Analysing the impact of pre-cooling on mine refrigeration systems

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ABSTRACT

Title: Analysing the impact of pre-cooling on mine refrigeration systems

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Globally the mining sector is facing a harsh economic climate, with sharp increases in production costs and decreased productivity. In South Africa the situation is worsened by the continuous increase in labour and electricity costs. The South African mining sector consumes close to 15% of the total electricity supply, which contributes to 30% of their operational costs. Refrigeration systems are one of the largest energy consumers on mines, accounting for 28% of a mines total power usage.

As development expands deeper underground the cooling requirements increases. There is a clear need to improve the efficiency of the existing refrigeration system infrastructure. The main focus of most studies lies on the energy intensive refrigeration plants; however, they form only a small part of the mine cooling system. Pre-cooling plays a vital role in the efficiency of the cooling system. There is also a lack of maintenance on cooling towers, creating the possibility to investigate the impact that Pre-cooling towers have on the whole cooling system.

This dissertation investigates the effect Pre-cooling towers have on mine refrigeration systems. Specifically, how deteriorated pre-cooling negatively effects the performance of refrigeration system compared to the optimal operating conditions. This was done by identifying ineffective pre-cooling, developing an optimised solution and implementing the solution on mine refrigeration systems.

Implementation of the proposed solution resulted in an observed increase in the pre-cooling efficiency. The improvement in efficiency can lead to a reduction in the operation cost of the refrigeration system. It must however be noted that mines which exceed their cooling capacity will not experience a reduction in their refrigeration system's operational costs. They will, however, experience an increase in their cooling ability. The case study showed a reduction of 6.7°C on the chill dams. The energy savings and operational improvements are subjected to external factors such as the ambient conditions and water usage.

It can therefore be concluded that, through improving the efficiency of the cooling towers, the overall performance of a mine’s refrigeration system can be improved along with an associated reduction in the operational costs. The focus after optimisation must however be on continued maintenance of the pre-cooling towers in order to derive a sustainable benefit.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF SYMBOLS

#	Denotes a mining shaft
$	United States Dollar
%	Percentage
C_p	Specific heat capacity of water
η	Efficiency
h	Enthalpy
m	Mass flow
P	Electrical power
Q	Heat
R	South African Rand
ρ	Density
t	Temperature
U	Overall heat transfer coefficient
v	Volume
K	Overall mass transfer coefficient
a	Area of water interface per unit volume
W	Absolute humidity
E	Evaporation loss
M	Circulating cooling water
C	Cycle of concentration

LIST OF UNITS

°C	Degrees centigrade
K	Kelvin
kg/m^3	Kilogram per cubic metre
kg/s	Kilogram per second
$kg/s \cdot m^2$	Kilogram per second square metres
kJ/kg	Kilojoule per kilogram
kJ/kg·K	Kilojoule per kilogram Kelvin
km	Kilometre
kW	Kilowatt
l/s	Litres per second
m	Metres
m^2	Square metres
m^3	Cubic metres
m^3/h	Cubic metres per hour
MW	Megawatt
Pa	Pascal

LIST OF ABBREVIATIONS

BAC	Bulk air cooler
CCT	Condenser-cooling towers
COP	Coefficient of performance
FP	Fridge Plant
LS	Load shift
EE	Energy efficiency
GDP	Gross domestic product
HVAC	Heating ventilation and air Conditioning
KPI	Key performance indicator
PA	Performance assessment
PCT	Pre-cooling tower
PTB	Process Toolbox by TEMM International®
SCADA	Supervisory control and data acquisition
TES	Thermal energy storage
VFD	Variable frequency drive

Chapter 1

1 Introduction

1.1 South African mining industry

1.1.1 Background

South Africa is a country rich with natural resources. The discovery of gold in the 19th century had an exceedingly important impact on South Africa [1]. The gold produced by South Africa primarily comes from the Witwatersrand reef, which stretches across 400km and is considered as one of the largest deposits in the world.

The Witwatersrand reef is not continuous and covers areas in the Free State, Gauteng and North West as seen in Figure 1. More than two billion ounces of gold has been mined from this reef [2]. The discovery of the Witwatersrand Basin led to the development of cities like Johannesburg and other mining towns like Carletonville, Welkom and Klerksdorp; which contributed to the growth of the South African economy.

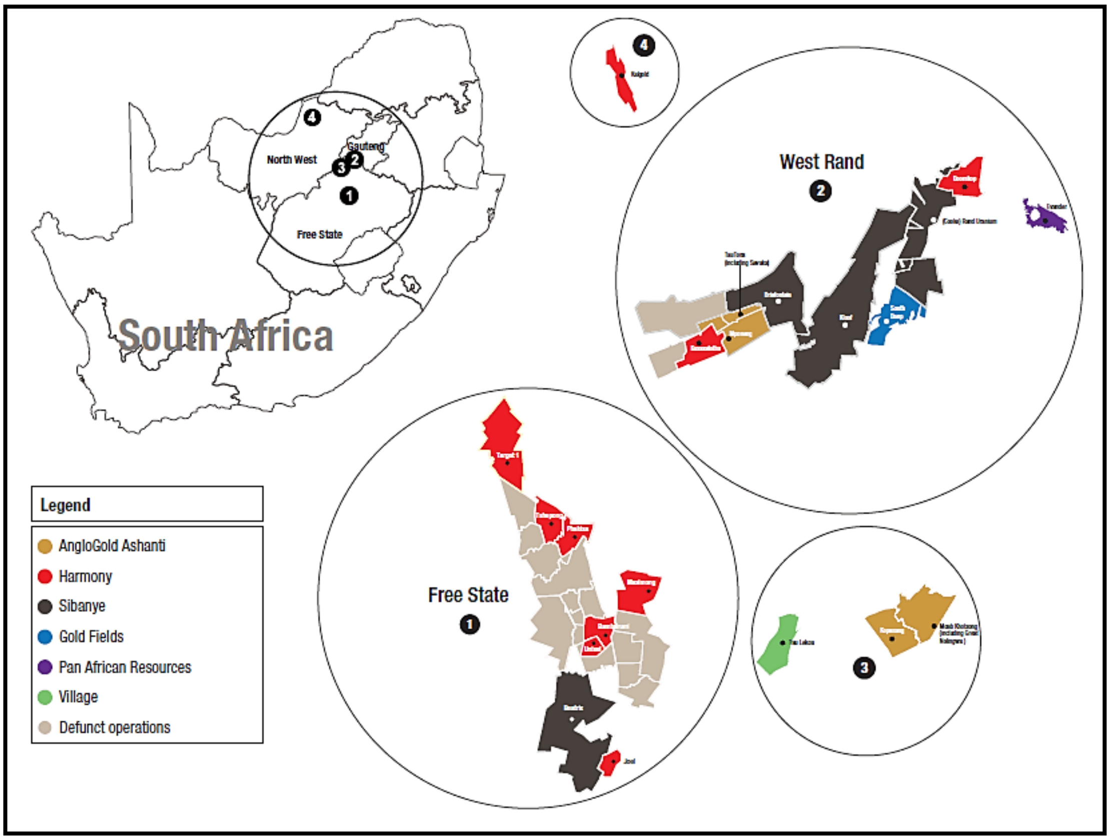


Figure 1 – Gold mining locations within the Witwatersrand Basin [1]

Despite having one of the largest gold deposits in the world, the South African gold production currently only contributed to 5.3% of the global production; making South Africa the sixth largest gold producer in the world in 2015, down from the first position in 2007. Moreover, production has decreased by 87% in January 2015 compared to January 1980 [3]. Figure 2 depicts the significant reduction in production for this period.

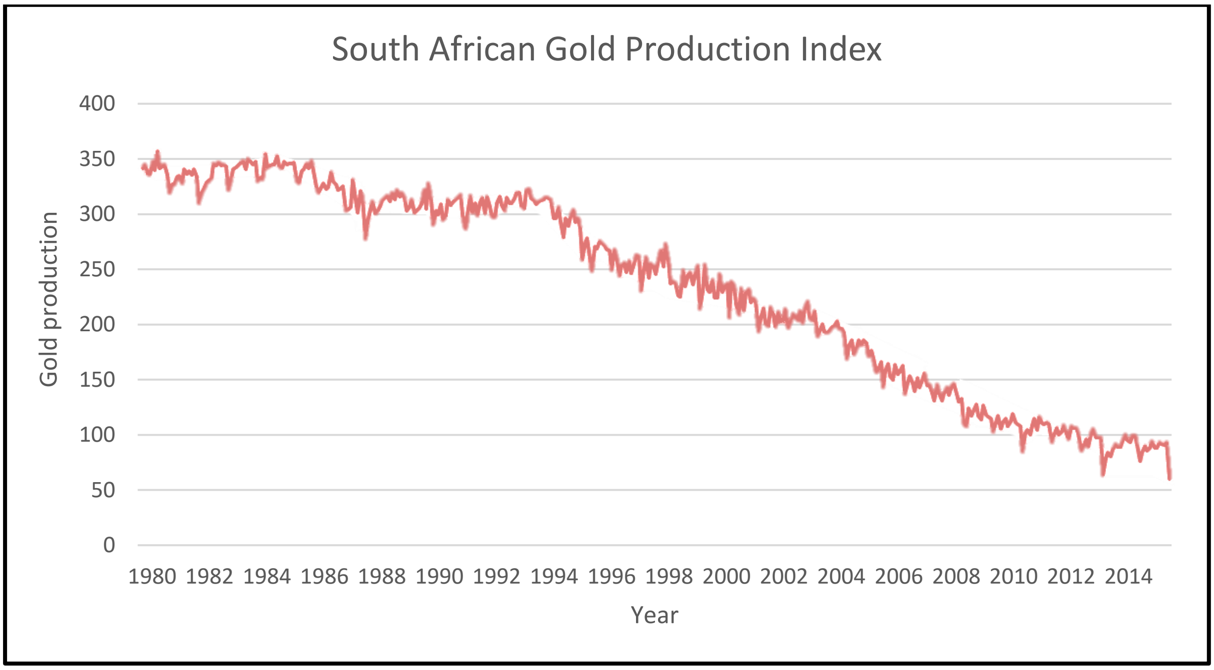


Figure 2 – Yearly gold production from 1980 to 2015 [3]

Consequently, the contribution of gold mining to the South African economy reduced significantly. In 1980 gold made up 67% of all mineral sales, which had reduced to 12.5% in 2014. Gold contributed 3.8% to South Africa’s Gross Domestic Product (GDP) in 1993, which decreased to 1.7% in 2013 [3].

Despite this major decline in gold production, the mining of gold still plays a major role in the South African economy. The industry currently employs approximately one hundred and sixteen thousand people and millions more are directly and indirectly dependent on the industry [1]. It is thus important for gold mining to stay economically viable. The next section gives an overview of the challenges mining faces in the South African environment.

1.1.2 Challenges in the mining industry

An estimated two billion ounces of gold remains underground in South Africa [1]. This was however not reflected in the performance of the South African gold mines in 2017. Figure 3 compares the financial performance of different gold mines in South Africa for the year 2015. Blue indicates a profitable mine, while red shows mines which are operating at a loss. As can be seen from this figure, more than half of the mines were operating at a financial loss, while the profitability of the remainder was marginal.

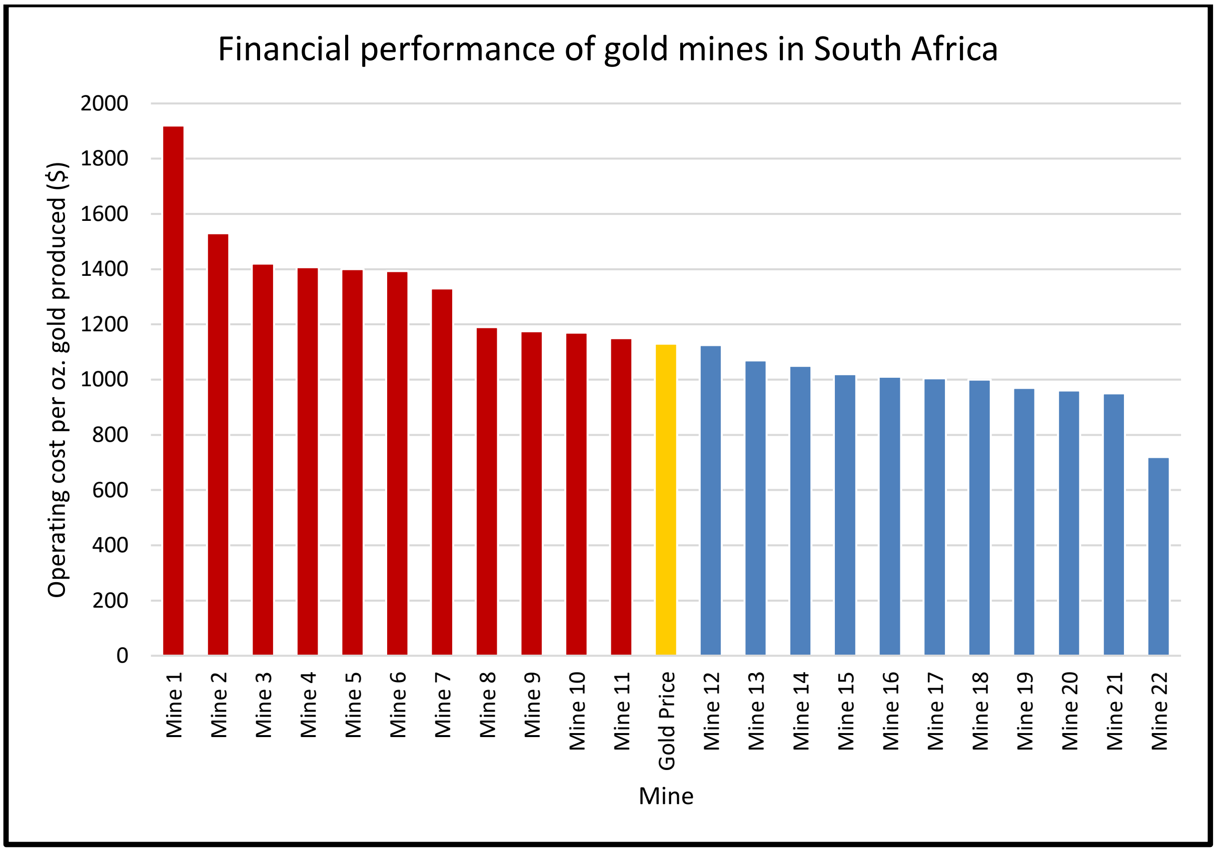


Figure 3 - Financial performance of South African gold mines [2]

The weak financial performance of the South African mining industry is caused by four main challenges. These four main challenges are i) declining gold prices, ii) increased operational costs, iii) declining worker productivity, and iv) a sharp increase in electricity costs.

The gold price had fallen considerably in 2013 as seen in Figure 4. Since then the gold price remained relatively stable at close to $1200 per fine ounce. The reduced gold price was a result of a weak global gold market, mainly caused by reduced Chinese economic growth. [2]

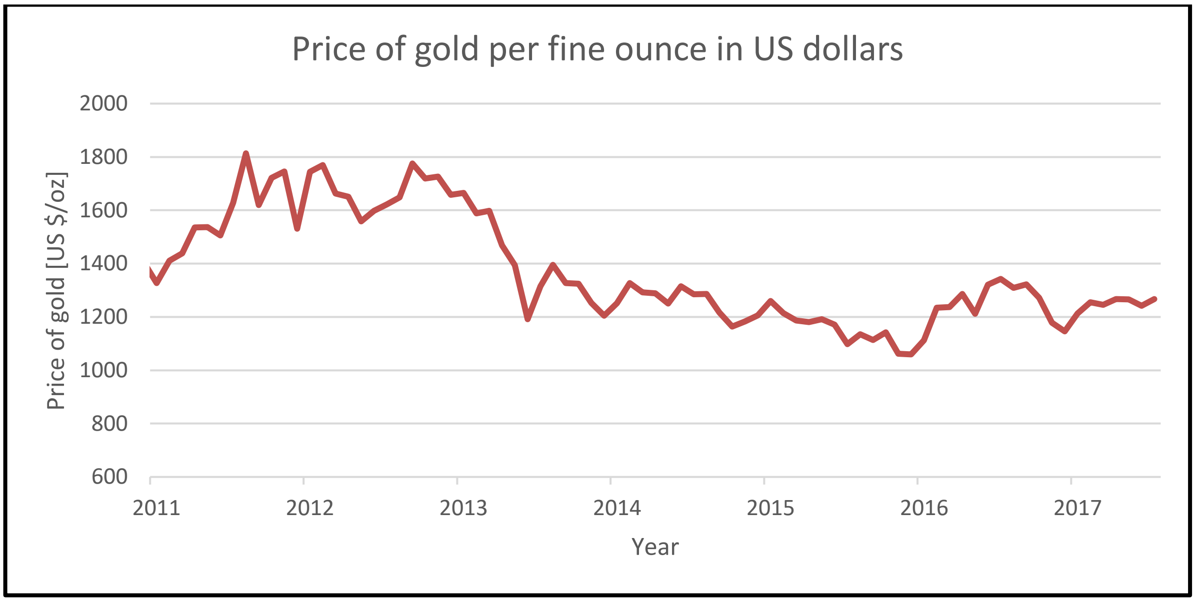


Figure 4 – Gold price in US dollars per fine ounce [4]

While the gold price had decreased, mining operational cost had grown; further reducing the profitability of mining in South Africa. Figure 5 shows the cost inflation on commodities required for gold mining. The increase in operational cost could be attributed to the increase in electricity -, diesel steel and increased labour costs. The focus of the study will however be on the increase in electricity and labour costs.

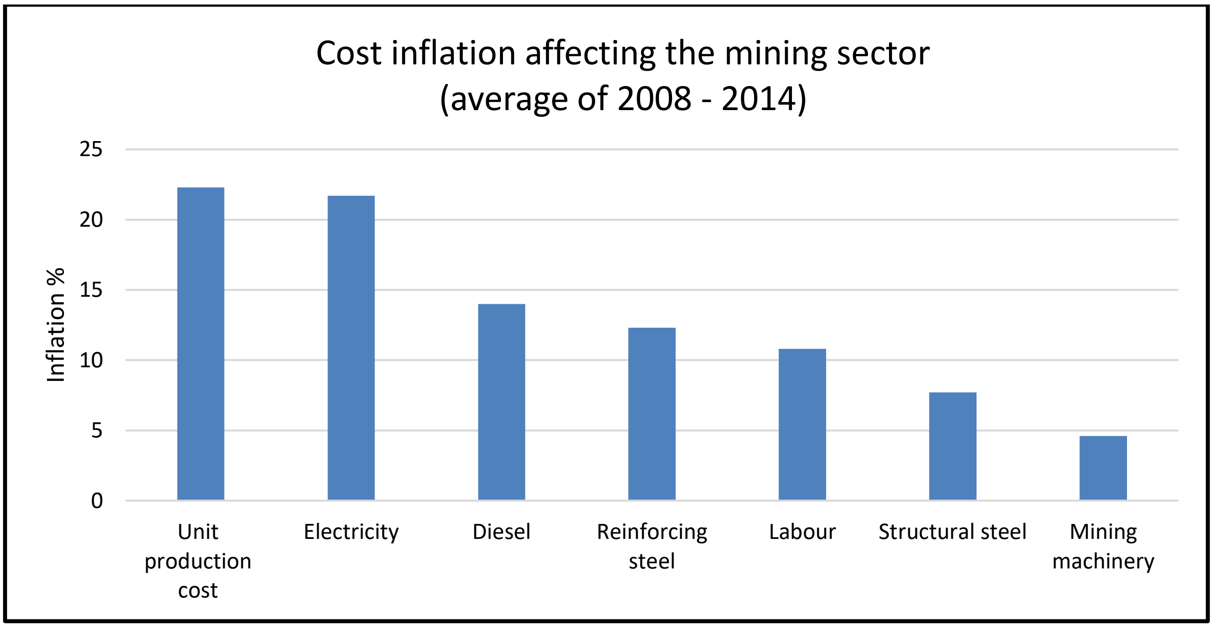


Figure 5 – Cost inflation of various mining expenditure categories [5]

Despite the increase in labour costs, as illustrated in Figure 6, productivity decreased substantially during the last decade. Mining at increased depths also led to a number of challenges; with longer travelling time and harsher working conditions affecting the productivity of the work force [6]. From Figure 6 it could clearly be see that the amount of gold mined per employee had declined. Considering that production occurred on an estimated 274 days of the year, it could be deduced that only two thirds of a day was utilised by mine employees [5].

Figure 6 - Productivity and labour cost per employee [5]

While the productivity of the workers decreased the maintenance on a mine only increase as time passes by. Mining operation can last up to a 100 years. During this period the systems start to deteriorate and the required maintenance increases.

Due to the challenges of mining and ever rising costs, funding for maintenance is limited. Funding for maintenance firstly goes to the crucial components and the capital left over is then used to maintain or replace smaller, less vital components. This often leads to inefficiencies as maintenance is neglected due to both financial constraints and reduced productivity.

Considering the above, it was clear that factors such as price fluctuations and labour costs play an important role in a mine's profitability. However, shifting the focus to reducing operational costs could improve their financial position considerably. The cost of electricity is directly related to the mines usage thereof. There is thus potential to reduce the energy consumption and the operational costs of the mine.

The mining sector in South Africa is dependent on a constant supply of electricity for their mining operations. Figure 7 illustrates the electricity consumption breakdown of South Africa. From this figure it is seen that mining consumed 14.7% of the total electricity demand, of which gold mining consumed almost half [7],[8].

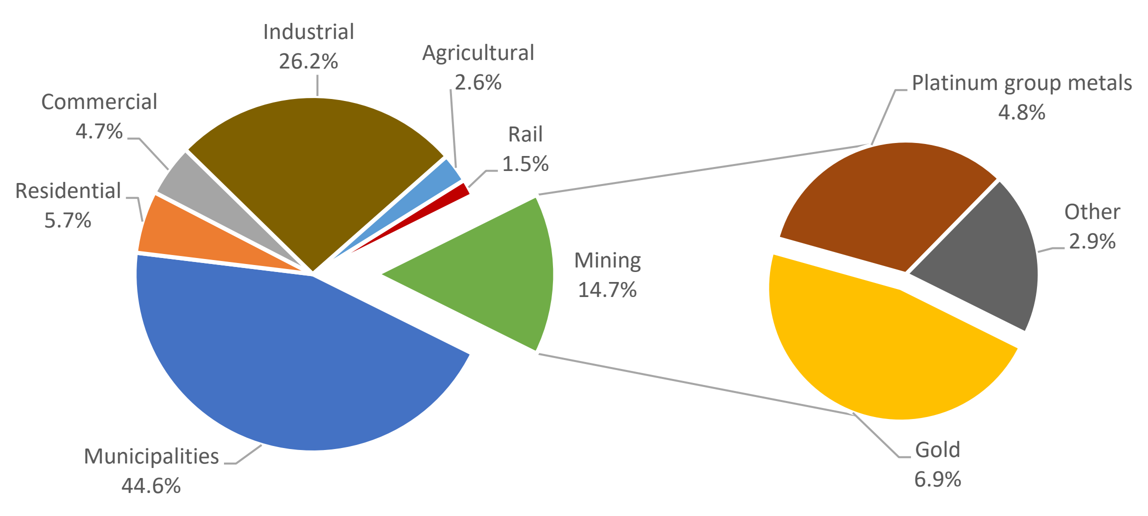


Figure 7 - South African electricity usage breakdown

A typical gold mine had six large energy consumers. As could be seen from Figure 8, these systems were considered to be refrigeration and ventilation, compressed air, dewatering, hoisting, ore processing and loading. Refrigeration and ventilation accounted for 28% of the mine's electricity demand and was thus the largest energy consumer on a typical gold mine. This is due to the high virgin rock temperatures of the rocks being mined underground. A large amount of energy is required to cool the mine and maintain safe working conditions [9].

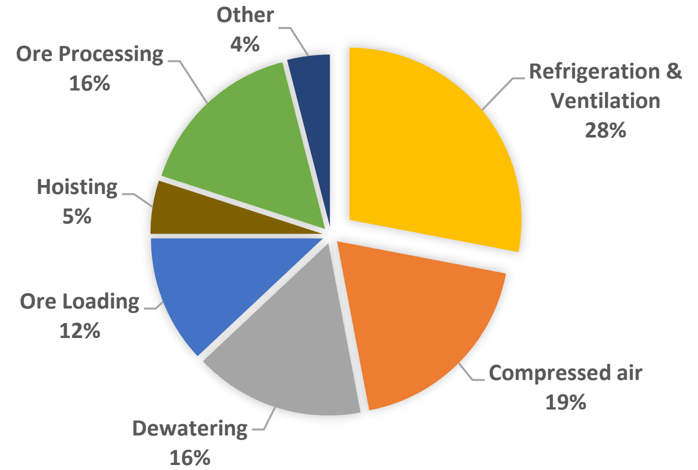


Figure 8 - Gold mine electricity usage breakdown [10]

It is clear that the mining industry in South Africa is struggling to stay competitive. This is due to the many challenges of which increased electricity cost is one of the main challenges. Due to high underground temperatures, large energy intensive refrigeration systems are required. For this reason, refrigeration systems are the largest energy consumers on mines.

1.2 Overview of cooling systems in a mining system

1.2.1 Background

When gold mining first started in South Africa, it was in the form of open pit mines [11]. At the time gold was obtainable through this method due to the shallow nature of the gold reefs. It was not until the early 1900’s that the depletion of the easily accessible reserves led to the need for deep-level mining. The first deep-level mine was sunk to a depth of 800m in 1906. This was the deepest gold mine in the world at the time [11].

Mining was limited to these depths for more than half a century [12]. That was due to high underground temperatures and the risk of toxic gasses like methane [13]. In order to provide a safe working environment at these depths, these mines had to be ventilated. Surface ventilation only proved to be effective up to a depth of 900m where virgin rock temperatures reached up to 32°C [14].

The elevated ambient temperatures had a severe impact on the health and ultimately productivity of the work force, with resulting conditions such as heat exhaustion and heat stroke [15]. Figure 9 shows how the worker performance decreased as the temperatures underground increased.

It was only in 1996 that laws were introduced in the South African mining industry to govern the maximum allowable working temperatures. The Mine Health and Safety act stated that the maximum allowable underground temperatures are 27.5°C at the stations and 32.5°C at the working places [16][17].

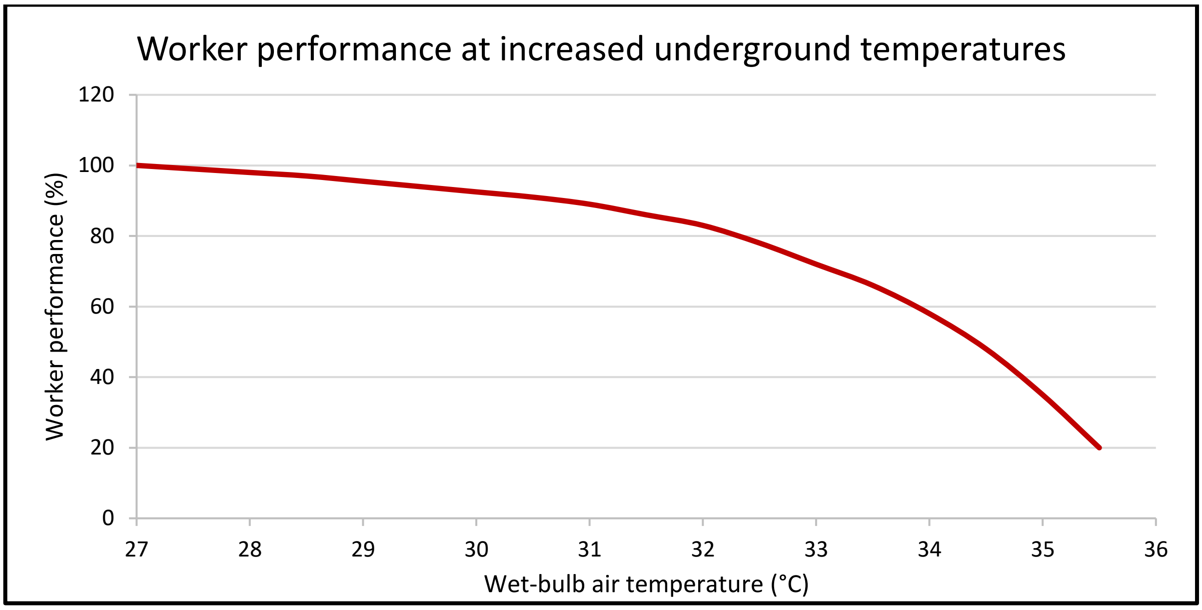


Figure 9 – Worker performance as underground temperatures increases [18]

Figure 10 displays the expected underground temperature at certain depths across mines in South Africa. The study illustrated that underground temperatures increased the deeper mining activities became. From this figure, it is clear that to be able to mine at depths greater than 800m additional cooling was required in order to comply with the mine health and safety act [17].

