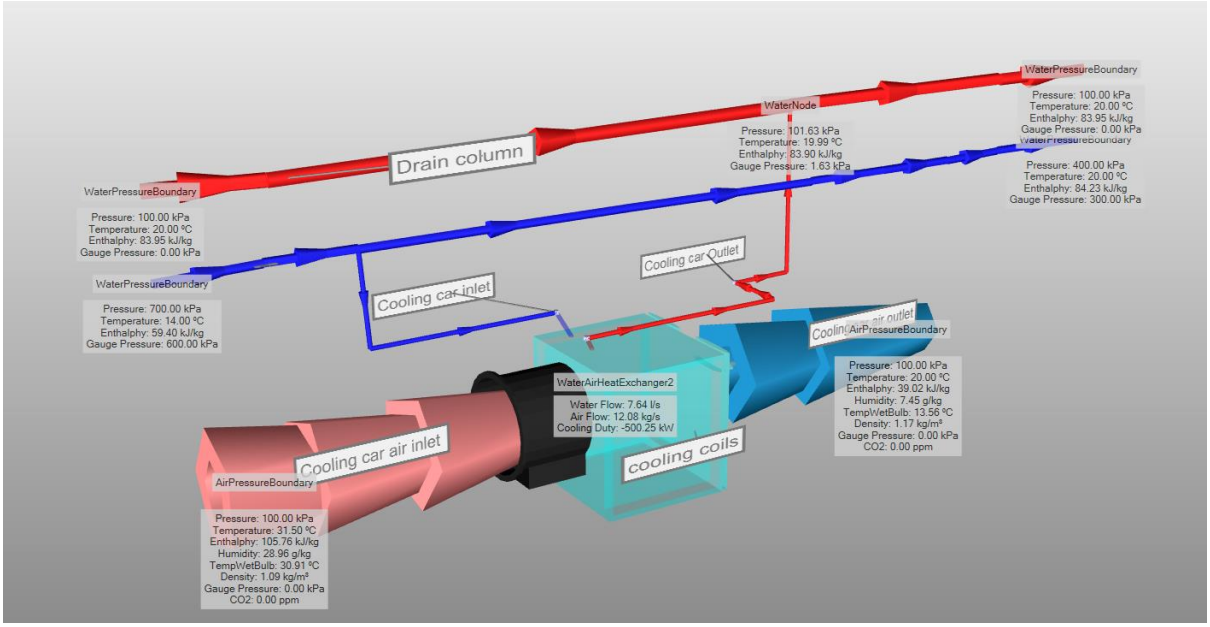



*Figure 45:Type B cooling car simulation model*

The drain column line represents the actual drain column or the footwall which was necessary because some of the cooling cars were dumping directly onto the ground. The following assumptions were made when building the model:

- The heat pickup as a result of the water dumped next to the cooling car was negligible.
- The cooling car heat transfer coefficient remained constant for the period of 24 hours.
- The air inlet temperatures were not top varying and were relatively constant for a 24hour period.

## 3.4 STEP 4 – MODEL CALIBRATION

The measured values were used to calibrate the models. Each cooling car model was built to analyse the current configurations of the cooling cars as well as the general performance. The built simulation needs to match the measured results as well as the calculated values. The model can be used if the error between the measured and simulated values is withing the reasonable range. Table 11 outlines the measured cooling car inputs, outputs and calculated UA and duty values.

Not all the UA values of the cooling cars could be calculated because some of the cooling car results indicated an increase in wet-bulb temperatures – the cooling car is meant to reduce the temperatures. The recommended UA value for the cooling cars, according to literature, is 25 kW/°C [113],[114]. Some of the cooling cars indicated UA values above 100 kW/°C. The measured values were used as input on the simulations. The simulation screen shots per cooling car are outlined in **Appendix D**. Table 12 illustrates the values used as input on the simulation model as well as the output values from the model.

*Table 12: Cooling Car simulation outputs (Calibration)*

| Cooling car | $Tw_{in}$ (°C) | Flow(l/s) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | Flow (kg/s) | $Tw_{out}$ (°C) | $Tout_{_db}$ (°C) | $Tout_{_wb}$ (°C) | Duty (kW) | UA kW/°C |
|---|---|---|---|---|---|---|---|---|---|---|
| #C1 | 26.5 | 3 | 31 | 28.45 | 14.41 | 28.57 | 29.86 | 27.91 | 37 | 16 |
| #C2 | 28.7 | 15 | 34.5 | 34 | 15.06 | 30.14 | 33.35 | 33.08 | 91 | 4 |
| #C3 | 21.3 | 7.8 | 36 | 34 | 16.13 | 29.5 | 32.12 | 31.45 | 267 | 7 |
| #C4 | 27.3 | 0.2 | 30.5 | 30 | 12.24 | 20.5 | 30.5 | 30.1 | 0 | 0 |
| #C5 | 19.1 | 20 | 35.5 | 31.9 | 13.99 | 24.95 | 25.97 | 25.97 | 498 | 15 |
| #C6 | 19.6 | 6.5 | 30.5 | 29.03 | 13.49 | 25.4 | 27.22 | 26.55 | 158 | 8 |
| #C7 | 22.9 | 2.4 | 33.5 | 33 | 13.93 | 33.2 | 31.62 | 31.6 | 122 | 7 |
| #C8 | 19.2 | 10 | 32 | 32 | 13.3 | 25.79 | 28.09 | 28.09 | 276 | 8 |
| #C9 | 20.5 | 4 | 32.5 | 30 | 15.35 | 31.69 | 28.79 | 27.38 | 191 | 40 |
| #C10 | 31.2 | 9.7 | 32.5 | 31 | 13.01 | 31.21 | 32.41 | 30.94 | 0 | 0 |
| #C11 | 21.6 | 0 | 34 | 31 | 13.99 | 34 | 34 | 31 | 0 | 0 |
| #C12 | 16.8 | 2.3 | 32.5 | 29.89 | 15.58 | 18.16 | 32.5 | 29.89 | 0 | 0 |
| #C13 | 14.3 | 1.9 | 32 | 30 | 18.02 | 30.91 | 29.72 | 28.48 | 141 | 12 |
| #C14 | 22.5 | 6.2 | 31.5 | 29.5 | 15.2 | 28.92 | 28.31 | 27.27 | 168 | 14 |
| #C15 | 22.5 | 6.1 | 34.5 | 30.84 | 14.67 | 28.92 | 30.94 | 28.66 | **165** | 9 |
| #C16 | 19 | 7.4 | 31.5 | 29.98 | 15.06 | 29.28 | 25.73 | 25.53 | **319** | 20 |
| #C17 | 19 | 7.4 | 32 | 30 | 14.81 | 31.15 | 24.82 | 24.57 | 377 | 40 |
| Average | **22** | **6** | **33** | **31** | **15** | **28** | **30** | **29** | **165** | **12** |
| Total | | 110 | | | | | | | 2809 | |

The simulated UA values are withing the acceptable range, the highest UA value from the models being 40 kW/°C .The model could not simulate instances where the temperatures of

the system increases. This is demonstrated by cases where the Duty and the UA values are 0 kW/°C. The cooling cars with a UA value of 0 kW/°C could not be calibrated. An average UA value for the cooling cars which could be calibrated was used. Table 13 outlines the comparison between the measured results and the simulated results to determine the UA values of the cooling cars.

*Table 13:Cooling car calibration error evaluation*

| | Cooling car inputs | | | | | Cooling car outputs | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cooling car** | **$Tw_{in}$ (°C)** | **Flow(l/s)** | **$T_{in_db}$ (°C)** | **$T_{in_wb}$ (°C)** | **Flow (kg/s)** | **$Tw_{out}$ (°C)** | **$Tout_{_db}$ (°C)** | **$Tout_{_wb}$ (°C)** | **Duty (kW)** | **UA** kW/°C |
| #C1 | 0% | 0% | 0% | 0% | 0% | 2% | 5% | 0% | 12% | 23% |
| #C2 | 0% | 0% | 0% | 0% | 0% | 9% | 2% | 0% | 0% | 97% |
| #C3 | 0% | 0% | 0% | 0% | 0% | 8% | 3% | 1% | 1% | 70% |
| #C4 | 0% | 0% | 0% | 0% | 0% | 34% | 0% | 1% | #DIV/0! | #NUM! |
| #C5 | 0% | 0% | 0% | 0% | 0% | 7% | 2% | 2% | 16% | 86% |
| #C6 | 0% | 0% | 0% | 2% | 0% | 5% | 1% | 2% | 4% | 80% |
| #C7 | 0% | 0% | 0% | 0% | 0% | 0% | 1% | 1% | 39% | #NUM! |
| #C8 | 0% | 0% | 0% | 0% | 0% | 2% | 2% | 2% | 4% | 77% |
| #C9 | 0% | 0% | 0% | 0% | 0% | 7% | 6% | 1% | 7% | 38% |
| #C10 | 0% | 0% | 0% | 0% | 0% | 5% | 1% | 3% | #DIV/0! | #NUM! |
| #C11 | 0% | #DIV/0! | 0% | 0% | 0% | 0% | 0% | 3% | 100% | #NUM! |
| #C12 | 0% | 0% | 0% | 1% | 0% | 39% | 8% | 0% | #DIV/0! | #NUM! |
| #C13 | 0% | 0% | 0% | 0% | 0% | 5% | 1% | 3% | 71% | 57% |
| #C14 | 0% | 0% | 0% | 0% | 0% | 13% | 5% | 1% | 0% | 8% |
| #C15 | 0% | 0% | 0% | 1% | 0% | 4% | 5% | 3% | 37% | 86% |
| #C16 | 0% | 0% | 0% | 0% | 0% | 18% | 2% | 2% | 0% | 24% |
| #C17 | 0% | 0% | 0% | 0% | 0% | 21% | 3% | 2% | 1% | 19% |
| Average | 0% | 0% | 0% | 0% | 0% | 2% | 2% | 0% | 13% | #NUM! |
| Total | | #DIV/0! | | | | | | | #DIV/0! | |

The deviation between the measured results and the simulated results indicates that the cooling cars were not operating as expected. The simulation is based on the first law of thermodynamics and the measured values could not match the simulations. The average percentage error for input values was less than 1% and the average percentage error for output values, excluding the Duty and the UA values, was less than 5%. This is less than the recommended 20% margin of error for model calibration.

The UA values and the Duty values of the measured results and the simulated results displayed a greater deviation. Since the model has been used countless times and proven to be accurate, according to literature , the simulation results are taken to be more trustworthy than the actual measured results [112], [86],[88]. The average error on the Duties is less than

20%. All values with errors above 30% were reported inaccurate. These cooling cars will be based on corrected UA values from the design specs and the average calibrated UA values.

## 3.5 STEP 5 – PERFORMANCE ANALYSIS AND PROBLEM IDENTIFICATION

Actual measurements and inspections were done on cooling cars. The measurements focused on the cooling car inlet and outlet conditions. These conditions were used for analysis and evaluation of the cooling car performance. Inspections of cooling cars mainly concerned the cooling car pipeline configurations and identification of additional inefficiencies which may cause the cooling car as a whole to be inefficient. Cooling car measurements are outlined in **Appendix C.** The measurements were analyzed and compared with the expected cooling car operations. Key performance indicators include:

- Cooling car air outlet Wb temperatures
- Cooling car inlet water temperatures
- Cooling car water flows
- Cooling car overall duty

According to the literature the expected underground wet-bulb temperatures are 29°C wet-bulb [15],[50]. The temperatures on the development ends need to be maintained at 28°C. The cooling cars are generally located far from the working ends, distances ranging between 200 and 400 m. The outlet temperatures of the cooling cars must be lower than 28°C in order to maintain a temperature of 29°C on the working ends.

Yi,X. Ren,L. Ma,L. et al. [115] performed a study to determine the effects of seasonal air temperature variation on air flow and surrounding rock temperature of mines. The general heat pickup for a given length could be applied between the cooling car position and the working ends. Figure 46 outlines the relationship between the length between the cooling car and the development end, and the temperature pick-up over the length.

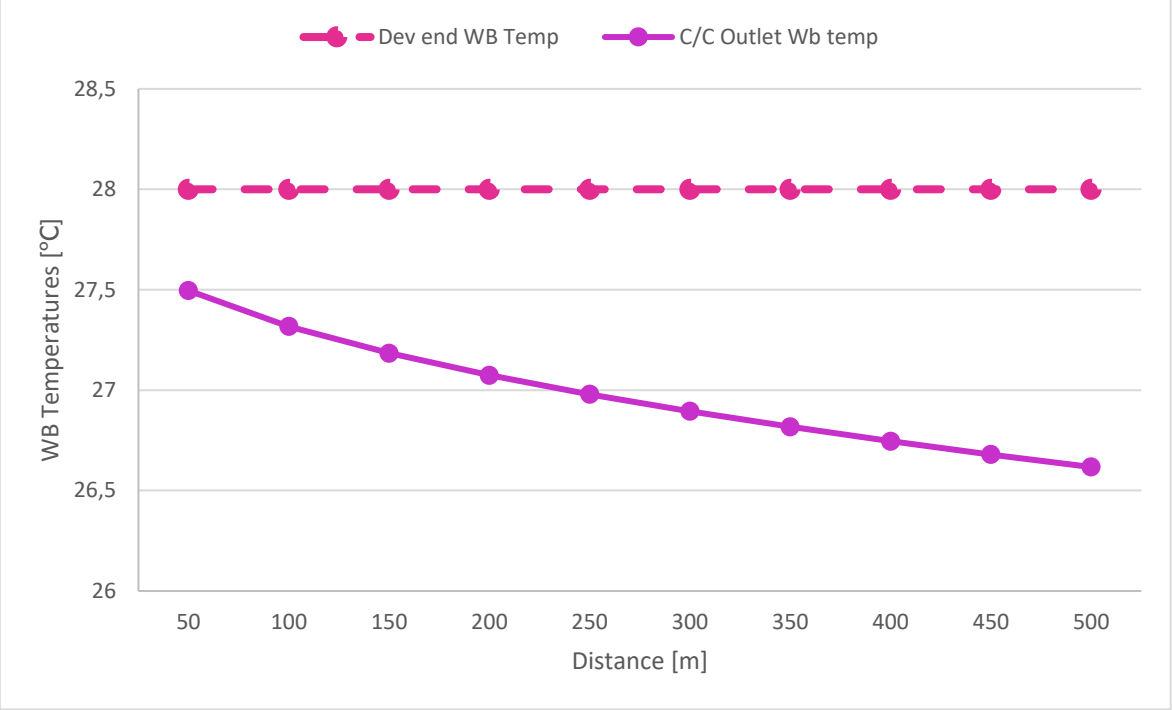



*Figure 46:Relationship between stope length and expected cooling car outlet temperature*

It is evident from Figure 46 that the position of the cooling car plays an important role in the expected outlet temperatures. The further the cooling car is located from the working face, the lower the expected outlet wet-bulb temperature of the cooling car. The expected outlet wet-bulb temperatures will influence the expected cooling car operating conditions. Most of the cooling cars are typically located about 350 m away from the development ends. The average expected wet-bulb temperature of 26,5°C from the cooling cars will be assumed to be the overall baseline. Figure 47 shows the outlet wet-bulb temperatures of the cooling car.

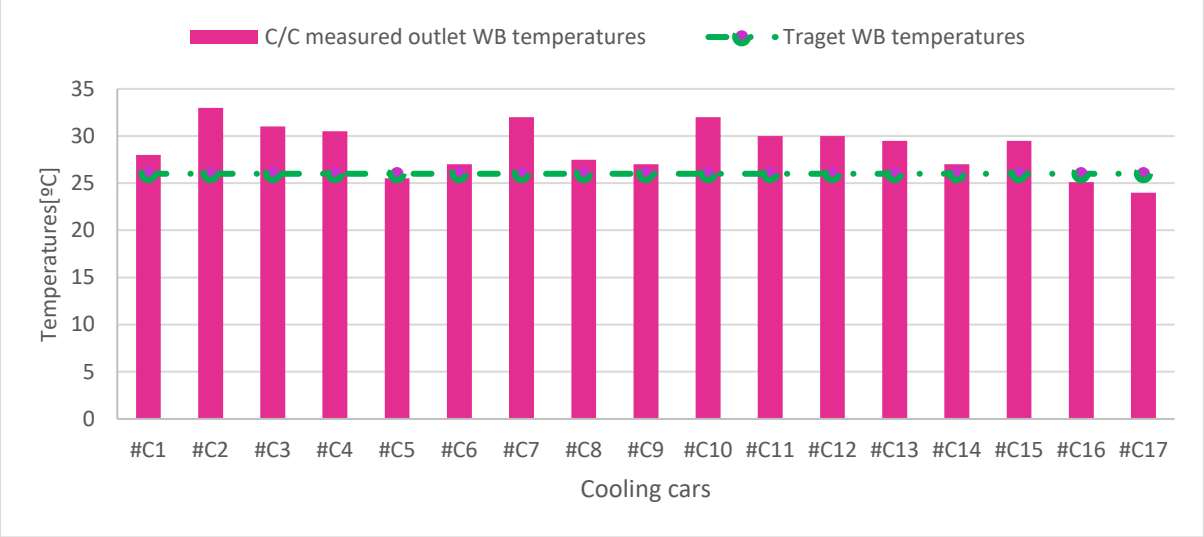



*Figure 47: Cooling car outlet wet-bulb temperatures*

The average outlet wet-bulb temperature of the cooling cars was found to be 28.5°C, which is far higher than the expected baseline temperatures. It can be concluded that most of the cooling cars are not reaching the expected limit of 26.5°C outlet wet-bulb temperatures.

## COOLING CAR (C/C) DESIGN CONDITIONS.

The design duty of the cooling cars is either 300 kW or 500 kW. The underground temperatures are very humid and as a result the real-life application of the cooling cars is close to their actual design duties. In order to achieve duties of 300 kW or 500 kW on the cooling cars, they are rated to operate with a water flow rate of 10 ℓ/s at a temperature of 11ºC and an air flow rate of 11 kg/s at a temperature of 25ºC dry-bulb temperature on 100% relative humidity. Figure 48 shows the typical cooling car tables as received from the manufacturer.

Date : **Thursday, 09 May 2019**

Type of Coil : **300 kW MONGOOSE COOLING COIL**

| | | |
|---|---|---|
| ***Temperature of Water In*** | ***11.5*** | ***°C*** |
| ***Wet Bulb Temperature of Air In*** | ***25*** | ***°C*** |
| ***Dry Bulb Temperature of Air In*** | ***25*** | ***°C*** |
| ***Barometric Pressure*** | ***117.5*** | ***kPa*** |

MANOS ENGINEERING (PTY.)LTD.

| l/s | kPa | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| L ▼ | ΔPw ▼ | G'► ΔPa► | 5<br>135 | 6<br>186 | 7<br>244 | 8<br>308 | 8.5<br>343 | 9<br>379 | 10<br>456 | 11<br>540 | m3/s<br>Pa |
| 3.0 | 21 | q | 126.47 | 133.71 | 139.04 | 143.11 | 144.79 | 146.27 | 148.81 | 150.87 | kW |
| | | two | 21.57 | 22.14 | 22.57 | 22.89 | 23.03 | 23.15 | 23.35 | 23.51 | oC |
| | | tao | 19.02 | 19.8 | 20.42 | 20.91 | 21.12 | 21.31 | 21.65 | 21.92 | oC |
| 4.0 | 36 | q | 146.07 | 157.41 | 166.22 | 173.19 | 176.15 | 178.82 | 183.43 | 187.26 | kW |
| | | two | 20.22 | 20.9 | 21.42 | 21.84 | 22.02 | 22.18 | 22.45 | 22.68 | oC |
| | | tao | 17.96 | 18.77 | 19.43 | 19.97 | 20.2 | 20.42 | 20.8 | 21.13 | oC |
| 5.0 | 56 | q | 159.64 | 174.56 | 186.57 | 196.4 | 200.66 | 204.55 | 211.37 | 217.16 | kW |
| | | two | 19.13 | 19.84 | 20.41 | 20.88 | 21.08 | 21.27 | 21.6 | 21.87 | oC |
| | | tao | 17.21 | 18 | 18.66 | 19.22 | 19.46 | 19.69 | 20.1 | 20.45 | oC |
| 6.0 | 80 | q | 169.41 | 187.29 | 202.09 | 214.53 | 219.98 | 225.02 | 234.01 | 241.73 | kW |
| | | two | 18.23 | 18.96 | 19.54 | 20.04 | 20.26 | 20.46 | 20.81 | 21.12 | oC |
| | | tao | 16.65 | 17.41 | 18.06 | 18.61 | 18.86 | 19.1 | 19.52 | 19.88 | oC |
| 7.0 | 107 | q | 176.7 | 196.98 | 214.19 | 228.9 | 235.46 | 241.54 | 252.51 | 262.1 | kW |
| | | two | 17.53 | 18.22 | 18.81 | 18.68 | 19.53 | 19.74 | 20.12 | 20.44 | oC |
| | | tao | 16.23 | 16.95 | 17.58 | 17.73 | 18.37 | 18.61 | 19.03 | 19.4 | oC |
| 8.0 | 139 | q | 182.31 | 204.59 | 223.83 | 240.48 | 247.99 | 255.03 | 267.83 | 279.11 | kW |
| | | two | 16.94 | 17.61 | 18.18 | 18.68 | 18.9 | 19.11 | 19.5 | 19.83 | oC |
| | | tao | 15.9 | 16.59 | 17.19 | 17.73 | 17.97 | 18.2 | 18.62 | 19 | oC |
| 9.0 | 174 | q | 186.73 | 210.68 | 231.6 | 250 | 258.36 | 266.24 | 280.64 | 293.48 | kW |
| | | two | 16.46 | 17.09 | 17.65 | 18.13 | 18.36 | 18.57 | 18.95 | 19.29 | oC |
| | | tao | 15.63 | 16.29 | 16.88 | 17.4 | 17.64 | 17.86 | 18.28 | 18.65 | oC |
| 10.0 | 213 | q | 190.32 | 215.65 | 238.04 | 257.9 | 267 | 275.6 | 291.48 | 305.72 | kW |
| | | two | 16.05 | 16.65 | 17.19 | 17.66 | 17.88 | 18.08 | 18.46 | 18.8 | oC |
| | | tao | 15.42 | 16.05 | 16.61 | 17.12 | 17.35 | 17.57 | 17.98 | 18.35 | oC |

L = Water flow in l/s
ΔPw = Water pressure drop in kPa
G'► = Air flow in m3/s
ΔPa► = Air pressure drop in Pa
q = Duty of coil in kW
two = Temperature of water leaving co
tao = Temperature of air leaving coil

*Figure 48: Cooling car performance table*

The cooling cars (C/C) used 45 kW fans which were rated at 10-11 kg/s of air flow. The air flow of the cooling cars was measured using the guide vane, and the water flow was measured using the hydraulic water flow meter.

The outlet temperatures of the cooling cars are influenced by the inlet operating conditions as well as the general pipeline configuration. The cooling car pipeline configuration affects the water flow through the cooling car. Figure 49 depicts the air and water flow through the cooling car as well as the inlet water temperatures and the wet-bulb inlet air temperatures of the system.

