Analysing the impact of refurbishing precooling towers on a deep-level mine

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ABSTRACT

Title: Analysing the impact of refurbishing precooling towers on a deep-level mine

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Keywords: Deep-level mines; Precooling towers; Induced draft towers; Refurbishment; Refrigeration network; Energy efficiency initiatives; Evaluation checklist

The challenges faced by South African gold mines are increasing operating costs, resulting in a decreased profit margin. Increased mining depths are one of the highlighted challenges but is required to remain competitive within the global industry. However, the increased depths generate higher working area temperatures.

Refrigeration systems are used to cool underground working areas. They are also one of the most energy intensive systems on a deep-level gold mine. Eskom electricity costing increased by 13.82% for 2019/20, necessitating strategies to mitigate costs. Optimising the refrigeration system by lowering the inlet water temperature is one strategy to mitigate cost.

Service water is precooled before entering the refrigeration cycle, making precooling towers a crucial component to the refrigeration network. High precooling tower performance will result in a lower outlet water temperature and an increase refrigeration network performance. To maintain optimal precooling tower performance, timely refurbishment is required.

This study focused on evaluating the impact of deep-level gold mine precooling tower refurbishment. This was done by developing a refurbishment strategy and analysing the impact thereof.

A five-step methodology process was developed to evaluate the impact of precooling tower refurbishment. In the first step a feasible location is identified. Step 2 continued by evaluating the identified precooling tower through a developed evaluation checklist. The checklist is used to identify and recommend solutions to common problems associated with induced draft precooling towers.

The recommendation will form the refurbishment solution to be implemented in Step 3. In Step 4, the precooling tower performance is re-assessed. If the performance is satisfactory, the impact is evaluated in Step 5 by analysing the changes to the refrigeration network.

The methodology strategy was validated through a case study. The evaluation checklist was used to identify precooling problems and develop a refurbishment solution. Precooling tower efficiency increased by 29.5% after refurbishment, which resulted in an annual cost saving of R6.86 million. The cost saving amount was quantified by evaluating the impact of precooling tower refurbishment.

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LIST OF ABBREVIATIONS

3CPS	Three-chamber Pump System
ANN	Artificial Neural Network
BAC	Bulk-air Cooler
CapEx	Capital Expenditure
COP	Coefficient of Performance
CWSAT	Chilled Water System Analysis Tool
DCT	Dry Cooling Towers
FAP	Factory-assembled Products
FP	Fridge Plant
HVAC	Heating, Ventilation, and Air Conditioning
MINLP	Mixed-Integer Nonlinear Programming
NDWCT	Neutral Draught Wet Cooling Tower
NERSA	National Electricity Regulator of South Africa
PCT	Precooling Tower
PTB	Process Toolbox
RCA	Regulatory Cleaning Account
RSM	Response Surface Method
RTDS	Resistance Temperature Detectors
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-use

VRT	Virgin Rock Temperature
VSD	Variable Speed Drive
WCT	Wet Cooling Towers

NOMENCLATURE

Symbol	Unit	Description
°C	Celsius	Temperature
K	Kelvin	Temperature
kg/s	kg/s	Volume flow rate
kJ/kg	kJ/kg	Energy per mass unit
kJ/kg dry air	kJ/kg	Energy per mass unit of dry air
kJ/kg water	kJ/kg	Energy per mass unit of water
km	Kilometre	Head, depth or length
kW	Kilowatt	Power
l/day	Litre per day	Flow rate
l/s	Litre per second	Flow rate
m^3	Cubic metre	Volume
mm	Millimetre	Length
MW	Megawatt	Power

CHAPTER 1: INTRODUCTION

1

[1] S Jerling, Personal photograph. "Surface Ventilation Fans", Free-state, 2019

1.1 Preamble

In this chapter background information regarding the topic will be discussed. Currently deep-level mines in South Africa are becoming less sustainable due to Eskom electricity tariff increases. The high electricity cost coupled with harsh mining conditions are forcing mines to improve system performance in order to lower operating cost. One area which is commonly neglected are precooling towers (PCTs) used in the refrigeration system. This study will evaluate the benefits of PCT refurbishment and why optimal operation is important.

1.2 Deep-level mines

At its peak, the South African gold mining industry ranked as the number one gold producer. Today, due to challenges faced, South Africa struggles to gain a competitive advantage and is ranked seventh [1] . Some of the challenges faced include [2]:

- Gold price volatility
- Escalating costs of production
- Declining gold resource grade
- Depth and mining methods
- Labour issues
- Political, social, and environmental issues

With the South African mining industry being primarily minerals-intensive, gold production and mining depths are especially pertinent. One-fifth of South Africa's economy is dependent on the mining sector [3]. Gold sales declined by 15% (R69.9 billion in 2018 from R82.7 billion in 2017) [4], leaving approximately 75% of mines unprofitable [5].

Gold production decline

The Witwatersrand Basin in South Africa is still the world's largest gold deposit. Yet, only 4.2% of the global gold production is from South Africa. The South African industry had a production decrease of over 52% in the last 10 years [6]. Figure 1 illustrates the decrease in mining production.

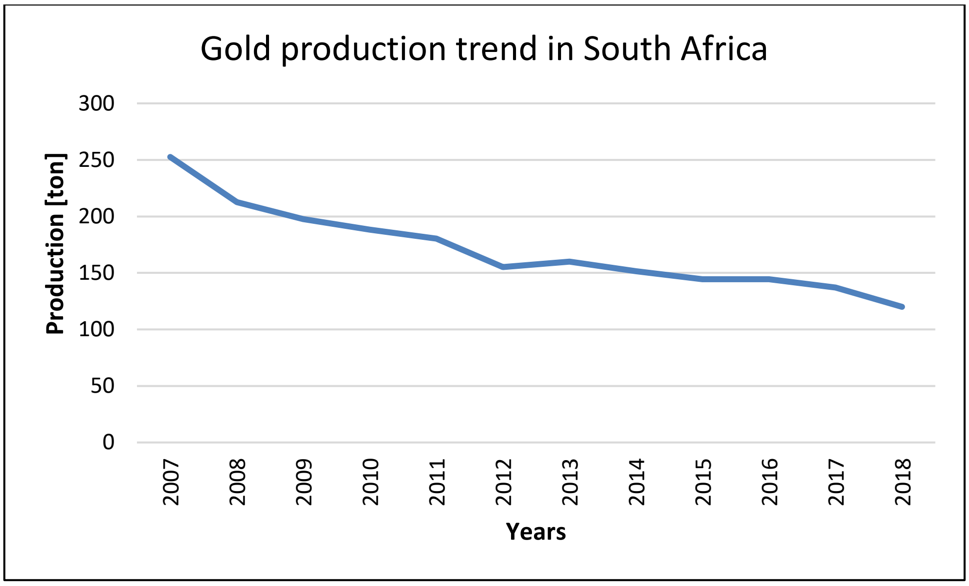

Figure 1: Gold production trend in South Africa [6]

For South African industries to remain competitive, deeper mining depths are required, however, deeper depths have challenges of their own.

Mining depths

Virgin rock temperatures (VRT) underground can reach 60 °C at a depth of around 4 km [7]. These high temperatures necessitate that ventilation and refrigeration are used to cool working environments below a wet-bulb temperature of 28 °C [8]. However, the increasing mining depths are required to remain competitive within the industry.

The most common cooling strategy used in South African gold mines is a centralised cooling system. It consists of two components namely bulk-air coolers (BAC) and refrigeration plants. BACs use evaporative cooling to lower the temperature of the surrounding air whereas refrigeration plants cool service water [9].

Refrigeration plants or fridge plants (FPs) supply chilled service water to underground operations. Figure 2 illustrates a typical deep-level gold mine water cycle. Starting at the FPs, the service water respectively enters and exits at around 18 °C and 3 °C. Recycled condenser water is used in the refrigeration process. The chilled service water is sent to the surface chill dam where it feeds underground operations and BACs. From underground the warm water is pumped to a surface hot water storage dam. The PCT draws water from this dam and cools it. The then cooled water is stored in a precooling dam where the FPs can draw water. Furthermore, excess water from the BAC dam is pumped to the precooling dam.

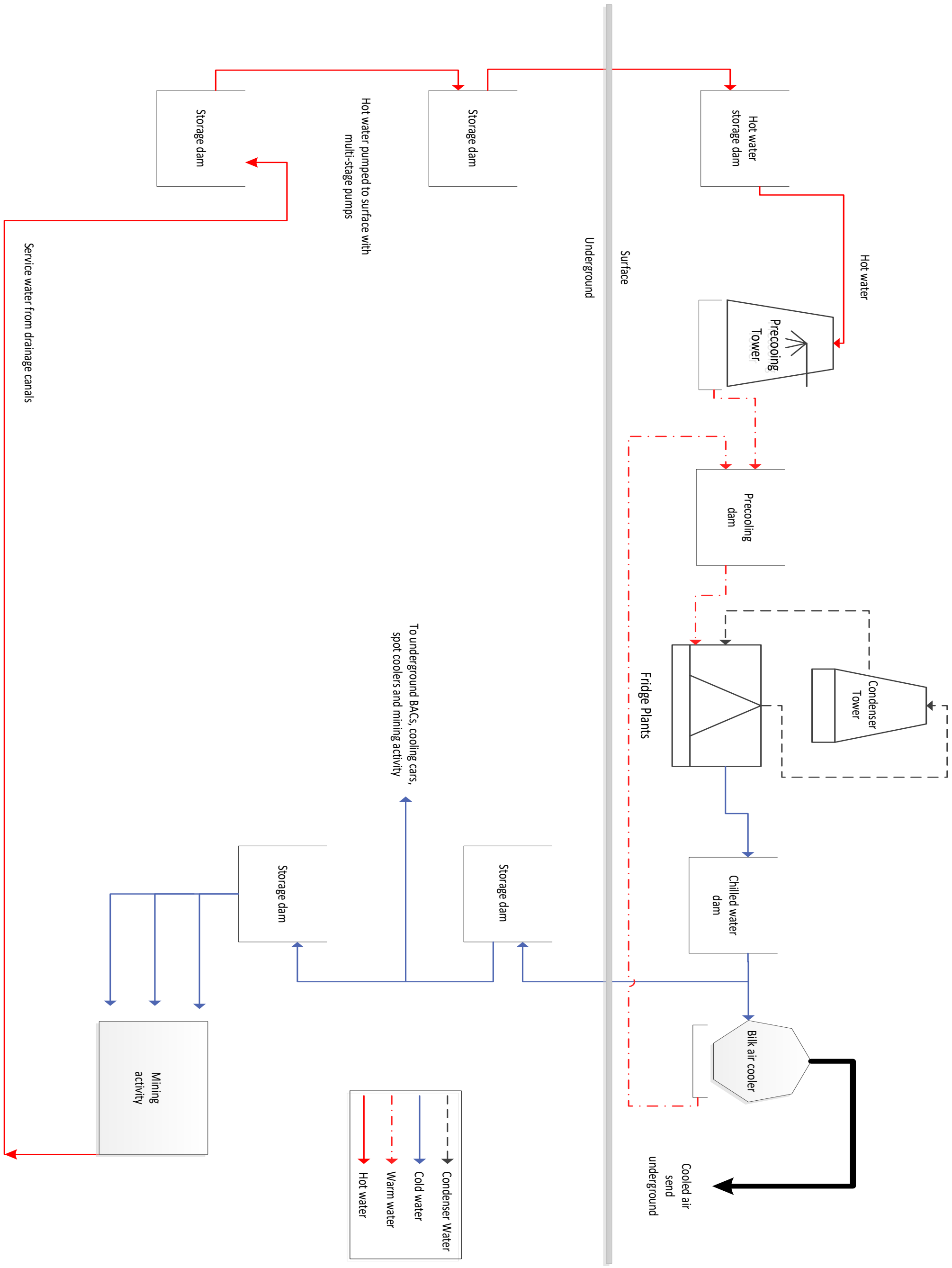

Figure 2: Typical deep-level mine water reticulation

The FPs specified in Figure 2 are substantial energy users and are efficient within its designed inlet temperature ranges [10]. The electricity usage on deep-level mines will be discussed in the next section.

1.3 Electricity usage on deep-level mines

The electricity usage of the South African gold mining sector comprises around 6.7% of Eskom's annual power supply [11]. Consequently, an increase in electricity cost will have a significant impact on the sectors viability. Earlier in 2019, an increase of 9.41% for 2019/20 was approved by the National Electricity Regulator of South Africa (NERSA), a further increase of 8.10% for 2020/21 and 5.22% for 2021/22 was also approved [12]. These increases are on top of the 4.41% approved Eskom's Regulatory Clearing Account (RCA) application of 2018 [13]. Furthermore, the mines have a load curtailment agreement with Eskom, where they are required to take non-essential equipment offline and reduce consumption by 15% to 20% at notice [14]. This agreement, together with the cost increase, will have a catastrophic effect on the sustainability of gold mines.

These challenges establish a need for gold mines to reduce their cost of operation by investigating energy consumers and efficiencies. Figure 3 illustrates the main energy consumers of a typical deep-level gold mine. Energy consumers between different mine operations will vary. Refrigeration is the third largest consumer on a typical gold mine [15].

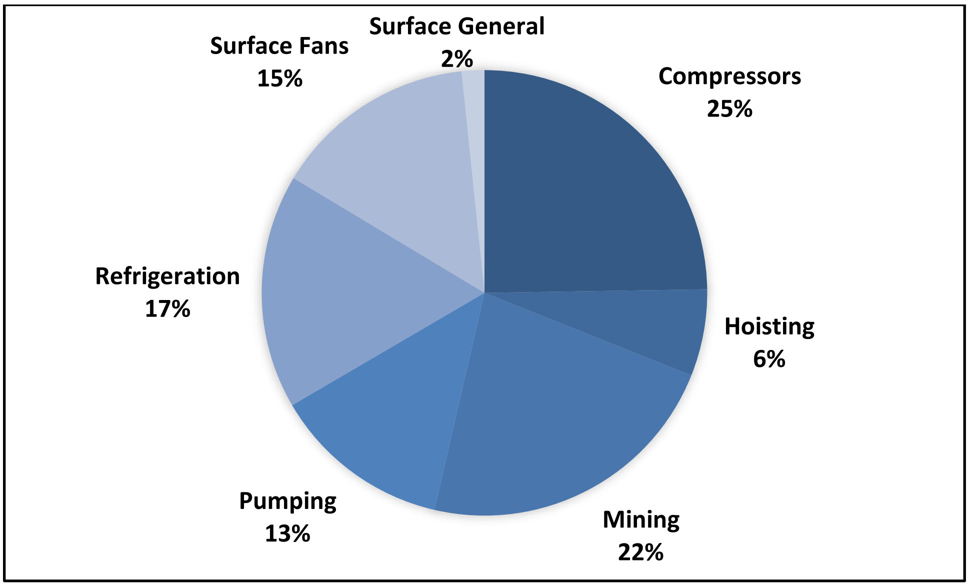

Figure 3: Typical deep-level mine energy consumers per system (adapted from [15])

Fridge plants

As mentioned in Section 1.2, FPs are an important component of the ventilation and cooling system. They use a vapour-compression cycle to cool service water down to approximately 3 °C. R134A, Ammonia, R22 and R21 are commonly used working fluids/refrigerants which absorb and remove heat. Most FP systems on deep-level mines have a cooling capacity of 6 MW(r) but can go as high as 20 MW(r) [16].

FPs consist of four components as seen in Figure 4. The working fluid as a saturated vapour enters the first component which is the compressor where the pressure and temperature are increased. The then superheated vapour condenses and the water moving through the coils absorb the heat. The heated water then travels to condenser towers to be cooled off before recycling back. After the heat is absorbed from the refrigerant, it is in a state known as saturated liquid, which is routed through an expansion valve where it endures a sudden reduction in pressure. This abrupt pressure reduction lowers the temperature of the refrigerant and when moved through the evaporator, it cools the service water moving through the coils [17].

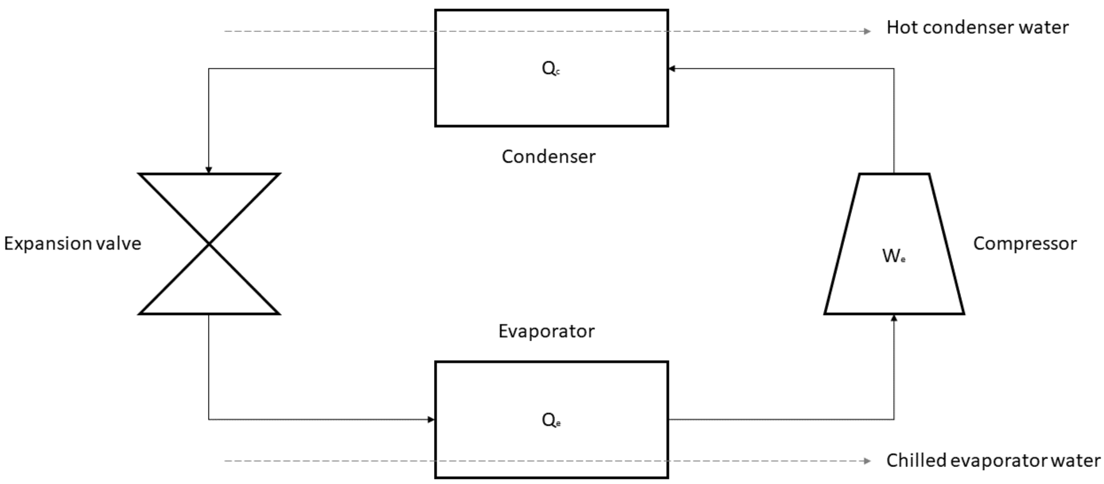

Figure 4: Vapour-compression refrigeration cycle (adapted from [17])

The chilled service water is then distributed throughout the entire mining complex by means of steel pipes. Chilled water is mainly used for rock drilling and cooling (underground BACs, cooling cars and spot coolers) [18]. After use, water accumulates in waterways that gravity feeds to holding dams on lower levels. The water is then pumped to surface by means of multi-stage pumps. The water enters holding dams and the refrigeration cycle continues.

