Automated dynamic control philosophy for sustainable energy savings on mine cooling systems

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

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DECLARATION OF AUTHENTICITY

My name is Jason Andrew Crawford (29901359) and I am currently studying towards the degree Master of Engineering in Mechanical Engineering at the Potchefstroom Campus of the North-West University. I hereby declare that this research study is solely my own unaided work and the relative sources of information have been acknowledged by means of a reference. Any sources unaccounted for should be communicated to me so that I can make the necessary alterations. This dissertation has not been submitted before for any other research project, degree or examination at any university.

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Date

ABSTRACT

Title: Automated dynamic control philosophy for sustainable energy savings on mine cooling systems

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Keywords: Automated control strategy; competitive; cost savings; dynamic; electricity; Energy Management System (EMS); mine cooling; operational costs; refrigeration; socio-economic; sustainability.

Financial instability in the mining sector was identified as a significant reason for reduced production trends in South Africa. Coupled with increasing operational costs, the South African mining sector is confronted with a challenging financial situation. To remain financially competitive, on a global scale, mines are adopting significant socio-economic changes.

Mineworkers require substantial cooling and ventilation to work in a safe and habitable environment. Deep-level mine cooling systems were identified as substantial energy-intensive consumers to supply such cooling. Mine cooling systems can make up to 28% of a mines total electricity consumption. Electricity cost-saving initiatives were studied, implemented and recognised as a viable solution to reduce end-use electrical energy consumption on mine cooling systems. Little attention has been directed, however, to the sustainability thereof.

Literature reveals a need for a simple, practical and integrated solution to optimise deep-level mine cooling systems dynamically for sustainable cost savings. Therefore, an automated dynamic control strategy was presented to optimise the control of mine cooling systems to reduce operational costs and improve system sustainability. An integrated Energy Management System (EMS) was identified as a suitable controller for the implementation of this strategy. The EMS analysed the theoretical impact with the aid of a verified simulation model.

The control strategy was implemented on a case study, Mine A, situated at a South African gold mining complex. An integrated dynamic temperature set point algorithm and ambient dry-bulb (DB) temperature prediction model was formulated, implemented and verified. The simulation results confirmed the accuracy of the automated dynamic control strategy with an average correlation error of 4%.

The feasibility of the automated control strategy was investigated and validated to identify post-implementation cost savings. Implementation results showed a power demand reduction of 45.7%, or 1960 kW during the evening peak time-of-use period. This translated to an annual cost saving of R1.1 million and an operational efficiency improvement of 15%. The optimised dynamic control model, when compared to existing control practises, also attained a chiller coefficient of performance improvement and compressor power reduction of 7% and 4% respectively.

An integrated performance monitoring daily report was established. Important KPIs were identified and included in the daily report. In addition to the implementation of automated cost saving measures, load shift savings were also reported for a period of 14 months; indicating the sustainable impact of this study. This strategy, demonstrated to be simple, showing significant performance improvements for South African mining industries.

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LIST OF EQUATIONS

NOMENCLATURE

List of units

Symbol	Description	Unit of measure
g	Measure of weight	Gram
J	Measure of energy	Joule
k	Denotes 1×10^3	Kilo
l	Measure of volume	Litre
m	Measure of distance	Meter
m^2	Measure of area	Square meter
M	Denotes 1×10^6	Mega
Pa	Measure of pressure	Pascal
R	Measure of RSA currency	Rand
Wh	Measure of energy	Watt-hour
W	Measure of power	Watt
°C	Measure of temperature	Degrees Celsius
%	Denotes a dimensionless number or ratio	Percentage
Δ	Difference	–

List of symbols

Symbol	Description	Unit of measure
$\boldsymbol{A}$	Area of heat exchanger tubes	m^2
$\boldsymbol{Adjusted_{baseline_i}}$	Half-hourly adjusted baseline	kW
$\boldsymbol{Actual_{impact_i}}$	Half-hourly actual power usage	kW
$\boldsymbol{COP}$	Coefficient of performance	$-$
$\boldsymbol{C_p}$	Specific heat constant	kJ/kgK
$\boldsymbol{Demand_{impact_i}}$	Half-hourly demand savings	kW
$\boldsymbol{k}$	Specific heat ratio of refrigerant	$-$
$\boldsymbol{kWh_{actual_i}}$	Half-hourly actual energy consumption	kWh
$\boldsymbol{kW_{baseline_i}}$	Half-hourly unscaled baseline	kWh
$\boldsymbol{\dot{m}_{air}}$	Mass flow rate of air	kg/s
$\boldsymbol{\dot{m}_{BAC}}$	Mass flow rate of water to BACs	kg/s
$\boldsymbol{\dot{m}_{UG}}$	Mass flow rate of water sent underground	kg/s
$\boldsymbol{n_{tot}}$	Thermal and mechanical compressor losses	$\%$
$\boldsymbol{n_w}$	Water-side efficiency	$\%$
$\boldsymbol{P_{out}}$	Outlet refrigerant pressure	kPa
$\boldsymbol{P_{in}}$	Inlet refrigerant pressure	kPa
$\boldsymbol{Q}$	Thermal energy absorbed	kW
$\boldsymbol{Q_{evaporator}}$	Thermal energy absorbed in the evaporator	kW
$\boldsymbol{Q_{generator}}$	Thermal energy absorbed in the generator	kW
$\boldsymbol{S}$	Humidity ratio	$-$
$\boldsymbol{SLA_i}$	Half-hourly SLA factor	$-$
$\boldsymbol{T_{actual}}$	Actual temperature	$°C$
$\boldsymbol{T_{adjusted@120min}}$	Adjusted temperature after 120 minutes	$°C$
$\boldsymbol{T_{average@120min}}$	Predicated temperature after 120 minutes	$°C$

$\boldsymbol{T_{average@0min}}$	Predicted temperature after 0 minutes	$°C$
$\boldsymbol{T_{ai(WB)}}$	Air inlet wet-bulb temperature	$°C$
$\boldsymbol{T_{dynamicsetpoint}}$	Dynamic temperature set point	$°C$
$\boldsymbol{T_{in}}$	Inlet refrigerant temperature	K
$\boldsymbol{T_{LMTD}}$	Log mean temperature	K
$\boldsymbol{T_{staticsetpoint}}$	Static temperature set point	$°C$
$\boldsymbol{T_{rate}}$	Temperature rate	$°C/min$
$\boldsymbol{T_{wi}}$	Water inlet temperature	$°C$
$\boldsymbol{T_{wo}}$	Water outlet temperature	$°C$
$\boldsymbol{t}$	Time	min
$\boldsymbol{U}$	Overall heat transfer coefficient	kW/m^2K
$\boldsymbol{Unscaled_{baseline_i}}$	Half-hourly unscaled baseline	kW
$\boldsymbol{W_c}$	Compressor motor power	kW
$\boldsymbol{x_{H_20}}$	Water removal rate	kg/s

LIST OF ABBREVIATIONS

Symbol	Description
ACU	Air cooling unit
ARS	Ammonia-absorption refrigeration cycle
BAC	Bulk air cooler
BEP	Best efficiency point
CCD	Cold confluence dam
CEO	Chief executive officer
CFD	Computational fluid dynamics
COP	Coefficient of performance
CWC	Chilled water coolers
DB	Dry-bulb
DEM	Design equipment manufacturer
DSM	Demand Side Management
EMS	Energy management system
ESCO	Energy service company
GDP	Gross domestic product
GUI	Graphical user interface
HCD	Hot confluence dam
HDI	Human Development Index
IDM	Integrated Demand Management
IGV	Inlet guide vane
KPI	Key Performance Indicator
LCC	Life-cycle costs
M&V	Measurement and Verification
MTR	Manual to remote
NIRP	National Integrated Resource Plan

NPV	Net present value
OPC	Open platform communication
PA	Performance assessment
P	Proportional
PCM	Performance-centered maintenance
PI	Proportional-integral
P&ID	Proportional-integral-derivative
PLC	Programmable logic controller
PRT	Power recovery turbine
PTB	Process Toolbox
RTS	Ready to start
SCADA	Supervisory control and data acquisition
SLA	Service level adjustment
SMTP	Simple mail transfer protocol
STP	Stop
STR	Start
TOU	Time-of-use
UG	Underground
VCR	Vapour-compression refrigeration
VSD	Variable speed drive
VRT	Virgin rock temperature
VUMA	Ventilation of Underground Mine Atmospheres
WB	Wet-bulb

GLOSSARY

"Automated cost saving measures"	Computerised procedures implemented for cost savings
"Baseline"	Original performance point used for comparisons
"Dry-bulb temperature"	Air temperature measured by a thermometer that captures atmospheric conditions
"Demand Side Management"	Procedures implemented to reduce the demand for electricity
"Dynamic control"	Determine the behaviour of a system and/or process by monitoring and adapting to real-time characteristics
"Dynamic control model"	Summarised representation of the behaviour between control input and outputs
"Energy-intensive"	Process utilising a substantial amount of electricity
"Energy Management System"	A system of computer-aided tools used to control, monitor and optimise the performance of a process
"Fissure water"	Water collected through narrow cracks, open fractures and man-made underground workings
"Gross domestic product"	The value of services and goods provided in a country during one year
"Life-cycle costs"	Recurring and non-recurring costs involved over the total lifespan of an asset
"Operational costs"	Costs incurred for production
"Net positive suction head"	The minimum required pressure at the suction inlet of the pump to prevent cavitation

"Programmable logic controllers"	Hardware and software elements that control processes locally or remotely
"Refrigeration"	Process of removing heat from a confined space and rejecting the unwanted heat into another environment
"Service delivery"	Sets of actions and measures implemented to aid with production
"Sustainability"	Maintaining a process at a specified rate for a prolonged period of time
"Supervisory control and data acquisition"	Industrial computerised system that monitors and controls field instrumentation
"Virgin rock temperature"	The change in temperature of subsurface rocks at varied depths
"Wet-bulb temperature"	Adiabatic saturation temperature measured from a thermometer with the bulb wrapped in a wet cloth

CHAPTER 1: INTRODUCTION

[1]

This chapter summarises the socio-economic crisis in the South African gold mining sector. Production trends, labour relations and increased operating costs are discussed and critically evaluated. Sustainable cost savings policies are introduced and explored. The need for the study is formulated and discussed.

[1] *Photograph courtesy of Planet KB, http://www.planetkb.co.za/portfolio-detail.php?Mining-Photography-4*

1.1. Preamble

1.1.1. The South African power grid

Eskom, the state-run national electricity utility in South Africa, is struggling to remain financially stable. In addition to increasing electricity prices, end-users are finding cheaper alternative energy sources and solutions which is placing Eskom under extreme financial strain [1].

Sustainable and cost-effective energy resources are fundamental for the economic development and sustainability of Eskom. South Africa's primary energy generator, which is dominated by the coal industry, is depleting its coal reserves [2]. If radical changes are not implemented, Eskom will be faced with significant challenges to reduce spiralling operational costs and mitigate depleting coal reserves.

Eskom generates nearly 95% of the total electricity consumed in South Africa and 45% of the total electricity used in Africa [3]. Energy-intensive industrial users, such as mines, consume 16% of the total electricity generated [4]. Therefore, Eskom plays a critical role in meeting consumer demand.

Between 2008 and 2011 electricity prices increased by 78% [5]. It was during the period of 2005 to 2013 that Eskom initiated its expansion programme to increase its electricity generation capacity. The total capital expansion programme, from 2005 to completion in 2018, is estimated at R340 billion [3]. Expansion will increase the nominal generating capacity and is likely to make a substantial improvement in economic growth in South Africa.

South Africa demands in excess of 51 000 MW of energy, which is more than the generating capacity of Eskom [6]. In recent years, the demand for electricity increased by 100 MW per annum [7]. Due to a rapid increase in electricity consumption, Demand Side Management (DSM) initiatives have established a noteworthy focus.

In conjunction with the capital expansion programme, the National Integrated Resource Plan (NIRP) suggested with the inclusion of DSM initiatives, a displacement target of 57 MW can easily be achieved [7]. NIRP suggested further that the implementation of DSM initiatives in the industrial sector would improve machine efficiency [7].

Although, DSM assisted in alleviating the financial strain on Eskom's electricity supply network; increasing operational costs, depleting coal reserves and the costly expansion programme are collectively surpassing sales and revenues.

Figure 1-1 illustrates the Human Development Index (HDI) versus annual electricity energy usage per capita. Significantly, there lies a threshold of approximately 4 000 kWh per capita that corresponds to an HDI of 0.9 or larger. South Africa, which has an HDI of approximately 0.69, lies above the threshold of

4 000 kWh per capita. According to the suggested relationship between HDI and electricity usage per capita, South Africa abuses energy.

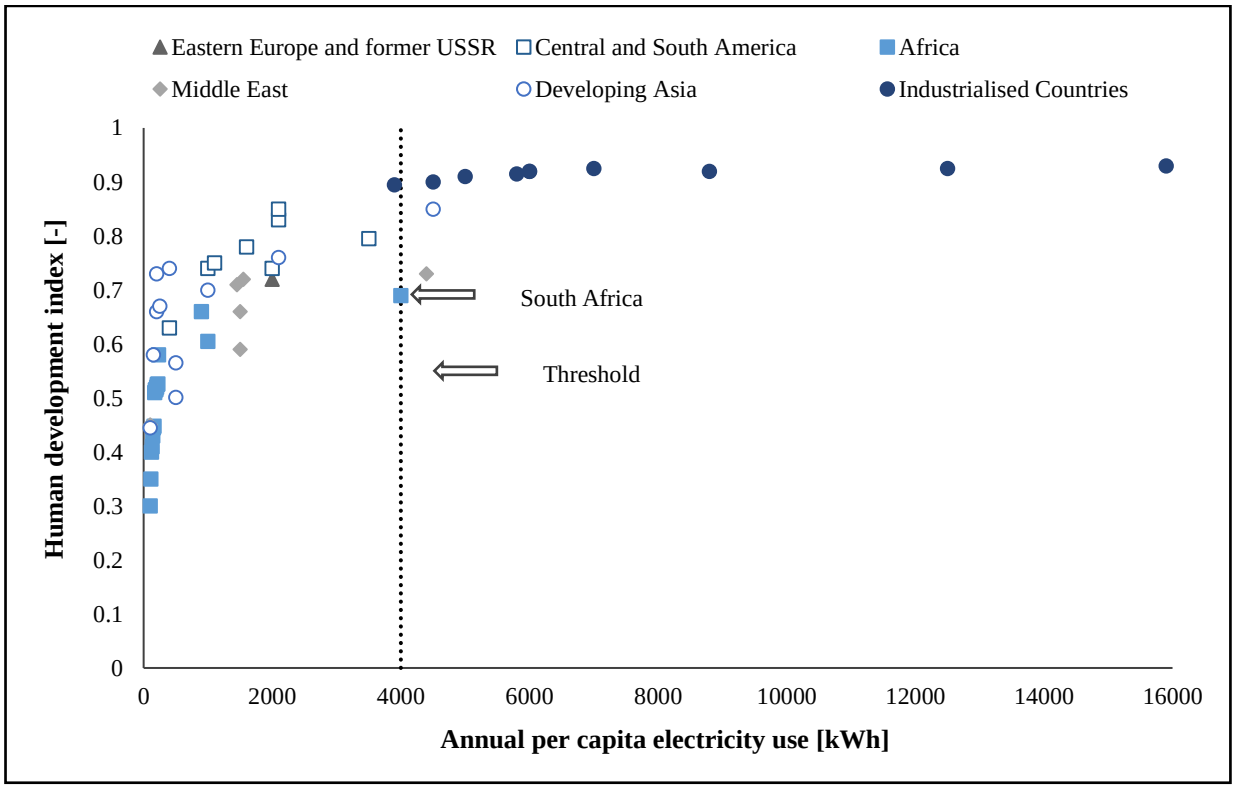

Figure 1-1: The United Nations' HDI and Electricity use per capita [8]

The sample of 60 populous accounts for 5.7 billion people that are forecast to use 90% of the world's total electricity in the year 2020 [8]. Countries with low HDIs who lie close to- or above the 4 000 kWh per capita threshold, include; South Africa, Kazakhstan, Saudi Arabia and Russia. Of the four, South Africa has a lower energy intensity capability and earns less per unit of electricity produced.

To ensure global sustainable energy reserve margins, it is important that countries such as South Africa with an HDI of 0.69, as discussed in Figure 1-1, reduce their energy usage to below the threshold of 4000 kWh per capita.

1.1.2. The importance of gold in South Africa

South Africa is a country steeped in minerals and natural resources that are mined, processed and exported. South Africa is home to the world-famous Witwatersrand gold basin, which accounts for approximately 40% of the world's gold output [9]. Gold is considered an essential resource that contributes extensively to the economy of a developing country like South Africa [10].

The South African mining industry contributes to approximately 18% of the Gross Domestic Product (GDP) and just over 50% in foreign exchange earnings [11]. Due to harsh economic environments, the

South African mining industry is struggling to remain financially competitive. South Africa, which was once ranked as the leading gold producer, has dropped to a seventh-place ranking in 2017 [12].

1.2. Financial instability in the South African mining sector

Mines utilise an integrated network of people, capital and infrastructure to function. These networks are complex and require large operating costs to remain profitable. The financial burden to comply with large operating costs has been brought to light. Large mining companies are struggling to remain competitive. South African mines are implementing alternative measures to cut back on operating costs [13].

During June 2017, AngloGold Ashanti announced that it planned to curtail cash losses with a questionable restructuring process. The restructuring process would involve the retrenchment of approximately 8 500 employees [14]. In light of the unfavourable restructuring proposal, AngloGold Ashanti's chief executive officer (CEO) stressed the importance of protecting the long-term sustainability of mining operations [13]. In addition to the suggested restructuring process, AngloGold Ashanti planned to place the Savuka mine on *"planned care and maintenance"* [15]. To maintain economic viability, industry is forced to abandon existing mines to reduce operational costs.

The retrenchment massacre continued as Sibanye Gold announced the retrenchment of approximately 10 200 mining personnel [16]. Although the retrenchment process is deemed viable, Sibanye Gold are considering alternative solutions. Economic strain on the mining sector has affected the GDP adversely by reducing investments, which negatively impacts the economic growth of South Africa.

South Africa is faced with a dynamic socio-economic crisis. To sustain profitability and competitiveness, the mining industry is forced to restructure. Mining companies are, however, engaging with all the relevant stakeholders in an effort to reduce the risk of unemployment [16].

1.2.1. Gold production trends in South Africa

Gold production contributes considerably to the socio-economic development of South Africa. Because gold is considered a finite resource, it is sought after due to its increasing value. Figure 1-2 illustrates the increase in global gold production from 2007 to 2017. Although the gold price increased for nine consecutive years, in 2017 the gold price dropped by R31 580 per kilogram (ZAR/kg) [17]. Without the adoption of drastic cost reducing measures, the mining industry is vulnerable to insolvency.

Decreased gold prices indicate that South Africa is under massive financial strain to remain globally competitive. It is suggested that reducing operating expenses can alleviate the financial strain on the mining industry. Despite these economic challenges, mines are curtailing production costs to maximise profitability.

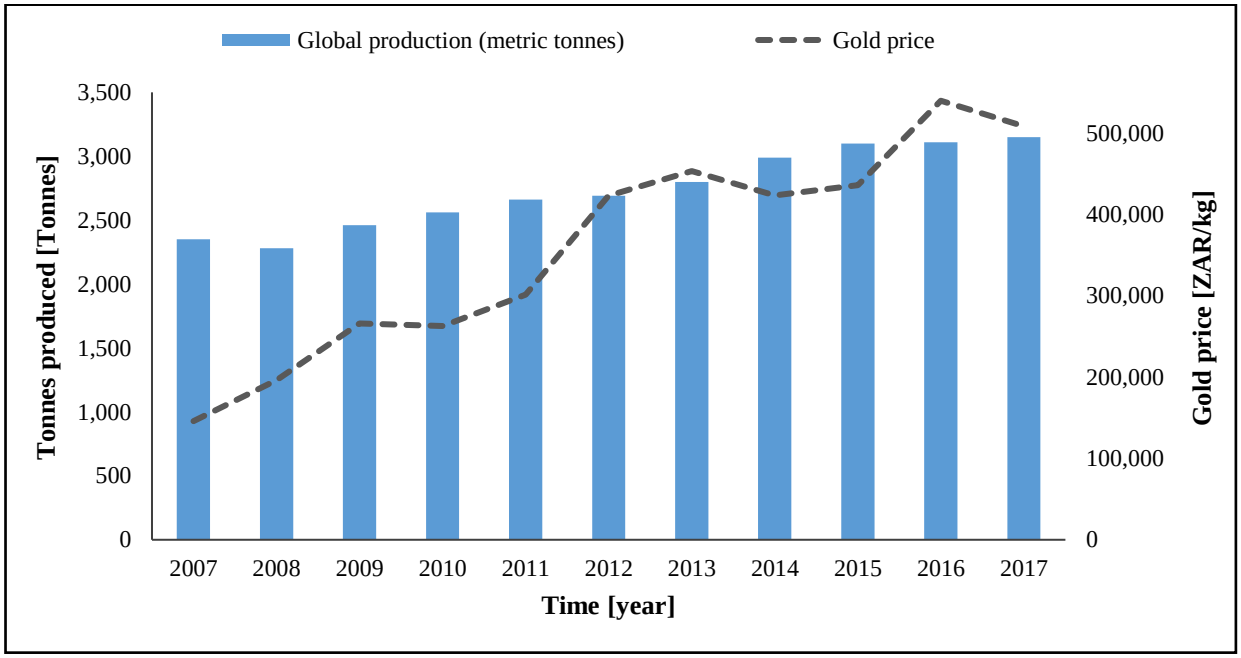

Figure 1-2: Global gold production and gold price [17], [18]

Increased global gold production indicates that gold resources are increasingly diminishing. It is therefore essential that gold production is maximised at low operating costs. Figure 1-3 illustrates the South African mining contribution to the GDP and production decline in gold mining for the past 10 years. Although local gold production has declined, mining is still a significant contributor to the GDP [19].

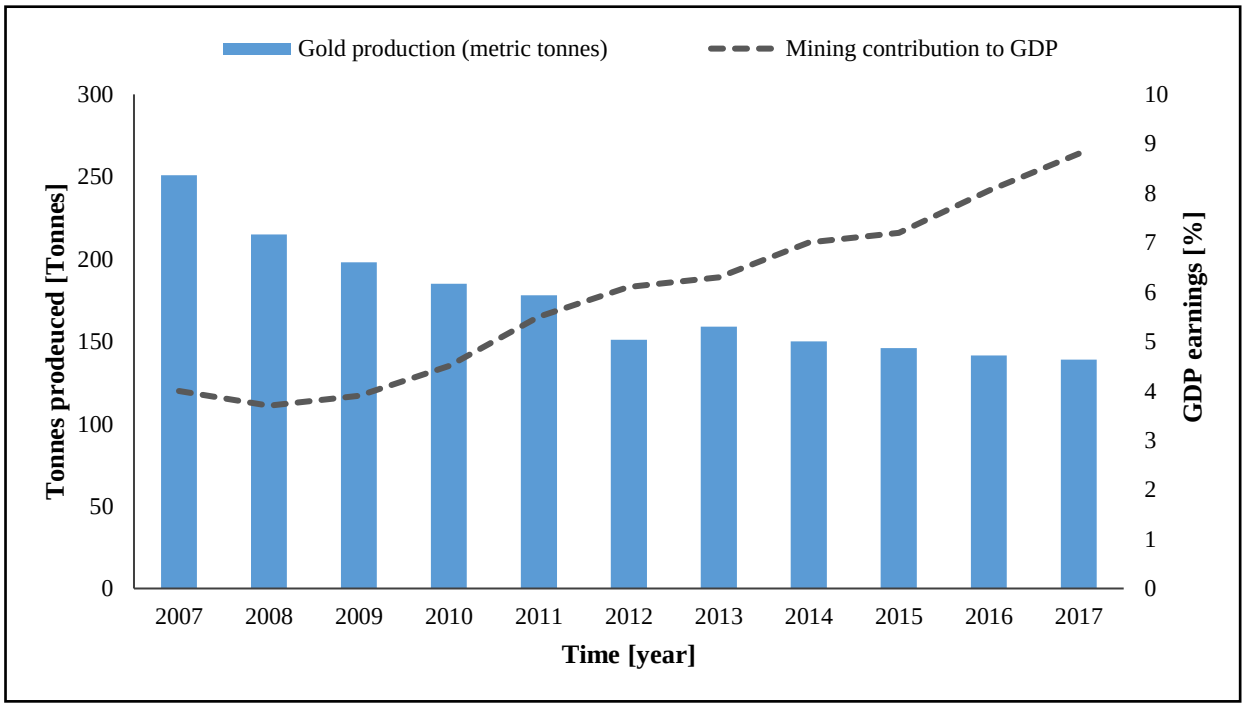

Figure 1-3: Mining contribution to the GDP versus Gold production in South Africa [19], [20]

A decline in South Africa's gold production suggests that gold reserves are diminishing, although South Africa was ranked third in the global gold reserve ranking in 2017 [21]. Therefore, although gold

production is declining, gold reserves remain available in South Africa, indicating that decline is more likely due to the significant financial cost of doing business.