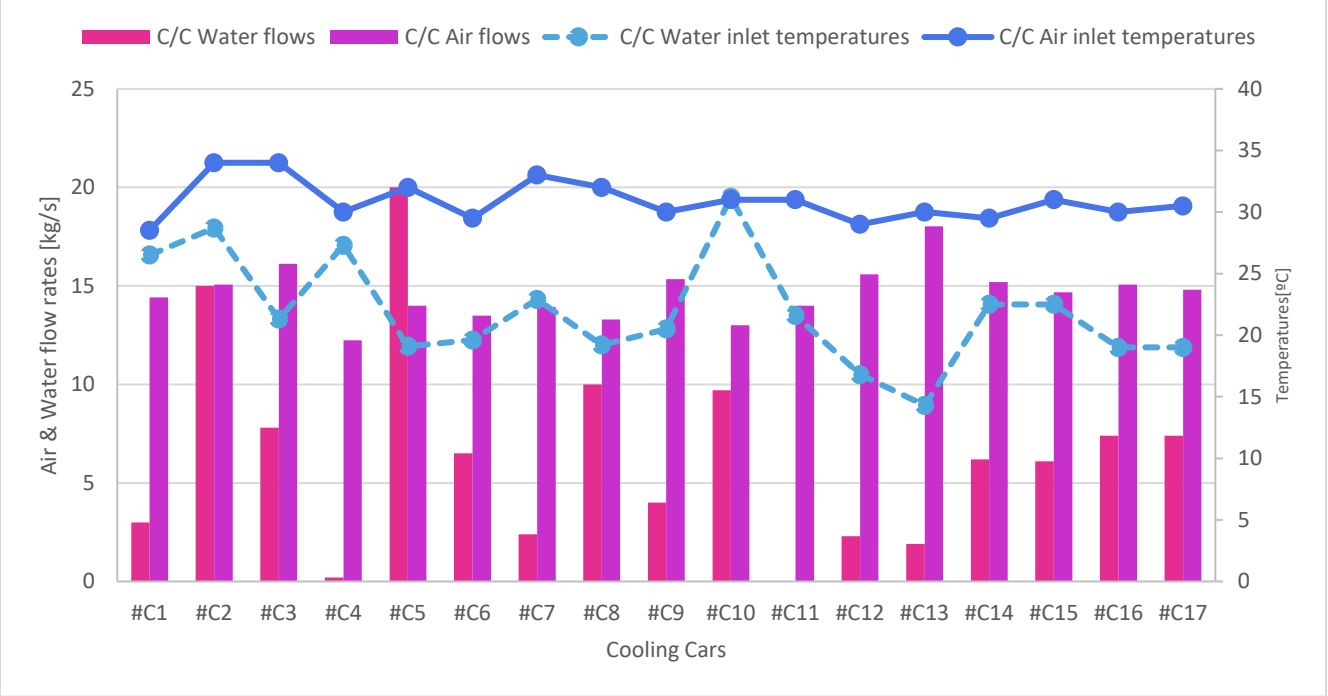



*Figure 49: Cooling car inlet conditions*

### INLET AIR TEMPERATURES

The average inlet wet-bulb temperature of the cooling cars is 32°C. The relative humidity of the air was measured at above 90% for most of the cooling cars. It is obvious that the cooling cars were operating outside the designed operation conditions of 25°C wet-bulb and dry-bulb temperatures. Inlet temperatures show that underground temperatures are higher than the recommended operating temperatures.

This suggests a great need for improved cooling. It is evident that the air inlet temperatures cannot be controlled, because the cooling car is expected to cool down the air which, under the circumstances described, it is unable to do. With the higher inlet air temperature, it is expected that the inlet water temperatures be lower than the design in order to allow the cooling car to achieve the expected temperatures.

### INLET WATER TEMPERATURES

The design operating water temperatures for the cooling cars are rated at 10-11°C. In real-life application, this factor is limited by the mine's water reticulation system and the heat pick-up. From Figure 49 it is obvious that most of the inlet water temperatures were higher than 14°C, which is far in excess of the recommended operating temperature.

The water temperatures of the crosscuts leading to the cooling cars were also measured to confirm the inlet water conditions. Figure 50 depicts the comparison between the cooling car inlet water temperatures and the crosscut inlet temperatures.

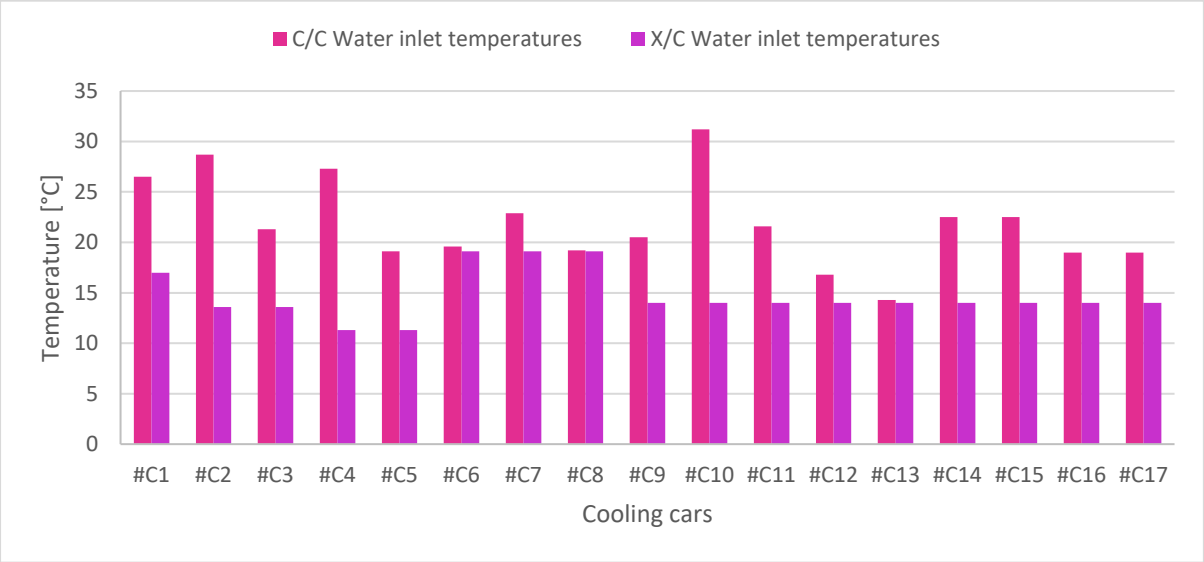



*Figure 50: Cooling car water inlet temperatures vs Crosscuts inlet temperatures*

It was noted that most of the cooling cars displayed temperatures higher than the crosscut inlet temperatures. It was also noted that these cooling cars represented type A configurations. The model was used to further analyse the cooling car configurations and to identify the drawbacks of the systems.

The incoming pipeline pressure on the crosscuts ranges between 200 kPa and 800 kPa. The cooling cars located on the crosscuts are exposed to these pressures. The pump installed on the cooling car outlet pipe is an 11 kW pump which supplies a total head of 400 kPa. This information was used on the simulation to set up the scenario to investigate the possible drawbacks of the system. Figure 51 depicts the current configuration of the cooling cars located on the crosscuts.

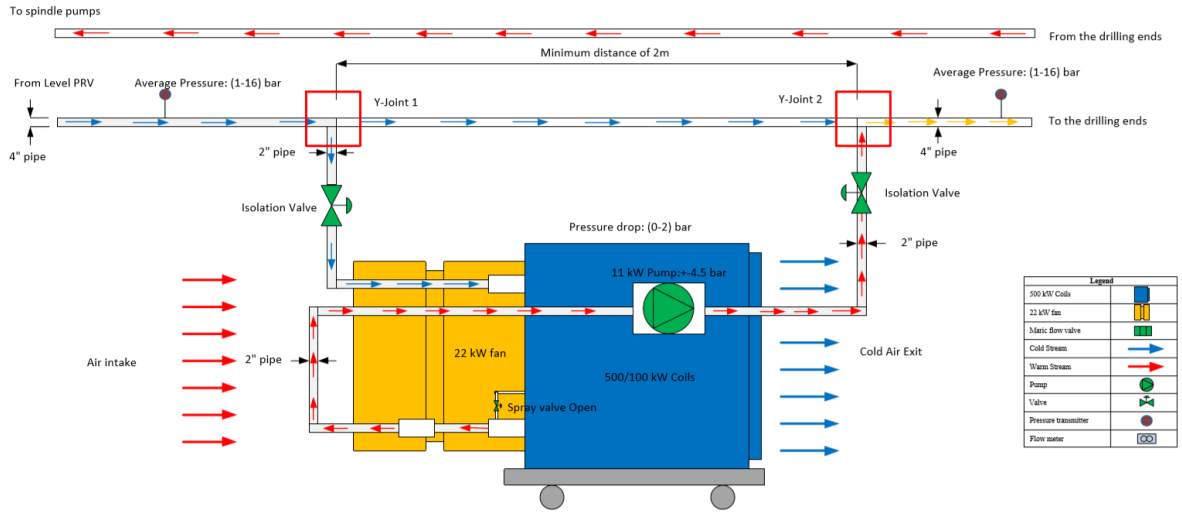



*Figure 51: Mines cooling car configuration*

The following challenges could be inferred from the configuration and the simulation.

## PUMP AND PRESSURE

### Crosscut cooling cars (Type A)

The location of the pump resulted in water recirculation on the cooling cars. The pump is supposed to push the water back into the system through joint 2. It was observed from the simulation that when the water pressure of the incoming water is less than 400 kPa, which is less than the pressure supplied by the pump, the water turns to split on joint 2 resulting in some of the outlet water from the cooling car returning back into the cooling car inlet.

The outlet water of the cooling car is generally warmer than the inlet cooling car water temperature. The mixture of the flows results in an increase in the cooling car inlet. The configuration also depends on the usage of water on the drilling ends. When there is no water usage on the stopes, the pump pushes the water back into the cooling car inlet. This results in water recirculation in the system.

With the 11kW pump as well as the 45kW fan on the system the cooling car results in an additional heat generator, continuously heating up the water that is being recirculated as well as the surrounding environment.

Although the cooling cars need to provide cooling for 24 hours, the simulation indicated that they provide no cooling when there is no water flow towards the drilling ends. Thus, the

configuration for the cooling cars needs to be pressure proof and it needs to be able to manage the supply of enough chill water through the cooling cars. Cooling car duty is dependent on the water flow through the cooling car. That is why there has to be a continuous flow through the cooling car, although the flow needs to be regulated to ensure that the water is not wasted.

The water inlet temperatures have to be the same as the crosscut inlet temperatures. A configuration is required to solve the above-mentioned challenges and allow for maximum flow through the cooling car with minimal water dumped.

**Haulage cooling cars (Type B)**

The cooling cars on the main haulages were simulated. The pressure on the main haulage pipeline was found to be between 800 kPa and 1600 kPa depending on the time of the shift. The pressures in the system usually increase when water is not used in the mine. The following was observed from the simulation and general inspections:

- The water flow through the cooling car is not controlled. The increase in pressure in the system results in increase flows through the cooling cars. The flow through the cooling cars can reach up to 15 ℓ/s when not controlled. As a result, water is wasted during off-peak periods, which means that the configuration needs to be updated to allow water saving and control on the flows.

- Some of the cooling car outlets are dumping water on the footwall resulting in flooding in the mine. When the water outlet gets in contact with the outlet air temperature, the result is a temperature increase in the system. The configuration needs to ensure that the water is not dumped on the footwall, but is rather dumped in the designated drain column for the system.

## WATER FLOW USAGE

It has repeatedly been stated that there is a great need to save water on mine A. It was observed that some of the cooling car flow rates were higher than the design flow rate of 10 ℓ/s. The flow needs to be optimized to allow for just enough flow to supply the required duty and outlet wet-bulb temperatures on the cooling cars.

The water outlet temperature of some of the cooling cars is still low enough for them to be reused by the mine. Also, the water can still be reused on the drilling ends. This would in turn reduce the total flow demand.

### ENERGY USAGE

The 11 kW pumps use electrical energy to pump the water back into the system. The configuration of the cooling system can be reconfigured to eliminate the use of pumps with a resultant saving on electrical energy. The cost of one pump operating for 24 hours has been calculated at R80 000 p.a using the Eskom Megaflex tariffs as outlined in the introduction.

The return water is usually pumped back to surface via pumps. Equation 3 in the introduction section can be used to quantify the total energy saving from the reduced flow, and the Megaflex tarrif data can be used to quantify the financial benefit. It is evident that any reduction in water usage will result in reduced electrical usage in the system.

### COOLING CAR DUTY

The measured information was used to calculate the overall duty of the cooling cars. The cooling car duty represents the overall heat transferred between the water and the air. Figure 52 illustrates the duty results of the cooling cars.

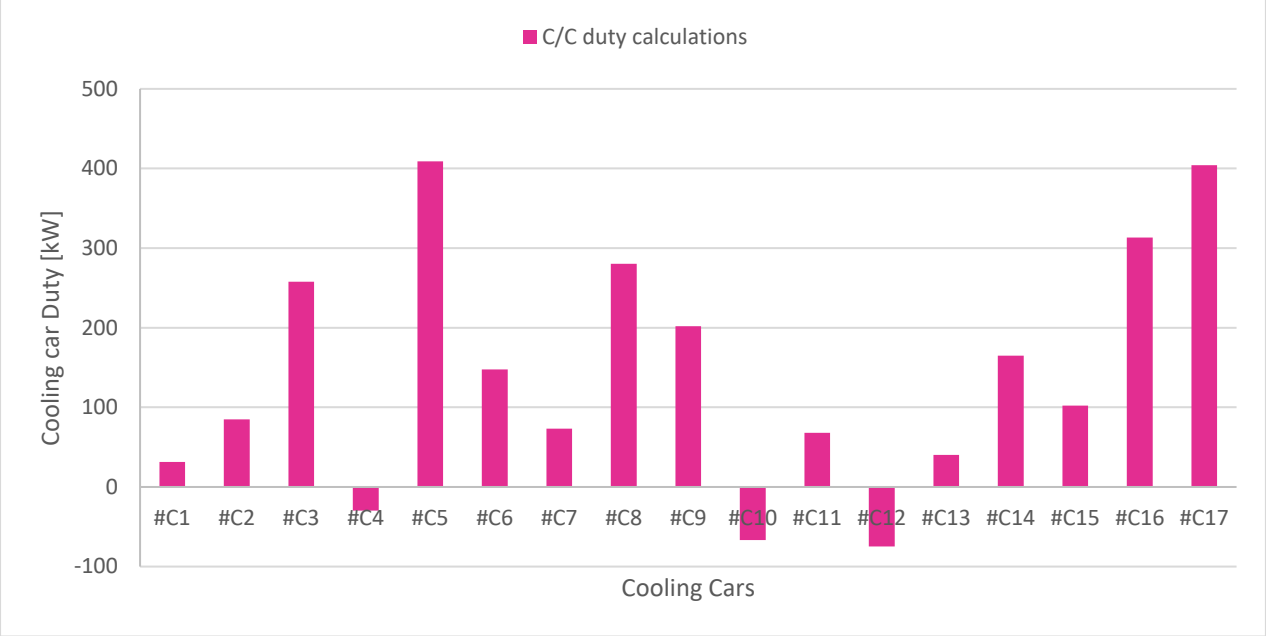



*Figure 52 : Calculated cooling car duties*

Cooling cars #C1, #C2, #C7, #C11 and #C13 showed relatively low duties; cooling cars #C4, #C10 and #C12 showed no heat transfer between the water and the air. Negative duties were seen on some cooling cars due to the water heating up the air. This usually occurs when the water temperature is higher than the cooling car inlet air temperatures. It was concluded that the cooling cars on the crosscuts had water flow challenges. The cooling cars on the main haulages seemed to perform well; their average duties were higher than 300 kW.

The measured data and the inspected configurations were simulated and analyzed. However, the data suggested that there was room for improvement on the configuration to allow for increase duty and cooling car performance. It was outlined that there is a potential to eliminate the additional energy usage from the system by reducing the number of pumps.

It was also indicated that the water flow can be optimized further in order to reduce the water demand while still ensuring the overall performance increases. The reduction in water usage can result in large energy savings. It was also evident that there is no control on the overall water usage by the cooling cars, and, as a result, more water is wasted during off peak hours due to increased pressure on the system. The configuration has to be upgraded to allow for optimal water control on the system.

## 3.6 STEP 6 – MODEL OPTIMIZATION & EXPECTED IMPROVEMENTS

A new configuration was developed which seeks to solve the challenges outlined during the investigation phase. The suggested method was followed to develop the new configuration. Both type A and type B configurations were optimized.

### TYPE A RECONFIGURATION

Type A reconfiguration had water recirculation challenges due to the presence of the 11 kW pumps. The problems were identified specifically when the following happens:

- When no work is done on the crosscut end water recirculates due to a lack of continuous flow and the availability of the pumps. Where there are no pumps, the water becomes stagnant.
- No duty on the cooling cars when the water is not used. (No flow in the system.)
- The incoming pressure is less than the pump pressure. (The water would split resulting in high cooling car inlet temperatures.)
- No flow control on the system, the water flow is not regulated and controlled. More water is used through cooling cars when system pressures increase.
- Low cooling car water flow due to crosscut water demand. The cooling cars need 10 ℓ/s as per design and the crosscuts are supplied with a 4 inch pipe which can only supply a maximum of 16 ℓ/s. If the cooling cars uses 10 ℓ/s. This limits the total flow supplied to the drilling ends.

The new configuration was developed by simply providing answers and solutions to the above-mentioned challenges. Figure 53 shows the suggested cooling car improved solution for type A configuration.

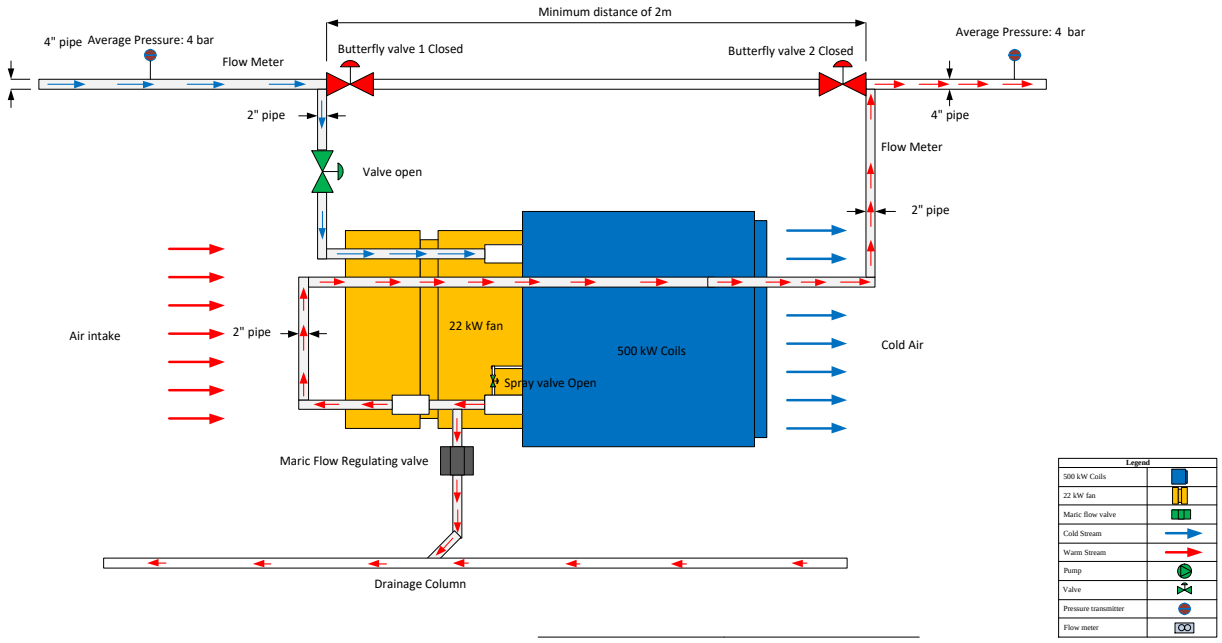



*Figure 53: Type A improved cooling car pipeline configuration*

The problem was solved by introducing a hybrid configuration. The configuration allows for water to be dumped and for drilling ends at the same time. It was found that the maximum water flow that the drilling ends require is approximately 8 ℓ/s, depending on the number of panels and drills used by the mine.

It was suggested that all the water be passed through the cooling car, because the cooling car design flow rate is 10 ℓ/s, indicating that the cooling car can supply the drilling end with about 10 ℓ/s. More water can be pumped through the cooling cars. Some of the measured values went up to 15 ℓ/s.

The main chill water line which supplies water to the drill ends was isolated by 2 butterfly valves which are always closed, except when cooling cars need servicing. This will also ensure that there are redundancies for chill water supply in the system.

The dumping side was put in place to allow for a flow through the cooling car when the water flow is closed on the drill ends. The dumped flow was selected through the cooling coil optimization process. The flow rates were regulated to allow for high enough flow rates to the drilling ends. A unique regulating valve was selected which had to allow for a constant flow rate under different pressures.

One of the main concerns from the mine engineers was the possibility that high water pressures might cause losses on the cooling car when water is supplied to the drilling end through the cooling cars. The drills require a specific pressure to operate and some of the stopes are located on an incline. This would in turn require additional pressure to overcome the head.

The supplier confirmed that the cooling car water pressure loss is 200 Pa when the flow is at 10 ℓ/s. Thus, if the inlet pressure is 400 kPa, the outlet pressure would be 380 kPa. The pressure was considered to be negligible. In the case where additional pressure is required on the stope, it was suggested that the 11kW pump be installed after the cooling car, noting that the pump will only serve the purpose of supplying additional pressure to the stopes and that it will not work on the cooling car configurations. Figure 54 shows the 11 kW pump on the line.

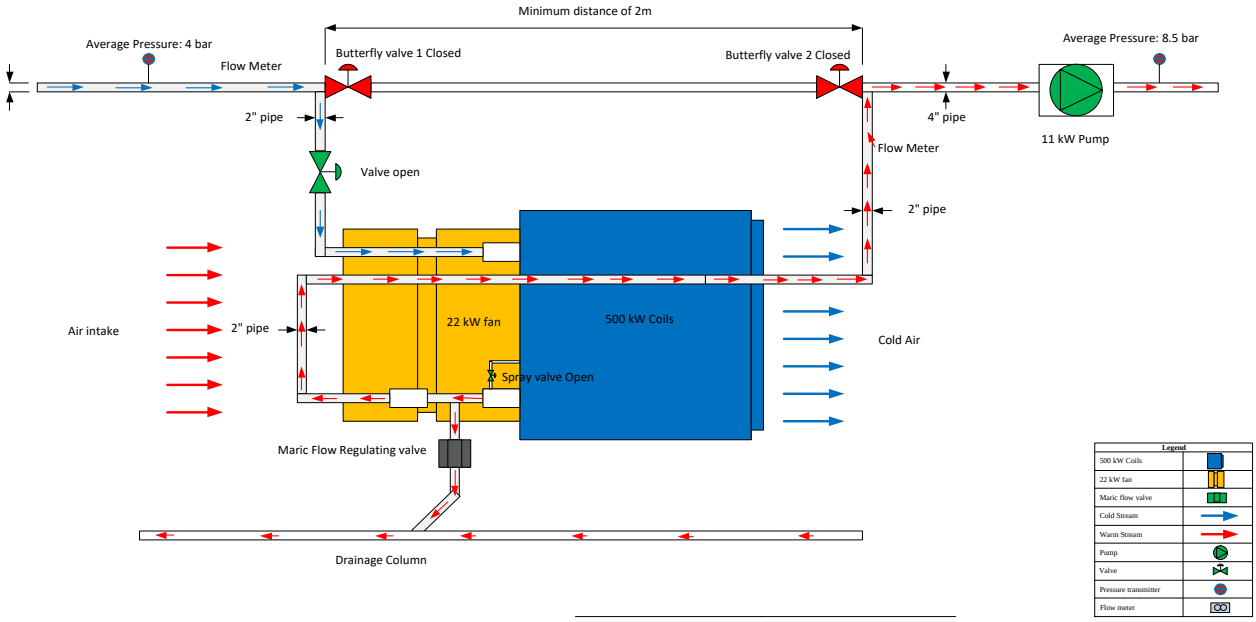



*Figure 54: Type A cooling car configuration with a pump*

All the questions posed by the challenges of the initial configuration were answered throughout the development of the new configuration. The configuration needs to be simulated to confirm the impact and improvements.