As seen in Figure 2, PCTs are used to decrease the FP inlet temperatures. The performance of FPs is dependent on the inlet water temperature. Lower water inlet temperatures will result in less power usage required to achieve the target outlet temperature. This is a good strategy to reduce the energy costs of gold mines.

1.4 Precooling towers

A cooling tower is a type of heat exchanger. The working fluid, usually water, is cooled with air through various heat transfer methods. In the mining sector, PCTs serve as a first stage cooling process, before the service water is cooled by the FPs. This aids in lowering the inlet temperature of the FPs.

1.4.1 Precooling tower classification

Precooling towers can be classified according to certain characteristics. These classifications can be divided into the following categories [19]:

- Classification by manufacture type
- Classification by heat transfer method
- Classification by fill type
- Classification by air draft
- Classification by air flow patterns

Figure 5 is a graphical representation of PCT division and subdivisions.

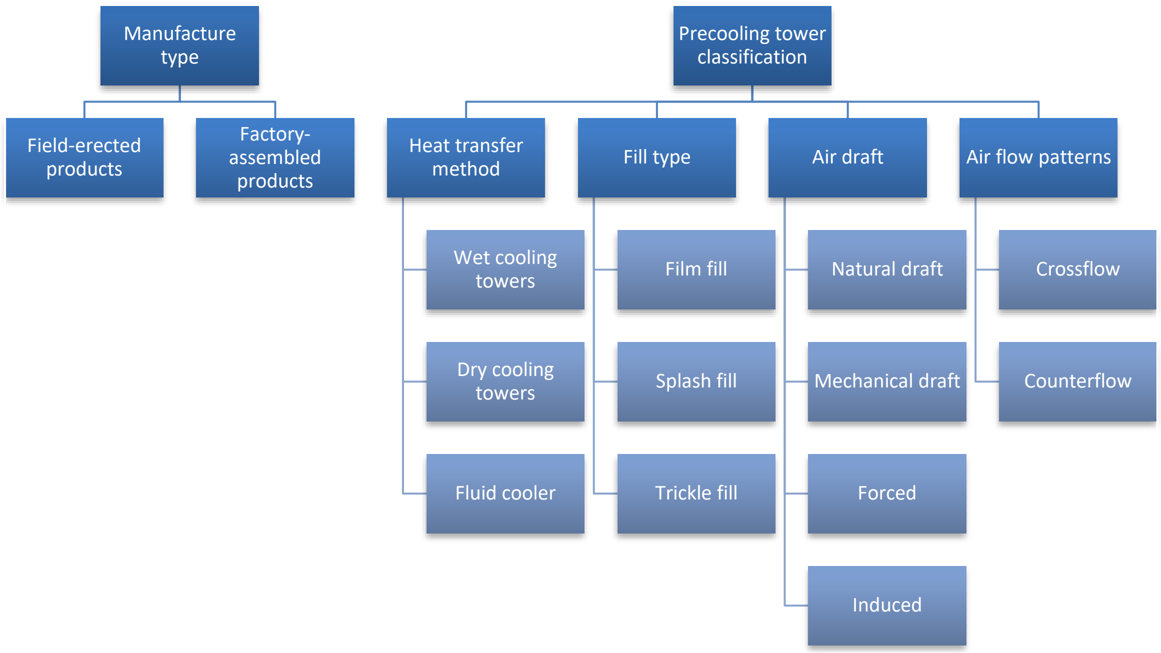

Figure 5: Classification schematic (adapted from [19])

Classification by manufacture type [20]

This is the broadest classification category and consists of two primary build variants i.e. field-erected products and factory-assembled products (FAP). FAPs are commonly used in heating, ventilation and air conditioning (HVAC) systems, light industrial and commercial markets. They are pre-built at manufacturing plants and can be easily shipped and installed on site. On-site constructed cooling towers used in the power and heavy industrial market are on the other side of the classification. They are commonly used when heat rejection requirements and water volumes are very large.

Classification by heat transfer method

This classification summarises the method in which heat is removed from water. The first and most common is wet cooling towers (WCT). They work on the principle of evaporative cooling, where the water and air are in direct contact. The heat is transferred from the water to the air, which raises the temperature and relative humidity of the air [21]. They are a cost-effective way to cool water, making them a preferred choice for the mining industry.

With dry cooling towers (DCT) the water and air are not in direct contact. Instead they conduct heat through air-cooled heat exchangers. This separates the working fluid from the air, which means there is no water loss in this type of system. They are most commonly used in situations where the working fluid needs to be protected from the environment [21].

WCT are preferred above their counter parts due to their cost-effective nature. DCT require higher power rating fans due to the larger mass flow requirements. Furthermore, the investment cost and land area involved are usually higher than that of WCT [22].

The final classification is a fluid cooler, where water is sprayed over tubes filled with the working fluid. The working fluid is kept in a closed loop and cooled by incorporating the same evaporative cooling method used in WCT. The main disadvantage of fluid coolers are their relatively higher water temperatures when compared to normal cooling towers [23].

Classification by fill type

Fill or packing material is used to increase the water's surface area and contact time with the air. The fill zone is where most of the heat transfer occurs and is crucial to the efficiency of the cooling tower [24]. Three general fill types can be found in the industry: film, splash and trickle fill.

Film fill provides a large surface area causing the water to form a thin film. The pressure drop over this packing material is lower when compared to splash and spray fill, allowing for smaller fans to be used. Additionally, they are less expensive and more efficient than the other options, making them popular in the mining industry [19]. Typical film fill can be seen in Figure 6.

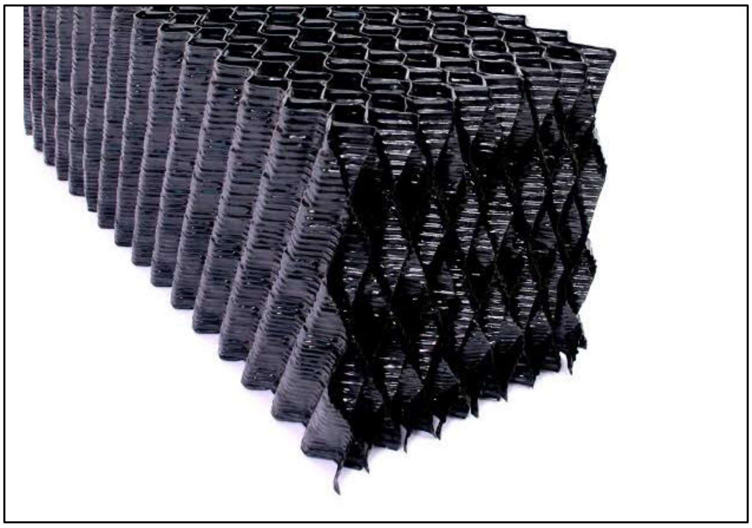

Figure 6: Film fill[2]

Instead of a large surface area, splash fill breaks down the water into small droplets. This is a different technique than film fill but yields similar results. The small droplets increase the area of contact between the water and airflow. The main disadvantage of splash fill is the low efficiencies accompanying the technique. Furthermore, large tower size and airflow is required [25]. An example of splash fill is shown in Figure 7.

Figure 7: Splash fill[3]

[2] *Cooldeck Industries (2016). Film Fills for Cooling Towers. [image] Available at: http://www.cooldeckin.com/film-fills.html [Accessed 3 Nov. 2019].*
[3] *SPX Cooling Technologies (2019). Omega Crossflow Splash Fill. [image] Available at: https://spxcooling.com/parts/omega-crossflow-splash-fill [Accessed 3 Nov. 2019].*

Trickle fill is a combination between film and splash fill. It offers advantages of both fill types by simultaneously breaking water into small drops and creating a thin film layer of water.

Classification by air draft

Cooling towers can be divided in three airflow methods. Natural and mechanical draft being the two main methods. The seldom used third method would be atmospheric towers. Atmospheric towers are dependent on the wind conditions since the air enters the tower through louvers and is propelled by its own velocity. They are mostly inefficient because the performance of the towers is coupled to the wind conditions. Compared to the other two methods, atmospheric towers are relatively inexpensive [19].

A natural draft tower is easily identified by its hyperbolic shape. Although, like atmospheric towers, there is no mechanical device. Natural draft towers are dependable and consistent. The upward draft through the tower is caused by a density differential between warm air inside and cooler, denser ambient air outside. Figure 8 describes this principle. The hyperbolic shape enhances the natural upward draft and is structurally stable [26]. When equipped with a fan, a natural draft tower is referred to as a hybrid draft tower.

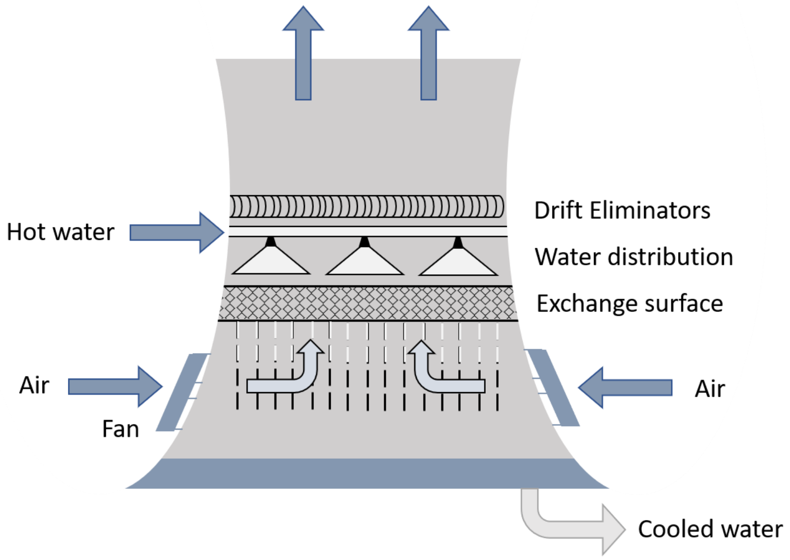

Figure 8: Natural draft tower (adapted from [26])

Mechanical draft towers can be subdivided into forced draft and induced draft towers. Forced draft towers have a fan located at the bottom which causes a positive pressure inside the tower, forcing the air out. With induced draft towers, the fan is located at the top, creating a negative pressure inside the tower. This pressure difference will pull air in from the bottom [27]. Figure 9 shows the difference between the two subdivisions.

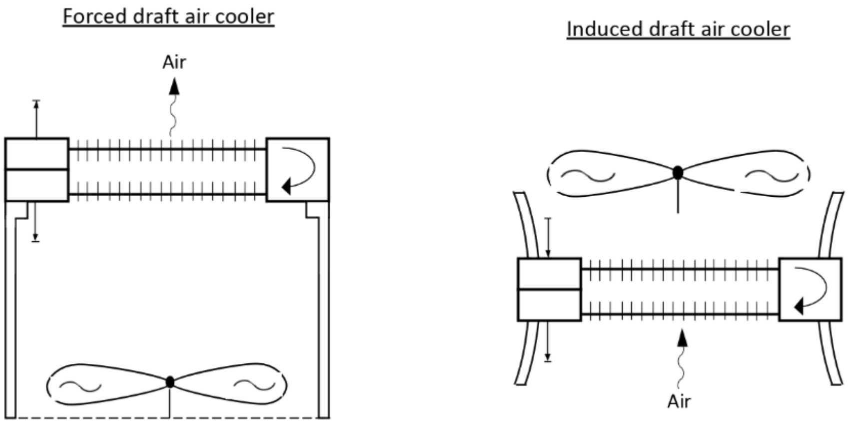

Figure 9: Forced vs induced draft[4]

Classification by air flow patterns

The final classification describes how air interacts with the water. In a crossflow cooling tower, air travels horizontally across the water. While in counterflow cooling towers, as the name suggests, air travels in the opposite direction of the water [28]. Figure 10 illustrates the two methods. When compared to crossflow towers, the space requirements and capital cost of counterflow towers are considerably lower. These advantages make induced draft counterflow towers ideal for the mining sector [29]. Thus, the study will further focus on induced draft counter flow PCTs.

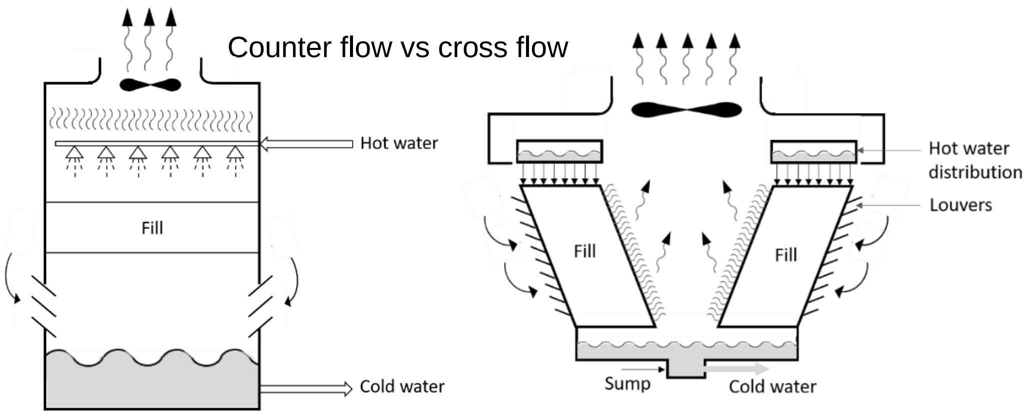

Figure 10: Counterflow vs cross flow[5]

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[4] Engineering360 (2019). Two types of air coolers. [image] Available at: https://www.globalspec.com/reference/81438/203279/chapter-17-air-coolers-fin-fan-coolers [Accessed 3 Nov. 2019].
[5] Engineering360 (2015). Schematics of a counter-flow and cross-flow cooling tower. [image] Available at: https://insights.globalspec.com/article/1695/fundamentals-of-cooling-tower-heat-transfer-part-2 [Accessed 3 Nov. 2019].

1.4.2 Precooling tower performance

The parameters that determine a PCT's performance will be discussed in this section. The performance of a PCT is essential to the FP inlet water temperature.

Heat load

Heat load or heat capacity is the measurement of a PCT's ability to remove heat from water. It is calculated using Equation 1 [30].

Equation 1: Heat rejection

$$Q = Cp_w m_w \Delta T_w$$

Where: Q = Heat load or rejection [kW]

Cp_w = Specific heat of water [kJ/kg · K]

m_w = Mass water flow rate [kg/s]

ΔT_w = Difference between outlet and inlet water temperature

Efficiency

The efficiency of a PCT can be determined by calculating the range and approach parameters as illustrated by Figure 11. The wet-bulb temperature is the minimum cooling point for an evaporative cooling tower. Range is the value used to denote the difference between the inlet and outlet temperature. Approach is the difference between the outlet and wet-bulb temperature.

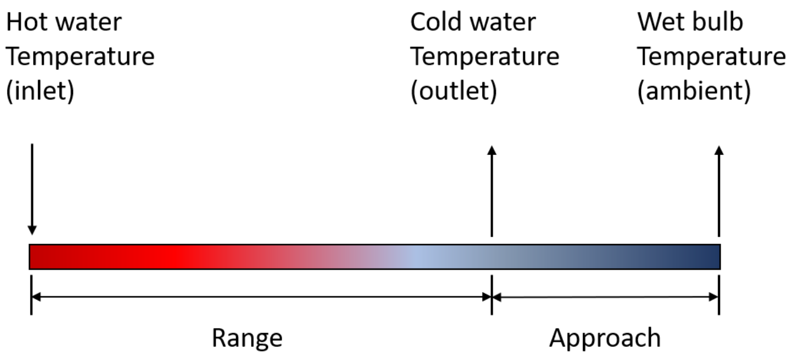

Figure 11: Range and approach of a PCT[6]

[6] Chemical Engineering Site (2019). Cooling Tower Efficiency Calculations. [image] Available at: http://chemicalengineeringsite.in/cooling-tower-efficiency-calculations/ [Accessed 3 Nov. 2019].

Range: PCT inlet and outlet water temperature difference. Calculated using Equation 2 [30].

Equation 2: PCT range

$$\boldsymbol{Range = T_{w,in} - T_{w,out}}$$

Where: $T_{w,in}$ = Water inlet temperature [°C]

$T_{w,out}$ = Water outlet temperature [°C]

Approach: Difference between PCT outlet water temperature and the temperature of the wet-bulb air entering. Calculated using Equation 3 [30].

Equation 3: PCT approach

$$\boldsymbol{Approach = T_{w,out} - T_{WB}}$$

Where: $T_{w,out}$ = Water outlet temperature [°C]

T_{WB} = Wet-bulb temperature [°C]

Efficiency: Function of range and approach

For an ideal PCT the water outlet temperature will equal the wet-bulb temperature. However, in real world circumstances the wet-bulb temperature is a limiting factor to the PCT efficiency, as the water outlet temperature will never equal the wet-bulb temperature. Efficiency is determined with Equation 4 [30].

Equation 4: PCT efficiency

$$\boldsymbol{\eta = \frac{Range}{(Range + Approach)} * 100 = \frac{T_{w,in} - T_{w,out}}{T_{w,in} - T_{WB}} * 100}$$

Where: η = PCT efficiency [%]

Temperature measurements

The inlet and outlet temperatures are typically measured with either resistance thermometers, better known as resistance temperature detectors (RTDs) or thermocouples [31]. Table 1 shows the difference between the two.

Table 1: Difference between RTDs and thermocouple [32]

Type	Range	Response time	Size	Accuracy	Stability	Photo
RTD[7]	-200 to 500 °C	Seconds	3.175 to 6.35 mm	0.1 °C	Years	
Thermocouple[8]	180 to 2320 °C	Fraction of a second	< 1.6 mm	Within 2 °C	Hours	

Wet-bulb temperature (Appendix E) is a function of relative humidity and ambient air temperature. Ambient temperature and relative humidity are almost always measured through an on-site weather station consisting of a thermometer and hygrometer [33].

Mass flow measurements

The mass water flow rate is commonly measured using the pitot tube traverse method. This method is based on Bernoulli Equations. The accuracy of a common pitot tube water flow meter is within 0.5% to 5% of actual flow rate [34]. Figure 12 is an example of a typical flow meter.