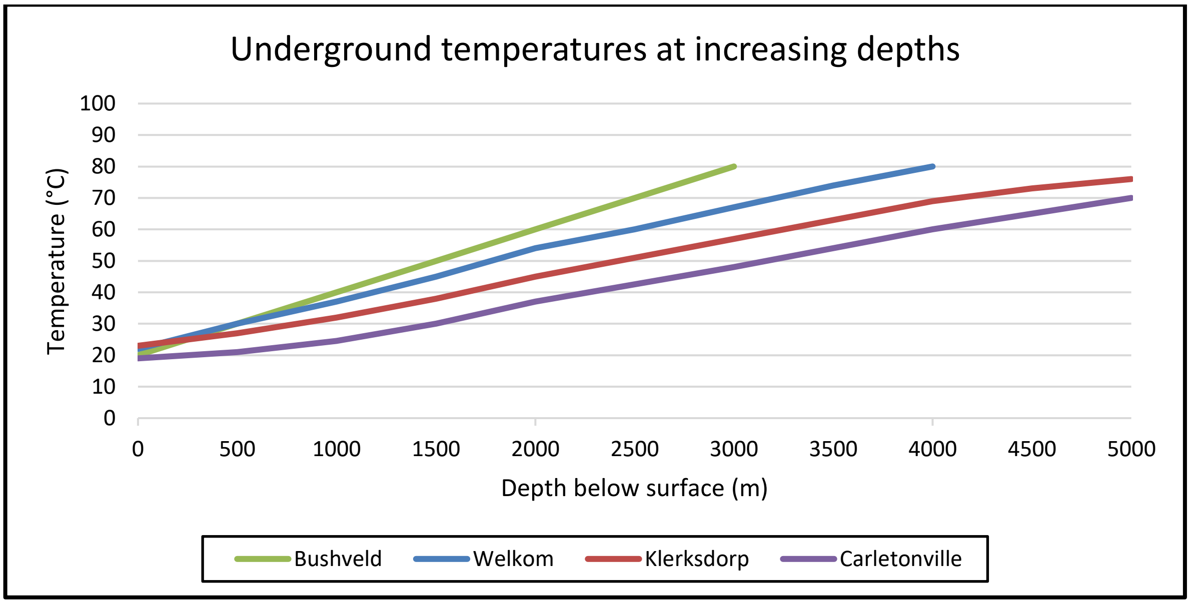


Figure 10 – Expected underground temperatures at increasing depths [19]

The first cooling systems were introduced to the South African mining industry in the 1930's. These cooling systems were however widely adopted in the 1960's after the gold reserves in the shallower reefs were exhausted [13]. Further technological advancements allowed deep-level mining to reach depths of up to 4000m [20]. Figure 11 gives a guideline of the cooling infrastructure required for specific underground depth; based on the anticipated underground temperature.

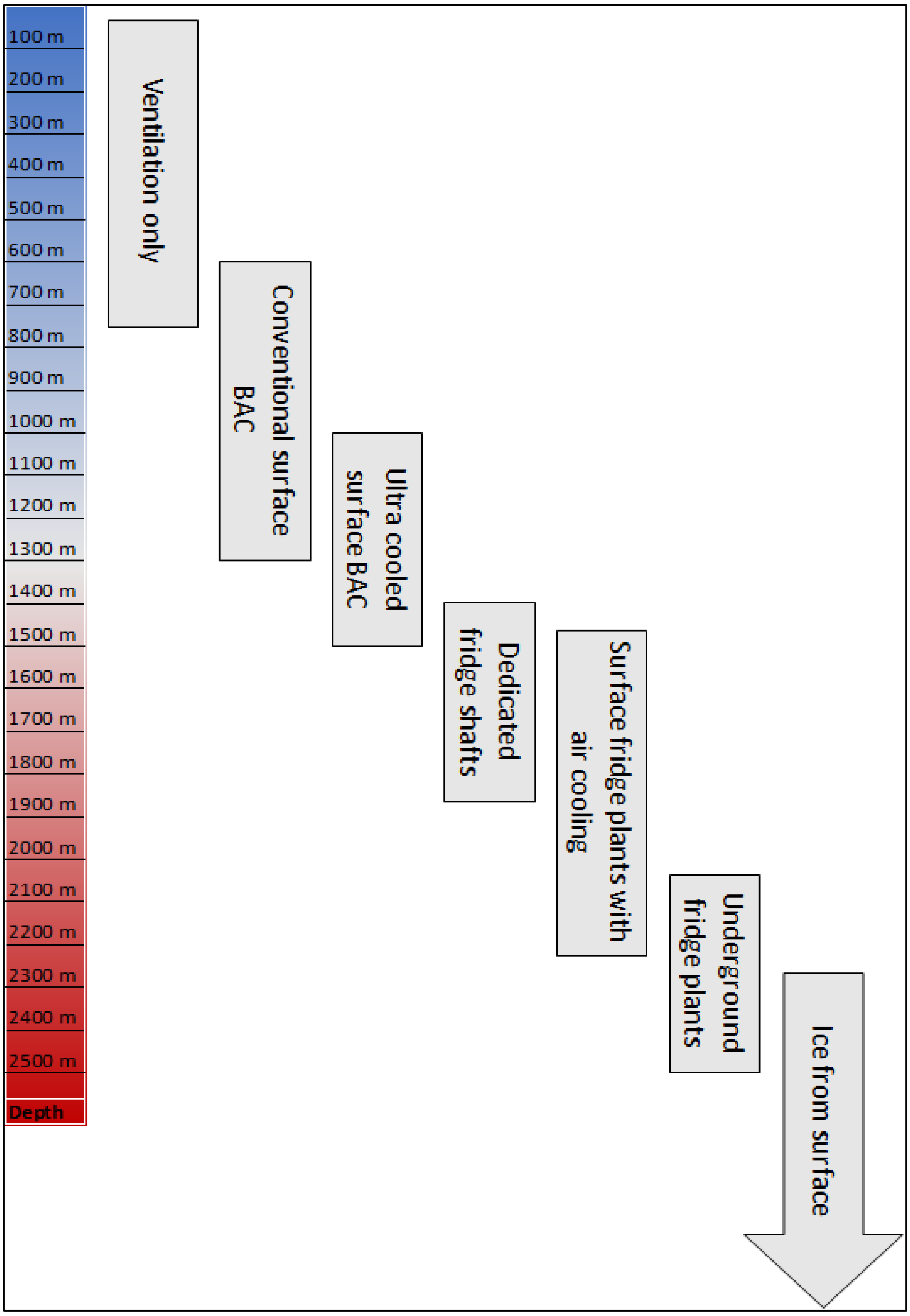


Figure 11 – Required cooling at certain depth below surface [21]

Once an ambient temperature of over 32°C is reached, additional cooling is required [22]. Surface ventilation and bulk air coolers (BAC) were sufficient for depths of up to 1300m [21]. Dedicated surface refrigeration plants are required once these depths are exceeded. Surface refrigeration plants are used to cool down the water supply to the BAC for improved cooling capabilities. The chilled water is then sent underground to cool down the rock face and mining equipment at working areas.

Once greater depths were reached additional underground cooling systems are required. Typical surface refrigeration plant can cool the water down by 15°C, depending on the FP type, efficiency and layout [21].

1.2.2 Existing cooling systems on mines

The basic operation of a typical refrigeration system is shown in Figure 12. The major components of the system are also shown and will be thoroughly discussed throughout the next section.

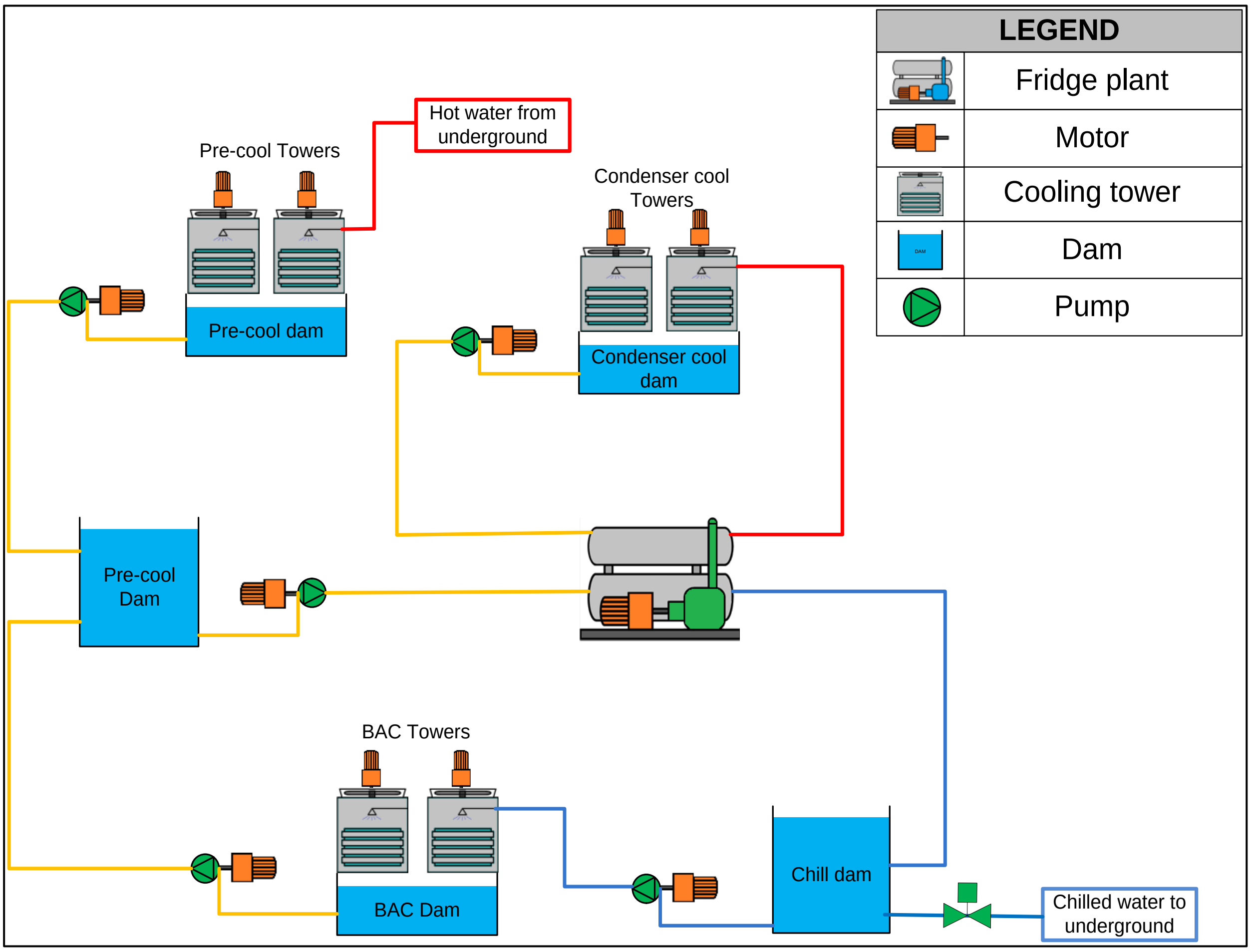


Figure 12 - Simplified refrigeration system [23]

Hot water is pumped from underground up to surface. Once at the surface the cooling process starts as the water is passed through the pre-cooling towers (PCT). PCT work on the principle of evaporation and heat transfer to the environment. The cooling capabilities are dependent on the ambient temperatures. PCT are designed to only cool the water to a minimum of 3°C above the ambient temperature [24].

The typical PCT used in the mining industry is based on induced draft mechanics. This refers to a fan which is used to pull air through the tower to facilitate the heat transfer. Another device used to improve the cooling potential of the tower is the fill. As warm water is sprayed into the tower it passes over a fill. The fill increases the period that heat transfer takes place and increases the surface contact area between the water and air [25]. PCT and their inner workings are discussed in more detail in chapter 2.

Once the water had passed through the PCT it falls to the pre-cool dam. The dam provides water storage capacity for periods when the refrigeration plants are not running at optimum capacity. It also ensures that there is reserve capacity available during periods of reduced underground water supply [26].

Pre-cooled water is transferred from the pre-cool dam to the chiller. It is here that the water is cooled down to the required temperature. This process is energy intensive and is by far the largest energy consumer in this cooling system, consuming up to 66% of the used electricity [27]. The refrigerant of the refrigeration plant is cooled through rapid expansion. Figure 13 indicates the basic layout of the refrigeration cycle.

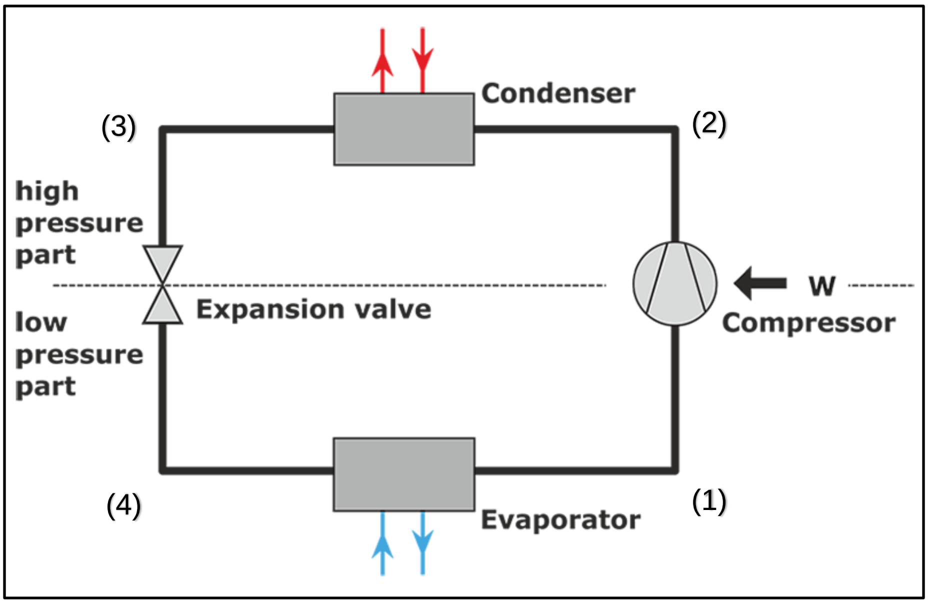


Figure 13 - A basic refrigeration cycle

The refrigerant is compressed under a high pressure by the compressor. Heat is removed from the refrigerant on the condenser side through means of a heat exchanger. As heat is rejected the refrigerant becomes condensed and remains at a high pressure. The refrigerant is then passed through an expansion valve causing a sudden drop in pressure and temperature. The cooled refrigerant is then passed through the evaporator. The heat from the process water is absorbed by the refrigerant through means of the tube in shell heat exchanger [28].

Figure 14 shows the pressure-enthalpy (P-h) diagram of the refrigeration cycle shown in figure 13. This graphically indicates the state changes of the refrigerant as it passes through each component as well as the addition and removal of heat.

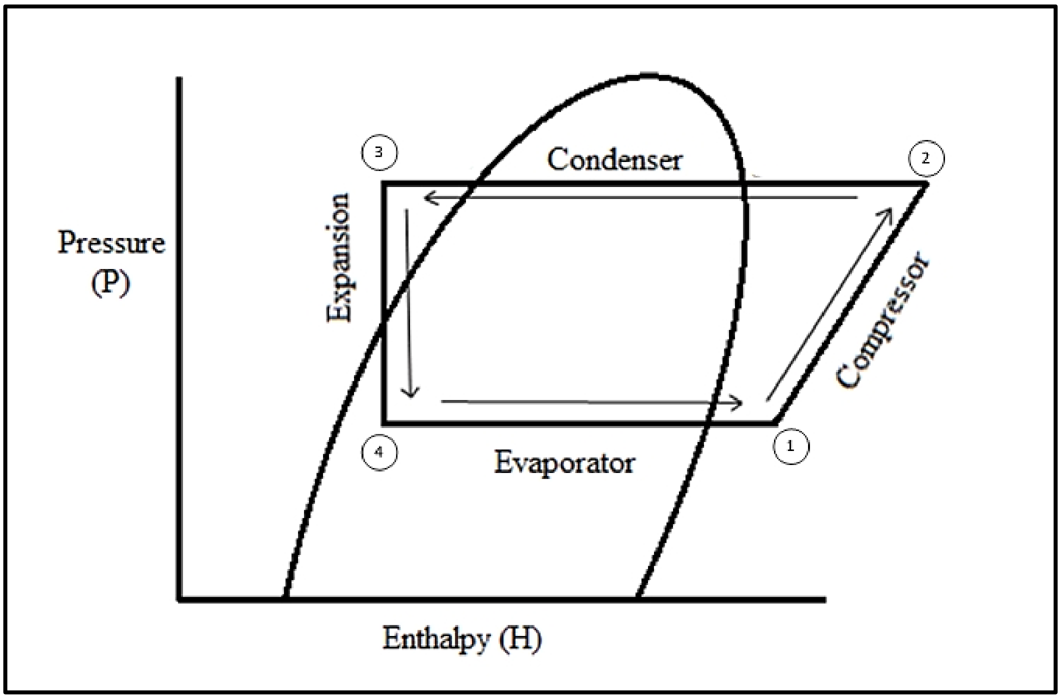


Figure 14 - P-h diagram of a refrigeration cycle [27]

Chillers are used in conjunction with one another to reach the required differential temperature. This allows the mines to configure the chillers as required upon installation. There are three different configurations for chillers in a deep-level mine’s refrigeration system [29], namely:

- Series configuration
- Parallel configuration
- Parallel-series configuration

The deferent configurations are determined according to the mines requirements. For a series configuration, temperature of the outlet water can be varied. For a parallel configuration, the water flow rate can be varied. The parallel-series configuration is most commonly used since this configuration allows for both a variable flow rate and differential temperature to be achieved [29].

Condenser-cooling towers (CCT) are used to cool the warm water on the condenser side of the chiller. Heat is thus absorbed from the refrigerant of the chiller and rejected into the atmosphere. Once the water is passed through the tower it is stored in sump dams and transferred to the condenser side of the chiller, completing the condenser side loop. The principles of CCT are the same as for PCT. The CCT are however designed specifically for the flow rate and thermal load of the chiller's condenser side.

The chilled water from the evaporator is sent to the cold dam. The function of the cold dam is the same as with the pre-cool dam. Here the cold water from the refrigeration plants is stored in the cold dam [26].

Water is transferred from the cold dam to the BAC. The function of the BAC is to cool down the ambient air sent underground for ventilation cooling. The BAC works on the same principle as the PCT and CCT. The function is just reversed as cold water is used to cool down the ambient air. A secondary but also important function is the process dehumidifies the air by condensing water from it. The air is then sent to the shaft through the use of fans. The induced draft due to the surface ventilation fans takes the cold air from the shaft and distributes it throughout the mine. The BAC outlet water is then recirculated to the pre-cool dam to be cooled again.

Pumps are used to transfer water from one system component to the next. These pumps are typically centrifugal pumps with a fixed operating speed. The flow is then controlled with valves. In some cases, pumps are fitted with Variable Frequency Drives (VFDs) to control the delivery flow.

The surface refrigeration systems play an integral part in the mining industry. To provide a greater understanding, the basic operation of the refrigeration system and the components there off were discussed. This information will be used through out to the rest of the chapters.

1.3 Problem statement

Profitable gold mining in South Africa has become increasingly difficult. Challenges such as the decreased gold prices, increased labour and operational costs, as well as low productivity contributed largely to the reduced profit margins. The increased operation costs are partially associated with mining at increased depths, as well as the use of energy intensive equipment.

Mining at increased depths are a result of the continuous search for higher-grade ore. One of the main challenges associated with deep-level mining is the extreme underground temperatures. While there are cooling systems used to reduce the underground temperatures, a lot more can be done to improving the efficiency of these systems.

The use of PCT is an efficient means to reduce the load on the cooling system. PCT provide significant cooling for the amount of electricity needed. With passing time and constant usage, the performance of the pre-cool towers deteriorates. This in return has an adverse effect on the refrigeration system.

There is thus a clear need to identify deteriorated pre-cool towers, methodically improve their performance and to show the impact of this on the mine refrigeration system.

1.4 Objectives of study

During the introduction, it was illustrated that pre-cooling plays a vital role in the efficiency of the cooling system. However, cooling towers are maintenance intensive and are often over looked as an integral part of the cooling system. The main objective of this dissertation is to investigate the effect of PCT on mine refrigeration systems. Specifically, how the deterioration of pre-cooling systems affects the performance of refrigeration plants in comparison to the optimal operating conditions. This was done through deploying the proposed solution on a mine at which instances of ineffective pre-cooling had been observed.

The proposed solution will aim to achieve the following objectives:

- Identification of inefficient pre-cooling towers
- Identifying the impact on the refrigeration system,
- Improving service delivery, and/or
- Reducing operational cost.

1.5 Dissertation outline

Chapter 1: Gives a high-level overview of the gold mining history in South Africa. This highlights the deteriorated performance of the mining industry. Challenges mines face are identified and discussed. The reduction of electricity usage is identified as a possible means to increase profitability, specifically the energy consumption on the cooling systems. Research was proposed to be conducted on existing mine cooling technologies. Lastly, the problem statement and research objective were formulated.

Chapter 2: Cooling towers are discussed in this chapter. The different types and the components of cooling towers used in the mining industry are examined. Common problems of these types of towers were examined. The mathematical modelling, as well as the fundamental formulas, used to evaluate the cooling systems performance were researched. An overview of existing studies and technologies in the field were researched. Lastly, the advantages of simulation software were given and software used in this dissertation was discussed.

Chapter 3: A methodology was developed to identify and analyse the effect of pre-cooling on the refrigeration system. The methodology involved identifying ineffective pre-cooling, development of an optimised solution and implementing the solution on mine refrigeration systems. The information stated in chapters 1 and 2 was used as the basis in the development of the methodology.

Chapter 4: The methodology developed in chapter 3 was used to analyse the effect of pre-cooling on the refrigeration system. Ineffective pre-cooling was identified and characterised. A solution is developed with the application of simulation software. The simulation was validated. The solution was implemented on a mine cooling system and the effects thereof noted.

Chapter 5: Gives a conclusion of the dissertation by summarising the findings from the results obtained in chapter 4. Finally, recommendations are given for future research opportunities within this field.

Chapter 2

2 Pre-cooling in the mining environment

2.1 Introduction

Chapter 1 showed that the mining industry is struggling to stay economically viable. This is due to rising operational costs, of which electricity price increase is a major concern. The refrigeration system is one of the largest energy consumers on a mine, making it an ideal focus point for energy reduction initiatives.

PCT are used to cool down the hot water from underground before it enters the refrigeration system. Decreasing the differential temperature required of the refrigeration system greatly reduces the energy needed by the refrigeration system. PCT affect the whole system as the water passes through the towers before entering the refrigeration system. An example of PCT on an operating mine can be seen in Figure 15.

Figure 15 - Cooling tower example

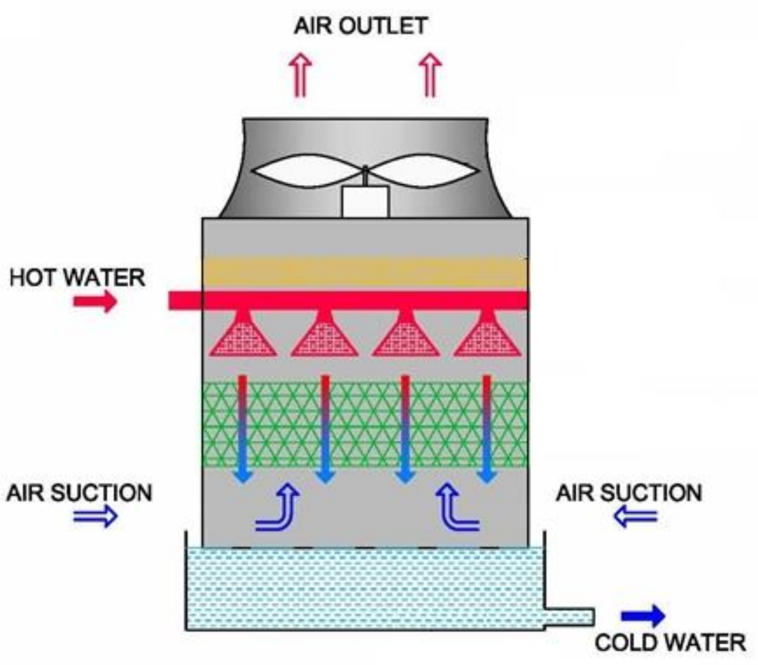
To understand the complete effect that PCT have on a specific refrigeration system, it is important to first understand the operation and dynamics of cooling towers. This chapter will therefore focus on the cooling tower operations, how to measure the performance, identify common problems, as well as the mathematics behind the cooling towers. Previous studies will also be looked at to identify the shortcomings of these studies and how they contributed to this dissertation.

2.2 Pre-cooling concept in mines

PCT are used to remove process waste heat from the system and rejects the heat to the atmosphere. Cooling towers work on the principle of evaporation and convection [13]. Some of the water is evaporated into the air stream and discharged into the atmosphere. As a result, the water is cooled down significantly [30][31].

Figure 16 shows the flow of both the air and water through the cooling tower. Hot water is distributed evenly at the top of the tower and allowed to flow to the bottom. At the same time ambient air moves in the opposite direction through the tower allowing heat transfer to take place [32]. Important factors that affects the cooling ability of the cooling towers are:

- The temperature of the air (both wet and dry bulb),
- The water inlet temperature,
- The contact time between the water and air,
- The efficiency of contact between air and water, and
- The uniformity of water distribution within the tower.



[1]

Figure 16 - Cooling tower flow diagram

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[1] Image courtesy of www.fansct.com

2.2.1 Types of cooling towers implemented on gold mines

Cooling towers can be classified into the different types based on how air is pulled through the system as well as the direction of the air flow. Natural draft cooling towers are seldom used in mining systems, thus just a brief overview is given on this tower type.

Natural draft cooling towers

Also known as hyperbolic towers, due to their shape, makes use of the difference in temperature between ambient air and resulting the hot air due to heat transfer of the water. As the hot air rises through the tower, cold air is drawn in at the inlet resulting in a natural draft. These towers are only used for very large capacity systems, such as power stations, due to their size and construction costs [33].

Mechanical draft cooling towers

As the name suggests, these towers use fans to push or pull air through the tower. These towers also make use of fill to increase the contact time between the water and air. As a result, these towers are relative small compared to natural draft cooling towers. These towers are the most common design used in the mining industry [34]. Mechanical draft cooling towers can be classified into forced draft and induced draft [33]. The difference is indicated in Figure 17 and further explained below.

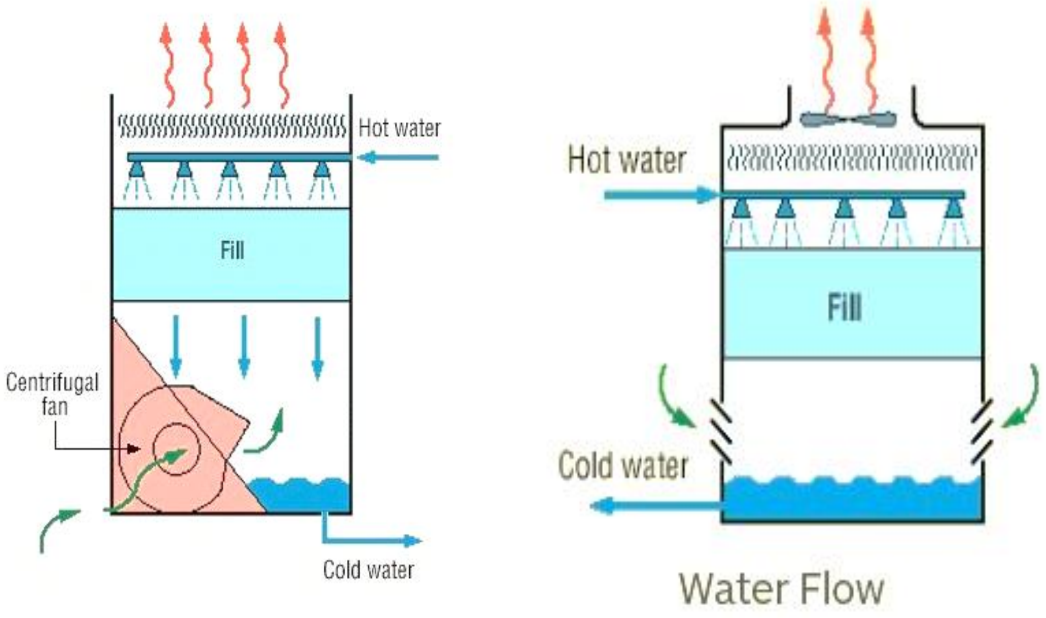

Figure 17 - Forced draft (left) vs induced draft (right) cooling tower [32]

Forced draft. The air is pushed through the towers by fans located at bottom of the tower. Air is sucked into the side of the tower and pushed up through the top of the tower at a low velocity. Drift eliminators are used to retain water which would otherwise have escaped through the top of the tower. Advantages of these towers are that vibration and noise are kept low because they are built on a solid foundation. The fans take in dry air, thereby reducing corrosion problems commonly found with induced draft towers [32], [33].

