Optimal use of mobile cooling units in a deep-level gold mine

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ABSTRACT

Title:	Optimal use of mobile cooling units in a deep-level gold mine
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South Africa has an international advantage in terms of gold deposit endowment, however there are several challenges faced by the gold mining sector that hinder the realisation of the country’s full production potential. Despite a decline in economic importance, the South African gold mining sector remains a significant contributor to the country’s economy. The sustainability of the gold mining sector can be improved through implementing measures to improve operational efficiency.

One such area offering large potential for optimisation is the use of mobile cooling units. These units are used as tertiary cooling and become inefficient as a result of harsh underground working conditions, corrosion and a general lack of maintenance. As a result, these inefficient mobile cooling units can negatively impact underground temperatures as well as increase operating costs.

A need is evident to optimise existing mobile cooling units with the aim of improving service delivery, reducing operating costs and improving underground temperatures. A method was therefore developed for accurately measuring the specific operational parameters of these mobile cooling units, characterise their performance, and thereafter select relevant optimisation strategies.

This method was then implemented on Mine X, which led to twenty-one mobile cooling units being removed. The results of which was a reduction in pumped water volume of more than 47 ML and 150 ML for July 2017 and August 2017 respectively. This gave rise to a reduction in operating costs through electricity cost savings of more than R580 000 and R1,8 million for July 2017 and August 2017 respectively. Furthermore, improvements of between 1℃ and 3℃ in wet-bulb temperatures were realised.

SAMEVATTING

Titel:	Optimale gebruik van mobiele verkoelingseenhede in ’n diep-vlak goudmyn
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Sleutelterme:	Diep-vlak goudmyn, mobiele verkoelingseenhede, optimalisering, dienslewering, bedryfskoste, ventilasie temperature

Suid-Afrika het ’n internasionale voordeel in terme van ondergrondse goudreserwes, maar daar is verskeie uitdagings wat die goudmynsektor in die gesig staar, wat die realisering van die land se volle produksiepotensiaal belemmer. Ten spyte van ’n afname in ekonomiese belang, lewer die Suid-Afrikaanse goudmynsektor steeds ’n beduidende bydrae tot die land se ekonomie. Die volhoubaarheid van die goudmynsektor kan verbeter word deur maatreëls te implementeer wat die operasionele doeltreffendheid daarvan verbeter.

Een sodanige gebied wat groot potensiaal vir optimalisering inhou, is die gebruik van mobiele verkoelingseenhede. Hierdie eenhede word gebruik as tersiêre verkoeling en word ondoeltreffend as gevolg van onherbergsame ondergrondse toestande, korrosie en ’n algemene tekort aan instandhouding. Ondoeltreffende mobiele verkoelingseenhede kan ondergrondse temperature negatief beïnvloed en lei tot verhoogde bedryfskoste.

’n Behoefte ontstaan dus om bestaande mobiele koeleenhede te optimaliseer, met die oog op ’n verbetering in dienslewering, verminderde bedryfskostes en ’n verbetering in ondergrondse temperature. ’n Metode is ontwikkel vir die akkurate meting van spesifieke bedryfsparameters van hierdie mobiele verkoelingseenhede, die karakterisering van hul prestasie asook die kies van relevante optimalisering strategieë.

Hierdie metode is op Myn X geïmplementeer, wat gelei het tot die verwydering van een-en-twintig mobiele verkoelingseenhede. Die resultate hiervan was ’n afname in die volume gepompde water van onderskeidelik 47 ML en 150 ML vir Julie 2017 en Augustus 2017. Dit het gelei tot ’n vermindering in bedryfskoste as gevolg van elektrisiteitskostebesparings van onderskeidelik R580 000 en R1.8 miljoen vir Julie 2017 en Augustus 2017. Verder is die nat-bol temperature met tussen 1℃ en 3℃ verbeter.

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- Finally, to my family – for your support, assistance and sacrifices. Words will never be enough. I have truly been blessed.

"There, but for the Grace of God, go I."

"Persistence is to the character of man as carbon is to steel" – Napoleon Hill

"Dis die flukse perd wat flou word" – C.J. Langenhoven

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LIST OF ABBREVIATIONS

ACU	Air Cooling Unit
AMD	Acid Mine Drainage
BAC	Bulk Air Cooler
DB	Dry-bulb
DMR	Department of Mineral Resources
DSM	Demand-side Management
GDP	Gross Domestic Product
HR	Humidity Ratio
KPI	Key Performance Indicator
MCU	Mobile Cooling Unit
N	North
PFHE	Plate Fin Heat Exchangers
RAW	Return Air Way
S	South
SCADA	Supervisory Control and Data Acquisition
TFHE	Tube Fin Heat Exchangers
VRT	Virgin Rock Temperature
WB	Wet-bulb
X/C	Cross-cut

SYMBOLS AND UNITS

Symbol	Description	Unit
-	Megalitre	ML
C_p	Specific heat of a substance at constant pressure	kJ/K
Δh	Difference in enthalpy between two points	kJ/kg
A	Cross-sectional area	m^2
h	Specific enthalpy	kJ/kg
m	Mass flow rate	kg/s
P	Pressure	kPa
Q	Heat transfer rate	kW
T	Temperature	℃
V	Fluid flow rate	l/s
v	Speed	m/s
W	Electrical power	kW
η	Efficiency	-
ρ	Fluid density	kg/m^3

GLOSSARY

Term	**Description**
102L	Level 102 of the mine.
Blasting	Process of using explosives to break the rock face into smaller pieces for ore extraction or mine development.
Cooling duty	A measure of the cooling system's capacity to remove heat.
Cross-cut	Travelling way from haulage to stope for men, materials and ventilation.
Development end	End of a cross-cut or haulage, currently being extended.
Dry-bulb temperature	Air temperature not affected by air moisture content.
Fissure water	Ground water filtering through into the mine workings.
Footwell	Gully or ditch to the side of the haulage or cross-cut, which transports used water to the settlers for pumping to surface.
Haulage	Travelling way from station to cross-cuts for men, materials and ventilation.
Life-of-mine	Remaining years of production based on production rate and ore reserves.
Location	Space occupied by an MCU with regards to the larger mine layout and infrastructure placement.
Mining block	Levels or sections of a mine which are used for production of gold.
Position	Space occupied by an MCU with regards to its immediate surroundings.

Rock face	Point of development or mining which is drilled and blasted.
Service delivery	Refers to operational/production utilities such as compressed air, chilled water and ventilation.
Station	The area on a level where men and materials exit the vertical transportation in the shaft.
Stopes	Site where rock face is found, situated at the end of a cross-cut.
Tonne(s)	Commonly referred to as metric ton, equal to 1000 kilograms.
Tramming	The practice of moving skips or wagons by rail from the mining area to the shaft loading area.
Vice versa	The main items in the preceding statement the other way around.
Wet-bulb temperature	Measure of the amount of water vapour contained in the air.

1 Introduction

[1]

The need for optimising the use of existing Mobile Cooling Units is established.

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[1] *ETA Operations (Pty) Ltd, Employee photograph. "New Mobile Cooling Unit", Carletonville, 2016.*

1.1 Preamble

In this chapter a clear background is given into the need for the study. It opens with the contribution of gold mining to the South African economy, the current state of this industry and its consumption of electricity and water. This is followed by an overview on mine cooling systems used to overcome temperature challenges associated with deep-level gold mining and ensure legislation compliance. Emphasis is placed on Mobile Cooling Units (MCUs), which are used near the working places, and the effect of harsh underground conditions on their performance. The objectives of the study are then formulated, followed by an overview of this dissertation.

1.2 Economic significance of gold mines in South Africa

Mineral resources in South Africa have long been the backbone of the country's economy, with gold being the most dominant. Mining contributed 21% to the South African GDP in 1980, with a peak employment rate of 763 319 persons [1]. In the same year, gold made up 67% of the country's mineral sales. South Africa further held the number one spot in global gold production until 2007 [2]. Gold mining alone made up 8.4% of the South African private sector GDP in 1980 [3]. However, due to a volatile Rand/Dollar exchange rate, increasingly strenuous labour laws, ever deepening mining activities, escalating production costs and continuous political instability the mining industry in South Africa is a much different scenario today.

1.2.1 Current economic contribution

The South African economy remains highly dependent on the export of minerals and metals, where directly exported minerals and metals account for as much as 60% of all export revenue [4]. South Africa is a top 10 producer globally of platinum group metals, gold, chromium and coal [5].

In 2017, mining directly contributed an average of 7% to South Africa's nominal GDP [6], equating to R312 billion [7]. In the same year, direct mining employment consisted of just over 464 000 jobs, with an additional 4.5 million dependants supported and annual employee earnings of R126 billion [7]. Furthermore, mining companies contributed R16 billion in tax and another R5.8 billion in royalties [7].

As depicted in Figure 1-1, mining is currently the 6th largest industry by GDP contribution, the largest of the primary sector industries.

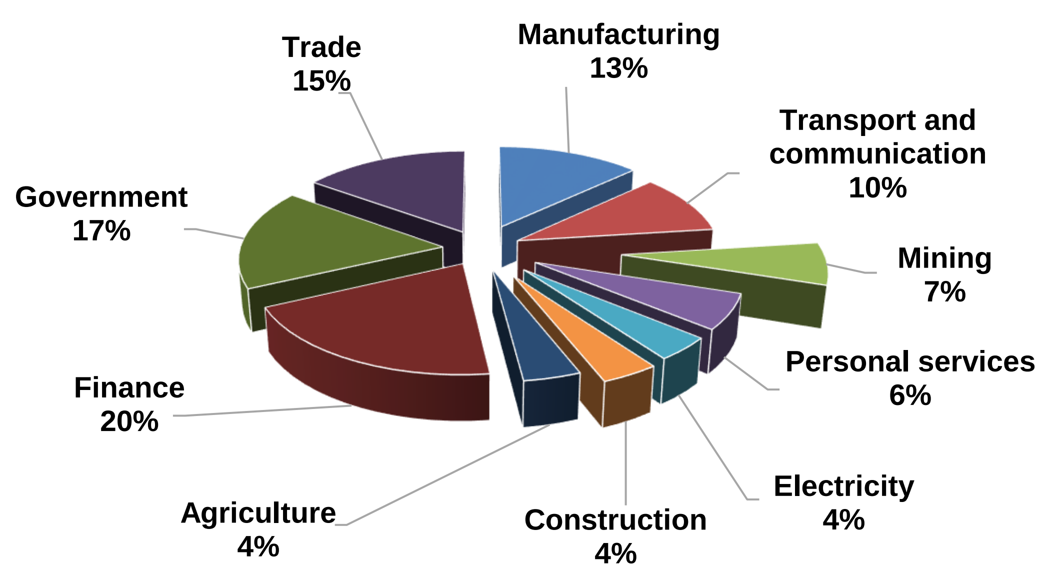

Figure 1-1: Industry shares of South Africa's nominal GDP for the 2nd quarter of 2017 (adapted from [6])

South African gold mining accounted for 4.4% of global gold production in 2016 with a total of 142.1 tonnes of gold produced [5]. In 2017 gold mines directly employed 112 200 persons, with total employee earnings of R29.9 billion [7]. In the same year, gold contributed 16% to mining revenue, shown in Figure 1-2, with a total market capitalisation of 25% [8].

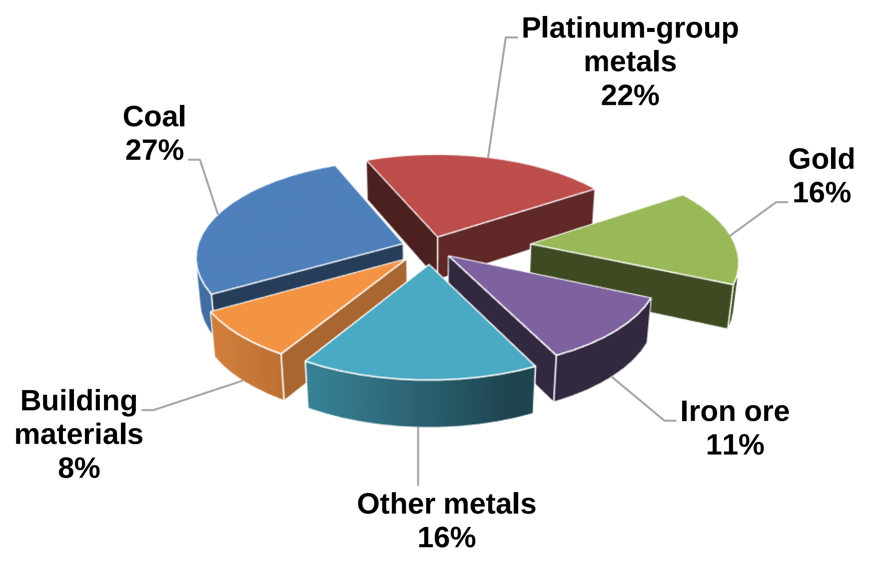

Figure 1-2: Percentage mining revenue per commodity for 2017 (adapted from [8])

The South African gold mining sector has seen a decline in economic importance. It employs fewer people, contributes less in taxes and slipped in global gold production rankings. The sector does however remain a significant contributor to the South African economy, albeit an industry facing several challenges. It is remaining a large consumer of water and electricity, which will be discussed in the next section.

1.2.2 Electricity and water consumption

Two of the prime requirements for the mining industry to continue exploiting South Africa’s considerable mineral resources are an adequate supply of electricity and, to a lesser extent, water. Mining activities account for up to 15% of the country’s electricity consumption and 3% of water consumption [9][10][11].

Within the mining industry, the gold mining sector is the largest user of electricity, responsible for 47% of the industry’s electricity demand [12]. The principal consumers of electricity in the gold mining sector are depicted in Figure 1-3. It should be noted that pumping, compressed air, ventilation and refrigeration could contribute considerably more in some cases, depending on mine depth and scale.

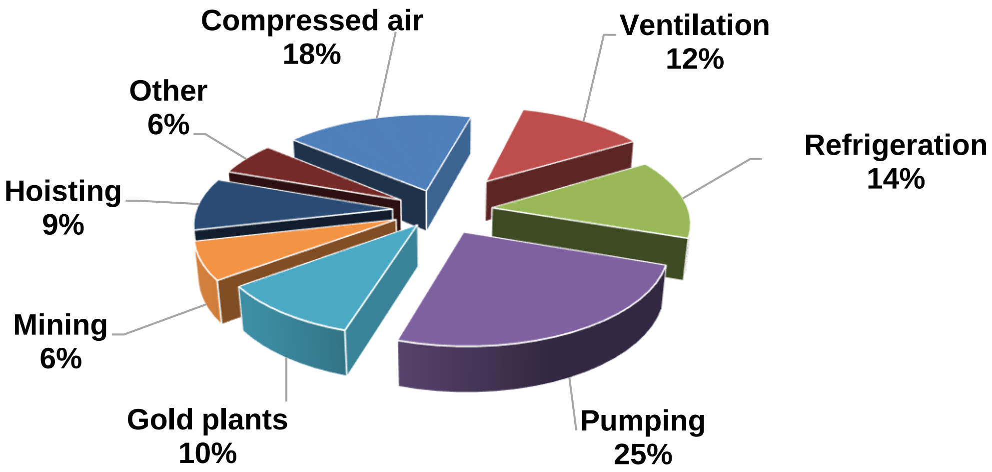

Figure 1-3: Primary electricity consumers in the gold mining sector (adapted from [13])

In comparison, mining does not consume as much of South Africa’s water resources. However, the effect of mining on water quality can be profound and any reduction in water usage will result in a reduction in water quality impact [11]. Acid mine drainage is recognised as one of the most serious threats to South Africa’s water sources and is a major problem on gold mines across the world [14].

Acid mine drainage is regarded as so persistent that some affected sites may never be completely restored without substantial intervention, even polluting groundwater and other freshwater sources [15]. Furthermore, it is estimated that the total acid mine drainage produced by the Witwatersrand Basin is comparable in volume to 10% of the potable water supplied by Rand Water to municipalities [15]. As such, correct water management is of the utmost importance.

1.2.3 An industry under pressure

South Africa dominated the world as the number one gold producer until 2007, dropping to 7th place by 2017 [16]. The country produced 87% less gold in January 2015 than in the same month in 1980 [2]. South Africa has an international advantage in terms of mineral endowment, however there are challenges faced by the mining industry that hinder the realisation of the country’s full mineral potential.

Global commodity price volatility has adverse effects on the local mining industry, making strategic planning challenging [17]. Escalating production costs, low economic growth and labour issues further impact mine productivity and profitability [17] [18].

An overall decline in gold resource grade compounds the escalating production costs of South African gold mines as most of the high-grade gold deposits have been exhausted and mines now exploit lower grades [17]. The average grade of South African gold mines have declined from 12 g/t in 1970 to 5 g/t in 2014 [19].

The mining relationship between ore grade and energy consumption is exponential, meaning the lower the ore grade the greater the consumption in energy, water and other consumables per unit of gold produced [17]. This means optimisation is required to derive optimal value from the remaining low-grade and deep-lying deposits [19].

Over 95% of primary gold production in South Africa comes from underground mines [17]. The orebodies in these mines are narrow and further characterised by geological discontinuities, preventing mechanisation and automation [17]. In addition, South Africa hosts some of the deepest mines in the world, leading to high underground temperatures and a further increase in production costs. Existing mining methods are also cyclic, non-continuous and rely on equipment of limited capacity and efficiency [17].

It is clear the South African gold mining sector faces many challenges that impact mine profitability and productivity, ultimately affecting the country’s GDP and economic growth. Productivity in the South African gold sector may be improved using the existing mining methods, but will require extensive research to review mine planning, design and optimisation [17].

1.3 Overview of mine cooling

The Witwatersrand Basin is one of the world's largest gold deposits, stretching through the Free State, North-West and Gauteng provinces [7]. Gold mining in this area has reached depths of up to 4000 meters, making South African mines among the deepest in the world [7]. Mining at this depth brings with it several unique challenges in terms of underground temperatures, of which the most significant are:

- Virgin Rock Temperature (VRT)
- Auto-compression
- Increasing distances to the working place or stope

The VRT underground can reach 60℃ [7], while auto-compression can contribute a $10℃/km$ increase in dry-bulb temperature [20]. However, mine legislation requires a working temperature of below 32℃ wet-bulb temperature to ensure safe working conditions. The mining industry makes use of complex ventilation and cooling systems to ensure legislation compliance [21], which can account for up to 25% of the mine's total electricity cost [22]. A simplified overview of a typical mine cooling system is given in Figure 1-4.

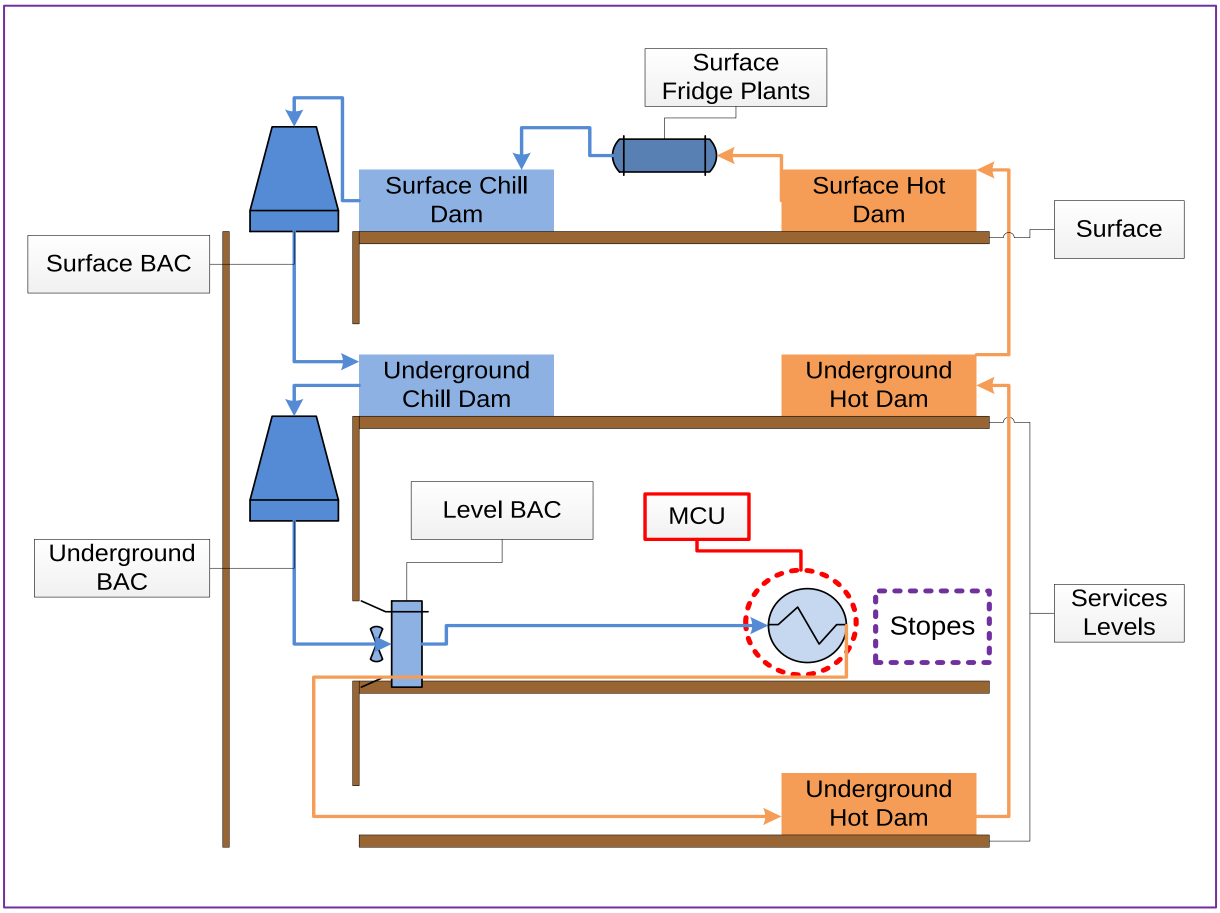

Figure 1-4: Simplified overview of a mine cooling system

Referring to Figure 1-4, surface bulk air coolers (BACs) are used as primary cooling, negating the effects of both VRT and auto-compression. With an increase in depth, auto-compression and VRT become more pronounced and underground BACs are used as additional primary cooling. In some cases, BACs will be installed on a specific mining level as secondary cooling to ensure acceptable temperatures at the working places. Secondary cooling re-uses the air sent down by primary cooling and ventilation, providing cascade cooling. The water used by surface, underground and level BACs is chilled using surface fridge plants. This water is usually cascade-pumped back to surface.

Mining starts with the recovery of easy resources and progresses to more and more difficult resources [23], which indefinitely leads to increasingly large distances to the working area [22]. A result of which is a decrease in ventilation and cooling effectivity, specifically with regard to primary and secondary cooling [22]. Mobile Cooling Units (MCUs) are then used as tertiary or in-stope cooling [22]. They are installed as close to the working place (stope) as possible, as outlined in red in Figure 1-4.

The MCU consists of a heat exchanger supplied by chilled water over which hotter air is forced using a sizeable fan. The air is thus cooled by the heat exchanger and proceeds to the working place. The used, hot water is then most commonly dumped onto the footwell where other sources of used water congregate.

MCUs are available in various configurations, with cooling duties of up to 500kW possible. The cooling duty is an ideal calculation according to specific assumptions and a sufficient chilled water temperature and flow. It is also for a new unit which has never been used underground, such as shown in Figure 1-5.

Figure 1-5: A new Mobile Cooling Unit[2]

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[2] *Renlyn Engineering, "Cooling Coil Car" [Online]. Available: http://www.renlyn.co.za/engineering/oem_equipment/cooling-coil-car/. [Accessed: 23-Mar-2018].*

However, MCUs are installed in harsh conditions near the working places. High ambient temperatures, humid ambient air, warm supply water temperature, acidic/alkalic supply water, large ducting distances, incorrect placement and general misuse/abuse all lead to MCUs becoming inefficient and substantially decrease their cooling performance.

Inefficient MCUs lead to:

- Chilled water wastage due to dumping of water onto the footwell
- Electricity wastage due to excessive dewatering, water refrigeration and running MCU fans needlessly
- Negatively affects ambient conditions in the working area due to decreased cooling performance and efficiency

An example of an inefficient MCU is given in Figure 1-6. It is clearly corroded, leaking water, and as a result, will be functioning poorly. The correct and efficient functioning of MCUs is critical for safe mining conditions, improved service delivery and the optimal use of electricity [24].

Figure 1-6: Inefficient Mobile Cooling Unit installed underground[3]

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[3] *ETA Operations (Pty) Ltd, Employee photograph. “Inefficient MCU”, Carletonville, 2016.*

1.4 Problem statement

The South African economy is still dependent on the mining industry. This is especially true of the gold mining sector, which contributes significantly to the economy in terms of employees, dependants and the GDP.

Additionally, the gold mining sector is a large consumer of utilities and remains in need of an adequate energy supply to exploit the country’s considerable mineral resources. It is also to a lesser extent a consumer of water; however, gold mining has a profound effect on water quality due to acid mine drainage.

The gold mining sector has recently experienced significant pressure as a result of volatile commodity prices, escalating productions costs and low economic growth. All of which is compounded by a decline in gold resource grade as the high-grade gold deposits have been exhausted and mines are forced to exploit lower-grade options. This means **optimisation** is required to derive optimal value from the remaining low-grade and deep-lying deposits [19].