A decline in gold production has prompted South Africa to reconsider the viability of gold mining. The gold mining industry is forced to adopt alternative measures to reduce operating expenses and maximise profitability. The following sections will investigate other financial challenges in the mining industry.

1.2.2. Increasing labour costs

Mining is a substantial provider of both direct and indirect employment. The mining industry is committed to contributing to the socio-economic development of mining societies by providing job creation for a considerable number of people in the country [22]. Figure 1-6 illustrates the annual remuneration versus number of employees hired in the gold mining industry.

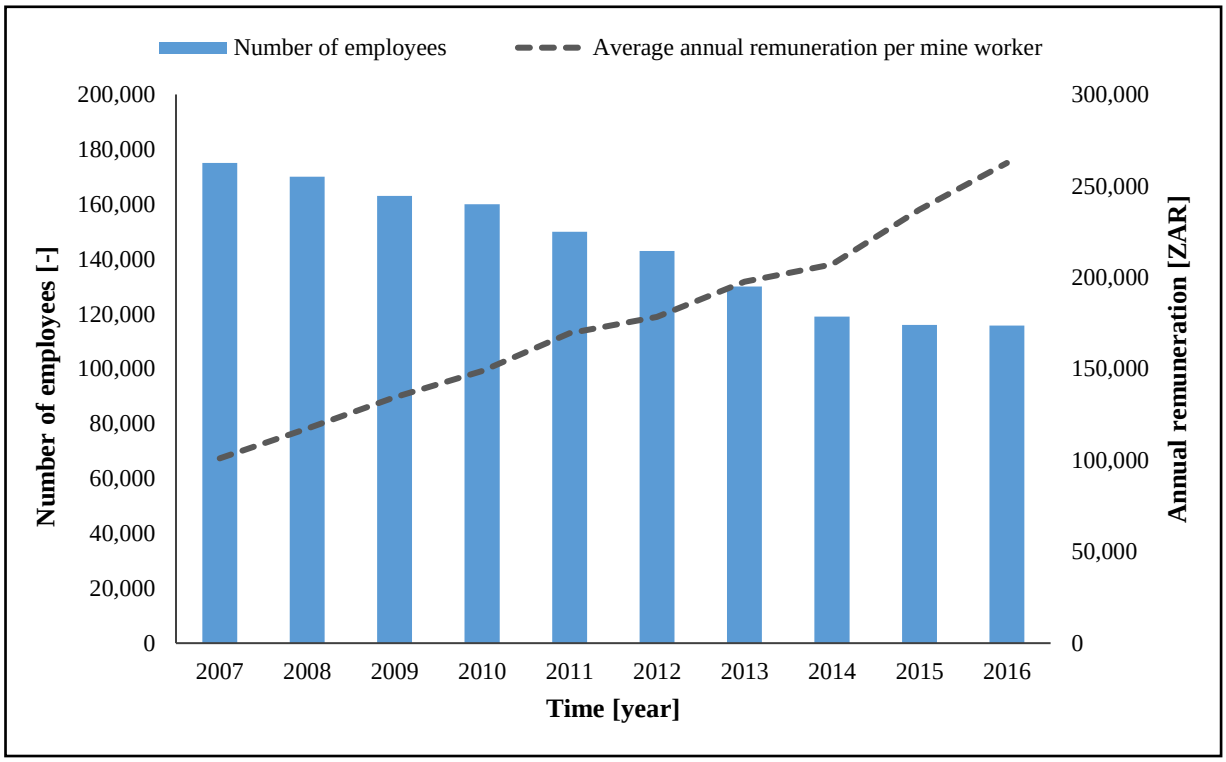

Figure 1-4: Annual remuneration versus number of employees in the South African gold mining industry [19], [22]

Due to increased labour costs, mines are forced to restructure and retrench employees. The rapid decline in employees and increase in annual remuneration has negatively impacted labour costs which further exaggerates the economic strain.

Figure 1-2 through to Figure 1-4 elaborates on how financial instability in the mining sector has negatively impacted production trends and the resultant socio-economic challenges. The mining sector, which was one of the largest revenue-generators for South Africa, is in a financial feud with labour unions with devastating consequences.

1.2.3. Electricity consumption in the mining sector

Electricity is an essential resource for both surface and underground mining activities. Important systems and thermodynamic processes that include ventilation and refrigeration are energy-intensive. The gold mining sector is considered the largest user of energy, consuming approximately 15% of South Africa's total energy generation [23]. Recently, many studies were completed to successfully correlate these energy-intensive processes to the tonnes of gold mined [24].

Figure 1-5 demonstrates the typical energy-intensive systems utilised at a deep-level gold mine. The largest electricity consuming subsectors include; ventilation and refrigeration, and compressed air. Both subsectors consume approximately 28% and 19% respectively. If these electricity subsectors are not managed efficiently and effectively, mines with a depth larger than 1 600 m can consume more than 25% of the total electricity generation in South Africa [25].

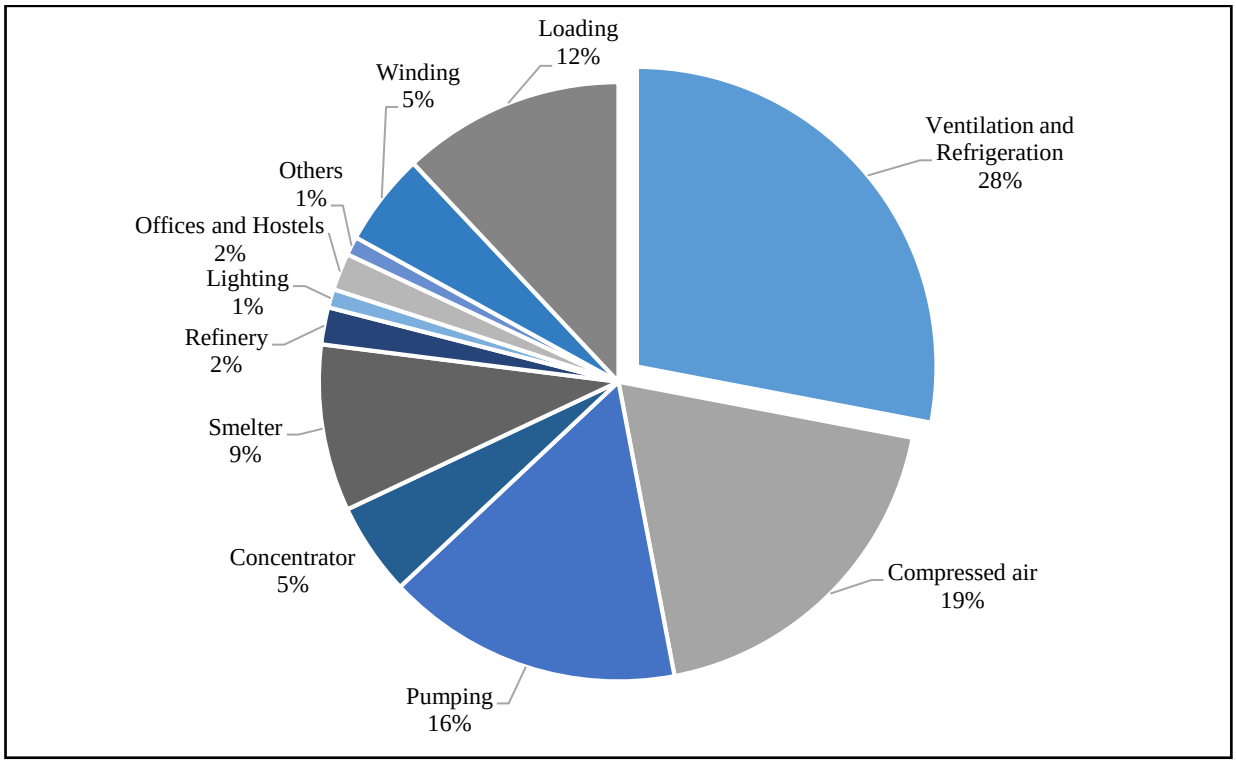

Figure 1-5: Allocation of energy usages within a typical mine [26]

Historically, Eskom was considered one of the world's most cost-effective electricity providers. As such, electricity costs were not a major concern for the mining sector [27]. Due to harsh economic circumstances, mines have established a massive focus to curtail increasing electricity costs.

1.2.4. Contribution of mining to the South African economy

In the past 100 years, the mining industry has played a vital role in securing a stable South African economy [19]. In 2017, the mining industry contributed to 6.8% of the economic growth of South Africa [19]. Although marginally lower than 2016, the South African gold mining industry still contributed a

total of R312 billion to the GDP in 2017 [19]. The gold mining industry was said to expand by 3.7% in 2017, prompting increased future revenue. Figure 1-6 displays the South African GDP growth at sectoral level.

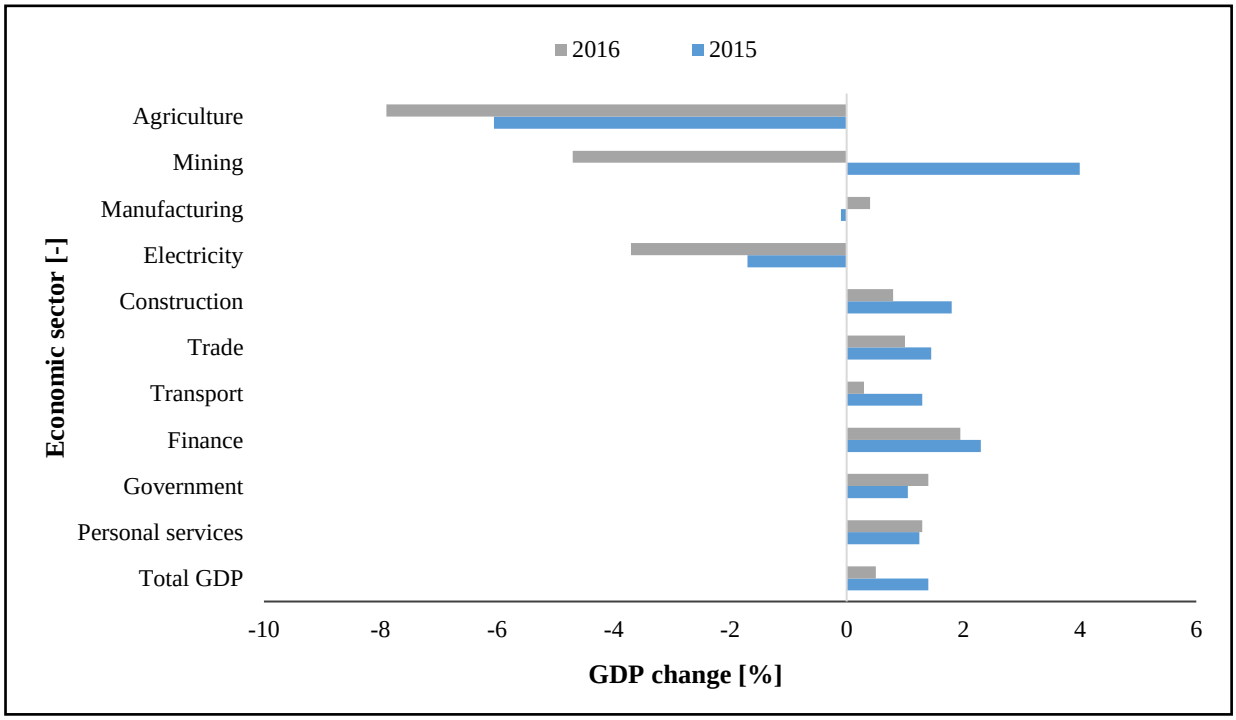

Figure 1-6: GDP growth at sectoral level [28]

South African gold mines were identified as a significant stakeholder for the economic growth of South Africa. Financial instability in the mining sector is attributed to increasing operating costs. Without effective interventions, the South African GDP will decline in rapid alignment with the decline in mining production. To mitigate the financial crisis, mines are endeavouring to curtail costs by adopting radical socio-economic solutions.

1.3. Energy management prospective on mine cooling systems

A typical mineshaft consists of several interconnected components that include pumps, compressors, fans, valves and steel pipe networks. The integrated network of these components is referred to as a cooling system. Mine cooling systems provide cool water and air for mining processes.

Globally, the energy systems with the highest potential saving capabilities are motor-driven systems that include pumps, ducting, fans and compressors. Motor-driven equipment accounts for approximately 60% of the total electricity usage in the mining industry [29]. According to Els, cooling underground relies solely on refrigeration systems [30]. Subsequently, the thermal capabilities of mine cooling systems are further dependent on virgin rock temperatures (VRTs) and mining depths [25].

VRTs represent the temperature of the rockface and geothermal gradient in °C/m due to auto-compression and geothermal heat. The required refrigeration capacity is generally dictated by VRTs. To meet the stringent legislation, cooling installations on mines are dependent on mining depths. Figure 1-7 displays geothermal temperature gradients of VRT regions in South Africa.

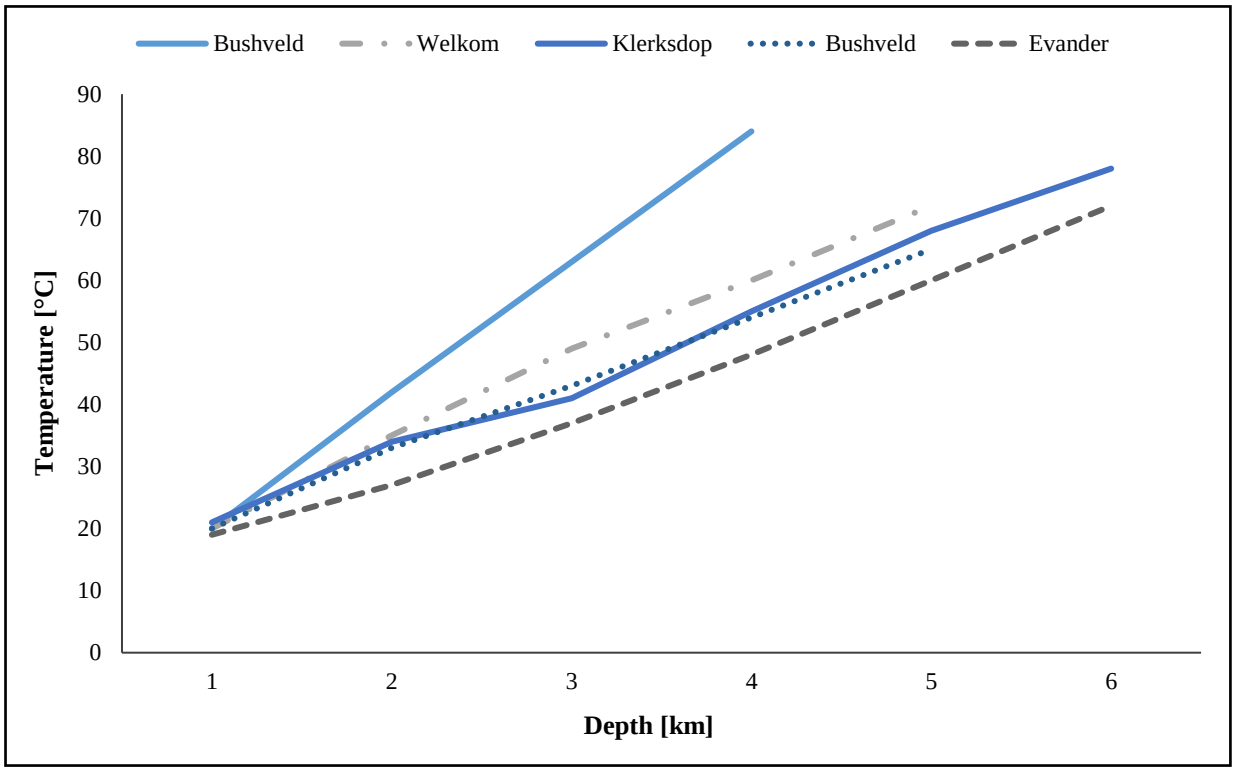

Figure 1-7: VRTs at different mining depths of regions in South Africa (adapted from [31])

Deep-level mine cooling systems utilise an abundance of electrical energy to manage steep geothermal gradients. Regions in the bushveld, whose geothermal gradient is very steep, require larger cooling capacities at shallower depths [32]. According to Nel, it is suggested that deep-level mine cooling systems require a cooling load capacity of 32 MW to accommodate for VRTs at depths of 3 km [33].

South African gold mines extend to depths of approximately 4 km, with VRTs of 60°C [34]. Therefore, extensive mechanical processes and machinery are required to mine in a safe and habitable environment. According to the South African mining legislation, deep-level mine cooling systems must provide operating conditions of less than 27.5°C WB or 32°C DB [35]. At mining depths of deeper than 3 km, refrigeration plants will typically supply 375 kW of cooling per kiloton per meter (kt/m) to provide adequate operating conditions [25], [33].

Deep-level mine cooling systems face a mammoth undertaking to achieve comfortable working conditions. A promising effort to adapt to thermal heat loads and underground temperature constraints is the implementation of an enhanced control strategy [36]. Cost-effective energy management measures have been implemented to mitigate the need for hefty cooling loads [37]. Energy saving measures on

mine cooling systems have also proven to be feasible without adversely affecting productivity and mine safety.

1.4. Implementing sustainable cost-saving policies

1.4.1. Demand Side Management (DSM) in South Africa

Within recent decades, the demand for electricity in South Africa exceeded the total capability to supply electricity [38]. South Africa's utilities are able to alleviate tension on the national power grid, while sinking the economic and environmental costs of electricity [39].

DSM provides a unique solution for reducing operational costs on deep-level gold mines. To sufficiently realise the electricity cost saving potential, DSM projects necessitate hefty sums of resources and assets to upgrade equipment for improved efficiency [40]. In addition, these strategies are implemented without affecting production intensities [41].

DSM projects have revealed prosperous reductions in electricity demands [42]. Figure 1-8 demonstrates the amassed demand savings after the implementation of DSM initiatives between 2005 and 2015 [43]. DSM strategies were considered the fastest, most viable tactic to reduce power consumption to accommodate for socio-economic development [44].

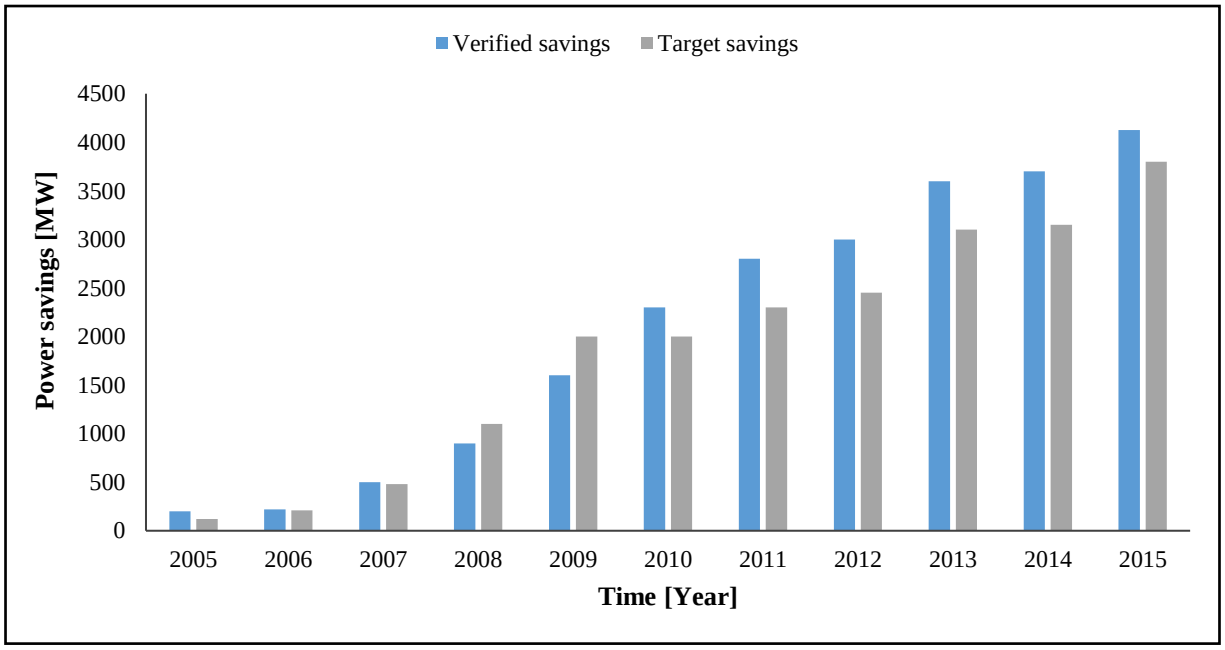

Figure 1-8: DSM demand savings from 2005 to 2015 [43]

The implementation of modern technology and DSM initiatives is crucial for the sustainability and economic growth of South Africa. Modern technology is essential for efficient energy management in the mining industry [45]. DSM has proven to provide support where needed and consequently complements the feasibility of energy projects for Energy Service Company's (ESCOs) [46].

1.4.2. Evaluating sustainable energy saving policies

Industrial sectors are adopting energy management and energy efficient policies to sustain financial competitiveness [47]. Sustainable energy saving practices have become the priority of large corporations nationwide [48]. Similarly, energy efficiency practices are deemed cost-effective for sustainable growth and development [49].

Implementing sustainable energy saving practices is challenging. Although sustainable measures have attained immense focus, several obstacles have prohibited the implementation of such policies [50]. Sustainable energy saving measures are best achieved through adapting to behavioural alterations [51]. A lack of awareness and unwillingness to change from mine personnel has prevented the application of sustainable energy management practices.

The application of sustainable energy saving measures is halted by poor maintenance [52]. Sustainable practices are largely dependent on maintenance and monitoring of key performance indicators (KPIs) [53], [54]. To enhance sustainability, Maré suggested training important stakeholders to increase the probability of sustainable energy savings [36].

Sustainable energy saving practices can be implemented to reduce the long-term financial strain on mines. Although industry has adopted sustainable energy saving measures, various challenges were identified. Application of sustainable energy saving technologies by the relevant stakeholders can efficiently reduce operating costs and improve total system performance.

1.5. Problem statement and study objectives

South Africa's gold production has shown no adequate improvement in the last decade. A decrease in gold production is attributed to a variety of socio-economic challenges. To remain financially competitive, mines are adopting radical socio-economic solutions.

Ineffective control and mitigation of increasing operational costs will, in the near future, increase the financial burden on the mining sector. It is essential that a sustainable solution is adopted to ensure South African gold mines remain globally competitive.

Refrigeration and ventilation was identified as one of the largest single consumers of electricity in the industrial sector. Without sufficient cooling, mines are critically challenged to produce gold effectively. Managing heat loads in a cost-effective manner will alleviate the financial strain on the mining industry.

DSM initiatives have been considered as an alternative approach to reducing operating costs. DSM has yielded significant cost savings potential. Literature, however, has indicated long-term challenges such as underperformance and sustainability.

Need for study

Electricity serves as an essential resource for both surface and underground mining activities. Mines rely heavily on energy-intensive thermodynamic processes to reduce heat stresses. To remain financially competitive, there exists an opportunity for the implementation of a sustainable cost-effective strategy on mine cooling systems. This identified solution enhances profitability and alleviates challenges such as underperformance, sustainability and increasing operating costs.

Problem objectives

To alleviate the rapidly increasing socio-economic crisis in the South African mining industry, operational costs such as electricity can be reduced by achieving the following study objectives:

- Identify, evaluate and review mine cooling cost saving strategies. Addressing such strategies will identify energy saving measures and service delivery improvements to enhance total cooling system performance.
- Develop a simple, practical and integrated energy saving strategy for sustainable savings on mine cooling systems. A simple and practical strategy can be easily adapted and implemented on multi-industrial cooling systems to significantly reduce the financial burden on South Africa.
- Quantify the financial impact of energy saving measures on mine cooling systems.