## TYPE B CONFIGURATION

The only challenge with the second configuration was that the water flow rates through the cooling cars increase when the pressure on the system increases. This usually occurred during off-peak time when less water is used on the stopes and other mining activities. Figure 55 displays the suggested solution for the configurations.

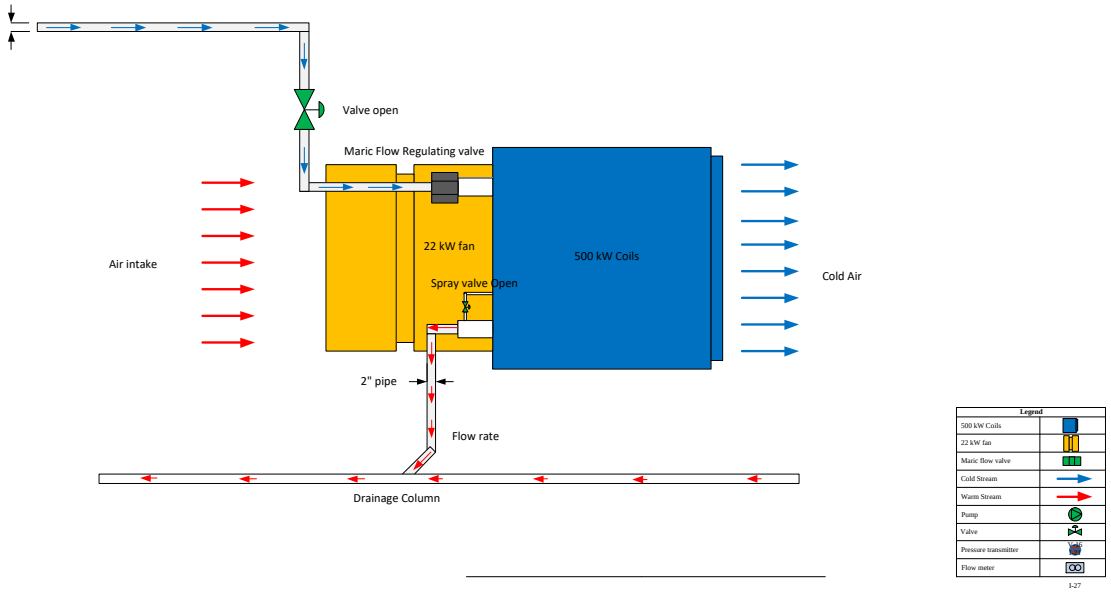



*Figure 55: Type B improved configuration*

A flow regulating valve was suggested on the system to ensure that constant flow is maintained through the cooling car, irrespective of the exposed pressures. This implies that the water flow would remain consistent when the system pressure increases, resulting in less water being wasted. The configuration also needs to be simulated to confirm the impact and improvements.

## FLOW AND TEMPERATURE OPTIMIZATION

In order to optimize the cooling car flow rates as well as the outlet temperatures, the suggested cooling car configurations had to be built on PTB. The models were simplified skeletons which outlined the air side and the water side of the cooling car. The UA values of the cooling cars which were initially used were again used as input for the new models. The average UA value of the verified cooling cars was used for those cooling cars which could not be verified. Figure 56 depicts the snapshot of the PTB simulations.

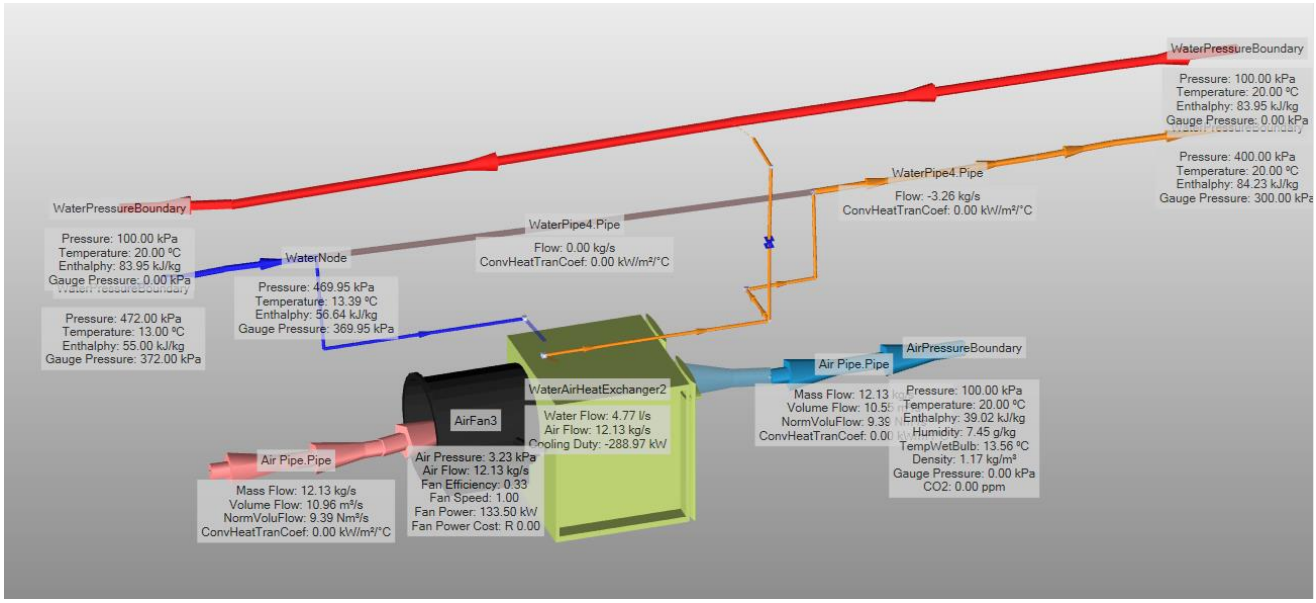
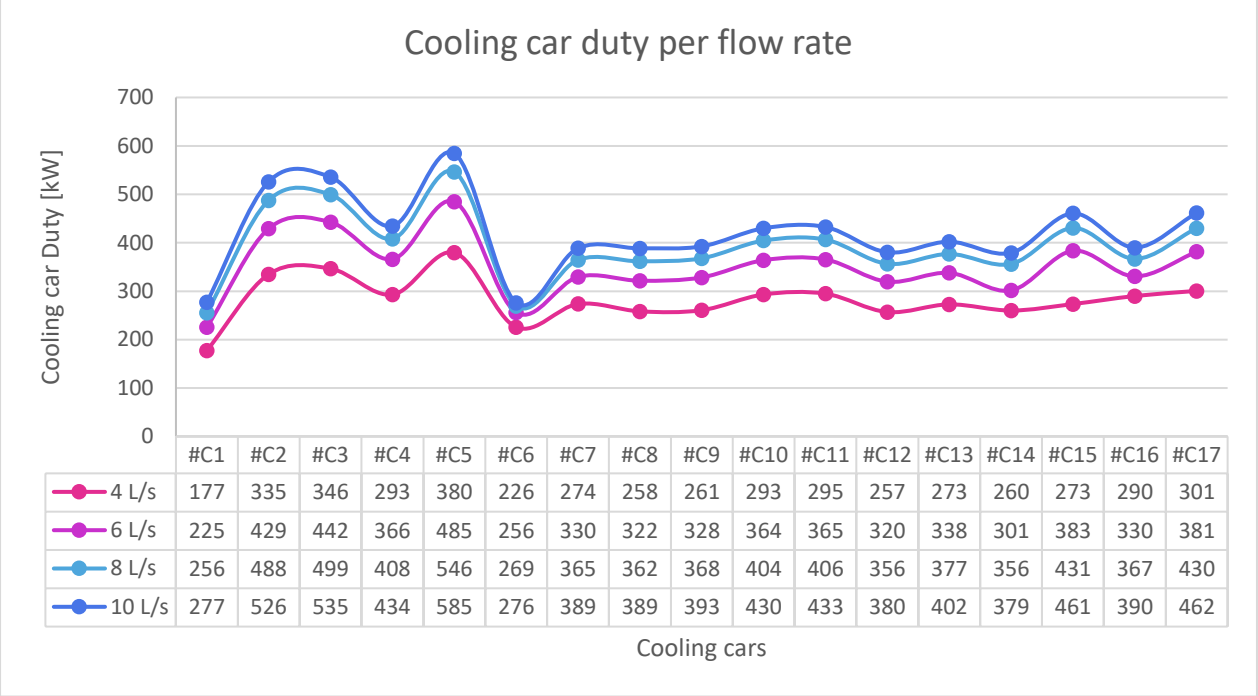



*Figure 56: Cooling car flow optimization simulation*

The cooling car dumping flow rates were selected. The selection of the dumping flow rates depends on the temperatures at the cooling car temperature outlet and the possible attainable duties. Individual cooling car simulations were used for the analysis. The lowest possible temperatures were selected on the crosscuts. The main objective of the simulation was to evaluate the outlet air temperatures and water temperatures based on the controlled conditions.

Four different flow rates were selected for the analysis, namely 4 ℓ/s, 6 ℓ/s, 8 ℓ/s and 10 ℓ/s. The flow rates were only simulated through the cooling cars to check the cooling car performance on the given flows. Figure 57 depicts the cooling car duties at different flow rates.




| | #C1 | #C2 | #C3 | #C4 | #C5 | #C6 | #C7 | #C8 | #C9 | #C10 | #C11 | #C12 | #C13 | #C14 | #C15 | #C16 | #C17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 L/s | 177 | 335 | 346 | 293 | 380 | 226 | 274 | 258 | 261 | 293 | 295 | 257 | 273 | 260 | 273 | 290 | 301 |
| 6 L/s | 225 | 429 | 442 | 366 | 485 | 256 | 330 | 322 | 328 | 364 | 365 | 320 | 338 | 301 | 383 | 330 | 381 |
| 8 L/s | 256 | 488 | 499 | 408 | 546 | 269 | 365 | 362 | 368 | 404 | 406 | 356 | 377 | 356 | 431 | 367 | 430 |
| 10 L/s | 277 | 526 | 535 | 434 | 585 | 276 | 389 | 389 | 393 | 430 | 433 | 380 | 402 | 379 | 461 | 390 | 462 |

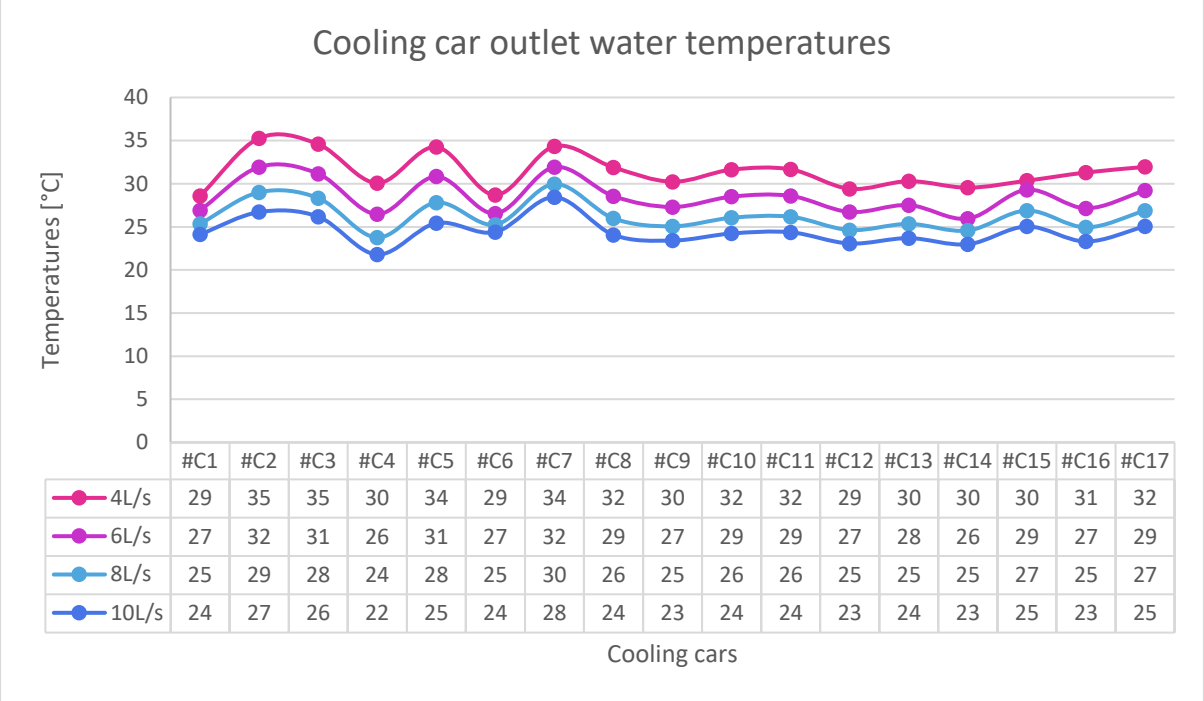
*Figure 57: Cooling car duties per flow rates*

It is obvious from the figure that the overall cooling car duty increases with the increase in water flow rates. The optimization strategy to select the optimal flow mostly depends on the water outlet temperatures and air outlet wet-bulb temperatures. The performance of the cooling cars with respect to the water outlet temperatures and the outlet air temperatures are outlined below.

### WATER EXIT TEMPERATURES

The water flow rate has a direct impact on the cooling cars' water exit temperatures. The cooling cars which are located near the crosscuts need to be studied further if the proposal of feeding the water into the main chill line still holds. The stopes need to receive water that still has a cooling potential, and this implies that the temperature of the water needs to be as low as possible to enhance cooling on the stopes.

Should the water temperature be higher than the wet-bulb temperature in the drilling ends, the water will heat up the air. Typically, the goal is to keep the air temperature as close to 29°C as possible; as such, the water temperature should also not be higher than this. For simulation purposes, the target temperature for the water outlet of the cooling cars is set to 30°C. Figure 58 shows the results obtained from the simulation.




| | #C1 | #C2 | #C3 | #C4 | #C5 | #C6 | #C7 | #C8 | #C9 | #C10 | #C11 | #C12 | #C13 | #C14 | #C15 | #C16 | #C17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4L/s | 29 | 35 | 35 | 30 | 34 | 29 | 34 | 32 | 30 | 32 | 32 | 29 | 30 | 30 | 30 | 31 | 32 |
| 6L/s | 27 | 32 | 31 | 26 | 31 | 27 | 32 | 29 | 27 | 29 | 29 | 27 | 28 | 26 | 29 | 27 | 29 |
| 8L/s | 25 | 29 | 28 | 24 | 28 | 25 | 30 | 26 | 25 | 26 | 26 | 25 | 25 | 25 | 27 | 25 | 27 |
| 10L/s | 24 | 27 | 26 | 22 | 25 | 24 | 28 | 24 | 23 | 24 | 24 | 23 | 24 | 23 | 25 | 23 | 25 |

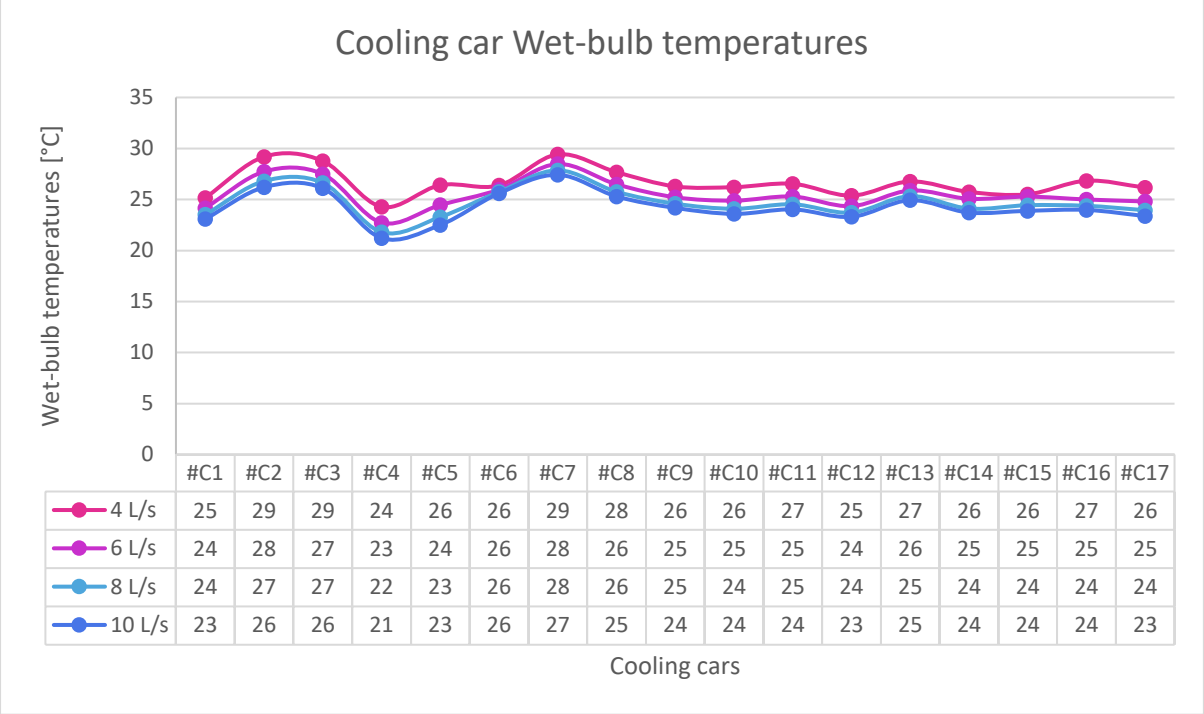
*Figure 58:Cooling car outlet temperatures*

When the flow rate is at 4 ℓ/s, only 23% of the cooling cars achieve temperatures below 30 °C. When the water flow is increased to 6 ℓ/s, 70% of the cooling cars showed a massive improvement in the water outlet. For a flow rate of 8 ℓ/s the water temperatures for all cooling cars were below 30°C, and lastly, when the flow was at 10 ℓ/s, the temperatures achievable are close to 20°C.

This implies that the water through the cooling cars can be sent to the crosscut ends without challenges when the overall water flow through the cooling cars is greater than 6 ℓ/s. The water flow of less than 6 ℓ/s needs to be sent directly to the drain.

### AIR EXIT TEMPERATURES

One of the main objectives of the simulation was to check the minimum attainable air outlet temperatures of the cooling cars. The wet-bulb temperature was mainly used as a reference. Temperatures lower than 30 degrees are achievable for all the given flow rates. Figure 59 depicts the results obtained for the air outlet temperatures during the optimization.




| | #C1 | #C2 | #C3 | #C4 | #C5 | #C6 | #C7 | #C8 | #C9 | #C10 | #C11 | #C12 | #C13 | #C14 | #C15 | #C16 | #C17 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 L/s | 25 | 29 | 29 | 24 | 26 | 26 | 29 | 28 | 26 | 26 | 27 | 25 | 27 | 26 | 26 | 27 | 26 |
| 6 L/s | 24 | 28 | 27 | 23 | 24 | 26 | 28 | 26 | 25 | 25 | 25 | 24 | 26 | 25 | 25 | 25 | 25 |
| 8 L/s | 24 | 27 | 27 | 22 | 23 | 26 | 28 | 26 | 25 | 24 | 25 | 24 | 25 | 24 | 24 | 24 | 24 |
| 10 L/s | 23 | 26 | 26 | 21 | 23 | 26 | 27 | 25 | 24 | 24 | 24 | 23 | 25 | 24 | 24 | 24 | 23 |

*Figure 59: Cooling car outlet wet-bulb temperatures (Optimization)*

Flow rates #6, #8 and #10 seem to accommodate both the water outlet temperatures and the cooling air temperatures. In the case where 4 ℓ/s is selected, it should be born in mind that the water outlet temperatures will be one of the main problems at the drilling ends.

It was noted that not all cooling cars send water back to the chill water lines. Cooling cars that are on the main haulages and RAWs can have a reduced flow as low as 5 ℓ/s and still manage to supply temperatures below 26°C.

## OPTIMAL FLOW SELECTION

Water flow through the cooling cars was selected based on the optimization results. The cooling cars on the crosscuts were set to operate at flows above 8 ℓ/s when water is required on the drilling ends. A maximum flow of 4 ℓ/s was selected on the dumping side to allow for the total flow through the cooling car to be greater than 6-10 ℓ/s when the flow on the drilling ends is between 3 ℓ/s and 5 ℓ/s. The cooling car is expected to dump a constant flow of 4 ℓ/s throughout the day. Table 14 illustrates the minimum selected water flow per cooling car and the expected outlet temperatures and cooling car duties.