Gold mining in South Africa has reached depths of up to 4000m. At these depths the VRT can reach $60℃$ and auto-compression will contribute an additional $10℃/km$. To provide acceptable working conditions, mines use complex cooling systems. These include surface and underground BACs used as primary and secondary cooling. However, due to increasingly large distances to the working places, Mobile Cooling Units (MCUs) are used as tertiary or in-stope cooling.

Eight of the ten deepest mines in the world are South African gold mines residing in a particular region of the country. They consist of Mponeng, TauTona, Savuka, Driefontein, Kusasalethu, Moab Khotsong, South Deep and Great Noligwa. All of these mines are more than 2600m deep, with Mponeng reaching 4000m [25]. These mines would be subject to similar environmental conditions underground, as they are situated in the same region. Due to their depth, most of these mines will utilise MCUs as part of their cooling strategy.

Owing to harsh underground conditions, MCUs become inefficient. They are exposed to corrosion, high ambient temperatures, insufficient supply water temperatures and large ducting distances. The non-existence of maintenance due to inefficient (or lack of) personnel further contributes to MCUs becoming inefficient and negatively impacts the very ambient conditions to which they should be positively contributing. Inefficient MCUs also lead to water and electricity wastage through running fans needlessly and the excessive consumption of chilled water.

Keeping the above in mind, optimal functioning of MCUs is critical for safe mining conditions, improved service delivery and the optimal use of electricity. The efficient operation of MCUs and their continued optimisation will thus contribute to ensuring South African gold mine productivity and competitiveness.

A clear, concise and easy to use strategy is therefore required to assess and optimise MCU performance. Such a strategy would assist in ensuring gold mines remain productive and continue contributing to the South African economy.

1.5 Aim of this study

The aim of this study is as follows:

- To devise a strategy for optimising the use and operation of existing underground mobile cooling units for:
  - Improved service delivery and safe mining conditions
  - Reduced operating costs

The study objectives are as follows:

- Develop an effective MCU performance investigation method
- Accurately determine the performance of these units and their contribution to mine cooling
- Develop and implement optimisation strategies in a real-world case study
- Quantify the impact of the optimisation strategies on service delivery and electricity costs to assess and ensure performance

Effecting these objectives will ensure a true and applicable study.

1.6 Synopsis of this dissertation

Chapter 1 gives an introduction into the background and need for the study. It opens with an outline of the fiscal significance of South African gold mines and the current challenges experienced by the sector. A summary of mine cooling systems used to overcome specific temperature factors associated with deep-level gold mining is given, with specific emphasis on MCUs. The importance of optimal and efficient functioning of these MCUs is discussed. It closes with the problem statement and aim of the study.

Chapter 2 delves into detail on the specific temperature challenges associated with deep-level gold mining in South Africa and why these necessitate the use of MCUs. An overview of primary and secondary mine cooling is given, after which follows a detailed discussion on the functioning of MCUs. This includes the heat-exchanger units used in MCUs and the mathematical formulas governing their working principle. The failings and shortcomings of MCUs is discussed. The chapter closes with the current MCU optimisation strategies to ascertain the need for this study.

Chapter 3 describes the process used to attain an MCU investigation and optimisation method. It opens with the development of Key Performance Indicators (KPIs) and their importance to mine cooling. The measurement equipment utilised to determine the operational parameters of the MCU in order to calculate the KPIs is discussed. A method for characterising the MCU performance through these KPIs is then developed to ensure quick and accurate measurements and calculations. Possible optimisation strategies are discussed, and the chapter concludes with the development of a method for quickly selecting these optimisation strategies.

Chapter 4 provides the details of implementing the MCU characterisation and optimisation method on a case study. MCUs at a mine in the Carletonville region of South Africa is measured and characterised through calculating their KPIs. Optimisation strategies are then elected for these MCUs based on their KPIs and the optimisation method developed in Chapter 3. These strategies are then executed and the results on service delivery, ventilation temperatures and operating costs are quantified. The chapter closes with the verification and validation of these results.

Chapter 5 summarises the study and ensures the study objectives have been met. An overview on the MCU optimisation method is given, as well as a summary of the result as implemented on the case study.

2 Mine cooling and ventilation

[4]

Deep-level gold mine cooling strategies and systems are reviewed. Current optimisation strategies are reviewed and analysed for relevance to Mobile Cooling Units.

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[4] *ETA Operations (Pty) Ltd, Employee photograph. “Vertical Surface Bulk Air Coolers”, Carletonville, 2016.*

2.1 Preamble

This chapter provides a detailed description of specific ventilation challenges on deep-level gold mines, including VRT, auto-compression, and increasing distances to working areas. Thereafter, an outline on common cooling and ventilation systems used to provide adequate underground working temperatures is given. This is followed by an overview of the larger primary and secondary cooling systems commonly found in the mining sector. Hereafter, a detailed discussion on the MCU, its specific working principles and its limitations is given. The current research available specific to MCUs is discussed and critically analysed.

2.2 Important temperature considerations in deep-level gold mining

As discussed in Chapter 1, mining at depths of up to 4000m brings with it several unique challenges in terms of underground temperatures. These can differ between mines, depending on mining depth, method and location and will require a study in itself. However, the most relevant underground temperature considerations are discussed below.

2.2.1 Virgin rock temperature

VRT is the temperature of natural rock at a specific depth underground. This means it is the rock face temperature without intervention. At a depth of 4000 meters, the VRT can reach recorded temperatures as high as 60℃ [17]. Figure 2-1 shows the geothermal gradient of key geological areas of South Africa. The lowest average geothermal gradient is that of the gold mines situated in the Carletonville region at around $10℃/km$.

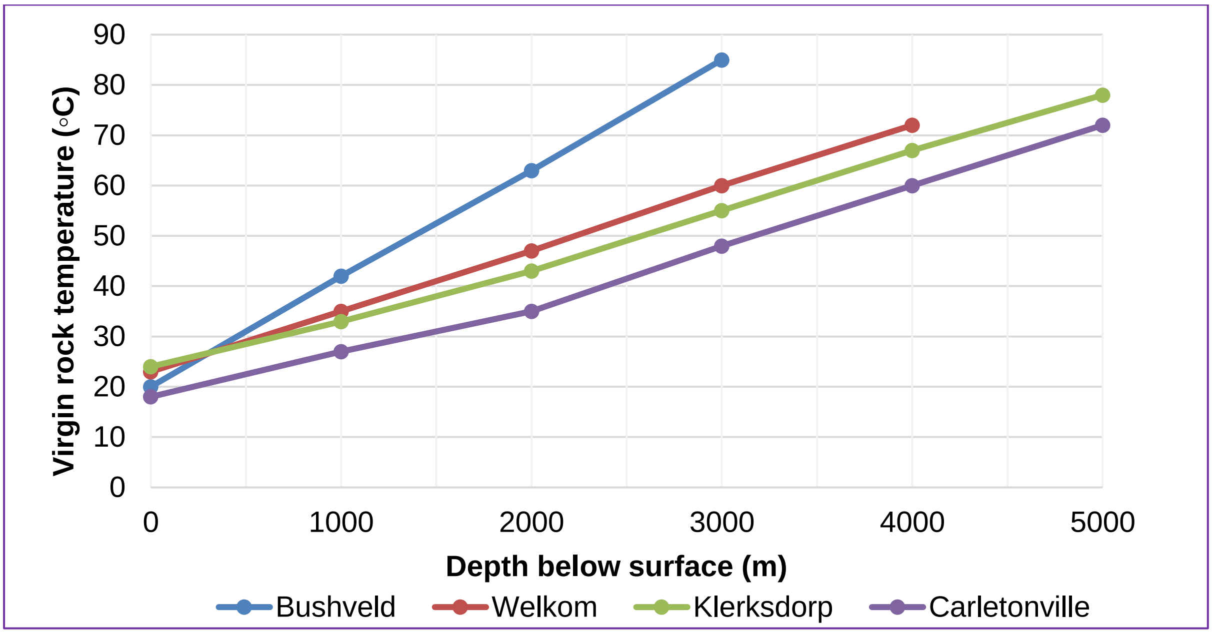

Figure 2-1: Geothermal gradient of key geological areas (adapted from [26]**)**

VRT is thus a key contributor to high underground temperatures. This is especially worsened by rock blasting, through which the surface area of the rock is enlarged, and it needs to be cooled down with ventilation and water. Fissure water at the same temperature as the VRT will further impact underground temperatures by adding to the latent heat of the air through evaporation. Furthermore, the increased humidity will reduce the effectiveness of the human body's own temperature regulating mechanisms.

2.2.2 Auto-compression

Auto-compression is the process in which the air temperature rises due to increasing pressure as it descends into the underground mine workings. There is no auto-compression in horizontal haulages, however at vertical descent auto-compression will add approximately $10℃/km$ to dry-bulb air temperature [20][27]. Figure 2-2 depicts the dry-bulb air temperature at various depths below surface due to auto-compression, assuming an ambient dry-bulb air temperature of 20℃ at surface and no artificial intervention.

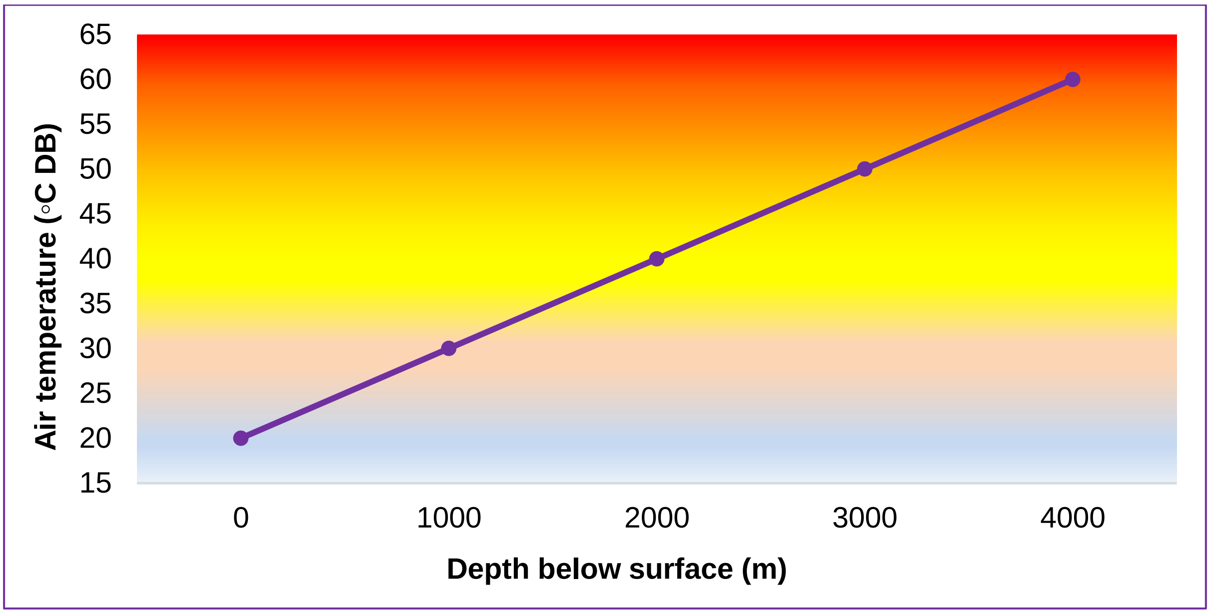

Figure 2-2: Effects of auto-compression on ventilation air temperature (adapted from [20])

For mines subject to higher surface temperatures and deeper than 2000m, a higher ventilation flow rate is required and auto-compression becomes a more important heat-load consideration [28]. This is clear from Table 2-1, which summarises the calculation for auto-compression at specific depths below surface. It provides an overview of atmospheric conditions without intervention at specific mine depths. It also contains the estimated heat dissipation required to obtain a target temperature of 19.85℃ at these depths for given inlet conditions.

Table 2-1: Auto-compression calculations for significant depths (adapted from [28])

	Depth $(\boldsymbol{m})$	**Air density at 19.85◦C** $(\boldsymbol{kg}/\boldsymbol{m}\text{^}\mathbf{3})$	**Pressure calculated at 19.85◦C** $(\boldsymbol{kPa})$	**Temperature at exit for selected initial temperatures shown in first row** (℃)		**Heat dissipation for a 1200** $\boldsymbol{m^3/s}$ **inlet flow and target temperature of 19.85** ℃ **for given inlet conditions** $(\boldsymbol{MW})$	
Inlet conditions	0	1.21	101.33	9.85	19.85		
	1000	1.31	113.58	19.56	29.56		15.38
	2000	1.42	126.85	29.28	39.28	16.15	33.29
	3000	1.53	141.20	38.99	48.99	35.40	53.90
	4000	1.65	156.68	48.71	58.71	57.49	77.41

From Table 2-1, at a mining depth of 3000m below surface, the dry-bulb air temperature would be 48℃ for an inlet dry-bulb temperature of 19℃. At this inlet temperature, for a ventilation air flow rate of 1200 m^3/s and a target temperature of 19℃ at 3000m, 54MW of heat needs to be rejected. Auto-compression is therefore a key consideration in the overall design and performance of mining ventilation systems.

2.2.3 Underground distance

Mining starts with the recovery of easy resources and progresses to more difficult resources [23]. This leads not only to an increase in vertical shaft depths, but also to an increase in the horizontal distance between shafts and the actual working place or stope. Distances of 4km to 5km is common and will increase in the near future [29].

A typical side view of a deep-level gold mine is given in Figure 2-3. The mine usually consists of two main shafts and two sub-shafts. The main and sub- man shaft is used for men, materials and downcast ventilation (fresh air). The main and sub-ventilation shaft is used for ore extraction and up-cast ventilation (hot air). A travelling way connects the main and sub-shafts.

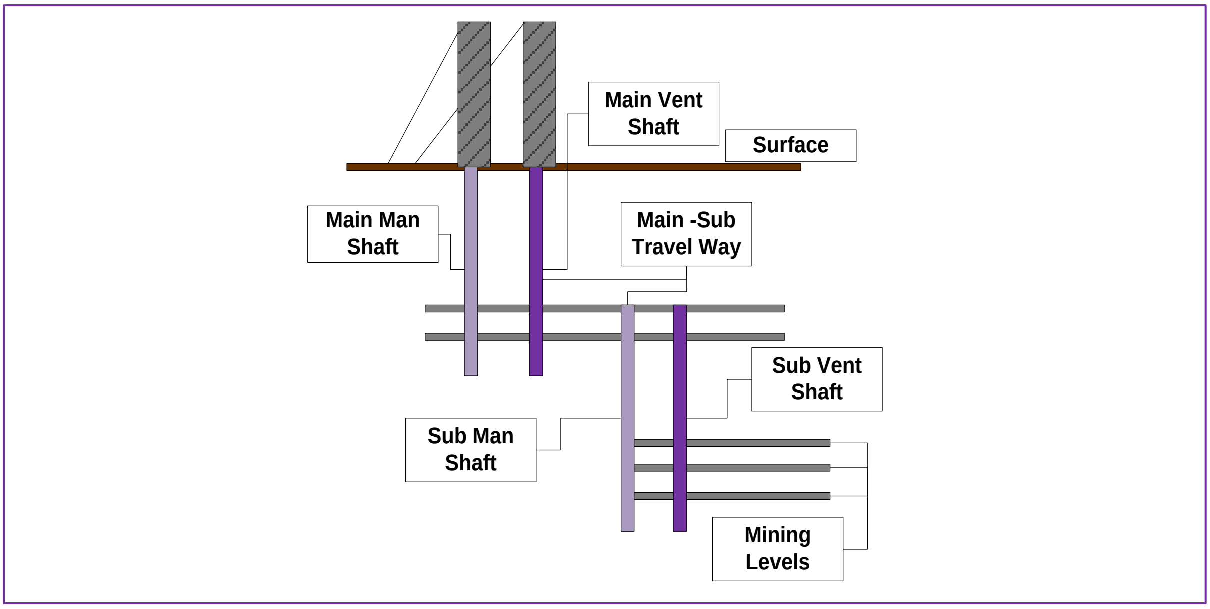

Figure 2-3: Typical side view of a deep-level gold mine

From Figure 2-3, ventilation air travels around 2000m down near the bottom of the main shaft. It is then required to travel an additional 1000-2000m down the sub-shaft, depending on the specific mining level.

Figure 2-4 shows a top view of a typical mining level. This usually consists of a sub-shaft which delivers men, material and ventilation to the level. The haulage connects the shaft to the various cross-cuts and development ends.

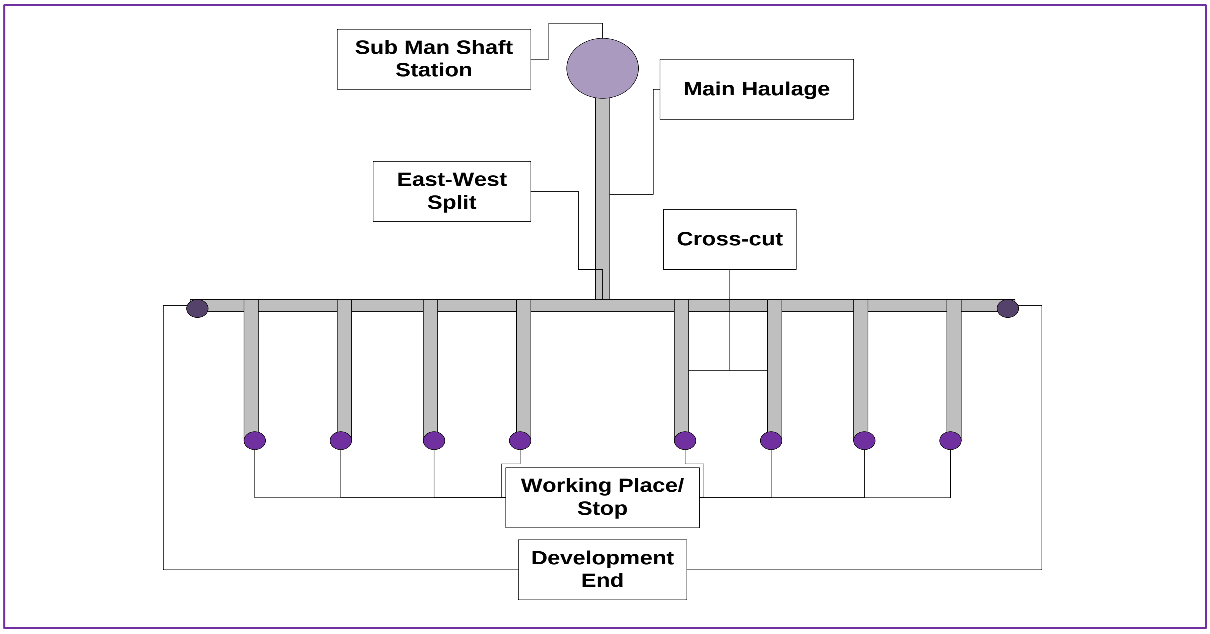

Figure 2-4: Typical top view of a deep level gold mine

As shown in Figure 2-4, with the air arriving at a specific mining level, it needs to travel horizontally along the main haulage to east/west split, a distance of 1500-3000m. From here it journeys into each of the eastern and western cross-cuts to the working place near the end, an additional distance of 50-2000m. The result is a total vertical distance of 3000-4000m and a total horizontal distance of 1500-5000m depending on cross-cut location and specific mining level

The effects of underground distance on mine temperatures are profound. In addition to VRT and auto-compression becoming more pronounced, the following occurs:

- There is an increase in friction pressure and temperature losses due to prolonged exposure of ventilation to various obstacles, such as people, machines and the haulage itself.
- There is an increase in temperature losses from broken rock, as these need to be transported longer distances.
- The amount of water in the vertical shaft and horizontal haulage will contribute significantly to air temperature and humidity increases [20] [30].

Cooling systems are designed to mitigate these effects, depending on factors such as mine depth and ventilation travel distance among others. Selection of the cooling systems will be discussed in the next section.

2.2.4 Ventilation and cooling systems

Mines are subject to several heat loads. VRT and auto-compression are amongst the most significant and have already been elaborated upon in the previous sections. Underground depth and distance aggravate these effects, which has been discussed as well. Additional major mine heat loads include broken rock, machinery, fissure water (ground water), explosive blasting and fluctuating surface ambient conditions [27].

Using several cooling and ventilation systems, mines control heat loads in order to ensure safe working conditions underground. In South Africa, mining legislation stipulates that underground ambient conditions are controlled and temperatures at the working places remain below 32.5℃ wet-bulb (WB) and 37℃ dry-bulb (DB) [31]. A guideline for cooling and ventilation system choice is given in Figure 2-5.

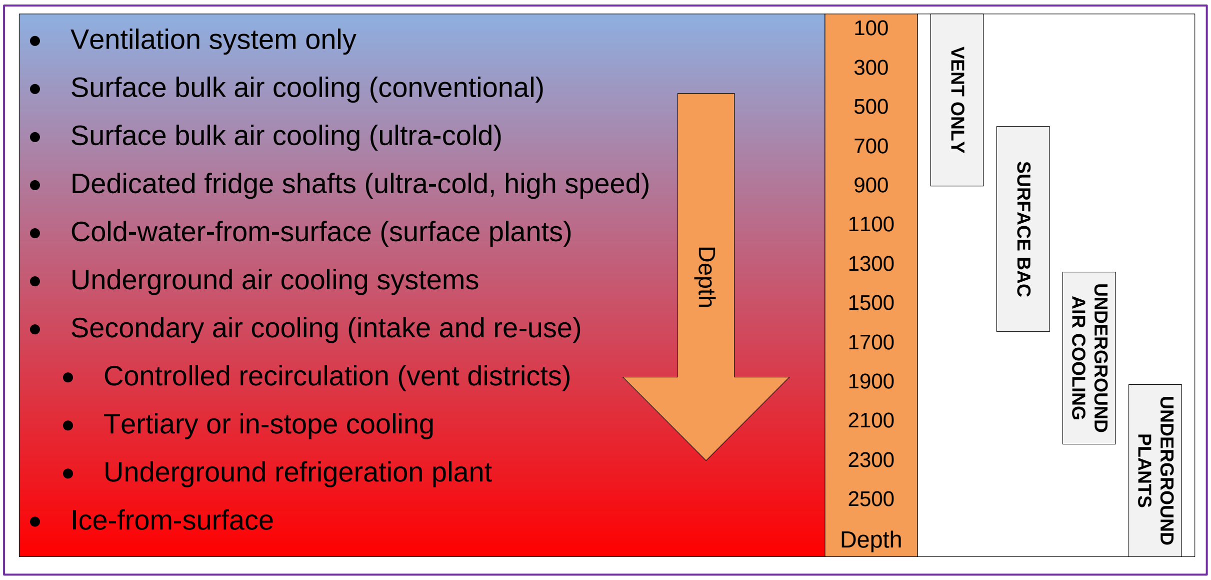

Figure 2-5: Refrigeration system vs. mine depth (adapted from [31]**)**

From Figure 2-5, the ventilation system used in conjunction with surface BACs (conventional and ultra-cold) is sufficient for depths of up to 1600m. Increasing mining depth will result in the need for additional underground cooling (secondary air cooling) up to 2200m. At greater depths, underground refrigeration plants are needed, ultimately giving way to ice-from-surface systems at depths 2500m upwards. Tertiary or in-stope cooling is required at around 2200m.

2.3 Primary and secondary mine cooling

In order to mitigate the effects discussed in the previous section, mines use complex ventilation and cooling systems [21]. Primary and secondary cooling commonly consist of large, centralised systems. Figure 2-6 shows a simplified location of the primary and secondary cooling systems, which consists of:

1. Primary cooling systems: Main BACs – commonly installed along vertical shafts, such as surface BACs and underground shaft BACs. These provide lower shaft intake temperatures on surface and a specific underground depth so as to mitigate the effects of VRT, auto-compression and various friction/pressure losses [32].
2. Secondary cooling systems: Level BACs – commonly installed on a specific mining level to provide a lower haulage intake temperature [32]. These are used to combat the effects of VRT and friction/pressure temperature losses associated with increased distances to the working places.