Induced draft. These towers have fans located at the top of the tower pulling cold air through from the bottom. This results in a low air velocity at the bottom of the tower and a high discharge air velocity, reducing the possibility of recirculation. Recirculation occurs when the discharge air flows back into the intake of the tower [33]. The disadvantage of this tower is that hot air with a high moisture content is passed through the fan, greatly increasing the rate of corrosion.

Cooling towers can further be classified into cross and- counter-flow towers according to the airflow through the tower [32], [33]. Figure 18 gives an example of both cooling tower types.

Counter-flow. Air flows in the opposite direction of the water. Air is drawn in at the bottom of the tower and discharged at the top of the tower while the water flows from top to bottom. The water is sprayed through pressurised nozzles located at the top of the tower and flows through the fill and into the basin [32], [33].

Cross-flow. Dry air enters through the side of the tower where it crosses the fill perpendicular to the direction of the water flow. The air is then collected in an open plenum area and pulled through the top of the tower [32], [33].

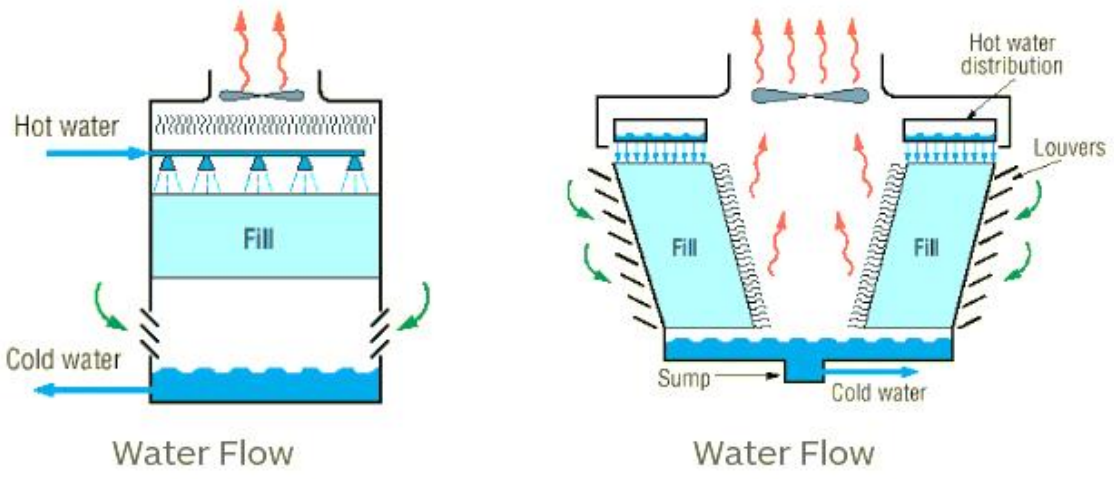

Figure 18 – Counter-flow (left) vs cross-flow (right) cooling tower [32]

2.2.2 Components

Cooling towers are made up of various components. Each component plays an important role in the cooling ability and efficiency of the tower. Figure 19 indicates the main components of a cross-flow cooling tower. Other cooling towers use the same components just in a different configuration. The main function of each component however remains the same. The components are discussed in more detail below.

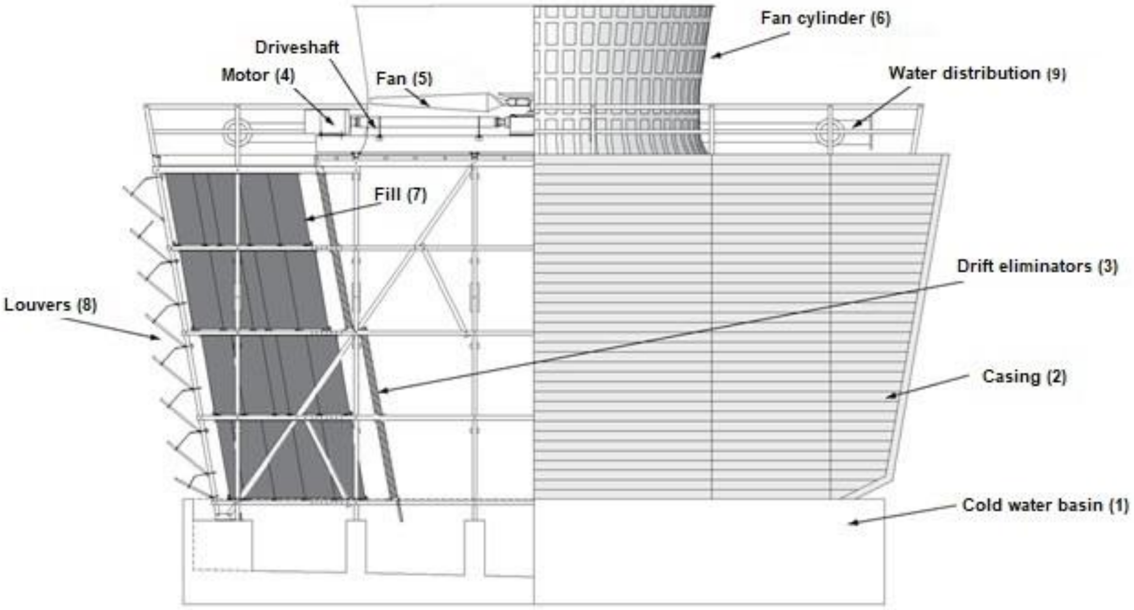

Figure 19 - Cooling tower components [33]

Cold-water basin (1): Functions as an accumulating dam after the water has passed through the tower. The cold-water basin also forms part of the foundation on which the cooling tower is build [33].

Casing (2): Contains the falling water within the tower and directs the airflow through the fill.

Drift eliminator (3): These are designed to remove water caught in the air stream. This is done by suddenly changing the direction of the air flow. Water is forced to separate from the air due to the resulting inertia forces. The air flows through the eliminator while the water is retained on the eliminator and allowed to flow back into the tower. Drift eliminators do however restrict the air flow resulting in an increased pressure drop. Eliminators are classified on the amount of directional changes or “passes”.

Motors (4): Are used to drive the fans of mechanical cooling towers. Electric motors are mostly used as they are reliable. The motor must be able to run in extremely adverse conditions.

Fans (5): Cooling tower fans are used to move air through the tower. Both propeller and centrifugal fans are commonly used for cooling towers. Propeller fans can move large amounts of air with the low static pressure in the system. Centrifugal fans operate against high static pressures making this fan type suitable for indoor installations. In comparison, these fans require higher specific energy inputs (in kilowatts) and move less air than propeller type fans. In addition to these fans, automatic variable-pitch fans can vary airflow throughout the tower, making it adjustable in times when a change in cooling requirements or ambient conditions occurs [32].

Fan cylinder (6): Typically used as a safety shield from rotating fans. However, the fan cylinder also contributes to the efficiency of the cooling tower. A well-designed fan cylinder can greatly improve the efficiency as it directly affects the air flow through the tower [32].

Fill (7): Fill is the surface on which heat transfer takes place. The fill of the cooling tower can greatly affect the efficiency of the tower [25]. The purpose of the fill is to increase the surface contact area as well as the contact time between the water and air [35].

There are two main types of fill, namely film and splash type fills. The material used for both fill types are mainly plastics. Film fills allows the water to form thin flowing sheets, exposing as much water surface area as possible to the air stream. Film fills are very efficient; however, they are sensitive to poor water distribution[36].

Splash type fill causes the water to break up and cascade through successive offset levels of parallel splash bars. This causes both the contact time and surface area to increase. Splash fill is less sensitive to a poor water distribution system even though it still plays a vital role. It also handles dirty water better than fill type. Splash type fill is usually not used with counter-flow towers due to restrictive airflow in the vertical direction [36].

Louvres (8): Are usually associated with the cross-flow towers. They are mainly used to retain water that would have splashed out of the system otherwise. Other benefits include keeping out dirt and other particles, as well as sunlight which impedes algae growth [32].

Water distribution (9): Consists out of water pipelines and spraying nozzles. The main purpose is to distribute water evenly across the fill of the tower [33]. The air flow velocity and water flow rate greatly affects the distribution of the water through the tower [37]. Proper distribution of water throughout the tower is important as it greatly affects the efficiency of the cooling tower.

Valves: Are used to regulate and control flow through the water distribution system leading to the cooling towers [32].

2.2.3 Pre-cooling tower problems

Cooling towers are prone to contamination problems due to their open design. This is worsened when cooling water evaporates and the contaminants are allowed to concentrate in the system. The contaminants can either enter via the air or through the recirculated water. When this is left untreated it leads to the problems described below in more detail.

Scale

Scaling formation on the fill leads to decreased heat transfer efficiency. Decreased efficiencies lead to either reduced production or an increase in energy consumption. Once a critical level of scaling is reached, the unit is stopped to perform the required descaling and other maintenance required [38].

Scaling is made up of inorganic minerals such as calcium carbonate, calcium phosphate, iron oxide and magnesium silicate. These minerals are dissolved in the water, however as the concentration increases they start to precipitate, forming scaling deposits on the fill [33]. Figure 20 shows an example of severe scaling build-up on fill.

Figure 20 - Severe scaling on fill [25]

Scaling usually occurs first in the heat transfer zones. Factors that influence the formation of scaling are;

- mineral concentration,
- water temperature,
- pH,
- availability of nucleation sites (the point of initial crystal formation), and
- the time allowed for scale formation to begin after nucleation occurs.

Due to the high concentration of minerals in open recirculating system, the makeup water is constantly in a saturated state. To prevent precipitation to take place a scaling inhibitor is used.

Fouling

Water entering the system contains particles of sand, silt, clay and other minor contaminant particles. Dust and dirt also enters through the air further contaminating the cooling water [39]. Micro bacterial growth and by products of corrosion also adds to the potential fouling of the cooling system.

The build-up of these solids leads to deposits being formed on the heat exchangers. This is due to the low velocity, laminar flow, rough metal surfaces, as well as scaled surfaces within heat exchangers. This causes reduced system efficiency and corrosion occurs underneath the deposits. Fouling can be controlled to a large extent by either mechanical methods or through chemical treatments.

Microbiological growth

The operating environment of cooling towers are an ideal place for micro bacterial growth. The ideal conditions for organisms to grow is in a temperature range of between 21-60 °C and a pH range of 6 – 9. The most common microbes found in towers are bacteria, algae and fungi. Unchecked levels can lead to reduced efficiencies, an increase in corrosion and energy losses throughout the cooling system [33].

Corrosion

Corrosion is the process where metal breaks down in the presence of water and air. The metal reacts with oxygen and the metal returns to its natural oxide states. Cooling towers especially open-air towers are very susceptible to corrosion. They are constructed from a wide verity of metals and are constantly in contact with warm water. Impurities in the water such as silt, dirt, scale, bacteria and other dissolvents all lead to corrosion. The pH level of the water can also greatly affect the rate at which corrosion takes place. Corrosion can result in reduced cooling efficiency, increased operation costs, increased maintenance and ultimately failure of equipment [33].

Besides contamination problems, cooling towers can also be affected by input factors such as water inlet flow rate and ambient temperatures.

Operating flow

Each cooling tower has a designed optimal operating water flow rate range. At this point the tower operates efficiently while supplying the required cooled water for the specific system. Factors such as shift changes, pumping load shift projects and eventually mine expansion results in varying water flow rates. In extreme cases, the water flow rate can increase to a point that the maximum designed water flow rate through the cooling towers is exceeded. The increased flow can result in the eventual need to by-pass the cooling towers.

Ambient conditions

Ambient conditions play a vital role in the cooling ability of the PCT. The greater the differential between the ambient air and hot water temperature, the greater the cooling performance of the tower.

During summer months, ambient temperatures increase drastically. If the ambient wet-bulb temperature approaches the hot water temperature, the range of the PCT is significantly reduced. This leads to energy being spent on pumps and fans whilst not realising the benefit of pre-cooling.

During winter, the ambient conditions can drop to such a degree that the cooling tower can ice up. Fortunately, the control of the system can be adapted according to the seasonal change in temperatures. For example, by-passing the PCT when the ambient wet-bulb temperature is equal or greater than the hot water temperature.

2.3 Thermal hydraulic system modelling

Prior to understanding the effect of pre-cooling on the refrigeration system, it is first important to understand the mechanics behind cooling towers. This enables us to identify and evaluate the pre-cooling towers before the whole system is analysed. The means to evaluate the cooling performants of the PCT is given in the section below.

2.3.1 Mathematical equation modelling

The rate at which heat is transferred in the cooling tower can be seen as the difference between the enthalpy of moist air at water temperature and the enthalpy of the moist air [40]. The heat transfer characteristics of fill is described by the Merkel equation. For this equation, several assumptions are needed;

- effect of evaporation does not exist,
- thermal and mass diffusion coefficients of air/water system is the same, and
- the system is at design conditions.

Both the sensible and latent heat transfer between the water and air is accounted for in this analysis. Thus, the total heat transfer rate for a unit volume of fill (dV) is the sum of the sensible heat (dq_s) and latent heat (dq_L) [41].

Equation 1: Sensible heat transfer rate

$$dq_s = U_G * a * dV * (t" - t)$$

Where

$U = \ Overall\ heat\ transfer\ coefficient\ (kJ/m^2.s.°C)$

$a\ =\ Area\ of\ water\ interface\ per\ unit\ volume\ (m^2/m^3)$

$V =\ Cooling\ tower\ volume\ (m^3)$

$t = Water\ temperature\ (°C)$

Equation 2: Latent heat transfer rate

$$dq_L = h_{fg} * dm = h_{fg} * K' * a * dV * (W" - W)$$

Where

$h =\ \ Enthalpy\ (kJ/kg)$

$K =\ Overall\ mass\ transfer\ coefficient\ (kg/s.m^2)$

$a\ =\ Area\ of\ water\ interface\ per\ unit\ volume\ (m^2/m^3)$

$W =\ Absolute\ humidity$

$m =\ \ Mass\ (kg)$

$$V =\ Cooling\ tower\ volume\ (m^3)$$

Merkel combined equations (1) and (2) based on the energy conservation principle. This leads to equation (3), which is based on enthalpy potential.

Equation 3: Total heat transfer rate

$$m_L * c_p * dt = K * a * dV * (h' - h)$$

Where

$m_L = \ Mass\ flow\ rate\ of\ water\ (kg/s)$

$c_p = \ Specific\ heat\ (kJ/kg.°C)$

$K = \ Overall\ mass\ transfer\ coefficient\ (kg/s.m^2)$

$a \ = \ Area\ of\ water\ interface\ per\ unit\ volume\ (m^2/m^3)$

$h = \ \ Enthalpy\ (kJ/kg)$

$V = \ Cooling\ tower\ volume\ (m^3)$

The integration of equation (3) provides a means to evaluate the cooling tower based on the NTU (number of transfer units).

Equation 4: Total heat transfer rate in NTU

$$NTU = \frac{K * a * V}{m_L} = \int_{t_2}^{t_1} \frac{c_p * dT}{\mathrm{h'} - \mathrm{h}}$$

Where

$a \ = \ Area\ of\ water\ interface\ per\ unit\ volume\ (m^2/m^3)$

$C_p = \ Specific\ heat\ (kJ/kg.°C)$

$m_L = \ Mass\ flow\ rate\ of\ water\ (kg/s)$

$h = \ \ Enthalpy\ (kJ/kg)$

$K = \ Overall\ mass\ transfer\ coefficient\ (kg/s.m^2)$

$V = \ Cooling\ tower\ volume\ (m^3)$

$$T = Water\ temperature\ (°C)$$

The NTU is a dimensionless parameter that represents the heat transfer capacity [42]. The heat transfer capacity of a cooling tower is thus a function of the water and air temperature, shape and type of fill and the size of the tower [41].

2.3.2 Pre-cooling tower performance calculations

It is important for the analysis of cooling towers to effectively measure the systems overall performance. This can be done by determining the amount of cooling tonne-hours it handles throughout a periodic basis. A cooling tonne-hour can be defined as one tonne of cooling provided for one hour of time. To determine this the cooling capacity and utilisation profile of the system is required.

By knowing the cooling tonne-hours of the system, the energy, water and chemical usage can be quantified on a per cooling tonne-hour basis. Making the evaluation of systems easier over different sites. The cooling tonne-hours is especially important when determining the whole system efficiency.

Capacity: A Cooling tower's capacity is usually defined in cooling tonnes. One tonne of cooling is equal to the removal of 3.5kW per hour from water. The capacity of a cooling tower determines the rate at which heat is transferred. The capacities of cooling tower used in the industry ranges from 50 tonnes to more than 1 000 tonnes. In most cases multiple cooling towers are used in situations where a greater capacity is required. [43]

To calculate the cooling capacity of the tower the following factors needs to be known;

- water flow rate of the system,
- specify heat capacity of the water, and
- range of the tower.

The following equation can be used to determine the capacity.

Equation 5: Cooling tower capacity

$$Q = m_L * c * (T_h - T_c)$$

Where

$Q = Quantity\ of\ energy\ (kJ/s\ \ or\ kW)$

$m_L = Mass\ flow\ rate\ (kg/s\ or\ L/s)$

$c = Specific\ heat\ \ (kJ/kg.K)\ (c\ of\ water\ = 4.19\ kJ/kg.K)$

$T_h = Hot\ water\ temperature\ (K)$

$T_c = Cold\ water\ temperature\ (K)$

Utilisation: Most cooling towers are situated in the open environment and are subjected to seasonal temperature changes. The cooling capacity required for any cooling tower system therefore varies with respect to the change in the seasonal ambient temperatures. It is therefore important to determine the utilisation profile of the system.

Liquid/Gas ratio: This is the ratio of between the water and air mass flow rate. During seasonal changes, adjustments can be made to the water and air flow rates to achieve the best cooling tower effectiveness. From the energy balance, the heat removed from the water must be equal to the heat absorbed by the ambient air as described by equations 6 and 7 below [41].

Equation 6: Energy balance

$$m_L(T_c - T_h) = m_G(h_h - h_c)$$

Equation 7: Liquid gas ratio

$$\frac{m_L}{m_G} = \frac{h_\mathrm{h} - h_\mathrm{c}}{(T_\mathrm{c} - T_h)}$$

Where

$m_G = Mass\ flow\ rate\ of\ the\ air\ in\ (kg/s\ or\ l/s)$

$m_L = Mass\ flow\ rate\ of\ the\ water\ (kg/s\ or\ l/s)$

$T_h = Hot\ water\ temperature\ (K)$

$T_c = Cold\ water\ temperature\ (K)$

$h_h = Hot\ water\ enthalpy\ in\ (kJ/kg)$

$h_c = Cold\ water\ enthalpy\ (kJ/kg)$

Figure 21 illustrates the effectiveness of a cooling tower at different m_L/m_G ratios. This indicates that a lower water flow rate results in a greater efficiency, whereas an increase in the m_L/m_G ratio the effectiveness of the tower is greatly reduced.

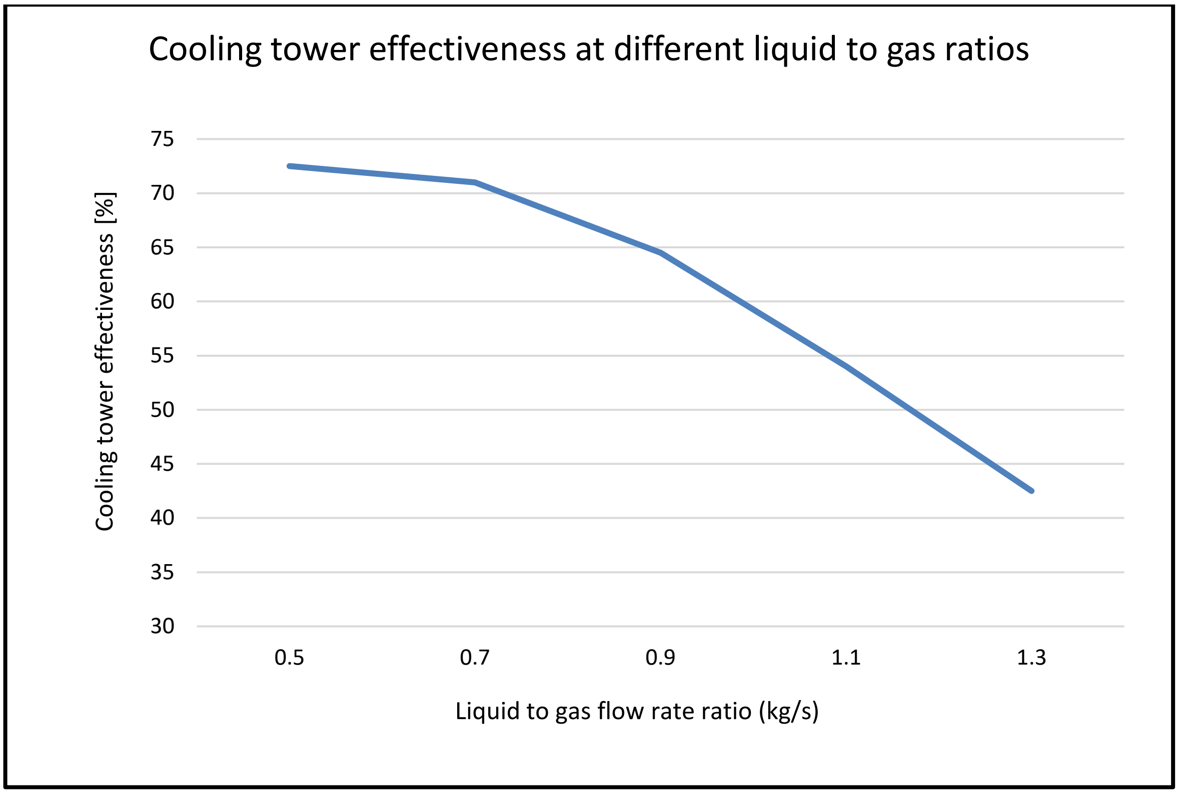

Figure 21 - The m_L/m_G ratio compared to cooling tower effectiveness [41]

Approach: The approach of the cooling tower is the difference between the cold water and wet-bulb ambient temperature as described by equation 8 [44].

Equation 8: Cooling tower approach

$$Approach = T_c - T_w$$

Where

$T_w =$ Wet bulb ambient temperature $(°C)$

$T_c = Cold\ water\ temperature\ (°C)$

Range: The range of the cooling tower is the difference between the hot water and cold-water temperature described by equation 9.

Equation 9: Cooling tower range

$$Range\ = T_h - T_c$$

With

$T_h = \ Hot\ water\ temperature\ (°C)$

$T_c = \ Cold\ water\ temperature\ (°C)$

Efficiency: To calculate the cooling tower efficiency, both the range and approach needs to be known, and is given by equation 10.

Equation 10: Cooling tower efficiency

$$\eta\ = \frac{Range}{(Range\ +\ Approach)} *\ 100$$

By substituting equation 8 and 9 into equation 10 results in equation 11, showing the alternative cooling tower efficiency.

Equation 11: Alternative cooling tower efficiency

$$\eta = \frac{(t_h - t_c)}{(t_h - t_w)}$$

Where

$T_h = \ Hot\ water\ temperature\ (°C)$

$T_c = \ Cold\ water\ temperature\ (°C)$

$T_w = \ \text{Wet bulb ambient temperature}\ (°C)$

From the above equation, it can be seen that the efficiency of the cooling tower is limited by the wet-bulb ambient air temperature. For an ideal system, the cold-water temperature will be equal to the wet-bulb ambient temperature. In practice, this is not viable as the evaporation and windage loss would be substantial. Consequently, the efficiency of cooling towers is normally in the range of 70% to 75%.

Evaporation Loss Calculation: Equation 12 gives the empirical evaporation loss in cooling tower.

Equation 12: Cooling tower evaporation loss

$$E = 0.00085 * R * 1.8 * M$$

Where

$E = Evaporation\ loss\ (m^3/h)$

$R = Range$

$M = Circulating\ cooling\ water\ (m^3/h)$

The evaporation loss can also be calculated with a heat balance equation across the cooling tower. The amount of heat that is removed from the circulated water is $C\ x\ Cp\ x\ R$ according to Equation 5. Thus, the amount of heat removed by evaporative cooling is shown in equation 13 below:

Equation 13: Heat loss through evaporation

$$Q = m * Hv = E * HV$$

From which the following can be derived:

$$E = C * R * \frac{C_p}{q_L}$$

Where

$E\ =\ Evaporation\ Loss\ (m^3/h)$

$C =\ Cycle\ of\ concentration$

$R =\ Range\ in\ °C$

$Cp =\ Specific\ Heat\ \ 4.184\ \ (\ (kJ/kg)\ /\ °C)$

$q_L\ =\ Latent\ heat\ of\ vaporisation\ (kJ/kg)\ =\ 2260\ kJ/kg$

Windage or Drift Loss: is usually stated by the cooling tower manufacturer, however if it is not available it can be assumed by the use of equation 14 as shown below:

Equation 14: Cooling tower windage loss

$$D\ =\ 0.1\ to\ 0.3\ *\frac{C}{100}$$

Where

$C =\ Cycle\ of\ concentration$

for an Induced draft cooling tower.

2.3.3 Simulation software for mine cooling systems

The development of computational power has increased substantially over the past few years. With this development, computer aided modelling has expanded over various industries. In the past, simulation software packages, especially for the mining industry was uncommon. In more recent times, simulation software designed specifically for the mining industry has drastically expanded. A study indicated that there are more than 45 simulation packages available, specific to the mining industry [45]. For this study, only the chosen simulation software package will be discussed and evaluated.

Process Toolbox

Process Tool Box (PTB) is a simulation software package based on thermal hydraulics. The software can simulate a variety of mining systems, including refrigeration, dewatering and compressed air system. It is a capable tool for the design, analysis and optimisation of a system’s performance [46].

The simulation software uses a graphics user interface (GUI) that enables the visualisation of the simulated system. Components can be added by dragging and dropping the required components in the simulation window. Components are connected through pipes and nodes to calculate the thermal hydraulic properties and flow after each component [47]. All of the required thermal hydraulic is available in the components window. Figure 22 sows a simple simulation of a cooling tower created using PTB.

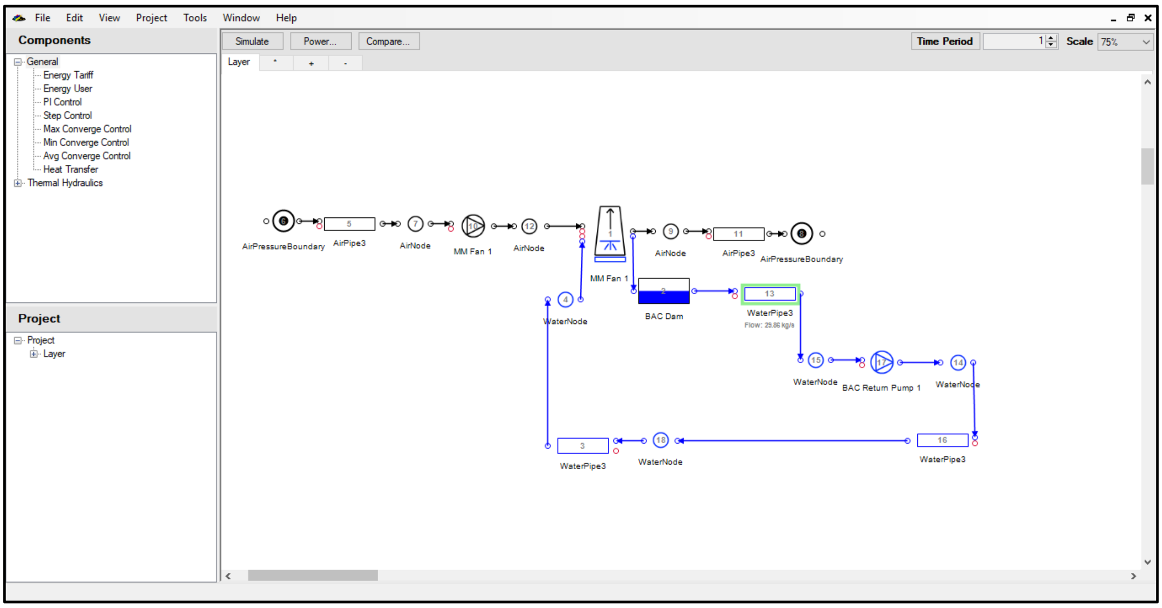

Figure 22 - A simple simulation using Process Tool Box

To validate the accuracy of PTB, previous studies that utilised PTB simulations were researched and evaluated. The results of the evaluation are as follows;

Mare used PTB to simulate optimised control on mine refrigeration systems. The simulated result corresponded to the actual results [48].

Oberholzer used PTB to simulate a reconfigured deep-level gold mine refrigeration system. The simulated result also corresponded to the actual results[21].