1.6. Overview of sections

Herewith includes a brief overview of the dissertation. The dissertation is split into six chapters with several subsections clarifying important research methodologies and assumptions. An overview of each chapter is explored below.

Chapter 1: Introduction - This chapter provides an introduction to the study. Gold mining and the costs associated thereof are included. Financial instability in the mining sector is critically explored and reviewed. Factors including production, ore reserves and labour costs are evaluated. Finally, the problem statement and study objectives are defined and discussed.

Chapter 2: Literature study - This chapter provides an overview of cooling systems in the gold mining industry. Important machineries, infrastructure and existing energy saving optimisation strategies are identified and analysed. The limitations and constraints of existing state-of-the-art optimisation strategies are discussed.

Chapter 3: Development of an automated dynamic control philosophy - In this chapter, a case study is identified and evaluated. Existing applications of DSM control strategies are examined and reviewed.

Assumptions and system limitations are developed to adapt existing optimisation strategies for sustainable energy saving measures. The development and authentication of an automated dynamic energy saving measure is discussed in detail.

Chapter 4: Strategy implementation and assessment monitoring - The chapter discusses the results obtained from the implementation of an automated dynamic control strategy on mine cooling systems. The feasibility of the study is discussed and reviewed. Measured results are compared to the simulated results for strategy verification. Post-implementation results are analysed and discussed to identify any limitations of the control strategy.

Chapter 5: Conclusion and recommendations - This chapter serves as a conclusion that summarises the findings of the study. Recommendations are provided to assist with future research and improvements to the control strategy. Study limitations and constraints are also evaluated in detail.

Chapter 6: References - This chapter provides a summary of the various citations used within this dissertation. The list of references summarises the relevant authors, titles and locations that will assist the reader in finding the sources.

1.7. Conclusion

Gold was identified as a finite resource that contributes largely to the economic growth of South Africa. Research indicates that South Africa's energy usage per capita exceeded the minimum threshold for developing countries, suggesting it overexploits energy.

Financial instability in the South African mining sector was accredited to socio-economic challenges and increasing operating costs. Combined with decreasing production trends, the sustainability of South Africa's mining longevity was questioned.

VRTs and geothermal gradients were investigated and reviewed. Without sufficient cooling and ventilation, deep-level mines are challenged to produce gold efficiently. To accommodate for safe and habitable working conditions, the electrical consumption of refrigeration and ventilation systems was considered.

The need to reduce electricity costs by implementing a sustainable cost-effective solution on mine cooling systems was identified. To remain financially competitive, it was suggested to implement a simple, practical and easily adaptable solution and investigate the financial impact thereof.

CHAPTER 2: LITERATURE STUDY

[2]

An overview of mine cooling systems is explored. Limitations and constraints of existing optimisation techniques are identified and critically evaluated. The performance and implementation of sustainable energy saving measures are discussed and reviewed.

[2] *Photograph courtesy of Planet KB, http://www.planetkb.co.za/portfolio-detail.php?Mining-Photography-4*

2.1. Introduction

The importance of implementing sustainable cost-saving policies to enhance financial growth and reduce operating costs of deep-level gold mines in South Africa was recognised in Chapter 1. Ineffective control of electricity expenditure is heightening the financial struggle in the South African mining sector.

Mine cooling systems were identified as one of the largest single consumers of electricity in the mining sector. The financial burden of managing heat loads in a sustainable cost-effective manner for the safety of mineworkers was critically evaluated in Chapter 1. This prompted the need to develop a simple, practical and easily adaptable control strategy, with sustainability as the principle focus area, to reduce end-use electricity consumption on mine cooling systems. This will, in turn, enable South Africa to remain financially competitive on a global scale, as discussed in Chapter 1.

According to Nel, it is necessary to ascertain key areas for improvement on system performance, reliability and efficiency [33]. As a result, energy-intensive mine cooling systems and the operation of typical cooling auxiliaries are critically evaluated and discussed in this chapter. This serves to simplify the study problem and meet the research objectives discussed in Chapter 1.

The impact of energy saving measures on mine cooling systems is discussed and conveyed in this chapter to identify a practical and adaptable solution. This ensures that the scope of implementing an automated dynamic control strategy on mine cooling systems by focusing on sustainability is feasible. This also enables an integrated control approach to develop the impact of sustainable energy saving measures on mine cooling systems, as suggested by the problem objectives.

The performance of existing DSM initiatives and state-of-the-art control optimisation techniques will be reviewed to identify reasons for underperformance on mine cooling systems. Literature of previously implemented strategies are furthermore analysed to identify a broader understanding of integrated mine cooling systems to identify the feasibility of implementing a practical automated control strategy.

2.2. Refrigeration and cooling systems on deep-level mines

2.2.1. Overview

Deep-level mines extend to depths of 4 km [34] and experience VRTs of 60°C [55]. Mineral bodies are located well below the surface with geothermal gradient of rock surfaces varying between 10°C/km and 20°C/km [56]. At such depths, mines demand significant cooling to provide operating conditions of less than 27.5°C WB [34].

Apart from heat loads due to geothermal gradients, primary heat sources such as fissure water and heat machinery are rife [57]. A disturbingly large heat source is attributed to adiabatic compression [45].

Adiabatic compression, or better referred to as auto-compression, adds heat to air as a result of an increase in potential energy of air entering through the shaft. The weight of atmospheric air on the mass of air descending through the shaft leads to an increase in pressure, known as auto-compression.

To ensure safe and habitable working conditions underground, integrated infrastructure is utilised [58], [59]. Such infrastructure is costly resulting in mines delaying upgrades for long periods of times. Figure 2-1 summarises the infrastructure needed for ultra-deep gold mines at varied depths. This demographic is utilised to ensure optimal cooling of underground VRTs by considering essential infrastructure.

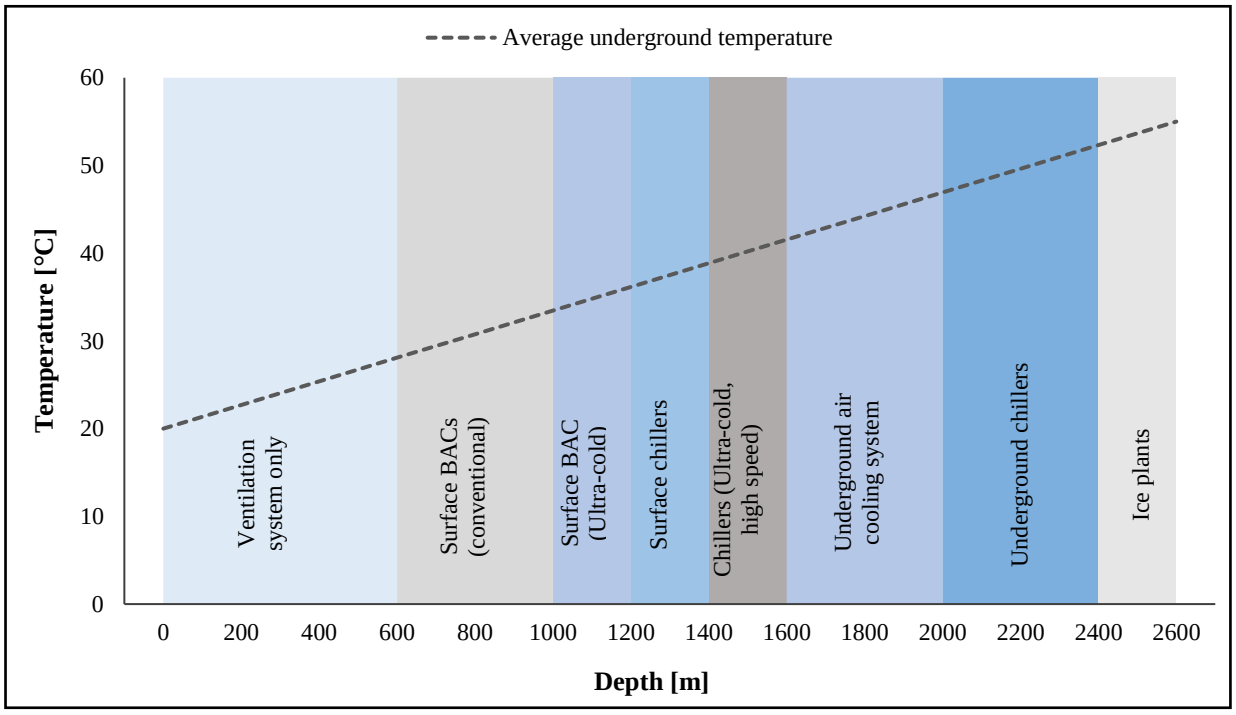

Figure 2-1: Cooling infrastructure for variable depths and temperatures [60]

As underground depths increase, larger and more effective cooling infrastructure is needed. This ensures that heat loads are managed to provide safe and comfortable working conditions. At such depths however, the demand for underground cooling and ventilation is erratic [61]. As a result, underground cooling equipment [62] and thermal storage dams are considered. These storage dams are thermally insulated [63] to store unwanted cooling energy [62]. Storage dams are closely interconnected to prevent frictional losses [64].

Chilled water and dehumidified air is required for various mining operations. This is achieved by utilising large integrated cooling systems [61]. These cooling systems are energy-intensive and demand a combined cooling capacity of 30 MW or more [65] for deep-level gold mines in South Africa. Mine cooling systems are typically installed on the surface and underground. However, surface cooling systems are favoured due to an augmented heat rejection capacity of return air from underground [66].

Depending on mining operations, geographical locations and mining depths, different cooling system configurations are preferred. Figure 2-2 displays a surface cooling network and water reticulation system of a South African deep-level mine. Mine cooling systems consist of integrated cooling components including pre-cooling towers, bulk air coolers (BACs), condenser towers, chillers and storage dams [58]. These components combined enable sufficient underground cooling and ventilation.

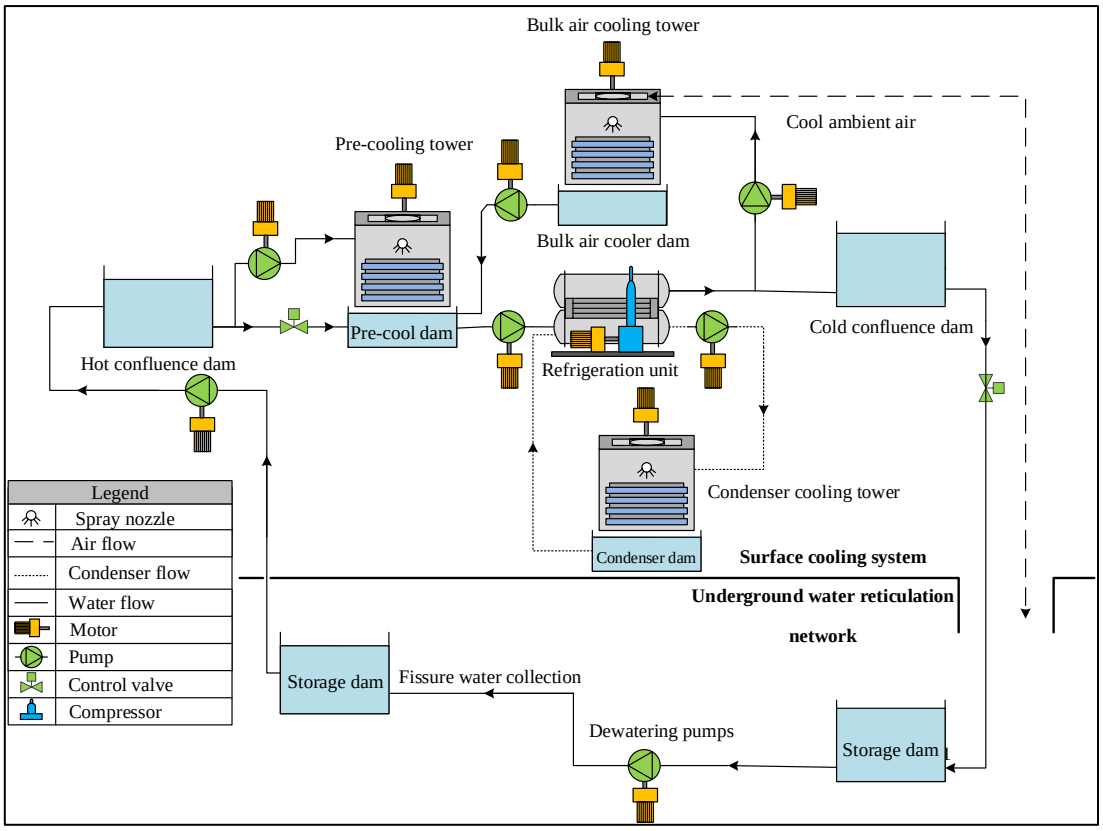

Figure 2-2: Typical schematic layout of cooling and water reticulation system

Hot service water is pumped from underground end-users to a surface dam at 26°C [34]. The hot service water is fed to the pre-cooling towers through spray nozzles for heat rejection. The water is adiabatically cooled within 2°C of the ambient DB temperature [33] before being circulated by evaporator pumps through the chillers. The water is passed through direct heat exchangers to cool the water below 4°C [67]. Depending on mining operations, chillers vary in terms of layout, configuration and control sequence.

Parallel chiller configurations, as depicted in Figure 2-2, deliver cool water at a constant temperature by fluctuating the quantity of chillers to meet water flow demand requirements [68]. South Africa is considered the leading user of chillers with over 300 chillers installed [67]. Condenser pumps circulate water through condenser cooling tower spray nozzles for heat rejection, after which the water is collected in the condenser sump. Mine cooling systems utilise motor-driven equipment that accounts for 60% of the total electricity usage in a mine [29]. This motor-driven turbomachinery is illustrated in Figure 2-2.

Water stored in the cold confluence dam (CCD) is sent to underground users for mining operations or circulated through BACs to supply cool ventilated air 7°C [69]. BACs ventilate mineshafts to ensure productive underground working environments [70].

An overview of refrigeration and mine cooling components were provided in this section. The purpose of supplying sufficient cooling for safe underground working conditions was also briefly discussed. The following section will characterise integrated cooling systems and their subsystems to identify an effective solution to mitigate increasing operating costs.

2.3. Control of energy-intensive cooling auxiliaries

2.3.1. Characterising integrated cooling systems

Mine cooling systems are categorised into two sections, namely: water and air demand requirements. This ensures characteristics of chillers, heat- absorption and rejection towers, auxiliary turbomachinery and thermal storage capacities are considered to distinguish mine cooling components and their requirements. Component control limitations and constraints are also discussed to identify sustainable cost savings and optimisation opportunities for deep-level mine cooling systems.

The effectiveness of mine cooling systems is costly and highly dependent on the complex nature of deep-level mine cooling systems, the inter-reliant operation of their subsystems and their variable flow capabilities. To enhance the control and optimisation of such integrated cooling networks for practical implementation, a generic control strategy is recommended [71]. Therefore, the control and functioning of the following water and air demand components will be extrapolated to identify a sustainable and generic solution to address the study problem:

- Refrigeration cycles;
- Bulk air coolers;
- Pre-cooling and condenser cooling towers;
- Auxiliary pumps and turbines;
- Thermal storage dams; and
- Service water valves.

The following subsections will elaborate on the functioning of the above-mentioned components in detail. System configurations and technologies are explored to determine sustainable cost savings opportunities for South African deep-level mine cooling systems.

2.3.2. Refrigeration cycles

Refrigeration plants are utilised widely in mine cooling systems to provide chilled water between 3°C and 6°C [37] to underground end-users. These chillers are the significant energy consumers, exhausting approximately 66% of a mines cooling system power [35]. Mines use surface and underground chillers to cool mining water. Due to the limited accessibility of exhaust air, the heat rejection capacity of underground chillers is restricted.

A mines cooling system typically comprises of more than one chiller. These chillers are arranged in three types of configurations. Such configurations are intended to handle variations in thermal loads [25]. The three types of configurations are: a series configuration, which is used to vary temperature requirements; a parallel configuration, used to vary flow requirements; and a cascaded configuration, used for variable temperature and flow requirements [71].

Refrigeration cycles used in the mining industry include ammonia-absorption (ARS) and vapour-compression (VCR) cycles. Such cycles vary depending on the requirements of the mine [72]. The VCR and ARS cycles are similar in principle and can be found in the majority of cooling systems tailored for vehicles, households and malls as heating, ventilation and air-conditioning (HVAC) systems [35].

Within in the mining industry, most chillers utilise VCR refrigeration principles [73]. Although, many models and design adaptations of chillers are available, the VCR cycle is preferred. VCR cycles offer simplicity and are available at low cost. VCR chillers have cooling capacities of up to nearly 20 MW, although most are in the order of 6 MW [37].

Unlike the ARS cycle, VCR is preferred because the working fluid is not toxic [25]. Depending on application, VCR refrigeration units use different refrigeration working fluids. The working fluid is selected to ensure optimum cycle efficiency. Properties such as temperature and pressure are critical for evaluating fluid criteria [74]. Commonly used refrigerants include R134a and ammonia (R717), because the fluid properties of these refrigerants are suitable for mine chiller applications.

Due to their low cost, Freon and R134a are the most common refrigerant gases utilised in the VCR cycle. Freon is preferred for surface chiller applications and is frequently used in industry as a substitute fluid for R-12 and R500 refrigerants [75]. Figure 2-3 represents a graphic representation of a vapour-compression refrigeration cycle. The cycle consists of a compressor, two shell tube heat exchangers and a throttling valve.

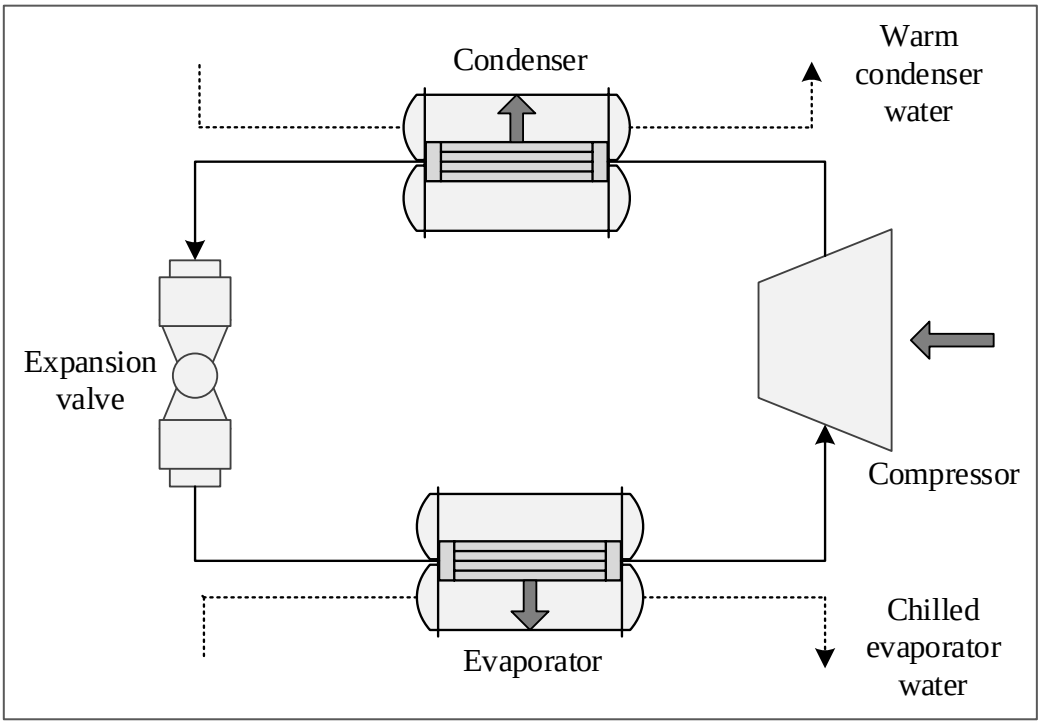

Figure 2-3: Vapour-compression refrigeration cycle

Figure 2-3 illustrates a typical VCR cycle and all its essential components. The cycle is explained briefly in the steps below:

A. *Compressor:* The low pressure and temperature vapour refrigerant is drawn into the compressor inlet through a suction valve [76]. The refrigerant is mechanically compressed adiabatically (irreversible) to a superheated vapour at a higher pressure [76]. Thereafter, the refrigerant is discharged to the condenser through the compressor delivery valve.

B. *Condenser (heat rejection):* The refrigerant is then condensed and cooled. The refrigerant releases latent heat which is transferred to the condensing medium. Condenser mediums include water or air. The refrigerant leaves the condenser as a high-pressure liquid.

C. *Expansion valve:* The refrigerant is throttled through the expansion valve to reduce the pressure of the refrigerant adiabatically. The refrigerant is throttled at a controlled rate to form a cold mixture of vapour and liquid [73]. During the throttling phase, the saturation temperature of the refrigerant will decrease. Some of the refrigerant evaporates as it passes through the expansion valve [77].

D. *Evaporator (heat absorption):* The refrigerant is passed through the evaporator at a low pressure and temperature [35]. The refrigerant absorbs its latent heat of vaporization from the water or air medium which is to be cooled [77]. The refrigerant is heated and vaporizes within the shell and tube heat exchanger of the evaporator. The refrigerant exits the evaporator as vapour before returning through the suction valve of the compressor.

Within the VCR cycle, two of the processes are at constant pressure and enthalpy. To study these properties more thoroughly, a pressure–enthalpy or *P–h diagram* is sketched. Figure 2-4 illustrates the *P–h diagram* for which both liquid and gas phases of the refrigerant are visible.

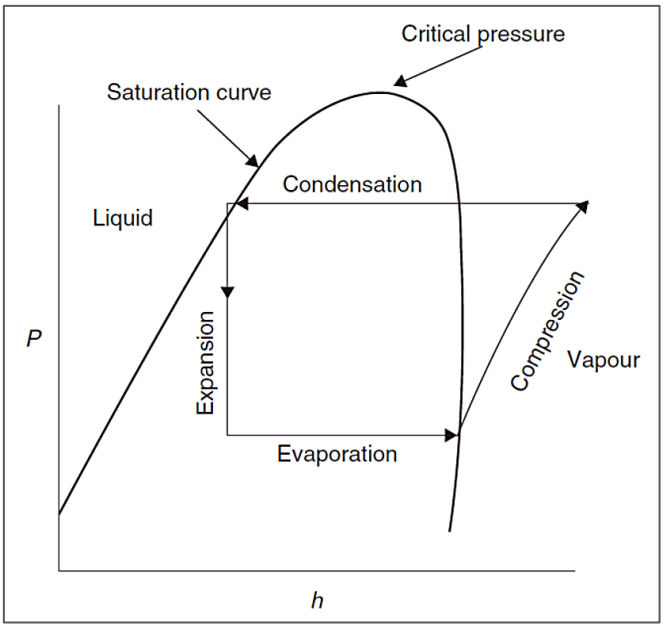

Figure 2-4: Pressure–enthalpy, P–h diagram, showing vapour-compression cycle [77]

The VCR cycle requires a compressor to circulate the refrigerant. The most common compressors types used for mining applications include: centrifugal and screw types [64]. Reciprocating compressors exist, but lack the required capacity compared with centrifugal and screw type compressors.

Condensing and evaporating temperature profiles are critical for ensuring compressor design requirements are met. The type of compressor used in refrigeration systems is regulated by system-particular pressures and volumes [78]. Design requirements that differ largely from operating temperature conditions are considered inefficient. Screw compressors have versatile condensing temperature ranges, which are favoured for variable heat loads [79]. Screw type compressors are favoured for chiller applications on mines [68].

Centrifugal compressors are made up of five focal components, namely; an impeller, guide vanes, a shaft, a volute casing and a diffuser [80]. Centrifugal compressors deliver the refrigerant at a stable discharge pressure [81]. These compressors are powered by an electric motor. Electrical motors are considered more efficient for the size of most compressors found on VCRs in mine cooling systems [82].

The compressors in refrigeration plants utilise either guide vanes (centrifugal compressors) or slide valves (screw compressors) to regulate the refrigerant flow rate [79]. The cooling load is controlled by guide vanes to ensure a predetermined evaporator water outlet temperature is achieved [79]. The compression required is determined by the difference between the inlet and predetermined outlet water temperature

[54]. The compressor vanes are set to 100% before they cutback to achieve the desired water outlet temperature [37]. Figure 2-5 illustrates an example of a multi-stage centrifugal compressor.