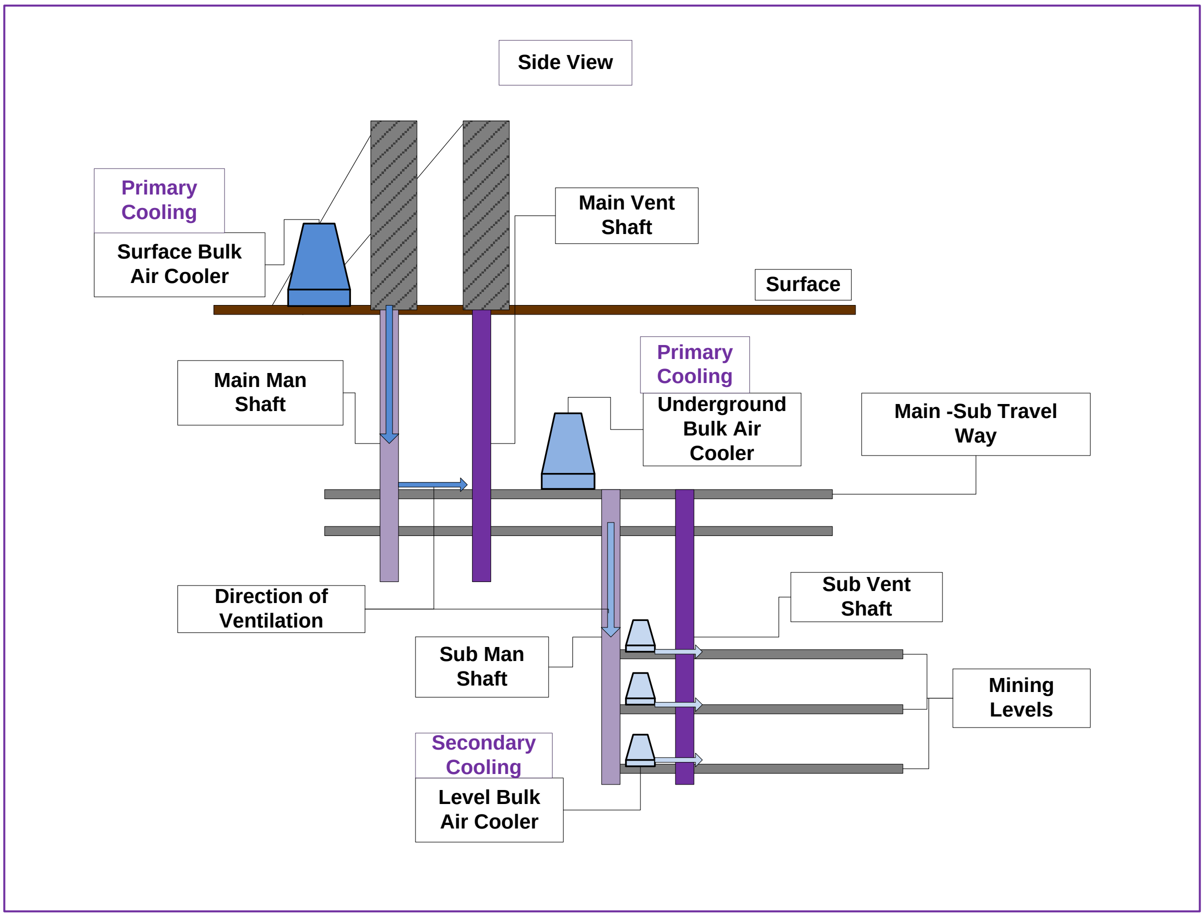

Figure 2-6: Simplified location of primary and secondary cooling systems on a gold mine

Primary BACs are most commonly direct-contact counter-flow heat exchangers, consisting of a vertical spray chamber fed by chilled water and a large fan [33]. This is diagrammatically presented in Figure 2-7. Ambient air is sucked into the bottom of the spray chamber through a honeycomb fill. Sprayers fed by chilled water wets the fill from the top downward (from here the counter-flow). Before the air is forced out of the BAC and into the shaft, a droplet catcher removes excess moisture from the cooled air. The used water is collected in the BAC sump and pumped back to the refrigeration circuit.

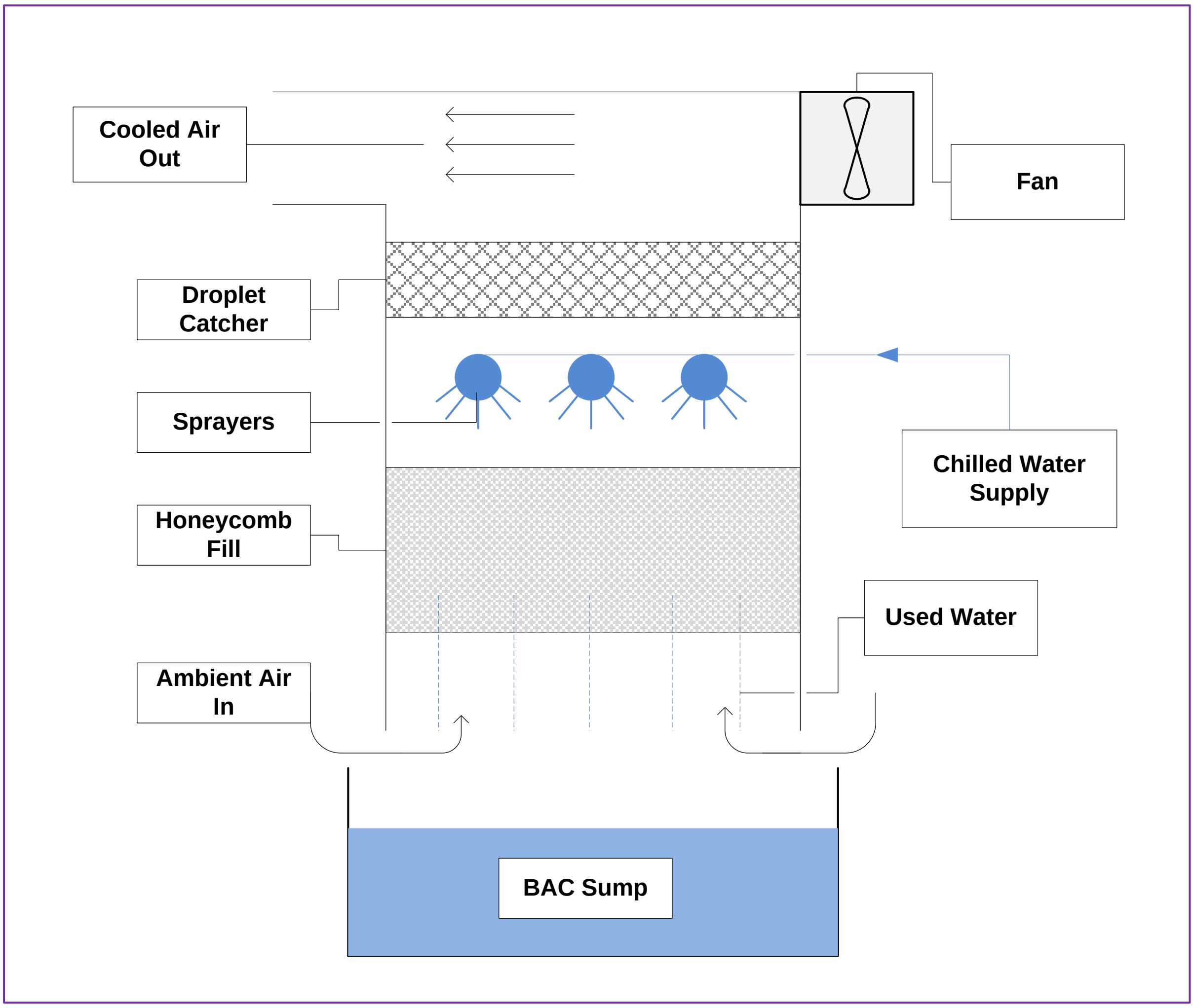

Figure 2-7: Typical cross-section of a vertical spray chamber BAC

Primary cooling utilises vertical spray chambers due the increased efficiency of the counter-flow design. These BACs tend to be large structures and are more suited on surface or dedicated underground tunnels [34]. Various designs and configurations of vertical spray chambers are available, depending on size constraints, required cooling duty and efficiency.

Secondary BACs are most commonly direct-contact heat exchangers, consisting of a horizontal spray chamber and a large fan. This is diagrammatically presented in Figure 2-8. Hotter air is forced through the spray chamber in which horizontal sprayers are supplied with chilled water, thus cooling down the air. A droplet catcher removes excess moisture from the cooled air before it is forced out of the BAC.

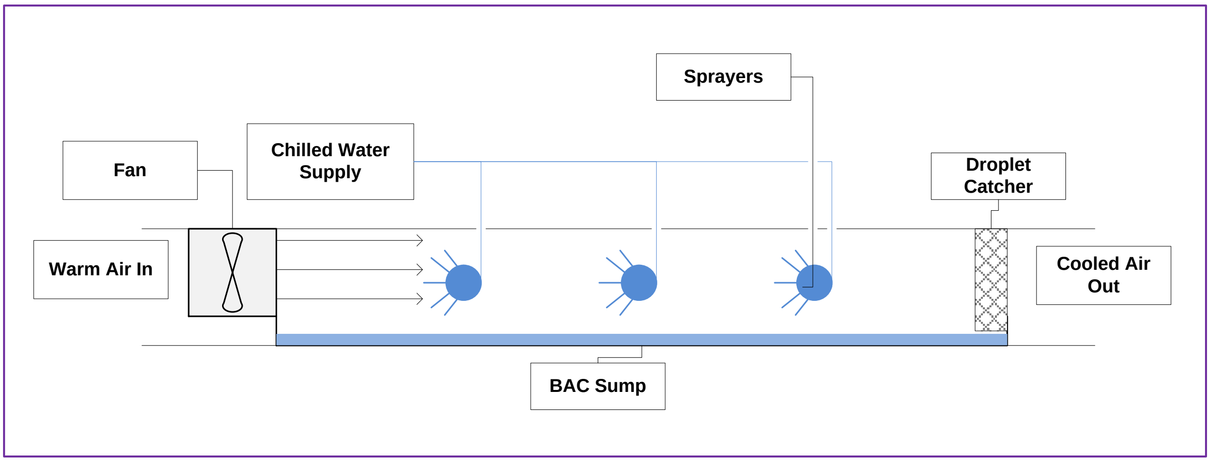

Figure 2-8: Typical cross-section of a horizontal spray chamber BAC

Secondary BACs are normally smaller than their primary counterparts. They are commonly configured in horizontal spray chambers mostly due to underground space constraints [35]. Their unique configuration allows these BACs to be installed in abandoned crosscuts or haulages, with little to no modification of existing mine tunnels [35]. They have lower cooling duties and are less efficient than primary BACs due to limited counter-flow heat exchanging, unless configured in two or more stages [35]. Various designs and configurations of horizontal spray chamber BACs are available, depending on size constraints, required cooling and efficiency.

In conclusion, primary and secondary cooling systems are used to mitigate the effects of mainly auto-compression and VRT. They are used as centralised cooling, where primary BACs provide cooling for the main shaft and/or sub-shaft and secondary BACs provide level-specific cooling. Both types of BACs are dependent on the ventilation infrastructure of the mine to act as a vector for the provided cooling.

Ever increasing vertical and horizontal distances lower the efficiency and ability of primary and secondary BACs to provide sufficient cooling in working places. This is aggravated by inefficient use of the main ventilation infrastructure. In order to provide safe working conditions and ensure legislation compliance, mines need a spot/localised cooler at or near the working place.

MCUs are then utilised as tertiary or in-stope cooling. They are also commonly referred to as spot coolers, cooling cars and cooling coils. The specific working principle of MCUs will be discussed in the next chapter.

2.4 Tertiary mine cooling: Usage of the Mobile Cooling Unit

Tertiary mine cooling is the use of localised or decentralised cooling systems as the final stage of mine cooling. These systems are usually localised or near the actual working place, much smaller in scale than their primary/secondary centralised counterparts and less efficient. They are also usually portable and can be moved to areas where they are needed most. Mobile Cooling Units are one such system and Figure 2-9 shows their location in the larger mine cooling system.

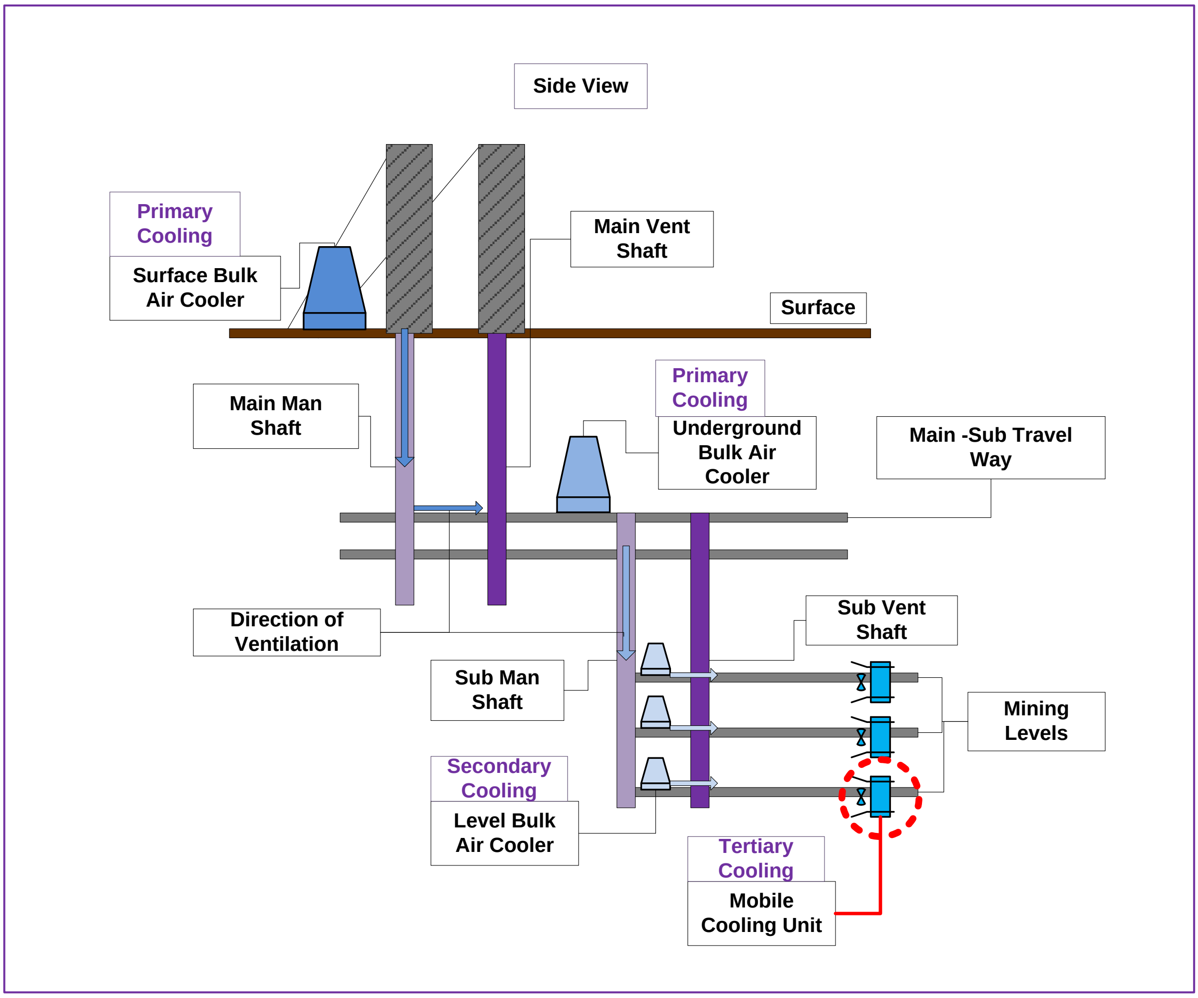

Figure 2-9: Simplified location of Mobile Cooling Units in a mine cooling system

Air is cooled by surface BACs and sent down into the main shaft. It is then cooled down again by the underground BACs and sent down the sub-shaft. Upon arrival at a specific mining level, the air is cooled by the level BACs and sent along the haulage to each crosscut. The air is then cooled near the end of the crosscut by MCUs and sent into the working place or stope. Numerous variations on the cooling system of mines exist, however the key points will remain the same.

2.4.1 Working principle of the MCU

As discussed in the previous section, MCUs are required near the working places as a result of the decrease in primary and secondary ventilation efficiency. These MCUs are usually mobile and available in numerous specifications. Figure 2-10 shows an MCU designed to be used on rail tracks. The air inlet side is on the reader’s left, with the outlet side on the reader’s right. A diagonal heat exchanger can be seen splitting the two sides [33].

Figure 2-10: 500kW portable Mobile Cooling Unit for use on rail tracks[5]

MCUs are configured as shown in Figure 2-11. A fan is used to force hotter air over a heat exchanger. The heat exchanger is supplied by chilled water and cooler air leaves the MCU to proceed to the targeted area. The hot used water is commonly dumped onto the footwell with other waste water, however the MCU can be configured in closed-loop as well (meaning the water is available for re-use) [33]. MCUs require sufficient chilled water supply and temperature, depending on cooling duty and MCU size. Commonly, $8 l/s$ of chilled water at 8-20℃ is required. They are usually available in the following configurations:

- 200kW cooling duty, coupled to a 15/22kW fan
- 300kW cooling duty, coupled to a 22/45kW fan
- 500kW cooling duty, coupled to a 45kW fan

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[5] *Manos Engineering (Pty.) Ltd. “500kW Radian Plate-Fin Cooling Cars” [Online]. Available: http://www.manos.co.za/ManosGallery/kwradianplatefincoolingcars.html [Accessed: 01-May-2018].*

Water in the footwell will eventually accumulate at the settlers and then be pumped back to surface for re-cooling and re-using.

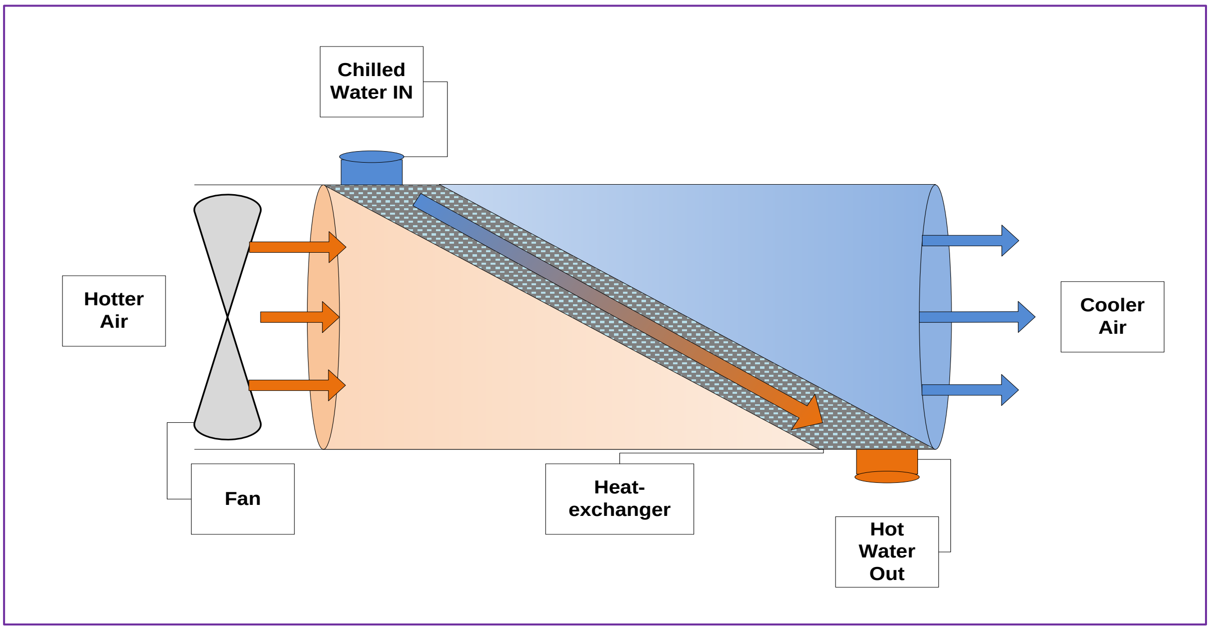

Figure 2-11: Schematic of Mobile Cooling Unit configuration

The heat exchangers used in MCUs are mostly of indirect crossflow configurations, either plate-fin heat exchanger (PFHE) or tube-fin heat exchangers (TFHE). They are slanted diagonally to further increase overall heat exchanger surface area and efficiency. Figure 2-12 and Figure 2-13 show a simplified schematic of PFHE and TFHE respectively. Both are orientated in crossflow, the most common flow arrangement in MCUs, however numerous configurations for both heat exchangers exist.

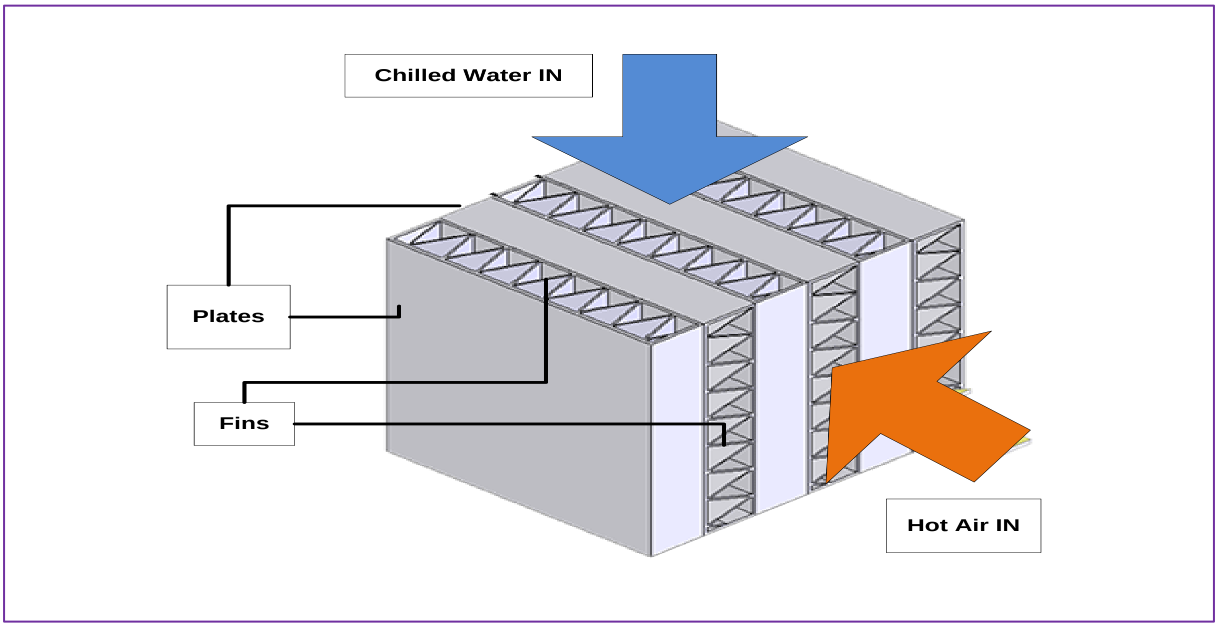

Figure 2-12: Schematic of a plate-fin heat exchanger

PFHE consist of plates coupled to fins in order to separate the working fluids [36]. Various designs of PFHE can be found, including different fin types and flow patterns. They can be used for several fluid streams at once, provide excellent heat transfer efficiency due to the enlarged effective heat transfer surface area, and are relatively compact [37]. In MCUs, they are mostly used for their compact and efficient nature. However, some disadvantages of their use include:

- They are prone to fouling and clogging. A clean water supply is thus of utmost importance [36]
- They are difficult to maintain and clean. PFHE normally need to be disassembled in order to be properly cleaned [37]
- Large fluid pressure drops are experienced due to the narrow passages of the fins, making closed-loop configuration difficult without return booster pumps
- Limited corrosion resistance due to manufacturing material limits, fouling and clogging [37]
- Relatively expensive [36]

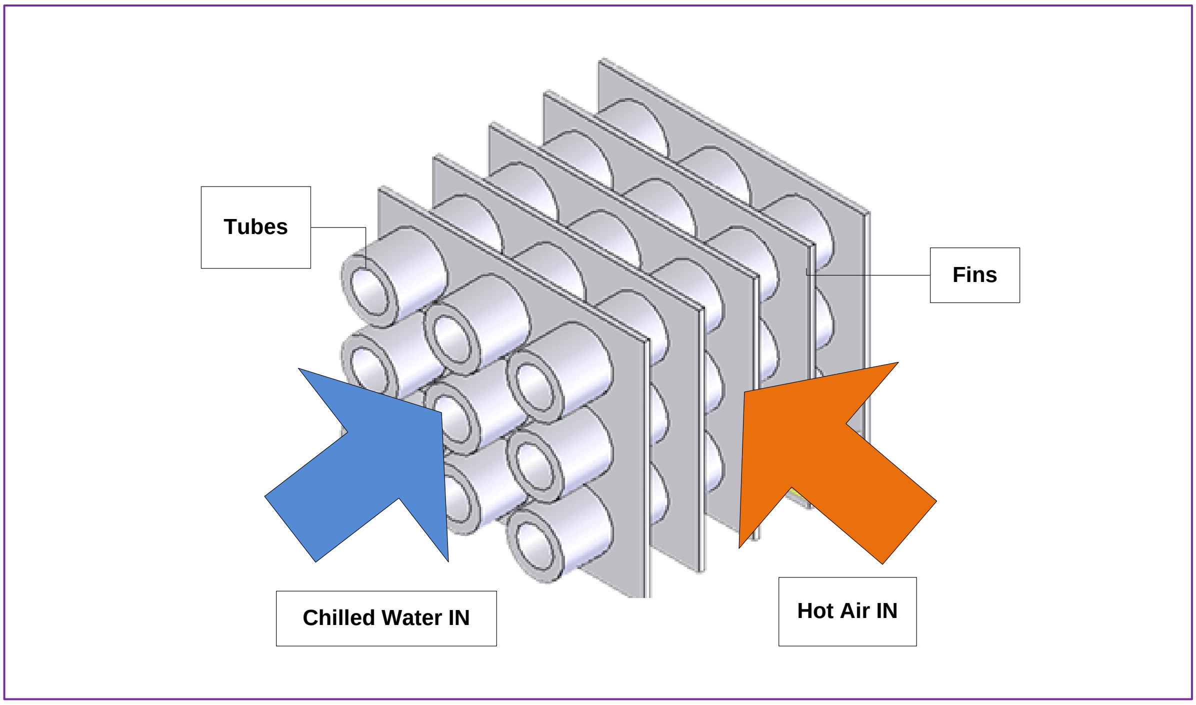

Figure 2-13: Schematic of a tube-fin heat exchanger

TFHE consist of several tubes connected through plates or fins [38]. In the case of the MCU, chilled water will flow through the tubes under pressure, while hot air is forced through the fins and over the tubes. Various configurations of the TFHE are available, such as different arrangement of tubes, different fin/plate design as well as different flow arrangements. TFHE provide efficient heat exchange and are relatively compact. They are less prone to fouling than

PFHE and provide better corrosion resistance. They are also less expensive and easier to maintain or clean. However, they are less efficient than PFHE, so larger units need to be used for the same effective heat transfer capability. An example of each type of heat exchanger is given in Figure 2-14.