Vermeulen used PTB to simulate management techniques to realise cost savings on mine refrigeration systems. The simulated result corresponded to the actual results [49].

For this study, the simulation program PTB was used since it had been proved to accurately simulate refrigeration systems on actual case studies, as described above.

2.4 Strategies and technologies for optimising pre-cooling systems

By fully understanding the operation of cooling towers and its components the effect of pre-cooling on deep-level mine refrigeration systems can be determined. The following literature revealed that the addition of PCT reduces the pre-cooling dam temperature which leads to a lower refrigeration plant inlet temperature.

Study 1: Improved implementation strategies to sustain energy saving measures on mine cooling systems Pre-cooling flow control

Mare identified pre-cooling as a means to reduce the power consumption of the refrigeration system. This was investigated by optimising the flow through the PCT. The study found that reducing the flow through the towers resulted in improved pre-cooling dam temperatures. Additional energy savings will be realised as a result of reduced pump utilisation [48].

Mare noted that the performance of the PCT should be monitored with the implementation of flow control, as the water distribution through the tower can be affected. The results of the case study were unsuccessful due to the following reason:

- Reduced water flow resulted in inadequate water distribution in the PCT, resulting in poor cooling of the processed water.
- The reduced water flow increased the possibility of scaling and fouling through the tower.
- The reduced flow caused damage to the transfer pumps.

Study 2: Improving cooling system efficiency with pre-cooling

Schutte investigated the consequence of incorrect fill selection for the PCT on a mining system. The study revealed that the use of high efficiency, film fill for a mining system was ineffective. This fill type was susceptible to clogging and scale build-up as a result of the dirty process water used in mining [25].

For the case study, a splash type fill with reduced efficiency and higher utilisation was suggested as a replacement. Results include improved utilisation of the PCT as well as cooler outlet temperatures, compared to the clogged film fill towers. The refrigeration plants showed reduced energy consumption as a result of the lower water inlet temperatures.

Study 3: The value of simulation models for mine DSM projects

Van Niekerk demonstrated the potential of using simulations models as a tool for analysing a system. This was done by analysing energy usage of complex technical mining systems and identifying energy savings potential. His case studies revealed that simulations can accurately evaluate a system and identify possible inefficiencies. In addition, it showed that simulation models reduce implementation time and cost. A recommendation was made to take a holistic approach when simulating a mining system. This allows the user to see the effect of deterioration in a component across the whole system [50].

Study 4: Thermal performance of forced draft counter-flow wet cooling tower with expanded wire mesh packing

Ramkumar and Ragupathy investigated the performance of a forced draft counter-flow cooling tower. The study provided an analytical approach in benchmarking the performance of the system. In addition, an experimental procedure was used to determine the effect of two different fill orientations [41].

2.5 Conclusion

To be able to fully understand the impact of pre-cooling on mine refrigeration systems it was required to first understand the basic concepts of cooling towers as well as the refrigeration system. The efficiency of the cooling tower as well as the components and different configurations were discussed. Previous studies on PCT were investigated and evaluated. This gave valuable insight for chapter 3 and the development of the methodology to be used in this study.

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Chapter 3

3 Optimised model development

3.1 Introduction

An appropriate methodology was needed to achieve the objectives of this dissertation. The methodology developed is thoroughly discussed throughout this chapter. Information provided up until now gave the background and an understanding of the relevant system and system components. The methodology was developed with this information in mind.

The effect of pre-cooling is most evident with a change in the pre-cooling performance. Thus, for the dissertation the pre-cooling of a mine will be analysed, improved and evaluated. By comparing the results with the initial system, the effect of pre-cooling on the complete system will be highlighted. Figure 23 indicates the steps that were followed to achieve the objectives of this study.

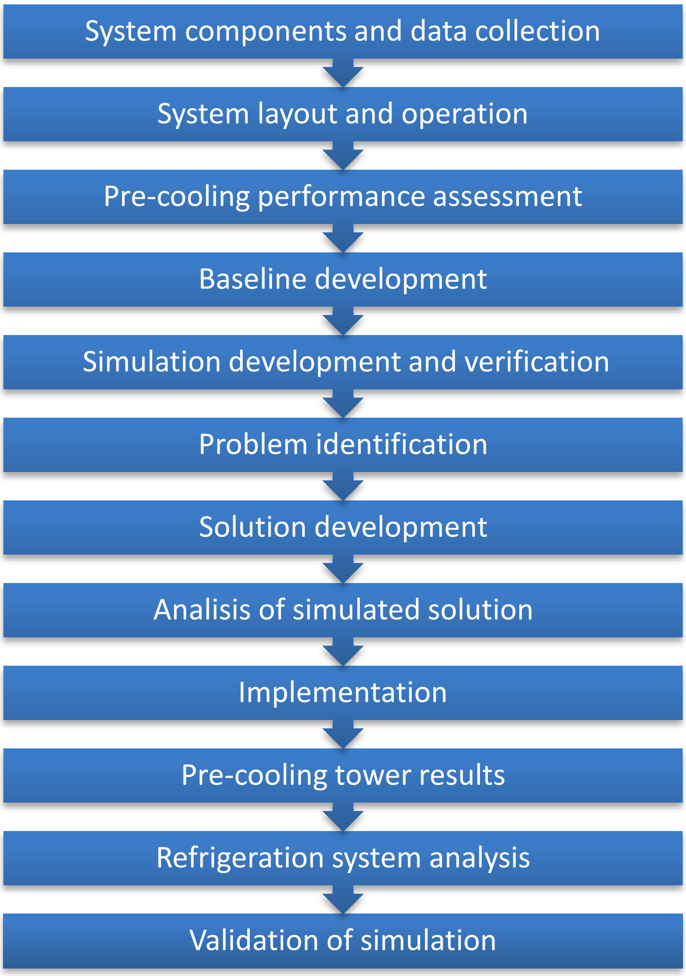

Figure 23 – Developed methodology

The first step in the methodology was to identify the components of the refrigeration system and operation. This was achieved by acquiring the necessary data, specifications and layouts of the refrigeration system. With the acquired data, the PCT can be investigated and analysed. Upon the identification of poor pre-cooling performance, the next step in the methodology can be followed.

Baselines of the current system needed to be developed which serve as a benchmark on which improvements are compared. Baselines were needed for both the electrical system as well as on the key performance indicators.

The information and data obtained from the first step was used to develop a simulation of the current system. The simulation was to be used to investigate a possible solution for the poor pre-cooling performance. However, before the simulation can be used it needed to be verified against the developed baselines.

With the knowledge obtained of the refrigeration system in the first few steps, the problems leading to the poor pre-cooling performance can be identified. With the problems identified a solution can be developed and analysed by using the developed simulation.

In the second last step, the optimum solution was implemented. With the change in pre-cooling performance, a change in system conditions can be observed. Finally, the effect of optimal PCT on the system was evaluated.

3.2 Characterisation of mine refrigeration systems

The first step as defined in the methodology illustrated in Figure 23 was to identify the unique refrigeration system specific to the mine. Information such as the components specification, available data and system layouts is vital for the characterisation of the refrigeration system.

3.2.1 System components and data collection

Table 1 detailed all the major components and the data required for the analysis of the refrigeration system. This checklist was developed to determine if specific components are used on the mine, as well as if the required data is available. The easiest way to obtain the data is through a site visit and physical inspection of the components. Mining personnel are also very helpful in this regard.

Table 1 – List of major refrigeration system components and their required data

Component	Required Data
Refrigeration Plants	Compressor motor installed capacity [kW]
	Evaporator inlet and outlet temperature [°C]
	Condenser inlet and outlet temperature [°C]
	Evaporator flow rate [l/s]
Pumps	Pump motor installed capacity [kW]
	Pump flow rate [l/s]
	Pumping elevation [m]
PCT	Water inlet and outlet temperatures [°C]
	Air inlet and outlet temperature [°C]
	Water flow rate [l/s]
	Fan motor installed capacity [kW]
	Air flow rate [kg/s]
CCT	Water inlet and outlet temperatures [°C]
	Air inlet temperature [°C]
	Water flow rate [l/s]
	Air flow rate [kg/s]
	Fan motor installed capacity [kW]
Bulk air coolers	Water inlet and outlet temperatures [°C]
	Air inlet and outlet temperature [°C]
	Water flow rate [l/s]
	Air flow rate [kg/s]
Dams	Water temperature [°C]
	Configuration
Valves	Valve positions [%]
	Automated capabilities

The complete design specifications of the PCT were also required. This information is not always available. In such a case, a physical inspection will be required. As stated in chapter 2, the ambient conditions are an important factor and should be obtained for the same period as for the above-mentioned data. Table 2 indicates the required information specific to the PCT.

Table 2 – PCT required specifications list

Component	Component description
Tower	Type
	Height
	Width
Fan assembly	Number of fans per tower
	Position
	Condition
Fill	Type
	Condition
Drift eliminator	Type
	Condition
Distribution system	Number of sprinklers per tower
	Condition
	Pipe network layout

3.2.2 System layout and operation

All the components in the refrigeration system had been identified. The next step was to determine how each component interact with and influence the system. The easiest way to determine this was through a system layout. Schematics for the refrigeration system were readily available and can be found on the SCADA. Figure 12 in chapter 1 shows an example of a simplified mine refrigeration system layout. An accurate layout of the components is vital. It gives a clear view of the process and thus the influences that each component has on the system.

3.2.3 Pre-cooling performance assessment

The data obtained in the first step was then used to quantify the performance of the existing PCT. The calculations required to correctly model the PCT for the simulations were based on the equations discussed in chapter 2.

The first calculations determine the approach and range of the cooling towers. From this, the efficiency can be calculated. Other factors that influence the efficiency of the PCT are scaling and the liquid to gas flow ratio (L/G ratio). Scaling has a direct effect on the efficiency of the pre-cooling and will be clearly shown by comparing the results to the design specifications. The L/G ratio plays a larger role when the water demand varies. Other existing energy initiatives such as DSM load shift could also have a significant effect on the L/G ratio and thus the efficiency.

Computed calculations were necessary for the calculations due to the time intervals of the data obtained. Thus, a calculation sheet was developed to calculate all the required information. This is a standardised sheet that can be used on any case studies if the correct parameters are available. The calculation sheet example is shown in Appendix C.

3.3 Benchmarking and analysis of refrigeration system

In the next steps, the performance of the refrigeration system and specifically the PCT should be benched marked and analysed. This was done by benchmarking, simulating and calculating the performance of the refrigeration system and PCT. The baselines were also used to verify the simulation and calculations.

3.3.1 Baseline development

Baselines were developed as a reference point for any future improvements. The baselines consisted of both electrical and system operational conditions. The electrical power baseline was used as a comparison tool to indicate any increase or decrease in electricity usage. Cost savings can be directly calculated from this baseline. The operational baselines were used to determine the effect on the system KPIs.

Baseline adjustment

There are two main variables that influence the overall performance of the refrigeration system. The variables are ambient temperature as well as the amount of chilled water used. A suitable baseline adjustment method is required for the electrical power baseline.

A baseline adjustment model ensures credible cost savings are calculated and reported. Adjustments will be made to the baselines if the energy performance indicators no longer reflect the systems energy use and consumption. The effect of ambient conditions can be accounted for by creating seasonal baselines.

The refrigeration plants power consumption is directly proportional to the chilled water usage when the ambient temperatures are similar. This is evident from Equation 5, where the energy required is directly proportional to the mass flow. Thus, the adjustments were based on the daily chilled water usage as indicated by the following equations.

Equation 15: Baseline adjustment factor

$$\boldsymbol{Ba = \sum_{i=0}^{n} \frac{L_{Actual_i}}{L_{Baseline_i}}}$$

Where:

$L = Water\ flow\ to\ underground$

$i = intervals\ for\ the\ day\ period$

Equation 16: Scaled baseline calculation

$$Scaled\ Baseline_i = \ Ba \times Original\ Baseline_i\ [kW]$$

By using Equation 15 and Equation 16, a suitably scaled baseline can be determined. Figure 24 shows the influence of baseline adjustments on the system. In this case an increased water usage caused the baseline to increase accordingly.

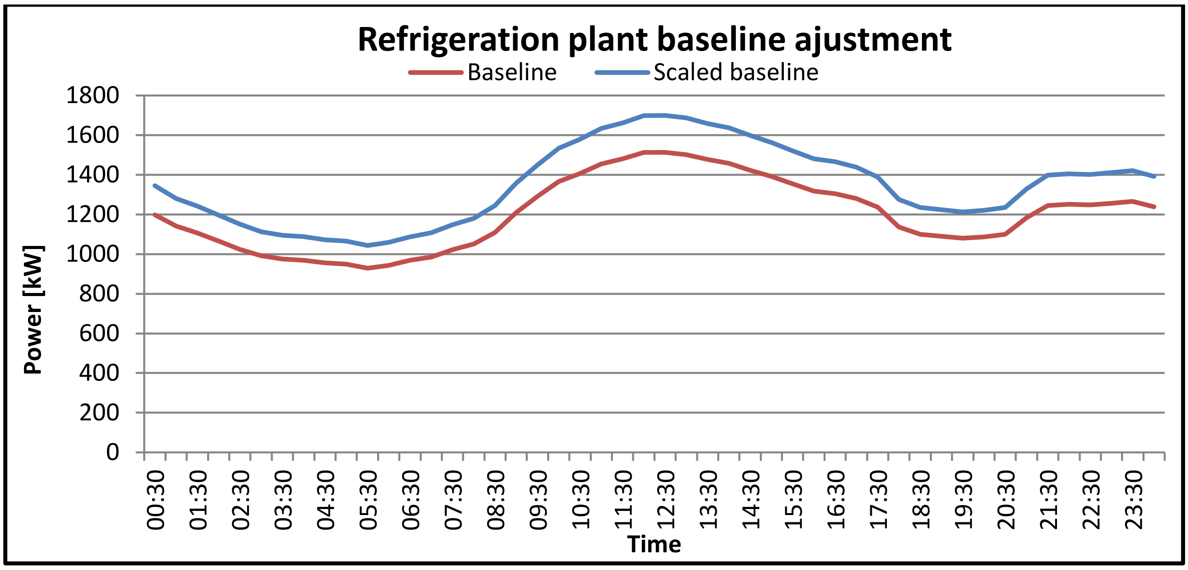

Figure 24 – Baseline adjustment

Electrical power baseline

The power data used for the electrical baseline is in half-hour intervals. As stated, season specific baselines were developed for the system. This was done to ensure that the average ambient temperature for the two evaluation periods are the same. An example of a seasonal electrical power baseline is shown below in Figure 25. The electrical baseline will be used to determine the impact that effective pre-cooling has on the power consumption and operational cost of the system.

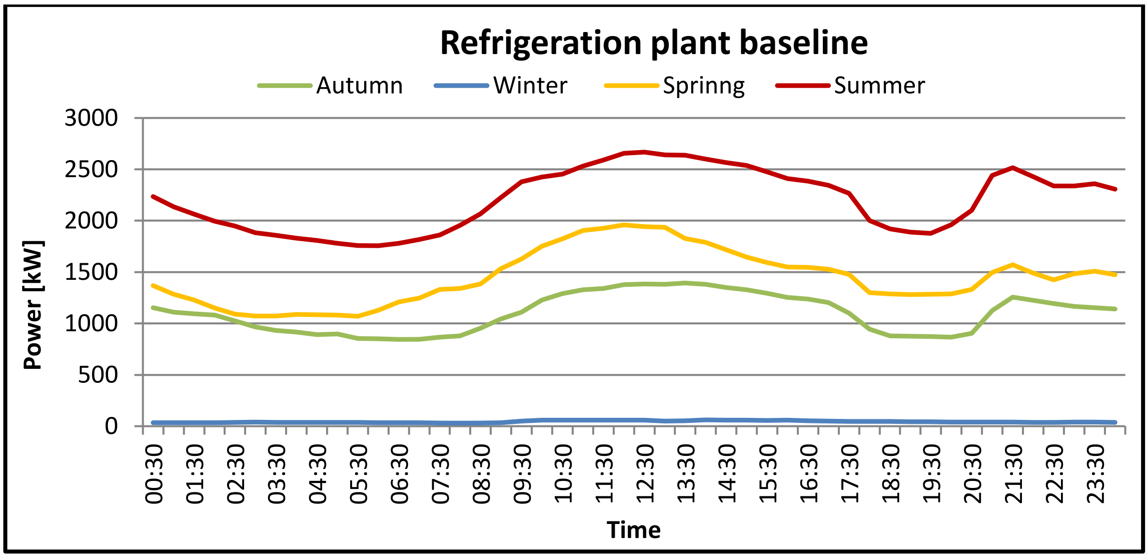

Figure 25 - Seasonal power baseline

Key performance indicators

With the increased understanding of the mine system, points in the system can be identified that will show a change in cooling efficiency of the system. These points are referred to as KPI's (key performance indicators). The KPI's will indicate what the effect of the pre-cooling is on the refrigeration system. Table 3 covers the most important KPI's of the refrigeration system specific to the analysis of pre-cooling.

Table 3 – Possible KPI's

KPI	Description
Pre-cooling inlet temperature	Change in underground conditions can cause the underground outlet water temperature to fluctuate. Resulting in varying pre-cooling inlet temperatures. This directly affects the pre-cooling outlet temperatures.
Pre-cooling outlet temperature	Improvement of the pre-cooling performance will first be noticed on the outlet of the PCT. Any improved efficiency will be indicated through a decrease of the pre-cooling outlet temperature.
Pre-cooling by-pass valve position	The position of this valve is an indication of increased in the water flow rate of the mine.
Chill dam temperature	The temperature of the chill dam is a direct indication of the refrigeration systems and pre-cooling performance.
BAC outlet temperatures	The purpose of the refrigeration system is to cool the mine underground. Thus, the outlet temperature of the BAC is vital in determining the overall performance of the refrigeration system.

Operational baselines are required to determine if there is any change in the conditions of the systems after the improvement has been implemented. As in the electrical baseline, season specific baselines for each of the KPI's needs to be developed. Due to dynamic climate in South Africa, the ambient conditions should also be compared for the period of the baselines to the period of the analysis.

3.3.2 Simulation development and verification

A simulation needed to be developed for the analysis of the whole system. This was done through the use of Process toolbox (PTB) as motivated by literature in chapter 2, and the data obtained through out this chapter will be used in the simulation.

The PTB simulation software is a powerful tool that can be used to analyse the cooling system performance. It can also be used to predict any changes in the system which is vital in the development of a solution. However, the simulation must first be verified. This was done by comparing the simulation of the original system to the baselines developed. The simulation and both the electrical and KPI baselines must correspond in order for the simulation to be verified.

3.4 Optimal pre-cooling performance

3.4.1 Cause identification of ineffective pre-cooling

Before a solution can be developed, the problem resulting in poor pre-cooling performance needs to be identified. Common problems of poor pre-cooling are summarised in Table 4. These problems are fully explained in section 2.2.3 of chapter 2. To effectively develop a solution to the problem, it is also important to understand the root cause.

Table 4 - PCT problems

Problem	Description
Increased operating flow	The water flow rate is greater than designed conditions of the cooling tower.
Extreme ambient conditions	A change in outside temperatures that negatively affects the performance of pre-cooling.
Poor water quality	Dirty water causing build-up of contaminants in the pre-cooling system.
Lack of maintenance	Insufficient maintenance on the pre-cooling and a lack of a maintenance plan.

Increased operating flow: Various factors can cause a change or increase in water flow rate. Most common cases are mine expansion and pumping load shift initiatives. Expanding mines require additional cooling water. The water problem progresses as the mine expands year on year.

Pumping load shifts aim to reduce power consumption during peak Eskom times. Reducing the amount of time in the day water can be pumped from underground. To pump the same amount of water in less time the flow rate needs to be increased.

These problems can be identified by measuring the current flow rate of the tower and comparing it against the designed flow rate. Historic data, if available, will also aid in determining if the water usage has increased.

Ambient conditions: The changing of seasons is usually associated with a change in ambient temperatures. Climate change also results in a steady increase in ambient conditions. The approach of the tower should be calculated to ensure that the cooling tower is operating at an effective rate.

Poor water quality: Dirty water is a by-product of the mining industry. High temperatures underground increase the amount contaminants dissolved in the water. This leads to scaling, fouling, microbiological growth and corrosion.

The build-up of these contaminants is easy to identify through physical inspection of the cooling towers. Further test can be conducted to determine the water quality. These tests include conductivity, pH, alkalinity and hardness tests and will indicate the likeliness of build-up in the system.

Lack of maintenance: Funds for maintenance are often limited, especially with a production driven industry. This results in only the major components of the refrigeration system being inspected and maintained on regular bases. Poor maintenance is seen through inspection of the PCT condition. Failure of components and extreme build-up of contaminants is an indication thereof.

3.4.2 Solution development

To completely understand the effects of pre-cooling, a change in the performance of the PCT is required. The current pre-cooling system has now been analysed and the problems related to the cooling performance identified. The current system must now be compared to the optimal pre-cooling for the mine. However, before the optimal pre-cooling can be evaluated a solution to the problem must be developed.

A realistic approach was followed in the development of the solution. Meaning that the PCT will be optimised for both efficiency and reliability. Factors such as ambient conditions, draft, water flow, water quality and costs are going to play a large role during the solution development. It is important that the solution is economically viable for the proposal to, and eventual implementation on the specific mine.

The specific solution to optimum pre-cooling differs from mine to mine. A solution can range from reconfiguration of components, to change in the control strategy, to the repair of the PCT. That is why the characterisation of the complete system is important.

Common problems on the pre-cooling system were identified, and can be overcome by the following possible solutions:

Water flow optimisation to the PCT; involves adapting the water flow supply to the PCT to ensure a constant water flow rate. This will involve determining the required water flow rate for the mine. The PCT should be able to operate efficiently with the required flow rate. If this is not the case, then additional towers are required.

A control strategy should be developed to obtain a certain flow rate through the cooling towers by controlling the transfer pumps to these PCT. This control strategy will only be possible if the pre-cooling dam has a large enough capacity. It is also worth mentioning that this should work in conjunction with existing pumping load shift projects.

Control optimisation based on ambient conditions; involves monitoring the daily ambient temperature changes to run the PCT only when they are operating effectively. As the wet-bulb ambient temperatures rises above the hot water temperatures no cooling takes place. Thus, during such extremes, the pre-cooling fans should not be running to save on energy. In winter months care should be taken to avoid icing on the cooling towers. The control on the fans can be optimised during these extremes.

Water treatment: entails adding chemicals to ensure that the pH, hardness and alkalinity of the water remains within the accepted limits. A method to measure these properties should be investigated. The chemicals should be added based on the measurement results.

3.4.3 Simulating the solution

Once an optimal solution has been developed, a PTB simulation of the solution will be done. The simulation method has already been verified earlier in this chapter by numerous studies. Thus, the simulation method can be seen as accurate. The results from the simulation were compared to the actual implementation results to validate this statement.

The results of the optimal simulation can now be compared to the developed baselines. There are two scenarios possible depending on the mine. The first was where the overall cooling duty remained constant, however a clear decrease in power usage was evident. The second was where the key performance indicators showed an improvement. This will not lead to a cost saving on energy usage but improve the service delivery of the cooling system.

Any improvements visible through the simulation can be used as the motivation for the implementation of the solution. The expected cost savings, as well as the payback period, were calculated based on these results.

3.5 Implementation

3.5.1 Implementation

Once the solution has been successfully motivated to the mine, implementation can be commenced. Implementation is simple and will mostly require changes to the PCT leaving the other main system components unaltered and operational. If possible, implementation should be done when the refrigeration system is offline, usually during the winter. If this is not possible, a period should be identified in which the process will least affect the system e.g. during a scheduled maintenance shut down.

Once implementation is completed the system can be analysed and validated against the results in section 3.4. The exact same steps used in the previous section can be followed to analyse the system performance.

3.5.2 Validating the methodology

The validation of the developed strategy can only be done after implementation. The cooling performance must be compared against the developed solution. A comparison was done on both the operational and electrical performance of the system. This served as the validation of this methodology. In some instances, historic data before the deterioration of the PCT can be used for validation. However, for this to be accurate, the rest of the system should have remained unchanged during the comparison period.

3.6 Conclusion

A method was developed to analyse, improve and evaluate the pre-cooling performance and the overall performance of the system. The method consisted of the identification and characterisation of the refrigeration system, benchmarking and analysis of the current system performance, and the improvement and evaluation of the PCT performance.

The method was developed as a guideline for pre-cooling optimisation and can be adapted for any system utilising PCT. The next section will focus on the actual implementation of the proposed methodology on a unique case study.

Chapter 4

4 Solution development and implementation

4.1 Introduction

In this chapter, the methodology developed in the previous chapter was applied to a case study. The case study was based on a deep-level gold mine near Carletonville, South Africa. The specific case study was identified based on the data available and its potential for improvement on the PCT. The mine will be referred to as Mine A to keep the information of the mine confidential.

4.2 Identification of mine refrigeration systems

This section focuses on the identification of the case study's refrigeration system. This was done by identifying each component of the system and determining the operation of each component. This gave an indication of how the system components influence each other.

4.2.1 Major components and data collection

As discussed in chapter 3 the data for Mine A was collected. The data presented in Table 6 to Table 9 was obtained through the assistance the mine's personnel as well as physical inspections of the components and SCADA.

Table 5 gave an overview of the PCT on Mine A. There are eight PCT capable of cooling water at a rate of 400l/s. The water is supplied by two transfer pumps. The temperatures in Table 5 is based on actual data as design specifications were not available. For a more detailed pre-cooing tower specification list, refer to Appendix A

Table 5 - Mine A PCT specifications.

Description	Surface
Number of cooling towers	8
Water inlet temperature (°C)	30
Water outlet temperature (°C)	25
Water flow (kg/s)	400
Air inlet wet-bulb temperature (°C)	6
Pump motor rating (kW)	75
Number of pumps	2

Table 6 gave the specifications of the refrigeration plants on Mine A. There are four refrigeration plants which operate in a series-parallel configuration. The combination of these plants was designed for a water flow rate of 300l/s through the evaporation side and an exit temperature of 5.9°C.

Table 6 - Mine A refrigeration plant specifications.

Description	Surface
Number of refrigeration plants	4
Make	Hitachi
Compressor type	Centrifugal
Refrigerant	R134a
Voltage (V)	6 600
Cooling capacity (kW)	13 300
COP	6.65
Evaporator outlet temperature (°C)	5.9
Condenser inlet temperature (°C)	18.5
Evaporator water flow (kg/s)	300
Condenser water flow (kg/s)	600
Evaporator pump motor rating (kW)	90
Number of evaporator pumps	4
Condenser pump motor rating (kW)	185
Number of condenser pumps	5

The design specifications of the CCT are presented in Table 5. The four cooling towers are capable of cooling the condenser water of the refrigeration plant by 4.5°C at a rate of 670l/s.

Table 7 - Mine A CCT specifications.

Description	Surface
Number of cooling towers	4
Water inlet temperature (°C)	32
Water outlet temperature (°C)	27.5
Water flow (kg/s)	670
Air inlet wet-bulb temperature (°C)	22
Pump motor rating (kW)	75
Number of pumps	5

There are 3 main BAC installed at Mine A. The BAC cools down the ambient air being sent to underground by 11°C, provided the refrigeration plants can produce the required chilled water. Table 8 gives additional information regarding the BAC. The BAC are mainly used in the summer periods as the ambient temperatures in the winter is sufficient to cool the mine.

Table 8 - Mine A BAC specifications.

Description	Surface MM	Surface RV
Number of BAC	2	1
Water inlet temperature (°C)	3	3
Water outlet temperature (°C)	14	14
Water flow (kg/s)	150	150
Air flow (kg/s)	225	230
Air inlet wet-bulb temperature (°C)	18	18
Air outlet wet-bulb temperature (°C)	7	7
Pump motor rating (kW)	75	75
Number of pumps	2	1

Table 9 indicates the average dam temperatures expected. The capacity of the dams was not obtainable and an average capacity of 5 000 Ml was estimated for the simulation values.

Table 9 - Mine A dam specifications.

Description	Temperature (°C)
Hot dam	30
Pre-cooling dam	25
Chill dam 1	6
Chill dam 2	6

The information obtained in these tables were the design specifications. These values are however not a true indication of the systems current values. Due to age and other system variables most of the components are running less efficiently and further away from design specifications. To accurately analyse the system the actual data for the current system was also required.

This data was obtained through a data logging PC connected to the SCADA. This PC is running REMS, which is an automated control program developed by TEMMI International. The program is also able to log the required information once the system tags are added. The data is logged in two-minute intervals and is then sent to a localised server at HVAC International. It was at this point where the data was accessed. The data was vital to accurately create daily average profiles for both the simulation model and baselines.

4.2.2 Refrigeration system layout and operation

The basic layout of mine A’s refrigeration system was drawn as stated in chapter 3. The layout can be seen in Figure 26. A total of 26 Ml/day is pumped from underground during an average summer day, and a total of 24 Ml/day during the winter months. Hot water from underground enters the surface hot dam at a temperature of 30°C. From the hot dam, the water is pumped through PCT. A total of 8 PCT cools the water down to an average temperature of 24°C in the pre-cool dam.