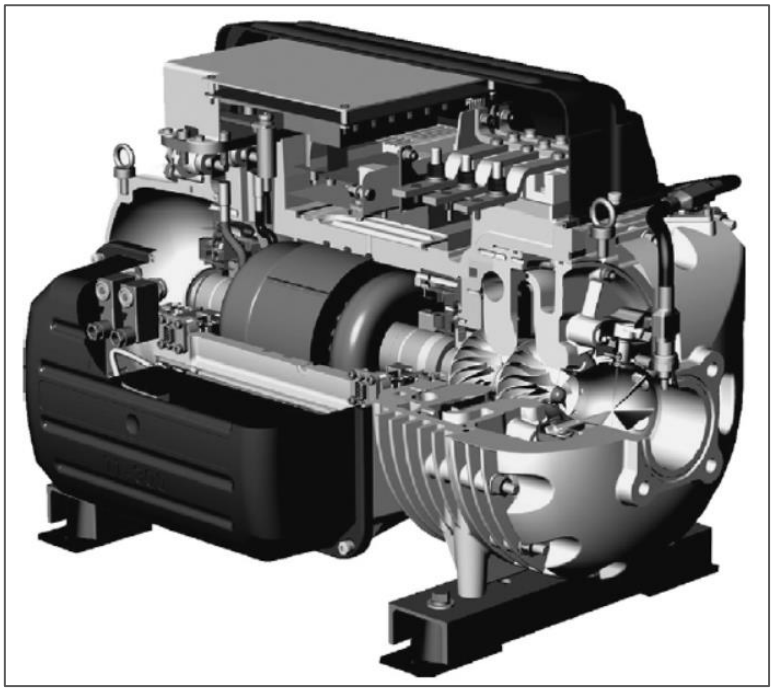

Figure 2-5: Multi-stage centrifugal compressors [77]

The electrical power utilised by the compressor to deliver the refrigerant at a certain mass flow rate and pressure discharge is calculated with Equation 2-1:

Equation 2-1: Compressor power requirements

$$W_c = \frac{\dot{m}\, C_p T_{in}\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{k-1}{k}} - 1\right)}{n_{tot}} \qquad [kW]$$

Where:

$W_c = compressor\ motor\ power$	$[kW]$
$\dot{m} = mass\ flow\ rate\ of\ refrigerant$	$[kg/s]$
$C_p = specific\ heat\ constant$	$[kJ/kg.K]$
$T_{in} = inlet\ refrigerant\ temperature$	$[K]$
$P_{in} = inlet\ refrigerant\ pressure$	$[kPa]$
$P_{out} = outlet\ refrigerant\ pressure$	$[kPa]$
$k = specific\ heat\ ratio\ of\ refrigerant$	$[-]$
$n_{tot} = thermal\ and\ mechanical\ \ compressor\ losses$	$[-]$

Equation 2-1 indicates that parameters including: mass flow rate; inlet refrigerant temperature; discharge pressure; and compressor losses largely affects compressor power. Such parameters are predetermined according to the demand of refrigerant required for cooling. To achieve energy savings, the discharge pressure and delivery flow of compressors is adjusted to match a predetermined temperature output.

The coefficient of performance (COP) is used to quantify the efficiency of chillers on deep-level mines. The COP represents the ratio between thermal energy output and electrical energy input. A study illustrated that the COP of chillers typically decreases at lower condenser flow rates and increases at lower evaporator flow rates [83]. Therefore, lower evaporator flow rates are preferred. Although, the inlet guide vane (IGV) strategy is predominantly used to vary flow, various control strategies have an effect on the COP of the chiller. A compressor ability to manage the fluctuating cooling-load conditions is vital for improving the COP of chillers [84]. It is clear from Equation 2-2 that changes in evaporator flow and temperature will affect the cooling load of the chiller.

The COP of VCR refrigeration cycles typically range between 3 and 6, which is considerably larger than ARS cycles that range between 0.54 and 1.1 [85]. A COP value of 6 is considered energy efficient, while a chiller cycle with a value of 3 or less is considered inefficient [76]. The COP of the chiller is optimised by reducing the compressors electrical power input. The slide valves and guide vanes vary the refrigerant flow to reduce the compressor power input. The COP of VCR chiller is illustrated by Equation 2-2.

Equation 2-2: Coefficient of performance for vapour-compression refrigeration cycles

$$COP = \frac{Q_{evaporator}}{W_c} \qquad [-]$$

Where:

$COP = coefficient\ of\ performance\ of\ chiller$ $[-]$

$Q_{evaporator} = thermal\ energy\ absorbed\ in\ the\ evaporator$ $[kW]$

$W_c = compressor\ electrical\ power$ $[kW]$

Water cooling in the evaporator is largely dependent on the compressors ability to regulate the demand flow of refrigerant. Heat transfer between the refrigerant and mine water is enhanced with the use of a shell and tube heat exchanger. This consequently increases the COP of the chiller as displayed by the relationship in Equation 2-2.

The refrigerant typically passes over the tubes within the pressure vessel, while the water from the auxiliary pumps flows through the tubes. Special occurrences where size is one of the design constraints, a compact plate heat exchanger is preferred [78]. Figure 2-6 illustrates a shell and tube heat exchanger.

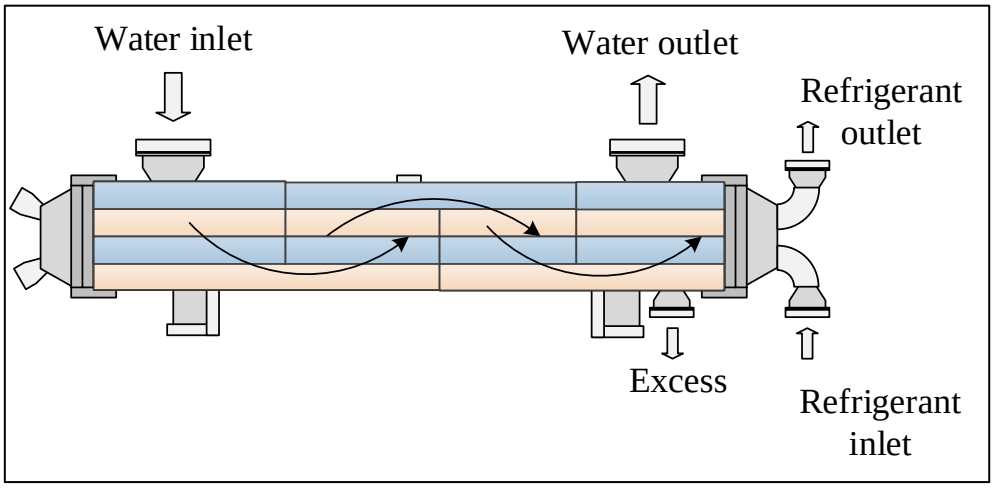

Figure 2-6: Schematic representation of a shell and tube heat exchanger [86]

The thermal energy transfer from the refrigerant to the water in the heat exchanger is described by Equation 2-3.

Equation 2-3: Thermal energy absorbed from a chiller

$$Q = UA\Delta T_{LMTD} \qquad [kW]$$

Where:

$Q = thermal\ energy\ exchanged$ $[kW]$

$U = overall\ heat\ transfer\ coefficient$ $[kW/m^2K]$

$A = area\ of\ heat\ exchanger\ tubes$ $[m^2]$

$\Delta T_{LMTD} = \log mean\ temperature\ difference$ $[K]$

Equation 2-3 indicates that parameters such as heat transfer coefficient and area of heat exchanger tubes affects heat absorption adversely. It can be suggested that reducing scaling or fouling in heat exchanger ducts will greatly improve thermal heat transfer in a shell and tube heat exchanger.

2.3.3. Auxiliary pumps and turbines

Pumps are widely utilised on deep-level mine cooling systems to circulate water. These pumps are referred to as auxiliary equipment [87]. Auxiliary equipment operates self-sufficiently and is used to circulate condenser and evaporator water flow [88]. Auxiliary pumps are independently controlled and do not form part of the refrigeration units [54].

Depending on mining operations and delivery requirements, different pump configurations exist. Pumps are configured in either a direct-inline or parallel-set configuration. Figure 2-7 illustrates a direct-inline pump configuration and a parallel pump configuration. Direct-inline pump configurations supply water

to an individual refrigeration unit. Inline pump configurations are beneficial because variable speed control only disturbs individual chillers and not an entire refrigeration network [63].

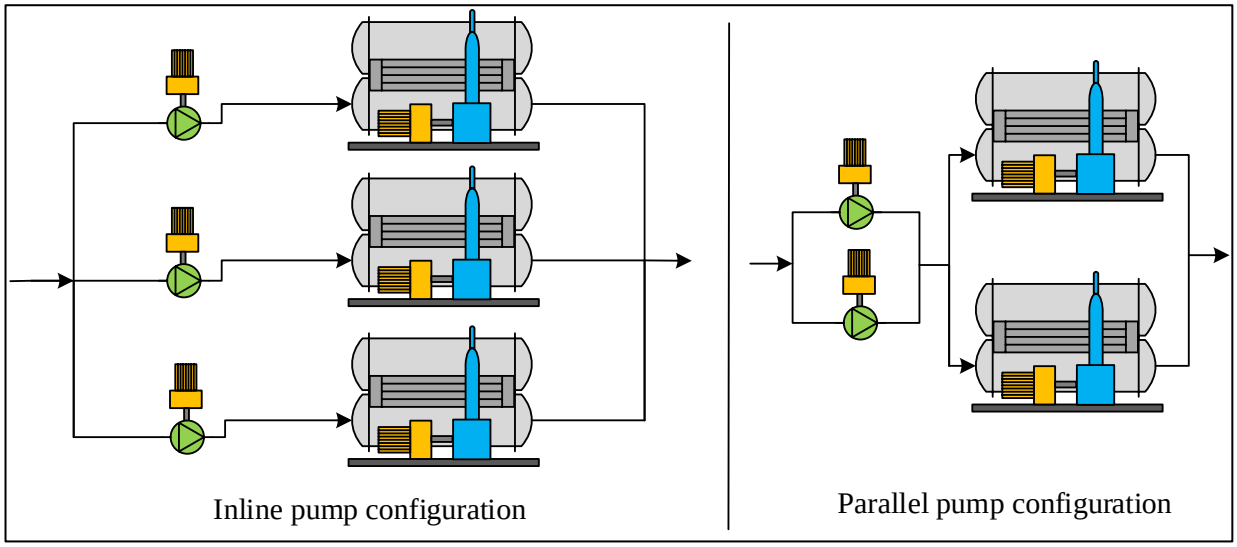

Figure 2-7: Auxiliary pump configurations [63]

Parallel pump arrangements circulate water into a conjoint pipe network to supply a network of chillers. Due to significant pressure drops over the conjoint pipe networks, parallel pump configurations require inlet chiller valves. The valves aid in sufficiently controlling the flow rate and pressure of water entering into the chiller [54]. Parallel pump configurations are complex and require extensive control strategies to affectively regulate the demand flow. Parallel pump configurations are preferred for their use in cascaded mine cooling systems.

Mines use single-stage axial and centrifugal pumps in water flow reticulation systems [89]. Although single-stage axial pumps are commonly used, multistage centrifugal pumps are favoured in current mining environments. Multistage centrifugal pumps provide improved serviceability, pumping capacity and availability [88]. Through improved scientific discoveries, computational fluid dynamics (CFD) analysis has enhanced pump design. CFD assisted in mitigating factors such as cavitation and surging to circumvent pump failure [90].

Within in a centrifugal pump, the fluid is typically accelerated radially by a rotating impeller. The fluid enters the impeller with a large quantity of kinetic energy. After being radially accelerated, the fluid is converted to pressure energy at the rotating impeller outlet [89]. The ability of the fluid to convert kinetic energy into pressure energy is largely dependent on the type of diffuser, impeller- and volute design [89].

The operational performance of a pump is typically expressed by means of a characteristic curve, as illustrated by Figure 2-8. To ensure optimal pump selection, a characteristic curve is necessary [91]. A characteristic curve allows for simplified pump selection by corresponding the system head (resistance) curve with the pump characteristic curve [91], as illustrated by Figure 2-8.

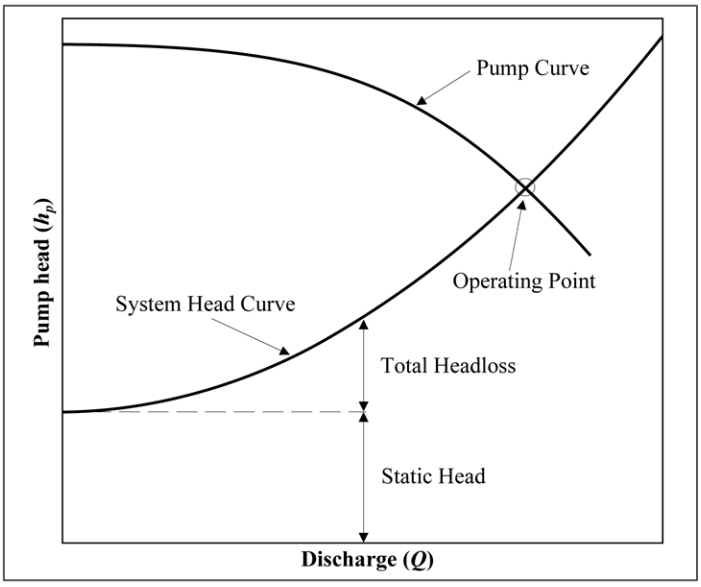

Figure 2-8: Pumps characteristic curve [92]

The point where the system resistance curve and pump characteristic curve meet is referred to as the operating point [93]. It is suggested that the operating point be selected within the highest pump efficiency range. The operating point with the highest efficiency is referred to as the best efficiency point (BEP). The BEP is selected to ensure the pump is operating at its uppermost achievable efficiency [89].

Figure 2-8 illustrates that for a system only comprising of static head, the operating point at a specific rotational speed is lower than that at higher speeds. Variations in speed cause the operating points to shift along the iso-efficiency curve line. This singularity is favoured for deep-level mine cooling system pumps with minor static heads and significant friction [37]. A system with substantial static head operates at an efficiency lower than the efficiency of the operating point [94].

In cases where the associated pump operates at efficiencies higher than the BEP, factors including 1) increased wear and tear rates, and 2) increased life-cycle costs (LCC) are rife. Although factors such as LCC include procurement costs, electricity costs and maintenance costs, all factors affecting LCC are to be considered [37].

The laws of similarity are used to govern the operation of a centrifugal pump [89]. The laws of similarity distinguish the diverse relationships among the operating parameters. The laws illustrate that changes in rotational impeller speeds will adjust the characteristic curve of the associated pump [95]. Although changes in impeller speeds are important, valve operations will affect the systems pressure and flow profiles further [93]. Controlling the pressure of a pump system is limited by valve operations [96].

The need to reduce energy consumption has led to the implementation of pump variable speed drives (VSDs) [97]. VSDs are mounted to the power supply of the motor [98]. The VSD modulates the motor

speed by converting the supply voltage to a variable- frequency and voltage. VSDs do not alter the torque output of the motor.

Implementation of VSDs on deep-level gold mine cooling systems has displayed significant energy savings potential [99]. The VSD varies the frequency, allowing the motor to operate in an unloaded phase. In an unloaded phase, the impeller speed is lowered. Consequently, the electricity consumption is reduced [100].

Although VSDs enhance energy-saving initiatives, reduced motor speeds can lead to concerns of the operating temperature of the motor. Studies have illustrated that speed reductions of approximately 50% have little effect on variable torque applications due to increases in temperature [100].

On deep-level mine cooling systems, pump configurations operate in variable torque applications. As a result, VSDs applications are preferred with insignificant effects on motor temperatures. Although, VSDs improve the chiller's efficiency, increased temperature requirements can lead to an increase in energy consumption. To ensure the energy savings potential is viable, it is suggested that the chiller's load is kept constant [58].

Other undesirable effects of VSD applications include harmonics and motor-bearing pitting. Harmonics are current or voltage waveforms on an electricity network with a different frequency to that of the electricity network [101]. Although harmonic filters have been developed, VSD can cause members on the electricity network to behave erratically. Installing isolated bearings and shaft grounding brushes reduces motor-bearing pitting [100].

Although VSD applications are ideal for increased energy savings potential, VSDs are commonly used to 1) extend the life expectancy of electric motors [102], 2) improve the system -reliability and performance of motors [103], 3) improve the correction power factor [104] and 4) provide reduced maintenance on motors [105].

According to studies, VSD installations have proven great success in: boiler houses [106]; cement plants [107]; gold mining cooling and ventilation systems [37]; petroleum plants [108]; and platinum mining cooling and ventilation systems [32].

Although centrifugal pumps are used extensively on mine water reticulation networks and cooling systems, their low maintenance and installation costs offer an economical way to recover energy [109]. To extract and recover pressurised energy, a hydraulic turbine is used. Traditionally, hydraulic turbomachines are categorised according to the type of energy used: potential; pressure; kinetic energy. Hydraulic turbines are more frequently classified as either action or reaction turbomachines [110].

In reaction turbomachines, the pressure head between the inlet and outlet of the impeller is varied. Varying the pressure flow transfers hydraulic power from the impeller into mechanical shaft power. Examples of reaction turbomachines include Francis and Kaplan turbines. Action turbines, however, utilise kinetic energy (atmospheric pressure) to transfer hydraulic energy into mechanical energy. Pelton and Turgo turbines are referred to as action turbomachines [110]. Reaction and action turbines are used for large and small hydropower technology. Figure 2-9 indicates the operating ranges of turbomachines. The operating ranges are dependent on the nominal flow and available head of the hydraulic turbines.

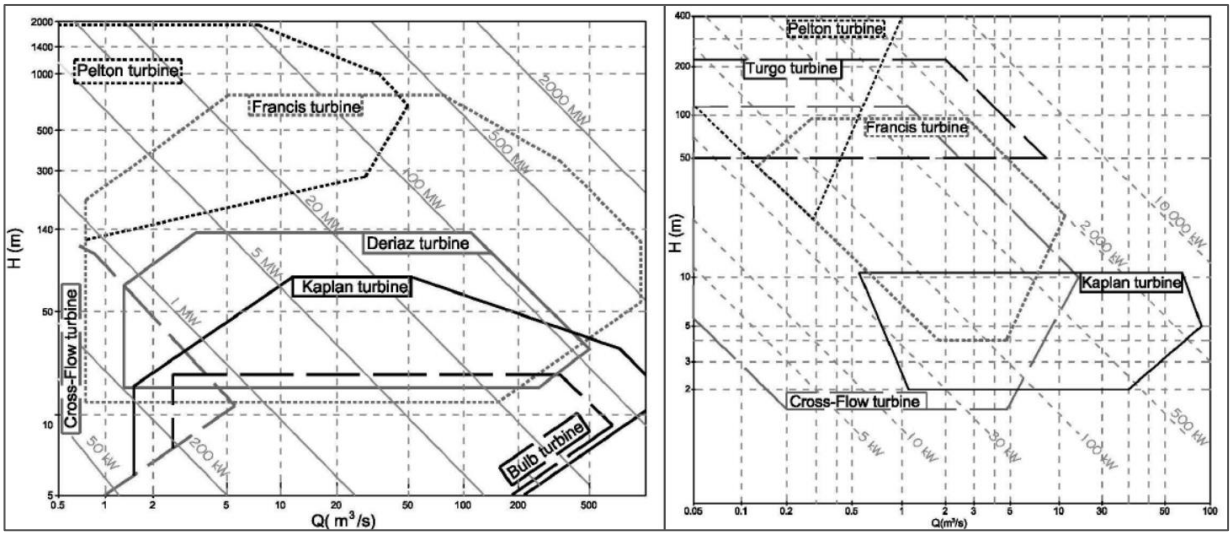

Figure 2-9: Turbine selection models for large (left); and small (right) hydropower [110]

Currently, most of the turbines installed for large hydropower are Pelton, Francis, Kaplan, or Deriaz turbines [111]. The performance of a turbine is expressed in terms of a performance curve, which depends on the specific speed and discharge number of the hydraulic turbine [112]. A study illustrated that performance curves assisted in increasing the efficiencies of turbines from approximately 50% in 1920 to above 96% in recent cases [113].

The efficiency of hydraulic turbines is categorised according to the turbine type and head ratio. For head ratios between 0.2 and 0.8, Pelton turbines experience efficiencies of approximately 90% [114]. At a similar head range, Francis turbines are less efficient. Francis turbines are approximately 85% efficient for head ranges between 0.9 and 1.

To extract and recover pressurised energy, hydraulic power recovery turbines (PRT) [115], tubular propellers [116], and positive displacement machines [117] are used. A PRT is a device that operates in two modes - as a pump and a turbine [109]. PRTs recover the available downstream head of the fluid, which is stored or used to power the pump. PRTs reduce energy costs and consumption [118].

As with pumps, the PRT is designed to meet a set of operating requirements. The performance of hydraulic turbomachines is found on different flow characteristic curves. These flow characteristics include: volumetric flow rate (Q); pressure head (H); power (P); and efficiency (η).

2.3.4. Heat absorption systems

Mines typically make use of: Surface and/or underground BACs; mobile cooling units; and spray chambers to provide artificial cooling. Artificial cooling is critical for sustaining a productive working environment [70]. BAC units are referred to as heat absorption systems and consume approximately 7% of a mine cooling systems total power consumption [74].

Air cooling of an underground mining network is performed by a centralised unit called a BAC [119]. BAC units are installed on the surface or underground level/s of a typical mineshaft. Water that is chilled from the chillers is stored in a surface cooling dam which is transported to the BACs using feeder pumps. BACs utilise the chilled water to cool the ambient air. Ducting transports the cool, dehumidified air underground. There are two types of BACs, namely; vertical and horizontal forced draft BACs [120]. Figure 2-10 illustrates a vertical forced draft BAC.

Vertical forced draft BACs are situated on the surface of a deep-level mine. Ambient air is extracted and displaced into the BAC with mechanically driven axial fans. The ambient air is extracted near the bottom of the BAC unit as the downward pressure energy pulls the air mixture into the shaft ducts, preventing the air mixture from escaping into the atmosphere. The cooled air passes through a mist eliminator filter to remove water droplets before being sent underground.

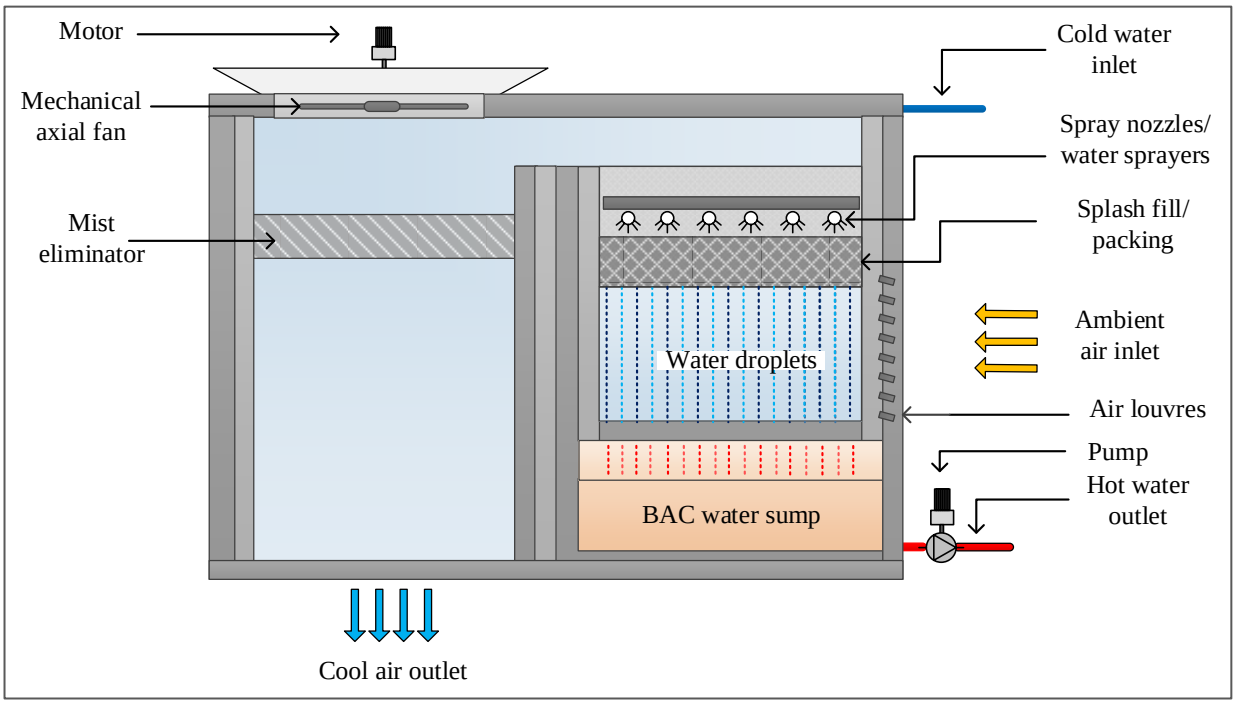

Figure 2-10: Schematic illustration of a single-stage vertical forced draft BAC [74]

Water nozzles spray chilled water mist from the chiller into the BAC unit. Thereafter, the water mist is gravity-fed into the BAC sump dam, which is pumped to the surface pre-cool dam. To ensure optimal heat transfer, the water and air flow in the opposite direction. The chilled water absorbs the thermal energy

of the ambient air. Vertical draft BACs are preferred over horizontal draft BACs because they are inexpensive and have a larger cooling capacity [68].