[7] ATO (2019). RTD Sensor, Pt100, Sheath, 3 Wire. [image] Available at: https://www.ato.com/rtd-sensor-pt100-sheath-3-wire [Accessed 3 Nov. 2019].
[8] IndiaMart InterMesh (2019). J Type Thermocouple. [image] Available at: https://www.indiamart.com/proddetail/j-type-thermocouple-14476900488.html [Accessed 3 Nov. 2019].

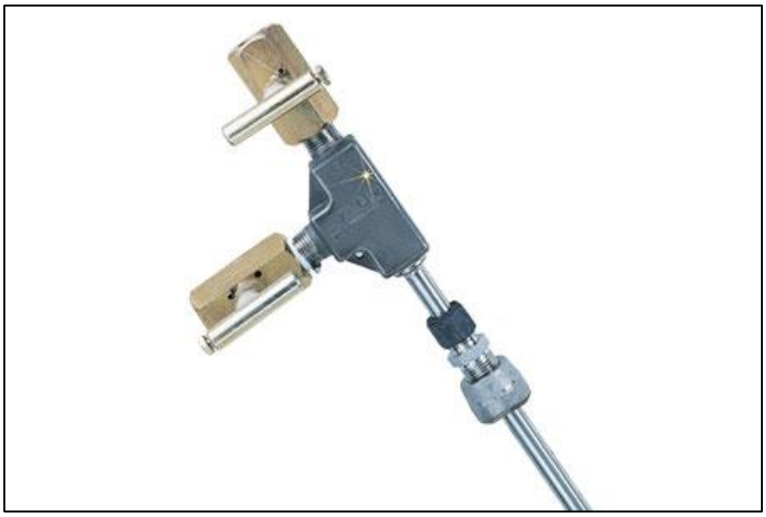

Figure 12: Pitot tube water flow meter[9]

1.4.3 Precooling tower problems

The performance of precooling systems is dependent on the condition of the components within. However, due to the nature and environment of deep-level gold mine, PCTs experience complications. Below is a discussion of the most common concerns encountered.

Scaling [35]

Service water used underground when funnelled to lower levels are in contact with ground deposits. Scaling is when ground minerals dissolve into water through a process called precipitation. Scale formations build up within the fill zone and nozzles of a PCT, decreasing the heat transfer of the system. Figure 13 is an image of scaling formation on film fill.

[9] Omega Engineering (2019). How does a pitot tube work?. [image] Available at: https://www.omega.com/en-us/resources/pitot-tube [Accessed 3 Nov. 2019].

Figure 13: Scale formation on film fill[10]

The minerals dissolved in water are mostly uniform in their contribution to conductivity. Thus, an electrical conductivity meter can be used to measure the total amount of dissolved materials. The accuracy of a conductivity meter is approximately 1% [36]. Figure 14 is a photo of a conductivity meter.

Figure 14: Portable conductivity meter[11]

Fouling [37]

Like scaling, fouling decreases the performance of PCTs by hindering the air and water flow. Small suspended solids or foulants decreases the thermal performance of the fill material as well as increasing the packing weight. The latter could cause support failure. Foulants usually consist of organic matter, silt and process oils.

Corrosion [38]

Corrosion gradually destroys materials over time and is caused by an electro-chemical or chemical reaction within the environment. The dissolved minerals in the mine service water increases the rate of corrosion. Damaged components can break down, increasing

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[10] Dhaka, S (2018). Cooling Tower, Major Scaling in Film Fills. [video - Screenshot] Available at: https://www.youtube.com/watch?v=NkHHVkkLcXw [Accessed 3 Nov. 2019].

[11] Hanna Instruments (2018). Heavy Duty Waterproof Portable Conductivity Meter. [image] Available at: https://hannainst.com/hi9033-multi-range-portable-conductivity-meter.html [Accessed 3 Nov. 2019].

maintenance, lowering efficiency and/or causing total system failure. Figure 15 shows a corroded precooling structure.

Figure 15: Corroded PCT[12]

PCT efficiency is severely affected by various elements due to the nature of the mining industry in South Africa. To ensure PCTs are in optimal working condition they need to be regularly maintained and refurbished timeously. However, this is a costly exercise and with the contributing financial challenges, mines typically overlook this.

[12] Belzona (2017). Cooling Tower Internal Corrosion Damage. [image] Available at: https://blog.belzona.com/cooling-tower-maintenance/ [Accessed 4 Nov. 2019].

1.4.4 Precooling tower components

This section will focus on the components of a wet induced draft PCT. Figure 16 is an illustration of an induced draft counterflow PCT with all its components listed.

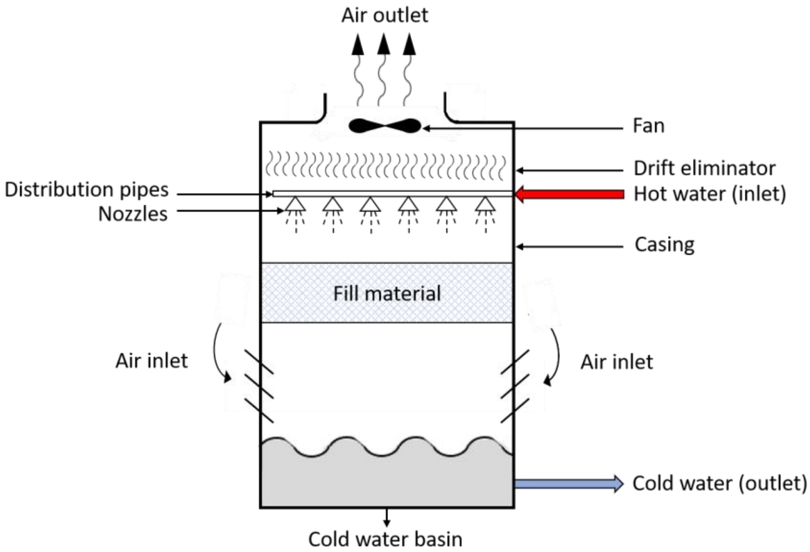


Figure 16: PCT components[13]

Water distribution network

PCT water distribution networks consist of the cold-water pipes, warm-water pipes and spraying nozzles.

The pipeline is used to transfer water to and from the system. Broken pieces caused by corrosion and other debris can easily block the pipe network. High pressure water jets are commonly used to remove blocked materials [39]. Galvanized mild steel pipes have good corrosion resistant qualities and should be used for the distribution network [40]. Any broken or damaged pipe section should be replaced.

PCT nozzles are used to enhance even water distribution throughout the cooling zone. Dry zones are a particular serious problem for PCTs, as dry fill will have a lower resistance to airflow and air will always take the path of least resistance. Furthermore, the droplets created by nozzles are small, increasing the evaporation process [41]. Broken nozzles should be

[13] Europages (2019). Induced draft counter flow. [image] Available at: https://www.europages.co.uk/Mechanical-draft-cooling-towers/HAMON/cpid-5561193.html [Accessed 4 Nov. 2019].

replaced. Blocked nozzles can be cleaned with high pressure water jets or replaced with new ones. Nozzles can improve PCT efficiency by up to 2.9% [42].

Drift eliminators

With evaporative cooling, two types of water loss to the environment is expected. One, which is harmless to the environment, is in the form of pure water vapour. The second is called drift, where water is released to the surroundings via small water droplets in the air. The water droplets are contaminated with chemicals and minerals from the mining environment [43]. Drift eliminators are used to minimise the rate of water droplets being released. Manufacturers guarantee that efficient drift eliminators will reduce drift losses to a maximum of 0.0005% [44], this will increase PCT efficiency up to 2% [45].

Blocked drift eliminators can be cleaned with high pressure water streams. Broken eliminators should be removed and replaced as it could cause blockages further down the system. The support structure should be regularly inspected for corrosion.

Framework

The framework should often be inspected for signs of corrosion. Corroded, damaged or weakened structures could cause entire PCT collapse [46]. Affected sections should be stripped and replaced.

Fill material

The function and type of fill was discussed in Section 1.4.1. To recap, packing material increases the time and surface area of hear transfer between water and air. This makes fill the most important component of PCT performance. Fill can be tailored for different PCTs by stacking to create various thickness and heights.

Fill is one of the most crucial PCT components as it can increase efficiency by up to 20% [47]. Broken or blocked fill should be replaced to ensure optimal heat transfer. Pieces of broken fill could cause blockages further down the system.

Precooling tower fans

With induced draft cooling towers the fans are located at the top. A negative pressure inside pulls the air in from the bottom. This is required to overcome the pressure drop created by packing material. Non-operational fans could lead to almost 100% cooling loss [48]. Furthermore, any obstructions from the air ways should be removed as to not hinder air flow through the PCT.

The most commonly used fans for PCTs are direct drive and gearbox fans [49]. Multiple smaller direct drive fans can be used for the same workload as a large single gearbox driven fan. Direct drive fans have a significant advantage over gearbox fans. Table 2 is a summary of these benefits [49], [50].

Table 2: Direct drive vs gearbox fans

Benefits of multiple 7.5 kW direct driven fans vs single 30 kW gearbox fans	
1	Less vibrations
2	Less maintenance required
3	Easier to replace – no crane required
4	Greater energy saving possibility due to higher control possibility
5	Fans can be stopped/started more frequently
6	In case of motor failure, only part of the cooling is lost, not the total
7	Variable speed drives (VSDs) are not required for temperature control

1.5 Simulation models

Simulations allow for a safe and efficient method of solving real-world problems on a virtual model. It's mainly used as a method of analysis or verification. Most simulation packages are designed with industry and discipline specific condition in mind.

The most commonly available simulation packages used for mine refrigeration systems are summarised in Table 3. A short description and the main disadvantages of each package is stated in this table.

Table 3: Simulation packages

Package	Description	Disadvantages
ENVIRON [51]	A Pascal written program that uses two main modules, heat flow and air flow. The two are solved iteratively until the solution converges.	Eskom Time-of-use (TOU) tariff not integrated
Process Toolbox [52]	Thermal hydraulic system package with a graphical user interface using a drag and drop process. Enables users to design, analyse and optimise system performance.	All components require input information
VUMA [53]	Windows-based software used for mine ventilation, cooling, and environment control. Allows for simultaneous steady-state simulation of air flow and air thermodynamic behaviour.	Training required

The packages listed in Table 3 can be used to simulate deep-level gold mine refrigeration networks. Each having their own advantages and disadvantages. The first two packages are more user friendly as little training is required, making them more accessible. By simulating the refrigeration network certain problems can be efficiently solved. Simulations allow for a risk-free method to analyse changes to a refrigeration network.

1.6 Previous studies

This section provides an overview of various research done in the field of PCTs. The purpose of this is to compare similarities and shortcomings that fall within the boundaries of this study, i.e. refurbishment, modelling, PCT performance and optimisation, the impact thereof and practical verification.

Advanced cooling tower concept for commercial and industrial applications (2014 – Study 1) [54]

The theoretical cooling limit of a cooling tower is the wet-bulb temperature of the incoming air, however, in practice, due to inefficiencies, the water is cooled to a temperature higher than the ambient air wet-bulb temperature. In this study a method of integrating advanced dew-point cooling concept to indirect evaporative cooling approach is described.

The concept modifies the flow path arrangement though fill material which allows for ambient air to be precooled through direct evaporation. This drastically decreases inefficiencies and lowers the practical cooling limit of cooling towers.

The study results were proven through numerical modelling over a large range of climate and operating conditions.

Optimization of operating parameters and performance evaluation of forced draft cooling tower using response surface methodology (RSM) and artificial neural network (ANN) (2012 – Study 2) [55]

This work focused on the optimisation of cold-water temperature in forced draft cooling towers. Through statistical experiments and analysis, it was shown that packing height, air and water flow had significant effect on cold water temperature. The optimum operating parameters were predicted using response surface method (RSM) and an artificial neural network (ANN).

MINLP optimization of cooling towers (2008 – Study 3) [56]

An optimal design for a mechanical counterflow cooling tower through a mixed-integer nonlinear programming (MINLP) model was developed. The goal of the optimisation was to minimise the total annual cost. The parameters to be optimised were water-to-air flow ratio, the water flow rate, the water inlet and outlet temperatures, the operating temperature approach, the type of packing, the type of draft, the volume of packing material, the total pressure drop due to the air flow rate, the fan power, and the water consumption. The following results were observed:

- Cooling towers with low temperature approaches are not suitable
- Dry-bulb temperature variations have a negligible effect on the tower size
- Through the parameters analysed, the temperature approach is shown to be a critical factor in cooling tower design

Improving cooling system efficiency with precooling (2012 – Study 4) [57]

The effect of poor water quality and broken draft fans on a PCT's cooling efficiency and utilisation were investigated. A case study was conducted on a gold mine refrigeration system. The following changes resulted in an average electrical power saving of 1 MW:

- Replaced packing material with lower maintenance fill
- Replaced individual cell fan with four smaller high-speed direct drive fans

Improving deep-level mining refrigeration through increasing precooling efficiency (2018 – Study 5) [58]

In this article the effect of precooling auxiliaries on a mine's refrigeration system were analysed. By improving the efficiency of a PCT with 24.4%, a reduction of 10.3 °C was observed in the chill dam temperature, thus opening the potential for a load management project that will yield an annual electricity cost saving of R500 000.

Investigation of the effect of a new splash grid on natural draught wet cooling tower (NDWCT) performance (2015 – Study 6) [24]

Through an experimental investigation, A. Michaels showed a significant increase in performance characteristic due to a reduction in mean droplet diameter. The case study was done on a natural draught wet cooling tower (NDWCT), with the focus being in the rain zone. This thesis proved the importance of packing material used in precooling towers.

A complete model of wet cooling towers with fouling in fills (2006 – Study 7) [59]

A model was developed to calculate the effect fouling has on cooling tower performance. This model incorporated the three basic cooling tower zones; namely, spray, packing and rain zone. Three models were developed, the first only considering the packing zone and showed an error in calculation of the tower volume of 6.5%. The next two models incorporated another zone each time and by doing so the error decreased to 2.65% by the third model.

This study proved two statements. The first being fouling is a source of cooling tower performance and therefore it is important to develop a strategy to model fouling. The second being the three cooling tower zones (spray, packing and rain) should be included when developing the model as it decreases the error in calculation.

Creating a new model to predict cooling tower performance and determining energy saving opportunities through economizer operation (2015 – Study 8) [19]

Cooling towers are an integral part of any chilled water systems and constitute to a large portion of the system's energy consumption. Furthermore, it is documented that cooling towers are not operated optimally, presenting an area of study.

The chilled water system analysis tool (CWSAT) software is used as a screening tool for energy evaluation of various chilled water systems. However, the tool is limited at both lower wet-bulb temperatures (4.4 °C and below) and low fan power.

Due to the limitation mentioned, this study focused on developing a new model to predict cooling tower performance. Additionally, the study also investigated the feasibility of having surplus cooling tower capacity to allow for economizer cooling.

Design and analysis of cooling tower (2018 – Study 9) [60]

A cooling tower is used in power plants, petrochemical plants, petroleum refineries, etc. They are a vital component to a chilled water system. There is a diverse array of cooling tower types. This study illustrates the performance study, working principle and analysis of induced draft cooling tower.

With a practical analysis, this study observed and calculated various parameters of an induced draft cooling tower (i.e. effectiveness, range, approach and evaporation loss). The study concluded that by passing more volumes of air through a tower, the efficiency will increase due to dissipating more heat through the tower.

Performance evaluation of wet cooling tower fills with computational fluid dynamics (2012 – Study 10) [61]

This study can be divided in two parts. The first is an evaluation and comparison of a wet cooling tower fill performance model developed by Reuter. The Reuter model is compared to cross- and counterflow Merkel, e-NTU and Poppe models. It is found to effectively give the same results.

The second part investigates a second order upwind discretisation method which is applied to the Reuter model for increased accuracy.

Performance comparison for NDWCT using trickle fill at different weather conditions (2015 – Study 11) [62]

With a prototype design and experimental tests, a performance comparison for a NDWCT at different weather conditions were established. The tests were done in summer (hot and dry) and winter (cold and wet) conditions.

The results showed that in winter conditions the tower range, cooling capacity and air temperature change are higher. While in summer, the relative humidity and enthalpy change are higher. Furthermore, it was found that the water consumption in winter conditions are greater than in summer.

Energy performance estimation of cooling towers (2016 – Study 12) [63]

Throughout this project two models were used, specifically the effectiveness-NTU model and a developed empirical model. They investigate and compare the performance of cooling towers. The models were used to predict the performance of the HVAC cooling towers on the campus of the University of Alabama; through this the limitation of each models were determined.

Furthermore, the models were designed to predict mass flow rate of air and temperature of the leaving air by using the temperature and relative humidity of the entering air. The fan status and energy consumption of cooling towers were predicted according to the mass flow rate of air.

Table 4 is a summary of the above studies and highlights the focal points. The purpose of this table is to summarise the similarities and shortcomings of research within the boundaries of this study. The focal points mainly focused on precooling tower refurbishment and optimisation; and whether the changes were practical (real-world applications) or models of a real-world problem.

Table 4: Summary of previous studies and focal points

Focal Points	**Study 1**	**Study 2**	**Study 3**	**Study 4**	**Study 5**	**Study 6**	**Study 7**	**Study 8**	**Study 9**	**Study 10**	**Study 11**	**Study 12**
Modelling	X		X				X	X		X		X
Performance	X	X	X	X	X	X	X	X	X	X	X	X
Impact			X	X	X							
Refurbishment				X								
Optimisation	X	X	X	X	X	X			X			
Practical				X	X	X			X		X	

From Table 4 it is shown that little investigation on PCT refurbishment is done. PCT refurbishment is not a common theme in the industry due to high capital cost as discussed in Study 4. There is adequate research done on PCT performance and efficiency increase, however, these studies neglect to directly address the issue of poor precooling tower operation and the impact thereof.

This study will thus aim to investigate the shortcoming of previous studies by analysing the impact of precooling tower refurbishment on the mining industry specifically. In Section 1.7 a problem statement and objectives will be developed.

1.7 Problem statement

The sustainability of deep-level gold mines in South Africa are more volatile than ever. These include the unique challenges faced by this industry, increasing operating costs and consequently crippling profit margins. As mentioned in Section 1.2, increasing mining depths are one of the highlighted challenges contributing to higher operating costs. However, increased mining depths are necessary to be competitive within this industry, especially with the ever-decreasing gold production rate.