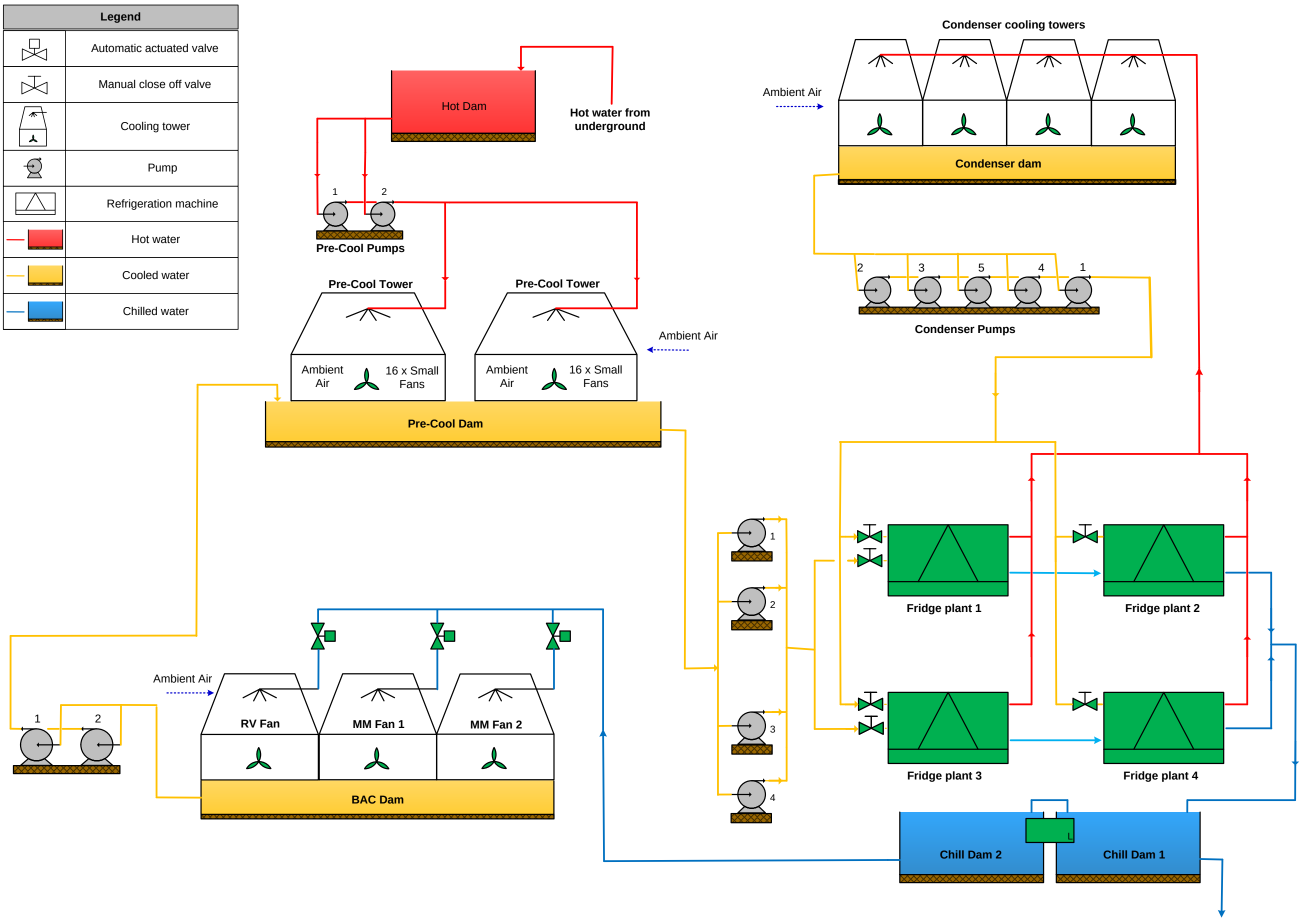

Figure 26 – Mine A Refrigeration system layout

The pre-cooled water is pumped through the two parallel sets of refrigeration plants, to provide chilled water at 6°C in the chilled dam. The condenser side water is cooled by four CCT. The combined cooling capacity of the surface refrigeration plants is 42MW. The combined COP of the surface refrigeration plants is 5.25 at design conditions. From the chilled dam 180 l/s flows through the BAC to the pre-cool dam and the remaining water is sent to the 71 Level chilled dam via three underground holding dams.

Figure 27 provides more information regarding the water flow through the refrigeration system. During high water flow rate periods, the pre-cooling by-pass valve is opened. The valve is located between the hot dam and pre-cooling dam. The hot water at 30°C is sent directly to the pre-cooling dam, missing the cooling provided by the PCT.

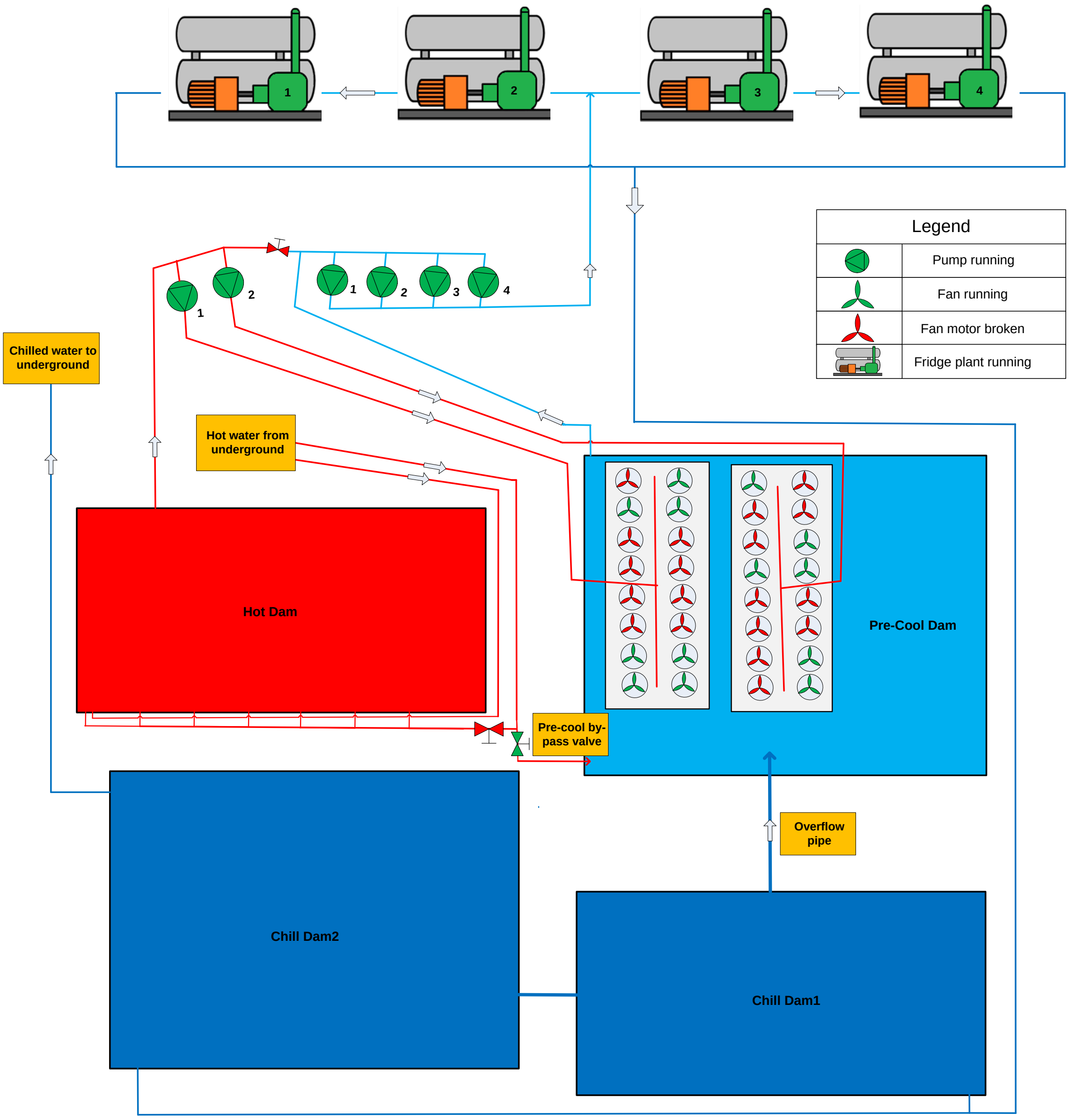

Figure 27 – Mine A detailed pre-cooling system

Secondly, the chill dam water is allowed to recirculate back into the pre-cool dam during low demand periods. The water is passed back to the pre-cooling dam and thus re-enters the refrigeration plants. Increased recirculation can greatly affect the pre-cooling dam temperature. Recirculating only occurs once the chill dam reaches 100%.

4.2.3 Pre-cooling tower performance assesment

Following the methodology in chapter 3 the next step was to assess the PCT performance. The period of the performance assessment (PA) was from 27 July to 27 August, excluding weekends. During winter months, the BAC are not used and thus were off for the evaluation period. The effect of pre-cooling can therefore be evaluated by using the selected KPIs. The baselines developed for this period also assisted with the assessment of the current system. Lastly a simulation was created of the current system conditions.

The calculation sheet mentioned in chapter 3 was used to determine the range, approach, efficiency and cooling capacity of the cooling towers for the evaluation period. The data obtained in the previous section was averaged hourly into a day profile for the baseline period. The calculation sheet used the profile data to determine the average, minimum and maximum values. Table 10 indicates the summarised results of the calculation sheet.

Table 10 - Pre-cooling performance assessment

PCT performance	
Ambient wet-bulb temperature [°C]	6.2
Pre-cooling inlet temperature [°C]	29.0
Pre-cooling outlet temperature [°C]	25.1
Approach [°C]	18.8
Range [°C]	3.9
Efficiency [%]	17.2
Cooling Capacity [kW]	5 264.2

Table 10 gives the results of the pre-cooling performance assessment. It was clear that the PCT were very inefficient with an efficiency of only 17.2%. An average wet-bulb ambient temperature of 6.2°C provides a large temperature difference for heat transfer to take place. With an inlet temperature of 29°C, the PCT only managed to cool the water down by 3.9°C. The resulting approach of the towers is very high which reaffirmed the poor efficiency of the tower. It was also a good indication of the available scope for improvement on the PCT.

4.3 Baseline development and analysis of refrigeration system

4.3.1 Baseline development

The period selected as a baseline was 27 July to 27 August. This is the only period that could be used as the mine started with maintenance and improvements shortly thereafter. Weekends were excluded from the baseline due to lower production over Saturdays and Sundays. This in return affects the water usage and thus the power consumption of the refrigeration system.

Figure 28 indicates the power profile of the refrigeration during the assessment period. A reduction in power usage can be seen between 17:00 and 20:00. This is the Eskom peak period time in which additional charges occurs for electricity. The mine switches some of the refrigeration plants off to reduce electricity costs during this period.

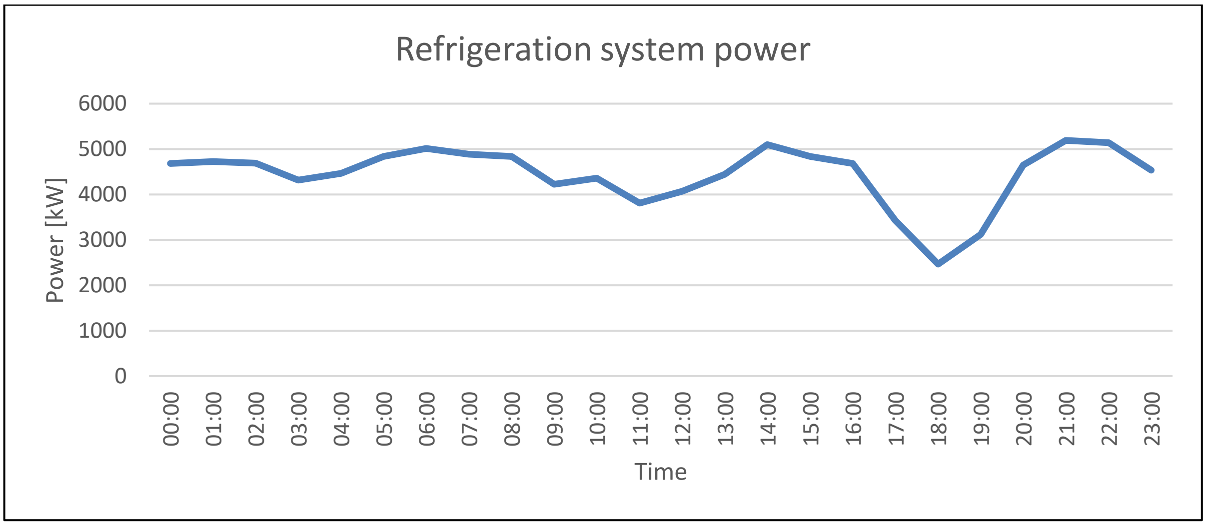

Figure 28 - Refrigeration system power baseline

The electricity baseline showed in Figure 28 will be used to evaluate the systems performance once improvements on the PCT were completed. It is important to note that the power usage of the refrigeration system is low due to the decreased water usage and the winter conditions.

4.3.2 Key performance indicators

The power consumption of the refrigeration was not the only indication of the refrigeration systems performance. To investigate the effect of pre-cooling on the system additional system parameters to the power usage must be monitored. These parameters are called key performance indicators (KPIs) as stated in chapter three. The KPIs used for Mine A's refrigeration was selected based on the data available and the accuracy of the data. For Mine A, the following KPIs were selected;

- Pre-cooling outlet temperature
- Chill dam temperature

Additional factors that impacts upon the system are the PCT water inlet temperature, the ambient temperature and the water flow to underground. Baselines for these conditions were also created. These baselines will be used as a comparison to the improved PCT results.

Factors such as the chill dam back pass -and PCT by-pass valves also greatly affect the overall temperatures. During the investigation, the occurrence of these factors were kept to a minimum.

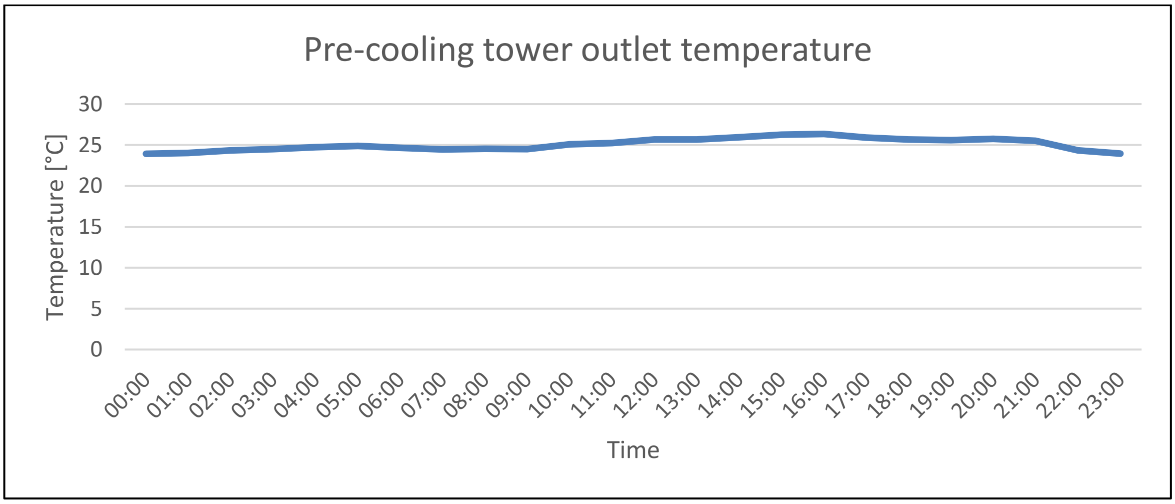

Figure 29 – Pre-cooling outlet temperature baseline

Figure 29 and Figure 30 shows the temperature profile for the pre-cooling outlet and chill dam respectively. In both cases the temperature increases slightly during the peak ambient temperature. This reaffirmed that the ambient temperature affects the system. It also indicates that a change in pre-cooling outlet temperature affects the chill dam temperature.

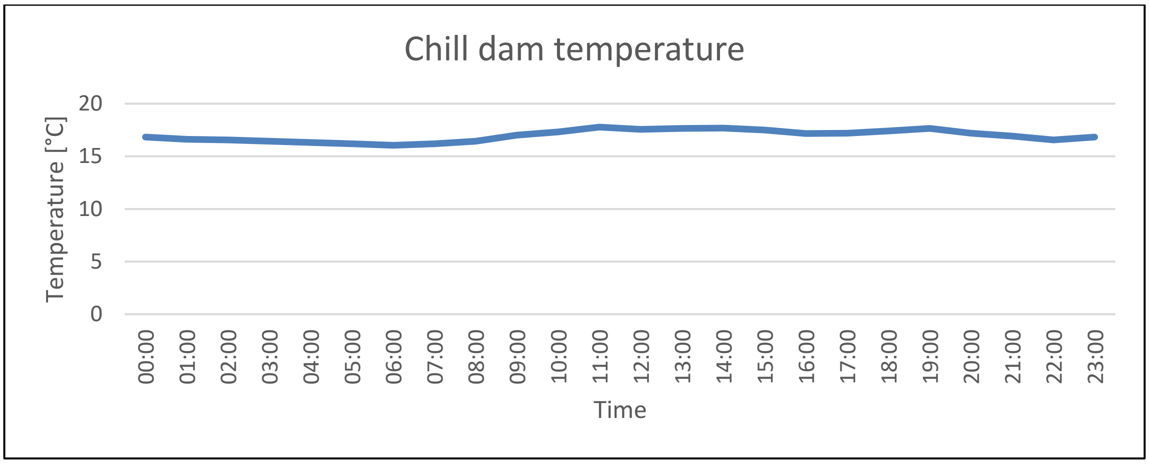

Figure 30 – Chill dam temperature baseline

The wet-bulb ambient temperature profile for the baseline period is shown in Figure 31. It is seen that the ambient temperatures start to rise at 6:00 to a maximum of 9°C. The temperatures start to decline after 16:00 and drops to a low 4°C.

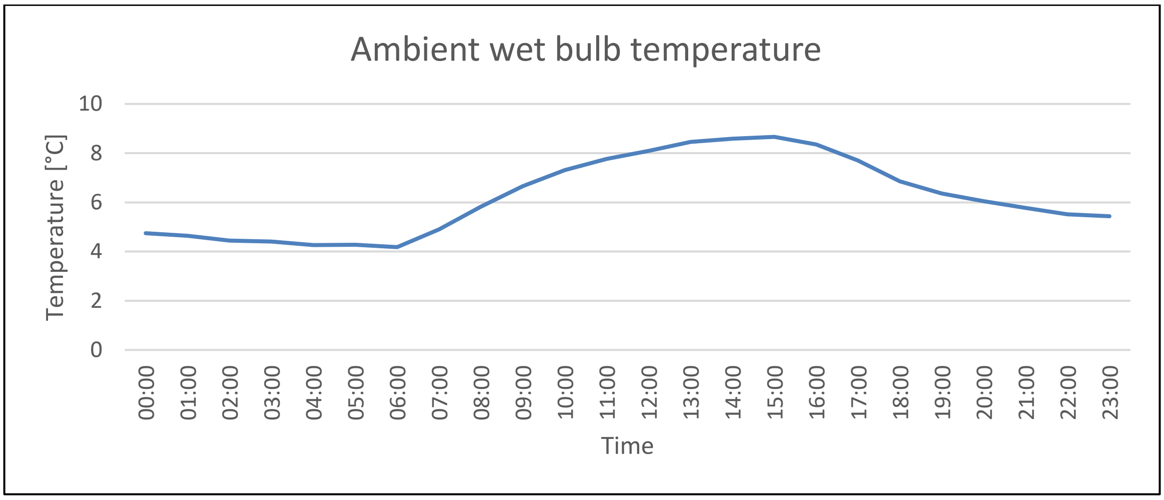

Figure 31 - Ambient wet-bulb temperature baseline

The water usage profile of the mine is indicated in Figure 32. The highest water usage occurs during peak drilling shifts. The water usage decreases in the evening during blasting periods.

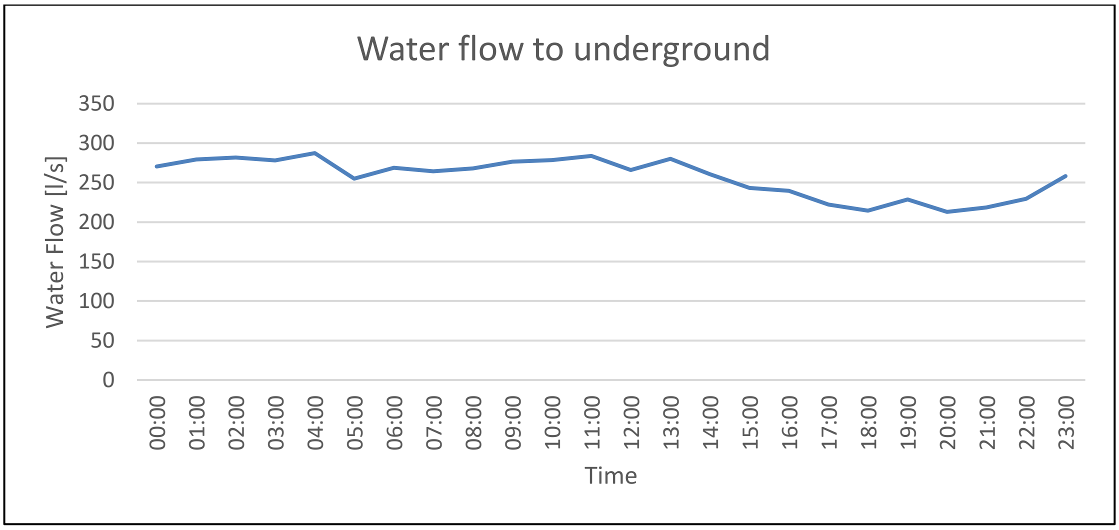

Figure 32 - Water flow to underground baseline

4.3.3 Simulation development and verification

A simulation model of the mine was developed through the use of Process Tool Box (PTB). The simulation model was used to recreate a single day (19th of August) during the baseline period. A single day was simulated due to the amount of data processing required for all the components for the refrigeration systems. The result of the simulation can be seen in Table 11. More detail regarding the simulation development and verification thereof can be found in Appendix A.

Table 11 - Simulation result comparison

	Simulated Values	Actual values (19 August 2016)	% Difference
Pre-cooling dam temperature [°C]	28.2	28.1	0.35
Chilled dam temperature [°C]	11.3	10.8	4.42
Evaporator inlet temperature[°C]	28.2	28.2	0
Evaporator outlet temperature [°C]	11.3	11.9	5.31
Water flow to underground [l/s]	373.8	375.9	0.56

The largest difference between the actual and simulated values is the evaporator outlet temperatures of the system. This is due to the automated control over the refrigeration plants in the simulation, whereas the actual system is dependent on operators to manually stop and start the system.

From the verification results, it can be seen that the simulation is accurate with an average percentage error of 2.2%. The simulation can now be used to simulate improvements on the PCT and the effect thereof.

4.4 Optimal pre-cooling performance

4.4.1 Problem identification

The refrigeration system components of mine A and the operation thereof was identified by using the first steps of the methodology in chapter 3. The next step in the methodology was to determine possible problems with the system. The following were identified as concerns regarding the pre-cooling performance.

Increased operating flow: The production of mine A has steadily increased to a point where the existing equipment, especially the PCT, were over extended. The water flow rate through the PCT had increased to a point where it exceeds the design specifications. Resulting in decreased efficiency of the PCT.

Water distribution system: The increased water flow resulted in an additional problem. The pre-cooling transfer pumps were not designed for the current water flow rate. As a means to circumvent the problem, the mine opens a valve between the hot water and pre-cooling dam. Allowing the hot water coming from underground to directly flow to the pre-cooling dam, by-passing the PCT. This significantly increases the temperature of the pre-cooling dam.

Ambient conditions: South Africa is known for its warm climate, easily passing ambient temperatures of 31°C (temperature reached during December 2016, Carletonville). Once the temperature difference between the water and air inlet of the PCT is less than 2-4°C the effect of pre-cooling becomes negligible.

This is once again a concern in the peak summer day periods. During the rest of the time the ambient wet-bulb temperature remains below the pre-cooling inlet temperature.

Poor maintenance: Upon inspection of the PCT, it was found that the fill was covered in scale and a build-up of sediment. In addition to this, it was found that out of the 32 fans only 14 fans were still operational. This was due to a lack of maintenance and constant operation of the fans. Both of these factors greatly reduce the ability of the PCT to cool the water.

Due to high utilisation, the PCT are scheduled to be cleaned only on a yearly basis during the winter. The time period proofed too long as scale, sediment and breakdowns occurs long before this scheduled time period.

Poor water quality: Poor maintenance is not only to blame for the scale sediment and build-up. Poor water quality with high concentrations of dissolved contaminants and impurities in the water increases the rate at which build-up occurs. The water is treated by adding a fixed amount of chemicals to the water. With varying flow rates, the fixed amount added is not always enough to treat the water.

The cause of inefficiencies on the PCT were identified. These problems need to be addressed to obtain the optimal pre-cooling performance. The proposed solution is simulated to evaluate the effectiveness of the solution. The objective of this section is thus to determine a possible solution and evaluate the effectiveness thereof.

4.4.2 Solution development

The first step in improving the pre-cooling performance is to repair the broken towers. This includes the repair of the broken fans and the replacement or cleaning of the fill, depending on the severity of the scaling and dirt build-up.

The repairing of the PCT will have little impact if the towers are by-passed. Thus, in addition to the repair work an actuated valve control must be implemented on the by-pass valve. The control can be either manual or automated based on the hot dam level. This decision will depend on the available funds for the initiative. This will ensure that the by-pass is used only when necessary.

The second step in the solution development needs to address the usage of the by-pass valve. This can be done by ensuring that enough water flow can be provided to the PCT. The installation of a third pre-cooling pump will provide sufficient flow to ensure that the by-pass is not needed.

With the increased water flow of a third pump the liquid to gas (l/g) ratio also increases. Resulting in reduced efficiency of the towers during high water flow periods. The last step for optimal pre-cooling will be the addition of a third pre-cooling bank. This will ensure that the pre-cooling remains optimal throughout the day.

4.4.3 Simulating the solution

The verified simulation developed in section 4.3.3 was used to simulate the effect of the proposed solutions. The solution can be seen a three-part solution with each part influencing the whole refrigerating system. The simulation will thus be simulated and evaluated accordingly.

Part 1: Recommissioning of PCT and the addition of an actuated valve on pre-cooling by-pass.

With the PCT repaired and the addition of the actuated valve the simulated power consumption of the system reduced on average by 700kW. Figure 33 indicates the difference between the original simulation and the first step of the solution.

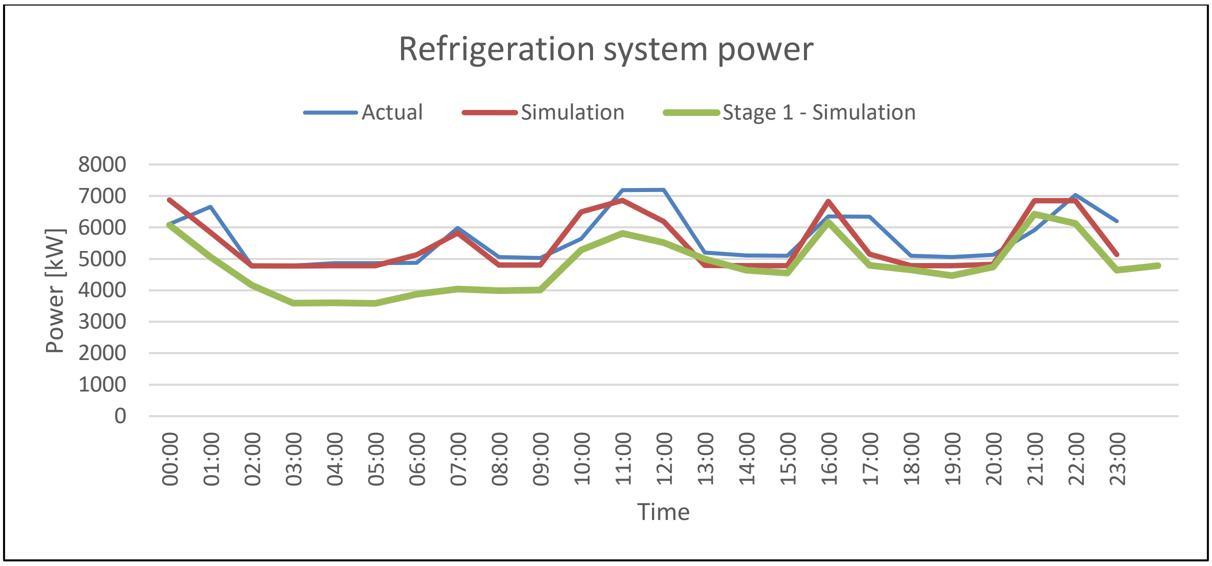

Figure 33 - Stage 1: Refrigeration system power

Figure 34 shows the water usage profile of the system. The changes to the system did not affect the water flow rate. The power consumption increases close to the baseline after 10:00, which is the time the water flow of the system also increased as indicated by Figure 34. During the increased flow periods, the PCT are by-passed, negatively affecting the pre-cooling dam temperatures and the power usage. The cooling ability of the towers are also affected by the ambient conditions which also increased by that time.