BAC units installed underground operate in either an open loop or closed loop water reticulation system. Open loop BAC systems consume unnecessary power to pump water from the BAC water sump to the surface chillers. Open loop BAC systems are considered inefficient.

As with the vertical forced draft BAC, ambient air is extracted and displaced into the horizontal BAC with mechanically driven axial fans. The air first passes through two cooling stages before passing through a mist eliminator filter to remove water droplets.

Water nozzles are located at the top and the bottom of the horizontal BAC. To ensure optimal BAC performance, it is crucial that the nozzles are accurately installed [73]. A uniform spray and airflow pattern is preferred. The water used from the sprayers to cool the air accumulates in a BAC sump dam. Chilled water from the first stage cooling is recycled in the second stage cooling chamber. Figure 2-11 displays a horizontal forced draft BAC.

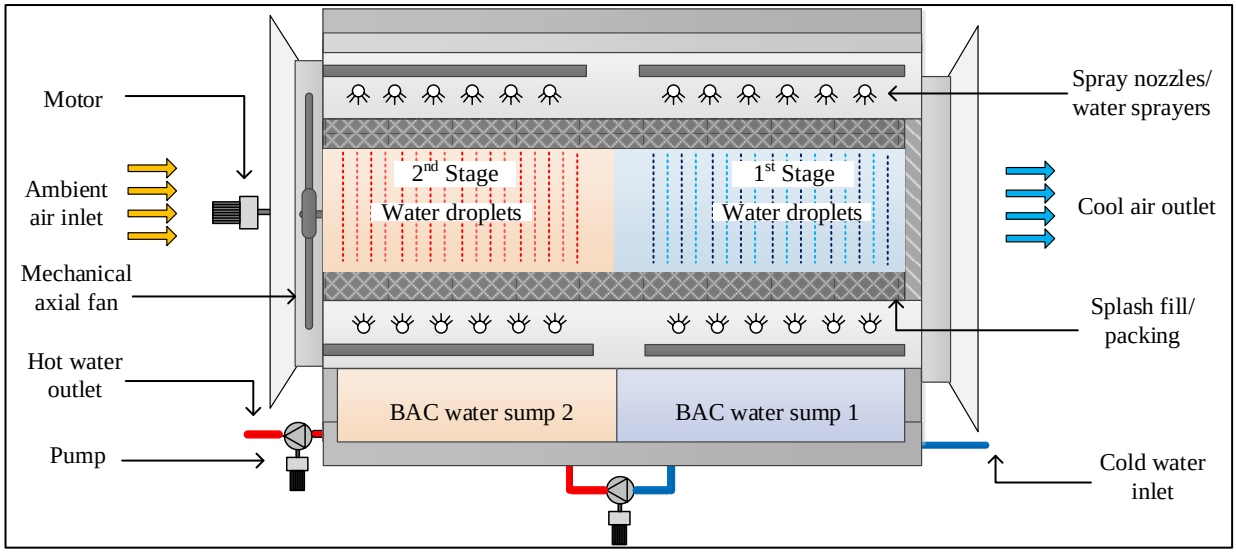

Figure 2-11: Schematic illustration of a multi-stage horizontal forced draft BAC [32]

Inefficient and ineffective BAC performance results in increased outlet air temperatures, which affect the cooling range of the chillers [73]. A temperature rise would significantly lower the COP of the cooling system [63].

The water-side efficiency of a BAC is calculated using Equation 2-4. The performance of BACs is dependent on the inlet temperature of the water and ambient air. During winter months, the ambient air is much cooler and BACs are not required. Typically, between June and August in South Africa, maintenance on BACs is conducted [54]. The water-side efficiency of a BAC has a large effect on the COP of chillers [121].

Equation 2-4: Water-side efficiency [36], [37]

$$\eta_w = \frac{T_{wo} - T_{wi}}{T_{ai(WB)} - T_{wi}} \quad [\%]$$

Where: [%]

$\eta_w = water - side\ efficiency$ [°C]

$T_{wo} = water\ outlet\ temperature$ [°C]

$T_{wi} = water\ inlet\ temperature$ [°C]

$T_{ai(WB)} = air\ inlet\ WB\ temperature$ [°C]

The water-side efficiency is expressed in terms of range and approach [122]. The approach of the BAC water-side efficiency equation is defined as the difference between the air inlet WB temperature and the water inlet temperature, $T_{ai(WB)} - T_{wi}$. The range of the BAC water-side efficiency equation is defined as the difference between the outlet and inlet water temperature, $T_{wo} - T_{wi}$ [45].

2.3.5. Heat rejection systems

Mines use heat rejection cooling towers to provide artificial cooling. Return service water is cooled in pre-cooling towers before entering into the evaporator flow circuit. In addition, condenser towers are used to cool condenser water within the condenser flow circuit [53]. Thermal energy from the water is transferred through heat rejection to the ambient air. Processes including evaporation and convection removes heat from the water [73].

As with BACs, mine cooling towers are categorised as direct heat exchangers. Although, cooling towers are similar to the operation of vertical forced draft BACs, the heat transfer direction is opposite [123]. A schematic illustration of a mechanical draft cooling tower is depicted in Figure 2-12. Mechanical draft cooling towers are predominantly used on surface cooling systems at deep-level mines [72].

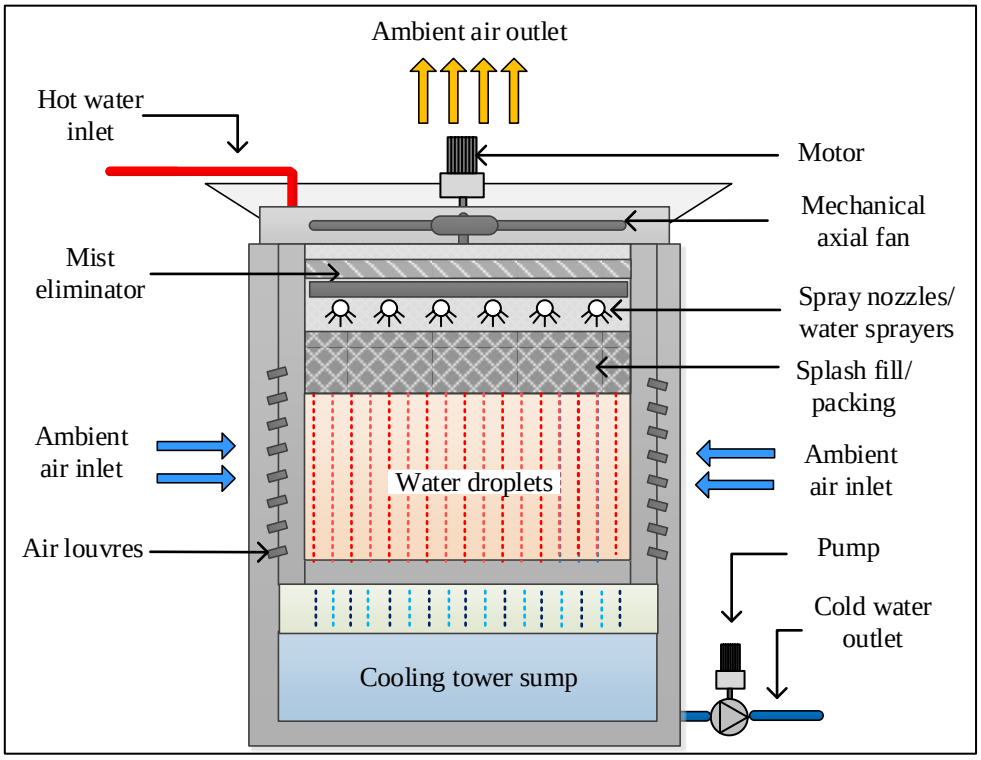

Figure 2-12: Mechanical draft cooling tower (adapted from [36])

Hot mining water enters the mechanical draft cooling tower and passes through nozzles that disperse the water. Consequently, the cooling tower is filled with water droplets [124]. Large water droplet formation results in increased heat transfer which consequently improve the thermal efficiency of the cooling tower. Important properties such as inlet water temperature and flow rate affect the size of the water droplet formation [124].

Ambient air is extracted and displaced into the cooling tower with mechanically driven axial fans. The air and water travel in a counter-flow direction. The air and water are mixed and passed through the packing. The packing distributes the flow evenly throughout the cooling tower chamber, increasing both contact time and area between the fluids [63]. Consequently, thermal heat transfer is increased, resulting in a higher thermal performance.

After thermal heat transfer the cooled water is stored in the cooling tower sump. Thereafter, the water is transported to the evaporator or condenser flow circuit. Water within the cooling tower sump is lost through evaporation and drift [63].

Cooling towers operate at high COP values of approximately 30 [54]. Research has proved that the performance of a cooling tower is largely dependent on the operational properties of ambient air and water. Properties such as temperature, flow, enthalpy and humidity affect the efficiency of cooling towers [35]. Uneven flow distribution patterns leads to scaling and fouling [54]. Scaling results in the collection

of sediments and impurities on important cooling tower components. Employing regular maintenance can prevent scaling, which will largely enhance the heat transfer performance.

2.3.6. Thermal storage dams

Cooling systems require storage capacity for reticulating mine water. Thermal dams provide storage capacity for both hot and cold service water [73]. Such dams increase the chilled water supply capabilities of the chillers [73]. Due to the daily change in demand requirements of service water, storage dams provide a viable solution for storing excess or unused water. The volatility of service water demand requirements is primarily attributed to seasonal changes [125]. Such changes reduce operating temperatures which prompt the operation of fewer chillers.

To ensure optimal operational performance, chillers are required to maintain set chilled dam water temperatures [67]. The volatility of mine water reticulation networks makes it difficult to meet such temperature set points. To prevent thermal losses, storage dams are thermally insulated [63]. In addition, thermal storage dams are placed in close proximity to prevent frictional losses [64].

Mines require pumps to reticulate mine water when thermal storage dams reach maximum capacity. Pumps, however, are energy-intensive components. Mines prefer to adopt manual valve operations to throttle chilled water through storage dams. Throttling water with valves is inefficient [126]. Adopting variable flow control is largely preferred [127].

Due to poor water quality, contaminants are frequently deposited into storage dams [128]. These contaminants lead to the accumulation of sediment build-up. Sediment build-up reduces storage capacity which restricts dam level control [54]. To prevent contamination of mining water, mines utilise settlers to purify water. Settlers improve water flow transportation within a water reticulation system [128].

To ensure optimal water reticulation, regular maintenance on cooling system components is crucial. Studies have illustrated that regular maintenance has realised significant electrical cost savings [129]. In addition, frequent maintenance can lead to reduced labour costs [54].

2.3.7. Water service valves

It is very important to regulate the flow of water in cooling systems. Pressure caused by head in pipe networks may result in pipe damages if the water is not controlled optimally [130]. A common method to control the flow of water is with the use of an actuated valve [131].

A valve is a device that regulates the flow and pressure of a fluid in a cooling system. In water reticulation systems, valves ensure that the water supply networks are within the designed service conditions [132]. Valves divert water flow to minimize service disruption.

In a mine's water reticulation system, valves are installed along pipe networks, pump stations and thermal storage dams. Valves are used for isolation, to prevent backflow and control the flow of water entering and exiting a storage dam.

Valve selection is critical for meeting the optimal delivery flow. Valve sizing and selection are calculated using Bernoulli's equation [133]. To ensure optimal valve selection, a list of service conditions must be compiled. Such conditions include fluid properties, flow rates and pressure requirements [134]. The valve flow factor best describes the relationship between the flow rate and pressure drop over a valve [135]. Higher flow factors are indicative of increased flow capabilities.

Valves are categorised by their operating method; manual or automatic [132]. Commonly used valves include; gate, butterfly, ball, globe and pressure-reducing valves, all of which serve different purposes. In mines, most valve positions are operated with pneumatic and hydraulic actuators. Actuators are controlled with a control signal and source of energy (pneumatic or hydraulic energy). Butterfly valves have a smaller control range when compared to that of globe valves [134].

The sizing of valves is crucial. Inaccurate actuator specifications may lead to the valve plug being forced into the valve seat [136]. Inaccurate valve control may lead to flow obstruction which may prompt turbulent flow.

Within the water pipe network, water reaches high flow velocities. At such velocities, the static liquid pressure drops below the vapour pressure, leading to the formation of bubbles. This process is referred to as cavitation [137]. Cavitation leads to the concentration of pressure which generates shock waves that destroy the valve trim [137]. Studies have illustrated that cavitation is more prominent on rough surfaces [138].

During valve operation, valves are often suddenly shut. When water hits the valve, the change in pressure creates a shock wave. The shock wave propagates throughout the pipe network [139]. This phenomenon is called water hammer. Water hammer is the conversion of a fluids momentum into pressure energy [140]. Water hammer is harmful to instrumentation and may lead to pipe separation [141].

Mine water reticulation networks are created to provide water to consumers at adequate pressures [142]. Inadequate pressure requirements could lead to production losses. Mechanical failure of valves will be detrimental to the system performance of a mine. To ensure optimal valve operations, valves must be regularly maintained.

Energy-intensive mine cooling components were thoroughly discussed and reviewed. Mine cooling components and subsystems were characterised to identify cost savings potential. The optimisation of these components will be discussed in the following section so as to develop a simple and practical control

strategy to reduce electrical energy consumption on mine cooling systems, as suggested by the need for this research study.

2.4. Cooling system optimisation strategies

2.4.1. Preamble

Mine cooling systems are required to function in volatile mining conditions. Consequently, optimal control is difficult to achieve. Mines require an integrated energy management system (EMS) to reduce inefficient control [119].

The implementation of simple, integrated EMSs are not well-versed topics in industrial processes such as mine cooling [143]. Corsini *et al.* [144] developed a multivariate KPI for energy management of cooling systems in the food industry. This study identifies a new KPI that relates energy consumption to different process variables. Ayyash *et al.* [145] developed a method that analyses the economic benefit of energy management measures on air-conditioning systems in Kuwait. Vosloo *et al.* [34] established a technique that simulates and controls the water reticulation network of a mine. There is a need for a similar technique that is able to dynamically control mine cooling systems, remotely, by means of an integrated approach.

An EMS for large integrated cooling systems was developed, tested and implemented [71]. Du Plessis *et al.* [71] developed REMS-CA™ that collectively controls mine cooling subsystems. The control system utilises a hierarchical control that optimises set points for these subsystems. This remote-control system is limited to chilled water pumps and water control valves. Therefore, a need still exists for a simple EMS that provides automated and remote control of entire mine cooling systems by means of an integrated systems approach. In addition, Dzene *et al.* [146] implemented a study that emphasised the need of an energy management plan to obtain sustainable energy performance.

Within this section, current employed EMS strategies will be analysed and integrated to identify areas of improvements. This section will focus on strategies that reduce power consumption and enhance operational performance to sustain energy and cost savings on mine cooling systems. Load management strategies will be firstly evaluated and analysed.

2.4.2. Load shifting optimisation techniques for cooling systems

The success of load management optimisation techniques relies largely on the Eskom time-of-use (TOU) tariff periods, thermal storage capacity and environmental circumstances [147]. Prior to the implementation of load management strategies, factors such as mine safety and production must be considered [148]. Several load management strategies have been implemented that utilise the

technologies mentioned above. The following load shifting strategies are implemented on mine cooling systems:

- Thermal storage capacity
- Chiller shutdowns
- Back-pass valves
- Thermal ice storage, and
- Temperature set point controllers.

To accurately enhance load shifting potential, process parameters are investigated. Load shifting may not compromise the integrity of such parameters. The parameters include; dam level percentages; temperatures; chiller flow rates; and machine operating constraints [129]. The parameters are determined with the assistance of mine personnel [149].

Thermal storage capacity

The application of thermal storage dams offers significant load management potential. Thermal storage dams behave like a form of capacitance that stores unwanted cooling energy [62]. Managing thermal storage capacity, according to the TOU tariff periods, has proven to be a viable load shifting strategy. Increased cooling capacity allows the cooling load to be shifted into the Eskom off-peak periods. Subsequently, large cost savings are realised.

Chiller shutdowns

To ensure optimal chiller load shifting, the cooling system's thermal energy must be effectively balanced [62]. This is achieved by providing adequate chilled water for mining operations. During the off-peak TOU tariff periods, water is chilled. The chilled water is stored in a chilled dam and is supplied to the mine for mining operations during the peak TOU tariff period. During the peak TOU tariff periods, the chiller and its cooling auxiliaries are shutdown [62]. Optimal load shifting of chillers is optimal with the use of an automated system [149]. Significant cost savings are realised during chiller shutdowns in the peak TOU tariff periods.

Thermal ice storage

To reduce the cooling load on chillers, mines make use of ice slurry systems. Ice slurry dams store ice that is used to supply the mine with chilled water during Eskom's evening peak periods. Due to the latent heat of fusion, ice will supply cooler water compared to the chilled water supply from surface chillers. Thermal ice storage uses cooling capacity to reduce the cost of cooling during peak periods.

When the ice water is required, warm evaporator water is pumped through the ice plant to melt the ice. Ice plants provide increased cooling capacity that reduces the flow of water to the mine [88].

Back-pass valves

A chillers cooling load during the peak period can be further reduced with the utilisation of back-pass valves. The back-pass valve system consists of an actuated control valve and connecting pipe section. The back-pass valve ensures that the flow is varied to maintain a constant pre-determined evaporator discharge temperature. The back-pass valve control is indicated by the purple square in Figure 2-13.

The valve transports the chilled chiller water to the chiller inlet. At the inlet, the chilled chiller water mixes with the warm inlet chiller water to reduce the inlet chiller temperature [150]. Consequently, the compressors' IGVs cutback (supply less refrigerant) and power is saved. Utilisation of the back-pass valve control is beneficial during the Eskom peak periods. It is suggested that for maximum peak period load reduction, the back-pass valve control only be utilised during the peak periods. Efficient back-pass valve control can prompt complete chiller shutdown.

During winter months (June to August) there is a decreased demand for cooling. Lower ambient temperatures reduce the need for chillers and subsequently, the need for load management. Complete load shift management is only viable in summer months.

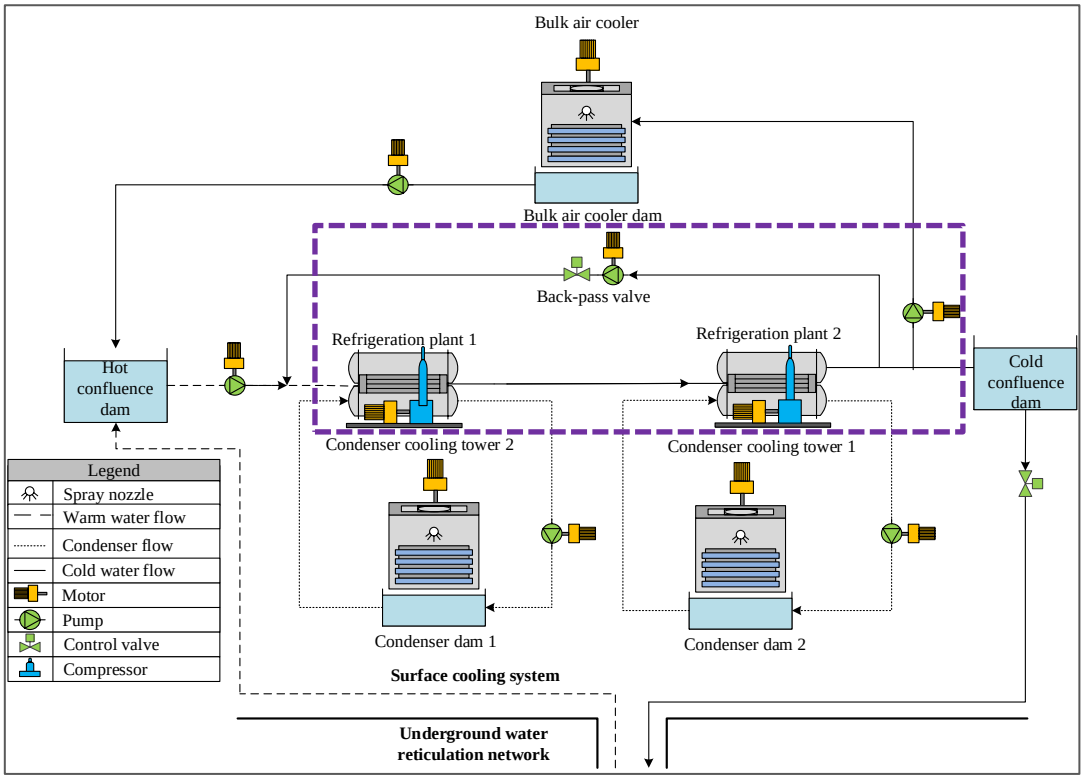

Figure 2-13: Back-pass valve control

Temperature set point controllers

The cooling load is further managed with proportional-integral (PI) controllers. PI controllers use control loop feedback systems that modulate chiller temperature control [151]. PI controllers control the chiller outlet temperature to a desired temperature set point. The compressor IGVs are controlled to meet the desired outlet temperature set point. Stricter temperature set points in the off-peak periods accommodates for effective load reduction during the peak periods.

The implementation of load shifting strategies are only beneficial for peak period power consumption reductions. Load shifting strategies should be critically analysed to create an adaptable energy management solution.

2.4.3. Energy efficiency optimisation techniques for cooling systems

State-of-the-art technologies have proven that variable-flow control on mine cooling systems has adequately benefitted system efficiency. Variable flow control is achieved with the use of VSDs. The VSDs provide automatic variable control with the use of an integrated EMS [61]. Various energy efficiency strategies utilise VSDs for improved control. Significant energy savings were realised with the application of VSD in the mining sector [152].

VSDs are mounted on the power supply of the motor [98]. The VSD modulates the motor speed by converting the supplied alternating current to a variable frequency and voltage. VSDs do not alter the torque output of the motor and have proven to be most effective whilst operating at varied loads [98].

VSDs are typically installed on condenser pumps, evaporator pumps and transfer auxiliary pumps. VSDs are used for various variable flow applications other than mine cooling systems. Several variable flow control strategies for mine cooling systems have been developed. The following mine cooling circuits utilise VSDs for variable flow applications [37], [45]:

- BAC circuit flow control
- Condenser circuit flow control
- Evaporator circuit flow control, and
- Pre-cooling circuit flow control

BAC circuit flow control

A variable flow optimisation technique was developed for the BAC circuit flow [37]. The BAC circuit flow strategy is constrained by the outlet air temperature of the BAC [35]. It is suggested that the BAC outlet air temperature does not exceed 8°C DB [37].

BACs were typically designed to operate at full load capacity. At full load capacity the temperature outlet is significantly reduced. During the winter months (June to August), however, full load capacity resulted in over-cooling. Installing VSDs on the BAC transfer and feeder pumps, enabled partial-load control with no effect on outlet temperature parameters. This strategy utilised VSDs on BAC feeder pumps to reduce the load dependent on environmental conditions [61].

Depending on the mine cooling system configuration, additional BAC variable flow optimisation techniques were developed. BACs utilised throttle valves to throttle the flow though the BACs for better full load control.

During operation, the valve is partially or fully open to regulate the flow to meet design conditions [36]. To prevent unnecessary pumping, an optimisation technique to include BAC sump dam levels was considered.

VSDs on BAC return pumps are typically controlled with closed loop proportional-integral-derivative (PID) controllers [63]. The controllers control the BAC sump dam level optimally for sufficient cooling and ventilation. The BAC circuit flow control is indicated by the purple square in Figure 2-14.