*Table 14: Cooling car flow selection on dumped flows only*

| Cooling car | UA kW/°C | $Tw_{in}$ (°C) | $Tw_{out}$ (°C) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | Flow (kg/s) | $Tout_{_db}$ (°C) | $Tout_{_wb}$ (°C) | Duty (kW) | Flow (ℓ/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| 66L X/C 38 | 16 | 17 | 29 | 31 | 29 | 14 | 26 | 25 | 177 | 4 |
| 69L X/C 71 | 14 | 14 | 29 | 35 | 34 | 15 | 27 | 27 | 488 | 8 |
| 69L X/C 75 | 14 | 14 | 28 | 36 | 34 | 16 | 27 | 27 | 499 | 8 |
| 71L X/C 73 | 14 | 11 | 24 | 31 | 30 | 12 | 22 | 22 | 408 | 8 |
| 71L X/C 36 | 17 | 11 | 34 | 36 | 32 | 14 | 27 | 26 | 380 | 4 |
| 73L X/C 38 | 10 | 19 | 27 | 31 | 30 | 13 | 26 | 26 | 256 | 4 |
| 73L X/C 40 | 14 | 19 | 34 | 34 | 33 | 14 | 29 | 29 | 274 | 8 |
| 73L South Dev | 11 | 19 | 32 | 32 | 32 | 13 | 28 | 28 | 258 | 4 |
| 75L X/C 38 | 13 | 14 | 30 | 33 | 30 | 15 | 27 | 26 | 261 | 4 |
| 75L X/C 40 | 14 | 14 | 32 | 33 | 31 | 13 | 26 | 26 | 293 | 4 |
| 75L X/C 41 | 14 | 14 | 32 | 34 | 31 | 14 | 27 | 27 | 295 | 4 |
| 75L X/C 43 | 14 | 14 | 29 | 33 | 29 | 16 | 27 | 25 | 257 | 4 |
| 75L X/C 44 | 13 | 14 | 25 | 32 | 30 | 18 | 25 | 25 | 377 | 8 |
| 75L RAW South Left | 13 | 14 | 30 | 32 | 30 | 15 | 26 | 26 | 260 | 4 |
| 75L RAW South Right | 15 | 14 | 30 | 35 | 31 | 15 | 26 | 26 | 273 | 4 |
| 75L RAW North Left | 13 | 14 | 31 | 32 | 30 | 15 | 28 | 27 | 290 | 4 |
| 75L RAW North Right | 16 | 14 | 32 | 32 | 31 | 15 | 26 | 26 | 301 | 4 |
| Average | **13** | **15** | **30** | **33** | **31** | **15** | **26** | **26** | **314** | **5** |
| Total | | | | | | | | | **5346** | **88** |

The cooling car outlet air temperatures were used as a guidance for the flow selection. The maximum allowable air wet-bulb outlet temperature was set to 27°C. The minimum flow for the maximum allowable outlet temperatures was selected.

Table 14 depicts the expected results of the cooling cars when they are using the dumping flows only. A total flow of 8 ℓ/s was selected for all the cooling cars on the main haulages and a total flow of 4 ℓ/s for all the cooling cars on the crosscuts. The total flow rates of all the cooling cars on the crosscuts is expected to increase to 8-10 ℓ/s when the water is used on the drilling ends. Table 15 represents the updated flow of the cooling cars and the expected performance.

*Table 15: Cooling car flow selection on maximum operation*

| Cooling car | UA kW/°C | $Tw_{in}$ (°C) | $Tw_{out}$ (°C) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | Flow (kg/s) | $Tout_{_db}$ (°C) | $Tout_{_wb}$ (°C) | Duty (kW) | Flow (ℓ/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| 66L X/C 38 | 16 | 17 | 25 | 31 | 29 | 14 | 24 | 24 | 256 | 8 |
| 69L X/C 71 | 14 | 14 | 29 | 35 | 34 | 15 | 27 | 27 | 488 | 8 |
| 69L X/C 75 | 14 | 14 | 28 | 36 | 34 | 16 | 27 | 27 | 499 | 8 |
| 71L X/C 73 | 14 | 11 | 24 | 31 | 30 | 12 | 22 | 22 | 408 | 8 |
| 71L X/C 36 | 17 | 11 | 28 | 36 | 32 | 14 | 23 | 23 | 546 | 8 |
| 73L X/C 38 | 10 | 19 | 25 | 31 | 30 | 13 | 26 | 26 | 269 | 8 |
| 73L X/C 40 | 14 | 19 | 30 | 34 | 33 | 14 | 28 | 28 | 365 | 8 |
| 73L South Dev | 11 | 19 | 26 | 32 | 32 | 13 | 26 | 26 | 362 | 8 |
| 75L X/C 38 | 13 | 14 | 25 | 33 | 30 | 15 | 25 | 25 | 368 | 8 |
| 75L X/C 40 | 14 | 14 | 26 | 33 | 31 | 13 | 24 | 24 | 404 | 8 |
| 75L X/C 41 | 14 | 14 | 26 | 34 | 31 | 14 | 25 | 25 | 406 | 8 |
| 75L X/C 43 | 14 | 14 | 25 | 33 | 29 | 16 | 25 | 24 | 356 | 8 |
| 75L X/C 44 | 13 | 14 | 25 | 32 | 30 | 18 | 25 | 25 | 377 | 8 |
| 75L RAW South Left | 13 | 14 | 25 | 32 | 30 | 15 | 24 | 24 | 356 | 8 |
| 75L RAW South Right | 15 | 14 | 27 | 35 | 31 | 15 | 25 | 24 | 431 | 8 |
| 75L RAW North Left | 13 | 14 | 25 | 32 | 30 | 15 | 24 | 24 | 367 | 8 |
| 75L RAW North Right | 16 | 14 | 27 | 32 | 31 | 15 | 24 | 24 | 430 | 8 |
| Average | **13** | **15** | **26** | **33** | **31** | **15** | **25** | **25** | **393** | **8** |
| Total | | | | | | | | | **6688** | **136** |

All the cooling cars were expected to supply at least 8 ℓ/s flow during the drilling times. This would allow for more cooling being transferred to the air. The water flow is directly proportional to the overall duty of the cooling cars.

## QUANTIFYING OVERALL IMPROVEMENTS

The cooling car flow rates were optimized to allow for maximum flow through the cooling cars with limited water wastage. The selection of the different flows was governed by the water outlet temperatures as well as outlet air wet-bulb. The following section quantifies the expected improvements on the system.

### *Potential water savings*

The optimization procedure led to changes in overall water flow rates through the cooling car. The method by which water is reused through the cooling car led to an overall reduction in water usage. This section outlines the overall expected water savings from the simulations. Table 16 shows the expected flow results for the cooling cars.

*Table 16: Cooling car flows*

| Output | Value |
|---|---|
| Total measured water flow | 112.5 ℓ/s |
| Total simulated flows | 136 ℓ/s |
| Total simulated dumping | 88 ℓ/s |
| Total measured recirculating flows | 24.7 ℓ/s |
| Total initial dumped flows | 88 ℓ/s |
| Total dumped flow (20% increased pressure) | 105 ℓ/s |

It was assumed that the flow increases by 20% when the system pressure increases. This means the dumping flow would be 105.6 ℓ/s. With the installed valves as suggested, the flow remains constant irrespective of pressure increase in the system. The total water saving in this case would be the 20% increase during off-peak times.

The expected water saving turns out to be 18 ℓ/s. Based on Equation 3 in the introduction section, The overall head to be pumped is 1 700m with a pump efficiency of 80%. This translates to a total energy usage of approximately 400 kWh, which works out to be R3.8m in annual savings based on the Mega tariff data. With about 8 booster pumps removed from the system, an additional of R640 000 can be saved annually.

**Cooling duty and wet-bulb temperature improvement**

Only the cooling duty during the drilling shift was evaluated. The total initial duty was calculated to be 2 629 kW at an average of 188 kW per cooling car. From the simulated results, the expected overall duty of the cooling cars is 6 688 kW at an average of 363 kW per cooling car – a total increment of 4 059 kW at an average 175 kW per cooling car.

The initial measured average wet-bulb temperature was 28,7°C , whereas the simulated average wet-bulb temperature was 26°C – a total average improvement of 2,7°C. The wet-bulb temperature pf 28,7°C yields about 18,6% loss in worker productivity. With the reduction in wet-bulb temperature, the productivity loss was reduced to 3,4%, and the expected productivity improvement is 15%.

## 3.7 STEP 7– IMPLEMENTING A DEVELOPED STRATEGY

It was proposed that the developed configurations on the cooling cars of mine A were implemented which would entail reconfiguring the current system of the cooling cars and implementing the proposed solution. Type A configuration was implemented on all the cooling cars located on the crosscuts and Type B configuration on the RAWs and the main haulages.

The implementation required additional infrastructure which included new Maric flow valves and flanges. The old pipes were used to connect the cooling cars to the main chill water pipeline. The principal delay of the project was the ordering of the valves and designing the flanges for the valves to fit on the cooling cars. The T-piece flanges were picked directly from the shelves. Figure 60 shows the flange for the cooling car on the main haulages and the T-piece for the crosscut cooling cars.



*Figure 60: Cooling car flange and T-piece*

## MOTIVATION FOR USE OF THE BETTER VALVE

The right Maric flow valves had to be selected to cater for the operating conditions of the cooling cars. A catalogue was used for the selection. The summary of the selection is included in **Appendix E**. 4 ℓ/s valves were selected for the cooling cars on the crosscuts and 7 ℓ/s for cooling cars on the main haulages. The valves were rated for pressures up to 20 bar. The selected valves are PVC Maric flow valves and they were selected in order to limit costs. The PVC valves were half the price of the stainless-steel valves and the PCV valves were less likely to be stolen than the stainless-steel valves. The quotations of the valves are outlined on **Appendix F.** The boiler makers designed and created all the required fittings and the fitters installed the valves according to an outline of the installation procedure supplied to them by the engineers. It took about 2 months, from placing the order for new Maric flow valves, performing the necessary tests, up to the installation stage.

**Appendix G** outlines the project management process including the project timeline, installation procedure documents, Maric valve costs and auditing schedule.

## TYPE A CONFIGURATION SET-UP

Figure 61 shows the type A configuration set up underground. The type A configuration was implemented on all the cooling cars located on the mine crosscuts.

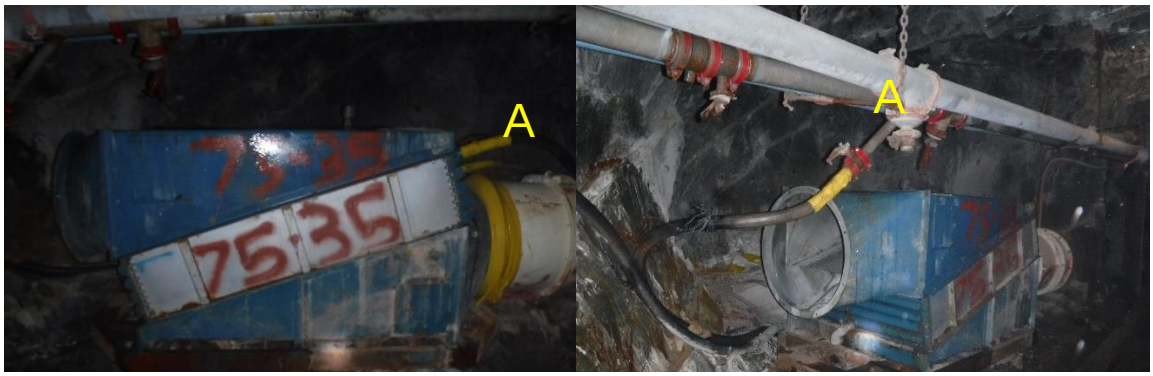



*Figure 61:Cooling car configuration set-up*

As explained in the configuration design, the water is expected to enter the cooling car from the chill water line indicated by A. The outlet of the cooling car is integrated with a T-piece which connects to the cooling car and the other 2 outlets leading to the dumping Maric flow valve and the crosscut ends. The Maric flow valve regulates the maximum water that can be

dumped by keeping the water flow constant irrespective of the system pressure. Figure 62 illustrates the dumping of the Type A configuration cooling car.



*Figure 62: Cooling car T-piece and dumping*

## TYPE B CONFIGURATION SET-UP

Figure 63 shows the type B configuration set-up underground. The configuration is the same for all the cooling cars located on the main haulages and the RAWs.

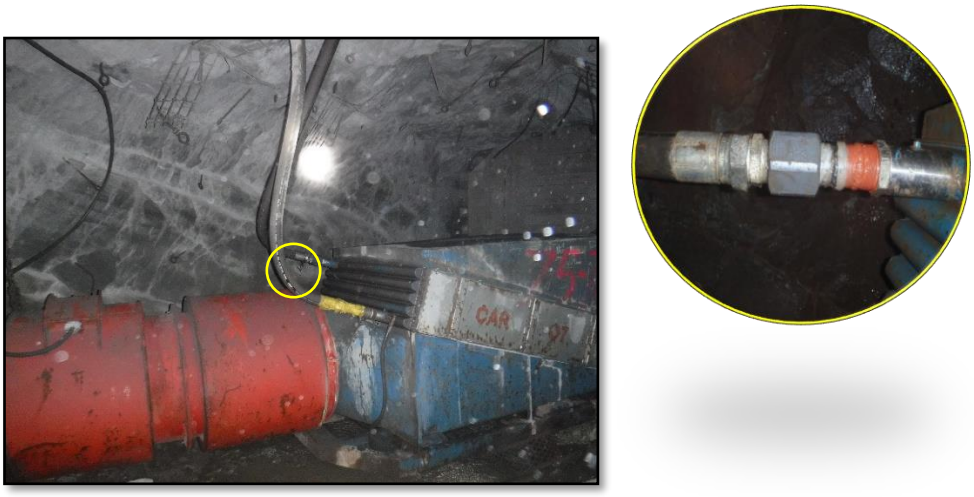


*Figure 63:Type B cooling car with Maric valve*

Type B configuration involved the installation of the Maric valve on the inlet of the cooling car. The valve regulates the flow through the cooling car irrespective of the increase in pressure on the system.

## 3.8 STEP 8 – QUANTIFYING IMPROVEMENTS, VERIFICATION AND VALIDATION

Once the implementation was complete, the cooling cars were remeasured to determine the impact of the new configurations. The collected data was analyzed and used to construct a new set of profiles compared with the simulated and the constructed baselines as well as the initial measured results. The implementation results are included in Table 27 in **Appendix H**.

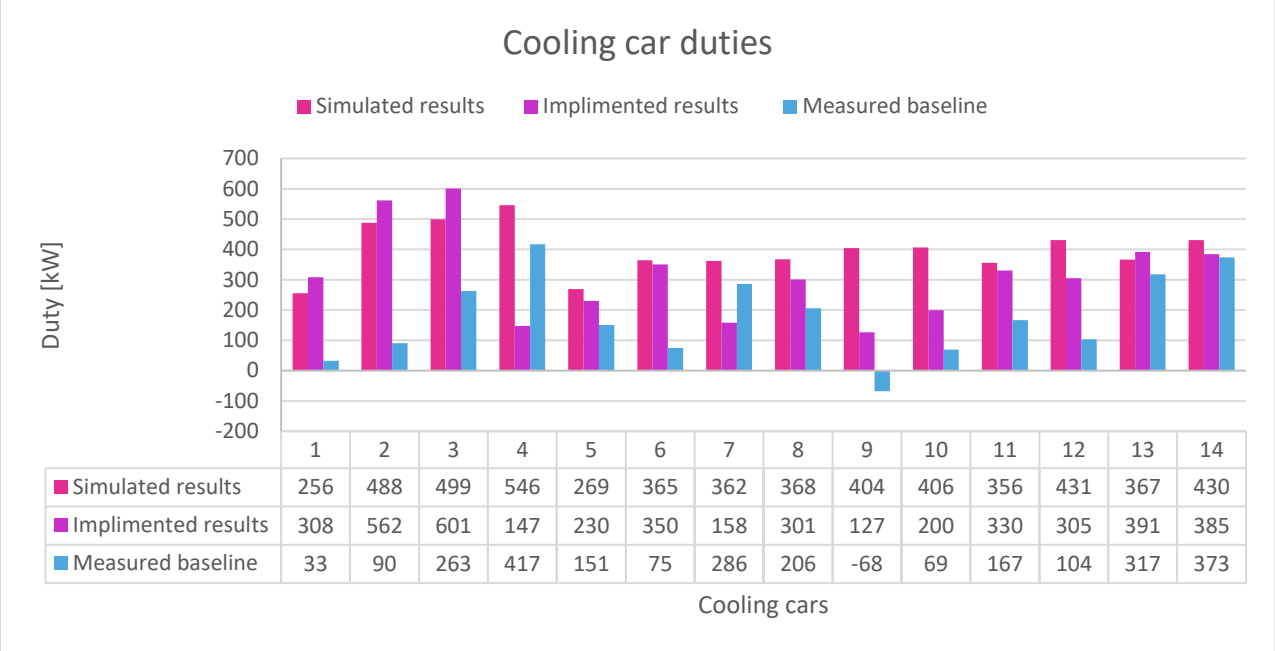
The measurements were also used to verify the results of the proposed reconfiguration strategies. Due to the continuous change in the systems and closing of some of the mining places, three cooling cars were disconnected. Therefore, the results from the removed cooling cars were excluded from the verification and will not be used to suggest improvements on the system. The total number of cooling cars was reduced to 14.

### INTERPRETATION OF RESULTS

The measured results were analysed and compared to the simulation results. The following sections include the overall interpretation of results.

### COOLING CAR DUTIES

Figure 64 depicts the comparison between the simulated duties, implemented and initial measured results. This shows the outcome of the overall improvements in terms of duties.



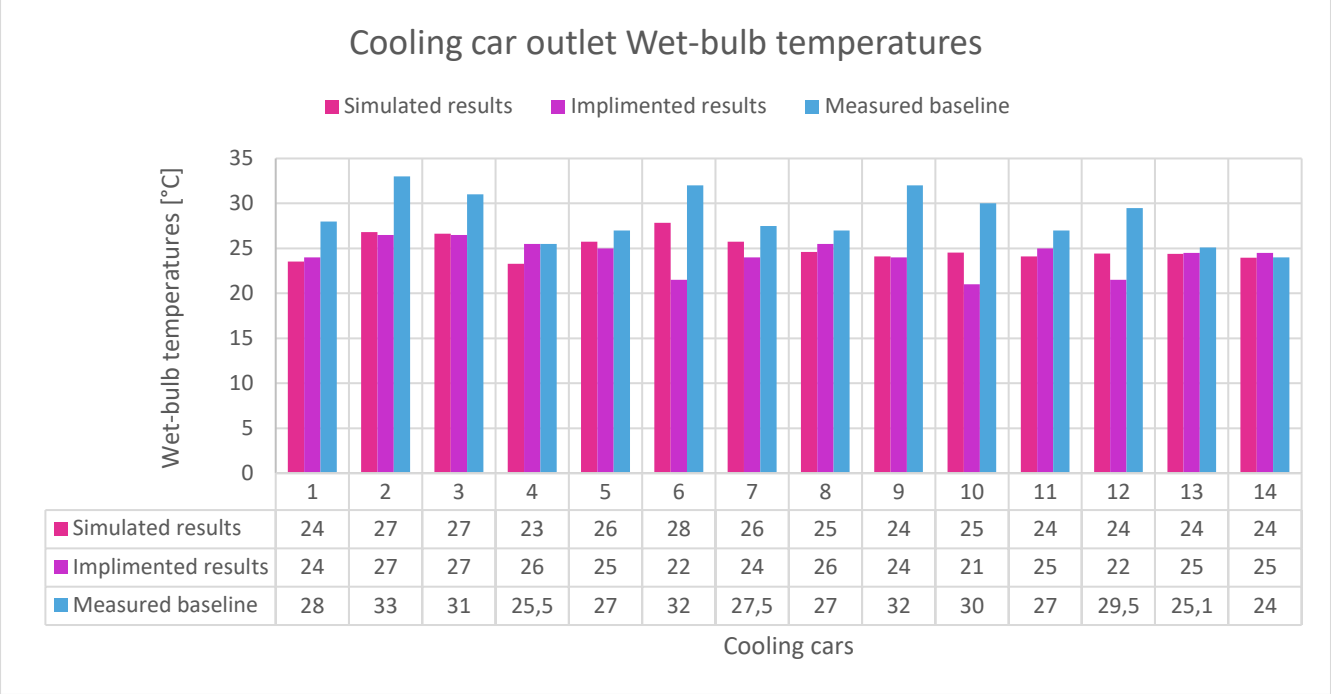

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Simulated results | 256 | 488 | 499 | 546 | 269 | 365 | 362 | 368 | 404 | 406 | 356 | 431 | 367 | 430 |
| Implimented results | 308 | 562 | 601 | 147 | 230 | 350 | 158 | 301 | 127 | 200 | 330 | 305 | 391 | 385 |
| Measured baseline | 33 | 90 | 263 | 417 | 151 | 75 | 286 | 206 | -68 | 69 | 167 | 104 | 317 | 373 |

*Figure 64: Cooling car duty results*

The overall implemented cooling duty was found to be 4,4 MW with a total average of 314 kW per cooling car, indicating an overall cooling duty improvement of 2 MW with an average cooling duty improvement of 143 kW per cooling car. The expected cooling duty improvement was 3 MW at an average cooling duty improvement of 219 kW per cooling car. This suggests that the implemented solution indeed had an impact on the overall duty of the cooling cars.

### WET-BULB TEMPERATURE

The main aim of the study was to reduce the outlet air wet-bulb temperatures from the cooling cars. The baseline was set up at 26°C. Figure 65 demonstrates the cooling car outlet wet-bulb air temperatures.




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Simulated results | 24 | 27 | 27 | 23 | 26 | 28 | 26 | 25 | 24 | 25 | 24 | 24 | 24 | 24 |
| Implimented results | 24 | 27 | 27 | 26 | 25 | 22 | 24 | 26 | 24 | 21 | 25 | 22 | 25 | 25 |
| Measured baseline | 28 | 33 | 31 | 25,5 | 27 | 32 | 27,5 | 27 | 32 | 30 | 27 | 29,5 | 25,1 | 24 |

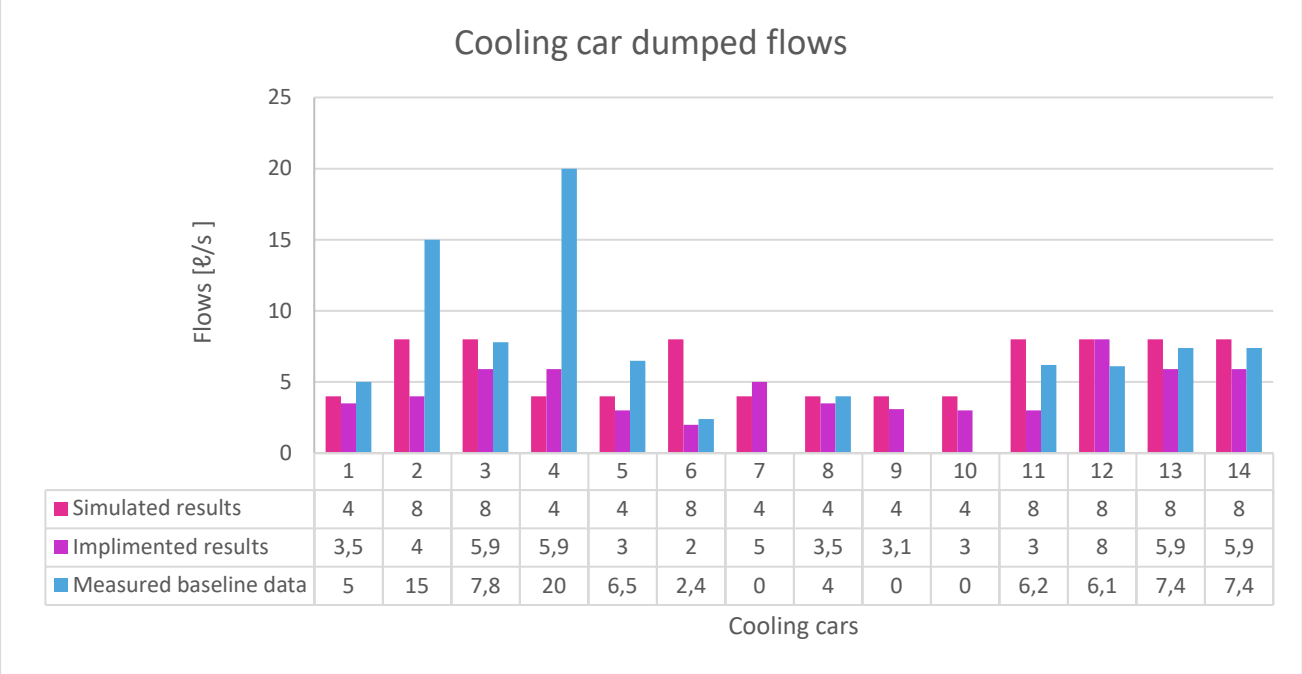
*Figure 65: Cooling car outlet air temperatures*

The baseline was set up at 26°C. The initial results showed an average outlet wet-bulb temperature of 28,5°C. The simulated results indicated average outlet wet-bulb temperatures of 25°C. Thus there was an expected decrease of 3,5°C. The implemented results suggested an overall decrease of 4,5°C in water outlet temperatures. However, the average outlet temperature was calculated at 24,3°C.