High working area temperatures are expected due to increasing mining depths, necessitating the importance of adequate cooling. Refrigeration networks are used to cool water for cooling purposes and underground operations. These networks are one of the most energy intensive systems on deep-level gold mines. With ever increasing Eskom electricity tariffs, mines are forced to optimise energy intensive systems to remain profitable.

As discussed in Section 1.4, PCTs are one of the key parameters within the refrigeration network. These towers are responsible for reducing the temperature of the service water before it enters the FP units. The performance of the FPs is dependent on the inlet water conditions. Lower inlet water temperatures will result in less power required by the FPs to achieve the target outlet temperature. Consequently, improving the coefficient of performance (COP) of the entire refrigeration network and reducing operating costs. Therefore, highlighting the importance of PCTs within the refrigeration network.

Due to the operating environment of PCTs, their performance deteriorates over time. This is because the performance of a precooling system is dependent on the condition of the components within. PCT components experience common complication like scaling, fouling and corrosion, caused by the nature and environment of deep-level gold mines. It is thus important that PCT components are kept at optimal condition, especially in the mining industry.

A poor precooling system performance will result in inadequate heat transfer and higher water temperatures to the fridge plant units. Reducing the water temperature by improving PCT heat transfer, the energy usage of fridge plants can be affected. Timely refurbishments are required to maintain optimal performance of PCTs. This is usually neglected because of high capital expenditure.

1.8 Objectives

The stated problem can be addressed by the following main objectives:

- Identify inefficient operating precooling towers.
- Evaluate operating parameters of the identified PCT to the original design specifications.
- Develop a refurbishment solution based on the evaluated parameters.
- Implement refurbishment solution.
- Validate refurbishment results through a simulation model.

By addressing the main study objectives, the impact of PCT refurbishment on deep level gold mines can be evaluated. The evaluated solution can be quantified by identifying the PCT improvement, cost- and service delivery impact.

1.9 Study overview

Chapter 1

In this chapter background information on the state of deep-level gold mines were discussed. Background information and literature regarding precooling tower refurbishment was researched.

Chapter 2

In this chapter a methodology strategy will be developed. The aim is to identify, evaluate, implement, re-assess and quantify a refurbishment solution.

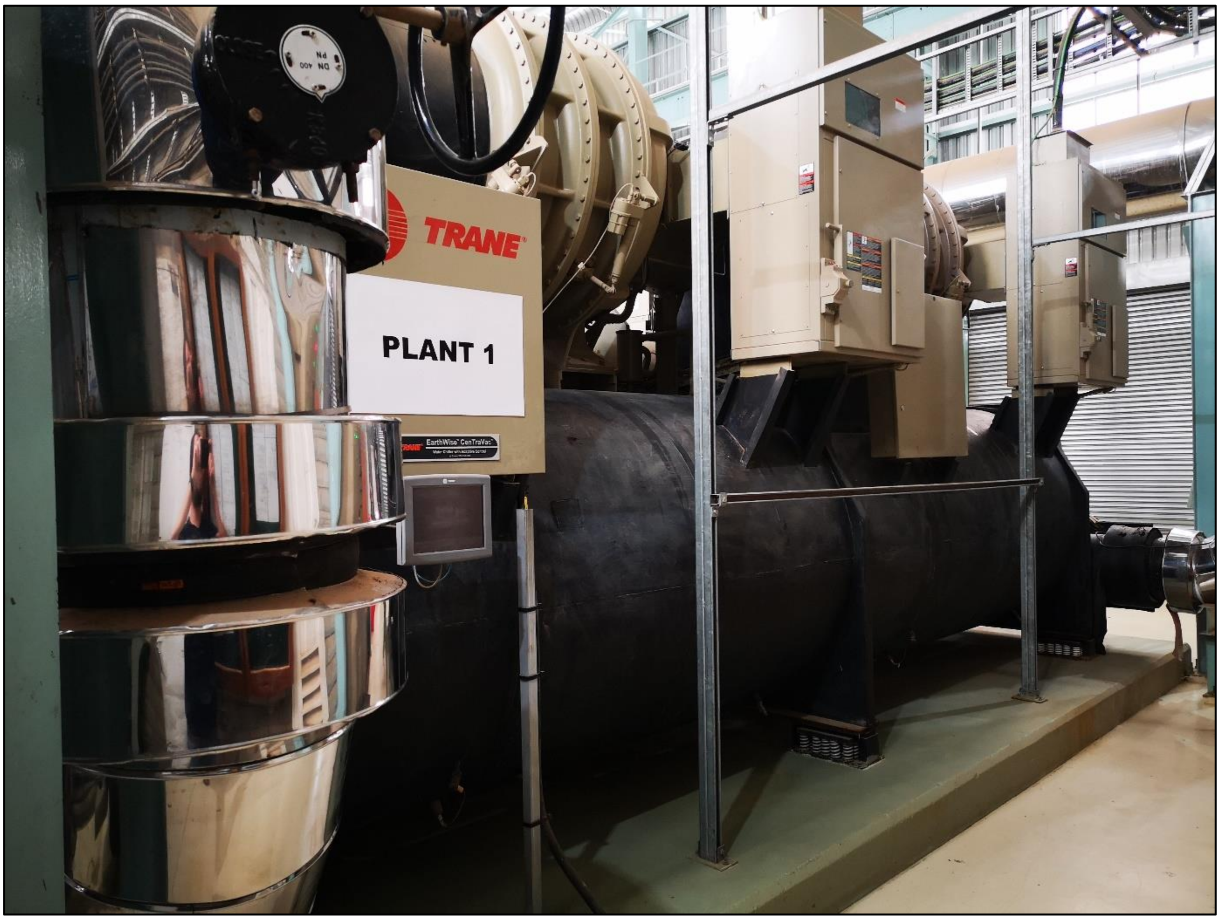
Chapter 3

Here the developed methodology strategy will be validated through a case study. This will aim to meet the goals mentioned in Chapter 1.

Chapter 4

The final chapter will conclude the study and give recommendations regarding future studies.

CHAPTER 2: DEVELOPING A PRECOOLING TOWER REFURBISHMENT STRATEGY



14

[14] S Jerling, Personal photograph. "Refrigeration plant", Free-state, 2019

2.1 Preamble

In this chapter a PCT refurbishment strategy will be developed by building on the background and literature information presented in Chapter 1. The aim of this methodology is to create a process to follow when identifying a refurbishment solution and evaluating the impact thereof on deep-level gold mines.

2.2 Methodology

A strategy was created to resolve the main objectives set in Chapter 1. Figure 17 illustrates the flow for developing the refurbishment strategy.

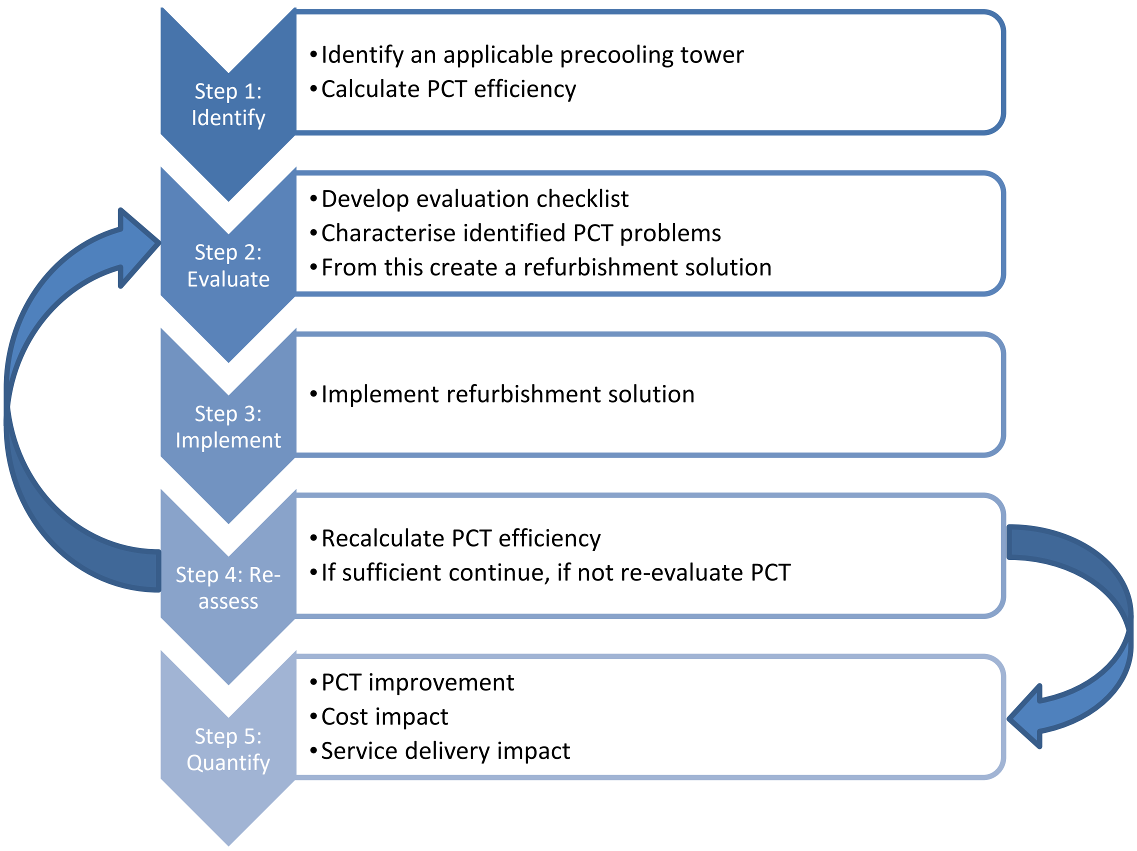


Figure 17: Solution strategy

The first step of the methodology is identifying a PCT to refurbish. The evaluation phase will concentrate on developing an evaluation checklist which can be used to characterise PCT problems. Afterwards a refurbishment solution will be defined and implemented. PCT efficiency should be recalculated after implementation, to ensure desired efficiency is achieved. The results will be quantified if the efficiency benchmark is met, otherwise Step 2 to 4 should be repeated. The final part of the methodology is to ensure that all the goals set in

Chapter 1 have been met by quantifying the impact of refurbishment. The refurbishment strategy will be fully discussed in the following sections.

2.3 Step 1: Identify

In Step 1 a process will be developed to identify a mine/site where a refurbishment solution for a PCT system will be applicable. Thereafter PCT efficiency will be compared to a benchmark value.

Preliminary investigation

As part of the identification process non-feasible locations should be eliminated. The following questions are used to separate non-feasible locations:

- Does the mine have PCT?
  The goal of the study is evaluation of PCT refurbishment. If the site does not have a precooling system, it will be a non-feasible location.

- Does the mine have a newly installed or refurbished PCT?
  Newly installed or refurbished PCTs will typically have good performance markers and the need for refurbishment will be small.

- Is the life-of-mine reasonable?
  It is ill-advised to start a new project on locations with a short life-of-mine, especially if the payback period will be longer than the life-of-mine.

After the preliminary inquiries have been answered, a location will either be identified for further investigation or declared as non-feasible. Thereafter, the PCT efficiency of the selected location will be analysed.

Precooling tower efficiency

With a mine identified, the PCT efficiency is analysed to determine if it should be refurbished. PCT efficiency is calculated with Equation 4, as discussed in Chapter 1.

A recent study conduction by W. Biermann found that the average efficiency of newly installed and refurbished PCTs is in a range of 70% to 75% [64]. Hence, a benchmark efficiency of 70% will be a good indication of the PCT condition. PCTs with efficiencies below the benchmark should be refurbished.

Summary of Step 1

The decision flowchart in Figure 18 is a summary of the developed identification process and can be used as a quick indication on whether a PCT should be refurbished.

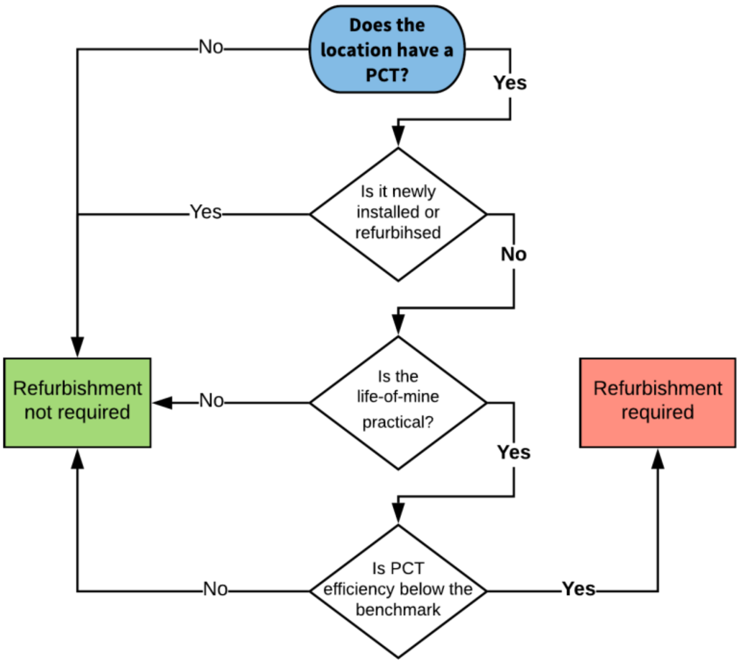


Figure 18: Identification decision flowchart

At the end of Step 1, a location will have been identified and PCT efficiency is compared to the benchmark. The following step is an evaluation of the precooling system.

2.4 Step 2: Evaluate

In Step 2 a checklist will be developed to evaluate the identified precooling system. From the evaluation checklist, specific PCT problems will be brought to light. Recommendations to solve the problems will form a refurbishment solution.

2.4.1 Evaluation checklist

In Chapter 1 PCT problems and solutions were considered. Here a method to analyse PCT components was developed in the form of a checklist. The checklist is divided into three sections; review of PCT efficiency, components effecting efficiency, and components not effecting efficiency. The evaluation checklist is developed in Excel.

Section 1 – PCT efficiency

In Step 1 PCT efficiency was calculated. PCT range and approach is used as input values to calculate the efficiency. PCTs with efficiencies below the benchmark value will be further investigated.

Section 2 – PCT component evaluation (non-efficiency impact)

In section 2 components that have little to no influence on PCT efficiency is evaluated. The common problems and solutions as discussed in Chapter 1 are summarised in Table 5. The solution for common problems identified will form part of the refurbishment solution.

Table 5: Non-efficiency impacting PCT components

Component	Common problems	Solution
2.1 Hot water inlet	Blocked	Clean blockage
	Leaks	Replace broken pipes
2.2 Distribution pipes	Blocked	Clear blockage
	Leaks	Replace broken pipes
2.3 Casing	Corroded, damaged or weakened casing	Replace or repair casing
2.4 Air inlet	Obstruction	Remove obstructions
2.5 Air outlet	Obstruction	Remove obstructions
2.6 Cold water basin	Little to no debris should be inside the cold-water basin	Remove any debris
	Leaking cold water basin	Fix leaks
2.7 Cold water outlet	Blocked	Clean blockage
	Leaks	Replace broken pipes
2.8 Framework	Corroded, damaged or weakened framework	Replace or repair framework
2.9 Deck	Corroded, damaged or weakened deck	Replace or repair deck

Section 3 – PCT component evaluation (efficiency impact)

Four components that have an impact on efficiency has been identified in Section 1.4.4. Table 6 is summary of the common problems expected, solutions and impacts as discussed in Chapter 1.

Table 6: Efficiency impacting PCT components

Component	Common problems	Solution	Impact
2.1 Drift eliminator	Broken or blocked	Replace or clean affected drift eliminators	Up to 0.2 °C improvement on cold water outlet or 2% efficiency
2.2 Nozzles	Broken or blocked	Replace nozzles	Up to 0.29 °C improvement on cold water outlet or 2.9% efficiency
2.3 Fill material	Broken or damaged	Replace fill	Up to 2 °C improvement on cold water outlet or 20% efficiency
2.4 Fan general	Single gearbox driven fan per cooling cell	Replace with multiple smaller direct dive fan units	Efficiency impact is a function of total working fans and calculated efficiency (See Equation 5)
	Non-operational fans	Replace/repair broken fans	

A rating index is created for drift eliminates, nozzles and fill material (see Table 7). The component conditions can be rated from zero to five, where zero is poor and five is good. Poor component conditions will have a negative impact on PCT heat transfer.

If the condition improves, an efficiency increase can be calculated based on the current condition of the component. Components in good condition (rating of five) will have 0% increase of maximum impact efficiency and components in severe condition (rating of zero) will have 100% increase of maximum impact efficiency when refurbished. For example, the maximum impact of drift eliminators is 2%, if the current condition is evaluated at two out of five, the expected efficiency increase will be up to 1.2%. Components with a rating lower than 2 should be added to refurbishment solution.

Table 7: Index rating

Rating	Drift [%]	Nozzles [%]	Fill [%]
	Percentage broken, missing and/or blocked		
0	75-100	75-100	75-100
1	60 - 74	60 - 74	60 - 74
2	45 - 59	45 - 59	45 - 59
3	30 - 44	30 - 44	30 - 44
4	15 - 29	15 - 29	15 - 29
5	0 - 14	0 - 14	0 - 14

Equation 5 was developed to calculate the impact of non-operational fans on a precooling system. The more non-operational the fans, the higher the cooling loss [48]. The equation is a function of the maximum achievable efficiency (75% as per Section 2.3), the current efficiency, and the number of non-operational fans.

Equation 5: Fan efficiency impact

$$\boldsymbol{\eta_d = (\eta_{max} - \eta_{cur}) * (\frac{\eta_{cur}}{\#Fans_t} * \#Fans_n)}$$

Where: η_d = Max efficiency impact [%]

η_{max} = Max achievable efficiency [%]

η_{cur} = Current PCT efficiency [kg/s]

$\#Fans_t$ = Number of installed fans

$\#Fans_n$ = Number of non-operational fans

The developed evaluation checklist is shown in Figure 19. When completed, certain problem areas will be identified as well as an expected efficiency increase if the problems are addressed. Appendix A shows the Excel formulas used for the checklist.