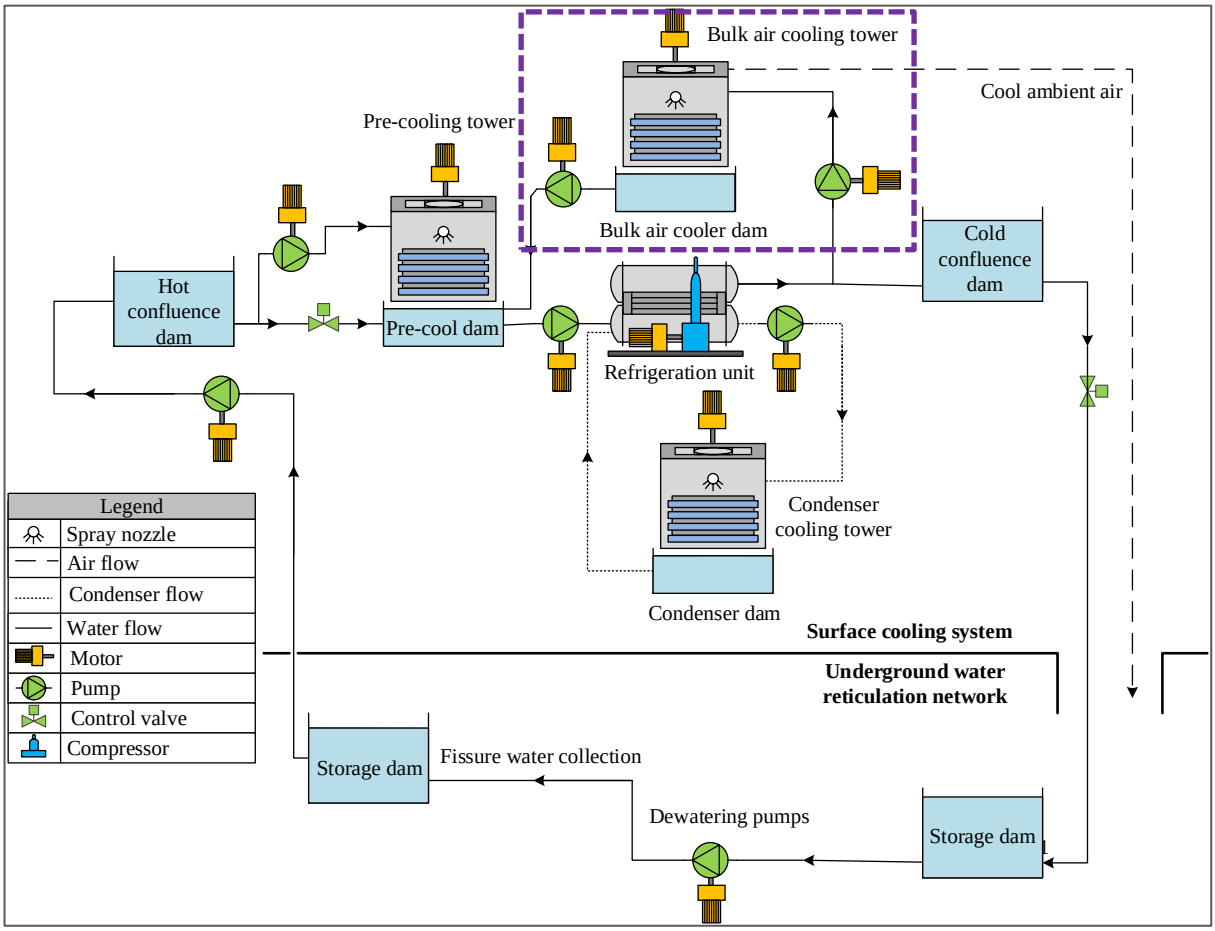

Figure 2-14: BAC circuit flow control

Condenser circuit flow control

A variable flow optimisation technique was developed for the condenser circuit flow in a typical mine cooling system [99]. The optimisation technique was applied to the condenser of the chiller [57]. As with the BAC circuit flow control, the condenser circuit flow is controlled with the installation of VSDs. The VSDs are installed on the condenser pumps of the chiller. The condenser circuit flow control is indicated by the purple square in Figure 2-15.

The VSDs utilise closed loop PID control to control the water flow rate through condenser pump [61]. The condenser PID control ensures a stable delta temperature across the condenser of the chiller [58].

When installing VSDs for the application of varying the load, it must be noted that the water flow rate may not be varied by more than 60% of the full load capacity [36]. As with BAC circuit flow control, throttle valves are utilised for complete design load control.

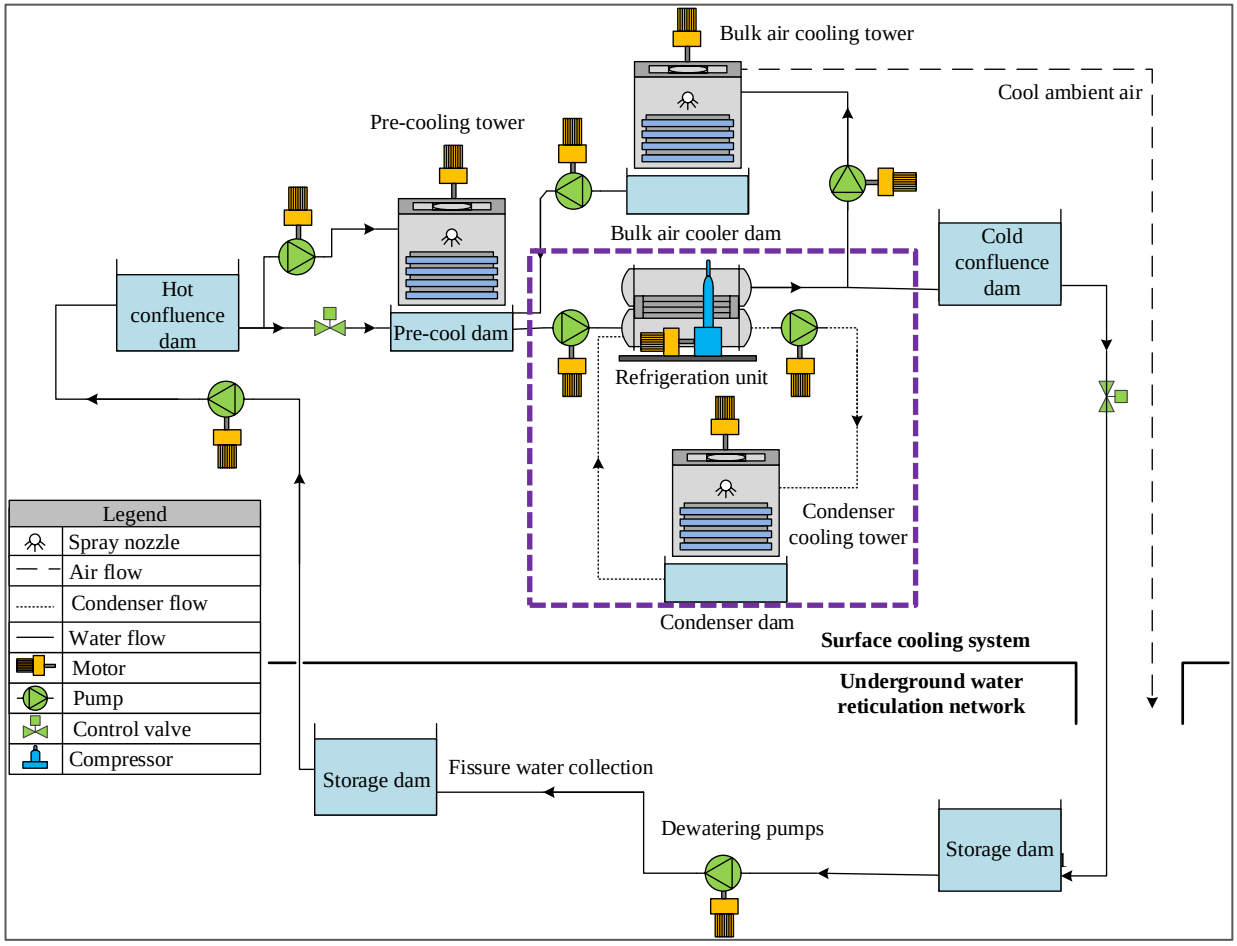

Figure 2-15: Condenser circuit flow control

When implementing condenser circuit control, factors such as scaling/fouling, reduced COP and increased chiller power usage cannot be ignored [33], [36], [37]. Together with these factors, it is essential to evaluate the flow distribution in the condenser cooling tower for optimal heat transfer [53].

Condenser circuit flow control cannot ignore the effects of environmental ambient conditions [103]. Ambient temperature conditions can adversely affect the outlet condenser water temperature. Condenser circuit flow optimisation techniques have realised large energy reduction cost savings [58].

Evaporator circuit flow control

A variable flow optimisation technique was developed for the evaporator circuit flow in a typical mine cooling system [153]. The optimisation technique was applied to the evaporator of the chiller [37]. Similar to the condenser circuit flow control, the evaporator circuit flow control utilises VSDs on the evaporator pumps. PID controllers are used to control the water flow rate through the evaporator of the chiller to achieve a desirable evaporator outlet temperature. The evaporator circuit flow control is indicated by the purple square in Figure 2-16.

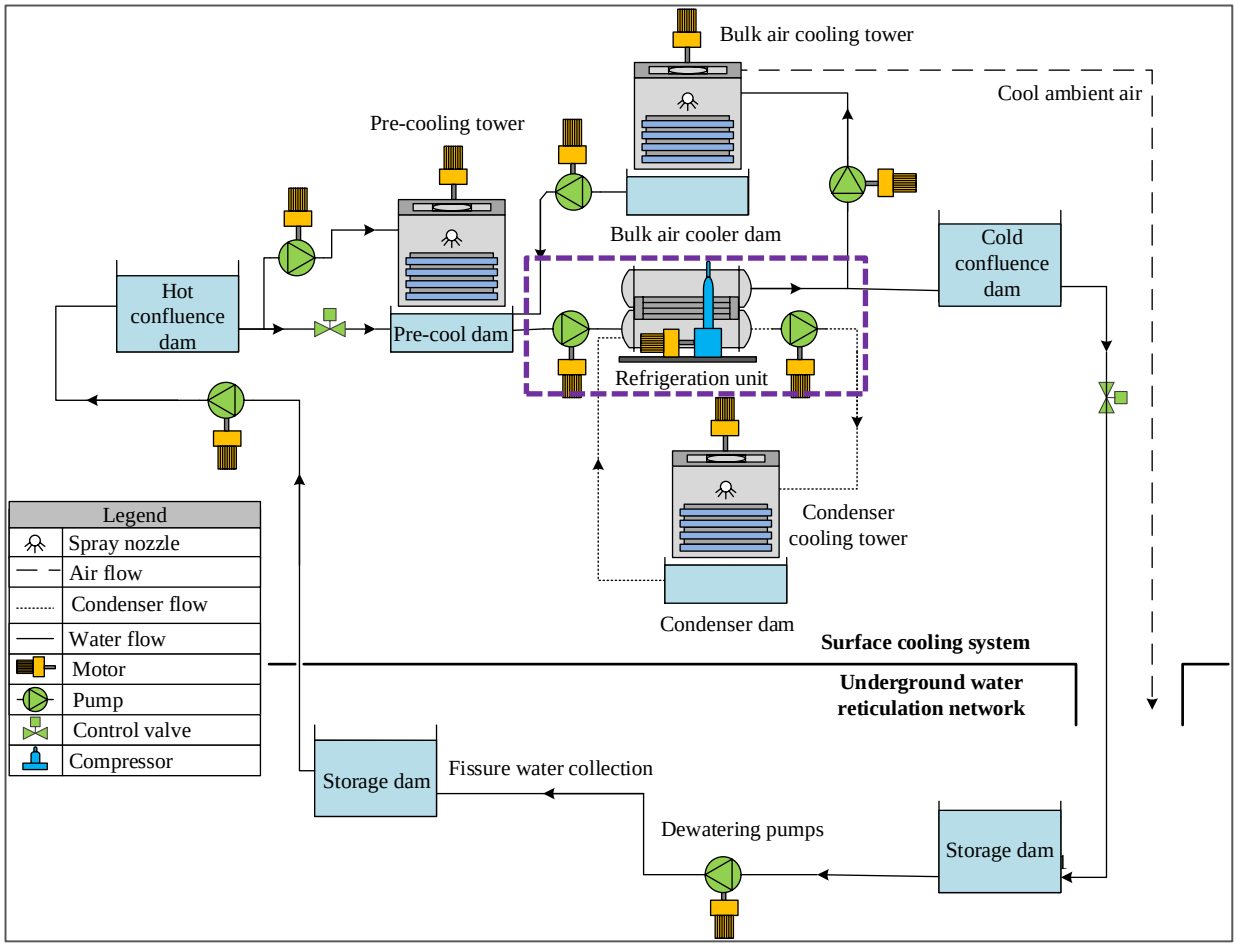

Figure 2-16: Evaporator circuit flow control

To ensure optimal mine performance, the evaporator circuit flow control is responsible for supplying sufficient chilled water to all the mine water consumers [35]. Hence, the evaporator circuit flow control is constrained by the evaporator outlet temperature [73]. Due to temperature constraints, the study of evaporator circuit flow control optimisation excludes valve throttling [58]. In addition, due to temperature constraints, back-pass valve control from the condenser circuit to the pre-cooling circuit is not required.

Through optimised evaporator circuit control, chillers are able to maintain a stable outlet evaporator temperature. To maintain the desired evaporator outlet temperature set point, chiller compressor control is necessary. Chiller compressors are controlled using programmable logic controllers (PLCs) and PID controllers to meet the desired temperature set point. Consequently, the refrigerant flow rate is reduced, yielding significant cost savings [154].

Pre-cooling circuit flow control

Pre-cooling circuit flow control was adapted from the implementation of evaporator and condenser flow optimisation techniques in mine cooling systems [61]. The pre-cooling circuit flow control utilises VSDs on the pre-cooling sump transfer pumps to supply pre-cooled water at partial-loads [37]. The VSDs use PID control to ensure a stable pre-cooling sump dam level. The pre-cooling circuit flow control optimisation has yielded favourable energy savings. The pre-cooling circuit flow control is indicated by the purple square in Figure 2-17.

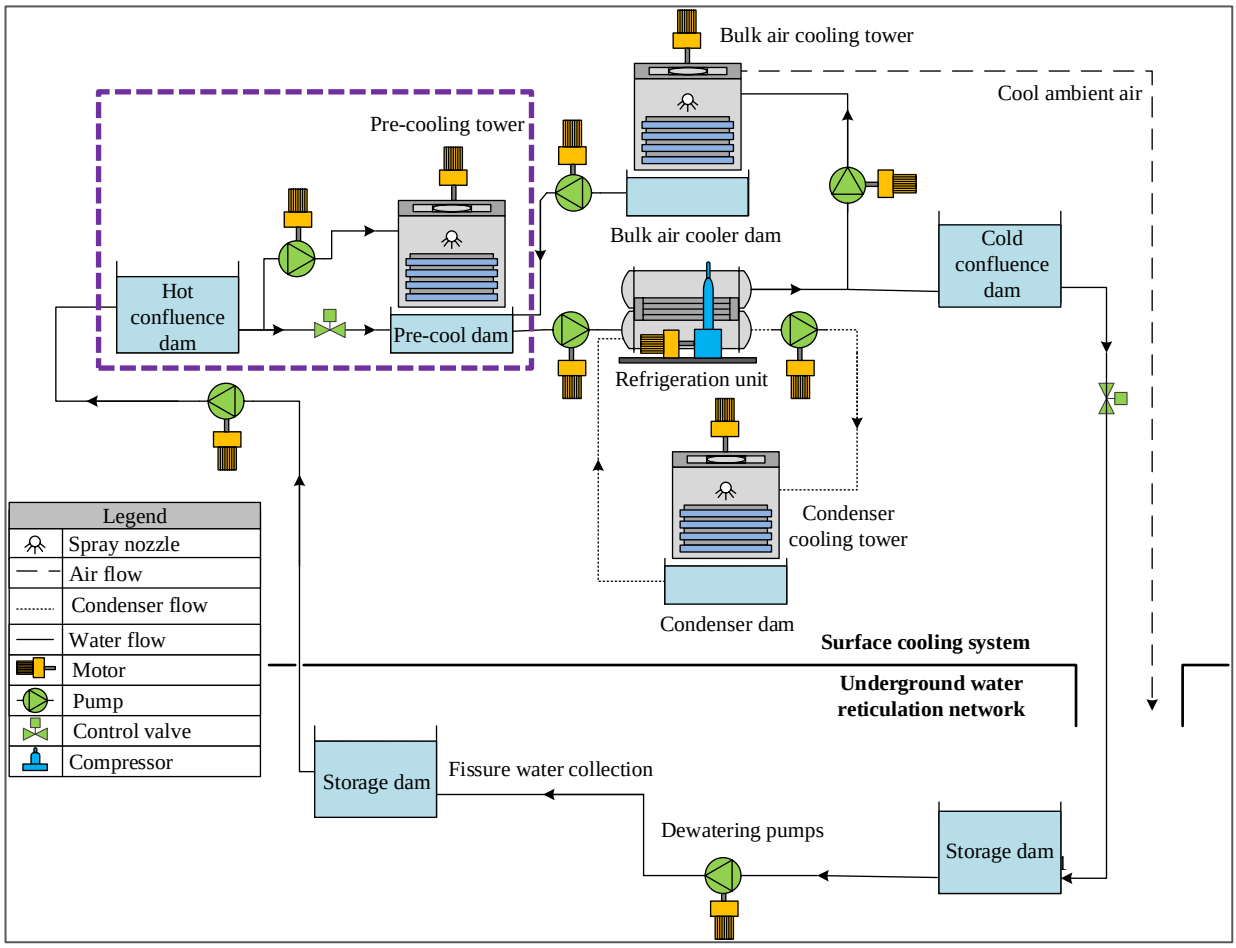

Figure 2-17: Pre-cooling circuit flow control

Similar to the evaporator circuit flow control, throttling valves are left completely open for optimal control. Open throttle valves ensure a balanced dam level system with favourable pre-cooling water sump temperatures.

As with condenser circuit flow, the pre-cooling tower performance is to be considered. It is essential to evaluate the flow distribution in the pre-cooling tower for optimal heat transfer [53].

Variable flow optimisation techniques are crucial for meeting optimal design flow requirements. The application of VSDs on: BAC circuits; evaporator circuits; condenser circuits; and pre-cooling circuits has returned favourable energy savings. Variable flow has established itself at the core for supplying sufficient chilled water at varied load capacities.

2.4.4. State-of-the-art cooling system optimisation strategies

Energy efficiency enhancement with the application of robust control systems and technology [155] has established massive focus. More specifically, the application of variable speed drives (VSDs) on auxiliary pump systems of chillers and mine cooling system components [61], [156], [157] have revealed significant cost savings. Du Plessis *et al.* [61] identified a potential cost saving of US$8.1million with the implementation of VSDs on chiller compressor motors. In their study, however, a payback period of 4 years was anticipated.

Qureshi and Tassou [158] reviewed the application of VSD chiller capacity control that revealed compressor savings of 12-24%. In addition, Aprea *et al.* [159] developed a fuzzy control algorithm to control the compressor speed of a vapour-compression refrigeration plant. Besides the cost of the inverter, this study realised an energy saving of approximately 13%. Due to the economic imbalances in the South African mining industry, it can be seen that it is not viable to continue with the application of VSDs in large integrated cooling systems. Although, such strategies have anticipated cost savings in excess of US$2.2 million [160], initial installation is costly [161]. Therefore, the potential for an optimised and cost-effective compressor power reduction strategy requiring no capital outlay remains.

Over the past years, various control models and energy saving measures have been developed for enhanced performance of cooling systems. Most of these control models do not from part of an integrated systems approach [160], with only specific considerations of certain subsystems and components. Sen Huang *et al.* [162] developed a new cooling load base chiller sequencing control (CLC) method that incorporates a Model Predictive Control (MPC) framework. In this study, Sen Huang *et al.* [162] utilised the MPC framework to identify the optimal critical utilisation points of the chillers, as well as the condenser water tower temperature set points. In their study, the MPC framework predicted the ambient WB air temperature to generate the optimal water temperature set point for the condenser tower. The study, however, assumed a static chiller outlet temperature set point. Therefore, there remains potential for the application of a similar predictive model that incorporates a dynamic chiller temperature set point algorithm.

Sun *et al.* [163] developed a strategy for energy efficiency through improved chiller sequencing control. The study calculated the instantaneous cooling loads of buildings using data fusion to determine the optimal chiller utilisation sequence. However, the study only focused on building automation systems. Therefore, there is scope for improving chiller control and utilisation in the mining sector.

Chow *et al.* [164] utilised optimisation modelling to achieve energy savings in HVAC systems in the building sector. In their study, an integrated optimisation strategy with water-cooled chillers, variable speed turbomachinery and heat exchangers was considered. A similar simulation modelling optimisation strategy by Fong *et al.* [165], considered ambient air temperature set point and water inlet temperature set point as important control variables for HVAC systems. The study achieved energy savings in excess of 0.15% per annum on HVAC systems, but failed to incorporate dynamic set points for variable cooling requirements. Vakiloroaya *et al.* [166] explained that ambient air DB temperatures and cooling demands were considered uncontrolled variables, which negatively impact the performance of simulation optimisation studies. Therefore, there remains a need to reduce the severity of ambient air temperatures on the performance of similar cooling systems in the mining sector.

Afram *et al.* [167] reviewed simulated industrial cooling optimisation models and concluded that simple and practical models should be considered to achieve stable and accurate control. Ding [168] stated that although simulation-based optimisation modelling strategies have yielded significant energy savings, the effects on accurate and stable control has shown no adequate improvement. Therefore, simple and practical models are required for accurate control of mine cooling systems.

2.4.5. Evaluating automated and manual control optimisation techniques

System control and automation

Field control on mine cooling systems utilise an integrated process management tool called a supervisory control and data acquisition (SCADA) system [169]. The SCADA uses PLCs and discrete PID controllers to interface with field instrumentation. The PLCs interact with field instrumentation and the SCADA using open platform communication (OPC).

SCADA systems are capable of gathering and logging data from field instrumentation. Field instrumentation used on cooling systems include thermocouples, power meters, flow meters, pressure sensors and dam level sensors [170]. The historical data is primarily used for forecasting. To ensure accurate data collecting, field instrumentation must be calibrated. Measuring errors can be mitigated through regular maintenance of field instrumentation.

Components such as chillers are controlled with PLCs located at the chiller house. The PLCs control temperature parameters, compressor IGVs, pressures and water flow rates through the evaporator pumps. To ensure accurate control and optimal component performance, errors are eradicated.

Chiller automation is necessary to control chillers and their auxiliaries from remote locations. Automatic chiller control needs to be implemented to ensure both human and machine safety. Various monitoring systems are required for the safe operational performance of automated control systems [88]. Monitoring systems that incorporate alarm notifications are crucial for improved performance.

Mining operations benefit greatly from automated control systems [133]. Automated control systems can adapt to dynamic system responses prior to human intervention. Automated control systems that involve human intervention are undesirable - humans have behavioural inconsistencies that can negatively impact control systems. Automated systems provide reliable control systems that maximise energy savings [171].

Chillers can be controlled either locally or remotely. Remote system control utilises automated infrastructure to control the chillers. Manual chiller control utilises an operator to send a start or stop signal to the chiller. Manual chiller control is predominantly used in the mining industry. The industry is evolving towards completely automated systems. Such systems utilise computers to determine the necessary control decisions [172].

Manual control

With manual control, operators typically monitor the SCADA and make an intuitive decision to start or stop a chiller. Manual control is primarily preference-based and entails the application of no scientific models or patterns. Mines, and labourers within the mines, have adapted to manual control, and hence manual control is preferred. Preference of manual control makes it difficult to motivate mines to utilise automated control systems [149].

Manual control was widely utilised on dewatering pumps in mines. The control room operator would monitor hot and cold dam levels to initiate the start-up or shutdown of a pump. The control room operator would communicate with the pump operator underground to start or stop the pump. This process was tedious and utilised minimal computerised participation [133].