The reduced wet-bulb temperatures are proportional to the workers' effectiveness and increase in productivity. By applying equation 1, the decrease in wet-bulb temperatures from 28,5 to 24°C leads to an overall improvement of 17% in workers' productivity. The overall production rate is expected to increase by 17%.

### COOLING CAR DUMPED FLOWS

Cooling car water dumping is one of the largest water consumers in the mining industry. Figure 66 illustrates the total flow dumped from the cooling cars.



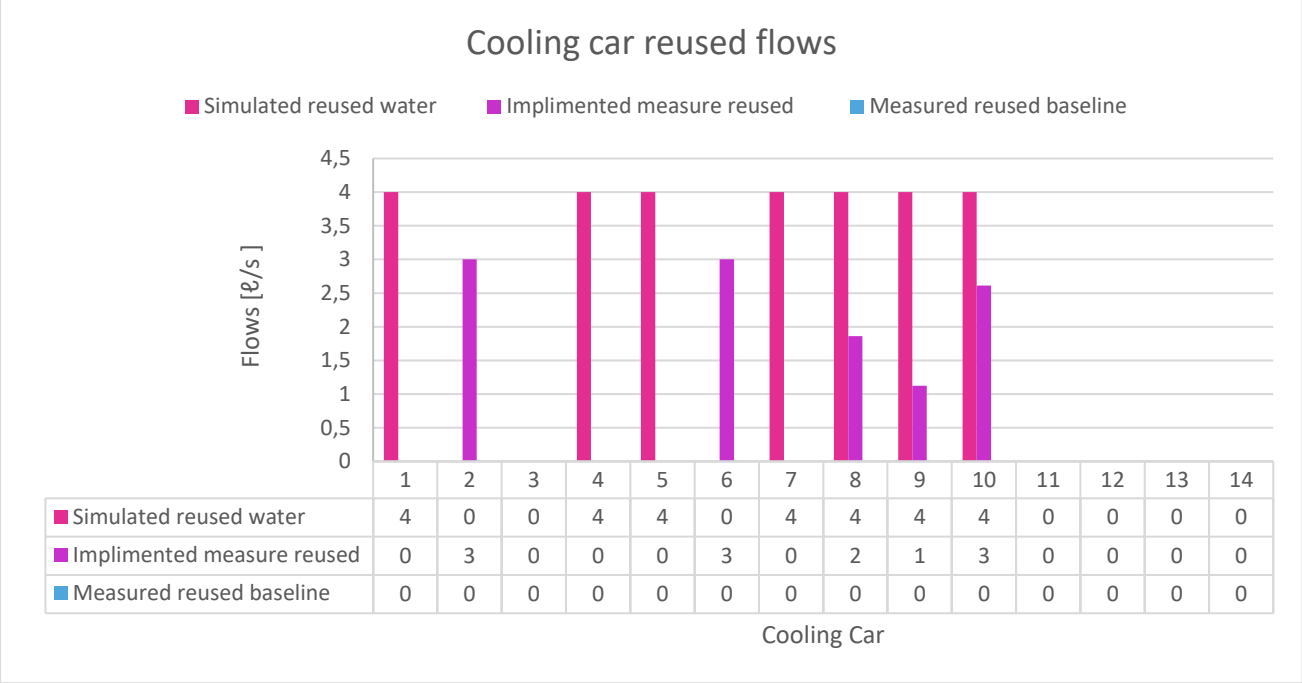

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Simulated results | 4 | 8 | 8 | 4 | 4 | 8 | 4 | 4 | 4 | 4 | 8 | 8 | 8 | 8 |
| Implimented results | 3,5 | 4 | 5,9 | 5,9 | 3 | 2 | 5 | 3,5 | 3,1 | 3 | 3 | 8 | 5,9 | 5,9 |
| Measured baseline data | 5 | 15 | 7,8 | 20 | 6,5 | 2,4 | 0 | 4 | 0 | 0 | 6,2 | 6,1 | 7,4 | 7,4 |

*Figure 66: Cooling car dumped flows*

Initially, a total of 87.5 ℓ/s was being dumped. The total simulated expected dumped water is 84 ℓ/s. After the implementation, the overall dumped flow was 64 ℓ/s, resulting in total water savings of 20 ℓ/s. The initial water flow was expected to increase by approximately 20% when the system pressure increases. The installed Maric flow valve will regulate and control the possible increase in dumped flows. The overall water saving achievable is 20.4 ℓ/s if the dumped flow increases to the maximum simulated dumped flow of 84 ℓ/s in total.

## COOLING CAR REUSED FLOWS

The study was based on re-using the water passing through the cooling car to minimize the overall water usage in the system. Figure 67 represents the simulated, measured and implemented results for the reused water in the mine.




| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Simulated reused water | 4 | 0 | 0 | 4 | 4 | 0 | 4 | 4 | 4 | 4 | 0 | 0 | 0 | 0 |
| Implimented measure reused | 0 | 3 | 0 | 0 | 0 | 3 | 0 | 2 | 1 | 3 | 0 | 0 | 0 | 0 |
| Measured reused baseline | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Figure 67: Cooling car reused flows*

Initially no water was being reused by the mine. The water used on the crosscut ends was calculated by considering the number of drills per panel. An average value of 5 ℓ/s was calculated. Every crosscut was expected to use 5 ℓ/s without the cooling cars and a flow of 10 ℓ/s in the presence of at least one cooling car. The overall expected reusable water was simulated to be 28 ℓ/s for all the cooling cars. After implementation, the total reused flow through the cooling cars was observed to be 12 ℓ/s. The cooling car received an additional cooling duty from the additional flow-through of 12 ℓ/s.

The implemented results differ from the simulated results due to the times at which the measurements for the cooling cars were taken. The usage of water in the crosscut ends depends on the activity of the miners. Most crosscuts were not utilizing enough water during the times of the test. It was proven that the increase in usage on the crosscut ends increases the total flow through the cooling cars and as a result the total cooling duty increases and the air outlet temperatures decrease. The overall cooling car outlet water temperature decreases, resulting in chill water supply to the drilling ends.

## ENERGY BENEFITS

A total of eight 11 kW pumps were removed from the system. This resulted in considerable energy savings . The electrical power used by the pumps previously, could be translated to an average cost of R80 000 p.a using Megaflex tariff data. The overall savings through the reduction of the pumps is R640 000 p.a.

A total water reduction of 20 ℓ/s was achieved. This resulted in the reduction in pumping power of 450 kWh from the dewatering pumps in the mine. The reduction in water resulted in a total savings of R4,8m p,a based on the Megaflex tariff data. The water savings combined with the reduction in pumping usage resulted in a total savings of R5,44m p.a.

## VERIFICATION OF RESULTS

The simulation model was used to predict the outcome of the derived methodology. Table 17 shows the comparison between the simulated results of the model and the implemented results. This serves to establish if the predicted results were achieved.

*Table 17: Cooling car model verification/validation*

| Cooling car | UA kW/°C | $Tw_{in}$ (°C) | $Tw_{out}$ (°C) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | Flow (kg/s) | $Tout_{_db}$ (°C) | $Tout_{_wb}$ (°C) | Duty (kW) | Flow(l/s) | Dumped flow |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 666L X/C 3 | 0% | 0% | 2% | 5% | 2% | 10% | 1% | 2% | 17% | 56% | 13% |
| 69L X/C 71 | 0% | 1% | 0% | 1% | 1% | 7% | 1% | 1% | 13% | 13% | 50% |
| 69L X/C 75 | 0% | 28% | 5% | 0% | 0% | 7% | 1% | 0% | 17% | 26% | 26% |
| 71L X/C 36 | 0% | 44% | 7% | 18% | 13% | 0% | 10% | 9% | 73% | 26% | 32% |
| 73L X/C 38 | 0% | 32% | 3% | 5% | 2% | 18% | 1% | 3% | 15% | 63% | 25% |
| 73L X/C 40 | 0% | 27% | 20% | 13% | 15% | 14% | 21% | 23% | 4% | 38% | 75% |
| 73L South Dev | 0% | 30% | 11% | 11% | 16% | 2% | 5% | 7% | 56% | 38% | 20% |
| 75L X/C 38 | 0% | 35% | 10% | 0% | 0% | 9% | 5% | 4% | 18% | 33% | 13% |
| 75L X/C 40 | 0% | 25% | 0% | 11% | 15% | 13% | 2% | 0% | 69% | 47% | 23% |
| 75L X/C 41 | 0% | 3% | 14% | 18% | 19% | 14% | 11% | 14% | 51% | 30% | 25% |
| 75L RAW South Left | 0% | 27% | 8% | 5% | 2% | 14% | 7% | 4% | 7% | 63% | 63% |
| 75L RAW South Right | 0% | 22% | 16% | 20% | 13% | 25% | 11% | 12% | 29% | 0% | 0% |
| 75L RAW North Left | 0% | 0% | 14% | 2% | 2% | 20% | 0% | 0% | 6% | 26% | 26% |
| 75L RAW North Right | 0% | 0% | 8% | 0% | 0% | 0% | 2% | 2% | 11% | 26% | 26% |
| Average | 0% | 8% | 2% | 8% | 6% | 9% | 2% | 3% | 21% | 35% | 27% |
| Total | | | | | | | | | 21% | 35% | 27% |

For the verification to hold, the percentage error needs to be minimal. The percentage errors were weighted and grouped from the lowest represented in green and highest in red. The factors which were mostly affected were the inlet temperatures, water flows and dumped flows.

This was due to the time at which the measurements were taken and the fact that the mine is dynamic, and therefore factors change continuously. The average calibrated simulation parameters were within 14% of the implemented measurements. The calibration is 4% out on the recommended average percentage error.

## Validation

The objective of the study was to optimise the water management strategies of Mine A in order to improve underground ambient conditions. A methodology was developed in Chapter 2 and was implemented on a case study. The cooling coils were selected as the main cooling system for the case study. The expected outcome of the case study needed to be in line with the main objective of the study. A model was built to simulate the expected results of the case study. The results were verified by comparing the simulated results with the measured results after the implementation of the method on mine A.

The verification average percentage error from the results was 14%. To render the study successful and valid, certain specifications had to be met. The results of implementing the developed strategy had to display and meet the following objectives:

- Optimise the water management strategy of the cooling cars to improve outlet air temperatures, specifically the wet-bulb temperatures.
- Improve the cooling duties of the cooling coils through increasing the total flow through the cooling cars.
- Minimise the overall water usage on the system and reduce wastages.
- Achieve possible energy savings through minimizing the water usage and removing redundant components in the system, like pumps.

The optimization of water management strategies included the reconfiguration of cooling car pipelines. This strategy enabled the water flow through the cooling cars to be maximized, and in turn allowing the cooling car to have more duty as the mass flow is directly proportional to the total energy transfer. This also resulted in a decrease in cooling car air outlet temperatures. Even though the water flow through the cooling cars was increased, the developed strategy insured that the water through the cooling cars can be re-used in the crosscuts, which in turn allowed for further reductions in water usage.

It was also observed that the cooling cars used to consume more water during off-peak hours when the pressure in the system increases. This was avoided by integrating the configured pipelines with a pressure regulating valve. The model was used to select the optimal flow, and this further assisted with the selection of the correct valves. Table 18 shows the matrix indicating whether the objectives were met through comparing the main result outcomes with the objectives as outlined initially. Each specification is awarded a rating between 0 and 1; 0 indicating that the objective was not met and 1 indicating that it was met.

*Table 18: Study validation matrix*

| Component | Objective | Results | Comment | Rating |
|---|---|---|---|---|
| Cooling car outlet temperatures (Wet-bulb) | Expected cooling car outlet temperatures to decrease | Average reduction of 4,5°C | The objective was met | **1** |
| Cooling car duties | Expected an increase in cooling car duties | Average increase of 1,9 MW. | The objective was met | **1** |
| Water usage | Expected the water usage to decrease due to the installed valves | A total decrease of 20,4 ℓ/s | The objective was met | **1** |
| Energy saving | Expected energy saving from pumping | R5,44 m was saved due to the decrease in water usage and removal of redundant pumps in the system | The objective was met | **1** |
| **Total rating** | | | | **4** |

It can be observed from the table that all the objectives which were outlined initially were met. Though the objectives were met, it is important to note that the case study was not performed on a 24 hour schedule, but was only tested during the drilling shift. This implies that there

could be more savings than reported as the research only outlines improvements achieved during the drilling shift.

Additional to the objectives, the effectiveness of mine workers was also evaluated during both the high wet-bulb outlet temperatures, and the lower wet-bulb temperatures and an improvement of 17% was realized. This is, however, only a theoretical value, as the miners' effectiveness cannot be determined empirically. An accurate method to measure the effectiveness of miners could not be outlined.

Underground temperature conditions continue to rise in the mining industry due to the increase in mining section and depth. The mining industry relies heavily on tertiary cooling systems to maintain underground condition to allow for desirable working conditions. The study can be applied in different mines which uses tertiary cooling systems. It can help deep mines with improving their underground conditions and optimising their water usage to achieve further savings.

# 4 CONCLUSION AND RECOMMENDATIONS

## 4.1 CONCLUSION

This chapter focused on applying the methodology that was developed in Chapter 2 on a case study. The cooling cars of mine A were investigated to outline the inefficiencies and configuration drawbacks. This was done through measurements and system simulations. A step by step approach was developed to reconfigure and improve the pipeline configuration of the cooling cars.

The solution strategy involved reconfiguring the cooling car pipelines to allow for maximum flow through the cooling cars. A specific valve was selected to regulate the water usage through the cooling cars irrespective of the incoming pressures on the system. Ineffective components which use energy unnecessarily were removed from the system to achieve savings.

The expected results were simulated to identify the theoretical impact of optimizing the water flow rates through the cooling cars. The simulation predicted an overall increase of 3 MW in cooling car duty, a total decrease of 3,5°C in wet-bulb temperatures and a total of 20,4 ℓ/s which amounts to savings of R4,8m p.a.

The proposed solution utilising the new configuration and the suggested infrastructure was implemented on the cooling cars. After the implementation measurements were taken to validate the impact of the reconfiguration of the cooling car chill water connection. Table 19 supplies a summary of the results realized through the implementation of the solution strategy.

*Table 19: Results summary*

| Output | Calculation | Units |
|---|---|---|
| **Initial duty** | 2 485 | kW |
| **Predicted average duty** | 5 547 | kW |
| **Measured average duty** | 4 396 | kW |
| **Initial wet-bulb temperatures** | 28,5 | °C |
| **Predicted average wet-bulb temperatures.** | 25 | °C |
| **Measured wet-bulb temperatures** | 24 | °C |
| **Total water savings** | 20.4 | ℓ/s |
| **Total energy savings** | 5 440 000 | R |
| **Worker effectiveness improvement** | 17 | % |
| **Average verification accuracy** | 14 | % |

The cooling cars do not have built-in instrumentation. All the measurements had to be taken manually. These limitations were the reason why an analysis over a 24-hour period was impossible. However, the inefficiencies on the system could still be identified and the drawbacks on the cooling car configuration could be identified through inspection and validation through the simulation model.

This study proved that the water flow through the cooling cars could be managed optimally to result in improved cooling car duties, reduced wet-bulb temperatures and energy savings through water usage reduction. The optimisation process involved maximising the flow through the cooling cars and reusing the water through the cooling cars to limit the overall water used.

The objectives of this study were addressed by optimising the water management through the cooling cars by reconfiguring the chill water pipeline and installing regulating valves to control the overall water used in the system.

## 4.2 STUDY LIMITATIONS AND FUTURE WORK

The following section outlines a few recommendations that have to be considered to improve the current implemented measures. The section will also outline the possible future research to improve the results of this study which was mainly related to the optimization of the cooling car pipeline configurations to improve cooling, reduce water usage and achieve possible energy savings.

The current suggested configuration is manually based and lacks the monitoring aspect. Any possible change in the water reticulation system may affect the configuration. This includes changing the pipelines and the general mining methodology.

Automation of the configuration is necessary to limit human interaction on the system. Miners tend to throttle the valves when encountering underground water problems. This results in changes in the suggested configuration with the result that the cooling cars do not receive water, which in turn affects the overall cooling.

The study mainly focused on water flow optimization. The water flow is directly proportional to the duty achieved by the cooling cars. The one neglected contributing factor was the inlet water temperature. The reduction in inlet water temperature leads to an increase in water duty and a decrease in the outlet wet-bulb temperature.

The impact of the inlet air temperature was not evaluated. The inlet conditions of the cooling car generally depend on the cooling car position. A future study might include the positional efficiency of the cooling cars.

The cooling coils are generally exposed to external and internal fouling. These factors were not analyzed in full. Internal and external fouling affects the heat transfer coefficient of the cooling cars and as a result the performance of the cooling cars is affected. A study of the fouling impact on cooling cars might assist with the improvement of the cooling car performance and the overall water flow through the cooling cars.

Due to limitations in the measuring instruments, the simulation was based on once-off measurements. The cooling cars operate 24 hours per day and their profile is dynamic. One needs to consider the overall 24-hour profile of the air inlet temperatures, pressures, water flows and crosscut water usage.

The suggested Maric flow valves were made from PVC. Due to the mining environment, the valves kept on clogging and breaking. The material was not strong enough for the conditions in which they were used. Figure 68 shows the valves which were removed underground due to high pressure exposure and external impact from the rocks and other mining equipment.



*Figure 68: Maric valves broken by external impact*

It is suggested that a different material is selected when working with Maric valves. The valves are exposed to high pressures and external impact, and therefore steel valves are recommended for underground applications.

It was also realized that the water quality of the mine is not of the high standard. As a result, the valves would get damaged from the inside by the chemicals in the water.Figure 69 shows the removed valves due to poor water quality.



*Figure 69:Maric valves damaged by poor water quality*

There exists a need to study the water quality of the mine. The water quality might be affecting other mining equipment and affecting their life span. Improving the water quality might allow for the use cost effective materials. A detailed study is required.

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# APPENDIX A : MAJOR HEAD LOSSES

## APPENDIX A

### *Bernoulli steady state energy equation*

The principle is represented by Equation 22.

$$\left[\frac{P_1}{\rho g} + \frac{\alpha}{2g}V_1^2 + z_1\right] = \left[\frac{P_2}{\rho g} + \frac{\alpha}{2g}V_2^2 + z_2\right] + \Delta h_{ls} \quad (22)$$

Where:

$P_1\ and\ P_2$ = Initial and final fluid pressure respectively $Pa$

$V_1\ and\ V_2$ = Initial and final fluid velocity respectively $m/s$

$g$ = Gravitational acceleration $m/s^2$

$\rho$ = Fluid density $kg/m^3$

$z_1\ and\ z_2$ = Initial and final fluid elevation respectively $m$

$\Delta h_{ls}$ = Hydraulic losses $m$ (Sum of the major and minor head losses)

### *Major head losses.*

Major head losses are normally induced by the flow regime of the fluid and its viscosity [34]. The losses depend on the characteristics of the pipes and the specific fluid and it is important to outline the correlation between these head losses and the pipeline problems. The correlation is outlined by using the Darcy-Weisbach equation:

$$h_f = f\left(\frac{LV^2}{D2g}\right) \quad (23)$$

Where:

$h_f$ = Friction head loss $m$

$f$ = Darcy friction factor –

$L$ = Pipe length $m$

$V$ = Flow velocity $m/s$

D = Pipe diameter $m$

G = Gravitational acceleration (9.81) $m/s^2$

The Darcy friction factor $(f)$ is the function of the Reynolds number, surface roughness to pipe diameter ration and shape of the pipe. The flow in pipeline can either be laminar or turbulent. This is generally determined by the Reynolds number. Different approaches are used to calculate the friction factor depending on the flow regime. For laminar flow conditions, the friction factor can be calculated using the following equation.

$$f_{lam} = \frac{64}{Re_d} \tag{24}$$

Where:

$Re_d$ = Reynolds number

$f_{lam}$ = laminar friction factor

In laminar flow, the friction factor decreases intensively with Reynolds number. The equation is only valid when the Reynold number is less than 2 300.

The Colebrook- white equation is used to determine the Darcy friction factor for turbulent flows. The Colebrook equation serves as the basis for the moody chart. The Colebrook equation is outlined below.

$$\frac{1}{f_{tur}^{\frac{1}{2}}} = -2.0 \log\left[\left(\frac{\varepsilon}{3.7D}\right) + \left(\frac{2.51}{Re_d f_{tur}^{\frac{1}{2}}}\right)\right] \tag{25}$$

Where:

$f_{tur}$ = Darcy friction coefficient for turbulent flow –

$\varepsilon$ = Surface roughness $m$

$D$ = Hydraulinc pipe diameter $m$

$Re_d$ = Reynolds number –

The Colebrook equation requires extensive iteration solving and the use of the ESS Equation solver. This makes it difficult to solve the friction factor. An alternative explicit formula is given to calculate the friction factor. This formula varies less than two percent to equation which is enough to be used to determine the friction factor. The formula is given by the following equation.

$$\frac{1}{f_{tur}^{\frac{1}{2}}} \approx -1.8 \log\left[\left(\frac{6.9}{Re_d}\right) + \left(\frac{\varepsilon}{3.7D}\right)^{1.11}\right] \quad (26)$$

Where:

$f_{tur}$ = Darcy friction coefficient for turbulent flow. –

$\varepsilon$ = Surface roughness $m$

$D$ = Hydraulic pipe diameter $m$

$Re_d$ = Reynolds number –

The given explicit equation also depends on the Reynolds number, surface roughness and the pipe internal diameter. The Reynolds number indicates the flow regime of the fluid through a pipe. It is a function of the dynamic flow properties and pipe dimensional characteristics. The flow regime can either be in laminar, transient or turbulent state [B]. The Reynolds number is calculated using the following equation:

$$Re_d = \frac{\rho V D}{\mu} = \frac{V D}{v} \quad (27)$$

Where:

$Re_d$ = Reynolds number $m$

$\rho$ = Fluid density $kg/m^3$

$V$ = Cross sectional fluid velocity $m/s$

$D$ = Pipe diameter $m$

$\mu$ = Dynamic viscosity $Ns/m^2$

$v$ = Kinematic viscosity $m^2/s$

The Reynolds number characterizes the type of flow present inside the pipe.Table 20 indicates the three different characteristic regions.