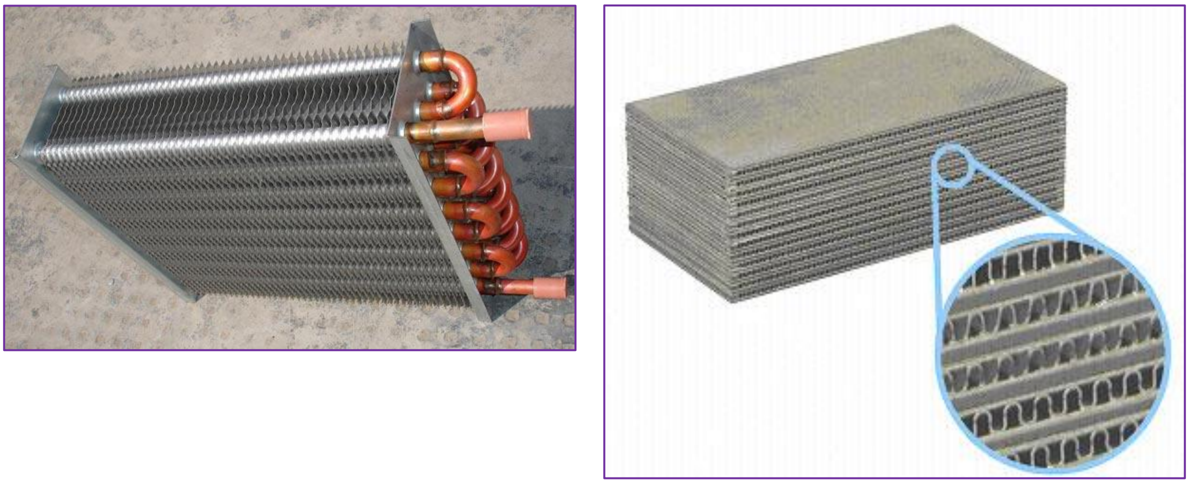

Figure 2-14: A tube-fin heat exchanger[6] (left) and plate-fin heat exchanger[7] (right)

Each type of heat exchanger is governed by its own unique set of equations for determining heat transfer and efficiency, however in the mining environment it will be quicker and more practical to look at MCU performance. Additional heat that is added to the intake air by the MCU fan and other sources can thus be considered. This means the MCU is simply ruled by the thermal energy equation [35], Equation 1 below:

Equation 1: The thermal energy equation

$$\dot{Q} = \dot{m} C_p \Delta T$$

Where,

$\dot{Q}$ = The rate of thermal energy transfer [kW]

$\dot{m}$ = Mass flow rate of the substance [kg/s]

C_p = Specific heat coefficient of the substance at constant pressure [kJ/kg.]

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[6] SmartClima, *“Finned U tube air cooled heat exchanger” [Online]. Available: http://www.smartclima.com/finned-u-tube-air-cooled-heat-exchanger.htm [Accessed: 03-May-2018].*

[7] Lytron Inc., *“Titanium heat exchanger core showing close-up of fin” [Online]. Available: http://www.lytron.com/Tools-and-Technical-Reference/Application-Notes/Lightweight-Titanium-Heat-Exchangers [Accessed: 03-May-2018]*

ΔT = Temperature difference between inlet and outlet of the substance [K]

Equation 1 applies to the thermal energy transfer of the air as well as the thermal energy transfer of the water. However, to simplify the measurements and calculations it can be rewritten as Equation 2 [35]:

Equation 2: The thermal energy equation using change in enthalpy

$$\dot{Q} = \dot{m}\Delta h$$

Where,

Δh = is the enthalpy difference between inlet and outlet [kJ/kg]

$\dot{m}$ = Mass flow rate of the substance [kg/s]

Which again holds true for both water and air. The MCU efficiency relative to its design duty can now be calculated as shown in Equation 3:

Equation 3: MCU efficiency relative to its design duty.

$$\eta_{design} = \frac{\dot{Q}_{air}}{\dot{Q}_{design}}$$

Where,

η_{design} = The efficiency of the cooling car in terms of actual air cooling duty relative to design air cooling duty.

$\dot{Q}_{air}$ = The rate of thermal energy transfer of the air [kW]

$\dot{Q}_{design}$ = The design cooling duty of the cooling car [kW]

2.4.2 Failings of the MCU

MCUs are subject to various limitations specific to the general design used as well as the underground conditions in which they are installed. These include:

- The MCUs are prone to fouling or clogging [39]
- They are difficult to clean and maintain regularly [24]

In addition, MCUs are usually installed in less-than-ideal conditions, such as:

- High inlet air temperatures, meaning a higher outlet air temperature

- High inlet water temperatures, leading to a decrease in heat exchange efficiency and higher outlet air temperatures
- Humid air, meaning a decrease in heat exchange efficiency
- Corrosive mine water which leads to malfunctioning MCUs

All the above will eventually lead to a degradation in MCU performance. The MCU will not contribute optimally to the cooling of the mine and will:

1) Negatively impact ambient conditions. Leaking MCUs caused by corrosive mine water and general neglect will increase air humidity and thus the wet-bulb temperature (even if there is a decrease in dry-bulb temperature).
2) Cause water wastage by purposelessly using water and dumping it on the footwell. This will add to the effect of a wet haulage such as discussed earlier, increasing the wet-bulb temperature of the surrounding air.
3) Cause electricity wastage due to return cascade pumping of water to surface and re-cooling thereof. The MCU fan will also consume electricity without providing any benefit.

By ensuring efficient MCU functioning, mines can provide safe, reasonably comfortable and legislatively compliant underground working conditions. At the same time mines will limit water and electricity wastage, which can either be used for more significant applications or lead to electricity cost savings.

The result is better underground conditions, increased service delivery and electricity cost savings. Optimal functioning of MCUs will also add to ensuring mines remain profitable and continue to contribute to the South African economy as well as lessen their environmental impact in terms of electricity usage and AMD.

2.5 Existing MCU optimisation strategies

Cooling and ventilation in the mining sector are well-documented topics. However, most of the available research is aimed at DSM projects on the larger primary and secondary systems such as the main ventilation fans, BACs and refrigeration plants. This section will aim to summarise the previous research conducted which included MCUs.

Maré, P. [24] conducted a study on MCU water flow control through the use of specialised valves in order to reduce water consumption without affecting performance. However, individual valve control on each MCU is impractical on large scale deep-level mining as a result of its extensive nature. Limited personnel and knowledge are available to ensure correct functioning of the valves, and a there is a cost implication as well. The study only focused on the practical implementation of the valves on a single MCU and no mention is made of the overall impact on larger mining systems, such as pumping and electricity. In addition, the MCU efficiency was not determined and therefore performance-specific optimisation strategies is not developed.

Van Eldik, M. [21] designed a new MCU, known as a modular ACU (Air Cooling Unit), focusing on the techno-economic potential thereof and investigating the DSM potential of the unit. The ACU unit is based on heat pump technology for use as a localised refrigeration unit. However, this study did not contribute recommendations and investigations on the optimal use of existing conventional MCUs. The design was also not practically implemented.

Greyling, J. [40] investigated different configurations of the ACU developed by Van Eldik, M. The study found that MCUs supplied by ice is the best economical option of the two, however potential exists in using the ACU as additional cooling using the hot water of the MCU as a potential heat sink. Again, no mention is made on the optimal use of existing MCUs. The study was also not practically implemented.

Buys, J.L. [33] conducted a study that included research into optimisation of MCU water usage through the use of two different constant flow rate valves. The research was based on electricity cost savings, is impractical on large scale deep-level mining, and does not provide performance-specific strategies for existing MCUs.

Stanton, D.J. [32] designed a mobile refrigeration unit which used MCUs in both the evaporator and condenser circuits. The mobile refrigeration plant chills water, which is then sent to the evaporative MCUs and returned to the mobile refrigeration plant. The refrigerant of the plant is cooled using water which is sent to condenser MCUs to be cooled. This study does not investigate, and provide solutions for, optimal MCU performance.

Du Plessis et al. [41] shortly discussed reconfiguring MCUs to function using hydropower, in which the MCU fan is driven by high-pressure water, which is then also used to cool the air. Again, no mention is made on the optimal use of existing MCUs and no performance-based solutions are provided.

Schoeman, W. [42] investigated the effects of DSM initiatives on the performance of MCUs. The study is based on the effects of DSM initiatives on cooling and refrigeration systems, and as such, it does not go into detail on the optimal use of existing MCUs or performance-based analysis.

As this study will aim to satisfy the problem statement and objectives as set out in Chapter 1 of this document, applicable criteria for previous research done needs to be developed. A summary of the discussed studies measured against this is given in Table 2-2.

Table 2-2: Summary of available research on MCU optimisation

Author	Practically implemented	Focused on tertiary cooling	Focused on existing MCUs	Practical on large-scale deep-level gold mining	Service delivery based	Provides quantification method for MCU performance
Maré, P	X	X	X			
Van Eldik, M		X		X	X	
Greyling, J		X		X	X	
Buys, JL			X			
Stanton, DJ		X	X	X	X	
Du Plessis et al					X	
Schoeman, W			X	X		

The criteria used for the critical analysis as summarised in Table 2-2 is as follows:

- The study should have been practically implemented and not only simulated or researched.
- The primary focus of the study should have been tertiary cooling or MCUs.
- The study should be concerned with existing MCUs and optimising their use “as is”. This excludes total reconfiguration and other modifications to the MCU itself.
- The study should be practical on large scale deep-level mining. Some of the deeper, larger mines could have in excess of 20 of these MCUs. It is impractical to provide solutions which are expensive or require regular inspection/maintenance.

- The study should be service delivery based. This means an improvement in operational conditions, such as lower temperatures and lower water flow demand, not necessarily cost savings.
- The study should be based on, and provide a method for, quantification of MCU performance to ensure optimal functioning of the unit.

It is therefore clear from Table 2-2 that no study specifically addressing all the above criteria has been completed. There is limited literature available concerning the optimal functioning of existing MCUs regarding improved service delivery and safe mining conditions. The quantification of MCU performance in terms of efficiency and contribution to mine cooling is also severely neglected in currently available research. This study will therefore aim to address these shortcomings.

2.6 Conclusion

In this chapter, a detailed portrayal on specific temperature considerations associated with deep-level gold mining in South Africa was given, followed by common cooling and ventilation systems used to ensure legislation compliance and provide adequate underground working conditions.

A short overview on primary and secondary ventilation, used to mitigate the effects of VRT and auto-compression, was given. This was followed by a discussion on the need for MCUs as a result of increasing underground distances, the specific working principle of MCUs, and their associated limitations.

The chapter concludes with an overview of available literature on the optimal use of MCUs and a critical analysis thereof, using criteria which is relevant to this study. The succeeding chapters will then use the information gathered in this chapter to develop and implement a suitable solution.

3 The MCU optimisation method

[8]

A method is developed to characterise Mobile Cooling Unit performance and select relevant optimisation strategies based on Key Performance Indicators.

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[8] *ETA Operations (Pty) Ltd, Employee photograph. “BAC Heat Exchanger Bank”, Carletonville, 2016.*

3.1 Preamble

This chapter will describe the methodology used to characterise MCU performance and the process of selecting optimisation strategies. It opens with the development of Key Performance Indicators (KPIs) for MCU performance quantification. An overview of the operational parameters essential to the KPIs is then given, including a discussion on the required measurement equipment. This is followed by a method for characterising MCU performance through calculating the KPIs. The development of relevant optimisation strategies by using the MCU characterisation is debated, after which a method for selecting optimisation strategies is established.

3.2 Measurements and performance analysis

In this section, the MCU's operational parameters are characterised through measurement and analysis. By developing an effective MCU performance investigation method, the efficiency and cooling contribution of the MCU can be accurately established.

3.2.1 Development of KPIs

In order to create an effective MCU performance investigation method, specific KPIs will have to be developed. These KPIs will be used to characterise the MCU and allow for quick and accurate determination of MCU performance to identify and implement relevant optimisation strategies.

As the main function of the MCU is to contribute positively to mine cooling, heat exchanger efficiency of the MCU can be ignored. This means, for practical purposes, the water side of the MCU can be ignored as only the actual cooling efficiency is of importance. The thermal energy equation therefore becomes applicable only to the air side of the MCU. As this study is focused on MCU cooling performance, the following KPIs will be used:

KPI 1: Humidity ratio (HR) – This is the ratio of inlet air humidity against outlet air humidity. For this study, the wet-bulb temperatures of the inlet and outlet air will be used for the humidity ratio. The human body exchanges heat with its environment by radiation, convection and evaporation [43]. In general, evaporative heat transfer is the most powerful avenue of body cooling in hot environments and will be at a maximum when evaporation is at a maximum [43]. The wet-bulb temperature is therefore one of the most important parameters concerning the ability of the human body to cool itself [43].

Wet-bulb temperature will influence the morale, motivation and performance of people working underground. Figure 3-1 shows the relationship between wet-bulb temperature and employee performance in underground mines. It is clear from this that wet-bulb temperature is an important factor, with a wet-bulb temperature of 28℃ already leading to decreased employee performance.

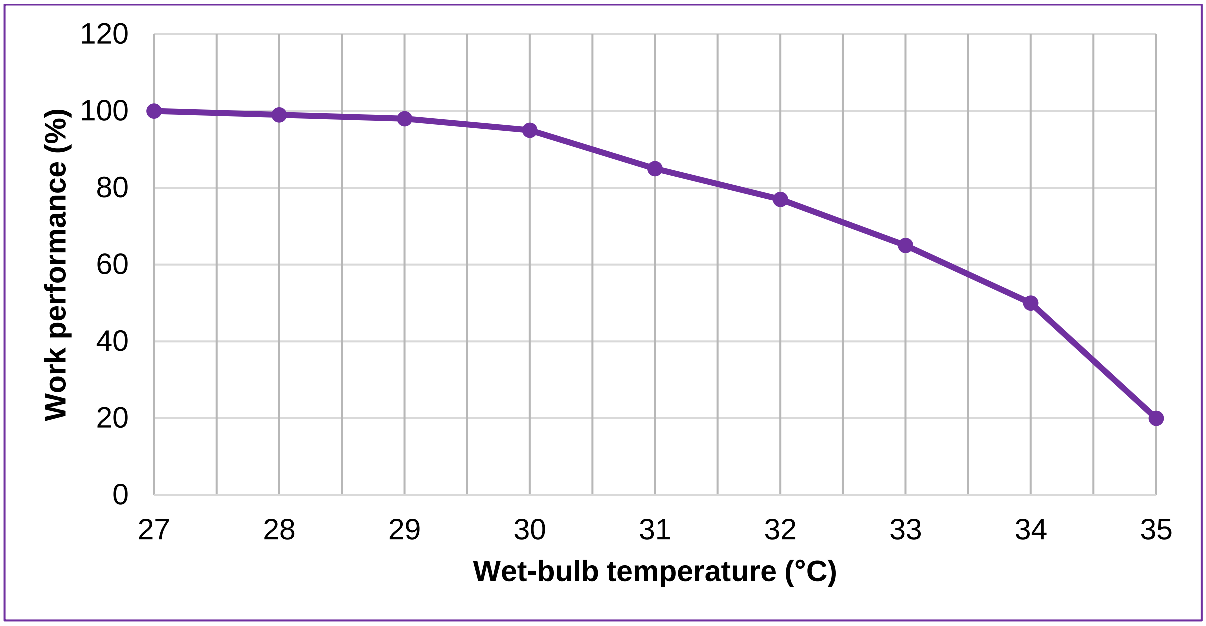

Figure 3-1: Effect of wet-bulb temperature on employee performance (adapted from [32]**)**

High wet-bulb temperatures will also adversely affect the health and safety of employees, further causing decreased employee performance and production. Figure 3-2 depicts the effect of wet-bulb temperature on the number of heat stroke cases per 1000 men per annum. A wet-bulb temperature of 28℃ leads to an average of 0,2 cases of heat stroke per annum for every 1000 employees. Additionally, this relationship is exponential.

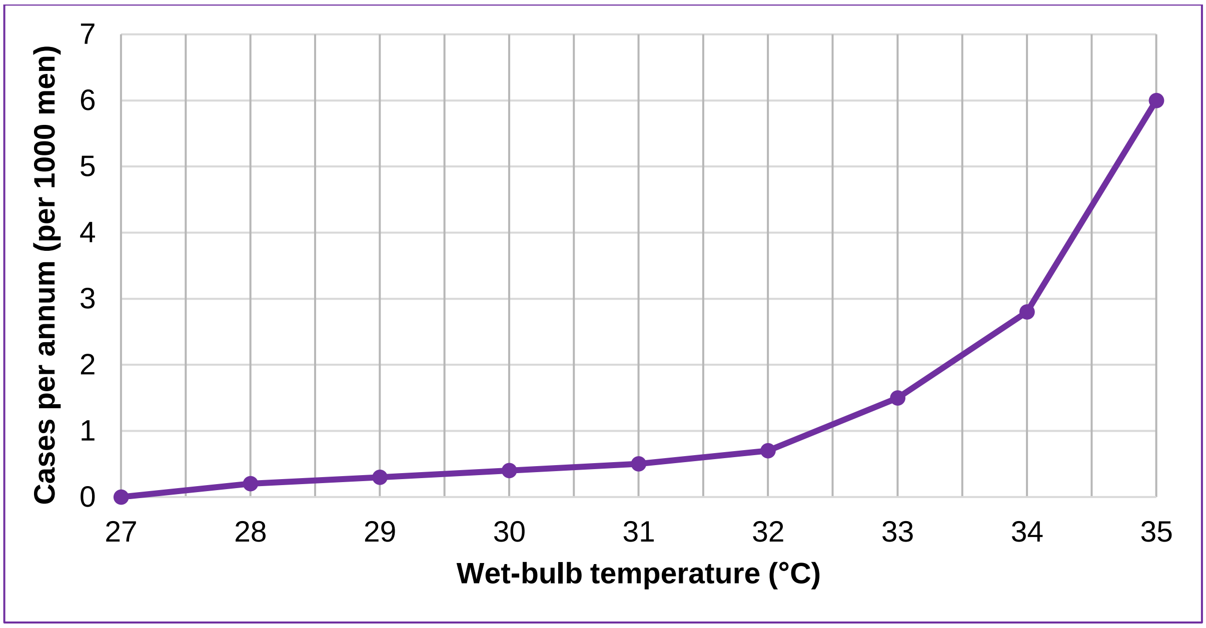

Figure 3-2: Effect of wet-bulb temperature on heat stroke cases (adapted from [32]**)**

A high wet-bulb temperature will therefore lead to heat stress, the consequences of which will be detrimental in terms of safety, health and productivity. As MCUs are indirect-contact heat exchangers, they should not contribute to increasing the wet-bulb temperature if functioning correctly. However, water leakage in malfunctioning MCUs will add to air humidity and increase the wet-bulb temperature of the outlet air, even if the dry-bulb temperature is decreased. This means the first and most important KPI for MCUs is the humidity ratio, defined as Equation 4:

Equation 4: The humidity ratio

$$HR = \frac{T_{wet_{out}}}{T_{wet_{in}}}$$

Where

HR = The humidity ratio

$T_{wet_{out}}$ = The MCU outlet wet-bulb temperature $[℃]$

$T_{wet_{in}}$ = The MCU inlet wet-bulb temperature $[℃]$

KPI 2: Efficiency – this is the efficiency of the unit when comparing the actual air cooling duty to the design cooling duty. Rewriting Equation 3 from Chapter 2, the efficiency of the MCU can be defined by Equation 5:

Equation 5: The efficiency of the MCU

$$\eta_{design} = \frac{\dot{m}\Delta h}{\dot{Q}_{design}}$$

Where:

η_{design} = The efficiency of the MCU in terms of actual vs design cooling duty

$\dot{Q}_{design}$ = The design cooling duty of the MCU $[kW]$

Δh = The air enthalpy difference between inlet and outlet $[kJ/kg]$

$\dot{m}$ = The mass flow rate of the air $[kg/s]$

The specific enthalpy of air is determined using wet-bulb temperature, dry-bulb temperature and ambient pressure. This means that if the wet-bulb temperature is increased by the MCU, the enthalpy of the air is increased, and the efficiency of the MCU will be a negative value. Thus, the MCU is adding heat to the air instead of cooling it.

For a normal functioning MCU, the efficiency should provide an indication into its overall performance. A low efficiency will mean little contribution to mine cooling, and the MCU must therefore be inspected to establish the root cause. These will normally include leakage, high supply water temperatures, incorrect water flow, fouling or blockage and a general lack of maintenance. Once the root cause of the inefficiency has been identified, relevant optimisation strategies can then be implemented to rectify the problem. The efficiency of the MCU is therefore the second KPI.

KPI 3: Position – This is the location in which the MCU has been installed. The importance of the MCU position as a KPI is determined holistically, as underground temperatures and conditions vary greatly. For example, in mining 27.5℃ (WB) is considered "heaven" whilst 32.5℃ (WB) is "hell" [32]. It is therefore clear that even a 1℃ reduction in temperature is of immense value [32]. However, a 1℃ reduction in temperature when the ambient air temperature is already satisfactory, is not an efficient use of the MCU's cooling ability. This is especially true if the MCU is located nearer the secondary cooling systems. In contrast, a 1℃ reduction in temperature far from the secondary cooling system in an area which is hot, is quite acceptable. This KPI also takes into account mining activity, that is if there is little or no mining activity, the MCU is less critical and vice versa.

In addition, air speed is also one of the most important parameters concerning the ability of the human body to cool itself [43]. Increasing the air speed from 0.1 m/s to 1.0 m/s could increase the cooling power of the human body by up to four times [43]. This effect diminishes quickly, with the benefits of increasing the air speed to above 2 m/s being small [43]. However, in areas associated with low ventilation air speeds, such as development ends, this effect would provide additional and much-needed cooling. This again means a holistic approach to MCU position as a function of cooling contribution is required. This KPI is therefore determined through analysing its importance within the current environment.

3.2.2 Measurement equipment

Specific measurement equipment is needed to establish the various operational parameters of the MCU, which is used to determine the KPIs. These parameters are summarised per relevant KPI in Table 3-1, including the applicable measurement equipment. It is clear from the table that only three pieces of equipment are required to complete the measurements, i.e. a whirling hygrometer, vane anemometer and a laser distance meter.

Table 3-1: Summary of operational parameters to be measured

	KPI		**Equipment required**
	HR	**Efficiency**	
Operational parameter to be measured	Wet-bulb temperature IN	Wet-bulb temperature IN	Whirling hygrometer
	Wet-bulb temperature OUT	Wet-bulb temperature OUT	Whirling hygrometer
		Dry-bulb temperature IN	Whirling hygrometer
		Dry-bulb temperature OUT	Whirling hygrometer
		Air pressure	Vane anemometer
		Inlet air speed	Vane anemometer
		Inlet duct area	Laser distance meter

Whirling hygrometer – This piece of equipment is used to measure both dry-bulb and wet-bulb temperatures. It consists of two thermometers mounted in a frame which is coupled to a sling, so the device can be whirled by hand. Figure 3-3 shows a side profile thereof.

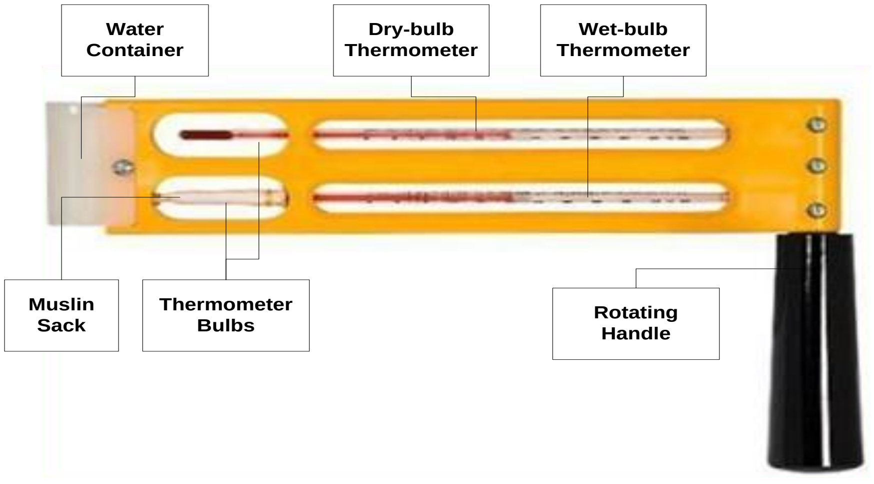

Figure 3-3: A whirling hygrometer [9]

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[9] indiamart, *"Whirling Hygrometer" [Online]. Available: https://www.indiamart.com/proddetail/whirling-hygrometer-13449520697.html [Accessed: 31-May-2018].*

As can be seen in Figure 3-3, the bulb of one of the thermometers is covered in a tight-fitting muslin sack. This sack is wetted with water before whirling the hygrometer, and this thermometer is known as the wet-bulb thermometer. The other is known as the dry-bulb thermometer.