Automated control

Chiller automation is necessary to control chillers and their auxiliaries from remote locations. To ensure optimal automated chiller control, health and safety requirements are to be adhered to. Consequently, automated control systems are required to be accurate and adapt effectively to dynamic system responses. The control system may become vulnerable if the automated system is not accurately installed and calibrated. Unlike manual control, automatic control thrives optimally with little to no human intervention. Automated systems require additional infrastructure, as stipulated by the requirements below:

- *Connection cables* [172]: Fibre-optic cables are used to communicate with the PLCs from a centralised control point. The control systems send a signal to the PLCs through the fibre-optic cable network.
- *Networking equipment* [173]: Important equipment such as; PLCs, the SCADA system and computers are required to ensure safe and stable networking with field instrumentation.
- *Field instrumentation* [174]: Installation and calibration of important field instrumentation is required. Field instrumentation includes; flow meters, temperature sensors, pressure transmitters and dam level sensors. All are necessary for effective chiller control.

A completely automated control system utilises a software package to interface with the field instrumentation. The software exploits process parameters to correctly start and stop chillers and their auxiliaries. Table 2-1 illustrates a compilation of advantages and disadvantages of auto or manual control.

Table 2-1: Advantages and disadvantages for automated and manual control systems [172]

Control	Advantages	Disadvantages
Manual	No additional infrastructure	Unsustainable data logging
	Short implementation period	Inefficient monitoring of process parameters
	No additional training of operators	Human supervision errors
	Reduced costs	Labour Union interventions
Automated	Accurate data logging	Installation of additional infrastructure
	Continual monitoring of process parameters	Costly due to additional infrastructure
	Immediate dynamic system responses are diagnosed	Additional maintenance
	Sustainable energy savings	Long implementation period
	Effective utilisation of predetermined chiller schedules	System required to respond to dynamic circumstances

To ensure dynamic system responses are accurately and efficiently detected, automated systems are required. Although, mines favour manual control, automated systems have returned encouraging results. It is believed that optimal chiller control is achieved through automating chillers and their cooling auxiliaries [33].

2.4.6. Investigating simulation software for optimised mine cooling control

Deep-level mine cooling systems are considered large complex systems. To accurately evaluate and analyse mine cooling challenges, dynamic simulation software packages are utilised [30]. Van der Bijl suggested that a simulation model with an error percentage of less than 10% is sufficient for mine cooling uses [129]. Prior to the implementation of control optimisation techniques, simulation software is used to predict the costly impact of such optimisation techniques [30]. Similarly, simulation software has a significant influence on the sustainability of mine cooling control [175].

Simulation software is utilised to accurately simplify and mimic mine cooling and ventilation systems [36]. Simulation software incorporates the functional properties of mine cooling components to enhance service delivery requirements. Factors that include; temperatures, thermal storage capacities, flow rates and components' efficiencies are included within the simulation model [176]. Due to the volatility of mine cooling systems, software is mandatory to adapt to dynamic system responses [36].

Simulation software applications and control packages developed for mine cooling systems will be critically discussed and evaluated in the following section:

ENVIRON [129] **-** is software that assists with the design of underground ventilation networks. ENVIRON accurately simulates the required cooling capacity necessary to supply sufficient cooling underground. ENVIRON, however, does not incorporate a TOU tariff structure.

Process Toolbox (PTB) [177] **-** is a dynamic thermal hydraulic simulation software package that simulates: mine water reticulation networks; mine cooling systems; and compressed air networks. The software package is used to determine the optimal operation of mine cooling equipment. PTB is utilised for the analysis and enhancement of mine cooling system performance [178]. In addition, PTB incorporates a TOU tariff structure to predict the cost savings potential of an optimised control technique.

PTB simulation software was utilised in previous studies to verify optimised control strategies on mine cooling systems. Maré, Nel and Peach utilised PTB to verify the accuracy of an optimised control strategy on mine cooling systems [33], [36], [179].

Ventilation of Underground Mine Atmospheres (VUMA) [180] - is a modelling tool used for the optimisation of complex mine water-cooling and ventilation systems. VUMA is capable of accurately simulating the heat and gas distribution in underground mining environments.

2.5. Existing DSM implementation approaches

2.5.1. Foreword

Energy conservation methods are widely accepted for industrial applications [181]. As mentioned in Chapter 1, DSM provides a unique and adaptable solution. DSM refers to modifying the level and pattern of energy consumption amongst consumers to alleviate the strain on the electricity utility. Three types of DSM initiatives exist, namely; peak clipping, load shifting and energy efficiency. Peak clipping refers to reducing the end-user's energy consumption during the peak TOU periods, while energy efficiency refers to a total reduction in energy consumption. Load shifting, however, refers to the shifting of energy during peak TOU periods to other TOU periods that are more affordable. Therefore, resulting in a cumulative cost saving. DSM measures are typically implemented and/or subsidised by utilities that reduce end-use electrical energy consumption [182], [183]. DSM is typically authorised by governments and implement by ESCOs [184].

DSM was first introduced to South Africa in 2005 [183]. To ensure the sustainability of DSM, newly developed DSM models are required to be cost-effective for industrial use [58]. In addition, a study compiled by Du Plessis suggested that there is a need for the development of additional DSM models [37]. Although this dissertation focuses on developing an automated dynamic control philosophy, the fundamentals of DSM are still applicable. Existing DSM initiatives on mine cooling systems will be critically investigated and evaluated to ensure sustainable cost savings.

2.5.2. DSM implementation considerations

For efficient system control, an integrated EMS and DSM initiative is required [185]. As previously mentioned, such EMSs are beneficial with real-time response capabilities.

Evaluating pre-implementation DSM concerns

For efficient system control, an integrated EMS and DSM initiative is required [185]. As previously mentioned, such EMSs are beneficial with real-time response capabilities. A study concluded that the success of DSM is largely dependent on the EMS [185], [186]. EMSs cannot be ignored when utilising DSM for composite cooling systems [33].

Evaluating pre-implementation DSM concerns

When analysing cooling systems, a pre-requisite for any EMS is to accurately monitor and control cooling sub-systems. The success of DSM if heavily reliant on the control and management of sub-system process parameters [99]. Application of DSM on mine cooling systems must take into account all dynamic

responses. An effective integrated EMS and DSM initiative will consider faulty field instrumentation for optimal control [37], [45].

Prior to DSM implementation, a detailed strategy should be compiled [36]. The strategy should include a list of pre-implementation boundary conditions. Such boundary conditions are compared to the overall post-implementation system performance [62].

To enhance the system performance of an integrated EMS and DSM initiative, KPIs are defined [52]. Crucial mine cooling system KPIs include: temperatures; flow rates; pressure ratios; and chiller compressor capabilities. Other studies have proven that an improved EMS and DSM initiative are reliant on Eskom TOU tariffs and ambient temperature conditions [25].

Evaluating implementation and post-implementation DSM concerns

Although boundary conditions and KPIs are identified during the pre-implementation stage, research has proven that system constraints are best defined during the implementation stage of the EMS and DSM initiative [103]. It is also suggested that cooling system limitations be compiled during the implementation phase.

Implementation constraints and limitations can be moderated by adapting a detailed operational performance analysis [52]. Groenewald said that an operational performance analysis is necessary to modify the integrated EMS and DSM initiative [52]. Literature also added that modifying system constraints is only viable for total increased system performance [25].

For improved sustainability, strategy modifications must be documented. Accurate documentation and data collection ensures that post-implementation control is still feasible. Any post-implementation control discrepancies should be compared to the pre-implementation design conditions. Thereafter, the necessary amendments must be documented.

As mentioned in Section 2.4.1, process variables are monitored and controlled with the use of an EMS. The necessary framework to integrate the SCADA and EMS is crucial for automatic control [37]. A study compiled by Du Plessis suggested that redundancy requirements must be completely met for optimal automatic control of mine cooling systems [37].

2.5.3. State-of-the-art DSM approaches

The study of mine cooling, refrigeration and ventilation are well-researched topics. State-of-the-art DSM studies have proven that load management strategies have positively benefitted efficiency, load reduction and operational performance. This section will be divided into two subsections, namely; DSM study contributions and DSM study limitations and recommendations.

DSM study contributions

Table 2-2 illustrates a study research matrix. The study research matrix displays a list of authors and their field of study contribution/s towards mine cooling and ventilation systems. Existing DSM study contributions on mine cooling systems are critically investigated and evaluated in the following section.

Arndt, DC [187] - investigated the feasibility of conducting load management strategies on deep-level mine cooling systems. Arndt suggested that integrated software development is required to dynamically represent the responses of the system components.

Bluhm, SJ [188] - conducted his field of study on mine cooling and ventilation systems. Bluhm focused his study on optimising cool ventilated air in high-speed developing tunnels.

Buys, JL [32] - conducted his field of study on improving the energy efficiency of a mine cooling system through the implementation of a DSM initiative. Buys installed VSDs on BAC transfer pumps, evaporator- and condenser feed pumps for variable-flow control. The strategy realised an energy efficiency saving of 64.8 MWh, which realised an annual cost saving of R12.5 million.

Du Plessis, GE [37] - developed an energy efficiency DSM model to apply to mine cooling auxiliaries. Du Plessis focused his study on optimising: the evaporator circuit flow control; the condenser circuit flow control; the BAC circuit flow control; and the pre-cooling circuit flow control with VSDs. The strategy realised an energy efficiency saving of 62.6 MWh and an annual cost saving of R8.1 million.

Du Plessis, JJL [189] - conducted his field of study on improving the energy efficiency of main surface fans on mine cooling systems. Du Plessis focused his study on reconfiguring the IGVs of the main surface fans for improved energy efficiency. The study illustrated an underground air flow reduction of 6.36% with an energy efficiency saving of 13.03 MWh.

Els, R [30] - conducted a load shift DSM study on the mine surface and underground cooling systems. Els focused his study on load shifting chillers for improved load reduction energy savings in Eskom's evening peak period. Els validated the strategy through the use of a simulation software called QUICKcontrol. Els realised a total load shift energy saving of 19 MWh.

Greyling, J [190] - investigated the feasibility of installing air cooling units (ACUs) or chilled water coolers (CWCs) in deep-level mines. Greyling concluded that ACU is preferred due to its large cooling capacity. The implementation of ACU reduced the total load required from the surface BACs by 49%. Although the ACUs are preferred, CWCs are also considered a viable underground cooling component due to a low net present value (NPV) of R206 million.

Holman, AM [54] - conducted a study that investigated the benefits of improved performance monitoring on mine cooling systems. Holman quantified the effectiveness of maintenance on mine cooling systems. He suggested that the implementation of the optimised maintenance strategy on large deep-level mine cooling systems will yield an annual conservative energy saving of 52 128 MWh. Holman suggested an expected annual cost savings of R28.6 million.

Kukward, WC [191] - conducted research on the optimisation of an underground ventilation network. Kukward suggested that the surface main fans efficiency be improved with the implementation of a new impeller and motor design practises. His study indicated an accumulated load shift energy saving of 11.5 MWh on two mine case studies.

Lambrechts, JV [33] - developed an empirical formula to predict underground temperatures. Lambrecht used the formula to predict underground ambient temperatures during the implementation of load reduction strategies on BACs.

Moropa, T [192] **-** investigated an adaptable load management strategy that can be implemented on closed or semi-closed loop mine cooling systems. Moropa studied the effect of load reduction on underground temperatures and relative humidity during Eskom's evening peak period. The study realised an evening energy saving of 9 MWh, which amounted to an annual cost saving of R2.3 million.

Maré, P [36] - implemented an optimised control strategy for sustainable energy efficiency savings on mine cooling systems. Maré validated his strategy using two case studies. His study concluded that case study one maintained power savings of 1.73 MW for 17 months, and case study two maintained power savings of 0.66 MW for 7 months. An annual cost saving of R11.7 million was accumulated.

Nel, AJH [33] - created an enhanced control strategy for existing DSM initiatives. The strategy focused on providing sustainable energy savings for mine cooling systems. Nel validated his strategy using two case studies. Nel's study concluded that case study one maintained power savings of 1.62 MW for 17 months, and case study two maintained power savings of 1.8 MW for 15 months. An annual cost saving of R24-million was accumulated.

Oberholzer, KJ [74] - investigated reconfiguring mine cooling auxiliaries for improved service delivery. Oberholzer focused his study on reconfiguring BACs, pre-cooling towers, evaporator pump impellers and chiller flow control. Oberholzer realised an energy reduction of 3.24%.

Peach, PFH [179] - developed an optimised load management control strategy for sustainable cost savings. Peach validated his strategy using two case studies. The study concluded that case study one maintained power savings of 7.28 MW for 8 months, and case study two maintained power savings of 2 MW for 9 months.

Schutte, AJ [25], [62] - investigated the demand side energy management of a cascade mine chiller configuration. Schutte developed a mathematical model for optimal cascaded chiller temperature control. Schutte validate the strategy using simulation software. He conducted an additional study that investigated the feasibility of an integrated energy-efficiency strategy for deep-level mine cooling systems. In addition, he developed a peak-clip strategy for closed loop surface BACs. He decreased the chilled water demand to meet design flow specifications. Schutte attained a load shift saving of 3.2 MW.

Swart, C [176] - developed a simulation model to determine optimal working conditions in underground mine cooling systems. Swart suggested cooling loads be reduced to adequately meet the required air cooling power. He further suggested an attainable energy saving of 57.6 MWh, which translated to an annual cost saving of R2.55 million.

Uys, DC [193] - investigated the feasibility of converting an ice storage facility into chilled water. Uys focused the study on reconfiguring ice storage facilities for load management on mine cooling systems. He increased the thermal storage capacity which resulted in a load shift power saving of 5.6 MW.

Van der Bijl, J [129] - developed a load reductions strategy to move chiller operations into Eskom off-peak periods. Van der Bijl developed a real-time control system that yielded savings of 3.6 MW and 4 MW respectively.

Vosloo, JC [194] - developed a novel energy efficiency and optimisation model for inefficient water reticulation systems. Vosloo conducted his research on numerous case studies to identify water reticulation inefficiencies. He proved the reduction in water consumption by 1.3 M per day on one of his case studies. Vosloo suggested an achievable annual cost saving of R20 million if the strategy were adopted by all deep-level mines in South Africa.

DSM study limitations and recommendations

Various DSM study contributions on mine cooling systems have been performed. The implementation of such contributions have realised lucrative cost savings for the industrial sector. Although DSM study contributions on mine cooling systems have been advantageous, numerous study limitations were encountered. Many authors have suggested unique solutions and/or recommendations to mitigate such limitations. Study limitations and recommendations for future studies on mine cooling systems are critically assessed and reviewed in the following section.

To better characterise mine cooling systems for sustainable energy saving measures, mines need to adopt alternative practises. Many authors suggested automating and integrating cooling auxiliaries for the sustainability of long-term performance. Maré suggested investigating the automation of cooling auxiliaries to match evaporator and condenser pump statuses for diverse chiller configurations [36].

Phillip Maré hypothesised that automating chillers can result in the enhanced management of chilled water reticulation systems. Studies compiled by Nel and Moropa motivated the need to investigate the automation of mine cooling systems [33], [192]. Nel added that the control of IGVs of compressors on chillers require additional focus [33].

Moropa suggested incorporating ambient temperature conditions to enhance the control of mine cooling systems. Moropa hypothesises that ambient temperature conditions affect mine cooling systems adversely. He added that integrating an automated system can practically improve the sustainability of mine cooling systems [192].

A study completed by Engles suggested incorporating an integrated control strategy that utilises underground turbomachinery. Engles theorised that integrating underground components with existing surface cooling components can greatly improve energy cost savings during Eskom's evening peak period. Engles added that integration of these systems will expand the control proficiency of mine cooling systems immensely [195].

From literature, it has become evident that the automation of chillers and their auxiliaries require additional focus. Although, the automation of chillers is limited to the constraints of mine personnel, many authors have hypothesised that automation will attain favourable sustainable energy savings [172]. The need to automate mine cooling systems is depicted by the purple square in Table 2-2.

From Chapter 1, it has become apparent that the mining industry is under massive financial strain to reduce operational costs. Although the implementation of state-of-the-art DSM initiatives has realised lucrative cost savings, the need to optimise cooling systems for sustainable energy saving measures has been brought forth. Recommendations and hypothesises have suggested the need to develop an automated dynamic control strategy for sustainable cost savings.

Table 2-2: Study research matrix (adapted from [74])

Author	Ventilation								Cooling							Implementation			Project		Operational performance
	Surface			Underground					Surface				Underground						DSM		
	Fans	BACs	Reconfiguration	Fans	BACs	Mobile units	Development cooling	Reconfiguration	Refrigeration	Pump control	Pre-cooling towers	Reconfiguration	Refrigeration	Pump control	Reconfiguration	New equipment	Improved strategy	Automation	Energy efficiency	Load shift	
Arndt, DC		×								×							×				×
Bluhm, SJ	×						×														×
Buys, JL		×								×						×			×		
Du Plessis, GE		×								×	×					×	×		×		
Du Plessis, JJL	×		×																×		
Els, R	×								×	×			×	×			×			×	
Greyling, J						×	×						×								×
Holman, AM									×	×	×						×		×		
Kukard, WC	×			×															×	×	
Lambrechts, JV							×														×
Moropa, TS					×					×	×						×			×	
Maré, P									×	×	×					×	×		×		
Nel, AJH					×					×	×					×	×		×	×	
Oberholzer, KJ					×			×		×	×	×				×			×		×
Schutte, AJ		×							×	×						×			×	×	
Swart, C	×												×	×			×				×
Uys, DC									×	×		×							×	×	
Vosloo, JC									×	×				×					×	×	×

2.6. Sustainability of existing optimisation strategies

2.6.1. Foreword

Sustainability has been identified as a principal focus area to enhance mining competitiveness. Industrial sectors are adopting cost-effective energy efficiency strategies to improve operational performance [181]. Sustainability measures are largely dependent on the type of strategy actions implemented [54].

Implementing sustainability strategies are considered to be challenging and thought-provoking. Personnel are unwilling to adapt to large system changes and alterations. Sufficient sustainability measures are primarily achieved by adapting to dynamic system responses [51]. Implementing sustainability measures should provide system modifications that enhance system productivity. Sustainability energy improvement demands the application of an analytical approach [51]. Chao and Yeo recommend a practical approach to achieving energy sustainability [196]. The implementation of a simple EMS for automated dynamic control of mine cooling systems, with sustainability as the principal focus area, prompts further investigation. Such systems have been presented by Trovão *et al.* [197] in the automotive industry.

Identification of KPIs is critical for enhancing sustainable energy saving measures [181]. Long-term sustainability is dependent on evaluating and reviewing important KPIs and operational parameters on mine cooling systems [53]. This section will focus on distinguishing crucial KPIs on mine cooling systems. Existing monitoring and reporting methods for mine cooling KPIs will be thoroughly investigated. Consequently, existing sustainable energy saving measures will be identified and critically analysed.

2.6.2. Cooling system performance evaluation requirements

To ensure an accurate representation of sustainable energy saving measures, comparable boundary conditions are to be considered. Comparable boundary conditions include ambient DB air temperature, and ambient air enthalpy [36].

Ambient temperatures affect mine cooling systems adversely. Ambient temperatures are considered variable and difficult to predict. Lambrechts [198] developed an empirical formula to predict underground WB air temperature to analyse the relationship between VRTs and underground WB temperatures. Zhang *et al.* [199] developed a time series ambient temperature prediction model for HVAC systems in buildings. This study explicitly focused on HVAC systems in the building industry. A need clearly exists for a similar prediction model for integrated mine cooling systems.

As discussed previously, mine cooling systems are responsible for providing chilled service water and air to consumers. Chilled water and air requirements have been recognised as important operational requirements. Flow rates and temperatures are essential for monitoring and evaluating chilled water and air requirements. For this reason, important temperature and flow constraints should be identified during the initial study investigation period [150]. For long-term sustainability, it is important that such constraints are re-evaluated during the post-implementation phase to better realise system changes.

It is hypothesised that by integrating a dynamic solution, post-evaluation of temperature and flow rate constraints will be rapidly mitigated. In addition, from literature, by adapting requirements to a set of tolerable boundary limits, productivity and safety is enhanced [59].

Suitable chilled water and air requirements are formulated by mine personnel. Although, mine cooling requirements are dynamic, chilled water requirements are to be aligned with health and safety protocols. Holman suggested that chilled water temperatures of 3°C to 6°C are sufficient for optimal cooling in mining environments [54].

Identifying and monitoring essential service delivery requirements is essential for implementing sustainable energy saving measures. Operational requirements are considered so that underground temperature conditions are not adversely affected [60]. From literature, it is suggested that the implementation of a sustainable cost savings strategy should account for the dynamic nature of operational requirements, comparable boundary conditions and mineworker safety.

2.6.3. Evaluating measurement and verification (M&V) procedures

The performance of industrial DSM projects has realised lucrative energy savings. The energy savings potential is typically measured by relating pre- and post-project performance. To ensure accurate quantification of energy consumption, DSM project performance is measured continuously. Accurate M&V is beneficial for the relevant stakeholders [200].

Due to the volatility of mines, factors such as ambient conditions affect the performance of mine cooling systems adversely. Therefore, the energy consumption of mine cooling systems fluctuates. To accurately measure and verify the performance of DSM projects on mine cooling systems, production and ambient conditions cannot be ignored [201]. Research, however, has indicated that to evaluate the effect of comparable boundary conditions on mine cooling systems, industry must adopt a generic strategy or model [201].

Eskom will appoint an independent M&V team to ethically report attained energy savings. An accredited M&V team is appointed to ESCOs by the National Energy Regulator of South Africa (NERSA). Independent M&V teams follow a unique M&V process that is governed by the International Performance Measurement and Verification Protocol (IPMVP) and the Federal Energy Management

Programme (FEMP) [202]. Although stringent bodies are required to govern ethical reporting of energy savings, the sustainability of DSM projects is affected by M&V challenges [200].

Normally, baseline models are constructed to accurately represent and quantify attainable energy savings on mine cooling systems. Inaccurate data collection could lead to the formulation of an erroneous baseline model [203]. A study compiled by Booysen indicated the importance of accurate M&V reporting. Booysen focused his study on analysing the effects of system constraints and challenges on the performance of projects. Booysen suggested that to mitigate M&V challenges, a holistic approach to represent DSM energy savings is required [204].

M&V challenges are fundamentally important for accurately measuring attainable energy savings on mine cooling systems. Factors such as seasonal changes affect mine cooling systems adversely. To mitigate this challenge, an independent M&V team is appointed. The M&V team summarises the socio-economic and environmental effects of mine cooling systems to precisely measure the total energy consumption. The formulated baseline model for the selected case study is discussed in Chapter 4.

2.6.4. Sustainable energy savings requirements and implementation strategies

The study of mine cooling, refrigeration and ventilation are well-researched topics. Although studies have focused primarily on the optimisation of mine cooling systems, little attention to the sustainability thereof has been considered. Literature has indicated that sustainability on mine cooling systems is achieved with the implementation of an automated EMS [129].

According to research, reporting KPIs provides an alternative tactic for improving the long-term sustainability of mine cooling optimisation strategies [33], [36]. KPIs are utilised for the sole purpose of monitoring behavioural changes for improved operational performance [54]. The KPIs evaluate the characteristics of mine cooling components. Such KPIs are reported for improved transparency between ESCOs and the client.

Literature also suggested that the application of an improved control strategy will benefit the sustainability of energy saving measures [128]. Through optimal monitoring and evaluating of KPIs, multi-engineering disciplines are capable of making formative decisions.

Application of reporting serves as a crucial tool for improved sustainability on mine cooling systems. Other than the swift identification of problem areas, reporting KPIs guarantees effective communication between the client and ESCOs [200]. Consequently, sustainable energy saving measures are realised. As mentioned previously, adopting an independent M&V team to accurately verify pre- and post-implementation energy savings also promotes sustainability.

An alternative approach to achieving sustainable energy savings is through the application of robust control systems [205]. Similarly, such applications provide effective communication between local and remote-control systems. Application of robust control systems on mine cooling systems assists the client and ESCO to ascertain causes for underperformance more rapidly [182].

Chapter 1 introduced important characteristics of the DSM model. Although, the model is aimed at enhancing sustainability, ESCOs are challenged to adapt to the dynamic nature of mine cooling systems. Similarly, the maintenance of such initiatives is vital for enhancing long-term sustainability measures [52], [53].