Evaluation checklist for PCT refurbishment					
Mine:			Location:		
Date:			Life-of-mine:		
Section 1 - Precooling tower efficiency					
Item	Description	Value	Notes		
1.1	Range [°C]				
1.2	Approach [°C]				
1.3	Efficiency [%]				
PCT below 70% benchmark efficiency should be refurbished					
Section 2 - PCT component evaluation (non-efficiency impact)					
Item	Description	Problem	Notes		
2.1	Hot water inlet				
2.2	Distribution pipes				
2.3	Casing				
2.4	Air inlet				
2.5	Air outlet				
2.6	Cold water basin				
2.7	Cold water outlet				
2.8	Framework				
2.9	Deck				
Section 3 - PCT component evaluation (efficiency impact)					
Item	Description	Rating 0 to 5	Max Impact [%]	Result [%]	Notes
3.1	Drift eliminator		2%	0.0%	
3.2	Nozzles		2.90%	0.0%	
3.3	Fill material		20%	0.0%	
	Fan calculation	Cooling fans	Non-working	Result [%]	Notes
3.4	PCT Fans			0.0%	
Components with a rating lower than 2 should be added to refurbishment solution					
Total efficiency improvement up to:				0.0%	

Figure 19: Evaluation checklist template

Problems identified

With completion of the evaluation checklist, certain components with common problems will be identified. The solutions therefore as per Table 5 and 6 will form the refurbishment solution. Completion of Section 3 in the checklist will also give an expected efficiency improvement. If required, the improvement can be simulated. The acquired refurbishment solution will be implemented in Step 3.

2.5 Step 3: Implement

Once the evaluation checklist is completed and a refurbishment solution is developed, Step 3 involves the implementation thereof. The solution will be implemented on an identified (Step 1) case study. Before implementation the refurbishment solution will first be discussed with the appropriate management team to ensure a realistic timeline and budget is approved.

Implementation will require coordination with mining personnel and any involved contractors to successfully apply the refurbishment solution. Regular meetings will help with project planning and discussions. The cost of implementation and timeline should be investigated before selecting any contractors.

Step 1 and 2 can be seen as the project scope, or primary deliverables that needs to be achieved. It is important that this is clearly discussed with all parties. A project timeline will help with planning and give a bird's eye view of the project.

Refurbishment will have an impact on both PCT parameters and the refrigeration network. Before the impact can be quantified, the PCT efficiency after implementation should be re-assessed.

2.6 Step 4: Re-assess

In Step 4 the PCT efficiency after implementation is recalculated. This is done to ensure efficiency is above the 70% benchmark after refurbishment, as discussed in Step 1. The same method followed in Step 1 will be used to re-calculate the efficiency, using Equation 4. The 70% benchmark value should be included in the project deliverables.

If, after refurbishment, the efficiency is still below 70%, Step 2 to 4 should be repeated. This is to ensure the refurbishment is successful and identify any previously missed complications or inefficiencies. This process should be continued until the efficiency benchmark value is achieved. This illustrates the importance of simulating the refurbishment solution as unsuccessful projects can be identified beforehand.

Once the efficiency is above the benchmark value, continue to Step 5 for quantification of refurbishment results.

2.7 Step 5: Quantify

In the final step a quantification strategy will be developed to analyse the impact of PCT refurbishment. The strategy will focus on PCT improvement, refrigeration cost impact and service delivery.

2.7.1 PCT improvement

Implementation of the refurbishment solution will not only result in an increased efficiency, but also impact to following parameters:

Evaporation loss [65], [66]

A PCT uses evaporative cooling to cool water with air. While the mass flow rate of dry air through a PCT will remain constant, a decrease in mass flow rate of water is expected. The loss of water flow rate is equal to the amount of water evaporated. To maintain a steady operating condition, the water which has been lost must be made-up. To calculate the amount of loss of water through evaporation, the energy balance through the tower must first be determined, see Equation 6.

Equation 6: PCT energy balance

$$(\boldsymbol{m_{a1}h_{a1}}) + (\boldsymbol{m_{w3}h_{w3}}) = (\boldsymbol{m_{a2}h_{a2}}) + (\boldsymbol{m_{w4}h_{w4}})$$

Where: m_{a1} & m_{a2} = Mass flow rate of dry air in and out the cooling tower [kg/s]

h_{a1} & h_{a2} = Enthalpy of dry air steams in and out the cooling tower [kJ/kg dry air]

m_{w3} & m_{w4} = Mass flow rate of water in and out the cooling tower [kg/s]

h_{w3} & h_{w4} = Enthalpy of water in and out the cooling tower [kJ/kg water]

However, the flow rate of dry air through the tower is constant ($m_{a1} = m_{a2} = m_a$). In Equation 7 m_a is solved.

Equation 7: Solved for mass flow rate of dry air

$$\boldsymbol{m_a = \frac{m_3(h_3 - h_4)}{(h_2 - h_1) - (w_2 - w_1)h_4}}$$

Where: w = Humidity ratio – grams of moisture per kilogram of dry air

Equation 7 is true under the following assumptions:

- Steady operating conditions
- Dry air and water vapour are ideal gases
- Kinetic and potential energy changes are negligible

- PCT is adiabatic

The parameters in Equation 7 can be determined from the psychrometric chart attached in Appendix B.

Makeup water can be calculated using Equation 8. The makeup water equals the evaporation loss, as the system is in steady operating condition.

Equation 8: Makeup water calculation

$$\boldsymbol{m_{makeup} = m_a\,(w_2 - w_1)}$$

Where: m_{makeup} = PCT makeup water [kg/s]

Alternatively, the evaporation loss/makeup water can be calculated through Equation 9 [67].

Equation 9: Alternative evaporation equation

$$\boldsymbol{E = 0.00085(R \times 1.8 \times m_w)}$$

Where: E = Evaporation loss [kg/s]

R = PCT range

m_w = Total circulating water [kg/s]

Drift loss [66], [68]

Because of the direct contact between water and air, a small amount of water is removed as droplets. The typical drift loss through a wet PCT is no more than 0.2% of the total circulating water. Equation 10 represents drift loss.

Equation 10: Drift loss calculation

$$\boldsymbol{m_{drift} = 0.002m_w}$$

Where: m_{drift} = PCT drift loss [kg/s]

m_w = Total circulating water [kg/s]

Blowdown [69], [70]

During evaporation water vapour is removed from the system, however, dissolved solids (calcium, chloride, magnesium and silica) remain in the recirculating water. Over time the concentration of dissolved solids increase. High concentrations can cause scale formation and corrosion. PCT blowdown can be calculated using Equation 11.

Equation 11: Blowdown calculation

$$m_{blow} = \frac{m_{makeup}}{n_{cycles}} - m_{drift}$$

Where: m_{blow} = PCT blowdown [kg/s]

n_{cycles} = Cycles of concentration [-]

PCT cycle of concentration is the amount of concentration of dissolved solids in the water. It can be measured with a conductivity meter.

<u>Heat load</u>

The heat load of a PCT is equivalent to the heat rejected during the precooling stage. A higher heat load will result in lower heat absorption required by the FP's evaporator vessel, as water will enter the vessel at a lower temperature. Heat load of a PCT is calculated with Equation 1.

2.7.2 Cost impact

PCT cost impact after refurbishment is quantified through the following:

- Change in refrigeration power usage
- Refrigeration network performance
- Cost saving

A lower PCT outlet temperature will result in a lower heat load over the towers, reducing the power required by the refrigeration system, consequently improving the performance of the entire refrigeration network. The outcome being a reduction in operating cost for the same amount of cooling provided.

Change in refrigeration power usage

An important step in evaluating the impact of PCT refurbishment is the change in refrigeration power usage. A lower FP inlet temperature after refurbishment will result in a lower power usage, for the same FP outlet temperature. This will translate to an electrical cost saving. Change in power usage can be determined by collecting and analysing the refrigeration system's electrical power usage before and after PCT refurbishment.

Refrigeration network performance

An increased PCT heat transfer will result in an improved refrigeration network performance. Performance of the refrigeration network and FP evaporator heat transfer is quantified with the Equation 12 to 16 [16].

FP evaporators are responsible for absorbing heat from the service water, while the condensers release the heat. The heat absorbed by the evaporator is calculated with Equation 12.

Equation 12: Heat absorbed by evaporator

$$\boldsymbol{Q_{evaporator} = \dot{m}Cp(T_{out} - T_{in})_e}$$

Where:	$Q_{evaporator}$	= Amount of heat absorbed by evaporator [kW]
	$\dot{m}$	= Mass water flow rate [kW]
	Cp	= Specific heat of water [$\mathrm{kJ/kg \cdot K}$]
	ΔT_e	= Difference between evaporator inlet and outlet water temperature [K]

COP of the fridge plant machines can be calculated with Equation 13.

Equation 13: COP of the FP system

$$\boldsymbol{COP_{machine} = \frac{Q_{evaporator}}{P_{FP\ System}}}$$

Where:	$COP_{machine}$	= Machine COP [-]
	$Q_{evaporator}$	= Amount of heat absorbed by evaporator [kW]
	$P_{FP\ System}$	= FP system electrical power usage [kW]

Refurbishment of the precooling system will also impact the entire refrigeration network. The heat load absorbed through the network is calculated with Equation 14.

Equation 14: Heat absorbed by refrigeration network

$$\boldsymbol{Q_{absorbed} = \dot{m}Cp(T_{out} - T_{in})_{network}}$$

Where:	$Q_{absorbed}$	= Amount of heat absorbed by refrigeration network [kW]
	$\dot{m}$	= Mass water flow rate [kW]
	Cp	= Specific heat of water [$\mathrm{kJ/kg \cdot K}$]
	ΔT_e	= Difference between network inlet and outlet water temperature [K]

From this, the COP of the refrigeration network can be determined with Equation 15.

Equation 15: COP of refrigeration network

$$\boldsymbol{COP_{network} = \frac{Q_{absorbed}}{P_{network}}}$$

Where: $COP_{network}$ = Refrigeration network COP [-]

$Q_{absorbed}$ = Amount of heat absorbed by refrigeration network [kW]

P_{motor} = FP electrical power usage [kW]

Cost saving

Electrical cost impact is calculated with Equation 16.

Equation 16: Cost impact

$$\boldsymbol{Cost\ impact\ =\ Project\ cost - Cost\ savings}$$

Where: $Cost\ impact$ = Refurbishment cost impact [R]

$Project\ cost$ = Initial investment amount [R]

$Cost\ savings$ = Refrigeration power usage electrical cost savings [R]

The cost savings for implementing the refurbishment solution is calculated with the change in refrigeration power usage and the ESKOM tariffs, see Equation 17. The cost savings calculation sheet is attached in Appendix C.

Equation 17: Cost savings

$$\boldsymbol{Cost\ savings\ =\ Power\ usage\ *\ ESKOM\ tariff}$$

Where: $Cost\ savings$ = Refrigeration power usage electrical cost savings [R]

$Power\ usage$ = Change in electrical power usage [R]

$ESKOM\ tariff$ = Tariff as shown in Appendix C [R]

A good payback period is advantageous to the mine and does not extend past the life-of-mine or a predetermined period. A cost savings initiative payback period is the time it takes for a project to recoup the initial investment amount and is calculated using Equation 18.

Equation 18: Payback period

$$\boldsymbol{Payback\ period\ (In\ months)} = \frac{\boldsymbol{Initial\ investment}}{\boldsymbol{Savings\ amount\ per\ month}}$$

Where: $Initial\ investment$ = Investment amount [R]

Savings amount = Cost savings calculated/simulated [R]

Payback period = Time period to recoup initial investment [Months]

2.7.3 Service delivery

In Section 2.7.2 the cost impact was calculated for the same amount of cooling provided before and after refurbishment. However, in some cases, the identified mine will require an improvement in the cooling provided, for the same amount of power usage.

A study conducted by Krige showed that a decrease in evaporator outlet temperature for the same amount of FP power usage may result in an improved service delivery [71].

2.8 Verification

The developed methodology strategy is verified through literature. As part of the strategy four components have been identified to have a measurable impact on PCT efficiency, see Table 6. Depending on the condition of these components, they can form part of the refurbishment solution. By implementing the solution, an efficiency increase is expected due to changes in the components.

A study conducted by Yadav et al. [45], showed the impact of PCT drift eliminators on PCT efficiency. Sadafi [42] investigated the importance of PCT nozzles and illustrated the effect thereof on efficiency. The study done by Khalifa [47] proved the importance of PCT fill material and calculated a potential efficiency impact. The efficiency impact due to PCT fans were researched and proven through a study conducted by Liu, Zhang and Jia [48]. Furthermore, a study done by Schutte, Pelzer and Mathews [57] proved that PCT efficiency increase will result in an improved PCT water outlet temperature. This was also validated by Biermann in 2017 [64].

A simulation model will be created in Chapter 3 as an extra means of verification. The simulation will aim to analyse the impact of the refurbishment solution.

2.9 Summary

In this chapter a methodology strategy was developed to evaluate the impact of PCT refurbishment. During the strategy development, an evaluation checklist was created to easily establish a refurbishment solution. With implementation of the solution, an improvement over the precooling system and refrigeration network is expected. The final step of the methodology is quantification of the expected improvements. In Chapter 3, a case study will be used to validate the methodology strategy.

CHAPTER 3: IMPLEMENTATION OF AN OPTIMISED PRECOOLING TOWER REFURBISHMENT STRATEGY

[15]

[15] S Jerling, Personal photograph. "Cooling towers", Free-state, 2019

3.1 Preamble

In Chapter 2 a methodology strategy for PCT refurbishment was developed. In this chapter a case study was used to validate the methodology strategy. The strategy will be followed to evaluate the impact of PCT refurbishment.

3.2 Case study

In this section a brief overview of the case study will be given. Due to confidentiality, the case study mine will be referred to as Mine A. All information was collected from reliable mine personnel and design documentation.

3.2.1 Mine A overview

Mine A is located in the Free State province of South Africa. The underground workings are accessed by two surface vertical shafts:

- One for the conveyance of men, materials and rock,
- Second as an unequipped up-cast exhaust ventilation shaft.

Gold deposits are mined at depths ranging from 1 600m to 2 600m below surface. Mine A has no sub-shaft rather a twin-end sub-decline which was developed to access deeper extremities of the orebody. Mine A has six main mining levels. 57L and 60L are located on the upper mining section while 69L, 71L, 73L and 75L form part of the decline mining section.

3.2.2 Mine A specifications

Mine A is equipped with a two-stage precooling system. With the first stage acting as a spray chamber and storage dam. After precooling, the service water is further cooled by the four surface FPs. The cooled mining water is stored in a surface chill dam. From here, the water is split between underground services and surface BAC's. Figure 20 illustrates the overview of Mine A's surface operation.

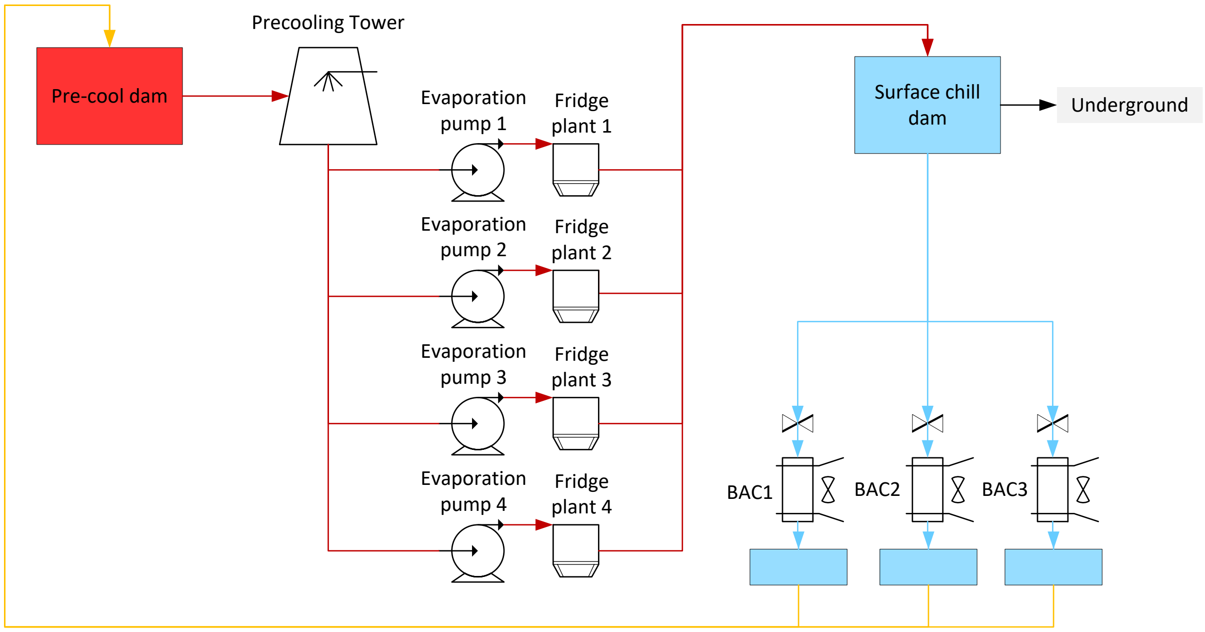


Figure 20: Mine A surface operation layout

Precooling system

Counterflowing induced draft PCT cells are used for Mine A's precooling system. For the purpose of this study, the first stage spray chambers and second stage cooling will form the entire precooling system. The second stage has eight cooling cells each with a single 30kW gearbox driven fan. The specification of Mine A's precooling system is summarised in Table 8. Figure 21 illustrates the side and top view of the PCTs.