When the device is whirled, air is forced over the two thermometer bulbs and water from the muslin sack evaporates, which cools the wet-bulb thermometer. The amount of cooling depends on the humidity of the air. A lower humidity would result in a lower wet-bulb temperature reading.

The whirling hygrometer is also rugged, contains no electronics which could malfunction, is lightweight, easy to carry and requires limited knowledge or skill to operate. For these reasons, it is popular for use by mine personnel and therefore further motivates the use of wet-bulb temperature in the humidity ratio KPI. Personnel can simply use the measurements from the device directly in the formula.

Vane anemometer – A vane anemometer is used to measure air velocity but will include a built-in barometer to also measure air pressure. The vane anemometer usually consists of blades running in a casing and a handheld user interface. An example of this is shown in Figure 3-4.

Figure 3-4: A vane anemometer[10]

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[10] IVY Tools, *“Extech AN100 CFM/CMM Vane Anemometer with Temp” [Online]. Available: https://www.ivytools.com/Extech-AN100-CFM-CMM-Vane-Anemometer-with-Temp-p/an100.htm [Accessed: 03-June-2018].*

The vane anemometer is simple and easy to use. The measurement sensor is positioned into the airflow which is to be measured, with the axis of the blades in parallel to the air flow direction (thus the "face" of the measurement sensor should be perpendicular to the air flow direction). The air velocity is simply noted down from the user interface, as is the air pressure.

Laser distance meter – This device is used to measure distances, and for this study it is used to determine the ducting size of the MCU fan in order to be able to calculate the mass flow of air through the MCU. It is therefore used in conjunction with the vane anemometer. The device is simply a small, handheld piece of equipment with a user interface, input buttons and a laser light/sensor. An example of the device is shown in Figure 3-5.

Figure 3-5: A laser distance meter[11]

The device is positioned in the ducting of the MCU and it quickly and accurately measures the distance between two relevant points. This can then be used to determine the MCU ducting inlet area, which is used to calculate the air mass flow.

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[11] The Home Depot, *"660 ft. Laser Distance Measurer with Color LCD, 4x Zoom Digital Camera and Bluetooth" [Online]. Available: https://www.homedepot.com/p/DEWALT-660-ft-Laser-Distance-Measurer-with-Color-LCD-4x-Zoom-Digital-Camera-and-Bluetooth-DW03201/206883283 [Accessed: 03-June-2018].*

3.2.3 Method for characterising MCU performance

The KPIs and their required operational parameters have been established, including an overview on the required measurement equipment. Therefore, a method for characterising the MCU performance can now be constructed. This method will provide for quick and easy MCU performance assessment using the three KPIs. The information flow required is shown schematically in Figure 3-6, while the steps in order of importance are:

1) Measure:
    a. The dry-bulb and wet-bulb temperature at the MCU inlet and outlet by using the whirling hygrometer. This is done first as the humidity ratio can be calculated from the inlet and outlet wet-bulb temperatures.
    b. The atmospheric pressure and inlet air speed using the vane anemometer.
    c. The inlet duct area using the laser distance meter.
2) Note:
    a. The design cooling duty.
    b. The MCU position.
3) Calculate:
    a. The humidity ratio.
    b. The enthalpy difference between MCU inlet and outlet.
    c. The mass flow of air.
    d. The actual cooling duty.
    e. Finally, the MCU efficiency.

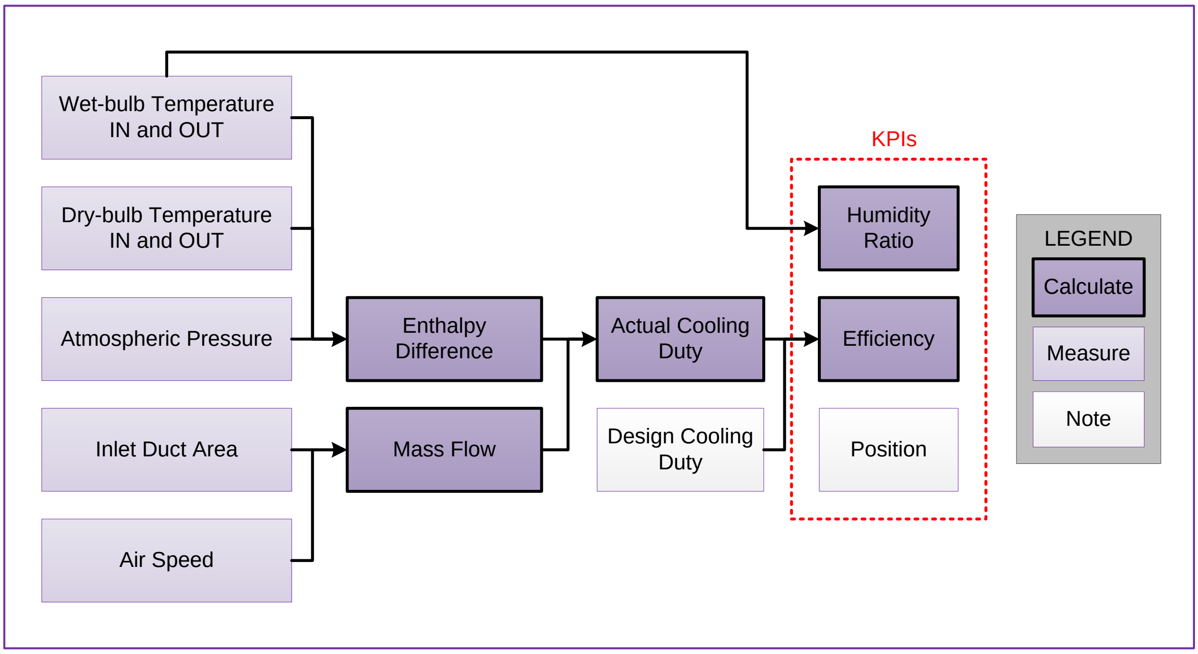

Figure 3-6: Schematic of the MCU performance characterisation method

Steps 1) and 2) are done underground at the MCU, while step 3) can be done on surface. From Figure 3-6, specific calculations are used to determine the humidity ratio and MCU efficiency. The humidity ratio is simply calculated using Equation 4. Due to its relevance and simplicity, the humidity ratio is always calculated first. This will be elaborated upon in the next section. The MCU efficiency is calculated by using Equation 5.

The MCU efficiency requires some pre-calculations. First, the enthalpy difference between the MCU inlet and outlet is needed. Enthalpy cannot be measured and is determined by using inlet/outlet wet-bulb and dry-bulb temperatures, as well as the atmospheric pressure. Assuming these parameters have been determined, the enthalpy of the MCU inlet and outlet is determined by using psychometrics. These comprise of either a psychrometric chart or software.

An example of a psychometric chart is given in Figure A- 1 in Appendix A. The user selects the applicable dry-bulb temperature at the bottom of the chart (yellow line) and crosses this with the applicable wet-bulb temperature on the left curvature of the chart (red line). The enthalpy is then simply read off the relevant scale (green line). For this example, air at a dry-bulb temperature of 30℃ and wet-bulb temperature of 20℃ will have an enthalpy of approximately 57 kJ/kg.

Please note that this is for an air pressure of 101.325 kPa. This means either a psychrometric chart at the measured underground pressure has be found and used, or applicable software is to be used. The simplest solution would be to use software to calculate the enthalpy of the air. Various calculators are available online and as downloads, either free or as paid software.

The mass flow of air now needs to be calculated. This is done by using the Equation 6:

Equation 6: Mass flow of air

$$\dot{m} = \rho \times V \times A$$

Where,

ρ = The density of the air $[kg/m^3]$

V = The inlet air speed $[m/s]$

A = The inlet duct area $[m^2]$

The inlet air speed and duct area were measured. The density of the air is subject to air temperature, humidity and pressure. As such, it is suggested that software is used to calculate the air density by using the dry-bulb temperature, wet-bulb temperature and air pressure that was measured at the MCU. Again, various calculators are available online and as downloads, either free or as paid software.

The actual cooling duty of the air can now be calculated by means of the air mass flow and enthalpy difference. This is then used in the applicable formula to determine the MCU efficiency in terms of actual cooling duty vs. design cooling duty. This concludes the MCU performance characterisation, as all KPIs are now known.

The MCU performance characterisation method is simple and easy to use. It should take up minimal time from an employee conducting the MCU investigation and provide a guided structure to ease calculations and recommendations. It is suggested that software be used to calculate the enthalpy and pressure of the air, so as to eliminate possible calculation errors etc. Therefore, the MCU performance characterisation method consists of three main steps, as set out in Figure 3-6, i.e. measure, note and calculate.

A structure or guideline for these three steps can be developed to further simplify the process and ensure accuracy. In Table B- 1 attached in Appendix B, is an example of an MCU inspection sheet. It contains all the operational parameters which the employee needs to note or measure, as well as a “notes” row which can be used to express MCU leakage, blockage and so forth. The employee simply determines all the parameters in the sheet and complete the applicable cell. This sheet will safeguard against missing critical information, as well as save time by eliminating irrelevant measurements.

Table B- 2 in Appendix B contains an example of an MCU calculation and recommendation sheet. This sheet contains all the relevant calculated parameters and the KPIs. This sheet can be completed on a computer, and the calculations can therefore be automated. This ensures accurate results and saves time. The sheet also contains a “recommendation” row, which will be used to give a recommended optimisation strategy derived through use of the KPIs. This will be elaborated upon in the next section.

3.3 Development of optimisation strategies

The steps on how to determine MCU performance have been discussed, and the various operational parameters (and especially the KPIs) should be known. However, the question remains as to what to do once all the information has been gathered. Optimisation strategies will have to be developed and implemented, using the KPIs to identify the correct course of action. For MCUs, there can really be only three possible optimisation strategies:

1) **R**epair – This will be done in the case of leakage, blockage or general neglect, which can be corrected on-site without moving the MCU. This will mostly concern leaks of the connections, slight blockage or dirty MCUs, which are easily fixed. An MCU should only be repaired if it is absolutely required in that specific position.
2) **R**eplace **–** This will be done in the case of leakage, blockage or general neglect, which cannot be corrected on-site. The existing MCU will then be replaced by a new unit. It will also be done only if an MCU is absolutely required in the specific position.
3) **R**emove **–** This will be done if the MCU is not absolutely required in its current position, it is inefficient, or it is not contributing to mine cooling.

The above will be referred to as the three R’s. The chosen course of action will depend on the KPIs, i.e. humidity ratio, efficiency and position. An element concerning ease of repair is also present, however this is not a KPI. The importance and relevance of the different KPIs have already been discussed. A method for electing one of the three R’s as an MCU optimisation strategy can now be developed by means of the KPIs.

The importance of the humidity ratio has been thoroughly established. A humidity ratio of more than one means the outlet wet-bulb temperature of the MCU is higher than the inlet wet-bulb temperature. In this case, the MCU is negatively affecting the ambient air and adding heat to the environment. Furthermore, it is decreasing the ability of the human body to cool itself. The efficiency of the MCU will also be a negative number, and it is therefore unnecessary to determine it. The first and most important rule of thumb for the optimisation of MCUs is therefore:

- If $HR > 1$, directly proceed to assessing whether the MCU is required in its current position as it is inefficient and not contributing to mine cooling

- If $HR \leq 1$, proceed to determine the MCU efficiency and thereafter determine whether the MCU is required in its current position

The efficiency of the MCU is a measure of its actual cooling duty referenced to its designed cooling duty, and considers incorrect supply water flow, incorrect supply water temperatures, blockage and general neglect. A low efficiency should be investigated to determine the root cause, which should be corrected if the MCU is required in its current position.

The position of the MCU is of critical importance, as was discussed earlier in this chapter. In some cases, even a 1℃ reduction in temperature is excellent, while in others it is dismal. Whether or not the MCU is required in its current position is therefore the next important consideration when choosing an optimisation strategy. All other KPIs will be assessed by means of the position (or need) of the MCU. The final decision in optimisation strategy therefore comes down to the following:

- If the MCU is not absolutely required – remove it
- If the MCU is required – either replace or repair, depending on the ease with which the problem can be corrected

Additionally, if the MCU humidity ratio and efficiency are satisfactory and the MCU is required in its current position, no action is required and the MCU is positively contributing to its environment. If the MCU humidity ratio and efficiency are satisfactory but the MCU is not required, it should ideally be removed but the responsible person can use his/her own discretion.

A schematic of the above is given in Figure 3-7 to simplify the optimisation strategy selection. It is given in the form of a series of questions, starting with the humidity ratio. If the humidity ratio is more than 1, the importance of the MCU in its position is assessed and a recommendation (one of the three R's) is then made. This eliminates the need for any further calculations and a recommendation can be speedily made. If the humidity ratio is less than or equal to 1, the MCU efficiency will have to be determined. Whether or not the MCU is efficient, its importance in its position is assessed and a recommendation (one of the three R's) is then made.

Figure 3-7 can be used to ensure accurate assessment of the KPIs, while also being time-effective. The correct optimisation strategy can then be selected and promptly recommended to ensure optimal functioning of the specific MCU. Due to the simplicity of this method, the MCU can be repeatedly investigated and optimised by personnel of limited technical knowledge.

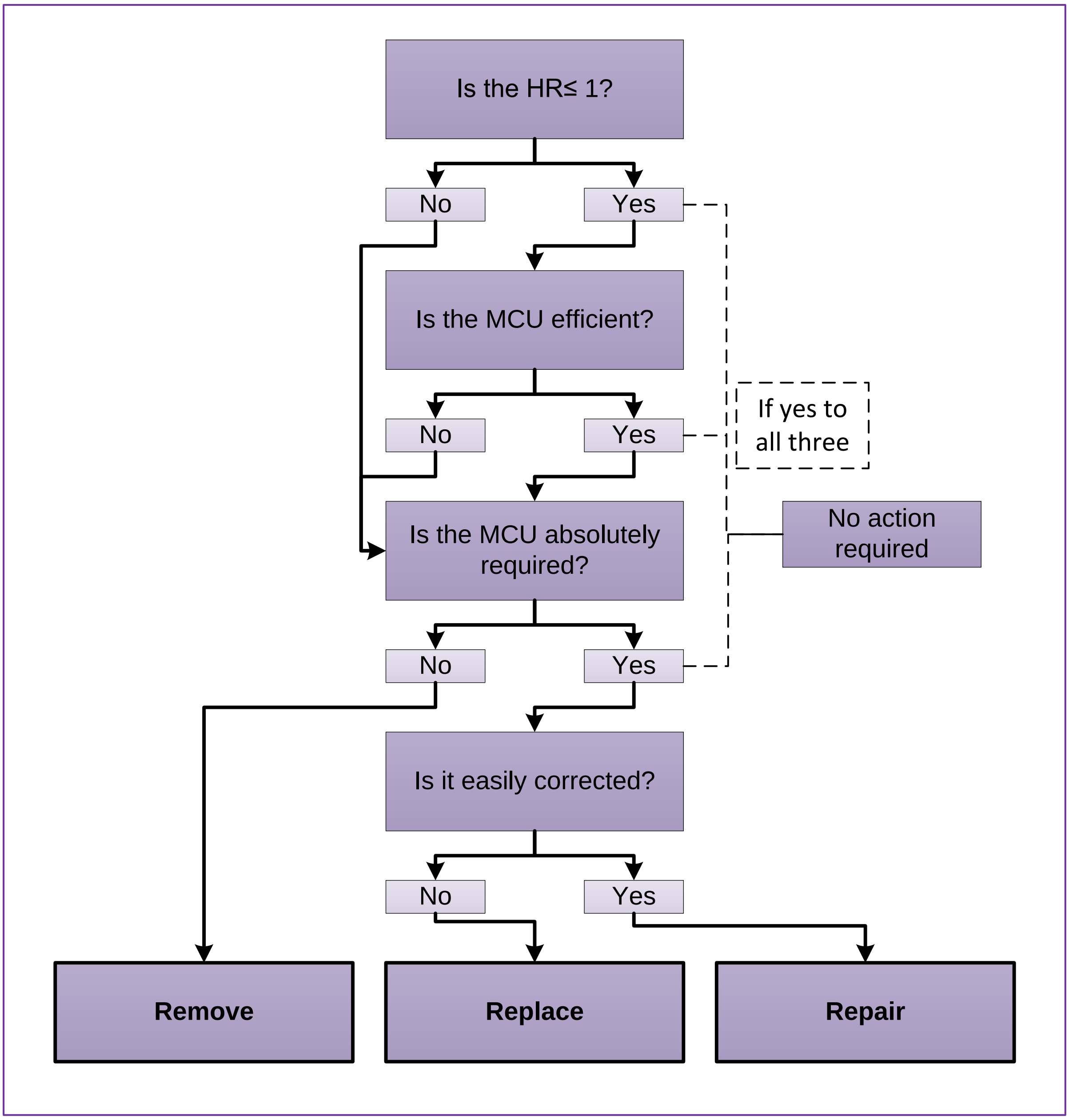

Figure 3-7: Method for selecting MCU optimisation strategies

3.4 Conclusion

This chapter opened with the development of KPIs, which are used to characterise the performance of the MCU. The critical nature of these KPIs were established, as have their ease of use in simplifying the selection of optimisation strategies. A methodology for determining and calculating the KPIs using template spreadsheets was also formed. Relevant optimisation strategies were then identified and elaborated upon, followed by the creation of a process for easy selection of these optimisation strategies. In the next chapter, a case study will be used to ascertain if the characterisation and optimisation methods is indeed of use.

4 Implementation and results

[12]

The Mobile Cooling Units at a case study mine is characterised and optimised.

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[12] *ETA Operations (Pty) Ltd, Employee photograph. "Main Ventilation Fan Impeller", Carletonville, 2016.*

4.1 Preamble

In this chapter the methodology for MCU performance characterisation and optimisation, as developed in Chapter 3, will be applied on a case study. The case study is a deep-level gold mine which incorporates MCUs as part of its underground cooling strategy. The chapter opens with a background on the mine used for the case study. Hereafter, the implementation of the methodology described in Chapter 3 is discussed and the recommended optimisation strategy per MCU given.

The results of the execution of the optimisation strategies are then analysed and discussed. These include a decrease in chilled water demand, an improvement in ventilation temperatures and significant electricity cost savings. The water demand results are verified using data from a third party contracted by the mine to perform pump tests and validated by using mine production data.

4.2 Background to the case study

This section provides background on the case study to ensure the MCU optimisation method is applicable. First, an introduction providing an overview of the current financial situation and the relevance of optimising MCUs are given. Hereafter, an outline of the MCU water reticulation is provided, followed by a description of the MCU locations.

4.2.1 Introduction

A deep-level gold mine in the Carletonville region of South Africa will be used for this case study. For confidentiality reasons, the mine will simply be referred to as Mine X. The mine comprises of twin main shafts and twin sub-shafts, one for men and materials, and the other for rocks and ventilation. Mine X employs over 4000 people and produced in excess of 4000kg of gold in the 2017 financial year [44].

Mining is conducted at a depth of around 3300m and as a result, major engineering infrastructure is complex [44]. The life-of-mine was shortened to five years due to depleting reserves, lower production and higher operating costs [44]. Capital expenditure decreased by one fifth due to the slow-down in mine development as a result of the reduced life-of-mine [44].

Referring to Figure 2-1, at a depth of 3000m the VRT for the Carletonville region would approach 50℃. Furthermore, Figure 2-2 shows that auto-compression will add 30℃ to the dry-bulb temperature at 3000m , assuming a surface intake temperature of 20℃. Complex cooling systems will therefore be needed to ensure safe underground working temperatures. Figure 2-5 suggests the use of primary, secondary and tertiary cooling.

Through underground audits, it was found that Mine X utilises 32 MCUs as part of its cooling strategy. The optimal function of these MCUs at Mine X would help ensure safe underground working conditions. Correctly functioning MCUs are also of significant monetary importance, as the mine is under financial pressure. Due to the shortened life-of-mine, minimal capital expenditure can be expected, and Mine X will have to make do with what is available. Optimal use of current infrastructure is thus the way forward.

4.2.2 Mine X key infrastructure and defining the boundary

The MCUs in Mine X are supplied by chilled water from surface. The water used by the MCUs is dumped onto the footwell, which conveys it to the settlers for return pumping to surface where it is re-chilled and re-used. Figure 4-1 provides a simplified overview water reticulation in Mine X.

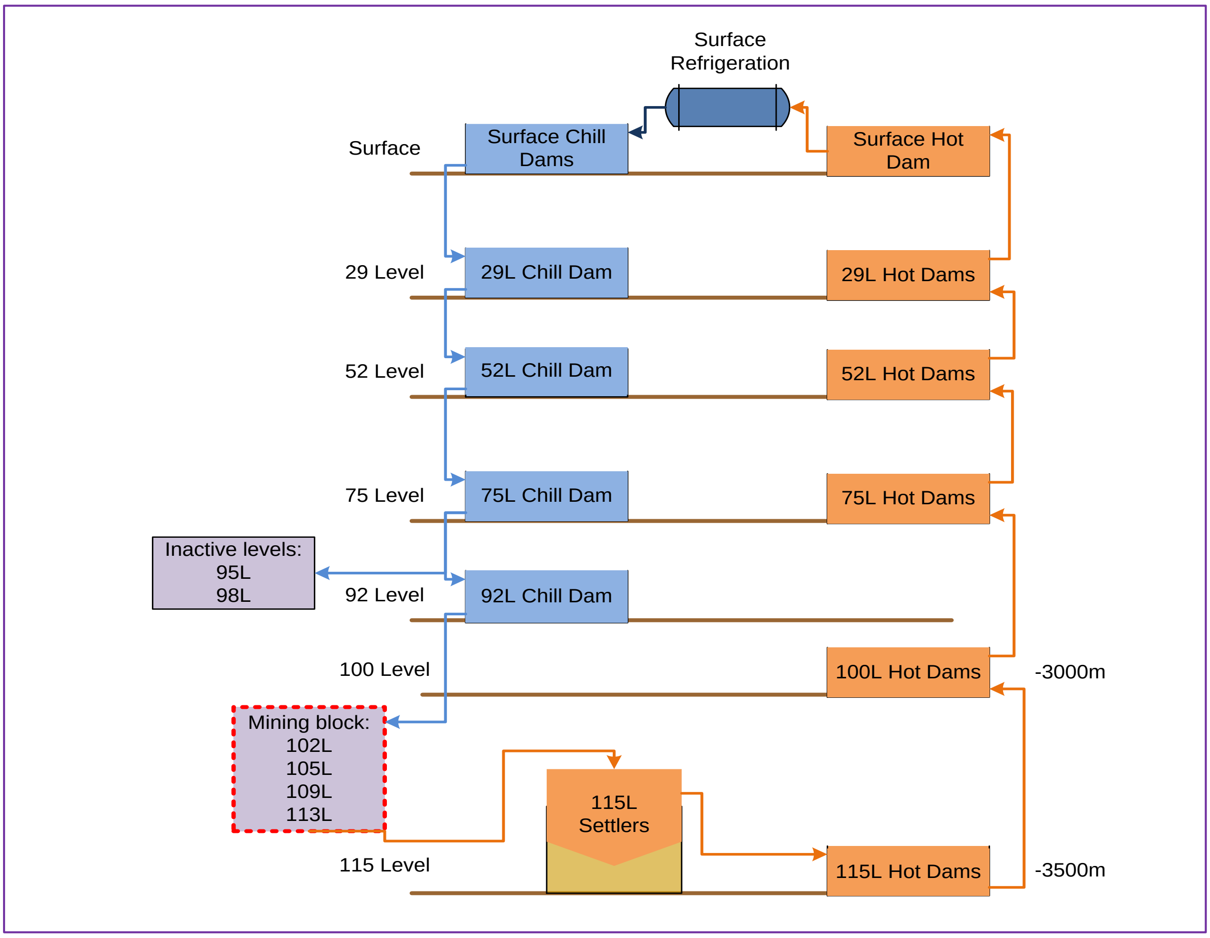

Figure 4-1: Schematic overview of Mine X water reticulation

Chilled water from surface is cascade-supplied from the surface chill dam to 92L chill dam. All the mining block water is supplied by the 92L chill dam, meaning its outlet flow is the water consumption of the productive section of the mine. Currently mining is conducted on 102L, 105L, 109L and 113L. This is also where all the MCUs are found. 75L chill dam supplies chilled water to the less productive levels of Mine X, i.e. 95L and 98L.

Used water from MCUs and other mining activities end up at the 115L settlers, which is used to clarify the water as it proceeds to 115L dam. From 115L dam, all the used water is then cascade-pumped back to surface. There is a pumping chamber on each of the hot dam levels (except surface). What is of importance, is that the MCUs can only be supplied by water from 92L dam and the used MCU water can only be pumped from 115L dam.