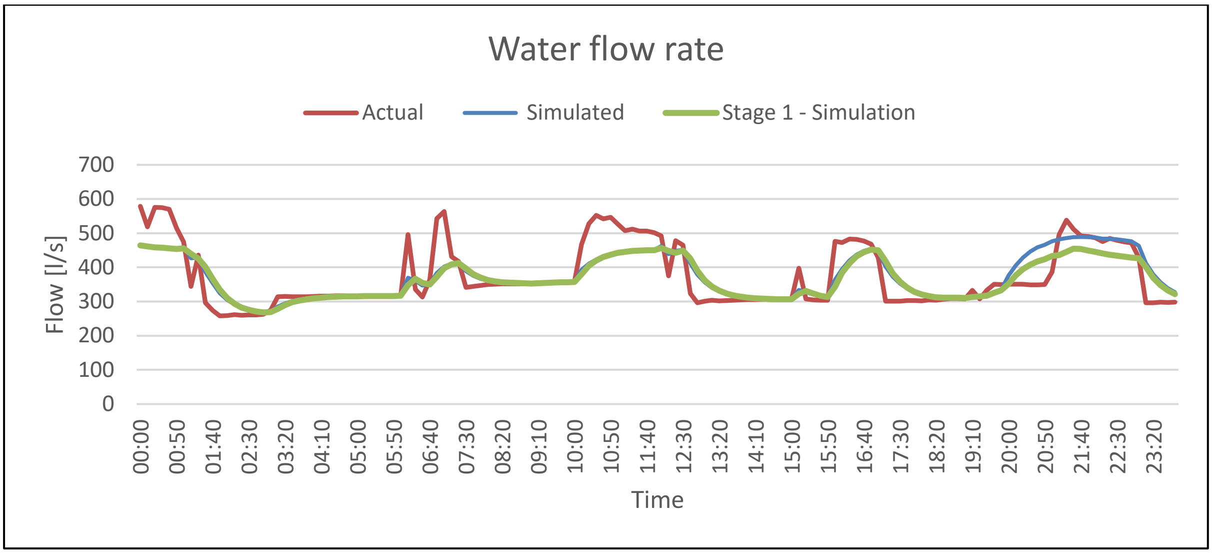

Figure 34 - Stage 1: Water flow through the refrigeration system

The repairs on the PCT resulted in improved efficiencies. This in return improved the pre-cooling dam temperatures as indicated by Figure 35. The reduced usage of the by-pass valve and the increased efficiency led to an improvement of 9°C on the pre-cooling dam.

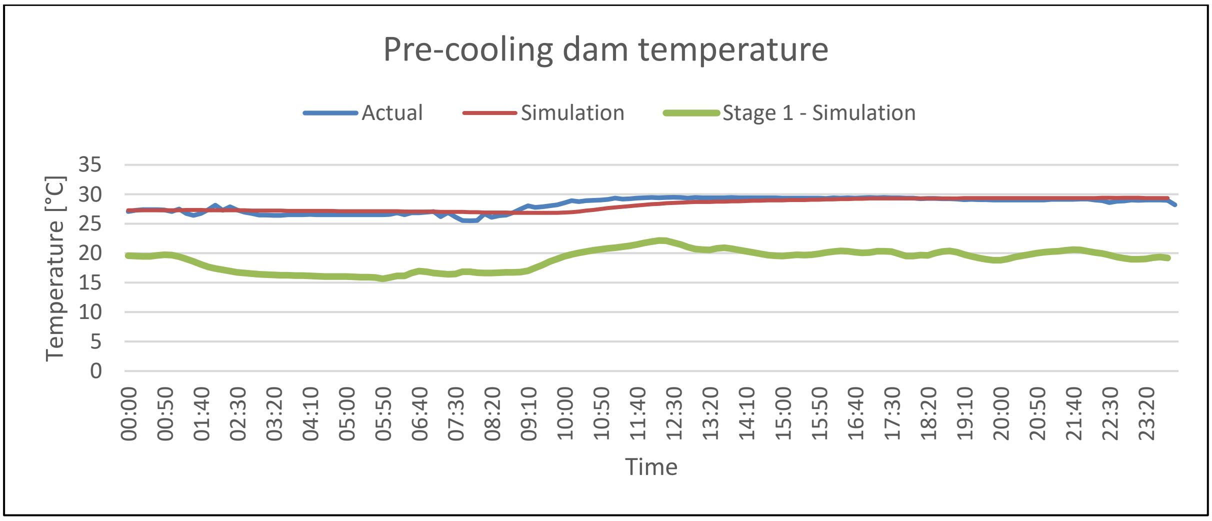

Figure 35 - Stage 1: Pre-cooling dam temperature

The chill dam also improved with 3.4°C, as seen in Figure 36. The reduction in pre-cooling dam temperature is not directly translated into the chill dam. This is due to the refrigeration plants being able to meet their set point. For this reason, both an improvement on service water temperature and power consumption is achieved.

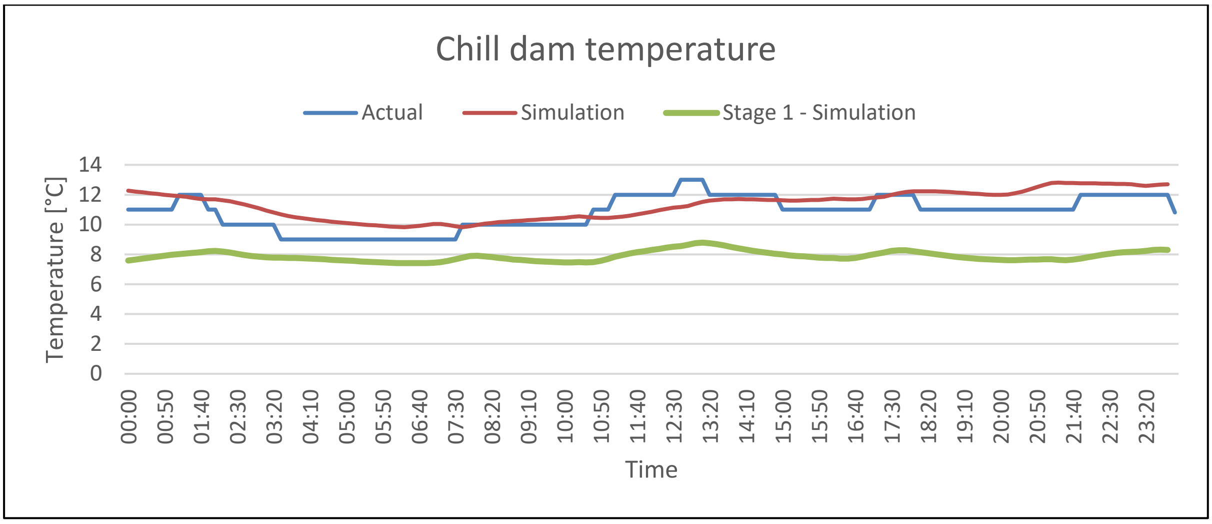

Figure 36 - Stage 1: Chill dam temperature

Part 2: The addition of a third pre-cooling pump.

The addition of a third pre-cooling pump eliminates the need for the by-pass valve. As a result, all the water is passed through the PCT. A significant simulated saving of 1.3 MW is achieved while maintaining the same water flow rate.

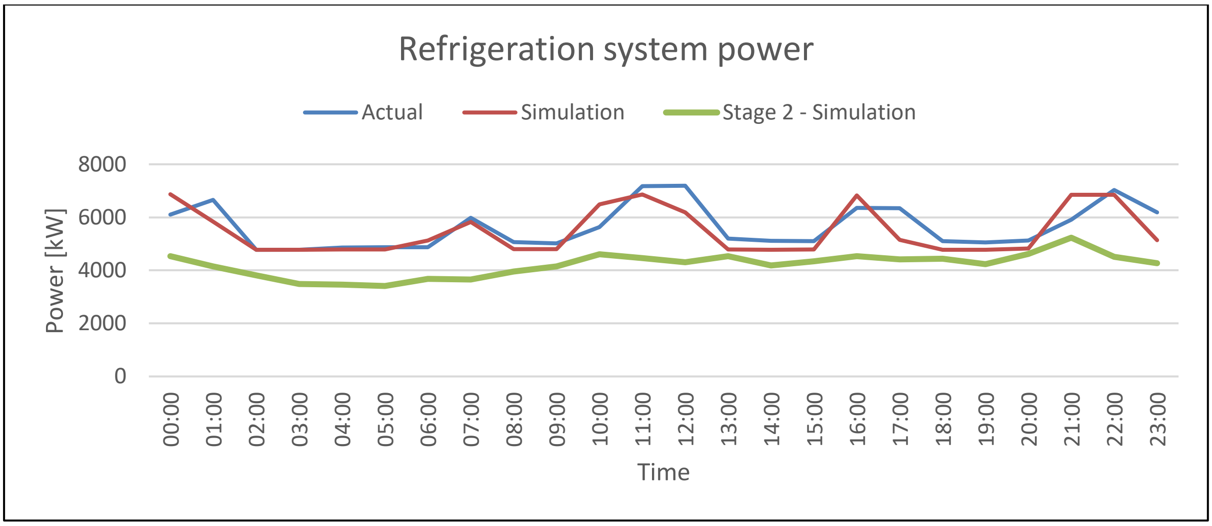

Figure 37 - Stage 2: Refrigeration system power

The water flow rate has a reduced effect on the power usage as all the water from underground passes through the PCT. Resulting in a more linear power consumption. Figure 38 shows the water usage profile remained unchanged during the simulation.

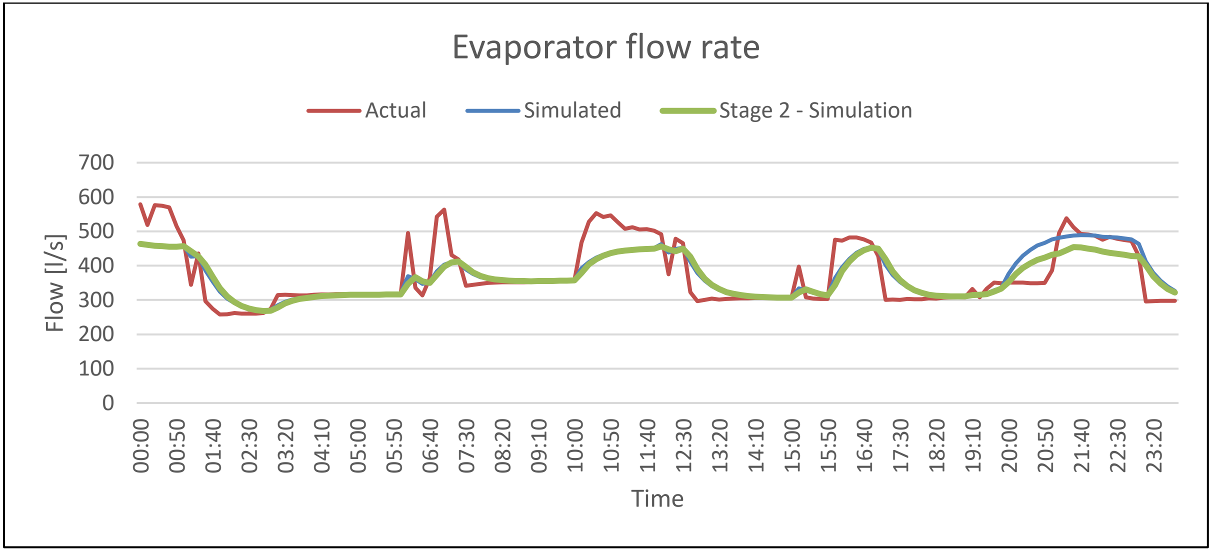

Figure 38 - Stage 2: Water flow through the refrigeration system

Both the pre-cool dam and the chill dam showed a decrease in temperature throughout the day as seen in Figure 39 and Figure 40 respectively. The differential in temperature is not translated from the pre-cool dam to the chill dam. This is due to the refrigeration plants being able to meet the set-point. A decision can be made to optimise the system for either reduced power usage or for improved cooling. For this simulation, a reduction in power usage was simulated and a savings of 1.3MW was achieved.

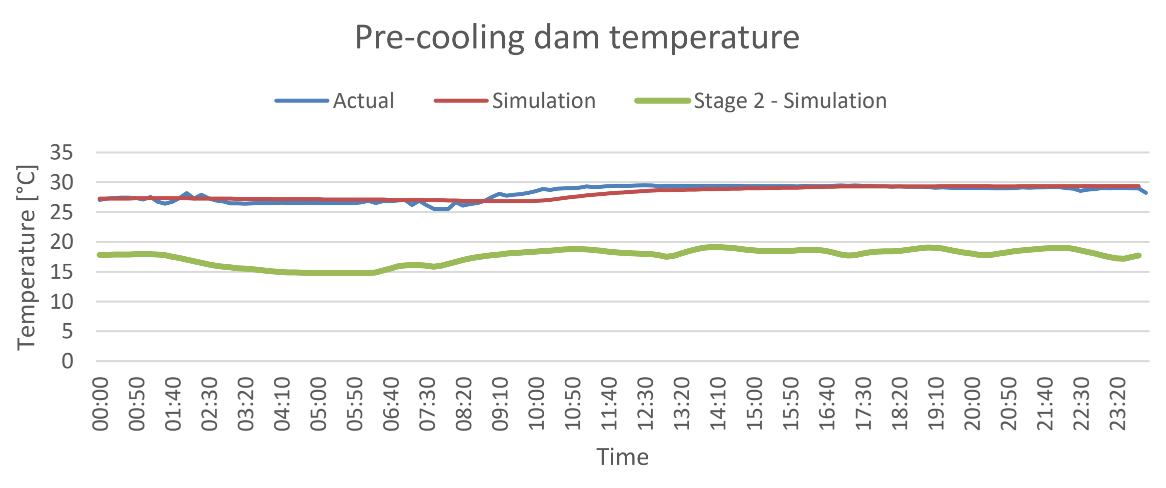

Figure 39 - Stage 2: Pre-cooling dam temperature

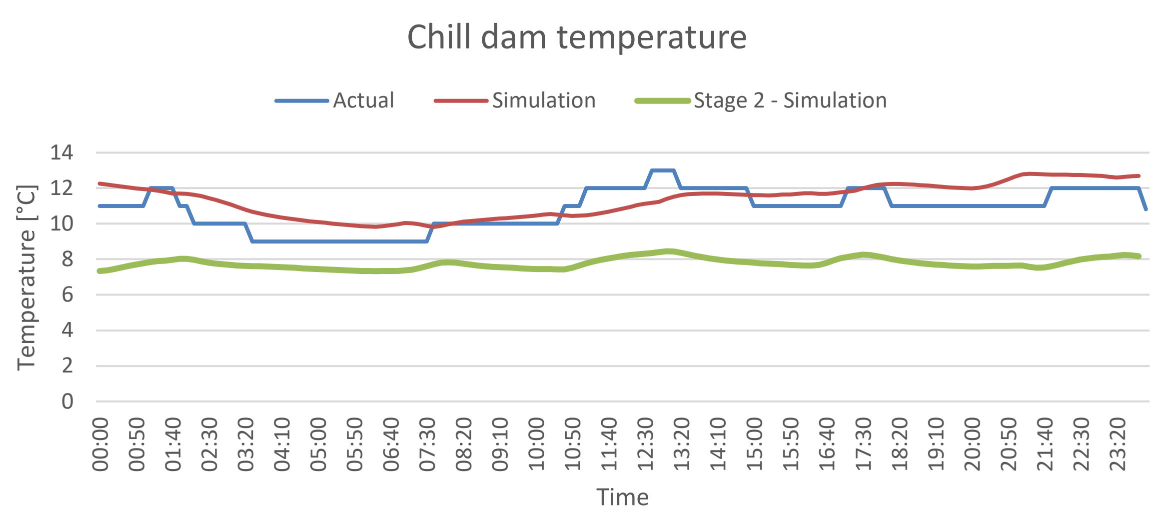

Figure 40 - Stage 2: Chill dam temperature

Stage 3: Additional PCT and additional pump

The addition of the third PCT bank resulted in the largest reduction in electricity usage. This do come at a cost as the installation of the PCT bank is expensive. Figure 41 indicates the daily power savings achieved through the pre-cooling optimisation. The savings is achieved while maintaining the same water flow through the mine refrigeration system. The water flow rate is indicated in Figure 42

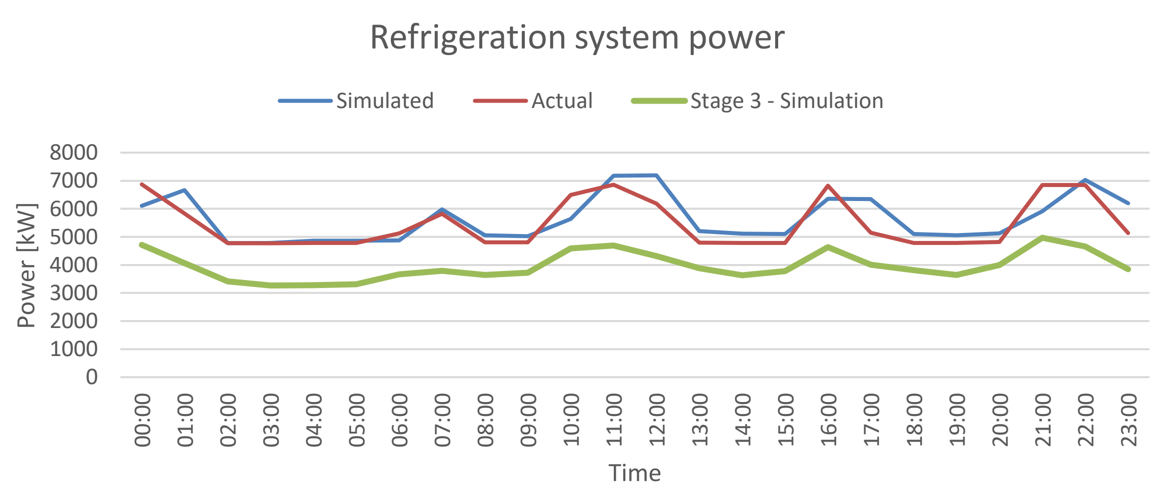

Figure 41 - Stage 3: Refrigeration system power

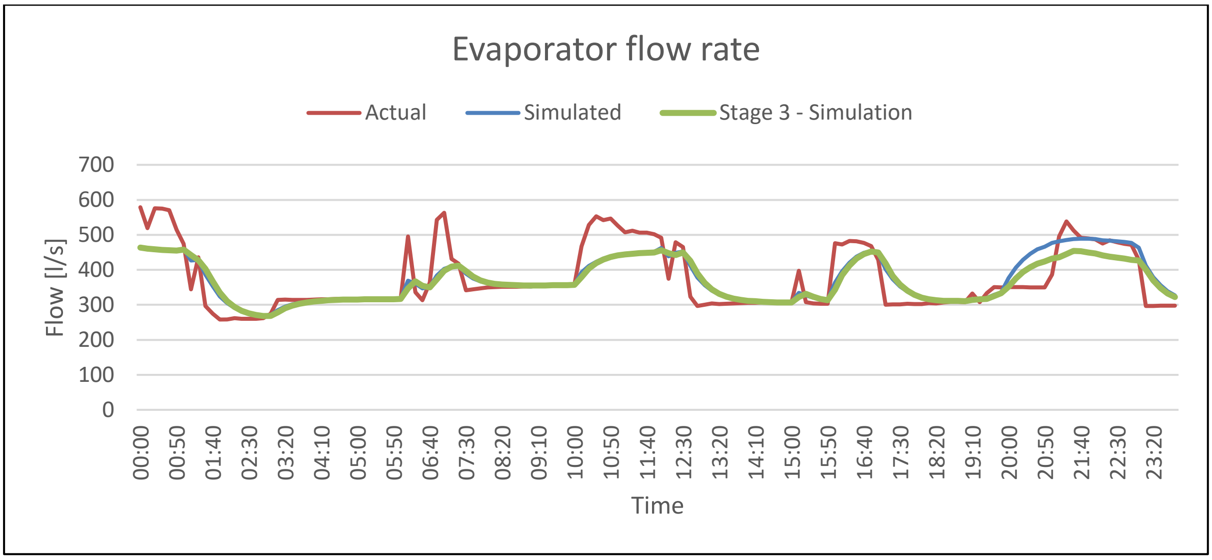

Figure 42 - Stage 3: Water flow through the refrigeration system

As expected the largest temperature differential over the pre-cooling dam is achieved with the installation of the 3rd PCT bank. Figure 43 indicates a pre-cool dam improvement of 13.6°C.

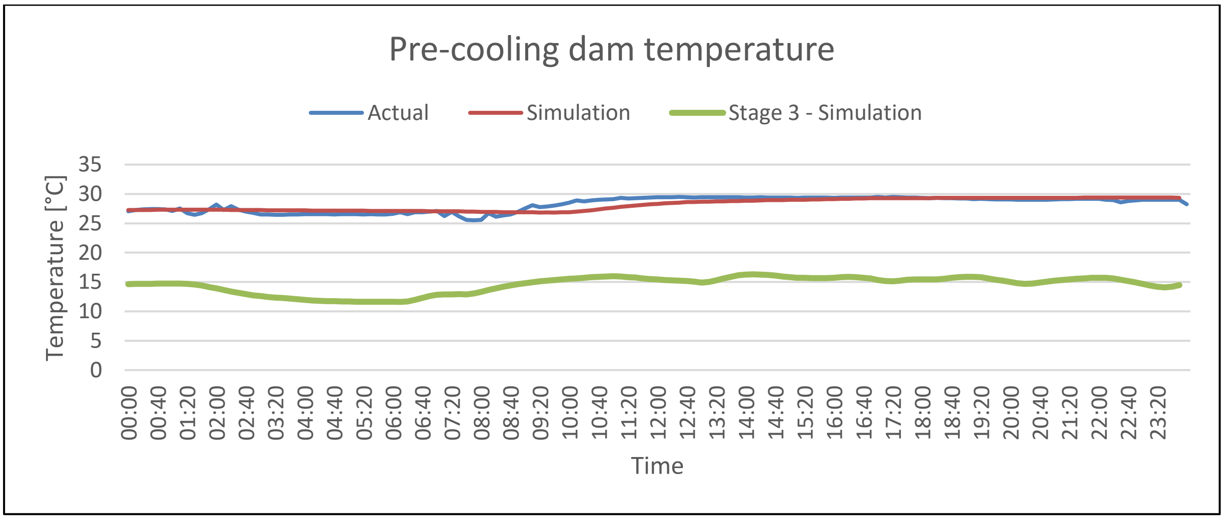

Figure 43 - Stage 3: Pre-cooling dam temperature

The same reduction in temperate as in the previous simulation was achieved on the chill dam as indicated by Figure 44. As in the stage 2, this simulation was optimised for reduced power usage while maintaining acceptable cooling levels. The improved pre-cooling dam temperature resulted in less load on the refrigeration plants, reducing the power usage.

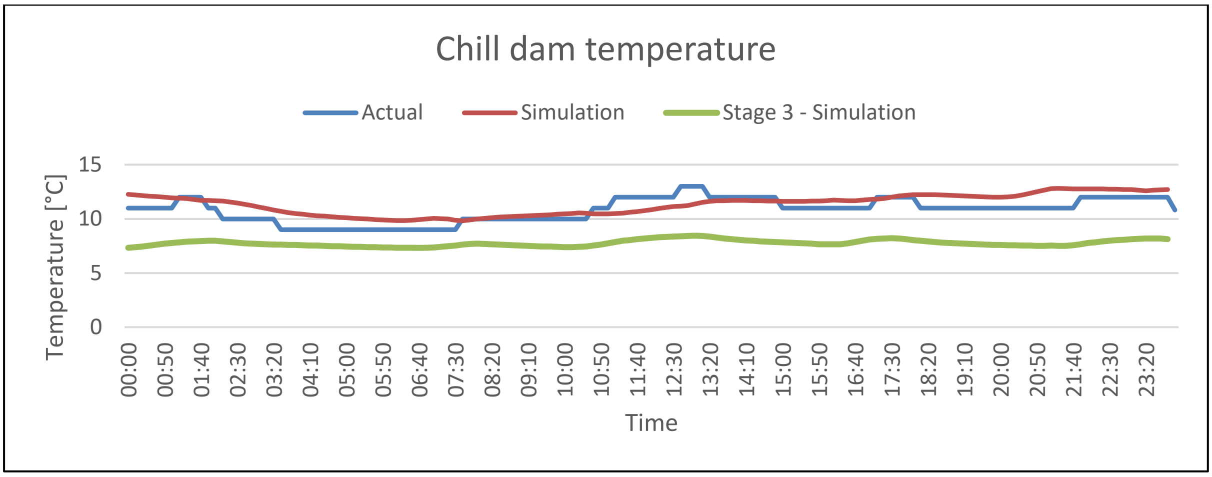

Figure 44 - Stage 3: Chill dam temperature

Table 12 gives a summary of the results in each stage of the simulated solution. It is important to note that the savings indicated in Table 12 are dependent on the water flow rate. An increase in water flow will always affect the refrigeration system negatively. However due to baseline scaling and the improved cooling capacity of the system the savings of the refrigeration system will increase. Conversely, a decrease in water usage will eliminate the need for the additional PCT bank.

Table 12 - Optimised simulation results

Simulated configuration	Part 1	Part 2	Part 3
Pre-cooling dam temperature reduction [˚C]	9.3	10.6	13.6
Chill dam temperature reduction [˚C]	3.4	3.6	3.6
Power saving [kW]	700	1 300	1 500
Annual cost saving [R]	4.1 million	7.0 million	8.5 million

A cost saving of up to R8.5 million is achievable with the full implementation of the solution. This saving is obtainable while the chill dam is improved by 3.6°C. Further service delivery improvements on the chill dam temperatures can be achieved by reducing the refrigeration plants set point. This will also reduce the costs saving.

4.5 Optimal pre-cooling results

The three-part simulated solution showed a significant improvement on the refrigeration system. An improvement on both power usage and system temperatures were achieved. The proposed solution was implemented in this section. The effect of the PCT can be evaluated on a real system with actual data. The solution was validated and the effect of the pre-cooling was determined.

4.5.1 Implementation

The simulated results were used to motivate the implementation of the solution on the PCT. The mine’s management decided to implement the solutions only until part 2.

The repairs on the PCT were completed during the month of October 2016. Out of the 32 fans, 4 were replaced and 13 were repaired. These fans are depicted in Figure 45. The fill was also removed and cleaned during this period.

Figure 45 - PCT of Mine A

An actuated valve with automatic control was installed on the PCT by-pass. The by-pass valve is now only used when the improved system cannot cope with the flow. The installed valve is shown in Figure 46.

Figure 46 - Actuated valve installation

The need for the by-pass valve was also reduced with the installation of a third pre-cooling pump. The installed pump is shown in Figure 47. To save costs the pump was installed on the same pipe network that feeds the first PCT bank. Thus, the flow is not evenly distributed between the PCT.

Figure 47 - Additional pump installation

The installation of a third PCT bank was not implemented. Funding for the installation was limited at the time of writing. However, this could still be implemented as a future project.

4.5.2 Pre-cooling tower comparison

The mine completed the installations in December 2016, shortly before the holiday break. The results of the improved PCT can be seen in Table 13. The actual data that was used was form the 27 July to 28 August 2017. The winter period was selected as the ambient temperatures corresponded with the baseline period. Water flow is also reduced during winter periods as less cooling is required.

Table 13 - Improved PCT comparison

Cooling tower performance		
	(27 Jul to 27 Aug 2016)	(27 Jul to 28 Aug 2017)
Ambient temperature [°C]	6.2	6.3
Pre-cooling inlet temperature [°C]	29.0	26.9
Pre-cooling outlet temperature [°C]	25.1	18.3
Approach [°C]	18.8	12.1
Range [°C]	3.9	8.6
Efficiency [%]	17.2	41.6
Cooling Capacity [kW]	5 264	10 135

The outlet temperature of the PCT was reduced by 6.8°C compared to the previous year. It is important to note that the PCT inlet temperate also decreased by 2.1 °C. Thus, in comparison the range of the pre-cooling only increased by 4.7°C as seen in Figure 48.