Table 8: Mine A precooling system specification

Description	Quantity
Number of cooling cells	8
Average water flow [l/s]	543
Combined fan motor rating [kW]	240
Storage capacity [m^3]	6 000

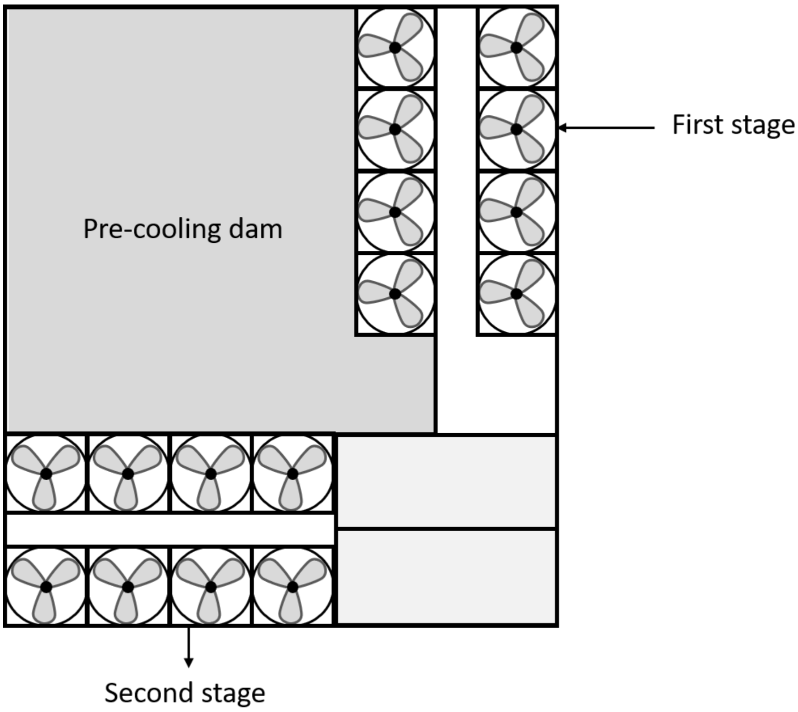


Figure 21: Mine A precooling system

Refrigeration system

Mine A uses four 2.1MW parallel configured FPs to cool the service water. Table 9 is the specifications of the refrigeration system.

Table 9: Mine A refrigeration system specification

Description	Quantity
Number of fridge plant units	4
Combined power rating [kW]	8 400
Design water flow per FP [l/s]	280
Surface storage dam capacity [m^3]	6 800
Average flow out of storage dams [l/s]	340.6
Max flow to BAC system [l/s]	390
Max flow to underground [l/s]	360

Water reticulation

Mine A is equipped with a three-chamber pump system used as both a supply and return for mining water from and to surface. There are two chilled storage dams located on 45L used to feed mining operations. Hot water is collected on 66L in four storage dams. From 66L hot dam water is pumped to 45L. From 45L the hot water is pumped to surface with a 3CPS, however, in some cases the 45L pump station is used. A simplified layout of Mine A's water reticulation is showed in Figure 22.

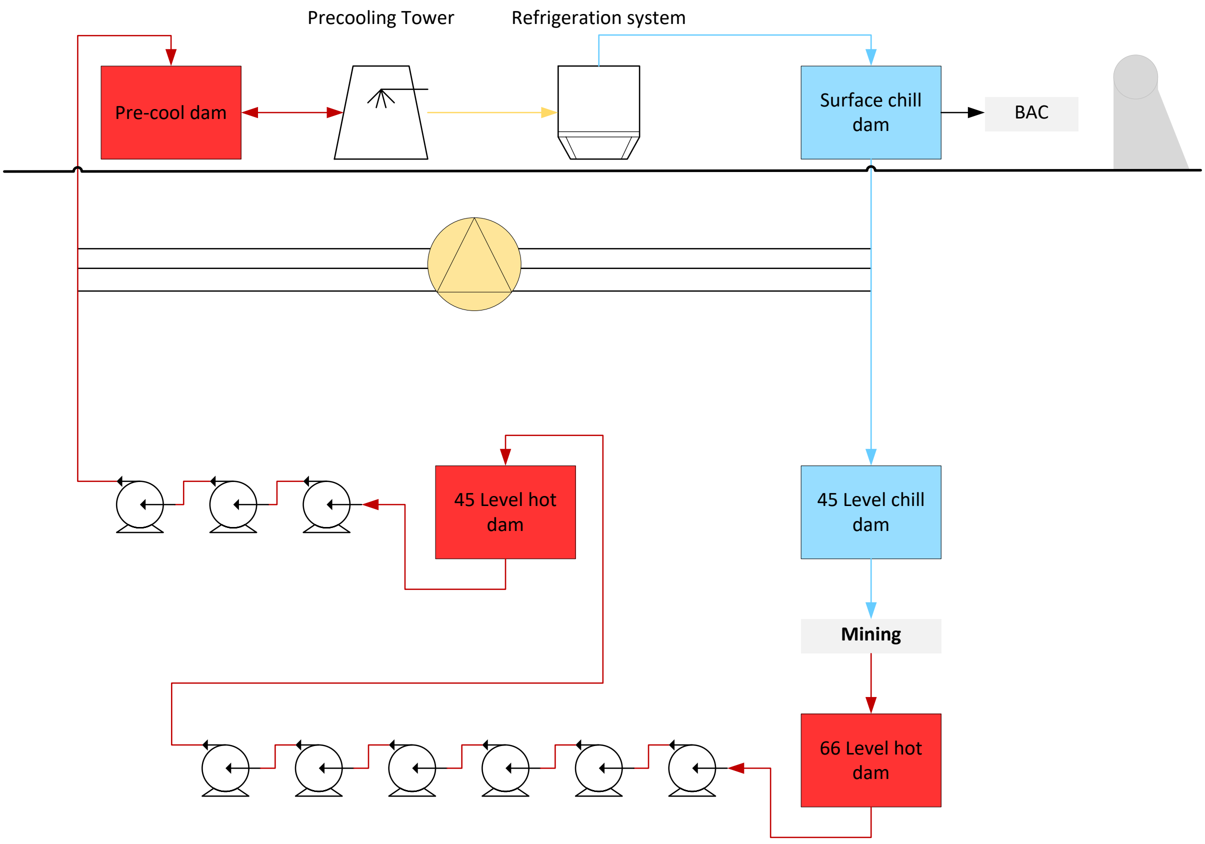


Figure 22: Simplified layout of Mine A's water reticulation

Table 10 is a summary of Mine A's water reticulation components specification.

Table 10: Mine A water reticulation specification

Description	Quantity	
3CPS max flow [l/s]	360	
45L chilled dam capacity [m^3]	6 200	
66L hot dam capacity [m^3]	16 000	
66L number of pumps and rating [kW]	6	9000
66L max flow	460	
45L hot dam capacity [m^3]	6 200	
45L number of pumps and rating [kW]	3	7500
45L + 3CPS max flow	425	

In case of 3CPS failure, Mine A is equipped with a double dissipator system to send chilled water underground.

3.3 Simulation for validation

A simulation model was created to validate the methodology strategy using Process Toolbox (PTB). In this section the developed refurbishment solution was simulated using PTB. As discussed in Chapter 1, PTB has the advantages of little training required and Eskom TOU tariffs built in to calculate cost impact. However, input data was required for each component. Furthermore, more PTB as a simulation program has been verified in studies done by W. Biermann [64] and P. Mare [72]. Appendix D lists the refrigeration network components and their input data requirements.

The following processes were followed when creating the simulation model:

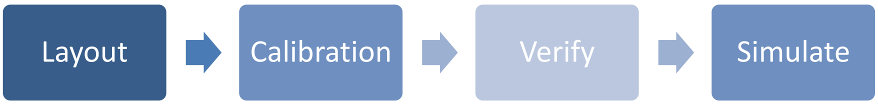


Figure 23: Simulation for verification flow

Model layout

Firstly, all the refrigeration network system components were added to the PTB interface. The simulation model layout is displayed in Figure 24.

Calibration

Here all the required input data as stipulated in Chapter 1 were collected. Appendix D is a summary of the required PTB input data for Mine A.

Validate

After calibration, the simulation model was verified using historical data. Figure 25 compares the actual and simulated power usage of Mine A over an average 24-hour period for April 2018.

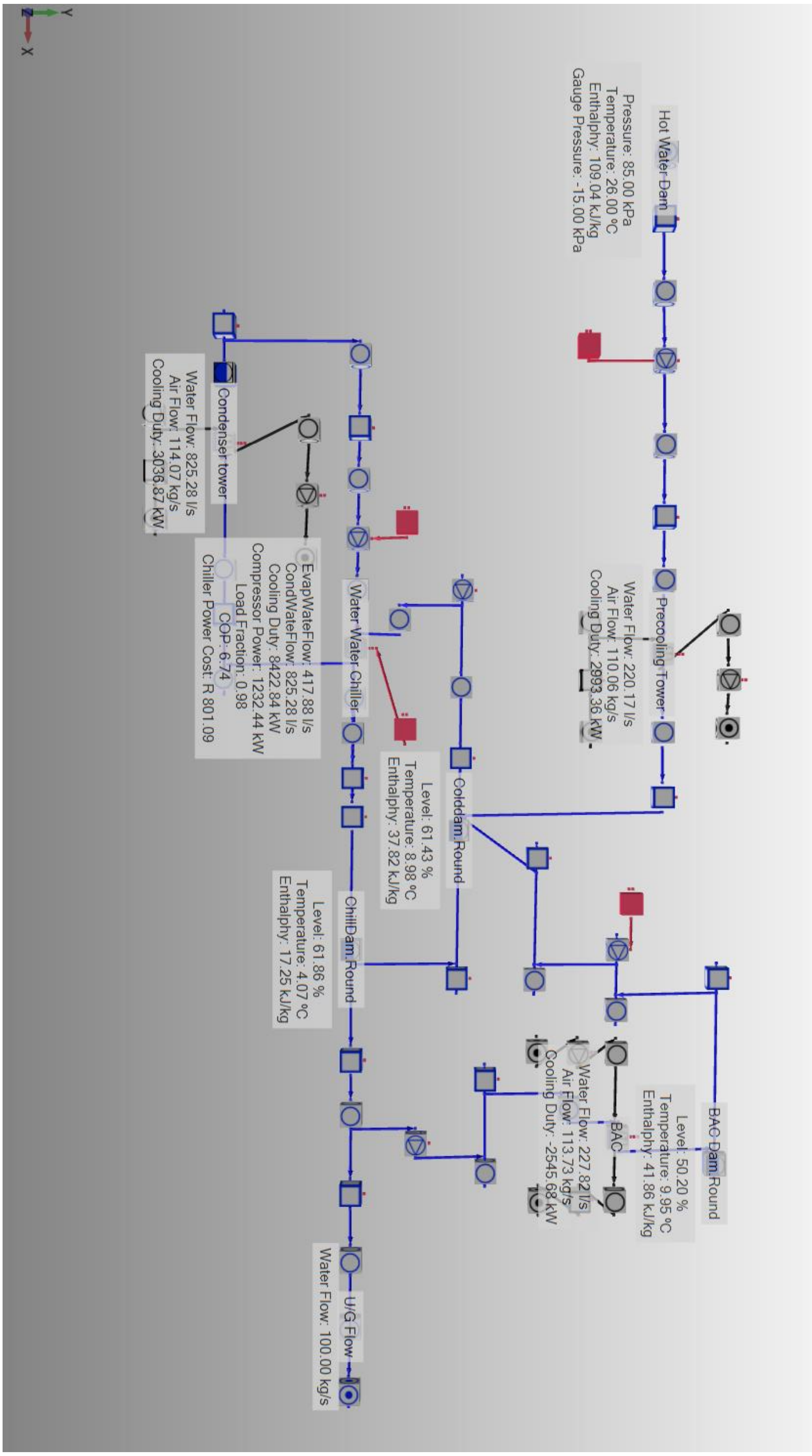


Figure 24: Simulation model interface

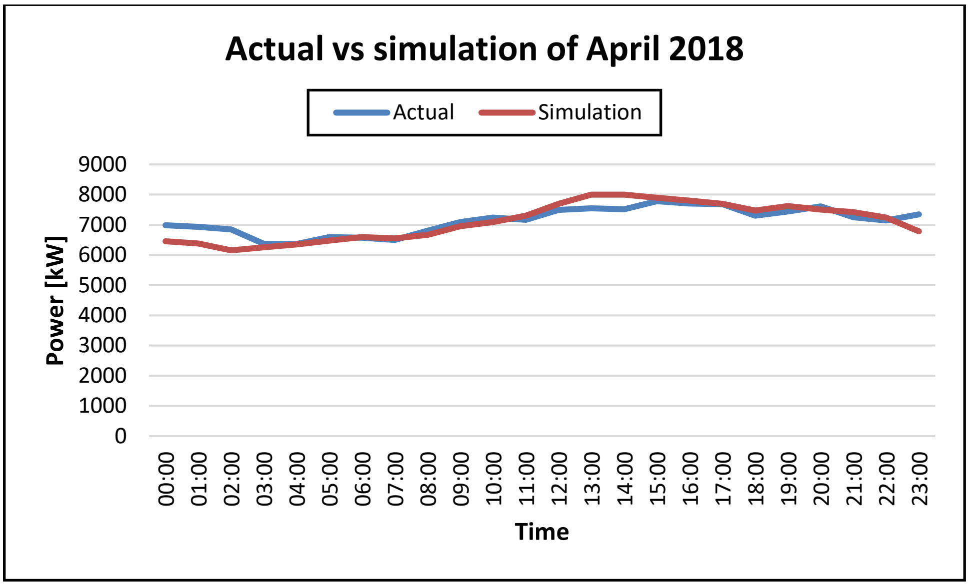


Figure 25: Comparison between actual and simulation of April 2018

Simulation

During the refurbishment evaluation step, the solution will be simulated and compared to actual results.

3.4 Application of methodology

In this section the methodology solution developed in Chapter 2 will be applied to Mine A. Firstly the process of identifying a mine will be discussed. Afterwards the evaluation checklist will be used to characterise precooling problems and create a refurbishment solution. The solution was simulated to demonstrate the change in refrigeration network. After implementation the efficiency was recalculated, before the results were quantified.

3.4.1 Step 1: Identify

The first step was used to identify Mine A as an applicable case study.

Preliminary investigation

The following inquiries were answered:

- *Does the mine have PCTs?*

Yes, Mine A is equipped with a precooling system.

- *Does the mine have a newly installed or refurbished PCT?*

No, the PCTs were installed in 1999. Little to no maintenance has been done. No refurbishments have been made in the last 5 years.

- *Is the life-of-mine reasonable?*

Yes, the life-of-mine for Mine A, due to the twin-end sub-decline, was extended to 2035.

From the preliminary investigation it was shown that Mine A is potentially a feasible refurbishment location. The next phase was calculating the precooling system efficiency.

Precooling efficiency

Equation 4 was used to calculate the efficiency of the precooling system. As mentioned in Mine A's specification, the water is recycled from both the BAC and FP chill dam, decreasing the water temperature of the PCT dam. For this reason, the water outlet temperature was determined through spot-checks using a temperature probe. The efficiency over the 2nd stage precooling system is illustrated in Table 11.

Table 11: Mine A's precooling system performance before refurbishment

Condition	Quantity
Water inlet temp [°c]	21.12
Water outlet temp [°c]	18.3
Wet-bulb [°c]	14.32
Range	2.82
Approach	3.98
Efficiency [%]	41.47

Mine A's precooling system efficiency of 41.47% was well below the benchmark efficiency of 70%, thus, exemplifying the necessity of refurbishment. To reach a 70% benchmark, the water outlet temperature had to decrease by 2 °C.

Summary of Step 1

The decision flow chart developed in Chapter 2 was used to confirm the identification process. Figure 26 illustrates the completed flow chart. Mine A was pre-approved for a capital expenditure (CapEx) project, making funds available for a cost saving project.

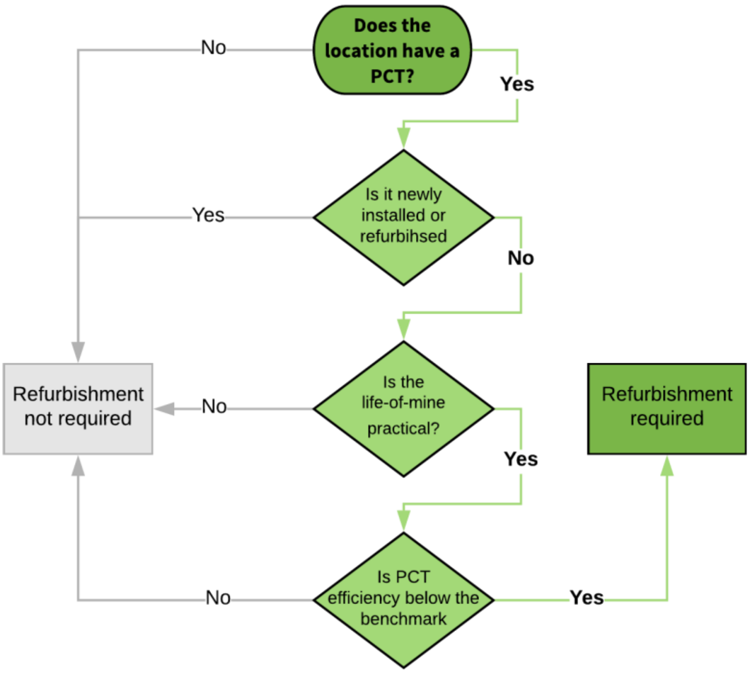


Figure 26: Mine A decision flow chart

The decision flow chart in Figure 26 had a “refurbishment required” outcome. Mine A was identified as a refurbishment location with a PCT efficiency below the benchmark value of 70%. In Step 2 the PCT will further be evaluated.

3.4.2 Step 2: Evaluate

In Chapter 2 an evaluation checklist was created to assist with PCT problem identification and solution thereof. The recommendations will form the refurbishment solution to be implemented.

Evaluation checklist

Table 12 is the completed evaluation checklist of Mine A. From this, certain problem areas were identified.