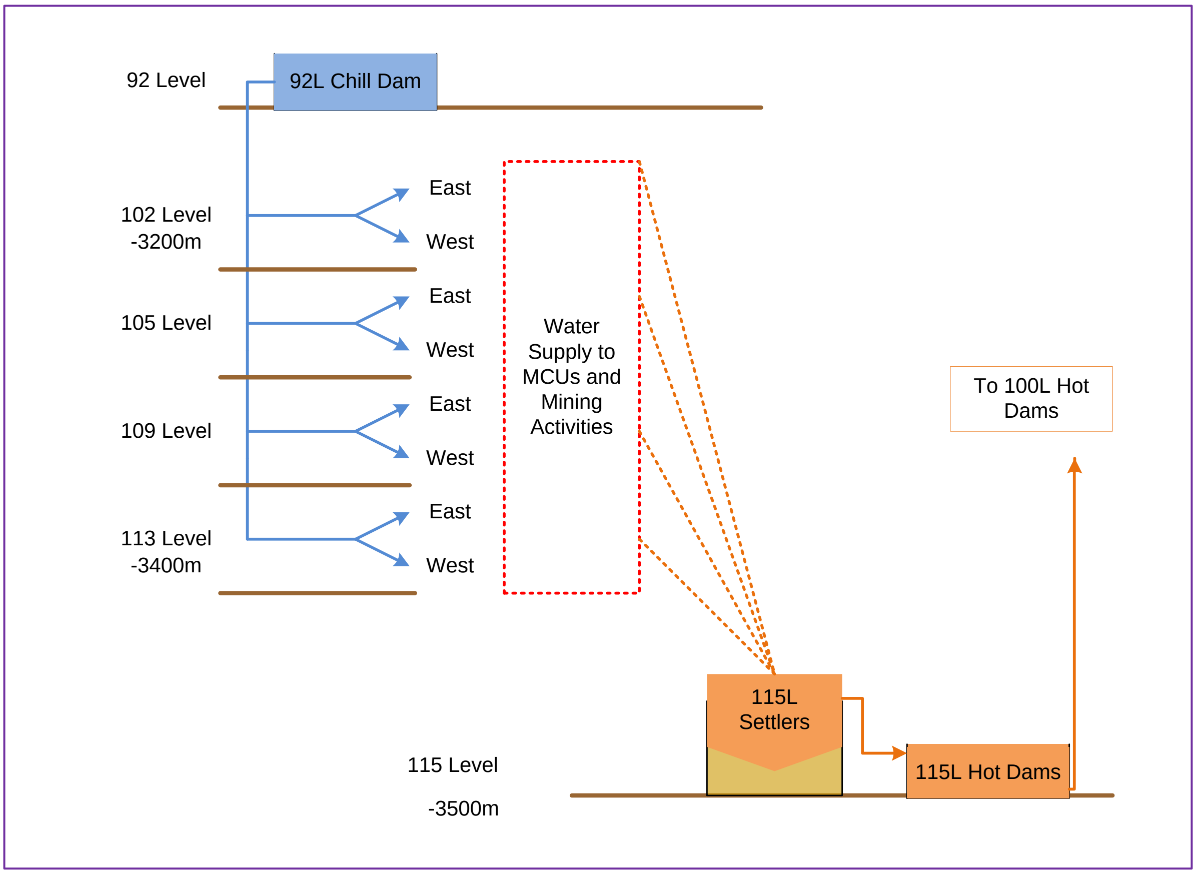

Figure 4-2: Water reticulation for the Mine X mining block

Figure 4-2 therefore defines the boundary for analysing water usage for this study. Any water reduction as a result of optimising MCUs will be evident from the 92L chill dam outlet flow and the 115L pumping flow. Defining the boundary in this way also eliminates the effect of leaks and usage increases on the other non-mining levels. It is important to keep in mind that a reduction in water pumped from 115L will lead to a reduction in water pumped from each of the other pumping chambers. Electricity cost savings can thus be expected from each pumping chamber.

4.3 Implementing the MCU optimisation method

In this section, the MCUs utilised in Mine X will be investigated, characterised and optimised. First, the relevant operational parameters are measured using the given template sheet in Appendix B. Hereafter, the KPIs are calculated and summarised, again using the applicable sheet in Appendix B. Optimisation strategies are then selected based on the KPIs and implemented.

4.3.1 Characterising the MCU and selecting optimisation strategies

The MCU optimisation method is commenced by characterising the MCUs. This consists of measuring the relevant operation parameters and calculating the KPIs. The MCUs in Mine X were investigated and characterised throughout February 2017. Upon inspection, it was found that Mine X utilises 32 MCUs on the mining levels. Table 4-1 shows a summary of the number of MCUs used on each of these levels. It is clear that more MCUs are used on the deeper levels due to increased temperatures associated therewith.

Table 4-1: Number of MCUs per level used in Mine X before optimisation

Level	Number of MCUs
102L	1
105L	8
109L	12
113L	11
Total	32

A detailed summary of the exact position of each MCU before optimisation is given in Table D - 1 in Appendix D. Each of the MCUs were measured according to the given template in Appendix B. Several MCUs were found to be negatively contributing to mine cooling. A summary of some of the measurement results is given in Table 4-2 and the complete results list is available in Table E - 1 to Table E - 3 attached in Appendix E. A layout of each of the four mining levels is also available in Figure C-1 to Figure C-4 in Appendix C and should provide a clear understanding of the position of each MCU.

Referring to Table 4-2, the MCU measurements were done according to the template developed in Chapter 3, and it is already clear that some of these MCUs are not contributing to mine cooling. For example, the MCU at 102L X/C 18 is not operational but is still consuming water. This means all its water consumption is wasted and it should either be switched on and tested or be removed. No measurements are necessary in this case. The MCU at 105L development east is situated in a very hot environment. From the temperature drop, it is clear that this MCU is positively contributing to mine cooling, but exact performance still needs to be established. The complete MCU measurement results can be found in Table E – 1 to Table E – 3 attached in Appendix E.

Table 4-2: Extract of MCU measurement results

Position	**102L X/C 18**	**105L Development East**	**105L X/C 20**	**105L X/C 24**
Design cooling duty [kW]	300	500	300	300
Wet-bulb temperature IN [°C]	NA	30	30	23
Dry-bulb temperature IN [°C]	NA	33	34	26
Wet-bulb temperature OUT [°C]	NA	27	30	24
Dry-bulb temperature OUT [°C]	NA	28	32	26
Air pressure [kPa]	NA	114	114	114
Inlet duct area [m²]	NA	0.261	0.261	0.261
Air speed [m/s]	NA	20	14	14
Notes	MCU fan running but water closed	Development end, hot		

The MCU measurements can now be used to calculate the KPIs, from which an optimisation strategy can be selected and implemented. A complete results list of all the calculations for the Mine X MCUs and the associated recommended optimisation strategies can be found in Table E - 4 to Table E - 6 in Appendix E. The KPIs, which were calculated for the MCUs in Table 4-2, are shown in Table 4-3. The KPIs were calculated according to the template developed in Chapter 3. It was also said that enthalpy and air pressure is ideally calculated using software, and for this study a spreadsheet macro was used.

Table 4-3: MCU KPI calculation results

Position	Humidity ratio	Efficiency [%]	Recommendation
102L X/C 18	NA	NA	Remove
105L Development East	0.90	17.18	No action required
105L X/C 20	1.00	-0.17	Remove, inefficient
105L X/C 24	1.04	-5.80	Remove, inefficient
105L X/C 37	NA	NA	Remove
105L X/C 38	NA	NA	Remove
105L X/C 39	NA	NA	Remove
105L X/C 41	0.96	5.10	Repair or Replace
105L X/C 43	NA	NA	Repair or Replace
109L Development East	0.95	11.24	No action required
109L X/C 26	1.00	-0.16	Remove, inefficient
109L X/C 26 RAW	NA	NA	Remove
109L X/C 27	1.13	-18.17	Remove, inefficient
109L X/C 28	NA	NA	Remove
109L X/C 34	0.92	12.82	Remove, not required
109L X/C 35	0.96	6.38	Remove, not required
109L X/C 36	0.93	10.71	No action required
109L X/C 37	NA	NA	Remove

109L X/C 38	1.00	-0.18	Remove, inefficient
109L X/C 39	1.00	-0.26	Repair or Replace
109L X/C 41	1.00	-0.37	Repair or Replace
113L Development East	0.93	16.84	Repair
113L X/C 30S	1.08	-13.85	Remove
113L X/C 30S	NA	NA	Remove
113L X/C 30N	0.87	29.30	No action required
113L X/C 31N	1.13	-21.14	Remove
113L X/C 31S	NA	NA	Remove
113L X/C 33	1.08	-14.72	Remove
113L X/C 34	NA	NA	Remove
113L X/C 37	0.96	5.15	No action required
113L X/C 38	0.94	11.13	No action required
113L X/C 41	NA	NA	Remove

Referring to Table 4-3, the optimisation strategy per MCU can now be recommended based on the calculated KPIs. The MCU at 102L X/C 18 should be removed, as it is needlessly consuming water. In contrast, the MCU at 105L Development East requires no action. It has a humidity ratio of less than one and, although its efficiency is relatively low, it is required in its position as it is in a hot environment. The MCU at 105L X/C 20 has a humidity ratio of one, but its efficiency shows it is not contributing to mine cooling and as it is not absolutely required in its position, it should be removed. The same holds for the MCU at 105L X/C 24.

4.3.2 Implementing optimisation strategies

The recommended optimisation strategies were handed to the responsible Mine X personnel for implementation. A total of twenty-one MCUs were recommended for removal, with six to be either repaired or replaced, and only five not requiring urgent intervention. Mine X personnel removed the suggested twenty-one MCUs. A list of the MCUs removed can be found in Table D - 2 in Appendix D. A total of eleven MCUs still remain and their locations are summarised in Table 4-4. Level 102 is not utilising MCUs anymore, however the deeper levels still require their use in some critical positions.

Table 4-4: Number of MCUs per level used in Mine X before and after optimisation

Level	Number of MCUs before optimisation	Number of MCUs after optimisation
102L	1	0
105L	8	3
109L	12	4
113L	11	4
Total	**32**	**11**

Of the remaining eleven MCUs, six were elected for replacement or repair. Mine X personnel will determine their ability to repair or replace these MCUs and proceed to do so when the resources are available. The MCUs in Table 4-4 will therefore have to be measured again to ensure these MCUs are optimised. At the time of writing this document, these MCUs have not been optimised and are still pending replacement or repair. Regardless, the impact of the MCUs that were removed can now be quantified.

4.4 Quantification of results

In this section, the results of implementing the MCU optimisation method on Mine X and the subsequent removal of twenty-one MCUs will be quantified and discussed. First, an appropriate baseline is developed to ensure a pertinent reference point and eliminate analytical errors or the influence of external factors. The decrease in water flow into, and out of, the boundary is then analysed. The impact of implementing the various MCU optimisation strategies on ventilation temperatures is then discussed, followed by an electricity cost saving analysis. The results are verified through third party audit outcomes and validated using mine production data.

4.4.1 Developing the baseline period

In order to develop a representing baseline, a baseline period first needs to be established. The timeline in which the MCU optimisation method was implemented on Mine X is shown schematically in Figure 4-3.

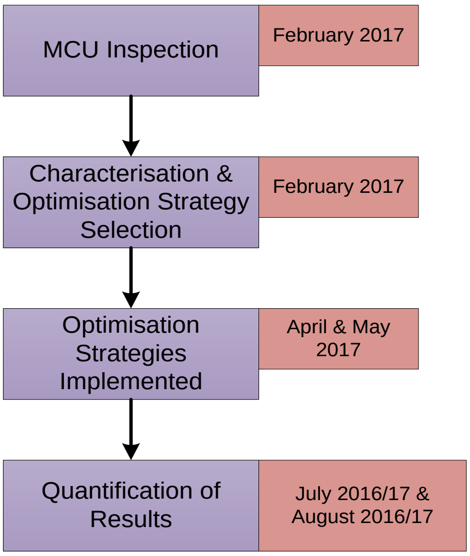

Figure 4-3: Timeline of MCU optimisation method implementation

The MCU inspection, characterisation and optimisation strategy selection was done in February 2017. Mine X experienced increasing labour unrest and industrial action in April 2017, during which time it was decided to extend the maintenance shutdown period from end of April 2017 to middle May 2017. The optimisation strategies were therefore implemented, and the twenty-one MCUs removed, throughout the course of May 2017.

As a result of the decrease in production throughout April and May 2017 due to the industrial action, production increased sharply in June 2017 to compensate for Mine X’s losses. June

2017 can therefore not be used as a normal operating month. This means the MCU results will have to be quantified from July 2017 onwards. Keeping in mind that mining is by nature very dynamic, it is best to limit the results quantification to two months after implementation. This eliminates external factors, such as a changing environment (winter to spring), production variations, and further labour issues. **The baseline period for the results quantification can therefore only be July 2016 to August 2016**. This means the impact of MCU optimisation will be quantified by referencing data for July and August 2017 to July and August 2016. Data acquisition will be discussed individually.

4.4.2 Service delivery – decreased water usage

As mentioned, any change in water demand will be evident from the 92L chill dam and any change in water pumped, will be evident from the 115L hot dam. The results are limited to these two systems so as to omit leaks and erratic usage patterns on other non-mining levels. The effect of removing the twenty-one MCUs on each of these systems within the boundary can now be elaborated upon.

92L chill dam outlet flow

The entire mining block of Mine X is supplied with water from 92L chill dam. Mine X uses its Supervisory Control and Data Acquisition (SCADA) system to log measurements of its own flow meters wherever possible. This data can be used to determine the outlet water flow performance of 92L chill dam. Figure 4-4 shows the total water demand from the 92L outlet in megalitres for the baseline period, comparing July 2016 to July 2017 and August 2016 to August 2017.

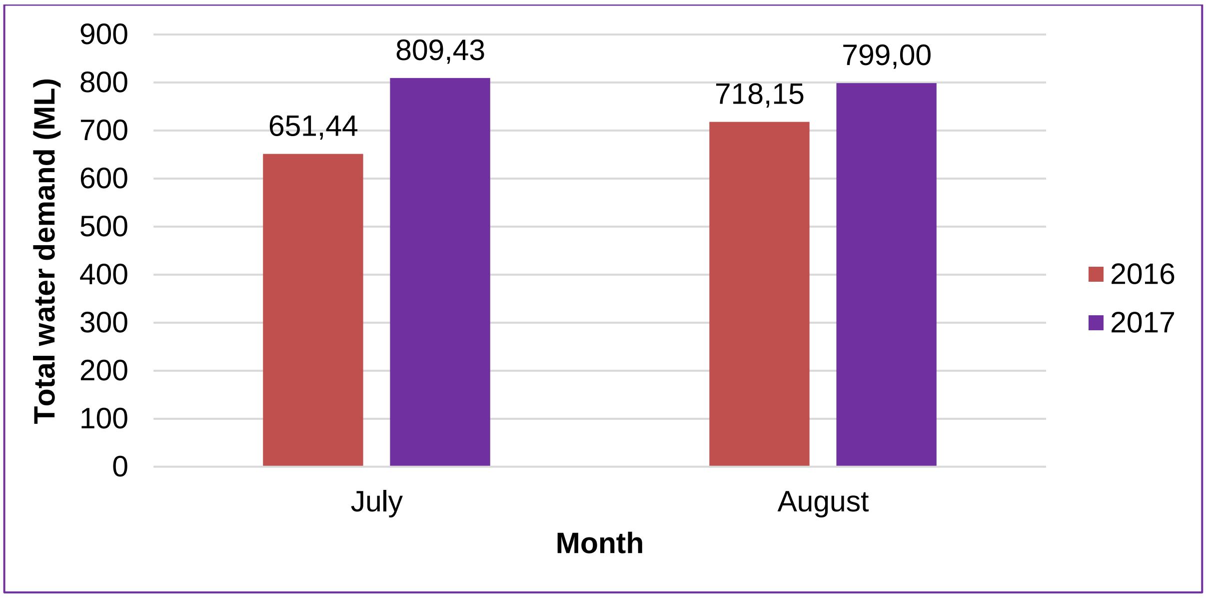

Figure 4-4: 92L chill dam total outlet water demand

Referring to Figure 4-4, an increase in water demand from the 92L chill damn can be seen. An increase in water demand between July 2016 vs July 2017 of more than 50ML is evident, while an increase of more than 80 ML between August 2016 and August 2017 is apparent. This is contradictory to what one would expect upon the removal of the twenty-one MCUs, as less water should be consumed by the mining block.

This discrepancy is the result of reconfiguring the outlet of the 75L chill dam, so it only supplies water to the 92L chill dam and not to the less productive levels of Mine X. Referring to Figure 4-1, 92L chill dam was then reconfigured so it supplies all the levels from 95L onwards with chilled water. The reason for this is mainly to reduce water pressure on less important levels, decreasing maintenance on piping and valves. This came into effect during the extended April 2017 maintenance shutdown. The outlet water flow from 92L chill dam can therefore not be used to successfully quantify the impact of the MCU optimisation.

115L hot dam outlet flow

As a result of the reconfiguration of the 92L chill dam outlet, the water pumped from 115L will have to be used to quantify the MCU optimisation impact. As mentioned, all of the water consumed by the mining block is pumped from 115L. The SCADA of Mine X logs the water flow out of 115L dam. The data can now be used to determine the change in water consumption after optimisation of the MCUs. Figure 4-5 shows the total water pumped from 115L in megalitres for the baseline period.

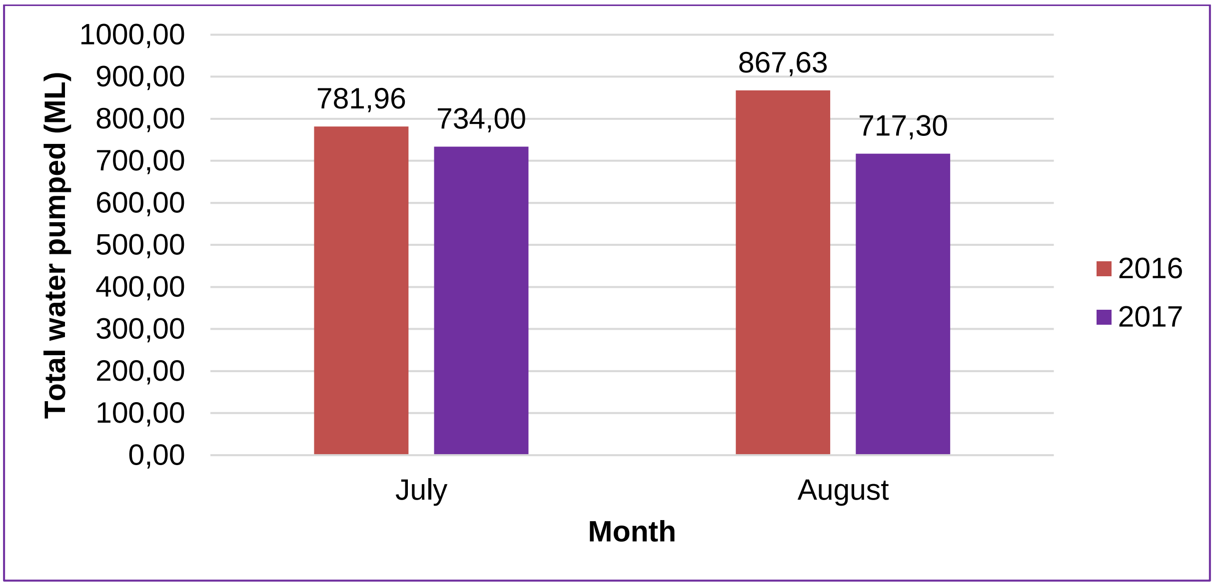

Figure 4-5: Total volume of water pumped from 115L hot dam

Figure 4-5 does show a decrease in water pumped from the 115L hot dam, not only when comparing the same month in 2016 and 2017, but also when comparing August 2017 to July

2017. The outlet water flow from 115L hot dam was reduced by over 45 ML between July 2016 and July 2017, while a reduction of more than 145 ML can be seen between August 2016 and August 2017. Table 4-5 shows the reduction in water pumped from the 115L hot dam of Mine X.

Table 4-5: Results of MCU optimisation on pumping from 115L at Mine X

	Month	2016	2017	Reduction
Average flow [l/s]	July	301.68	283.18	18.50
	August	323.94	276.73	47.20
Total flow [ML]	July	781.96	734.00	47.96
	August	867.63	717.30	150.34

From Table 4-5, the optimisation of the MCUs at Mine X resulted in a significant reduction of water pumped from 115L hot dam. The average flow decreased by more than 18 l/s for July 2016 to 2017, whilst a decrease of more than 150 l/s is evident between August 2016 and 2017. The reduction from July 2016 to July 2017 is less than that of August 2016 to August 2017. The reason for which is a decreased need for cooling in July due to it usually being a colder winter month. The primary and secondary cooling systems would provide sufficient cooling, and a lower auto-compression temperature increase can be expected as a result of lower surface intake temperatures.

The reduced water flow from 115L holds several positive points for Mine X:

- A decrease in pump wear as a result of decreased water volumes.
- The possibility of utilising the extra water capacity for improved cooling through primary or secondary cooling systems.
- Improved electrical load management due to reduced pump running times.
- Electricity cost savings as a result of less water cascade pumped to surface.

For this study, it was assumed Mine X would continue to optimise the remaining MCUs and opt for electricity cost savings rather than utilising more water for cooling. The electricity cost saving will be discussed in the next section.

4.4.3 Safe mining conditions – reduced ventilation temperatures

Optimal use of MCUs should always ensure safe underground working conditions, and this is the most important consideration of all. Some of the MCUs at Mine X were negatively contributing to underground cooling. It stands to reason that their repair, replacement or removal can therefore only positively contribute to the ventilation temperatures at Mine X.

The improvements of ventilation air temperatures, specifically the wet-bulb temperature as its importance has been well-established, is given in Table 4-6. It contains the position of the MCU and the implemented optimisation strategy, as well as the wet-bulb temperature before and after optimisation.

Table 4-6: Ventilation temperature improvement at Mine X

Position	Optimisation strategy implemented	Wet-bulb temperature before optimisation [℃]	Wet-bulb temperature after optimisation [℃]	Change in wet-bulb temperature [℃]
105L X/C 24	Removed	24	23	1
109L X/C 27	Removed	26	23	3
113L X/C 30S	Removed	26	24	2
113L X/C 31N	Removed	27	24	3
113L X/C 33	Removed	28	26	2

A substantial improvement in wet-bulb temperatures after removal of the MCUs can be seen when referring to Table 4-6. After optimisation, 109L X/C 27 and 113L X/C 31N experienced a significant 3℃ decrease in wet-bulb temperature. These MCUs all negatively contributed to cooling in their respective positions, and upon implementation of the elected optimisation strategy, a definite improvement in wet-bulb temperature can be seen.

The optimisation strategy for the MCUs in Table 4-6 was removal. As was mentioned, at the time of completing this document, Mine X is yet to repair/replace the applicable MCUs. No data is available regarding the effect of these strategies on the ventilation temperatures. Further improvement in ventilation temperatures is therefore possible after full implementation of the elected optimisation strategies of all MCUs.

4.4.4 Operating costs - electricity cost savings

The electricity cost saving as a result of the reduced volume of water pumped from 115L hot dam can now be calculated. Due to cascade return pumping to surface using all five pumping chambers, the electricity cost saving for each chamber needs to be calculated. This will be done for both July 2017 and August 2017.

Mine X contracted an external company to perform monthly audits on all of its pumps, providing valuable performance data such as pump electricity usage, electricity cost and pumping volumes. The company also determines pump efficiency, wear rates and general performance. The data from these audits is used to calculate the electricity cost savings of the Mine X dewatering pumps, the results of which is summarised in Table 4-7 for July 2017 and Table 4-8 for August 2017. The minimum electricity usage per pump chamber is given, as well as an average electricity cost. The average cost per megalitre of water is then calculated, after which the electricity cost savings for the total reduction in water volume can be determined.

Table 4-7: Electricity cost saving calculations for July 2017

Pumping chamber	Minimum pump chamber electricity usage [kWh/ML]	Average electricity cost [R/kWh]	Average cost of volume pumped [R/ML]	Electricity cost for 47.96 ML reduction
29L	2553.00	1.02	2593.41	R124 390.38
52L	2326.00	1.01	2355.93	R113 000.03
75L	2472.45	1.01	2493.20	R119 584.16
100L	2808.00	1.01	2829.50	R135 714.24
115L	1813.00	1.01	1839.15	R88 213.35
Total				**R580 902.15**

The total electricity cost saving for each pumping chamber for July 2017 is given in the rightmost column of Table 4-7. A total electricity cost saving of more than R580 000 for July 2017 was realised as a result of the reduced cascade pumping of 47,96 ML due to the MCU optimisation.

The results of calculating the electricity cost savings for August 2017 is given in Table 4-8. A much more substantial total electricity cost saving of more than R1,8 million was achieved as a result of the greater reduction in pumped water volume.

Table 4-8: Electricity cost savings calculations for August 2017

Pumping chamber	Minimum pump electricity usage [kWh/ML]	Average electricity cost [R/kWh]	Average cost of volume pumped [R/ML]	Electricity cost for 150.34 ML reduction
29L	2553.00	1.07	2725.59	R409 754.55
52L	2326.00	1.07	2499.62	R375 781.78
75L	2472.45	1.04	2573.73	R386 923.70
100L	2808.00	1.01	2829.50	R425 374.71
115L	1813.00	1.07	1938.27	R291 390.71
Total				**R1 889 225.45**

It should be noted that the minimum pump chamber electricity usage represents the lowest electricity consumption of the available pumps specific to that pumping chamber. In other words, the other pumps on that pumping chamber consume more electricity (kWh/ML). However, for the purpose of this study calculating the electricity cost savings based on the minimum pump chamber electricity usage is sufficient.