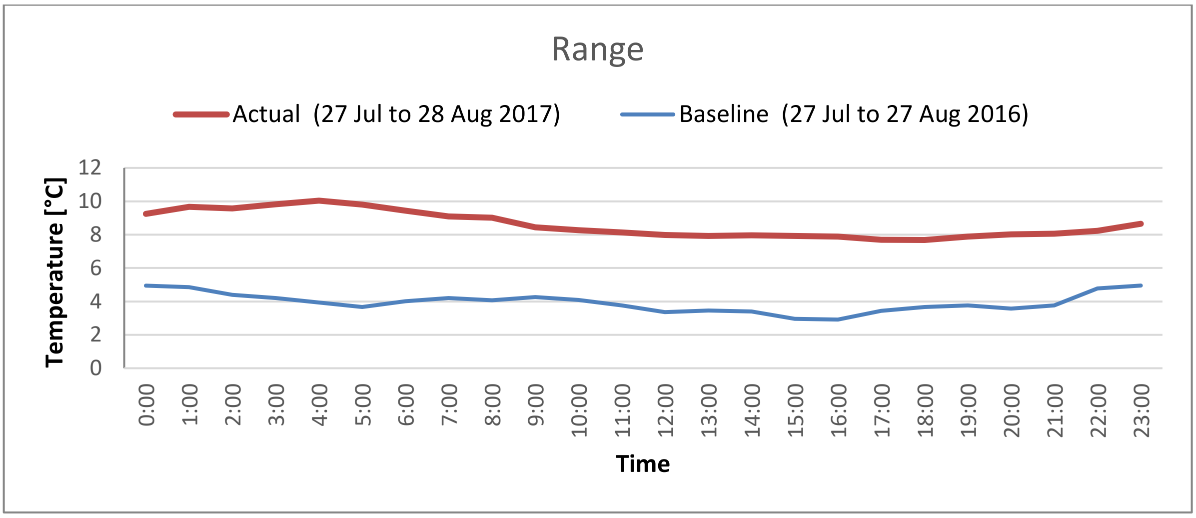

Figure 48 – Range comparison

With the cooler water inlet temperature and improved range, the difference between the pre-cooling outlet temperature and ambient temperature also decreased. The improvement of the approach can be seen in Figure 49.

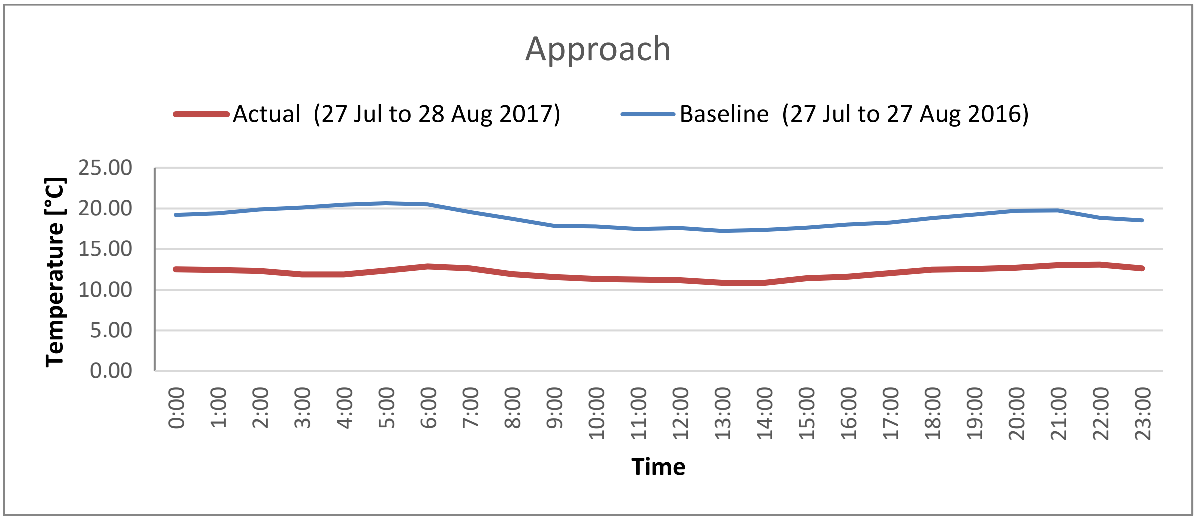

Figure 49 – Approach comparison

With an increased range and reduction of the approach the pre-cooling efficiency increased. An increased efficiency of only 25% was obtained as indicated by Figure 50. From the Equation 10 in chapter 2 the efficiency is reduced when the ambient temperature is decreased.

The PCT are only capable of providing a maximum temperature difference between inlet -and outlet water temperatures. With a large reduction in ambient temperatures the efficiency of the pre-cooling reduces even though the cooling capacity increases. The pre-cooling efficiency was further impacted by the distribution of the water from the pre-cooling pumps.

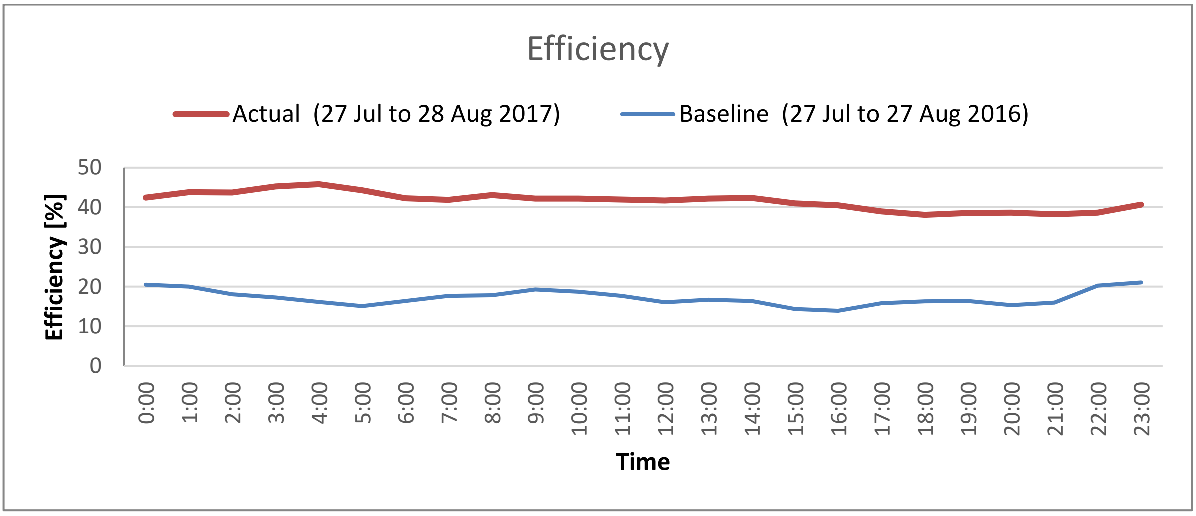

Figure 50 – Efficiency comparison

The cooling capabilities of the PCT improved significantly as indicated by Figure 51. The solution developed in section 4.4 proved to be successful.

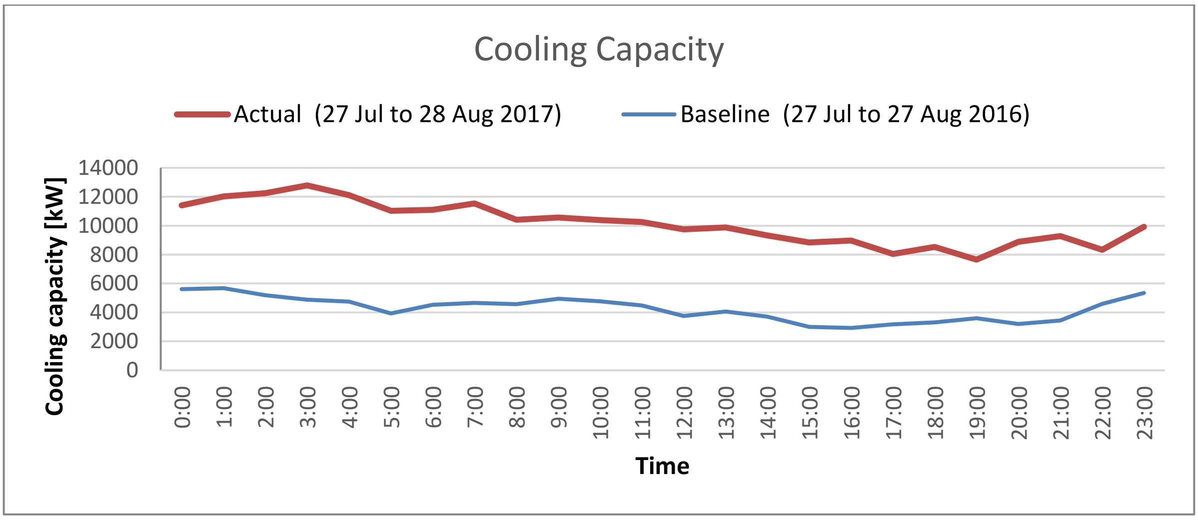

Figure 51 – Cooling capacity comparison

4.5.3 Refrigeration system comparison

The impact on improving the pre-cooling performance was seen throughout the refrigeration system. Table 14 compares the resulting power usage and KPIs to the previous year. It is important to note that the flow increased in 2017 and baseline scaling was implemented.

Table 14 – Refrigeration system improvement comparison

	Baseline **(27 Jul to 27 Aug 2016)**	**Actual** **(27 Jul to 28 Aug 2017)**
Power [kW]	4 438 (4 842 Scaled)	4 756
Pre-cooling dam temperature [°C]	25.0	18.3
Chill dam [°C]	17.0	6.7
Ambient wet-bulb temperature [°C]	6.2	6.3
Water flow to underground [l/s]	256	280

Figure 52 shows the wet-bulb ambient temperature for both periods. The average temperature of the two time periods differs with 0.1°C, with the 2017 results being the warmest. The periods are thus comparable according to the ambient temperatures.

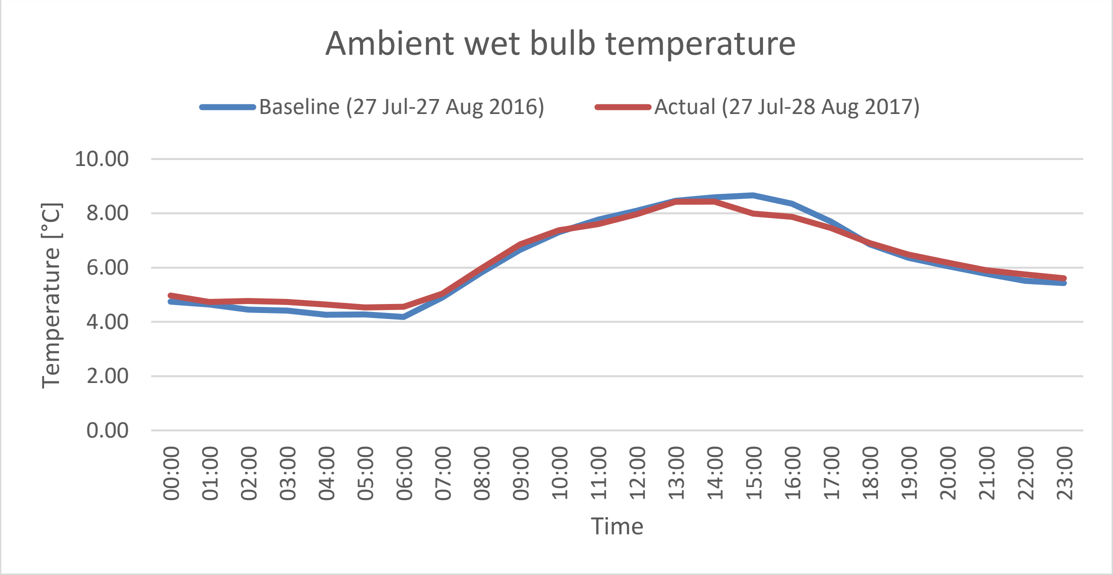

Figure 52 – Ambient temperature comparison

The water flow to underground increased for 2017 during the particular comparison period. An average of 24.3 l/s increase can be seen in Figure 53. An increase in water usage affects the power consumption of the refrigeration plants. Baseline scaling is thus needed to compare the power consumption for each period.

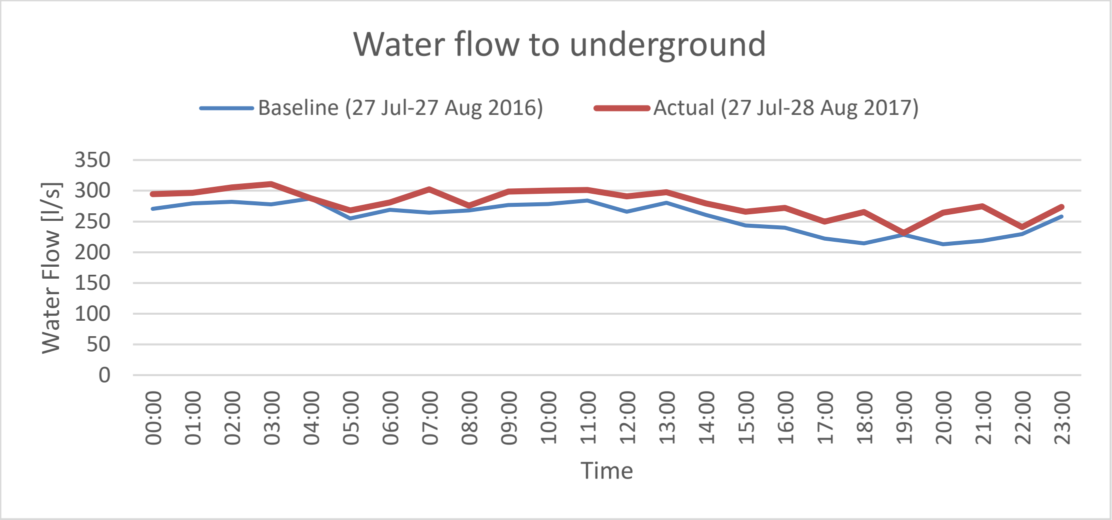

Figure 53 – Water flow to underground comparison

Figure 54 shows the power usage of the compared time periods. Also shown in the figure is the scaled baseline. The baseline was scaled with a factor of 1.095 which was calculated from the difference in water usage.

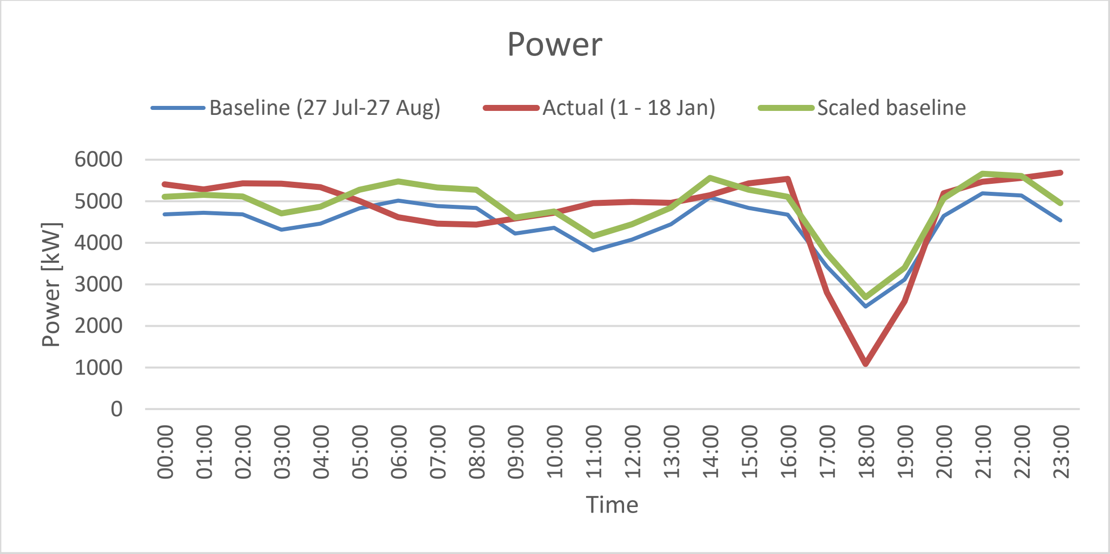

Figure 54 – Power comparison

With the scaled baseline, the power usage decreased to the comparing year by 86 kW. The power profile of the system changed with an improved evening load shift. The evening load shift does have an effect on the chill dam temperatures. This is indicated by Figure 55. The chill dam temperatures reduced by 10°C in comparison to the previous year.

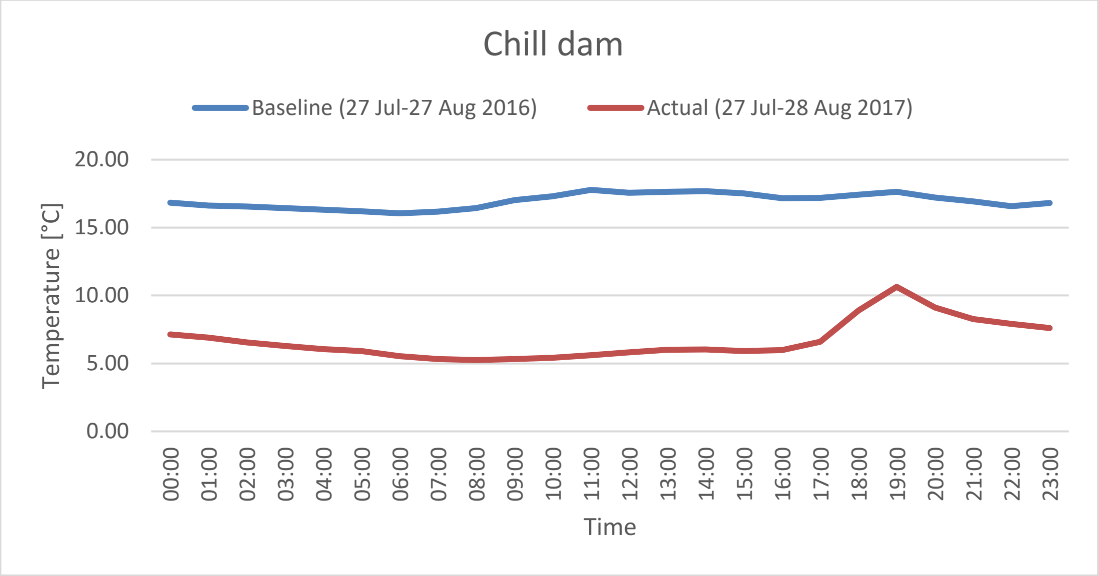

Figure 55 – Chill dam temperature comparison

The systems overall coefficient of performance has improved substantially. This is attributed to the PCT using very little electrical energy in comparison to their cooling performance. The improvement can be seen in Figure 56. The load shift also affects the COP of the system as the electrical energy used is reduced during this time period.

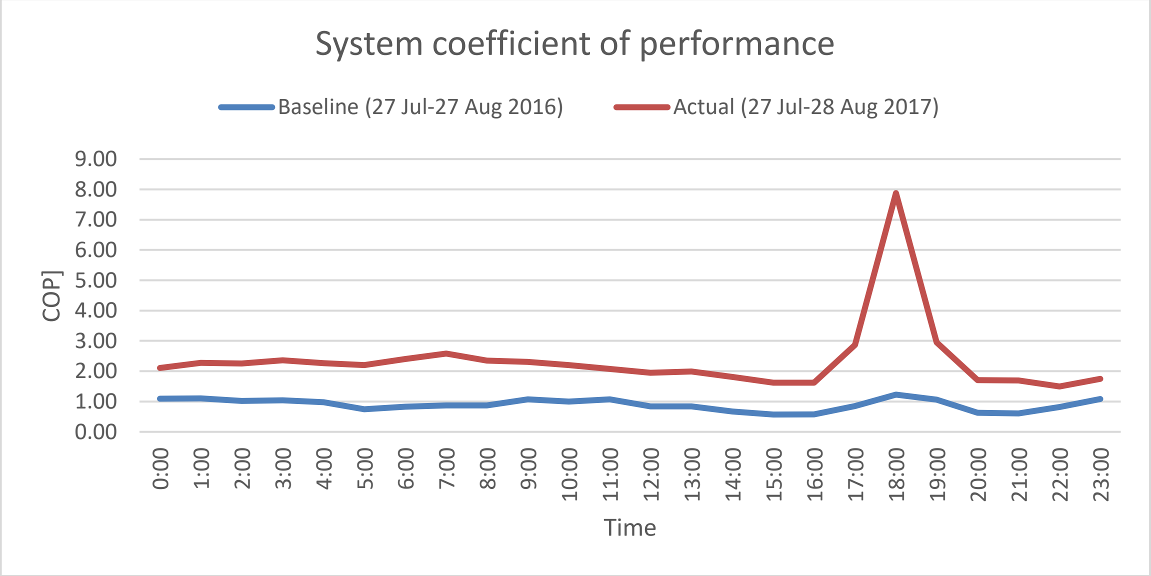

Figure 56 - System COP comparison

4.5.4 Validation of the simulation

Table 15 compares the actual results of the pre-cooling improvements to the predicted results of the simulation. As explained with the implementation of the PCT improvements, only until stage 2 of the solution has been implemented. As such, the stage 2 of the simulation is compared to the actual results.

Table 15 - Simulated versus actual results

	Simulated Improvement	Actual Improvement
Power [kW]	1 300	86
Pre-cooling dam temperature [°C]	10.6	6.7
Chill dam [°C]	3.6	10.3

An improvement of only 6.7°C was achieved in the implementation. This is quite far from the simulated 10.6°C. The use of the by-pass valve during the period contribute largely to the difference. Additionally, the uneven water distribution between the towers resulted in less efficient pre-cooling.

The chill dam showed a much larger improvement on the actual results than on the simulated values. The savings are also much less than predicted by the simulation. The reason for this large difference is due to the fact that the refrigeration plant set point was lowered to provide better cooling for the mine. A higher set point results in a greater power consumption and lower chill dam levels. This together with the less efficient pre-cooling resulted in the large difference between the simulated and actual results.

4.6 Conclusion

The characterisation of the refrigeration system is important to understanding the operation of the system. Once a proper understanding is obtained, inefficiencies on the pre-cooling system can be identified.

Once identified, the effect of the inefficient operation is determined through analysing the affected PCT. Baselines are created of the inefficient operation period to compare any change on the system.

The solution developed to address the ineffective operation of the refrigeration system was evaluated through the use of a verified simulation. The simulation showed significant savings of R8.3 million as well as an improvement of 3.6°C on the chill dam temperatures.

Simulated result was used to motivate the implementation of the solution on the mine. The implementation of the solution resulted in improved pre-cooling efficiencies, and thus improved pre-cooling outlet temperatures. A reduction of 10.3°C was achieved on the chill dams while the power usage showed an insignificant improvement.

Improvement of the PCT benefited the whole refrigeration. Improvement of the system temperatures were achieved while maintaining the same power consumption. The savings predicted by the simulation were not obtained. This is due to the mine lowering the refrigeration plant set point to further reduce the chilled water temperature.

Chapter 5

5 Conclusions and recommendations

5.1 Conclusions

Profitable gold mining in South Africa has become increasingly difficult. Challenges such as the decreased gold prices, increased labour and operational cost as well as low productivity contributed largely to the reduced profit margins. The increased operational cost is partially associated with mining at increased depths, as well as the use of energy intensive equipment.

Mining at increased depths are as a result of the continuous search for higher-grade ore. The main challenge associated with deep-level mining is the extreme underground temperatures. While there are cooling systems used to reduce the underground temperatures, a lot more can be done to improving the efficiency of these systems.

The use of PCT is an efficient means to reduce the load on the cooling system. PCT provide significant cooling for the amount of electricity needed. These towers are however maintenance intensive and are often over looked as an integral part of the cooling system. With passing time and constant usage, the performance of the towers deteriorates. This in return has an adverse effect on the rest of the cooling system.

To be able to fully understand the impact of pre-cooling on mine refrigeration systems, it was first required to understand the basic concepts of cooling towers as well as the refrigeration system. This also gave valuable insight the development of a methodology.

The developed methodology was used to analyse, improve and evaluate the pre-cooling performance, and the overall refrigeration system performance of a case study on an operating gold mine, Mine A. The method consists out of identification and characterisation of the refrigeration system, benchmarking and analysis of the current system performance and the improvement and evaluation of the PCT performance. The method was developed as a guideline for pre-cooling optimisation and can be adapted for any system utilising PCT.

Characterisation of the refrigeration system was important to understanding the operation of the system. With the improved understanding, inefficiencies on the pre-cooling system were identified. Baselines were created of the inefficient operation period to compare any change on the system.

A solution was developed to address the ineffective operation of the refrigeration system. A simulation of the refrigeration system was used to evaluate the solution. The simulation showed significant savings as well as improved system temperatures were possible. The simulated result was used to motivate the implementation of the solution on the mine.

The implementation of the proposed solution resulted in an observed increase of 24.4% in the pre-cooling efficiency. Factors such as installation cost and operational factors limited the full improvement of the PCT. Additional results are shown in Table 16.

Table 16 - Improved PCT comparison

	Baseline	Actual	Improvement
Approach [°C]	18.8	12.1	6.7
Range [°C]	3.9	8.6	4.7
Efficiency [%]	17.2	41.6	24.4
Cooling Capacity [kW]	5 260	10 130	4 870

The improvement of the PCT benefited the whole refrigeration system. Improvement of the system temperatures were achieved while maintaining the same power consumption. The savings predicted by the simulation were not obtained. This was due to the mine lowering the refrigeration plant set point to further reduce the chilled water temperature. Table 17 indicates the operational improvements obtained on the mine.

Table 17 – Refrigeration system comparison

	Baseline	Actual
Power [kW]	4 842	4 756
Pre-cooling dam temperature [°C]	25	18.3
Chill dam [°C]	17.0	6.7
Ambient wet-bulb temperature [°C]	6.2	6.3
Water flow to underground [l/s]	256	280

This dissertation investigated the effect PCT have on mine refrigeration systems. Specifically, how deteriorated pre-cooling negatively effects refrigeration plants compared to the optimal operating conditions.

It was found that, through improving the efficiency of the cooling towers, the overall performance of the mine's refrigeration system can be improved along with a reduction in the operational costs. Further improvement of the refrigeration system temperatures is possible at reduced energy savings. The focus after optimisation must however be on continued maintenance of the PCT to sustain the benefit realised.

5.2 Recommendations for future work

Due to the successful implementation of the proposed solution on the case study, it is recommended that additional mines should be investigated. The investigation should analyse the PCT on different mines to determine if there is scope for improvement. The proposed methodology should then be used to reduce the operational costs or obtain an operational improvement.

The dissertation focused primarily on PCT, however it is recommended that cooling towers in general should be investigated. This includes the CCT as well as the BAC. The developed methodology can be adapted to evaluate the different towers and determine the effect on the entire system. An improvement on these cooling towers can result in additional cost savings and operational improvements.

It is also recommended that the methodology should be used on any system containing cooling towers. Thus, expanding the investigation into additional industries. The main outline of the methodology can still be used in the analysis. Small changes may be needed to tailor the methodology to the system.

During the analysis of the PCT it was found that the ambient temperatures influenced the cooling ability and efficiency of the towers. The investigation was conducted in winter were the ambient temperatures are at the lowest. During this period the BAC were off due to the low ambient conditions. It is therefore recommended that the analysis is taken further during the summer months.

With the improvement of the pre-cooling performance came an improved operational temperature. To ensure that the improvement is maintained a maintenance plan can be developed and implemented.

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Appendix A: PCT specifications

Specifications on ICT 4800 cooling tower used at Mine A:

Internal structure:

- Side frames are constructed of 40 x 40 x 2 mm 3CR12 stainless steel.
- Bolds and nuts of grade 304 and 316 stainless steel are used to bolt frames together.
- 3CR12 channel is used for fill support.
- Each ICT 4800 cooling tower is divided into 4 cells by means of stainless steel sheeting to enable independent functioning.
- Roof support is fabricated from stainless steel channel.

Water distribution system:

- Four 7200mm galvanised pipes are used per tower.
- Four 2 ½ “nozzles are used per pipe. This results in 16 nozzles per tower.

Fill media:

- Stainless steel frames with layered mesh (biaxial polypropylene).
- The frames will be made into sizes 1200 x 1000 x 1000mm (L x W x H) to enable easy removal and cleaning.
- The polypropylene mesh used is of high strength for durability.
- Biaxial polypropylene mesh can handle constant working temperatures of 75°C and short period temperature spikes of up to 85°C.
- The mesh is installed inside a stainless-steel wire, allowing the mesh to vibrate, which makes the mesh self-cleaning to a large extent.
- These frames are lightweight and can easily be handled by a single person.

Figure 57 – Pre-cooling tower fill

External cladding:

- Fibreglass cladding secured by means of “turn-clips” for easy removal.
- Standard colour: Turquoise.

Ventilation fans:

- 4 of 1200mm fans per unit.
- Each fan delivering 17m³/s airflow.
- Fans are direct driven by means of 5.5Kw 6 pole 525/380V electric motors, IP 55 insulated.
- Fan blades are of aluminium construction.