Table 12: Mine A evaluation checklist

Evaluation checklist for PCT refurbishment					
Mine:	Mine A - Second stage		Location:	Free State province SA	
Date:	05-Jan-19		Life-of-mine:	16	
Section 1 - Precooling tower efficiency					
Item	Description	Value	Notes		
1.1	Range [°C]	2.82			
1.2	Approach [°C]	3.98			
1.3	Efficiency [%]	41.5%			
Efficiency of PCT should be above 70% benchmark					
Section 2 - PCT component evaluation (non-efficiency impact)					
Item	Description	Problem	Notes		
2.1	Hot water inlet	Y	Broken pipework		
2.2	Distribution pipes	Y	Broken pipework		
2.3	Casing	N			
2.4	Air inlet	N			
2.5	Air outlet	Y	Broken fans reduce airflow		
2.6	Cold water basin	Y	Needs cleaning		
2.7	Cold water outlet	N			
2.8	Framework	Y	Framework is corroded and may collapse		
2.9	Deck	Y	Deck is corroded and thus a safety concern		
Section 3 - PCT component evaluation (efficiency impact)					
Item	Description	Rating 0 to 5	Max Impact [%]	Result [%]	Notes
3.1	Drift eliminator	0	2%	2.0%	
3.2	Nozzles	1	2.90%	2.3%	
3.3	Fill material	0	20%	20.0%	
	Fan calculation	Cooling fans	Non-working	Result [%]	Notes
3.4	PCT Fans	8	3	5.2%	
Components with a rating lower than 2 should be added to refurbishment solution					
Total expected improvement				29.5%	

With the completion of the evaluation, certain problems have been identified. Resolving the problems will result in an efficiency improvement of up to 29.5%. Table 5 and 6 from Chapter 2 will now be used to give recommendations regarding the identified problems.

Problems identified

In this section the identified problem areas are described and an applicable recommendation is made. The recommendation will form the refurbishment solution to be implemented.

Fill material

The packing material used for Mine A's precooling system was completely brittle and, in most sections, non-existent. Figure 27 shows the condition of the PVC fill material. Also, due to the brittleness of the material, small pieces broke off and created blockages within the refrigeration system and cold-water basin. The fill material is the biggest driver for the low efficiency value.

Figure 27: Mine A fill material[16]

Recommendation: Install new fill material throughout the precooling system.

Drift eliminators

Drift eliminators in all eight cooling cells were completely blocked and thus not doing the required work load. The supports were also broken and needed to be replaced. Figure 28 illustrates the condition of Mine A's drift eliminators.

[16] S Jerling, Personal photograph. "Fill material", Mine A, 2019

Figure 28: Mine A drift eliminators[17]

Recommendation: Install new drift eliminators throughout the precooling system. *Replace broken supports.*

Precooling nozzles

Some of the spraying nozzles were blocked due to sediment accumulation rendering some sections inside the PCTs completely dry. Correct water distribution is critical to the performance of the precooling system.

Recommendation: Replace nozzles that cannot be cleaned.

Pipework

Due to broken and loose pipework, the water distribution throughout the precooling areas were very poor. Figure 29 is an example of how the broken pipes looked. Both warm and cold-water pipelines were affected.

Figure 29: Mine A pipework[18]

[17] S Jerling, Personal photograph. "Drift eliminators", Mine A, 2019
[18] S Jerling, Personal photograph. "Pipework", Mine A, 2019

Recommendation: Replace broken pipe sections. Mild steel galvanised pipes are advised due to corrosion resistance.

Steelwork

Mine A's PCTs were showing signs of corrosion within the steelwork; this was weakening the structure and support. Furthermore, without stripping down the structure it was difficult to determine the degree of corrosion on the inside. Figure 30 shows the damage caused by corrosion on the PCT deck.

The following sections were affected with corrosion:

- Fan unit support structures
- Packing material support beams
- Drift eliminator supports
- Cross beams and decking plates severely affected
- Framework

Figure 30: Mine A PCT damaged deck[19]

Recommendation: Strip entire framework, including decking, and replace corroded sections. It is crucial to strip the entire framework as it will be difficult to determine the extent of corrosion. Add extra support beams to improve structural integrity.

[19] S Jerling, Personal photograph. "Decking", Mine A, 2019

Fan assembly

Per cooling cell, a single 30kW gearbox driven fan was used. However, the single fan assembly caused major problems for two reasons:

- If there was a motor failure the whole cooling cell was lost. Replacement of the fans were difficult as a crane needed to be rented. For this reason, mine personnel usually waited until more than three fans were broken before replacing one.
- Most of the fan failures were caused by gearbox related problems, which caused vibrations. These vibrations, with an already compromised steelwork could cause the PCT units to collapse.

While completing the evaluation, Mine A had 3 non-operational fans. This alone reduced the precooling system efficiency by 5.2%. Furthermore, the single gearbox driven fans were not fitted with VSDs, limiting the heat transfer control as fans could not be controlled. Multiple smaller direct drive fans would have allowed for better control and a crane is not required when replacing a fan. The advantages of smaller multiple direct drive fans were discussed in Chapter 1.

Recommendation: Convert entire second stage single gearbox driven fan units to four direct drive fan units per cooling cell.

Refurbishment solution

In Step 2 the evaluation checklist was completed, identifying certain problem areas. Table 5 and 6 were used to make recommendations regarding the areas. These recommendations are summarised in Table 13 and will form the refurbishment solution.

Table 13: Mine A refurbishment solution

Component	Problem	Recommendation
Fill material	Brittle and non-existing	Install new fill material
Drift eliminator	Broken supports and blocked drift	• Clean or replace blocked drift eliminators • Supports to be replaced
Nozzles	Blocked nozzles	Clean or replace
Distribution system	Broken/leaking pipe sections	To be replaced with mild steel galvanised pipes
Steelwork	Corroded framework and decking	• Striped and corroded sections to be replaced • Additional I-beams added for support
Fan assembly	3 non-operational fans	Covert single gearbox driven fan units to four direct drive fan units per cooling cell

With a defined refurbishment solution, the next step was implementation, however, a simulation model was created to demonstrate the effect of refurbishment on the refrigeration network. This was required by the personnel of Mine A as extra assurance before implementation.

Simulation for validation

The refurbishment solution was simulated, and Table 14 reflects the results of the simulation. The PCT outlet temperature of 17.3 °C after an efficiency increase was obtained by changing the PCT heat transfer coefficient (UA value).

Table 14: Simulation results

Parameter	Before	After	Improvement
FP power usage [kW]	4872	4398	383

The simulation showed a FP power reduction of 383 kW. This will be compared to the actual data during the quantification step.

3.4.3 Step 3: Implementation

During Step 1 a feasible case study was identified through the preliminary and precooling tower efficiency investigation. In Step 2 the developed checklist was applied to the case study. The combination of Step 1 and 2 formed the basis of the project scope presented to Mine A management. During discussions with Mine A management a realistic timeline and budget was set. It was decided to contract a third-party company, which specialise in precooling tower refurbishment, to implement the refurbishment solution.

Regular meetings were held with the third-party company. This was done to ensure everyone agrees upon the given deliverables and timeline. The project was implemented on 17/01/2019 and finished 27/03/2019, a week prior to the first agreed upon deadline. During refurbishment the precooling system was offline. Figure 31: Smaller direct drive fans shows the newly installed direct drive fans and PCT framework.

Figure 31: Smaller direct drive fans[20]

In Figure 32 the difference between the old gearbox driven fans and the new direct drive fans can be seen.

[20] S Jerling, Personal photograph. "Smaller direct drive fans", Mine A, 2019

Figure 32: Gearbox vs direct drive fans[21]

Figure 33 shows a newly installed mild steel galvanised pipeline.

Figure 33: New galvanised pipeline installed[22]

3.4.4 Step 4: Re-assess

After implementation, the following step was re-calculating the PCT efficiency. This was to ensure the efficiency after refurbishment is above the 70% benchmark value. Efficiency were re-calculated using Equation 4. Table 15 shows the efficiency before and after implementation.

[21] S Jerling, Personal photograph. "Gearbox vs direct drive fans", Mine A, 2019
[22] S Jerling, Personal photograph. "Galvanised pipeline", Mine A, 2019

Table 15: Re-assessment of PCT efficiency

Efficiency calculation	Before	After
Water inlet temp [°c]	21.12	23.81
Water outlet temp [°c]	18.3	17.3
Wet-bulb [°c]	14.32	14.56
Range	2.82	6.51
Approach	3.98	2.74
Efficiency [%]	41.47	70.37

The efficiency was again determined through spot-checks. The measurements were made in April 2019, after the refurbishment solution was implemented. After implementation the PCT efficiency were calculated at 70.37%, which is within the benchmark range and the methodology application could continue to Step 5.

It is important to note that from the evaluation checklist it was expected that the PCT outlet temperature would decrease with 2 °C to achieve the expected increase of 29.5%. However, after implementation, the decrease on outlet temperature was 1 °C, this is because the inlet temperature increased by 2.69 °C. The higher inlet conditions were due to a change in Mine A's refrigeration system control. Because of the lower inlet temperatures to the refrigeration cycle and other changes to the system it was possible to implement EKSOM peak load shifts as part of another project. The load shifts increased the water inlet temperature because less water was being recycled on average. This optimised energy savings while still maintaining a lower outlet temperature.

Although the temperature decrease is less than expected, refurbishment still increased the PCT range and efficiency. The efficiency after implementation is above the benchmark value.

3.4.5 Step 5: Quantification

The final step of the methodology strategy aimed to evaluate the impact of refurbishing the PCTs. The impact was evaluated by analysing changes in both the precooling system and refrigeration network. All comparisons before and after refurbishment were made between April to August 2018 (before) and April to August 2019 (after), unless otherwise specified.

PCT improvement

The implemented refurbishment solution had an effect on the following PCT parameters.

Evaporation loss

The evaporation loss over the precooling system can be calculated through the energy balance across the system. Alternatively, Equation 9 was used. This was a better alternative in the case of Mine A as limited data measuring points were available. Table 16 is a summary of the evaporation loss calculations before and after refurbishment. The mass water flow rate through the system is calculated with a pitot tube and stored on Mine A’s SCADA historian.

Table 16: Evaporation loss after implementation

Evaporation loss calculations	Before	After
Range	2.82	6.51
Water flow [l/s]	326.28	254.79
Evaporation loss [l/s]	1.41	2.53

Evaporation is the method of removing heat from the system. A higher evaporation loss results in more heat being dispersed by the precooling system, translating to a higher PCT range. The evaporation loss after implementation is higher than that of before. The decrease in water flow rate is because of a water optimising initiative implemented at Mine A.

Drift loss

The amount of water removed via droplets was calculated using Equation 10. Table 17 is a summary of the drift loss before and after implementation.

Table 17: Drift loss after implementation

Drift loss calculations	Before	After
Water flow [l/s]	326.28	254.79
Drift loss [l/s]	0.65	0.51

Drift loss is the amount of water loss from water droplets forming in the air as steam. The drift loss decreased by 0.14 l/s or 12 096 l/day after refurbishment. This is because of the cleaned/new drift eliminators.

Blowdown

To calculate PCT blowdown the cycle of concentration is needed, which is not measured at Mine A.

Heat load

The heat load over the precooling system is equivalent to the heat removed from the water and is calculated using Equation 1. Table 18 is a summary of the heat load before and after refurbishment.

Table 18: Mine A's heat load analysis

Heat load of Mine A’s precooling system	Before	After
Specific heat of water [kJ/kg·K]	4.186	4.186
Water mass flow rate [kg/s]	326.28	254.79
Difference in water temperature in and out [K]	2.82	6.51
Heat load [kW]	3851.58	6943.25

After precooling, the water is sent to the refrigeration system. A higher heat load will result in lower heat absorption required by the FP’s evaporator vessel. The refurbishment resulted in a heat load increase of approximately 3090kW. The increased heat load after refurbishment is due to the decreased outlet temperature measured over the PCT.

<u>Cost impact</u>

The cost impact will be determined by analysing the impact over the refrigeration network.

Change in refrigeration power usage

With an increase PCT range of almost 3.7 °C an expected decrease in power usage over the FPs are suspected. This is because of the increased heat load of approximately 3090kW over the precooling system. Higher heat load over the PCT equals lower heat absorption required by FP evaporators. Table 19 is a summary of the power usage before and after refurbishment, as well as the simulated power usage. The simulated power usage was obtained through the PTB simulation model developed in Section 3.3. The simulation model was updated to accommodate the changes after the refurbishment implementation.

Table 19: Mine A power usage

Power usage	
Before refurbishment - Simulated [kW]	4872
Simulated [kW]	4398
After refurbishment - Actual [kW]	4027

The FPs used approximately 844kW less electrical power to achieve the same outlet temperature. There was an 8.4% error difference between the actual and simulated results, because of a control strategy change on the FP system. Figure 34 is a 24-hour profile of the power usage.

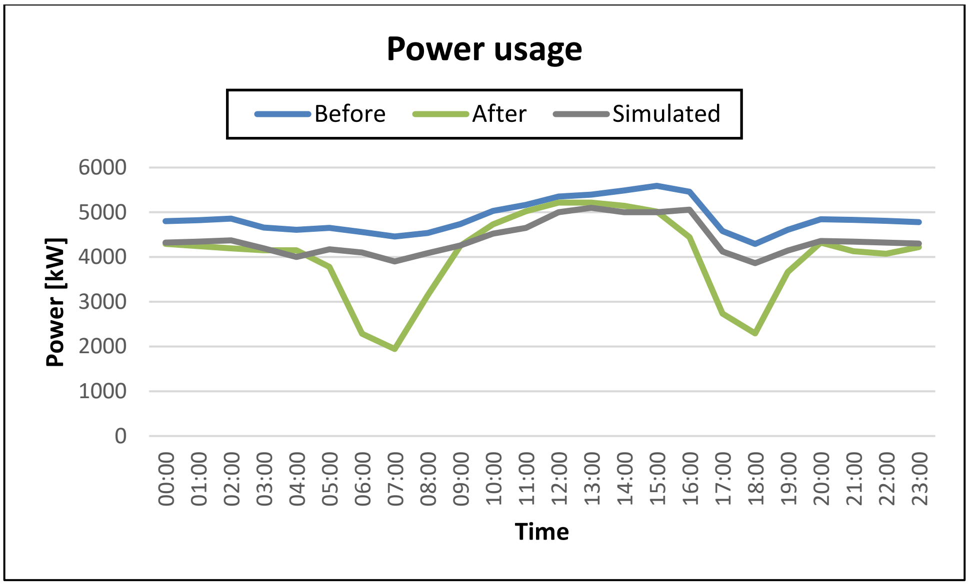


Figure 34: Refrigeration power usage

In Figure 34 a significant decrease between 05:00-08:00 and 17:00-20:00 can be seen. These periods are the Eskom high demand morning and evening peak periods respectively (summer and winter combined). As mentioned in Section 3.4.4, because of precooling tower refurbishment and other implemented projects Mine A was able to implement Eskom peak load shifts, reducing the energy usage during these periods and still maintaining the same water outlet temperature.

Because the refurbishment project was not the sole contributor to enable Mine A to implement load shifts, the periods between 05:00-08:00 and 17:00-20:00 were excluded from all result comparisons. This was done to ensure the study stayed within its scope and exclusively evaluated the impact of precooling tower refurbishment.

Refrigeration network performance

The impact of the refurbishment solution was determined by analysing the performance changes over the refrigeration network. Heat transfer over the evaporator and network, COP of FPs and networks were quantified with Equation 12 to 16. Table 20 is a summary of the refrigeration network performance before and after refurbishment.

Table 20: Refrigeration network performance

Fridge plant performance	Before	After
Heat absorbed by evaporator [kW]	12 990	11 010
COP of fridge plant system	2.67	2.74
Heat absorbed by network [kW]	19 765	18 366
COP of refrigeration network	4.06	4.56

The refurbishment solution reduced the outlet temperature of the PCT, consequently decreasing the inlet temperature to the FP evaporators. This resulted in a reduced heat absorption required by the evaporators. There was a small increase in FP COP. The COP of the entire refrigeration network increased by 0.5. The decreased power usage resulted in an electricity cost savings, for the same amount of cooling.

Cost saving

The cost saving amount was calculated using Equation 16 and 18. Payback period thereof was calculated with Equation 18. Table 21 illustrates the cost impact as a result of PCT refurbishment.

Table 21: Mine A refurbishment cost impact

Cost impact of refurbishment solution	
Average power usage reduction [kW]	844
Annual cost savings [R]	6.86 million
Project cost [R]	4.4 million
Payback period [months]	7.70
Annual cost impact [R]	2.46 million

By lowering the FPs' electrical demand by 844kW, a cost saving of R6.86 million per annum was achieved based on Eskom's 2018/2019 Megaflex tariffs. The payback period for the refurbishment initial investment was under 7.7 months.

Service delivery

Mine A's aim was a cost savings initiative not service delivery improvement. Thus, the refurbishment resulted in a power reduction of 844kW for the *same amount of cooling provided*. Figure 35 illustrates the water temperature sent underground before and after refurbishment.

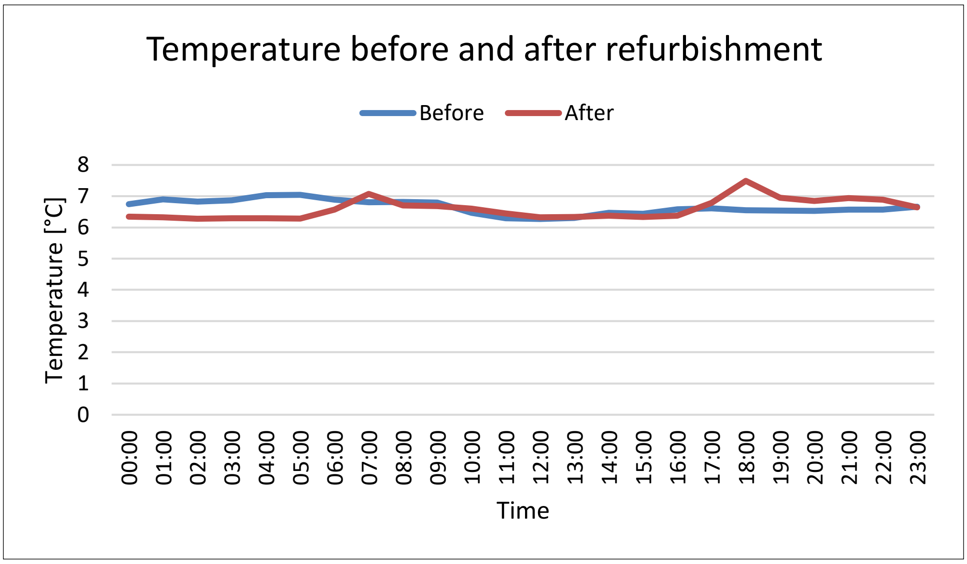


Figure 35: Temperature change

If focus was on temperature improvement, a realistic chill dam temperature of 5 °C could be achieved as per the simulation developed in Section 3.3.2. This will potentially decrease underground wet-bulb temperatures and result in an increase in productivity. The study done by Krige indicated that a change of 1 °C in wet-bulb temperature can increase productivity by up to 3% [71].