*Table 20: Reynolds number flow types*

| Reynolds number ($Re_d$) | $Re_d$<2300 | 2300< $Re_d$< 4000 | $Re_d$>4000 |
|---|---|---|---|
| Flow regime | Laminar flow | Transient flow | Turbulent flow |

In order to fully determine the friction factor, the surface roughness is also required. Table 21 supplies the recommended surface roughness for commercial ducts.

*Table 21: Surface roughness for ducts*

| **Type of material** | **Roughness (mm)** |
|---|---|
| Stainless Steel | 0.002 |
| Cast Iron | 0.26 |
| Brass | 0.0015 |
| Plastic | 0.0015 |
| Glass | Smooth |
| Concrete | 1.2 |
| Rubber | 0.01 |

| | |
|---|---|
| Wood | 0.5 |

# APPENDIX B : MINE A LEVEL LAYOUTS

## APPENDIX B

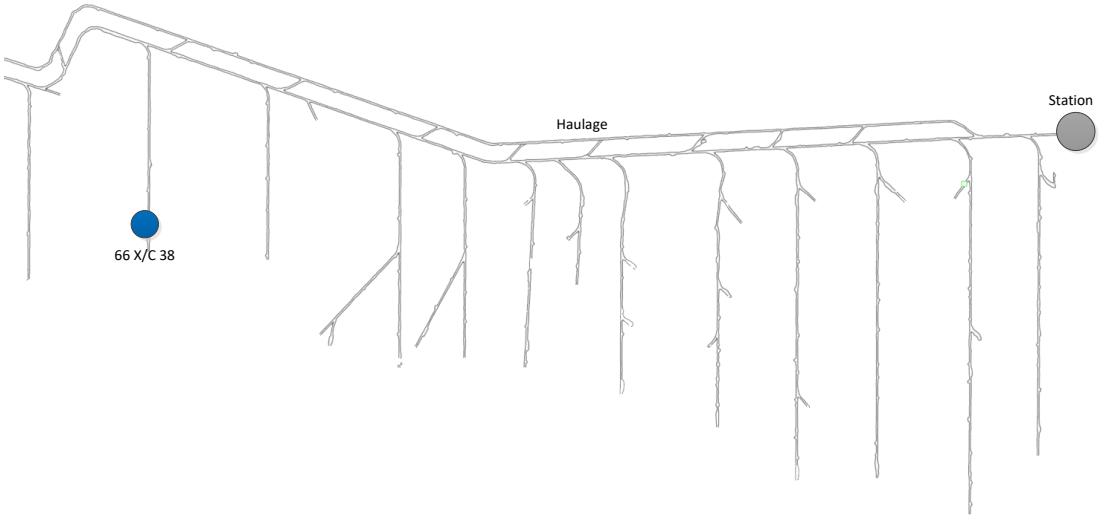



*Figure 70: Mine A 66L layout*

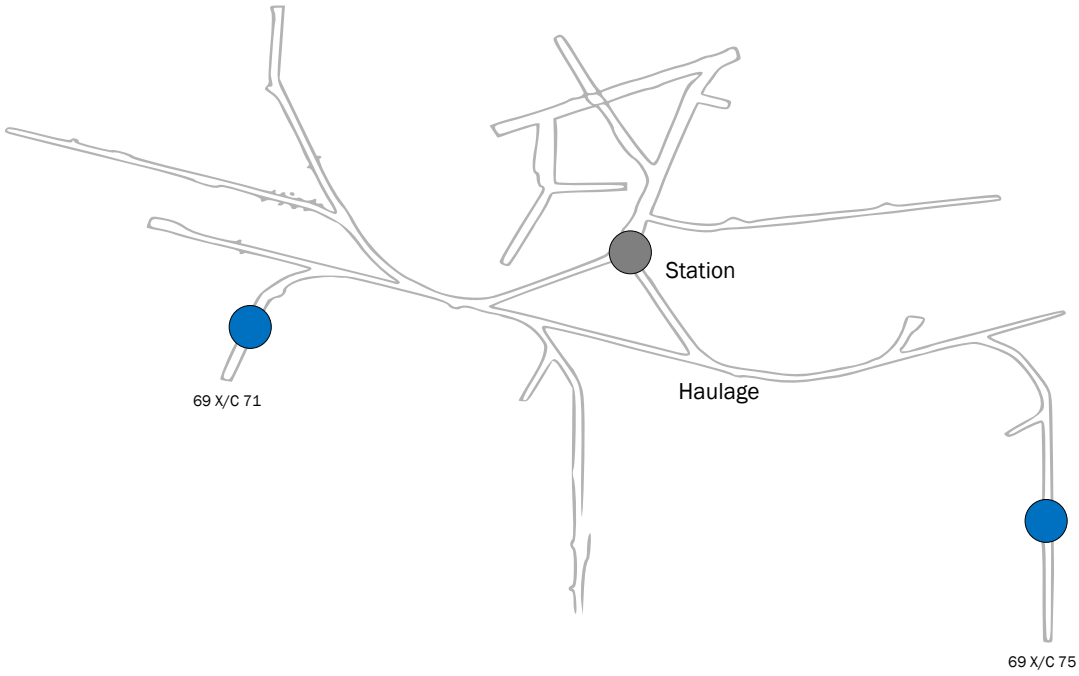



*Figure 71: Mine A 69L layout*

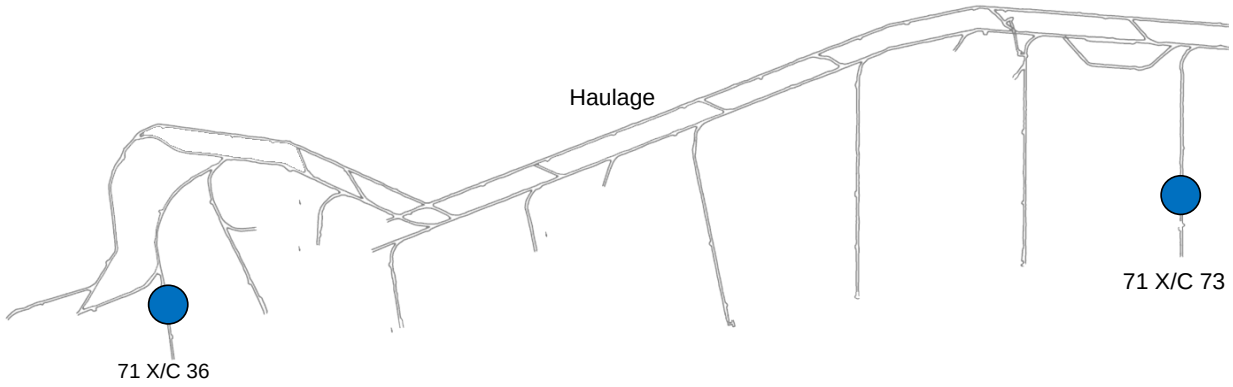



*Figure 72: Mine A 71 layout*

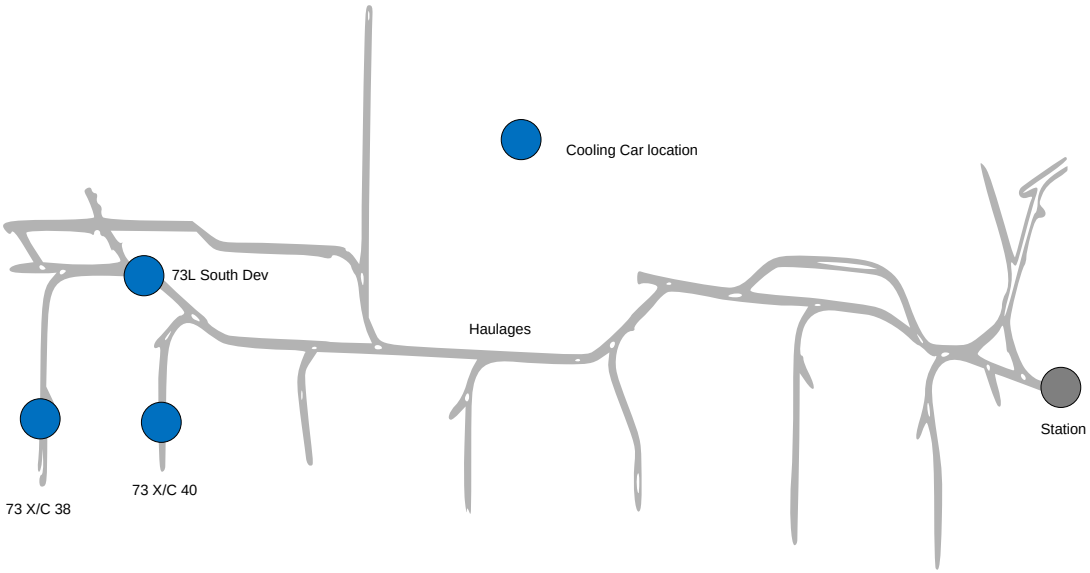



*Figure 73: Mine A 73L layout*

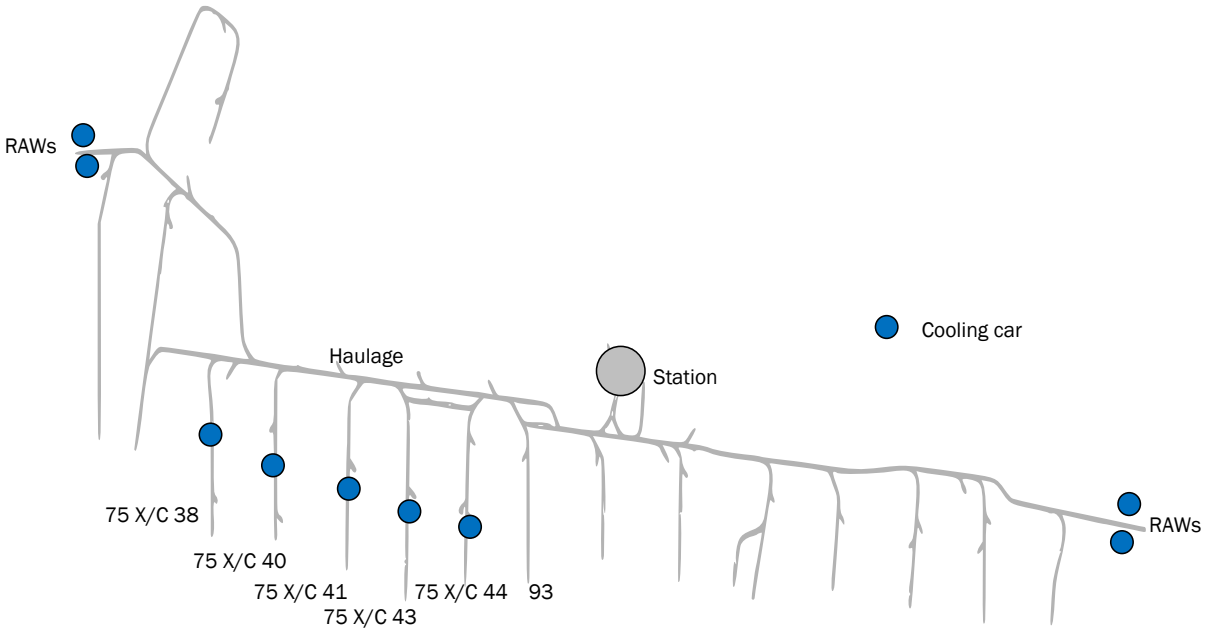



*Figure 74: Mine A 75L layout*

# APPENDIX C: COOLING CAR MEASUREMENTS

## APPENDIX C

*Table 22:Cooling car measurements*

| C/C NO | X/C T | Cooling car | Water | | | | Air | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | $T_{in}$ (°C) | $T_{out}$ (°C) | ΔT (°C) | Flow (kg/s) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | $T_{in_db}$ (°C) | $T_{in_wb}$ (°C) | $\Delta T_{db}$ (°C) | $\Delta T_{wb}$ (°C) | Flow (kg/s) |
| #C1 | 17 | 66L X/C 38 | 26.5 | 29.8 | 3.3 | 3 | 31 | 28.5 | 28.5 | 28 | 2.5 | 0.5 | 14.41 |
| #C2 | 13.6 | 69L X/C 71 | 28.7 | 33.2 | 4.5 | 15 | 34.5 | 34 | 34 | 33 | 0.5 | 1 | 15.06 |
| #C3 | 13.6 | 69L X/C 75 | 21.3 | 27.1 | 5.8 | 7.8 | 36 | 34 | 31 | 31 | 5 | 3 | 16.13 |
| #C4 | 11.3 | 71L X/C 73 | 27.3 | 31 | 3.7 | 0.2 | 30.5 | 30 | 30.5 | 30.5 | 0 | -0.5 | 12.24 |
| #C5 | 11.3 | 71L X/C 36 | 19.1 | 26.7 | 7.6 | 20 | 35.5 | 32 | 25.5 | 25.5 | 10 | 6.5 | 13.99 |
| #C6 | 19.1 | 73L X/C 38 | 19.6 | 26.7 | 7.1 | 6.5 | 30.5 | 29.5 | 27 | 27 | 2.5 | 2.5 | 13.49 |
| #C7 | 19.1 | 73L X/C 40 | 22.9 | 33.2 | 10.3 | 2.4 | 33.5 | 33 | 32 | 32 | 1.5 | 1 | 13.93 |
| #C8 | 19.1 | 73L South Dev | 19.2 | 25.3 | 6.1 | 10 | 32 | 32 | 27.5 | 27.5 | 4.5 | 4.5 | 13.3 |
| #C9 | 14 | 75L X/C 38 | 20.5 | 29.5 | 9 | 4 | 32.5 | 30 | 27 | 27 | 5.5 | 3 | 15.35 |
| #C10 | 14 | 75L X/C 40 | 31.2 | 33 | 1.8 | 9.7 | 32.5 | 31 | 32 | 32 | 0.5 | -1 | 13.01 |
| #C11 | 14 | 75L X/C 41 | 21.6 | 34 | 12.4 | 0 | 34 | 31 | 34 | 30 | 0 | 1 | 13.99 |
| #C12 | 14 | 75L X/C 43 | 16.8 | 30.3 | 13.5 | 2.3 | 32.5 | 29 | 30 | 30 | 2.5 | -1 | 15.58 |
| #C13 | 14 | 75L X/C 44 | 14.3 | 30 | 15.7 | 1.9 | 32 | 30 | 29.5 | 29.5 | 2.5 | 0.5 | 18.02 |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| #C14 | 14 | 75L RAW South Left | 22.5 | 25.1 | 2.6 | 6.2 | 31.5 | 29.5 | 27 | 27 | 4.5 | 2.5 | 15.2 |
| #C15 | 14 | 75L RAW South Right | 22.5 | 30.1 | 7.6 | 6.1 | 34.5 | 31 | 29.5 | 29.5 | 5 | 1.5 | 14.67 |
| #C16 | 14 | 75L RAW North Left | 19 | 24.1 | 5.1 | 7.4 | 31.5 | 30 | 25.1 | 25.1 | 6.4 | 4.9 | 15.06 |
| #C17 | 14 | 75L RAW North Right | 19 | 24.5 | 5.5 | 7.4 | 32 | 30.5 | 24 | 24 | 8 | 6.5 | 14.81 |

# APPENDIX D : COOLING CAR SIMULATIONS

## APPENDIX D

### Cooing car 1

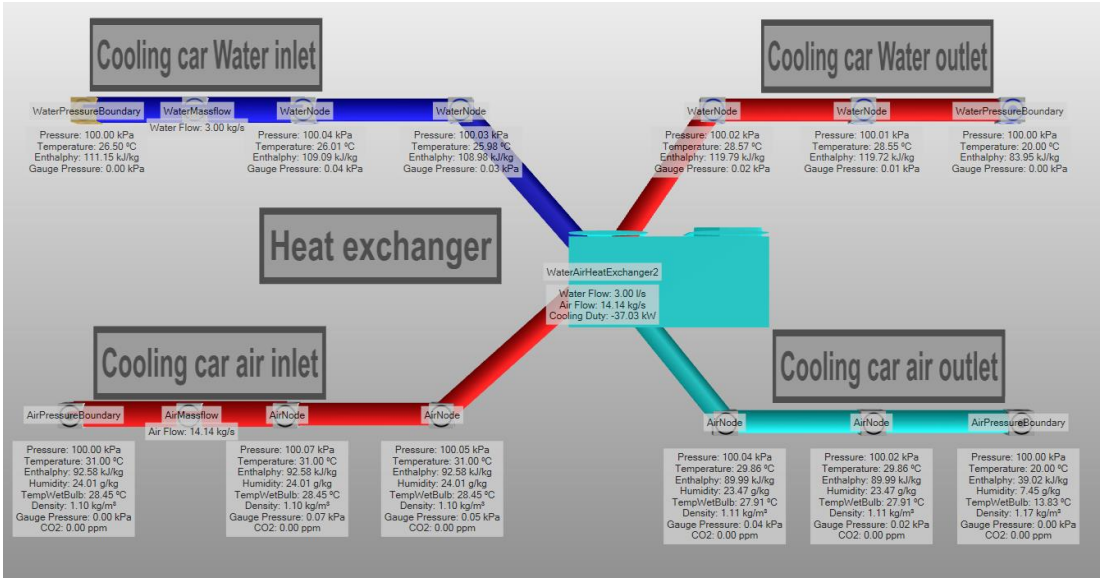



*Figure 75:Cooling car 1 (#C1) calibration model*

### Cooling car 2

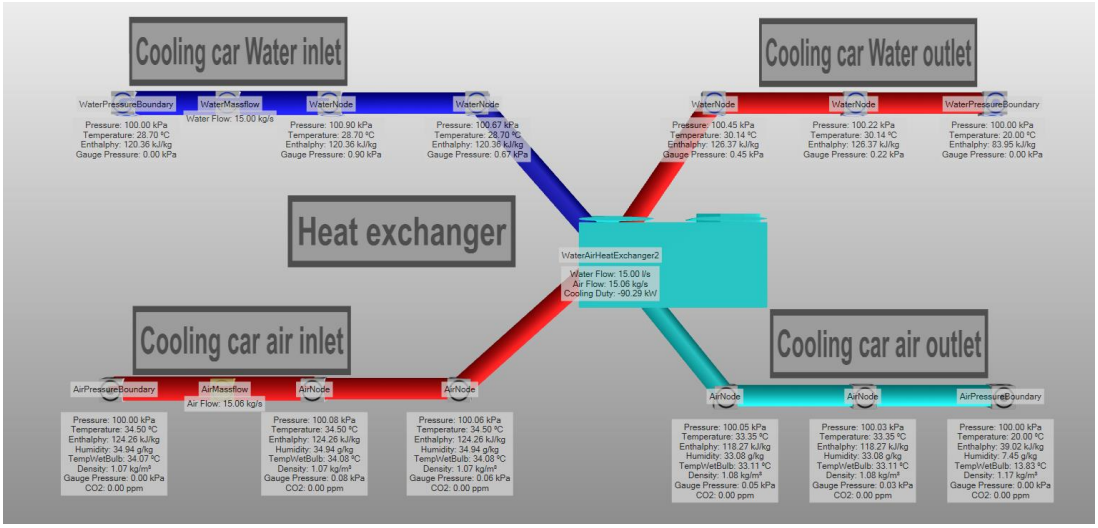



*Figure 76:Cooling car 2 (#C2) calibration model*

## Cooling car 3

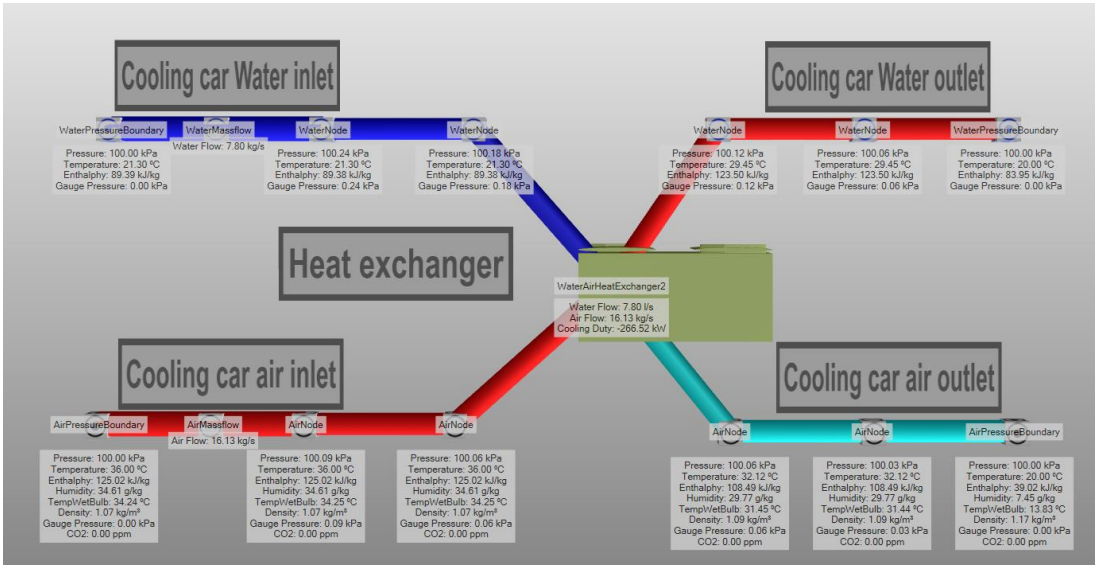



*Figure 77:Cooling car 3 (#C3) calibration model*

## Cooling car 4

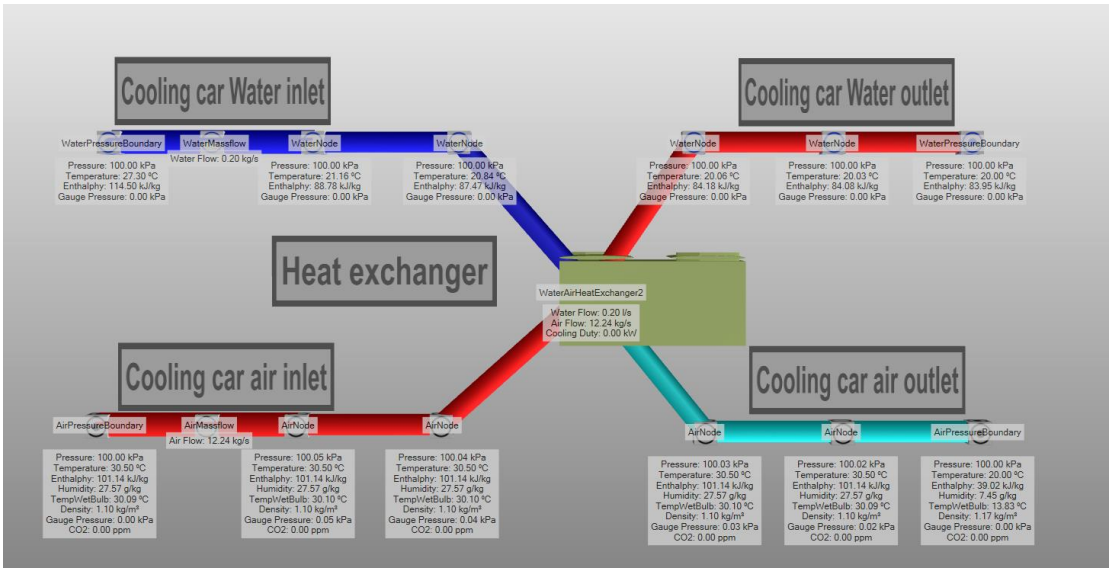



*Figure 78: Cooling car 4 (#C4) calibration model*

The model could not simulate the scenario where the cooling car increases the wet-bulb temperatures of the air. This is only applicable when the fan is clearly simulated and outlined. The one assumption is that the air mass flow represents the fan and this does not show the

thermal contributions of the fans. The simulation shows the Duty as 0, the calculations showed a negative value. The results were questionable and need to be studied further. The water flow through the cooling car was also too low and less than the recommended flow rate.