Appendix B: Simulation development and verification

Figure 63 indicates the layout of the developed simulation used throughout chapter 4. As in the real world the simulation developed recreated all the system components used in the refrigeration system. The information gathered in section 4.1 was then used to specify each component accordingly. Information such as day specific refrigeration plant schedules and the water flow through the system is then added to the simulation.

The results of the simulation can be seen in the figures below. It can be seen that the simulation follows the actual profile of each of the KPIs within a reasonable margin.

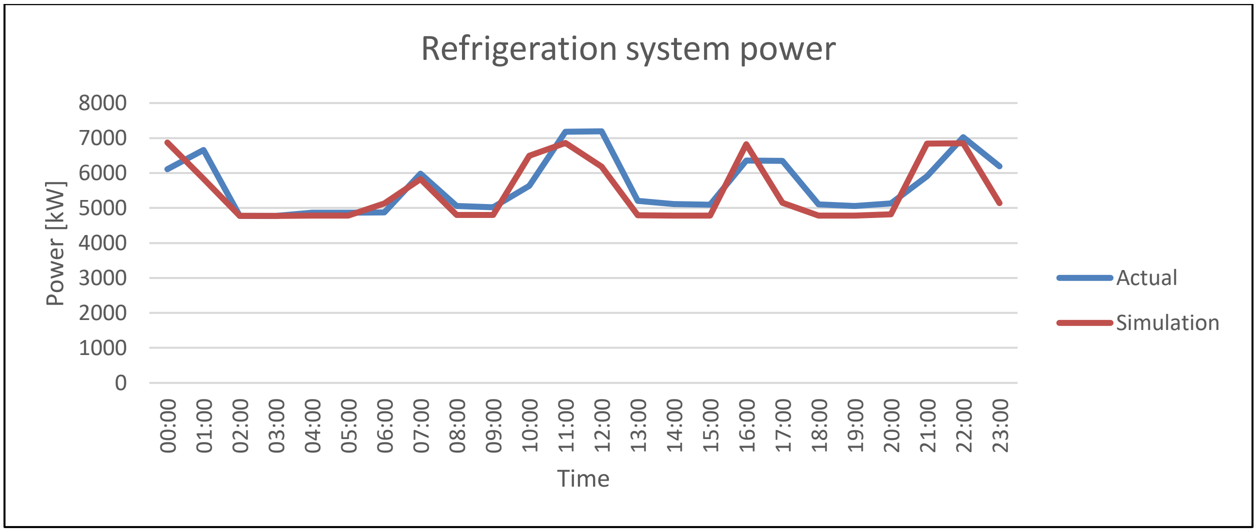


Figure 58 – Refrigeration system power comparison.

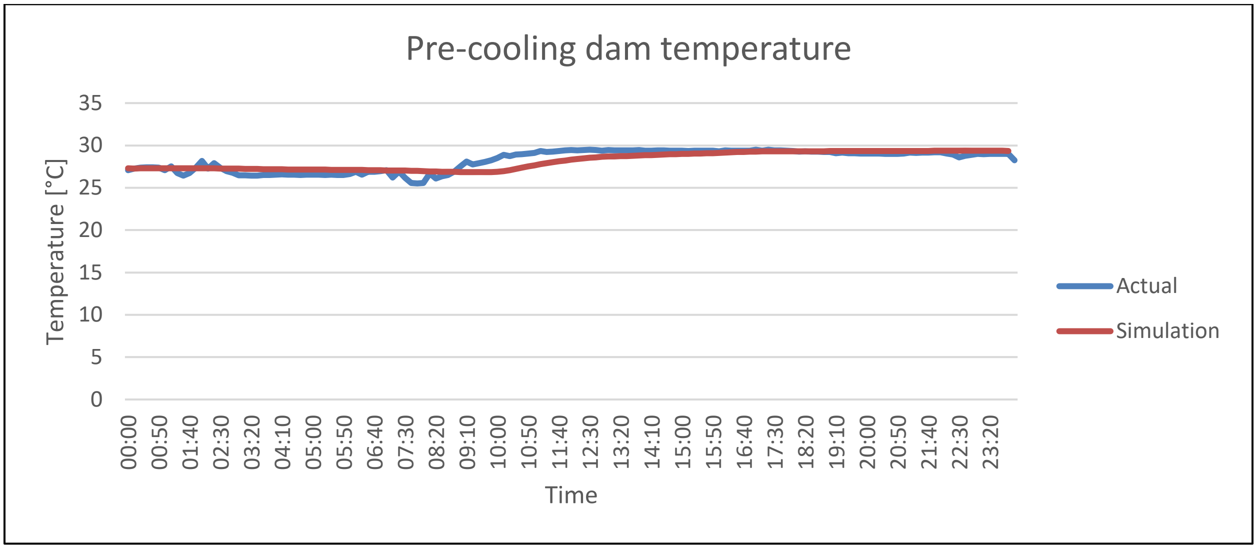


Figure 59 - Pre-cooling dam temperature comparison.

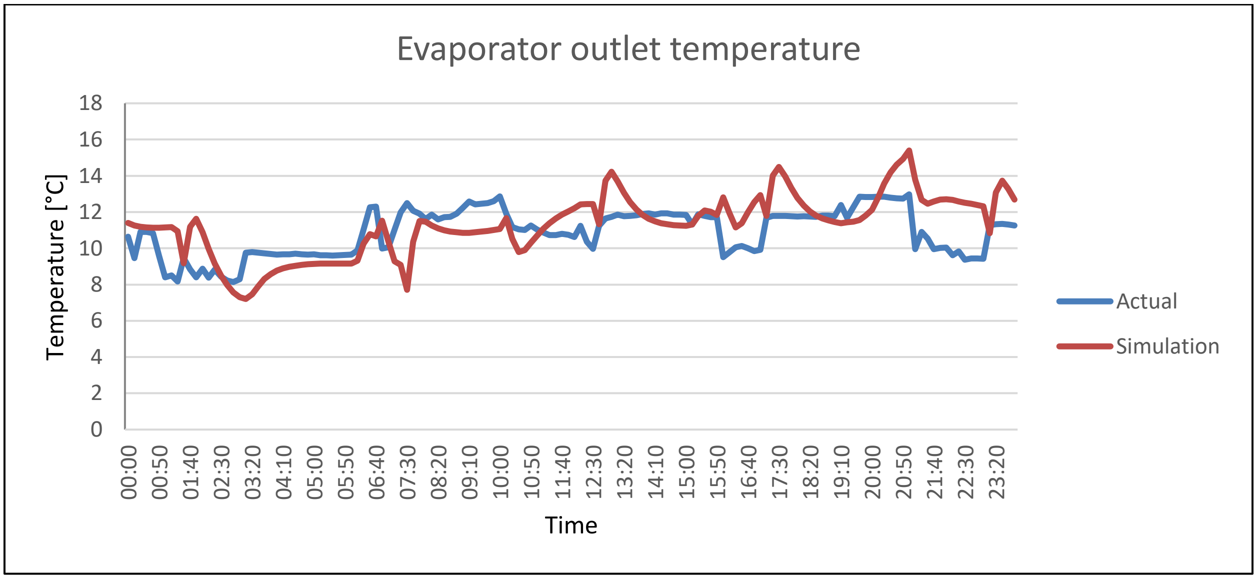


Figure 60 - Evaporator outlet temperature comparison.

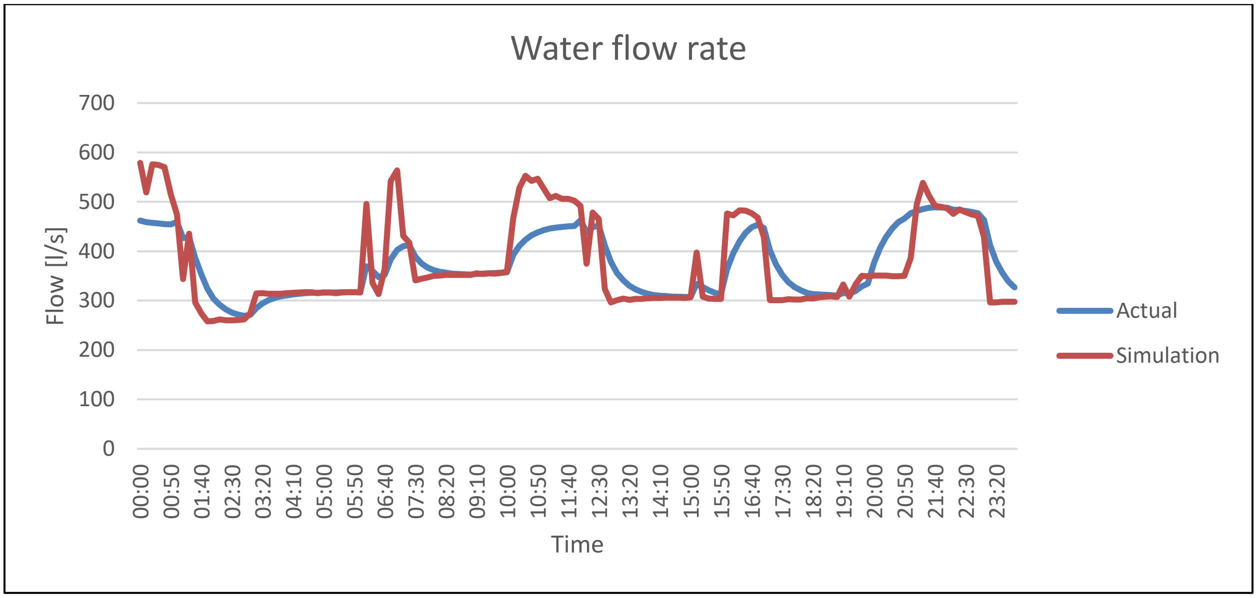


Figure 61 - Evaporator water flow comparison.

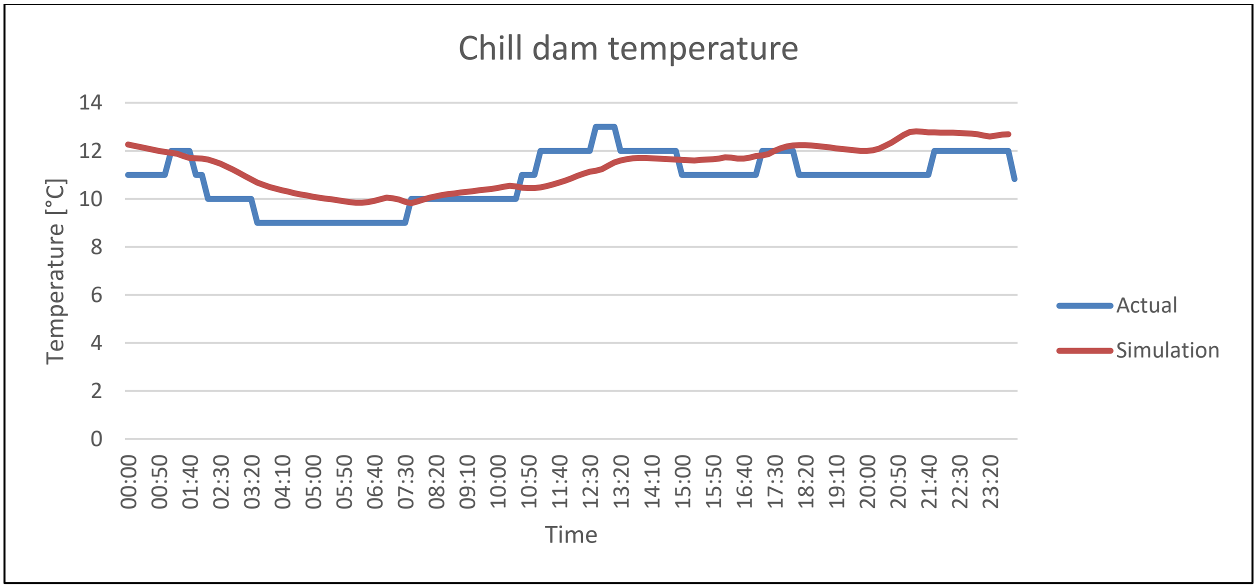


Figure 62 - Chill dam temperature comparison.

Appendix B

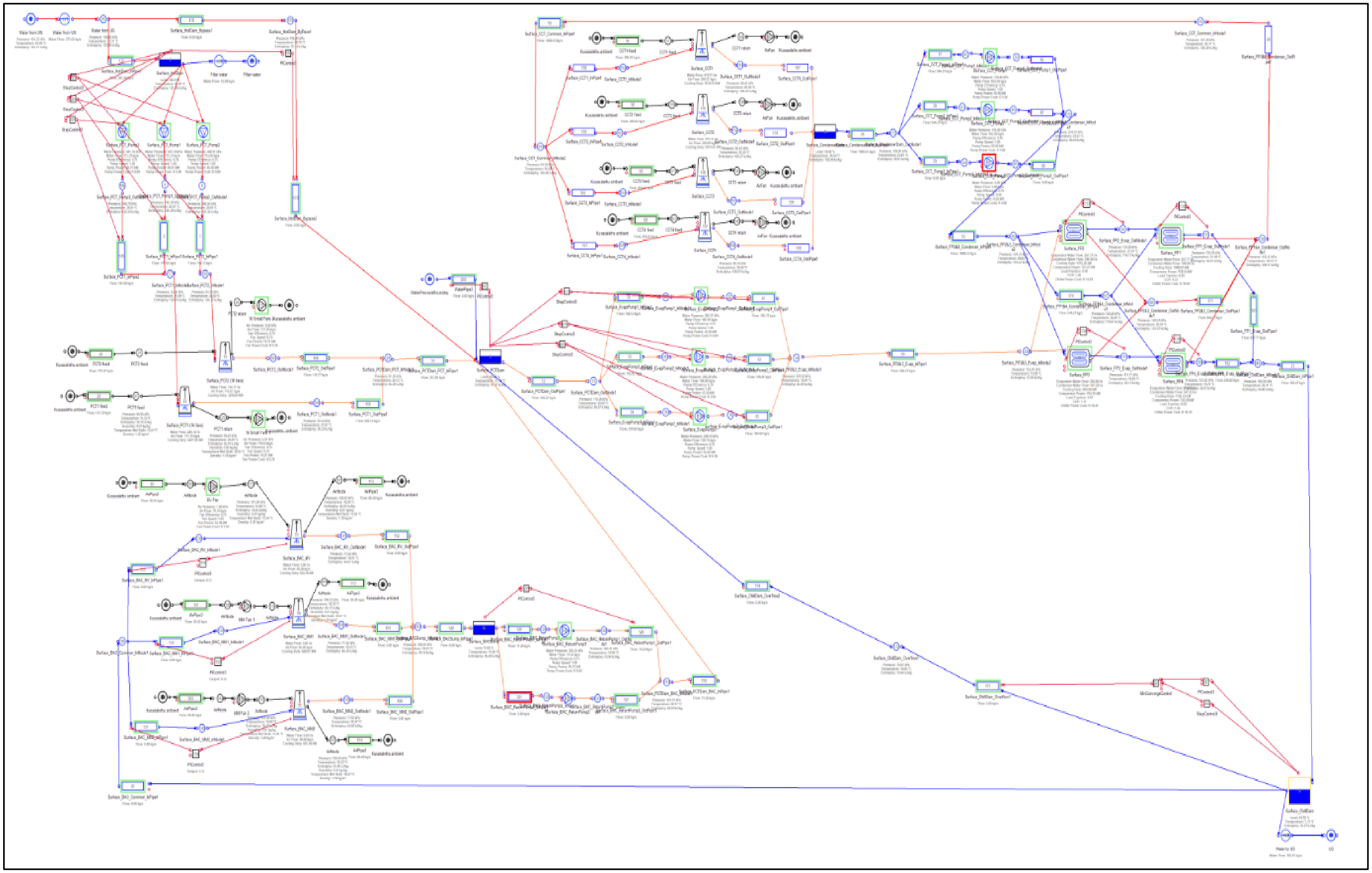
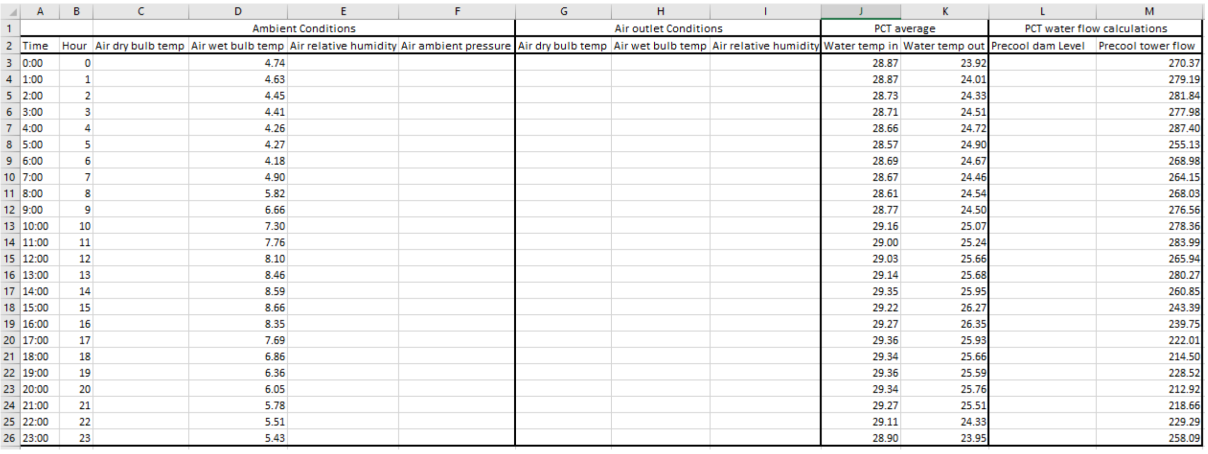


Figure 63 - Simulation layout

Appendix C: Calculation sheet inputs

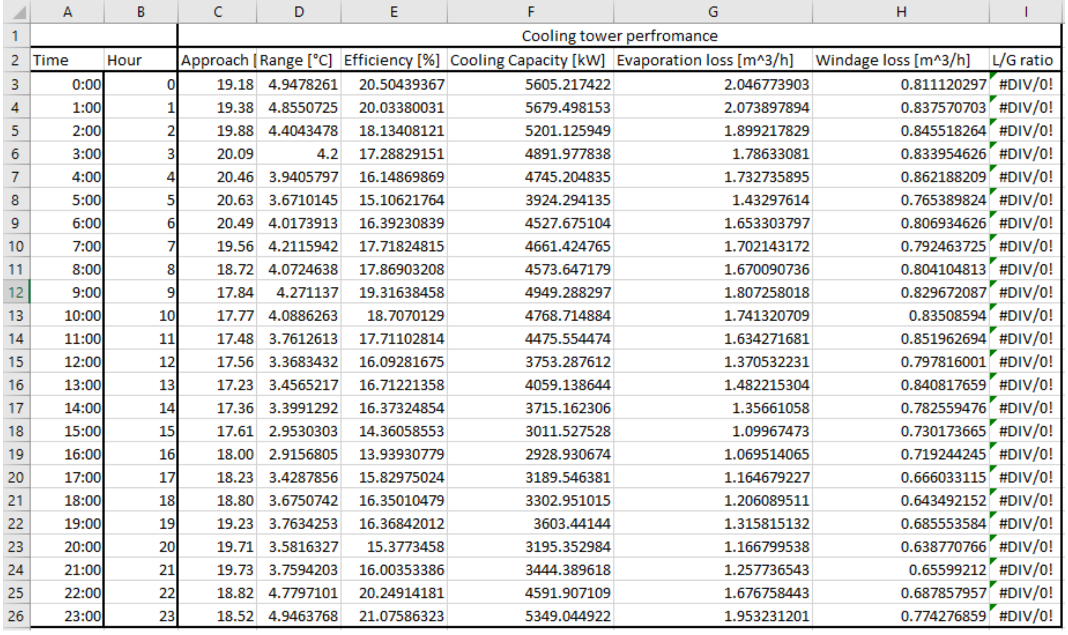
Microsoft Excel was used to create the calculation sheet. The inputs for the sheet is given below in Figure 64. Required inputs are the wet-bulb ambient temperature, pre-cooling in and out let temperatures and water flow rate. Most of the performance calculations can be calculated from these variables.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1			Ambient Conditions				Air outlet Conditions			PCT average		PCT water flow calculations	
2	Time	Hour	Air dry bulb temp	Air wet bulb temp	Air relative humidity	Air ambient pressure	Air dry bulb temp	Air wet bulb temp	Air relative humidity	Water temp in	Water temp out	Precool dam Level	Precool tower flow
3	0:00	0		4.74						28.87	23.92		270.37
4	1:00	1		4.63						28.87	24.01		279.19
5	2:00	2		4.45						28.73	24.33		281.84
6	3:00	3		4.41						28.71	24.51		277.98
7	4:00	4		4.26						28.66	24.72		287.40
8	5:00	5		4.27						28.57	24.90		255.13
9	6:00	6		4.18						28.69	24.67		268.98
10	7:00	7		4.90						28.67	24.46		264.15
11	8:00	8		5.82						28.61	24.54		268.03
12	9:00	9		6.66						28.77	24.50		276.56
13	10:00	10		7.30						29.16	25.07		278.36
14	11:00	11		7.76						29.00	25.24		283.99
15	12:00	12		8.10						29.03	25.66		265.94
16	13:00	13		8.46						29.14	25.68		280.27
17	14:00	14		8.59						29.35	25.95		260.85
18	15:00	15		8.66						29.22	26.27		243.39
19	16:00	16		8.35						29.27	26.35		239.75
20	17:00	17		7.69						29.36	25.93		222.01
21	18:00	18		6.86						29.34	25.66		214.50
22	19:00	19		6.36						29.36	25.59		228.52
23	20:00	20		6.05						29.34	25.76		212.92
24	21:00	21		5.78						29.27	25.51		218.66
25	22:00	22		5.51						29.11	24.33		229.29
26	23:00	23		5.43						28.90	23.95		258.09

Figure 64 - Calculation inputs

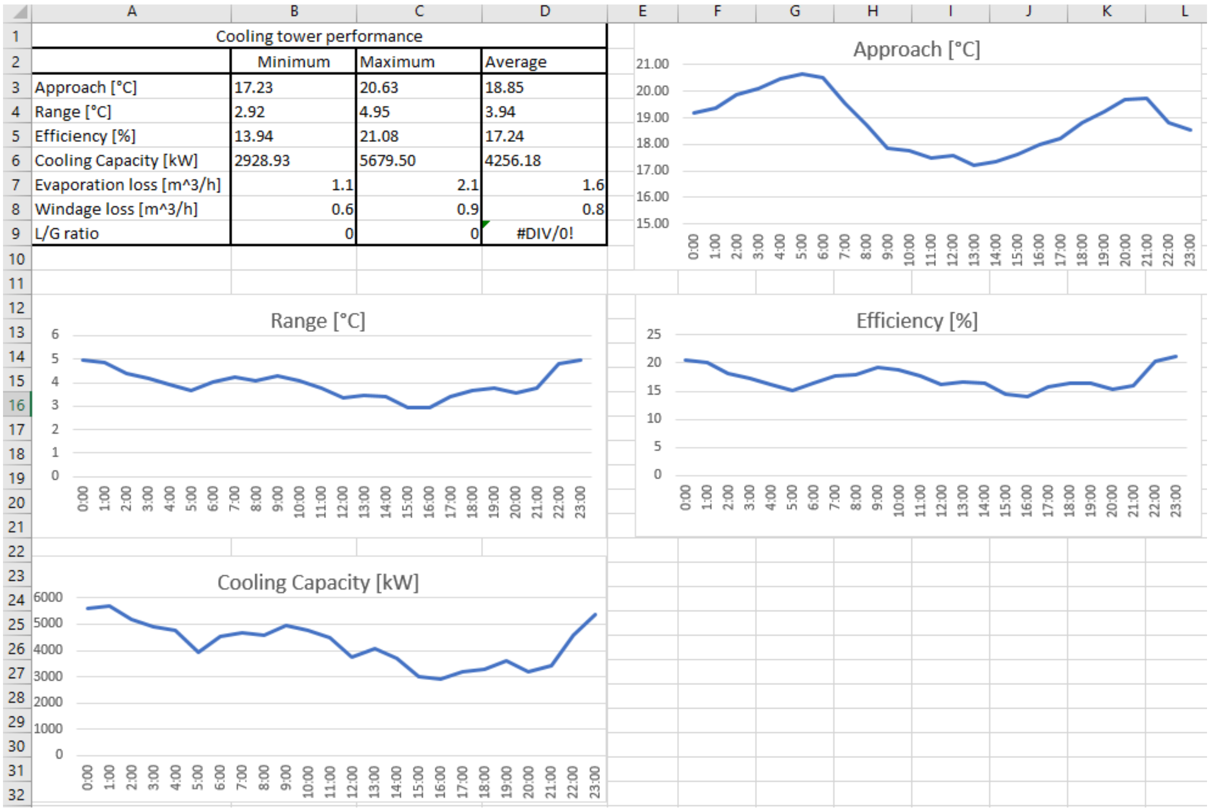
In the output sheet the data from the inputs used to calculate the efficiency approach, range and cooling capacity of the tower. An example of the outputs can be seen in Figure 65.



	A	B	C	D	E	F	G	H	I
1			Cooling tower perfromance						
2	Time	Hour	Approach [	Range [°C]	Efficiency [%]	Cooling Capacity [kW]	Evaporation loss [m^3/h]	Windage loss [m^3/h]	L/G ratio
3	0:00	0	19.18	4.9478261	20.50439367	5605.217422	2.046773903	0.811120297	#DIV/0!
4	1:00	1	19.38	4.8550725	20.03380031	5679.498153	2.073897894	0.837570703	#DIV/0!
5	2:00	2	19.88	4.4043478	18.13408121	5201.125949	1.899217829	0.845518264	#DIV/0!
6	3:00	3	20.09	4.2	17.28829151	4891.977838	1.78633081	0.833954626	#DIV/0!
7	4:00	4	20.46	3.9405797	16.14869869	4745.204835	1.732735895	0.862188209	#DIV/0!
8	5:00	5	20.63	3.6710145	15.10621764	3924.294135	1.43297614	0.765389824	#DIV/0!
9	6:00	6	20.49	4.0173913	16.39230839	4527.675104	1.653303797	0.806934626	#DIV/0!
10	7:00	7	19.56	4.2115942	17.71824815	4661.424765	1.702143172	0.792463725	#DIV/0!
11	8:00	8	18.72	4.0724638	17.86903208	4573.647179	1.670090736	0.804104813	#DIV/0!
12	9:00	9	17.84	4.271137	19.31638458	4949.288297	1.807258018	0.829672087	#DIV/0!
13	10:00	10	17.77	4.0886263	18.7070129	4768.714884	1.741320709	0.83508594	#DIV/0!
14	11:00	11	17.48	3.7612613	17.71102814	4475.554474	1.634271681	0.851962694	#DIV/0!
15	12:00	12	17.56	3.3683432	16.09281675	3753.287612	1.370532231	0.797816001	#DIV/0!
16	13:00	13	17.23	3.4565217	16.71221358	4059.138644	1.482215304	0.840817659	#DIV/0!
17	14:00	14	17.36	3.3991292	16.37324854	3715.162306	1.35661058	0.782559476	#DIV/0!
18	15:00	15	17.61	2.9530303	14.36058553	3011.527528	1.09967473	0.730173665	#DIV/0!
19	16:00	16	18.00	2.9156805	13.93930779	2928.930674	1.069514065	0.719244245	#DIV/0!
20	17:00	17	18.23	3.4287856	15.82975024	3189.546381	1.164679227	0.666033115	#DIV/0!
21	18:00	18	18.80	3.6750742	16.35010479	3302.951015	1.206089511	0.643492152	#DIV/0!
22	19:00	19	19.23	3.7634253	16.36842012	3603.44144	1.315815132	0.685553584	#DIV/0!
23	20:00	20	19.71	3.5816327	15.3773458	3195.352984	1.166799538	0.638770766	#DIV/0!
24	21:00	21	19.73	3.7594203	16.00353386	3444.389618	1.257736543	0.65599212	#DIV/0!
25	22:00	22	18.82	4.7797101	20.24914181	4591.907109	1.676758443	0.687857957	#DIV/0!
26	23:00	23	18.52	4.9463768	21.07586323	5349.044922	1.953231201	0.774276859	#DIV/0!

Figure 65 - Calculation outputs

The results sheet processes the information of the output file into easy to interpret information. Graphs are also automatically generated of the information on the output sheet.



Cooling tower performance

	Minimum	Maximum	Average
Approach [°C]	17.23	20.63	18.85
Range [°C]	2.92	4.95	3.94
Efficiency [%]	13.94	21.08	17.24
Cooling Capacity [kW]	2928.93	5679.50	4256.18
Evaporation loss [m^3/h]	1.1	2.1	1.6
Windage loss [m^3/h]	0.6	0.9	0.8
L/G ratio	0	0	#DIV/0!

Figure 66 - Calculation result