3.5 Summary

The developed refurbishment strategy was applied to a case study. This was done to verify the strategy and to illustrate the impact of PCT refurbishment. Mine A was identified, and the evaluation checklist was used to characterise PCT problems and recommendations. The solution was simulated and implemented.

3 MW of additional heat was rejected during the precooling stage. This resulted in less heat absorption required in the FPs' evaporator vessel as the water entered at a lower temperature. The lower inlet temperature led to an electrical power reduction of 844kW on the fridge plant system, as well as a COP improvement of 0.5 over the entire refrigeration network. This reduction in power resulted in an annual cost saving of R6.86 million. The payback period for the total refurbishment solution was under 7.7 months.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS

[23]

[23] S Jerling, Personal photograph. "Mine winder", Free-state, 2019

4.1 Conclusion

Deep-level gold mines in South Africa are less sustainable than ever. They face an array of challenges that increase operating costs and cripple profit margins. The gold production rate declined by 52% over the last 10 years. To remain competitive, gold mines are required to increase mining depths. However, increased mining depths generate higher working area temperatures.

At a depth of 4km the VRT can reach as high as 60 °C. High temperatures negatively influence production rates, emphasising the necessity of adequate underground cooling. Centralised cooling systems are commonly used by South African gold mines. They consist of BACs and FPs. The plants are used to cool service water but is one of the most energy intensive systems on a gold mine.

The Eskom electricity tariff increased by 9.41% for 2019/20 and further increases of 8.10% for 2020/21 and 5.22% for 2021/22 were approved. These increases are above the 4.41% approved RCA application of 2018, resulting in an electricity cost increase of 13.82% for the financial year of 2019/20.

Strategies to mitigate cost need to be developed. Optimising energy intensive systems like refrigeration is one solution. This can be achieved by lowering the inlet water temperature to the plants. Service water is cooled by a precooling stage before entering the refrigeration system, making PCT a crucial component to the refrigeration network.

PCT performance deteriorates over time due to the mining environment. Deterioration could cause complication like scaling, fouling and corrosion, which will in turn lower PCT performance. Lower performance will result in inadequate heat transfer and therefore increasing outlet water temperatures. Timely refurbishment is required to maintain optimal PCT performance. However, this is typically neglected because of the high capital expenditure.

This study focused on addressing the problem stated. The main objective was evaluating the impact of PCT refurbishment on deep-level gold mines. This was achieved by developing a refurbishment strategy and analysing the impact thereof.

A five-step methodology strategy was developed and used to identify, evaluate, implement, re-assess and quantify a refurbishment solution. Step 1 focused on identifying a feasible location. The evaluation phase, Step 2, concentrated on creating an evaluation checklist. This checklist can be used to characterise PCT problems and recommend solutions thereof.

The recommendation will form the refurbishment solution to be implemented in Step 3. In Step 4 PCT efficiency is re-assessed, to ensure a benchmark value of 70% is achieved after refurbishment. If satisfactory, the implementation results will be quantified in Step 5.

A case study, Mine A, was used to validate the methodology strategy. A simulation was created using PTB as an extra measure of verification. The deep-level gold mine is located in the Free State province of South Africa. The methodology strategy was used to identify Mine A and characterise PCT problems. The investigation and identification of these problems formed the basis of the refurbishment solution. The problems were successfully identified using the developed refurbishment checklist.

Before implementation a simulation package (PTB) were used to create a simulation model of Mine A's refrigeration network. This was then in return used as part of the project scope which was presented to Mine A's management team. The project scope also included the recommendations for the refurbishment that was obtained with completion of the developed checklist.

The project deliverables, budget and timeline were approved by management and a third-party company, specialising in precooling tower refurbishment were contracted to implement the solution. Implementation resulted in Mine A's precooling system efficiency to increase above the 70% benchmark value. Simulation of the increase showed an expected power reduction of 383kW.

The refurbishment solution was quantified by analysing the impact on both the precooling system and the refrigeration network. PCT evaporation loss increased by 2.53 l/s, resulting in more heat dispersed by the precooling system, increasing PCT range by 3.69 °C.

After refurbishment, the PCT heat load increased by 3090kW. This resulted in an evaporator heat absorption decrease, for the same amount of cooling provided. A lower heat absorption led to an electrical power reduction of 844kW over the refrigeration network. The difference between the simulated and actual power reduction is due to a change in control strategy, which were excluded from all result comparisons. The decreased water temperature allowed for better control over the refrigeration cycle. Mine A is now able to switch off a FP during Eskom high demand periods, where before refurbishment, this was not possible.

The cooling network COP increased by 0.5. The reduction in power usage translated to a cost saving amount of approximately R6.86 million. The payback period for implementing the refurbishment solution is 7.7 months.

If Mine A's focus was on service delivery improvement instead of cost reduction, a realistic chill dam temperature of 5 °C could be achieved. Literature indicated that a 1 °C wet-bulb temperature increase underground can increase productivity by up to 3%.

The study objective of evaluating PCT refurbishment was met by quantifying the results of the refurbishment case study. This study can be used on different deep-level gold mines to evaluate the impact of refurbishing their precooling towers.

4.2 Recommendations for further studies

4.2.1 Limits of this study

This study's focus was on evaluating the impact of induced draft precooling system. Further investigation can be made on natural draft PCT with little change to the developed methodology strategy. The evaluation checklist will need to be changed to accommodate different PCT components.

In the case of Mine A, the aim was improving operational cost and not service delivery. The effect of PCT refurbishment on underground temperatures and production rate should be further analysed.

4.2.2 Recommendations

It is recommended that this study and the developed methodology strategy is applied to different cooling tower systems. This can be either different precooling tower types or entirely different cooling systems i.e. condenser cooling towers. The literature and methodology were developed with different precooling types in mind, however, was only tested on a counterflow induced draft system. The application of different systems may yield various results as different complications will be identified and solved.

The methodology can then also be adapted to different cooling systems i.e. condenser cooling towers. Improving condenser cooling tower performance with refurbishment may result in an improved condenser performance. This may increase the performance of refrigeration systems. Different cooling systems include, but is not limit to:

- Condenser towers for fridge plants both underground and above.
- Condenser towers for compressors both underground and above.
- Bulk-air coolers both underground and above.

For this study the methodology was developed for the mining industry. It can be further adapted to be applied to different industries that use precooling/cooling systems i.e. power plants, coal plants or large HVAC installations. Furthermore, the impact of refurbishing closed loop cooling systems can be evaluated using the methodology.

During this study it was noted that the refurbishment, in combination with different projects, resulted in Mine A implementing Eskom peak load shifts. The impact of load shifts was however excluded from this study. It is recommended that precooling tower refurbishment in combination with different water reticulation projects be investigated. For example, what will the effect be on refrigeration energy usage if precooling tower efficiency is increased and overall water demand is decreased?

Mine A consisted of two precooling stages, but only reliable utilised the second stage. There is benefit in investigating the impact of multiple precooling stages on the refrigeration network. As discussed in Section 1.4.2, the cooling limit of evaporative towers are equal to that of the ambient wet-bulb temperature, but as in the case of Mine A, this was not reached. By including more cooling stages to a system inlet water can theoretically be cooled to wet-bulb temperature.

Focusing on Mine A specifically, precooling stage 1 was later decided to be used as a spray chamber to reduce water temperature before reaching stage 2. This was achieved by removing all fill material and increasing nozzle efficiency. The impact thereof should be investigated, and further studies should be done on the benefit of transforming a precooling tower into a spray chamber over refurbishment, where possible.

Alternatively, to increasing the number of precooling stages, a more cost-effective method of recycling chilled water from the FPs to the precooling dam should be investigated. This will lower PCT approach.

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Appendix A: Evaluation checklist Excel formula

Figure 36 illustrates the Excel formulas used in the evaluation checklists.

Evaluation checklist for PCT refurbishment					
Mine:			Location:		
Date:			Life-of-mine:		
Section 1 - Precooling tower efficiency					
Item	Description	Value	Notes		
1.1	Range [°C]				
1.2	Approach [°C]				
1.3	Efficiency [%]				
Efficiency of PTC should be above 70% benchmark					
Section 2 - PCT component evaluation (non-efficiency impact)					
Item	Description	Problem	Notes		
3.1	Hot water inlet				
3.2	Distribution pipes				
3.3	Casing				
3.4	Air inlet				
3.5	Air outlet				
3.6	Cold water basin				
3.7	Cold water outlet				
3.8	Framework				
3.9	Deck				
Section 3 - PCT component evaluation (efficiency impact)					
Item	Description	Rating 0 to 5	Max Impact [%]	Result [%]	Notes
2.1	Drift eliminator		0.02	=(E26/5)*(5-D26)	
2.2	Nozzles		0.029	=(E27/5)*(5-D27)	
2.3	Fill material		0.2	=(E28/5)*(5-D28)	
Fan calculation		Cooling fans	Non-working	Result [%]	Notes
2.4	PCT Fans			=(75%-D11)*(((D11)/D	
Components with a rating lower than 2 should be added to refurbishment solution					
Total expected improvement				=F26+F27+F28+F31	

Figure 36: Evaluation checklist Excel formula

Appendix B: SI Psychrometric chart[24]

The SI-unit psychrometric chart in Figure 37 can be used to determine certain air parameters used to calculate cooling tower evaporation loss.

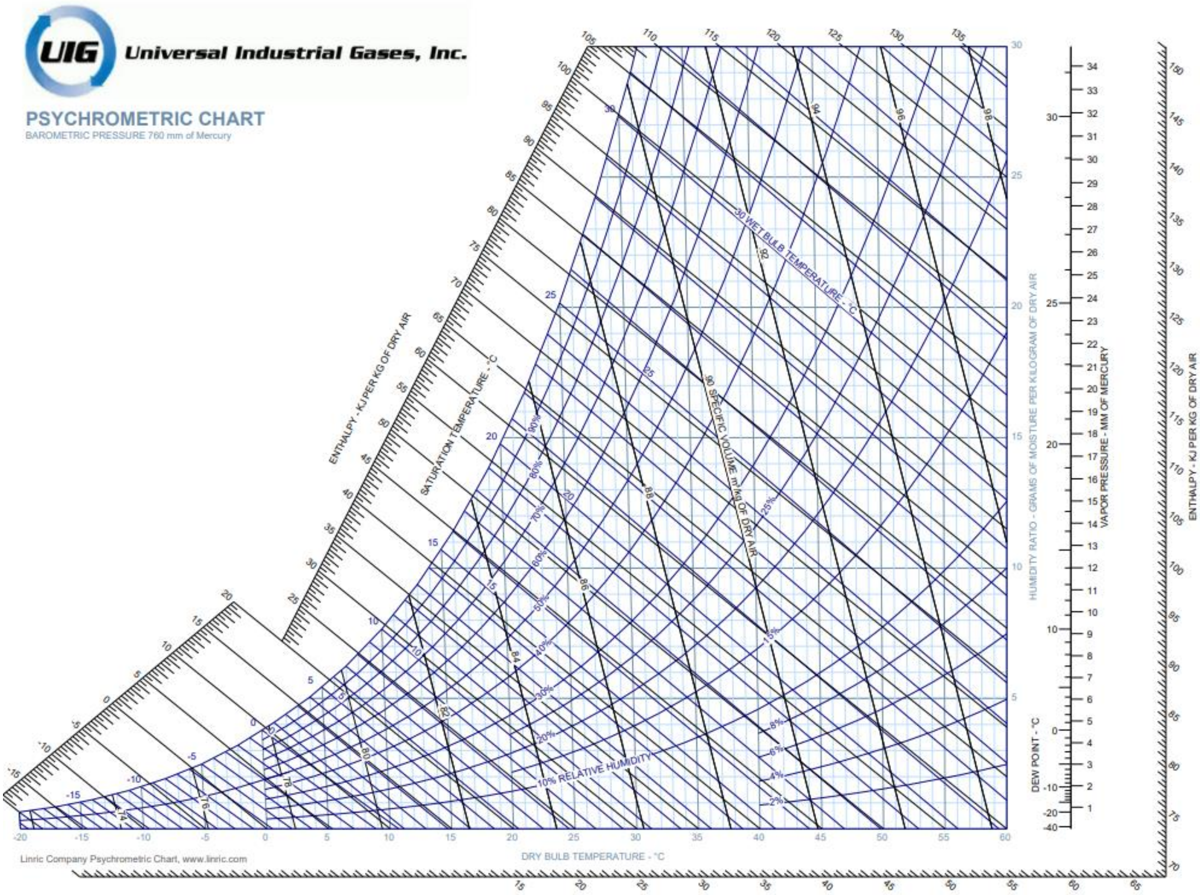

Figure 37: SI Psychrometric chart

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Appendix C: Eskom TOU tariffs

Deep-level gold mines use the Eskom TOU Megaflex tariff as shown in Figure 38 [73].

2019/20 ESKOM TARIF (excl. VAT)		
Period	c/kwh	r/kwh
Summer peak	107.07	1.0707
Summer Standard	73.71	0.7371
Summer Off-peak	46.76	0.4676
Winter Peak	328.28	3.2828
Winter Standard	99.45	0.9945
Winter off-peak	54.01	0.5401

Summer Tariff			
	Weekday	Saturday	Sunday
0	Off-peak	Off-peak	Off-peak
1	Off-peak	Off-peak	Off-peak
2	Off-peak	Off-peak	Off-peak
3	Off-peak	Off-peak	Off-peak
4	Off-peak	Off-peak	Off-peak
5	Off-peak	Off-peak	Off-peak
6	Standard	Off-peak	Off-peak
7	Peak	Standard	Off-peak
8	Peak	Standard	Off-peak
9	Peak	Standard	Off-peak
10	Standard	Standard	Off-peak
11	Standard	Standard	Off-peak
12	Standard	Off-peak	Off-peak
13	Standard	Off-peak	Off-peak
14	Standard	Off-peak	Off-peak
15	Standard	Off-peak	Off-peak
16	Standard	Off-peak	Off-peak
17	Standard	Off-peak	Off-peak
18	Peak	Standard	Off-peak
19	Peak	Standard	Off-peak
20	Standard	Off-peak	Off-peak
21	Standard	Off-peak	Off-peak
22	Off-peak	Off-peak	Off-peak
23	Off-peak	Off-peak	Off-peak

Winter Tariff			
	Weekday	Saturday	Sunday
0	Off-peak	Off-peak	Off-peak
1	Off-peak	Off-peak	Off-peak
2	Off-peak	Off-peak	Off-peak
3	Off-peak	Off-peak	Off-peak
4	Off-peak	Off-peak	Off-peak
5	Off-peak	Off-peak	Off-peak
6	Peak	Off-peak	Off-peak
7	Peak	Standard	Off-peak
8	Peak	Standard	Off-peak
9	Standard	Standard	Off-peak
10	Standard	Standard	Off-peak
11	Standard	Standard	Off-peak
12	Standard	Off-peak	Off-peak
13	Standard	Off-peak	Off-peak
14	Standard	Off-peak	Off-peak
15	Standard	Off-peak	Off-peak
16	Standard	Off-peak	Off-peak
17	Peak	Off-peak	Off-peak
18	Peak	Standard	Off-peak
19	Standard	Standard	Off-peak
20	Standard	Off-peak	Off-peak
21	Standard	Off-peak	Off-peak
22	Off-peak	Off-peak	Off-peak
23	Off-peak	Off-peak	Off-peak

Figure 38: Eskom TOU tariff

Appendix D: PTB simulation

The simulation designed in Section 3.3.2 is further discussed in Appendix D. Table 22 is a summary of the required input data for each component as per layout.

Table 22: PTB input data requirement

Simulation components	Input data
Climate boundaries	• Pressure [kPa] • Temperature [°C] – 24-hour profile • Relative humidity [%] – 24-hour profile
Energy tariff boundaries	• Eskom TOU tariff [R/kWh] – 24-hour profile
Operation boundaries (from and to underground)	• Temperature [°C] • Pressure [kPa] • Elevation [m] • Water flow to underground [kg/s]
Water pipes	• Flow [kg/s] • Inlet and outlet pressure [kPa]
Dams	• Temperature [°C] • Pressure [kPa] • Height [m] • Volume [m^3]
Pumps	• Two pressure points on pump curve [kPa] • Two flow points on pump curve [kg/s] • Efficiency [%]
Water-air cooling towers	• Water flow [kg/s] • Air flow [kg/s] • Water inlet and outlet temperature [°C]

Water chillers	• Cooling capacity [kW] • COP • Evaporator outlet and inlet temperature [°C] • Evaporator outlet and inlet pressure [kPa] • Evaporator flow [kg/s] • Condenser outlet and inlet temperature [°C] • Condenser outlet and inlet pressure [kPa] • Condenser flow [kg/s]
Air pipes	• Flow [kg/s] • Inlet and outlet pressure [kPa] • Inlet temperature [kPa]
Air fans	• Two pressure points on fan curve [kPa] • Two flow points on fan curve [kg/s] • Efficiency [%]

Appendix E: Wet-bulb calculation

Equation 19 is an empirical inverse formula to calculate the wet-bulb temperature from the ambient temperature and relative humidity [74].

Equation 19: Wet-bulb calculation

$$\boldsymbol{T_w = T \cdot \mathbf{atan}\,[0.151977(RH\% + 8.313659)^{1/2}\,] + \mathbf{atan}(T + RH\%) - \mathbf{atan}(RH\% - 1.676331)}$$
$$\boldsymbol{+\, 0.00391838(RH\%)^{3/2} \cdot \mathbf{atan}(0.023101RH\%) - 4.686035}$$

Where: T_w = Wet-bulb temperature [°C]

T = Ambient air temperature [°C]

$RH\%$ = Relative humidity (Where a humidity such as 50 % is an input of 50)

Equation 19 is valid for a relative humidity of 5% to 99% and a temperature of -20 °C to 50 °C. Wet-bulb temperature is higher during summer months, when ambient conditions are higher.