### Cooling car 5

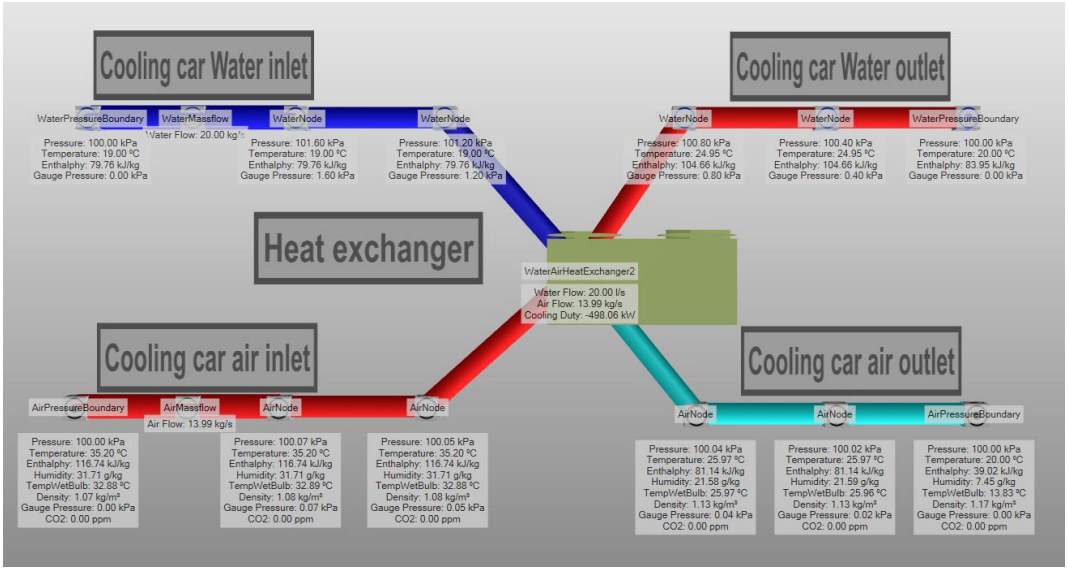



*Figure 79: Cooling car 5 (#C5) calibration model*

### Cooling car 6

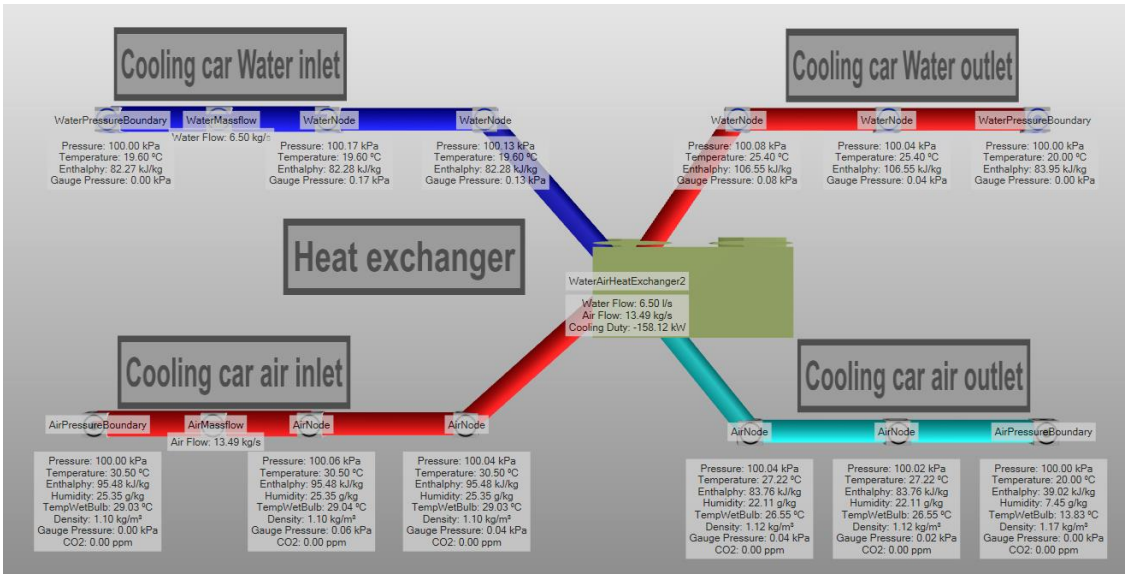



*Figure 80: Cooling car 6 (#C6) calibration model*

Simulated UA value withing the acceptable range and close to the standard as recommended by literature.

### Cooling car 7

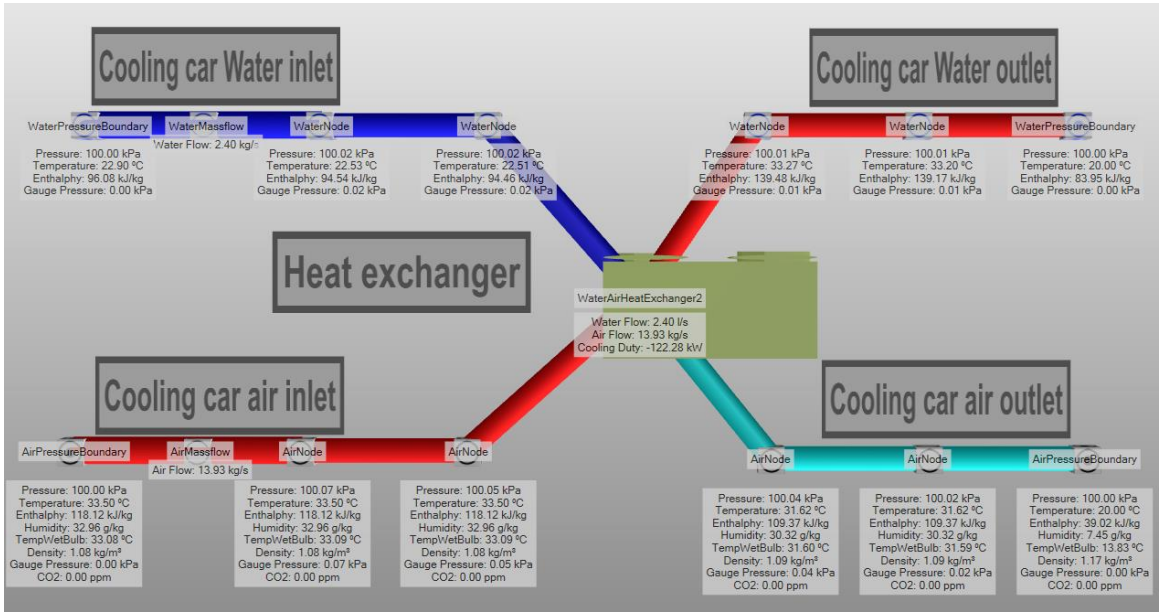



*Figure 81: Cooling car 7 (#C7) calibration model*

### Cooling car 8

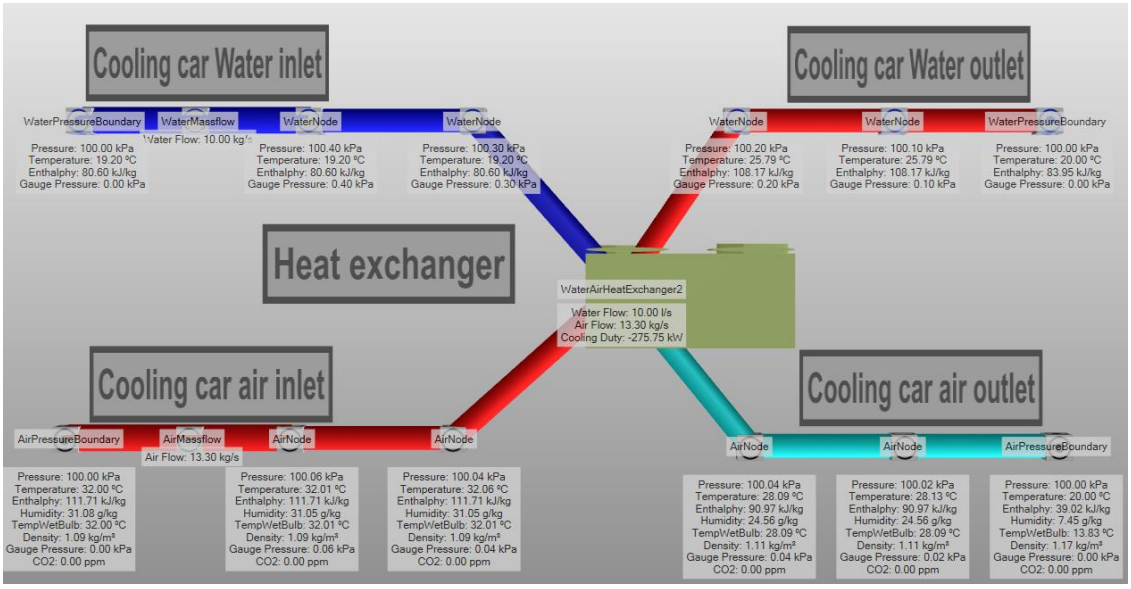



*Figure 82: Cooling car 7 (#C7) calibration model*

### Cooling car 9

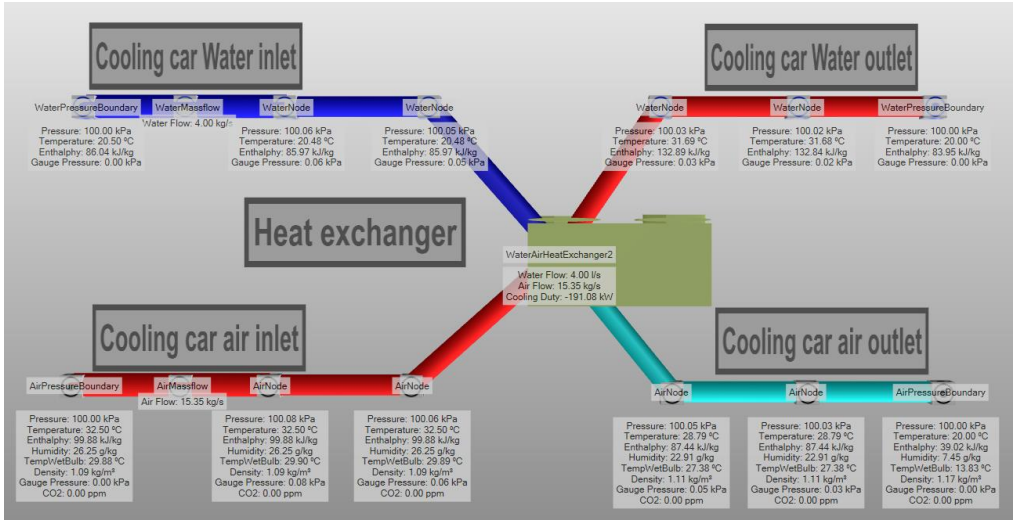



*Figure 83: Cooling car 9 (#C9) calibration model*

### Cooling car 10

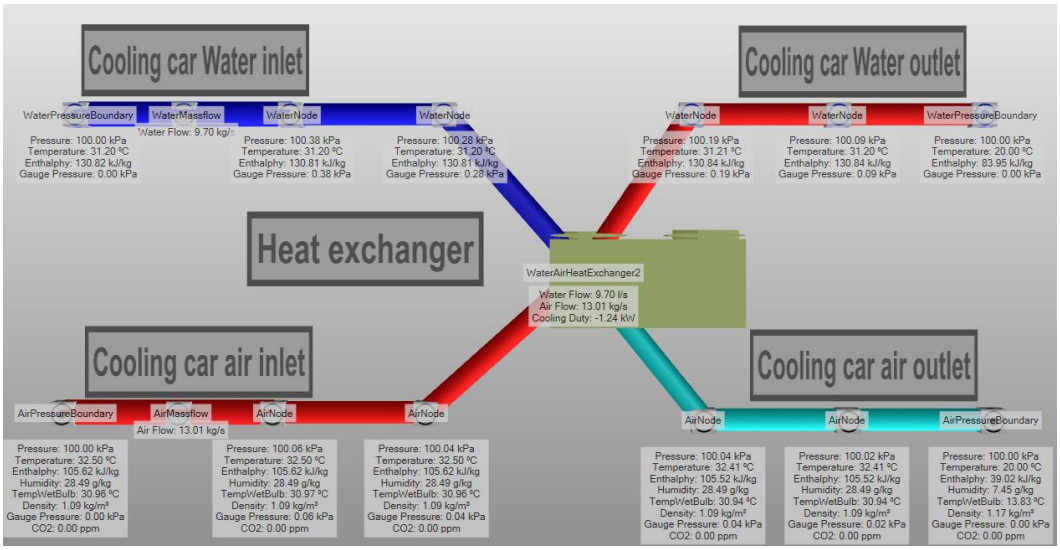



*Figure 84: Cooling car 10 (#C10) calibration model*

The model could not simulate the scenario where the cooling car increases the wet-bulb temperatures of the air. This is only applicable when the fan is clearly simulated and outlined. The one assumption is that the air mass flow represents the fan and this does not show the thermal contributions of the fans. The simulation shows the Duty as 0, the calculations showed

a negative value. The results were questionable and need to be studied further. The water flow through the cooling car was also too low and less than the recommended flow rate.

**Cooling car 11**

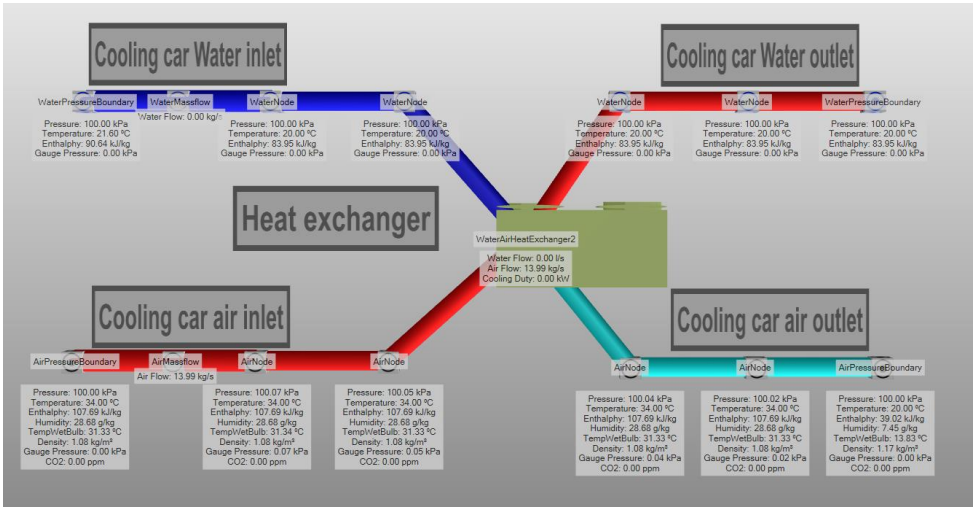



*Figure 85: Cooling car 11 (#C11) calibration model*

The cooling car does not have water flow. As a result, the cooling duty is zero and the air outlet is equal to the inlet air temperature. The cooling car could not be calibrated as the UA value of the cooling car could not be determined. The results could not be used for simulation adjustments.

**Cooling car 12**

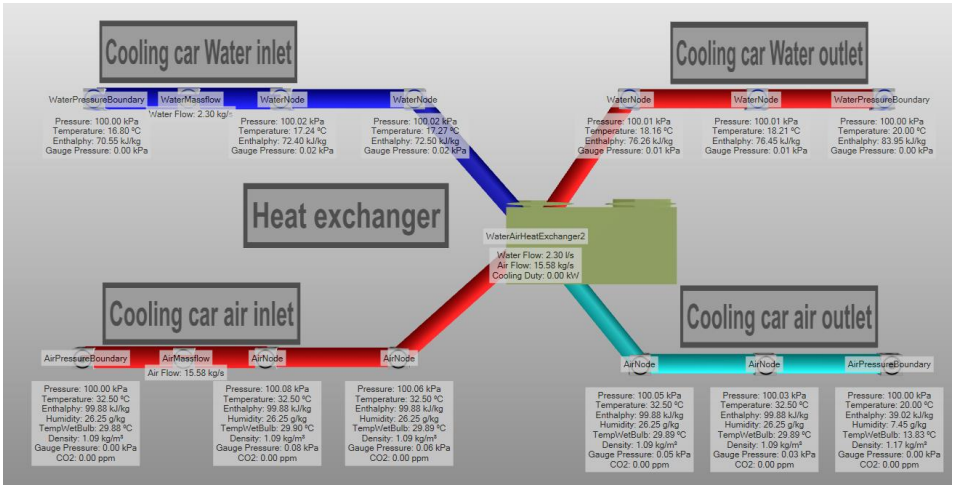



*Figure 86: Cooling car 12 (#C12) calibration model*

The model could not simulate the scenario where the cooling car increases the wet-bulb temperatures of the air. This is only applicable when the fan is clearly simulated and outlined. The one assumption is that the air mass flow represents the fan and this does not show the thermal contributions of the fans. The simulation shows the Duty as 0, the calculations showed a negative value. The results were questionable and need to be studied further. The water flow through the cooling car was also too low and less than the recommended flow rate.