A total of more than R2,4 million in electricity cost savings was therefore achieved for July and August 2017. Further savings can be realised by continuously re-implementing the MCU optimisation method. Savings can also be expected for the remaining months of 2017; however, these lie outside the baseline period and will not be discussed here.

4.5 Verification, validation and normalisation of results

The reduction in water pumped from 115L at Mine X needs to be verified and validated. The verification process will use the data gathered by the external company contracted by Mine X to complete monthly pump performance audits. The results of the implementation of the MCU optimisation method will then be validated by using mine production data. This will attempt to assess the impact of MCU optimisation on labour performance and mine production. Through verification and validation, the importance of the MCU method can be established beyond doubt.

4.5.1 Verification – external audits

The external company contracted by Mine X to complete monthly pump performance audits include a water volume analysis in their assessment. They use pump running hours and the results of their performance audits to determine the monthly pumped water volume. The data can then be used to verify the results of the MCU optimisation method such as given in the previous section. Figure 4-6 shows the water volume pumped from 115L hot dam according to the external company for the months of July and August of 2016 and 2017.

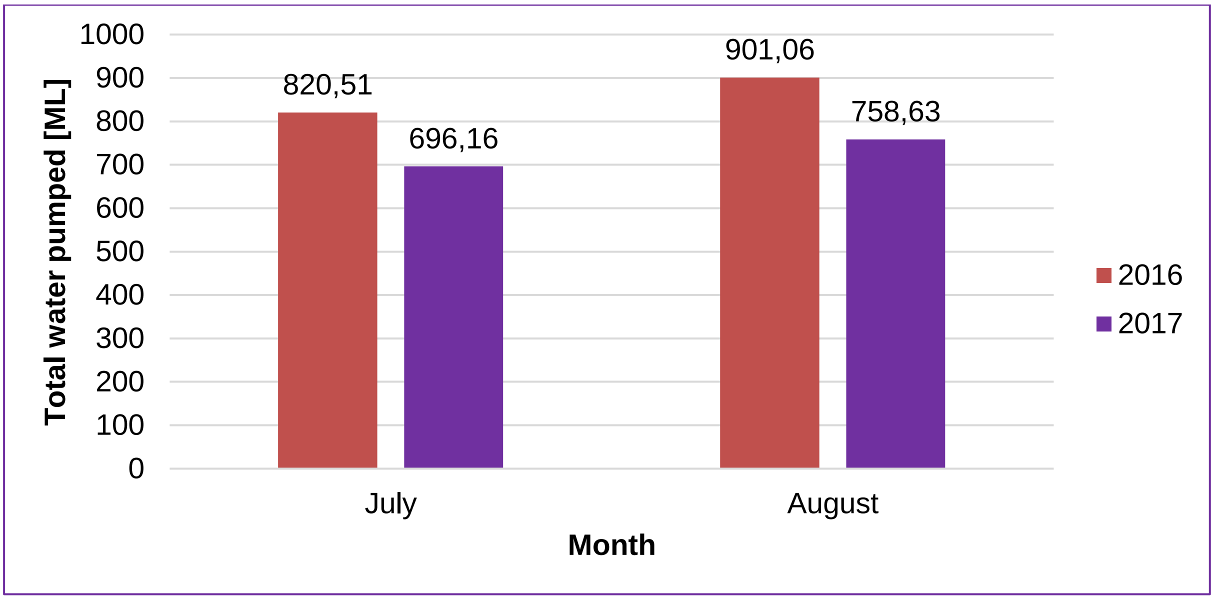

Figure 4-6: Total water pumped from 115L hot dam according to external audit

It is therefore clear from Figure 4-6 that the external company also notes a reduction in the water volume pumped from 115L hot dam when comparing the same month in 2016 and 2017. The results from the external company does however differ from that of Mine X. Table 4-9 shows the data of total water volume pumped from 115L hot dam for July and August 2016/7 obtained from Mine X and the external company, respectively. The difference between these values is calculated in the rightmost column.

Table 4-9: Accuracy analysis of Mine X data for total water pumped from 115L

	Mine X data [ML]	External company data [ML]	Difference [%]
Jul-16	781.96	820.51	-5%
Aug-16	867.63	901.06	-4%
Jul-17	734.00	696.16	5%
Aug-17	717.30	758.63	-6%

From Table 4-9 it becomes clear that the external company tends to log a greater volume of water pumped from 115L than Mine X, except for the month of July 2017. However, the largest difference is just -6% for August 2017. This is an acceptable error margin, as an error of ± 5% results in an adjustment to the electricity cost saving in August 2017 of just under R95000, which is negligible. The data from the external company therefore corroborates and verifies the results of the MCU optimisation method execution.

4.5.2 Validation – production data

The importance of the wet-bulb temperature on employee health and mine production has been well established in Chapter 3. Part of the results of implementing the MCU optimisation method is a change in ventilation temperatures at the MCU position, which was discussed in the previous section. In addition, a decrease in mine production will also lead to a decrease in mine water usage as a result of a reduction in water required for cooling and other mining activities.

In order to ensure that the implementation of the MCU optimisation method did not negatively impact mining activities at Mine X, production data will be used to validate the results discussed in the previous section. The total reef material produced by Mine X for the baseline period is depicted in Figure 4-7. The reef material is ore which contains gold and excludes any waste rock which is cleaned for development or advancing the mining area.

The total ore trammed on Mine X for the baseline period is given in Figure 4-8. Tramming ore includes rock from development ends or advancing the mining area. The ore trammed at Mine X can thus also be used to validate the results of implementing the MCU optimisation method, as development ends and advancing the mining area are associated with hot temperatures and therefore increased water usage and cooling requirements.

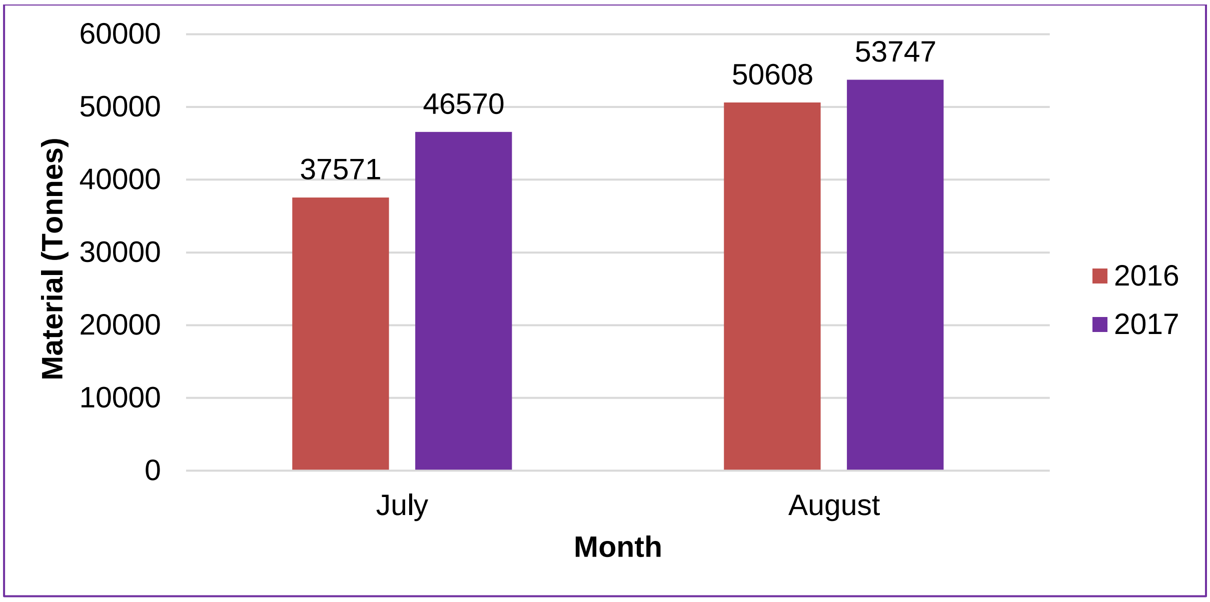

Figure 4-7: Total reef material produced by Mine X

From Figure 4-7 an increase in reef material production is evident. The same is true when considering the total ore trammed at Mine X as shown in Figure 4-8. An increase in the total ore trammed for the baseline period is clear. If hotter temperatures were experienced at Mine X, a decrease in production would have been seen. The reduction in water usage is further also not as a result of a decrease in production. It is therefore safe to conclude that implementing the MCU optimisation method did not negatively affect the production at Mine X.

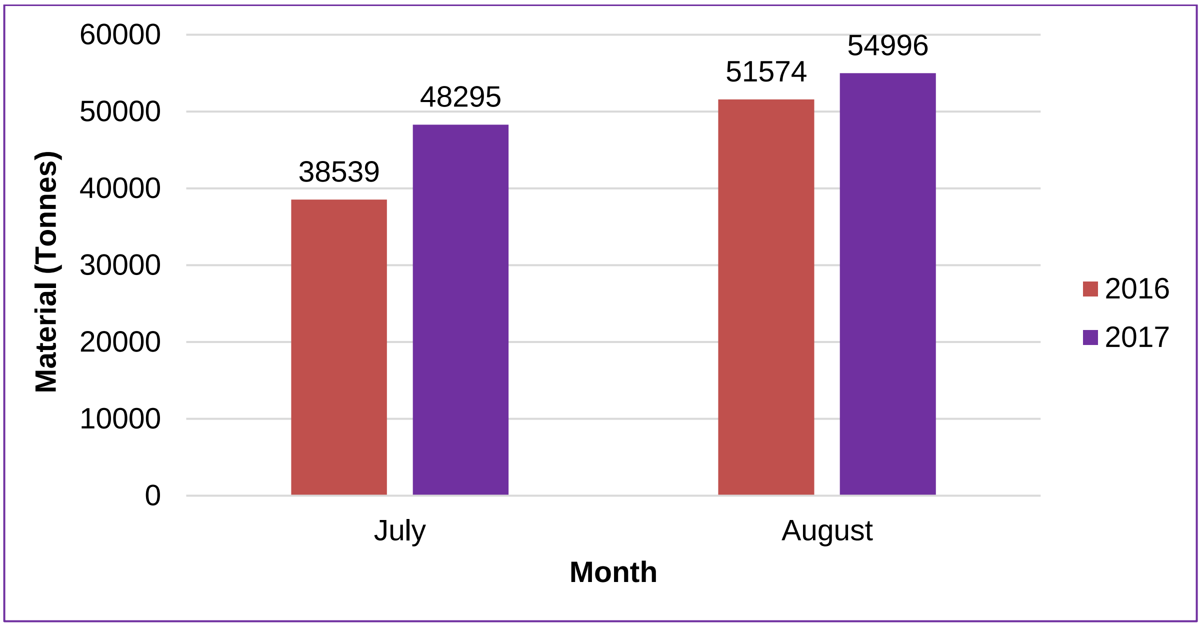

Figure 4-8: Total ore trammed at Mine X

4.5.3 Normalising the reduction in pumped water volumes

From Figure 4-7 and Figure 4-8 an increase in production at Mine X is evident, despite the reduction in water volumes pumped from 115L. From this it was concluded that the removal of the MCUs did not negatively impact employee health at Mine X, nor affect production volumes.

However, a greater reduction in water volume pumped from 115L would have been evident, should production in 2017 have equalled that of 2016. This effectively means a lower consumption of water per ton of ore was achieved in 2017. Shown in Figure 4-9 is the megalitres of water pumped from 115L per ton of ore trammed for the baseline period.

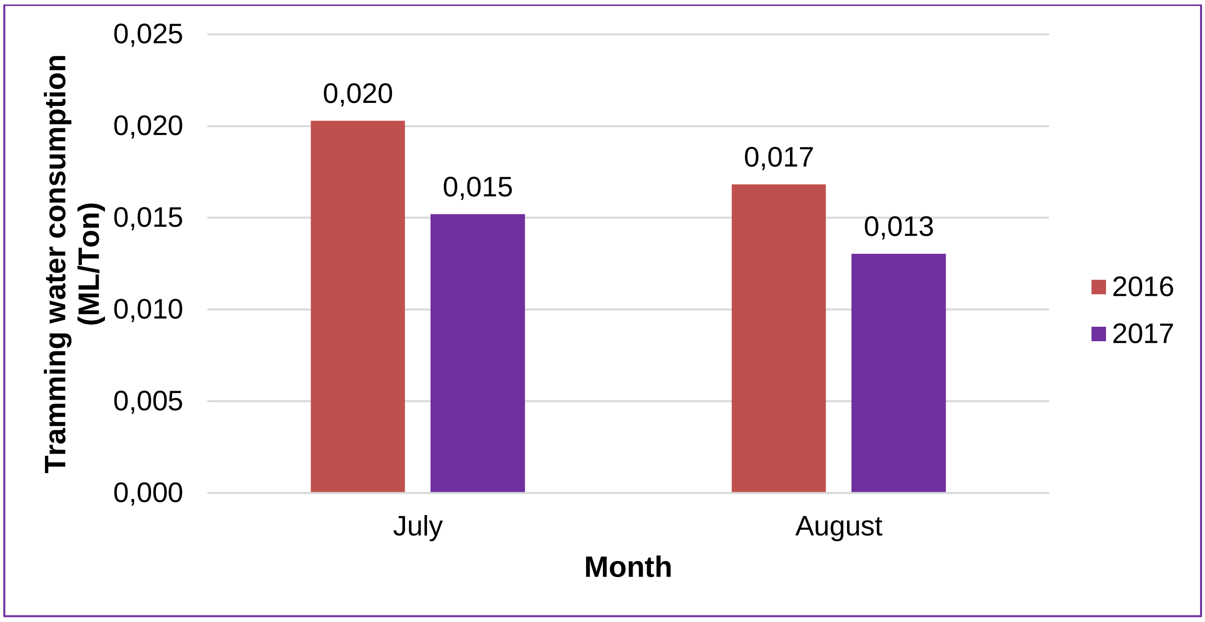

Figure 4-9: Megalitres of water consumed per ton of ore trammed

From Figure 4-9 a clear improvement in “efficiency” of production can be see, i.e. a lower volume of water consumed per ton of ore trammed. For July 2016 vs. July 2017 a reduction of 0.05ML per ton of ore trammed is evident, while a reduction of 0.04ML per ton of ore trammed is apparent for August 2016 vs. August 2017.

The reduction in water volume pumped from 115L can therefore be normalised according to the tonnes of ore trammed in 2016 to determine the impact of MCU optimisation without the influence of the production increase in 2017. Table 4-10 summarises and compares the average flow and reduction in water volume pumped from 115L with and without normalisation.

Table 4-10: Reduction in water pumped when normalised according to production

	July	August
Average flow 2016 [l/s]	781.96	867.63
Average flow 2017 [l/s]	733.99	717.29
Average flow 2017 normalised to 2016 tramming [l/s]	585.72	672.66
Reduction in flow [l/s]	47.96	150.33
Normalised reduction in flow [l/s]	196.23	194.96

From Table 4-10, a more significant impact on water pumped from 115L by optimising the MCUs at Mine X is evident. The normalised reduction in average flow is significantly greater. For July, an additional reduction in flow of more than 152l/s can be seen, while an additional 44l/s is evident for August.

However, what is of more significance is that the normalised reduction in flow for July and August is almost equal, i.e. almost 200l/s. This additionally verifies the results of the MCU optimisation at Mine X, as it eliminates the influence of the increase in production. Increased electricity cost savings at Mine X could therefore have been expected, should production in 2017 equalled that of 2016.

4.6 Conclusion

In this section it is determined if the methodology used in this study can be applied to other deep-level gold mines in South Africa, as well as the potential impact thereof. This is followed by a conclusion on the implementation of the MCU optimisation method on a case study.

4.6.1 Importance to other deep-level gold mines

The results of implementing the MCU optimisation method at Mine X confirms the importance of ensuring optimal functioning thereof. The same holds true for any deep-level gold mine, which utilises MCUs as part of its cooling and ventilation strategy. The five deepest mines in the world are located in South Africa [45], namely:

1. Mponeng gold mine
2. TauTona gold mine
3. Savuka gold mine

4. Driefontein gold mine
5. Kusasalethu gold mine

All of these mines are operating at depths of more than 3km, and as per the discussion in Chapter 2, will require extensive cooling and ventilation infrastructure and strategies to ensure safe and productive underground working conditions. It is therefore more than probable that these mines (and others besides) utilise tertiary cooling to compliment the primary and secondary cooling systems.

Mine X utilised 31 MCUs before optimisation and is operating at a depth of approximately 3km. It could therefore be assumed that the mines listed above utilise approximately the same amount of MCUs. When also assuming relatively the same water consumption and production, the total electricity cost savings across the five mines would exceed R9,5 million for the months of July and August. Moreover, the total reduction in average pumped water volumes would exceed 1000l/s. This will positively contribute to lessening the impact of AMD, reduce pumping maintenance costs and improve underground working temperatures.

The MCU optimisation method is generic and applicable to all mines utilising MCUs as part of their cooling strategy, including platinum mining. The method is simple to implement and uses inexpensive equipment. It can merely be adopted by any mine in the sector that uses MCUs and want to ensure their optimal performance.

There is a great need for efficient tertiary cooling, and tertiary type coolers will play an important role for mining in hot rock in the long term [46]. The MCU optimisation method was demonstrated to be a quick, efficient and accurate method for characterising the MCUs at a deep-level gold mine, electing and implementing optimisation strategies and determining the impact thereof. This method can also be used on other deep-level gold mines, and will result in better underground conditions, reduced operating costs and significant electricity cost savings.

4.6.2 Conclusion

This chapter discussed the implementation of the MCU optimisation method developed in Chapter 3 on an applicable case study. A mine, referred to as Mine X, in the Carletonville area in South Africa, is used for the case study. The chapter opened with a short background on Mine X, followed by an overview on the major infrastructure as relevant to this study. The implementation of the MCU optimisation method was then discussed, which included measurements on the MCUs at Mine X, characterising their performance through the relevant

KPIs and electing optimisation strategies. The execution of these optimisation strategies is then deliberated.

The results of implementing the optimisation strategies were discussed. First, an applicable baseline period was developed to ensure an accurate reference point. Hereafter, the reduction in water usage is elaborated upon. This is followed by a dialogue on the improvement in ventilation air temperatures. Finally, the reduced operating costs as a result of a reduction in return-water cascade-pumping is debated.

The reduction in water usage was verified using data from an external company contracted by Mine X to complete monthly pump performance investigations. The results of implementing the MCU investigation method were validated through using Mine X production data.

Lastly, the results were normalised through using production data and additionally verified. The importance of the MCU optimisation method to other deep-level gold mines is South Africa was then elaborated upon to establish industry significance.

5 Conclusion

[13]

The key findings are summarised, and recommendations are made for further research.

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[13] *HJ van Staden, Personal photograph. “Hitachi Chiller installed underground”, Carletonville, 2017.*

5.1 Preamble

This chapter provides an overview on the study and highlights the key points. It opens with a summary of the study, including an overview on the MCU optimisation method and the results of implementation on a case study. Recommendations for future work are then given to ensure continued MCU optimisation on deep-level gold mines.

5.2 Study summary

The gold mining sector in South Africa remains a significant contributor to the country's economy, not only through GDP involvement but also employment and the consumption of water and electricity. However, the sector is currently facing several unique challenges and optimisation is required to ensure productivity and continued economic viability.

Optimising the use of MCUs was identified as an opportunity to provide for continued mine productivity through improving service delivery, reducing operational costs and ensuring safe underground working conditions for mine employees. MCUs become inefficient as a result of harsh underground conditions, corrosion, incorrect placement and a general lack of maintenance. Inefficient MCUs lead to water wastage, increased electricity consumption and have a negative impact on underground ambient conditions such as temperature and humidity.

In order to ensure the optimal functioning of MCUs in a deep-level gold mine, the following objectives were formulated for this study:

- Develop an effective MCU performance investigation method
- Accurately determine the performance of these units and their contribution to mine cooling
- Develop and implement optimisation strategies in a real-world case study
- Quantify the impact of the optimisation strategies on service delivery and electricity costs to assess and ensure performance

With the aim of satisfying these objectives, Chapter 2 provided an overview on MCUs, their functioning, governing equations and shortcomings. Previous studies were then analysed to ensure work performed in this field of study is applied to the problem. Solutions to the limitations of MCUs were researched and critically analysed, and options pertaining to the optimal use of existing MCUs were found wanting.

A methodology for characterising the MCU was then constructed, which includes the development of KPIs and the measurements required to determine them. Strategies for optimising the MCUs were then discussed, as well as a method for how to quickly and accurately elect such a strategy for a relevant MCU.

This was then implemented on a case study. A mine in the Carletonville region of South Africa was used to determine the viability and impact of optimising existing MCUs. The elected optimisation strategies were implemented and resulted in 21 MCUs being removed. The consequences of which on service delivery, ventilation temperatures and reduced operating costs, were then discussed. These are summarised in Table 5-1 and Table 5-2.

Table 5-1: Reduction in pumped water volume and resultant electricity cost savings

Month	Reduction in total water pumped [ML]	Electricity cost saving [R]
July	47.96	R580 902.15
August	150.34	R1 889 225.45

Referring to Table 5-1, an improvement in service delivery manifested itself through a reduction in chilled water pumping of more than 47 ML for July 2017 and more than 150 ML for August 2017 when compared to the same month in 2016. This resulted in reduced operating costs due to decreased cascade-pumping of more than R580 000 for July 2017 and more than R1.8 million for August 2017. In addition, from Table 5-2 improvements in underground wet-bulb temperatures of between 1℃ and 3℃ were realised through MCU optimisation.

Table 5-2: Summary of improved ventilation temperatures

Position	Optimisation strategy implemented	Change in wet-bulb temperature [℃]
105L X/C 24	Removed	1
109L X/C 27	Removed	3
113L X/C 30S	Removed	2
113L X/C 31N	Removed	3
113L X/C 33	Removed	2

It is clear from Table 5-1 and Table 5-2 that the optimal use of MCUs in deep-level gold mining holds significant benefit. Not only does it contribute to improved service delivery and reduced operating costs, but also an improvement in underground ventilation temperatures. This will positively contribute to mine productivity, employee health and safety, and ensure continued economic feasibility.

It can be concluded that all the objectives of this study have been satisfied. The complete MCU optimisation method is given in Figure 5-1. It was used to accurately and effectively determine the performance of MCUs and their contribution to mine cooling in a real-world case study. Optimisation strategies were then elected and implemented, after which the impact of optimisation on service delivery, operating costs and underground working conditions were determined.

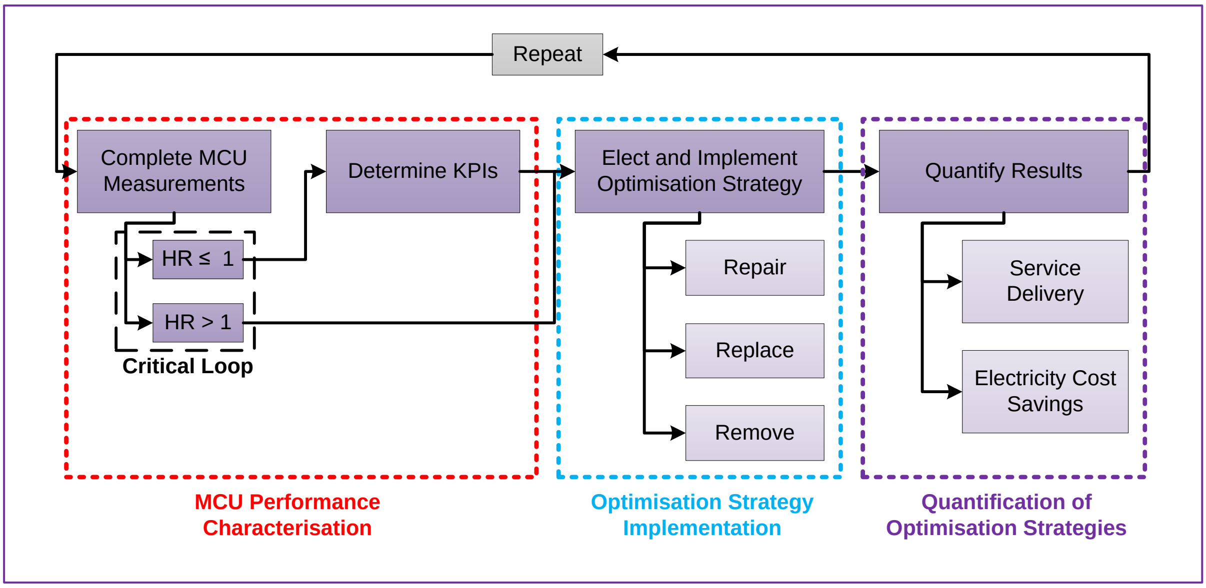

Figure 5-1: The MCU optimisation method

5.3 Recommendations for further research

The recommendations for further research are summarised as follows:

- The effects of MCU repair or replacement could not be determined for this study, as they were not implemented at the time of completion. It is therefore recommended that the impact of different optimisation strategies (repair & replace) on service delivery, cost savings and ventilation temperatures be established.
- As a result of seasonal variations and the dynamic nature of mining, a short time period (two months) was used in this study to evaluate the effectiveness of the solution .The use a longer baseline period to determine the continued impact of the MCU optimisation on service delivery, operating costs and ventilation air temperature could provide better results and further prove the MCU optimisation method as successful.

- As mentioned MCUs utilise fans of 15 – 75kW. Removal of the MCU therefore results in the removal of sizeable fan, which contributes to electricity cost savings. It is suggested that the electricity cost savings of the MCU fans that were removed be established, as this could further motivate the implementation of the MCU optimisation method.
- The impact of implementing the MCU optimisation method concerning employee performance, health and state of mind could not be determined in this study. Some further research can be conducted into establishing the psychological and physiological effects thereof, so to ensure employee productivity, safety and health.
- The MCU optimisation method was developed and tested in a deep-level gold mine, however it is most likely also applicable to deep platinum mines. Implementation of the MCU optimisation method on other mining sectors and its successes should be established.

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APPENDIX A: PSYCHOMETRICS

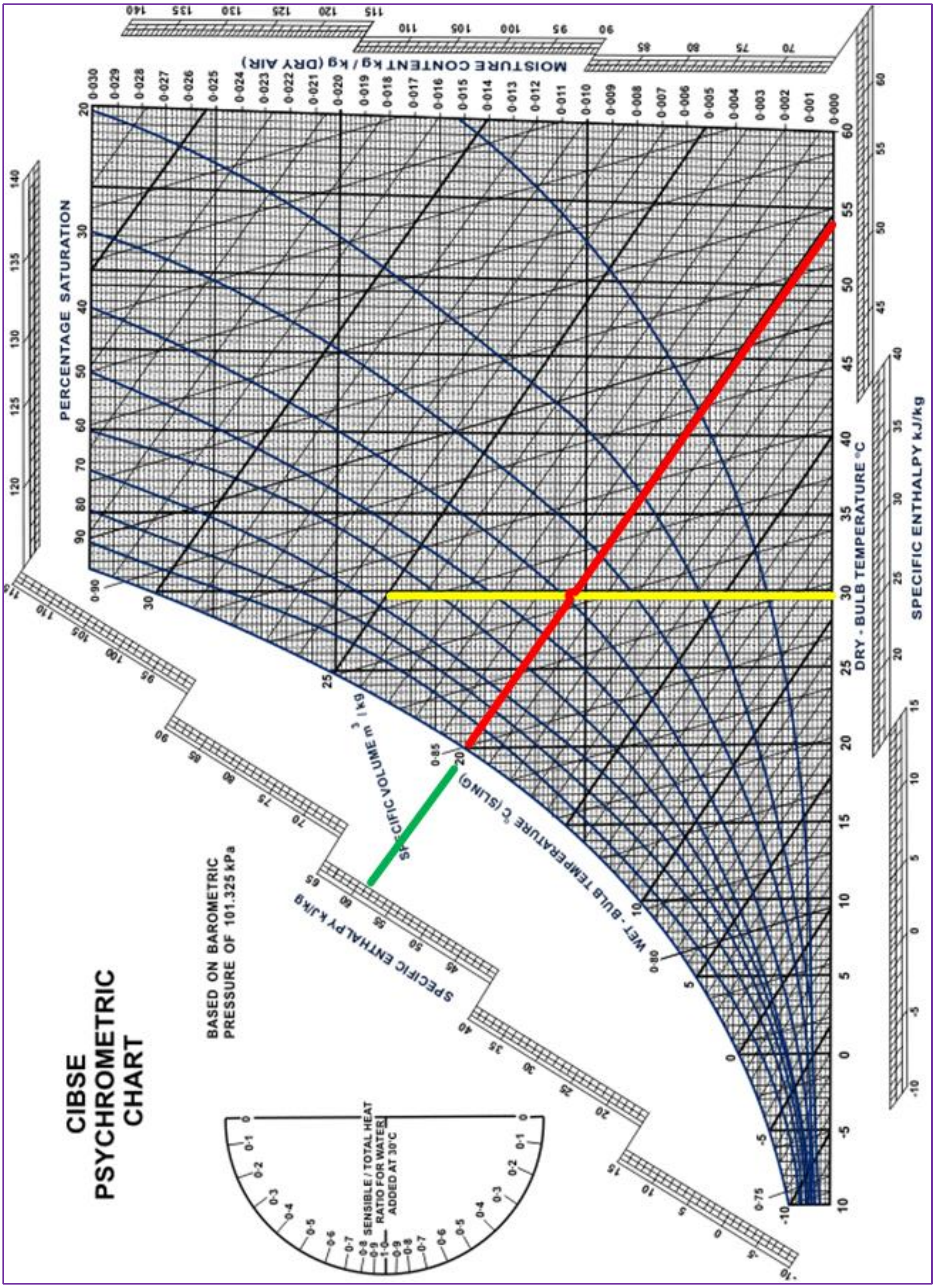

Figure A- 1: A psychrometric chart in SI units at sea-level (adapted from [47]**)**

APPENDIX B: MCU INSPECTION & CALCULATION

Table B- 1: Example of an MCU inspection sheet

Position							
Design cooling duty [kW]							
Wet-bulb temperature IN [°C]							
Dry-bulb temperature IN [°C]							
Wet-bulb temperature OUT [°C]							
Dry-bulb temperature OUT [°C]							
Air pressure [kPa]							
Inlet duct area [m²]							
Air speed [m/s]							
Notes							

Table B- 2: Example of an MCU calculation and recommendation sheet

Position					
Design cooling duty [kW]					
Humidity ratio					
Enthalpy difference [kJ/kg]					
Air mass flow [kg/s]					
Actual cooling duty [kW]					
Efficiency					
Recommendation					

APPENDIX C: MINING LEVEL LAYOUTS

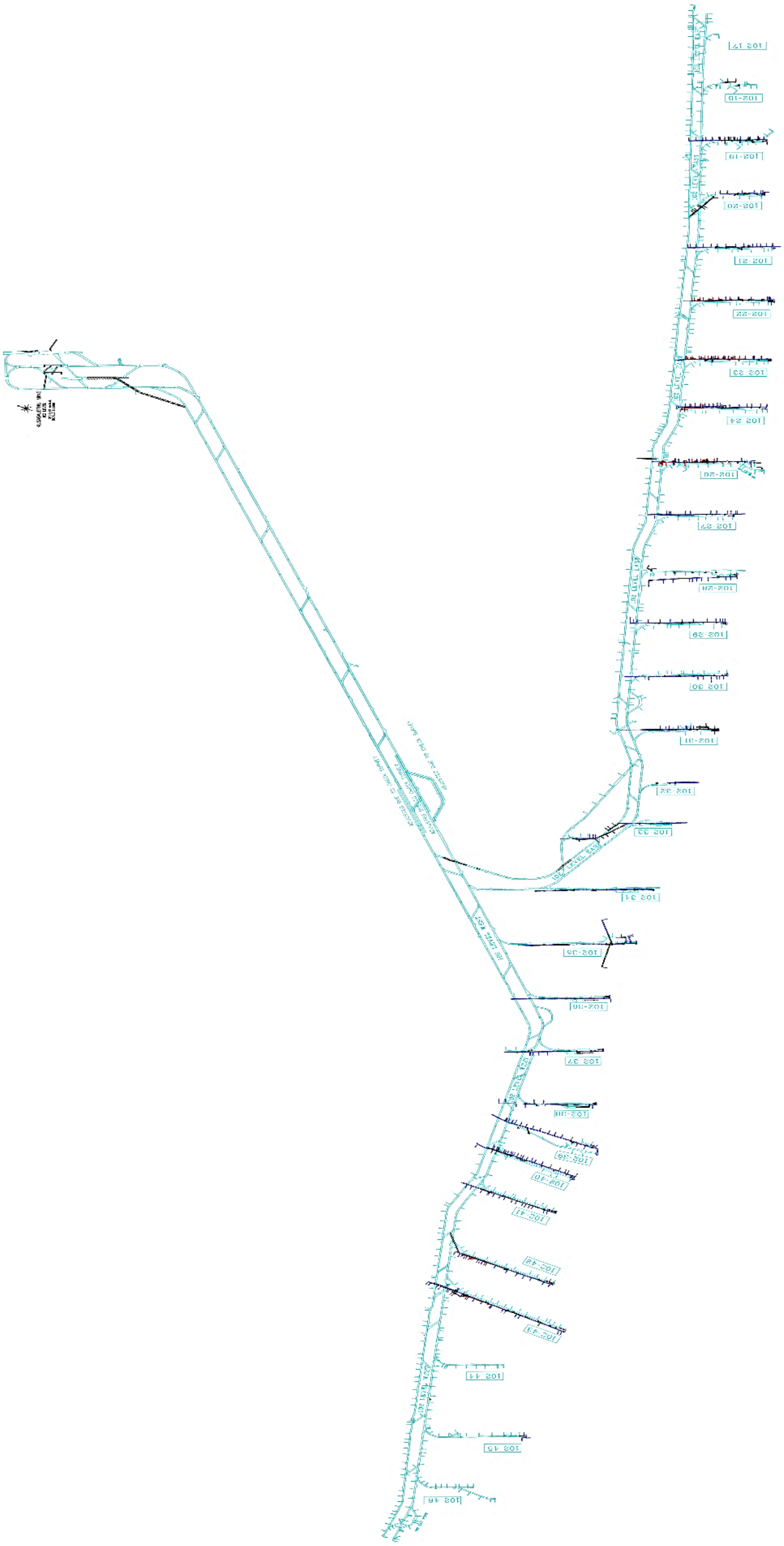

Figure C - 1: Layout of 102 level

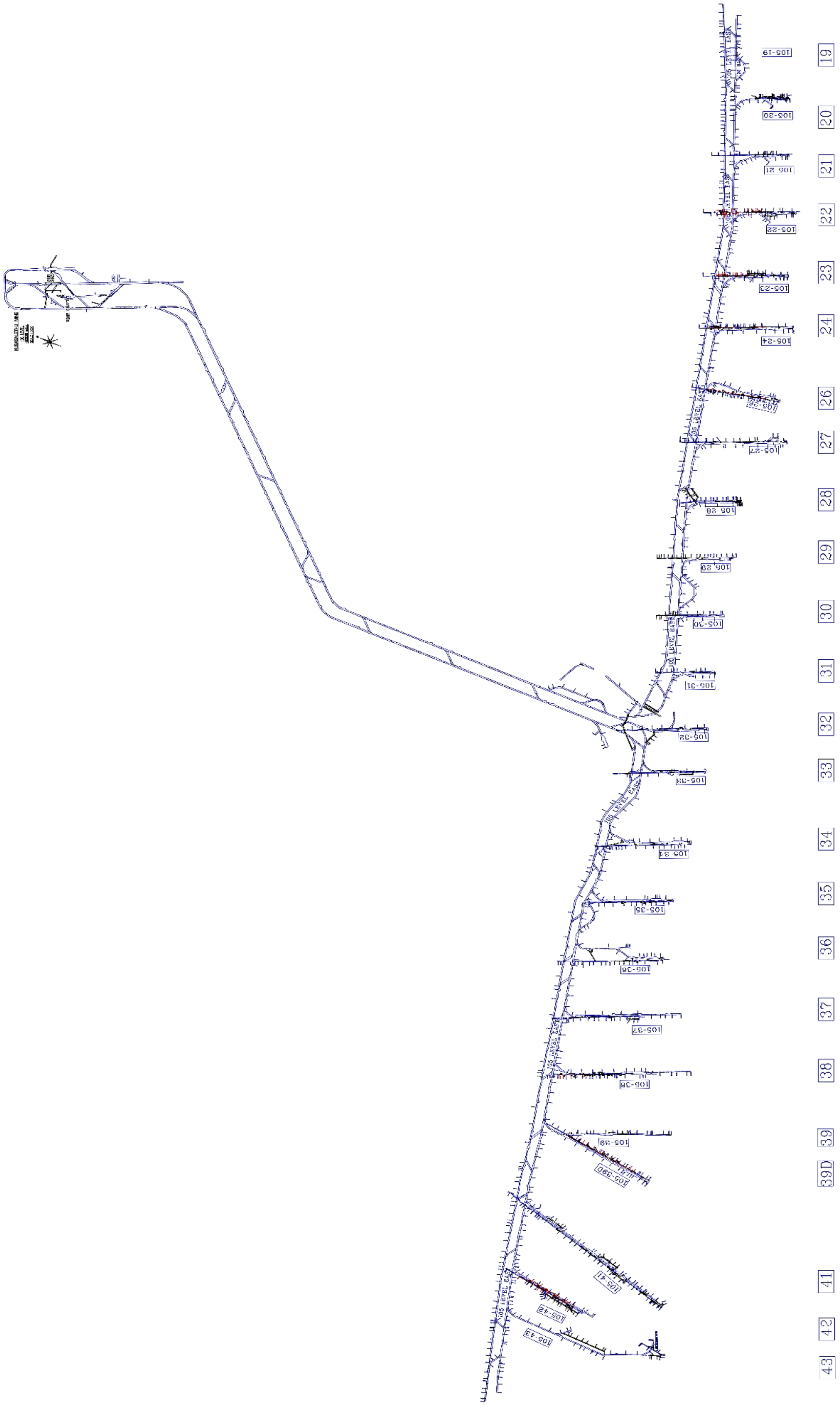

Figure C - 2: Layout of 105 level

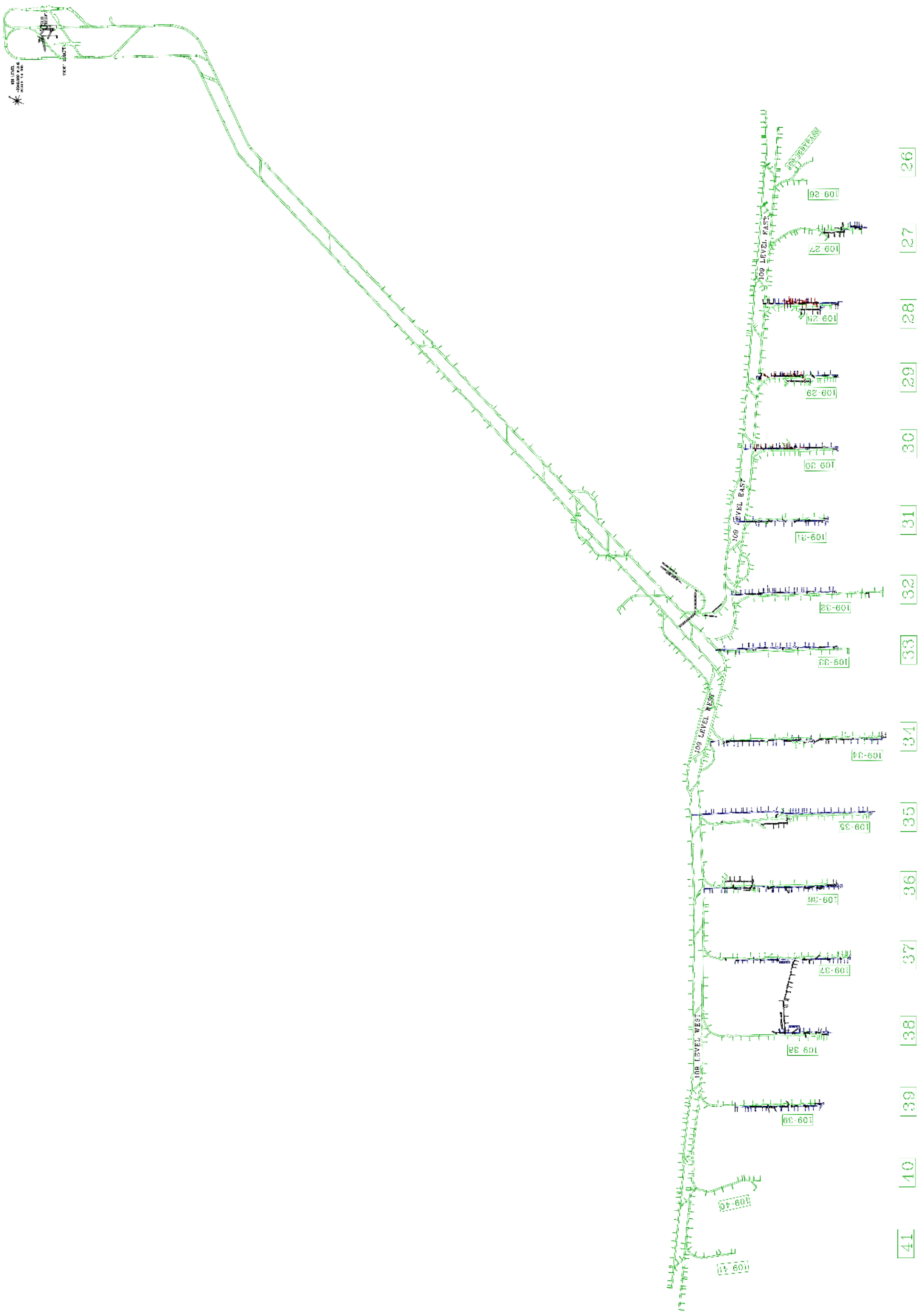

Figure C - 3: Layout of 109 level

Figure C - 4: Layout of 113 level

APPENDIX D: LIST OF MINE X MCUS

Table D - 1: Total Mine X MCUs before optimisation

Level	**Position**
102	X/C 18
105	Development East
105	X/C 20
105	X/C 24
105	X/C 37
105	X/C 38
105	X/C 39
105	X/C 41
105	X/C 43
109	Development East
109	X/C 26
109	X/C 26 RAW
109	X/C 27
109	X/C 28
109	X/C 34
109	X/C 35
109	X/C 36
109	X/C 37
109	X/C 38
109	X/C 39
109	X/C 41
113	Development East
113	X/C 30S
113	X/C 30S
113	X/C 30N
113	X/C 31N
113	X/C 31S
113	X/C 33
113	X/C 34
113	X/C 37
113	X/C 38
113	X/C 41
Total	**32**

Table D - 2: Total removed MCUs

Level	Position
102	X/C 18
105	X/C 20
105	X/C 24
105	X/C 37
105	X/C 38
105	X/C 39
109	X/C 26
109	X/C 26 RAW
109	X/C 27
109	X/C 28
109	X/C 34
109	X/C 36
109	X/C 39
109	X/C 41
113	X/C 30S
113	X/C 30S
113	X/C 30N
113	X/C 31N
113	X/C 31S
113	X/C 33
113	X/C 34
Total	**21**

APPENDIX E: MINE X MCU MEASUREMENTS & KPIS

Table E - 1: MCU measurements 102L - 105L

Position	102L X/C 18	105L Development East	105L X/C 20	105L X/C 24	105L X/C 37	105L X/C 38	105L X/C 39	105L X/C 41	105L X/C 43
Design cooling duty [kW]	300	500	300	300	NA	NA	NA	300	NA
Wet-bulb temperature IN [°C]	NA	30	30	23	NA	NA	NA	27	NA
Dry-bulb temperature IN [°C]	NA	33	34	26	NA	NA	NA	30	NA
Wet-bulb temperature OUT [°C]	NA	27	30	24	NA	NA	NA	26	NA
Dry-bulb temperature OUT [°C]	NA	28	32	26	NA	NA	NA	26	NA
Air pressure [kPa]	NA	114	114	114	NA	NA	NA	114	NA
Inlet duct area [m^2]	NA	0.261	0.261	0.261	NA	NA	NA	0.166	NA
Air speed [m/s]	NA	20	14	14	NA	NA	NA	18	NA
Notes	MCU fan running but water closed	Development end, hot.			Unable to measure due to heavy leakage	Unable to measure due to heavy leakage	Unable to measure due to heavy leakage		MCU not operational, consuming water

Table E - 2: MCU measurements 109L

Position	109L Development East	109L X/C 26	109L X/C 26 RAW	109L X/C 27	109L X/C 28	109L X/C 34	109L X/C 35	109L X/C 36	109L X/C 37	109L X/C 38	109L X/C 39	109L X/C 41
Design cooling duty [kW]	150	300	NA	300	NA	300	300	500	NA	300	300	300
Wet-bulb temperature IN [°C]	30	28	NA	23	NA	26	24	27	NA	27	30	31
Dry-bulb temperature IN [°C]	34	32	NA	27	NA	29	27	30	NA	32	34	37
Wet-bulb temperature OUT [°C]	28	28	NA	26	NA	24	23	25	NA	27	30	31
Dry-bulb temperature OUT [°C]	30	30	NA	27	NA	25	23	27	NA	29	31	33
Air pressure [kPa]	116	116	NA	116	NA	116	116	116	NA	116	116	116
Inlet duct area [m²]	0.166	0.261	NA	0.261	NA	0.261	0.261	0.261	NA	0.166	0.261	0.261
Air speed [m/s]	12	14	NA	14	NA	15	16	20	NA	17	14	15
Notes	Development end, hot		Unable to measure	Small leak	Unable to measure due to heavy leakage				Difficult to measure, large amount of ducting.			Very hot

Table E - 3: MCU measurements 113L

Position	113L Development East	113L X/C 30S	113L X/C 30S	113L X/C 30N	113L X/C 31N	113L X/C 31S	113L X/C 33	113L X/C 34	113L X/C 37	113L X/C 38	113L X/C 41
Design cooling duty [kW]	500	300	NA	300	300	NA	300	NA	500	200	NA
Wet-bulb temperature IN [°C]	28	24	NA	30	24	NA	26	NA	28	27	NA
Dry-bulb temperature IN [°C]	32	29	NA	34	30	NA	30	NA	30	31	NA
Wet-bulb temperature OUT [°C]	26	26	NA	26	27	NA	28	NA	27	25	NA
Dry-bulb temperature OUT [°C]	28	28	NA	27	28	NA	30	NA	28	30	NA
Air pressure [kPa]	171	171	NA	171	171	NA	171	NA	171	171	NA
Inlet duct area [m^2]	0.454	0.261	NA	0.261	0.261	NA	0.261	NA	0.261	0.261	NA
Air speed [m/s]	16	14	NA	14	14	NA	14	NA	17	10	NA
Notes	Development end, hot. Leak inside cooling car.	Heavy leakage	MCU not operational		Heavy leakage	MCU not operational, water still open	Heavy leakage	Unable to measure			MCU not operational

Table E - 4: MCU calculations results 102L - 105L

Position	102L X/C 18	105L Development East	105L X/C 20	105L X/C 24	105L X/C 37	105L X/C 38	105L X/C 39	105L X/C 41	105L X/C 43
Design cooling duty [kW]	300	500	300	300	NA	NA	NA	300	NA
Humidity ratio	NA	0.90	1.00	1.04	NA	NA	NA	0.96	NA
Enthalpy difference [kJ/kg]	NA	12.90	-0.11	-3.63	NA	NA	NA	3.95	NA
Air mass flow [kg/s]	NA	6.66	4.65	4.79	NA	NA	NA	3.87	NA
Actual cooling duty [kW]	NA	85.91	-0.50	-17.39	NA	NA	NA	15.29	NA
Efficiency	NA	17.18	-0.17	-5.80	NA	NA	NA	5.10	NA
Recommendation	Remove	No action required	Remove	Remove	Remove	Remove	Remove	Repair or Replace	Repair or Replace

Table E - 5: MCU calculations results 109L

Position	109L Development East	109L X/C 26	109L X/C 26 RAW	109L X/C 27	109L X/C 28	109L X/C 34	109L X/C 35	109L X/C 36	109L X/C 37	109L X/C 38	109L X/C 39	109L X/C 41
Design cooling duty [kW]	150	300	NA	300	NA	300	300	500	NA	300	300	300
Humidity ratio	0.95	1.00	NA	1.13	NA	0.92	0.96	0.93	NA	1.00	1.00	1.00
Enthalpy difference [kJ/kg]	6.50	-0.10	NA	-11.19	NA	7.43	3.43	7.79	NA	-0.14	-0.16	-0.22
Air mass flow [kg/s]	2.60	4.78	NA	4.87	NA	5.17	5.57	6.87	NA	3.70	4.74	5.03
Actual cooling duty [kW]	16.86	-0.48	NA	-54.50	NA	38.46	19.13	53.54	NA	-0.53	-0.77	-1.12
Efficiency	11.24	-0.16	NA	-18.17	NA	12.82	6.38	10.71	NA	-0.18	-0.26	-0.37
Recommendation	No action required	Remove	Remove	Remove	Remove	Remove	Remove	No action required	Remove	Remove	Repair or Replace	Repair or Replace

Table E - 6: MCU calculations results 113L

Position	113L Development East	113L X/C 30S	113L X/C 30S	113L X/C 30N	113L X/C 31N	113L X/C 31S	113L X/C 33	113L X/C 34	113L X/C 37	113L X/C 38	113L X/C 41
Design cooling duty [kW]	500	300	NA	300	300	NA	300	NA	500	200	NA
Humidity ratio	0.93	1.08	NA	0.87	1.13	NA	1.08	NA	0.96	0.94	NA
Enthalpy difference [kJ/kg]	5.98	-5.81	NA	12.53	-8.89	NA	-6.20	NA	2.98	4.39	NA
Air mass flow [kg/s]	14.07	7.15	NA	7.02	7.13	NA	7.12	NA	8.64	5.07	NA
Actual cooling duty [kW]	84.18	-41.54	NA	87.91	-63.43	NA	-44.15	NA	25.76	22.27	NA
Efficiency	16.84	-13.85	NA	29.30	-21.14	NA	-14.72	NA	5.15	11.13	NA
Recommendation	Repair	Remove	Remove	No action required	Remove	Remove	Remove	Remove	No action required	No action required	Remove