**Cooling car 13**

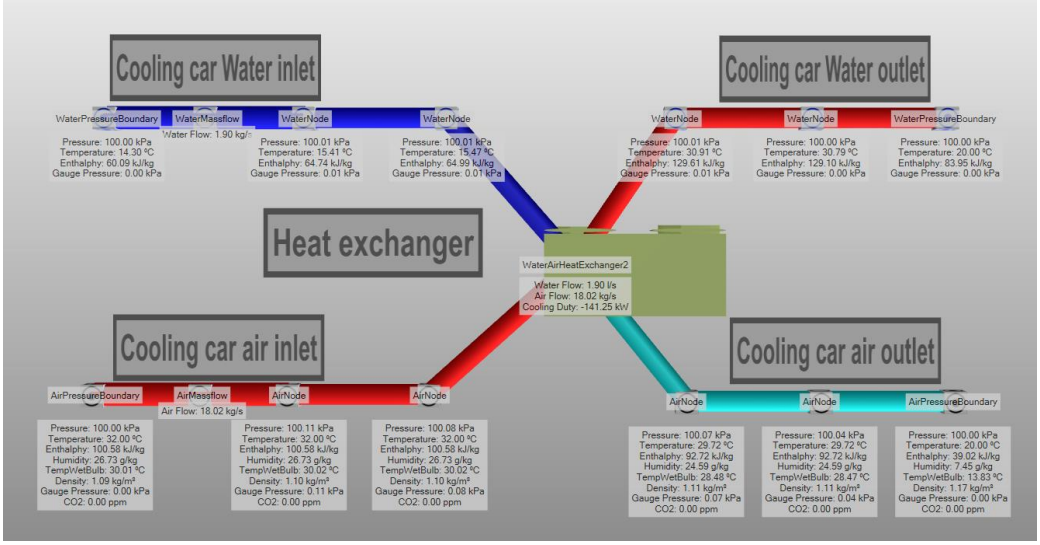



*Figure 87: Cooling car 13 (#C13) calibration model*

## Cooling car 14

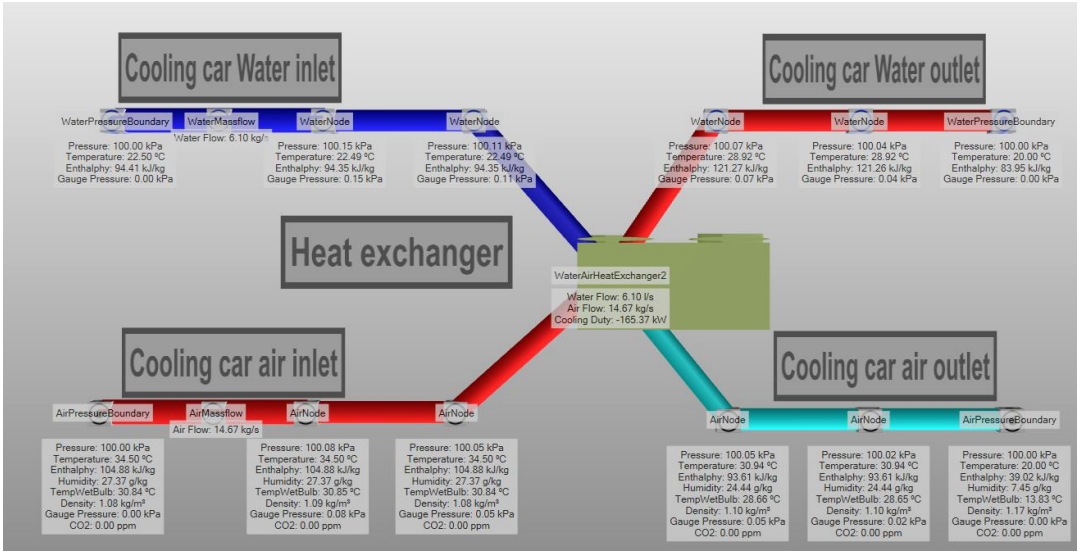



*Figure 88: Cooling car 14 (#C14) calibration model*

## Cooling car 15

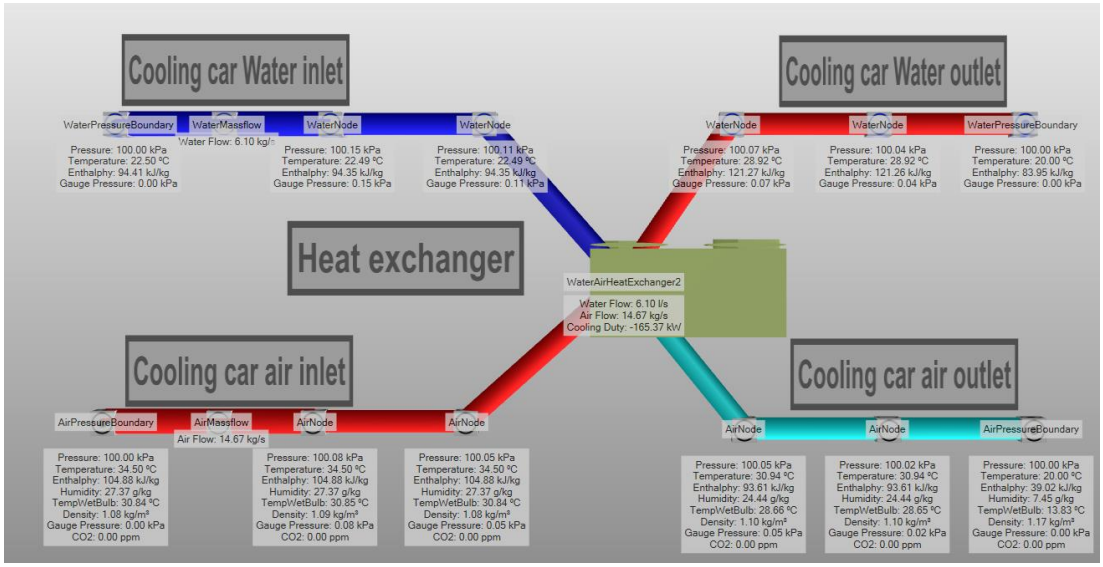



*Figure 89: Cooling car 15 (#C15) calibration model*

## Cooling car 16

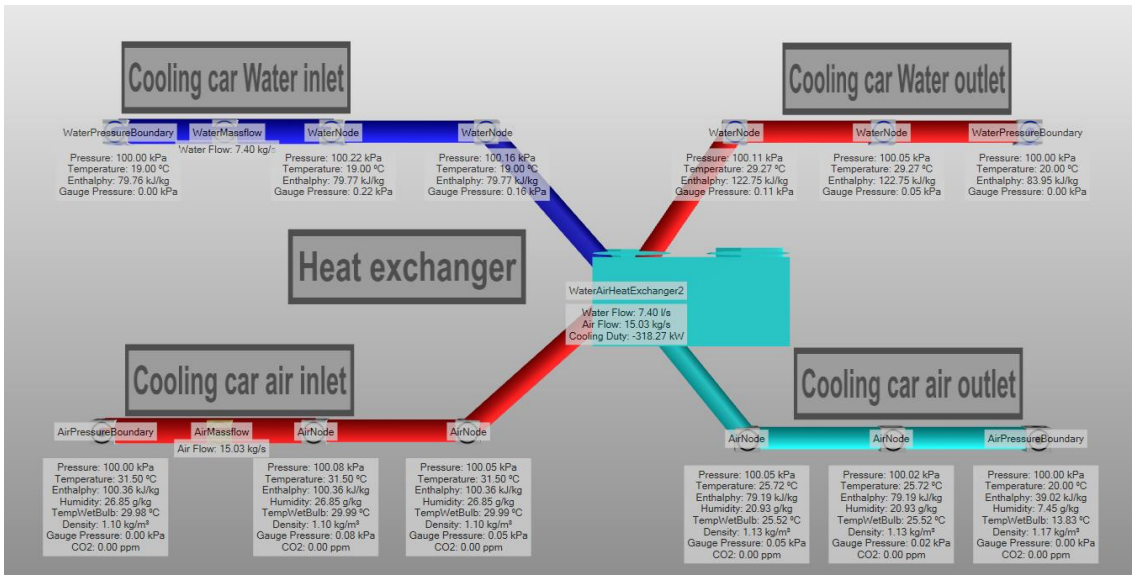



*Figure 90: Cooling car 16 (#C16) calibration model*

## Cooling car 17

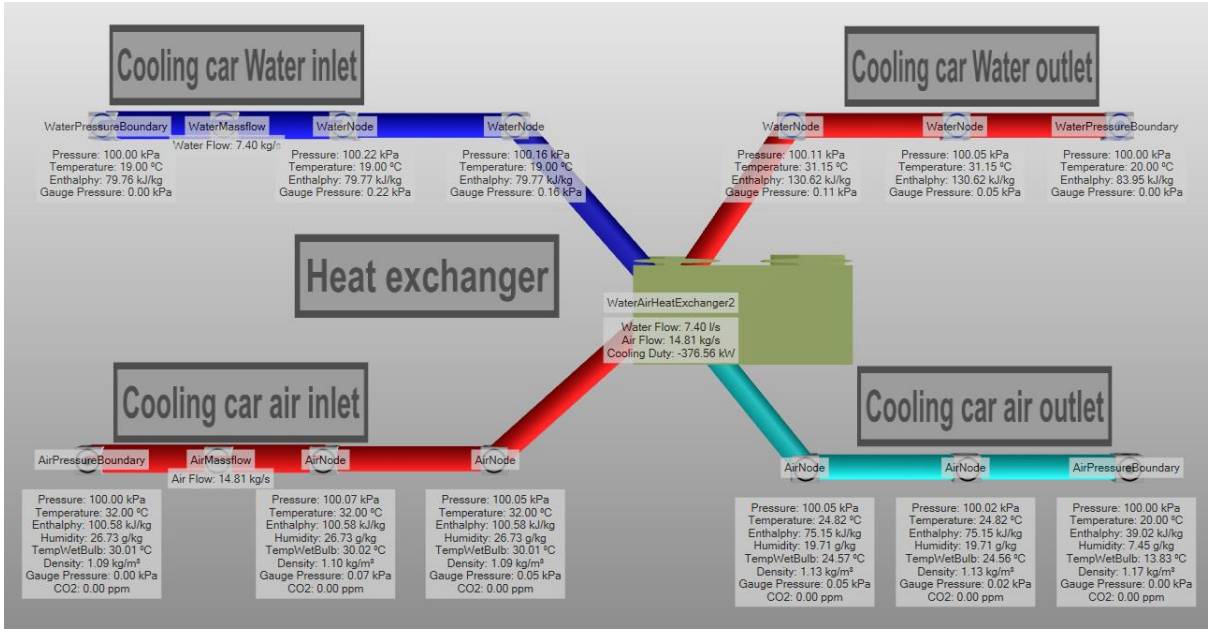



*Figure 91: Cooling car 17 (#C17) calibration model*

# APPENDIX E : MARIC VALVE SELECTION

## APPENDIX E

*Table 23:Maric valve selection*

| | Position | Body Size | Thread Specification | Configuration | Body Material | Control Rubber | Pressure Differential | Check Valve | Flow rate(l/min) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 66 - South dev(@ 38) | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |
| 2 | 66 South Dev(@36) | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |
| 3 | 69 - 75 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 4 | 69 - 71 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 5 | 71 - 73 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 6 | 71 - 74 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 7 | 71 - Haulage South | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |
| 8 | 73 - Haulage South | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |
| 9 | 73 - 40 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 10 | 73 - 38 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 11 | 73 - 37 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 12 | 75 - RAW North(77 X/Cut) | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |
| 13 | 75 - 75 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 14 | 75 - 44 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 15 | 75 - 43 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 16 | **75 - 41 X/Cut** | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 17 | 75 - 40 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 18 | 75 - 38 X/Cut | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 210 |
| 19 | 75 - RAW South | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |
| 20 | 75 - RAW South | 50mm | BSP | F&F | Brass/PVC | E7 | 170-2000 kpa | H | 342 |

# APPENDIX F: MARIC VALVE QUOTES

## APPENDIX F

ULTRA CONTROL VALVES

ULTRA CONTROL VALVES cc
Cell: +27 (0)83 458 8053
Tel: +27 (0)11 452 6514
Fax: +27 (0)86 547 0555
email: peter@ultravalves.co.za
www.ultravalves.co.za

CK No: CK2005009095/23
VAT No: 4410224077

Quotation

| | | | |
|---|---|---|---|
| **Att:** | Manchala Sithole | **DATE:** | 01.04.2019 |
| **Company:** | ETA Operatios | **Quotation No:** | UQDG19-1158 |
| **Address:** | | **E.Mail:** | don@ultravalves.co.za |
| **City:** | | | |
| **Phone:** | | | |

**Comments or Special Instructions:**

| SALES PERSON | | Delivery | SHIP DATE | SHIP VIA | F.O.B. POINT | TERMS |
|---|---|---|---|---|---|---|
| D. Green | | 4 to 5 weeks | Collection | | | |

| QUANTITY | SIZE | DESCRIPTION | UNIT PRICE | AMOUNT |
|---|---|---|---|---|
| 11 | 50mm 3 orifice | Maric flow control valves BSP Female screwed PVC | R4 835.22 | R53 187.42 |
| 11 | 50mm 3 orifice | Maric flow control valves BSP Female screwed Brass | R5 905.61 | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | | |
| | | | SUB TOTAL | R53 187.42 |
| | | | VAT 15% | R7 978.11 |
| | | | OTHER | R0.00 |
| | | | **TOTAL** | R61 165.53 |

**Terms and Conditions**

* Prices: - Ultra Control Valves prices are ex-works, unless otherwise arranged
* Delivery dates are subject to situations beyond our control i.e. Labour strikes, Shipping delays etc and subject to prior sale
* Validity: - Our quotation is valid for 30 days from quotation/email date for quote, unless otherwise stated
* Discount terms are strictly for 30 day payments
* Ex-stock items are subject to prior sale
* VAT: - All prices quoted are excluding VAT
* Payment Terms:- 30 Days from date of statement for Account Holders, otherwise C.O.D
* Please place the quotation number on your order for reference
* Cancellation Policy:- Orders placed for non UCV products are not returnable unless otherwise agreed
  UCV products are subject to a 20% handling fee.
* Ownership:- Goods remain the property of Ultra Control Valves until payment in full has been received.
* Transportation of goods is the sole responsibility of the Purchaser.

*Figure 92: Maric flow valve quotes*

# APPENDIX G : PROJECT MANAGEMENT

## APPENDIX G

*Table 24:Implementation timeline*

| Phakisa Cooling Car Implementation timeline | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Cooling Cars** | **Responsible forman** | **Fitter** | **Component Created** | **Joint Position** | **Design date** | **Valve Type** | **Installation Date** | **Testing date** | **Satifaction** | **Complete/sign off** |
| **66 - South dev(@ 38)** | Zuki | Zuki | Inlet Joint | Cooling Car Inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **66 South Dev(@36)** | Zuki | Zuki | Inlet Joint | Cooling Car Inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **69-38 X/Cut** | Zuki | Zuki | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **69 - 75 X/Cut** | Zuki | Zuki | T-joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **69 - 71 X/Cut** | Zuki | Zuki | T-joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **71 - 73 X/Cut** | Zuki | Zuki | T-joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **71 - 74 X/Cut** | Zuki | Zuki | T-joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **71 - Haulage South** | Zuki | Zuki | Inlet Joint | Cooling Car inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **73 - Haulage South** | Rui | Patric | Inlet Joint | Cooling Car inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **73 - 40 X/Cut** | Rui | Patric | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **73 - 38 X/Cut** | Rui | Patric | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **73 - 37 X/Cut** | Rui | Patric | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Install Valve | |
| **75 - RAW North(77 X/Cut)** | Rui | Lucky | Inlet Joint | Cooling Car Inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **75 - 75 X/Cut** | Rui | Lucky | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **75 - 44 X/Cut** | Rui | Lucky | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| 75 - 43 X/Cut | Rui | Lucky | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Cooling Car Out | |
| **75 - 41 X/Cut** | Rui | Lucky | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **75 - 40 X/Cut** | Rui | Lucky | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **75 - 38 X/Cut** | Rui | Lucky | T-Joint | Cooling Car Outlet | 11-Jul-19 | 1 hole valve | 15-Jul-19 | 19-Jul-19 | Install Valve | |
| **75 - RAW South** | Rui | Lucky | Inlet Joint | Cooling Car inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| **75 - RAW South** | Rui | Lucky | Inlet Joint | Cooling Car inlet | 11-Jul-19 | 3 hole valve | 15-Jul-19 | 19-Jul-19 | Not Started | |
| Bad | | | | | | | | | | |
| Good | | | | | | | | | | |
| Not Clear | | | | | | | | | | |

*Table 25: Cooling car baseline plan*

| Cooling Car Baseline Audit Plan | | | | | | |
|---|---|---|---|---|---|---|
| **Task** | **Date initiated** | **Number of hours** | **Shift** | **Time In** | **Time Out** | **% Progress** |
| Week 1 (01/29/2019-02/01/2019) | | | | | | |
| 75L Cooling Car Audit | 01/29/2019 | 7 hours | Morning | 05:00 | 12:00 | 100% |
| 75L RAW North Audit | 01/30/2019 | 7 hours | Morning | 05:00 | 12:00 | 100% |
| 75L RAW South Audit | 01/31/2019 | 7 hours | Morning | 05:00 | 12:00 | 100% |
| 73L South Development Audit | 02/01/2019 | 7 hours | Morning | 05:00 | 12:00 | 100% |
| Week 2 (02/11/2019-02/15/2019) | | | | | | |
| 71L Cooling Car Audit | 02/05/2019 | 8 hours | Morning | 05:00 | 12:00 | 100% |
| 71L South Development Audit | 02/06/2019 | 8 hours | Morning | 05:00 | 12:00 | 100% |
| 69L Cooling Car Audit | 02/07/2019 | 8 hours | Morning | 05:00 | 12:00 | 100% |
| 66L Cooling Car Audit | 02/08/2019 | 8 hours | Morning | 05:00 | 12:00 | 100% |

*Table 26: Cooling car auditing plan*

| Phakisa Cooling Car Project Plan | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Task | Investigation Report | Due date | Date Completed | Audit Plan | Due date | Date Completed | Audit | Due date | Date Completed | Capturing of Results | Due date | Date Completed | Analysis of Results | Due date | Date Completed | Results feedback and Report | Due date | Date completed |
| | | | | | | | | | | | | | | | | | | |
| 75L Cooling Car Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/29/2019 | 01/30/2019 | 100% | 02/15/2019 | 02/18/2019 | 10% | 02/18/2019 | | 0% | 02/22/2019 | |
| 75L RAW North Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 02/05/2019 | 02/06/2019 | 100% | 02/15/2019 | 02/18/2019 | 10% | 02/18/2019 | | 0% | 02/22/2019 | |
| 75L RAW South Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/31/2019 | 01/31/2019 | 100% | 02/15/2019 | 02/18/2019 | 10% | 02/18/2019 | | 0% | 02/22/2019 | |
| 73L South Development Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 02/06/2019 | 02/07/2019 | 100% | 02/15/0219 | 02/18/2019 | 10% | 02/18/2019 | | 0% | 02/22/2019 | |
| | | | | | | | | | | | | | | | | | | |
| 71L Cooling Car Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 02/12/2019 | 02/12/2019 | 100% | 02/18/2019 | 02/20/2019 | 0% | 02/19/2019 | | 0% | 02/22/2019 | |
| 71L South Development Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 02/13/2019 | 02/13/2019 | 100% | 02/18/2019 | 02/20/2019 | 0% | 02/19/2019 | | 0% | 02/22/2019 | |
| 69L Cooling Car Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 02/14/2019 | 02/14/2019 | 100% | 02/18/2019 | 02/20/2019 | 0% | 02/19/2019 | | 0% | 02/22/2019 | |
| 66L Cooling Car Audit | 100% | 01/25/2019 | 01/25/2019 | 100% | 01/25/2019 | 01/25/2019 | 100% | 02/14/2019 | 02/14/2019 | 100% | 02/18/2019 | 02/20/2019 | 0% | 02/19/2019 | | 0% | 02/22/2019 | |

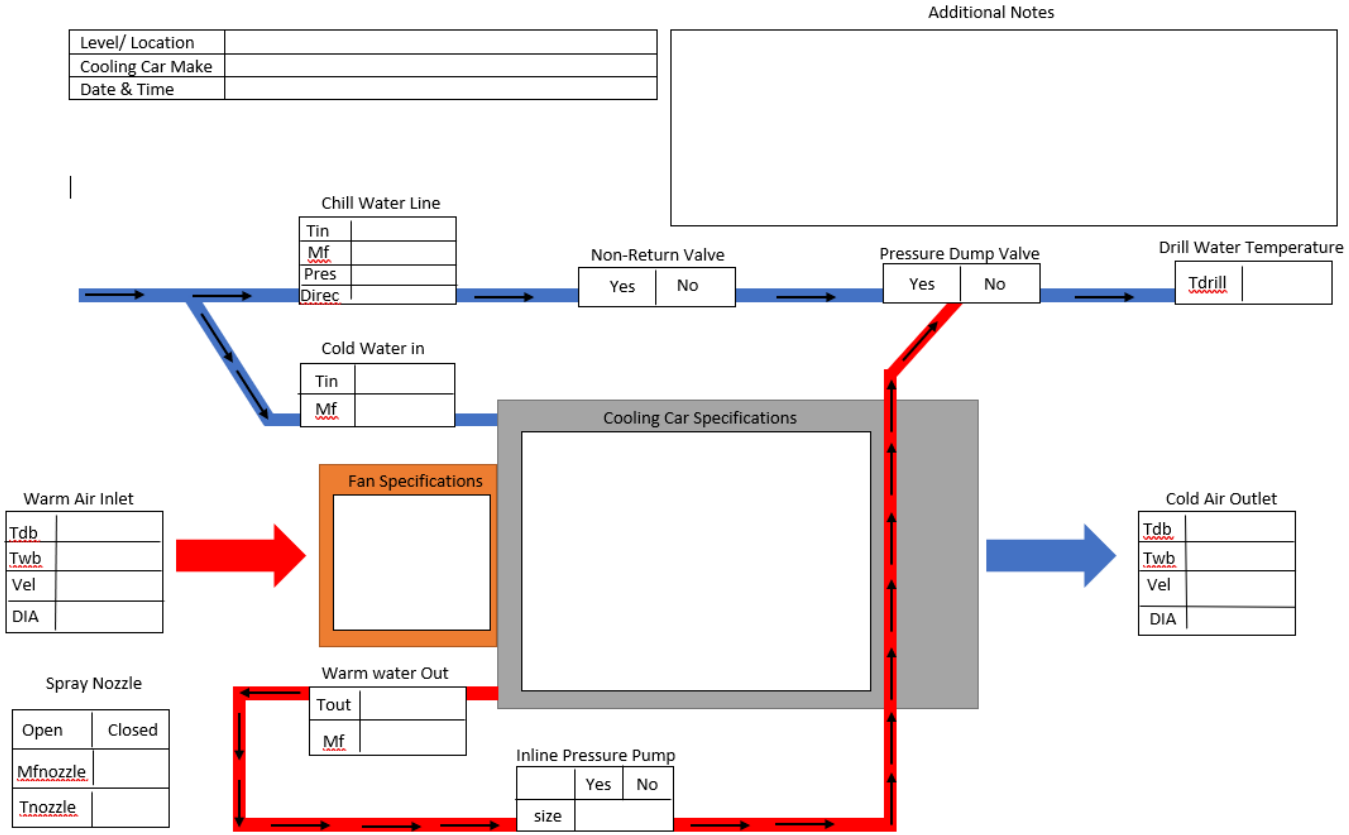



*Figure 93: Cooling car Audit template*

# APPENDIX H : IMPLEMENTATION MEASUREMENTS

## APPENDIX H

*Table 27:Implementation measurements:*

| | Position | Fan Size | last Flow Rate | Water flow rate | Dumping | Water inlet | Water Outlet | Dtwater | Water duty | Air flow | Wetb in | Dryb in | Wetb out | Dryb Out | Wetb Diff | Dry b diff | Induced | Tsurface | Enthalpy in | Enthalpy Out | diff | Air Duty | Heat Transfer efficiency |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 66 South Dev(@36) | 22 | 5 | 3.5 | 3.5 | 17 | 25.8 | 8.8 | 129 | 12 | 29 | 29.5 | 24 | 24 | 5 | 5.5 | -1.5 | 23.4 | 90955 | 69561 | 21395 | 257 | 50 |
| 2 | 69L X/c 71 | 45 | 15 | 7 | 4 | 13.5 | 29 | 15.5 | 454 | 13 | 34.5 | 34 | 26.5 | 26.5 | 8 | 7.5 | -1 | 25 | 116014 | 78693 | 37321 | 485 | 93 |
| 3 | 69 x/c75 | 45 | 7.8 | 5.9 | 5.9 | 19 | 27 | 8 | 197 | 13 | 34 | 36 | 26.5 | 27 | 7.5 | 9 | -1 | 26 | 115920 | 78669 | 37251 | 484 | 41 |
| 4 | 71 - Haulage South | 45 | 20 | 5.9 | 5.9 | 20 | 25.8 | 5.8 | 143 | 13 | 28 | 29 | 25.5 | 26 | 2.5 | 3 | -1.9 | 24.7 | 84628 | 74089 | 10539 | 137 | 104 |
| 5 | 73 - Haulage South | 45 | 15 | 5 | 5 | 13.4 | 23.1 | 9.7 | 203 | 13 | 27 | 28.5 | 24 | 24.5 | 3 | 4 | -1.8 | 22 | 79749 | 67858 | 11891 | 155 | 131 |
| 6 | 73 - 38 X/Cut | 45 | 6.5 | 3 | 3 | 13 | 24.5 | 11.5 | 144 | 13 | 29 | 29 | 25 | 26 | 4 | 3 | -2.5 | 24 | 88671 | 71650 | 17021 | 221 | 65 |
| 7 | 73 - 37 X/Cut | 22 | 2.5 | 5 | 2 | 14 | 24 | 10 | 209 | 12 | 28 | 29 | 21.5 | 22 | 6.5 | 7 | -1.3 | 20 | 84101 | 58980 | 25121 | 301 | 69 |
| 8 | 75 - RAW North(77 X/Cut) | 45 | 6.1 | 3 | 3 | 19.3 | 26.7 | 7.4 | 93 | 13 | 30 | 30 | 25 | 26 | 5 | 4 | -1.5 | 24 | 93391 | 71650 | 21741 | 283 | 33 |
| 9 | 75 - 75 X/Cut | 45 | 6.1 | 8 | 8 | 18 | 22.5 | 4.5 | 150 | 13 | 27 | 27.5 | 21.5 | 22 | 5.5 | 5.5 | -1.5 | 20 | 79797 | 58980 | 20817 | 271 | 56 |
| 10 | 75 - 41 X/Cut | 45 | 0 | 5.61 | 3 | 14.5 | 22.5 | 8 | 188 | 13 | 25 | 28 | 21 | 22 | 4 | 6 | -1.4 | 19 | 71561 | 57291 | 14270 | 186 | 101 |
| 11 | 75 - 40 X/Cut | 45 | 9.7 | 4.226 | 3.1 | 18.6 | 26 | 7.4 | 131 | 13 | 26.5 | 29 | 24 | 24.5 | 2.5 | 4.5 | -1.5 | 23 | 77606 | 67858 | 9749 | 127 | 103 |
| 12 | 75 - 38 X/Cut | 45 | 4 | 5.36 | 3.5 | 21.5 | 27.9 | 6.4 | 143 | 13 | 30 | 32.5 | 25.5 | 26 | 4.5 | 7 | -1.5 | 27 | 93255 | 73640 | 19616 | 255 | 56 |
| 13 | 75 - RAW North left | 45 | 7.4 | 5.9 | 5.9 | 14 | 29.1 | 15.1 | 372 | 13 | 30.5 | 32 | 24.5 | 24.5 | 6 | 7.5 | -2.5 | 23 | 95746 | 69767 | 25980 | 338 | 110 |
| 14 | 75-RAW North Right | 45 | 7.4 | 5.9 | 5.9 | 14 | 29.1 | 15.1 | 372 | 13 | 30.5 | 32 | 24.5 | 24.5 | 6 | 7.5 | -1.5 | 24 | 95746 | 69767 | 25980 | 338 | 110 |