Groenewald formulated a performance-centred maintenance (PCM) strategy for the sustainability of industrial DSM projects [52]. Groenewald identified that a large reason for project underperformance is improper maintenance. Groenewald hypothesised that by implementing a PCM strategy, project performance can be better sustained. The strategy utilised a plan-do-check-act cycle that prompted continuous improvement and evaluation of DSM project performance. Figure 2-18 displays the impact improvements of adopting a PCM strategy on an existing DSM project.

Although, Groenewald's study findings yielded an annual net cost saving of R62.7 million, Groenewald failed to investigate the need for PCM on fully automated mine chillers. Groenewald, however, suggested that if a fully automated control system is applied, improved maintenance and sustainability can be realised [52]. Groenewald also proffered that completely automated chiller control is yet to be explored because of high implementation costs [52].

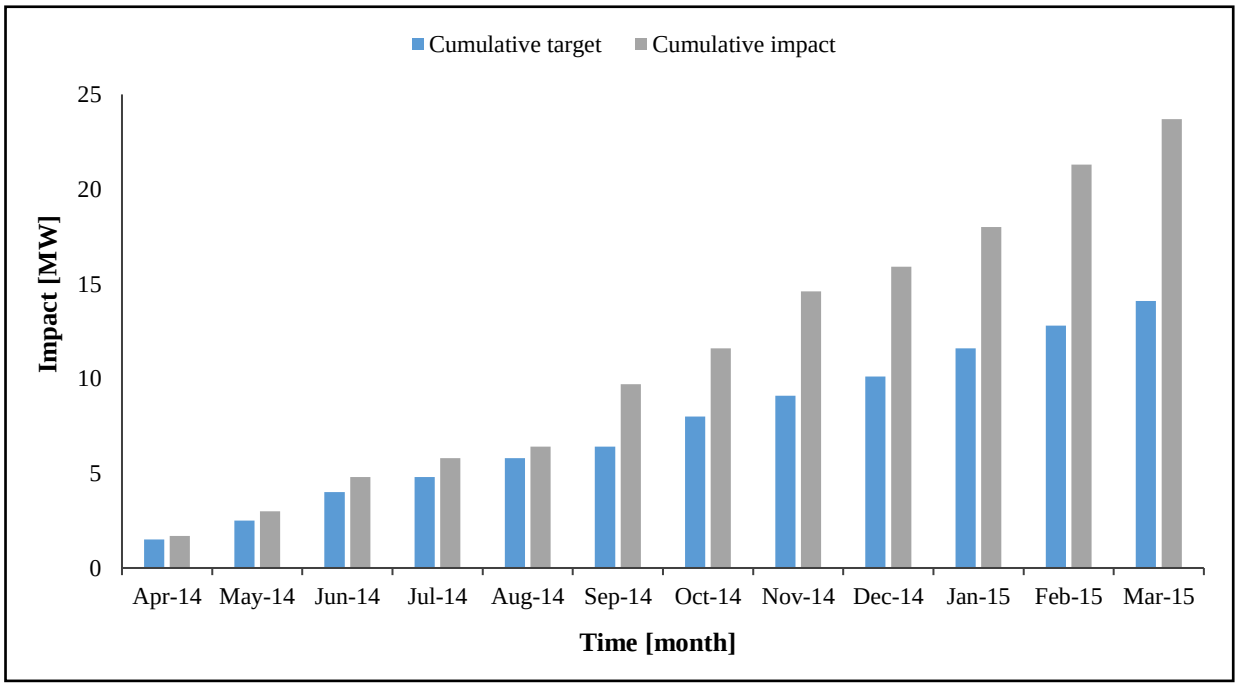

Figure 2-18: Cumulative target versus impact target generated by implementing a PCM [52]

Kriel conducted a similar study that investigated utilising an alternative approach for sustainable DSM [200]. Kriel's study indicated favourable improvements to the sustainability of industrial DSM projects due to active maintenance on industrial DSM projects. Similarly, Maré and Nel investigated the sustainable impact of an optimised strategy on mine cooling systems [33], [36]. Maré and Nel both realised sustainable energy savings. Both authors suggested investigating the sustainable impact of automating chillers and their cooling auxiliaries.

Literature has indicated that existing sustainability methodologies can be applied if energy savings are no longer realised. Implementation of sustainable energy saving measures has lucratively enhanced service delivery requirements and enabled thoughtful decision-making. However, little focus to the sustainability of automated cooling systems has been critically explored and evaluated.

Literature also shows that a need exists for the implementation of an automated dynamic control strategy for deep-level mine cooling systems. Such a strategy should be simple and practical, require no capital outlay, reduce the severity of ambient air temperature changes and offer sustainable improvements. The strategy will be addressed by utilising a holistic systems approach and predictive dynamic control strategy for sustainable cost savings on mine cooling systems, as suggested by the literature.

2.7. Conclusion

An overview of a deep-level mine cooling system was discussed. Important thermodynamic processes and machinery were thoroughly evaluated and reviewed. Existing optimisation techniques were critically investigated to develop a holistic understanding of mine cooling systems. Although, sustainable optimisation techniques are largely present on mine control systems, little focus to the application of such research on automated mine cooling systems is present.

The study of existing state-of-the-art approaches on mine cooling systems was comprehensively investigated. Important study shortfalls and recommendations were critically explored. The automation of chillers and their auxiliaries was identified as a field of study that requires additional focus. Although, the automation of chillers is limited to certain constraints, literature hypothesised that automation will attain an all-inclusive solution with favourable cost savings. Hence, emphasising the need to develop an automated dynamic control strategy. Operational requirements and KPIs on mine cooling systems were critically analysed. Monitoring and reporting of KPIs provides an alternative tactic for improving the long-term sustainability of mine cooling optimisation strategies. These factors will be integrated with the suggested implementation strategy to ascertain areas of underperformance. Similarly, the performance of the automated dynamic control strategy can be sustained for lucrative cost savings.

Comparable boundary conditions and control limitations were reviewed. The review indicated that if control limitations are managed effectively; productivity and sustainability is enhanced. The suggested

strategy should incorporate comparable boundary conditions to validate pre- and post-implementation strategy improvements.

The performance of existing energy saving measures was scrupulously investigated and reviewed. Underperformance was identified as a major concern for the viability of sustainable optimisation strategies on mine cooling systems. Factors that influence underperformance will be incorporated into the strategy development to better characterise the long-term sustainability of the suggested solution.

From literature, it has become apparent that a need exists to investigate the automation of cooling systems. The effects thereof can be quantified to scrutinise the impact on operational performance and sustainability. Chapter 3 will incorporate existing knowledge to develop an automated dynamic control strategy that will mitigate the problem areas highlighted in Chapter 1.

CHAPTER 3: DEVELOPMENT OF AN AUTOMATED DYNAMIC CONTROL STRATEGY

[3]

The development of an automated dynamic control strategy is discussed. This section includes a set of assumptions and limitations that were integrated with existing control philosophies to develop an automated dynamic control model. In addition, the verification strategy for the automated cost saving measures is discussed.

[3] *Photograph courtesy of Planet KB, http://www.planetkb.co.za/portfolio-detail.php?Mining-Photography-4*

3.1. Preamble

From literature, various optimisation techniques and DSM study contributions on mine cooling systems were critically explored. The implementation of such contributions had realised lucrative cost savings potential for deep-level gold mines. The primary focus for many of the DSM study contributions was to solely reduce cost through the application of a feasible load management or energy efficiency optimisation strategy. The sustainability thereof, was ignored.

Due to performance deterioration of existing control strategies on mine cooling systems, power savings were no longer attained. Underperformance of existing implementation strategies prompted the need for the implementation of a sustainable cost-effective solution. In addition, research indicated that as a result of project underperformance, mine personnel reverted back to pre-implementation control regimes [87].

The lack of an EMS and proactive maintenance has led to a situation where project performance deteriorated. Similarly, engineers were incapable of making intuitive decisions to improve total system performance. Automating mine chillers is suggested to be a viable solution to mitigate project underperformance.

Chapter 3 will therefore discuss the development of a simple, practical and automated control approach for sustainable cost savings on mine cooling systems. A deep-level gold mine, Mine A, with deteriorated energy savings will be selected as an appropriate case study. The automated dynamic control strategy will be implemented at Mine A with sustainability as the principal focus study area.

In addition to the post-implementation project deterioration, Mine A was selected due the availability of process data from previously implemented optimisation strategies. Existing infrastructure at Mine A will also aid in restoring optimal system performance. Furthermore, prior knowledge of Mine A will aid in identifying shortcomings with the existing control of cooling system components. This will assist in developing an integrated control approach.

This chapter will, therefore, serve as a tool to review system specifications and operational requirements. System limitations and constraints will be critically discussed to develop an automated dynamic control strategy. The impact of this strategy will be verified with the use of a calibrated simulation model.

This chapter will also integrate existing infrastructure to optimise the control of mine cooling components for sustainable cost savings and improved operational performance. A detailed mine cooling system layout will be formulated to critically evaluate existing control techniques.

3.2. Evaluating existing DSM initiatives

3.2.1. Overview of a case study

To develop a simple and practical control strategy, it is important to analyse existing control optimisation techniques. Existing DSM initiatives at Mine A are critically assessed and examined to discover areas of project deterioration and unsustainability.

With sustainability as a critical focal point, Eskom requested the implementation of an energy efficiency integrated demand management (IDM) intervention at Mine A in 2011. The IDM intervention was aimed at assisting Mine A with achieving energy efficiency savings on mine cooling auxiliaries. With no maintenance agreement in place, the project savings deteriorated.

Following the post-implementation phase of the original energy efficiency IDM intervention, production at Mine A increased. Similarly, higher cooling loads are required to meet increased productivity. To regain the benefit of an energy saving measure, a detailed project performance investigation is required.

The project performance investigation is utilised to confirm the feasibility of implementing an energy saving measure at Mine A. The performance investigation provided detailed technical specifications of previously implemented energy saving initiatives at Mine A. Important process parameters and control strategies were discovered in the project performance investigation.

To measure the practicality of an automated dynamic control strategy, a performance investigation is used to establish an existing control framework. Figure 3-1 represents the approach used to conduct a project performance investigation. To execute the project performance investigation, the approach is categorised into four steps:

Step 1: Investigation and system description

The investigation and system description phase require a comprehensive understanding of existing infrastructure to successfully identify system boundary conditions and operational parameters. Thereafter, the system constraints are accurately defined.

To construct an accurate representation of Mine A's cooling system, control manuals and component documentation are collated. Data is then collected to verify the operational parameters. After the verification process, process flow schematics are collected. These schematics provide information about the interaction of mine cooling components. Such components include; thermal storage dams, pipe networks, back-pass valves and turbomachinery. Thereafter, process flow schematics are compiled and analysed to ensuring the viability of automated control strategies.

Measurement devices are utilised on site to gather important data. As previously mentioned, an existing relationship with Mine A simplified the collection of important process data. Accurate data collection ensures that technical system specifications are measured and logged precisely. Technical system specifications are measured to provide more knowledge about existing control optimisation techniques. Finally, Mine A's cooling system layout and configuration was compiled, as presented in Figure 3-2.

Step 2: Analysing existing initiatives

Existing control strategies are critically explored and examined to accurately formulate a baseline model. A baseline model is utilised as a reference to measure energy savings from an implemented energy savings measure. A baseline model is only constructed after the system is accurately defined and characterised.

Therefore, existing initiatives are investigated to identify existing constraints and risks. Project deterioration is often accredited to such risks and constraints, therefore emphasising the importance of this investigation. Thereafter, historical trends are analysed to verify the risks and pre-implementation constraints. Finally, to accurately depict current operations, a baseline simulation model is constructed.

To ensure an accurate system response, the baseline simulation model must be configured and calibrated to incorporate existing control techniques for a certain time period. An accurate baseline simulation is utilised to identify root causes for project underperformance. Root cause KPIs are also closely examined to conduct comparison studies.

Step 3: Mitigation analysis

To mitigate project deterioration, comparison studies are conducted. Comparison studies identify methods to curtail existing project constraints. During the mitigation analysis phase, however, new project constraints can be realised. It is therefore critical to re-analyse constraints and mitigation control limits (human factors, infrastructure and operational limits). Consequently, a proposed solution is developed.

The proposed solution must be simulated to quantify system energy consumption as a result of the energy saving measure. Simulating the suggested solution will assist in identifying the operating conditions of certain mine cooling components. Inefficiencies will be identified and examined to successfully reduce energy consumption and optimise the operational performance of Mine A's cooling system. After completion of the comparison studies, a viable control strategy is developed. The optimised energy saving measure is compared to the baseline simulation model to quantify energy savings.

Step 4: Preliminary implementation strategy

To investigate the feasibility of energy savings measures, it is necessary to quantify cost savings and evaluate the performance of the cooling system. Thereafter, the reliability of the strategy is computed. An ideal way to measure the reliability of the energy saving measure is to quantify sustainability through the use of a simulation.

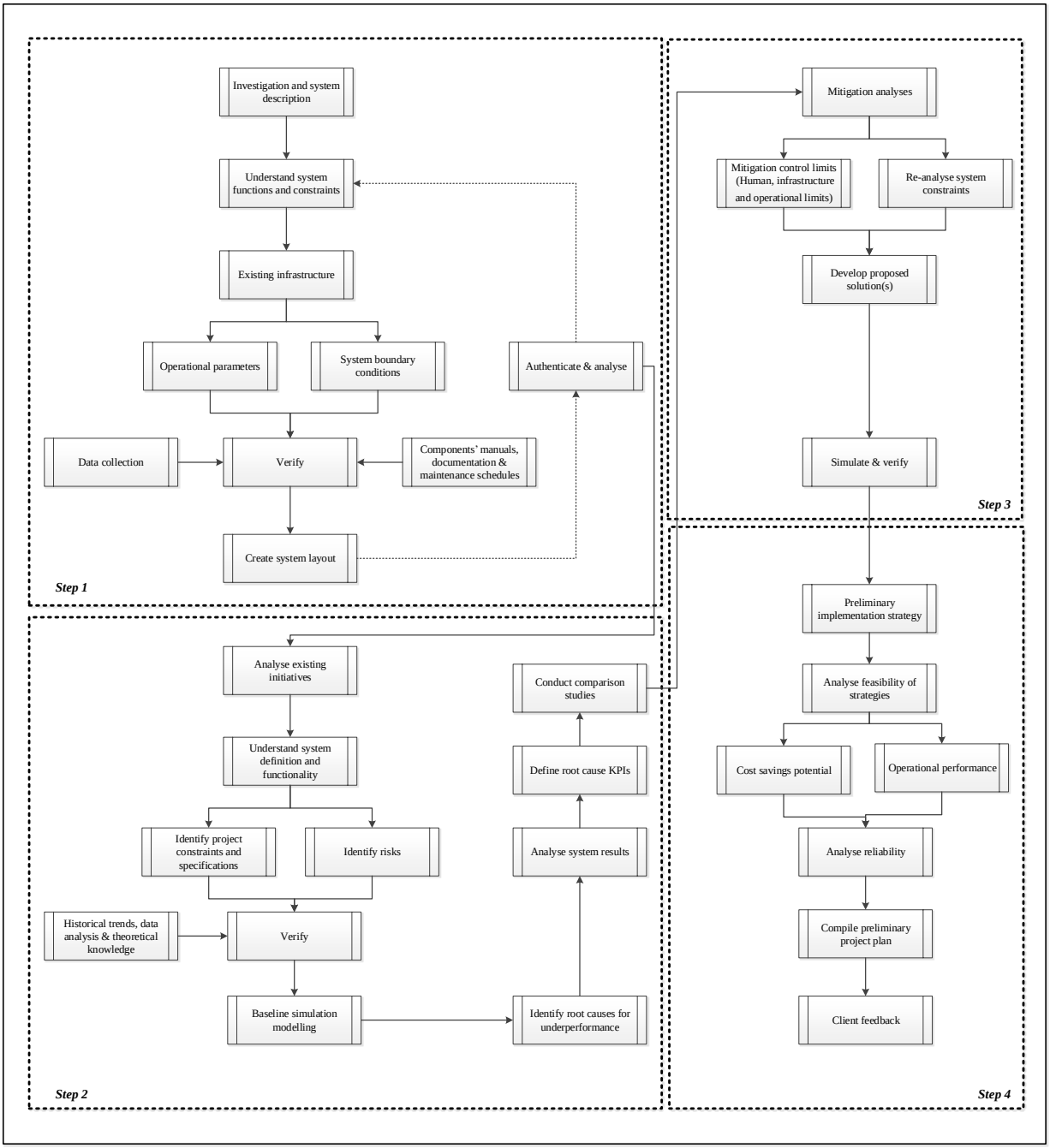

Figure 3-1: Systematic approach to conduct a project performance investigation

A preliminary project plan is created and provided to the client, Mine A, for review. The project performance investigation identified the initial project objectives through characterising existing optimisation techniques.

The project performance investigation concluded that a variable flow control energy saving measure was implemented on Mine A's cooling system. As suggested by literature, variable flow control optimisation techniques are utilised for energy efficiency savings. The chillers at Mine A are configured in a parallel arrangement to enhance variable flow control capabilities.

Details of the existing control optimisation strategy will be critically discussed in the following section. This section will serve as a tool to review system specifications and existing control philosophies. Existing infrastructure is thoroughly analysed and reviewed to develop an integrated EMS for sustainable energy saving measures. The systematic approach, as seen in Figure 3-1, will identify existing control strategies which will be used to formulate sustainable energy saving improvements.

The following sections will, therefore, integrate existing infrastructure to develop an automated dynamic control strategy for sustainable cost savings and improved operational performance. The focus of the dynamic control strategy will be to optimise chiller control and existing cooling auxiliaries.

3.2.2. System's technical description

To evaluate existing control strategies, Mine A's cooling system was well-defined. Existing infrastructure was thoroughly investigated to understand and improve existing control operations. Figure 3-2 displays the surface cooling system of Mine A.

At Mine A, hot service water at 26.5°C is pumped to a hot surface surge dam using underground dewatering pumps. Approximately 240 ℓ/s of hot service water is pumped from underground. There is a total of seven 2 MW underground dewatering pumps. Three of the pumps are located on Level 38 (38L) and four of the pumps are located on Level 75 (75L). A combined pumping capacity of 14 MW is available for underground pumping.

The hot service water is pumped from the hot surface surge dam through two pre-cooling towers. The hot service water is adiabatically cooled whilst simultaneously being passed through the spray nozzles of the pre-cooling towers. The water is pumped from the pre-cooling towers into the hot confluence dam (HCD) at a temperature of 20°C. The HCD has a thermal storage capacity of 650 Mℓ.

Water from the HCD is pumped through six 6.5 MW parallel chillers (VCRS) to supply cool chilled service water. 650 Mℓ of chilled service water is transported to the CCD using evaporator pumps. The chillers have a total design cooling capacity of 39 MW, with a nominal combined COP of 5.7.

From the CCD, water is pumped to the BACs. Approximately 500 ℓ/s of water is sent from the CCD to the BACs. The BACs supply the mine with cool dehumidified air at a temperature of 7.5°C. The water

that exits the BAC is directed to the HCD using BAC return pumps, which assists in cooling the HCD. As a result, less compressor power is required to achieve the desired cooling loads.

Similarly, the remaining chilled water from the CCD is sent to underground mining levels for cooling. The CCD feeds an underground chilled dam located on Level 39 (39L). Before the water is stored in the 39L cold dam, the chilled water is passed through a Pelton turbine. The mechanical shaft energy is utilised to pump hot service water stored in the 38L hot storage dam. Hot service water from mining operations is finally stored in a 75L hot thermal storage dam, from where it is pumped and stored into the 38L hot storage dam.

The service water and air are distributed throughout Mine A by means of an integrated pipe network. Controlled back-pass valves are installed along the surface pipe networks. The back-pass valves are installed to prevent flooding of the CCD and the hot surface surge dam. Butterfly valves are also installed to dispense water and air to the appropriate end-users.

Figure 3-2 displays the detailed surface cooling system layout of Mine A. The chillers' and respective cooling auxiliary configurations are presented in the layout. Crucial control instrumentation is also presented in the schematic.

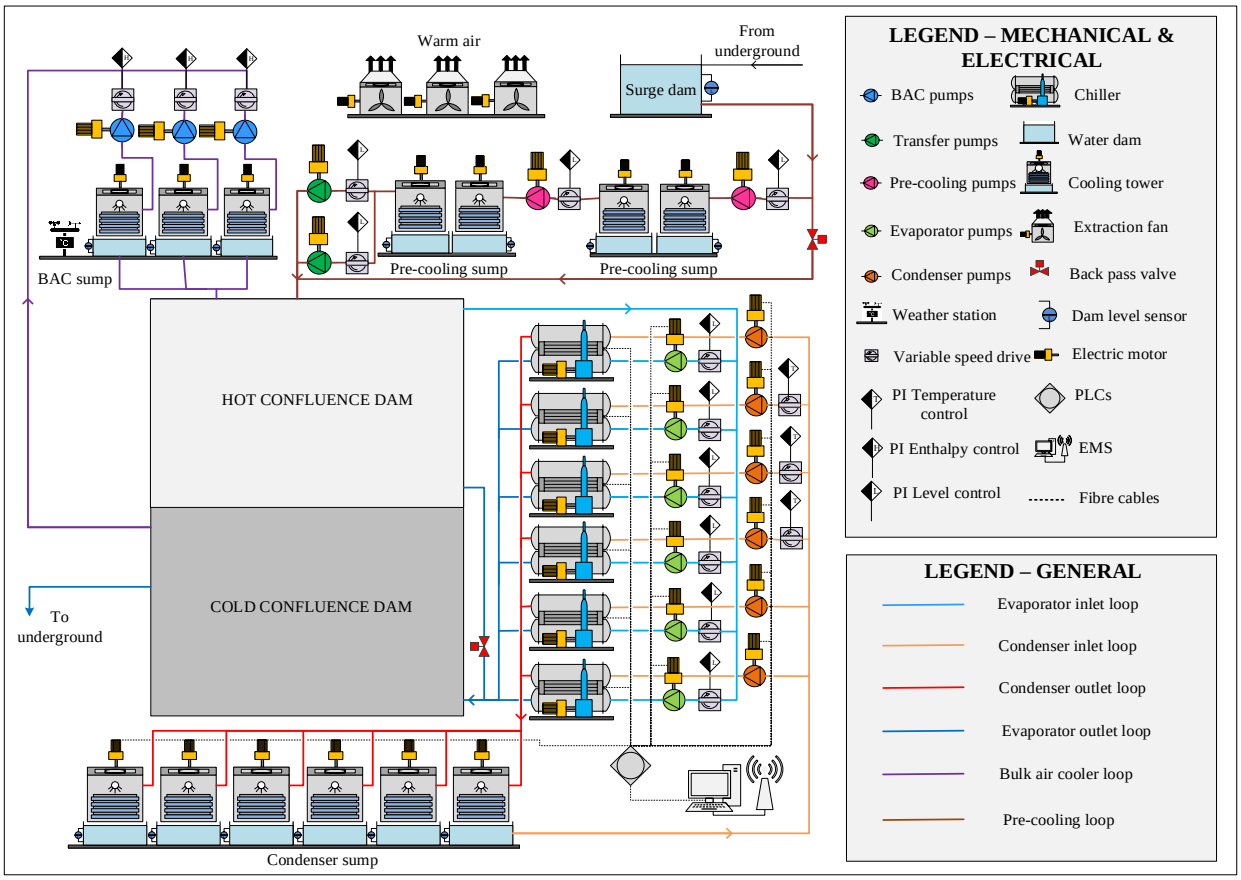

Figure 3-2: Mine A's surface cooling water system

System's operational summary

Mine A is completely operational throughout the year. During the warm summer periods (September to May), higher cooling loads are required to meet warmer conditions. Similarly, all the components within the mine cooling system are fully functional.

Due to cooler ambient temperature conditions in winter (June to August), Mine A's surface cooling system is shutdown. This allows for proactive maintenance of mine cooling system components. The chillers and BACs are subsequently shutdown during winter periods, without adversely affecting productivity and occupational health and safety (OHS) regulations. Although seasonal changes affect the operational performance of mine surface cooling systems, it is important to regularly maintain such systems for optimal performance.

Mine A's technical system specifications

The technical specifications of each component in Mine A's cooling system are tabulated in Table A-1. The technical specifications are crucial for identifying the operating conditions of installed components. To execute a new energy saving measure, pre-implementation component specifications are required.

Utilising the approach to fulfil a project performance investigation, as discussed in Figure 3-1, a list of technical specifications was compiled. The specifications provided important process control parameters that were utilised in previously implemented energy saving measures. To ensure optimal performance of a newly implemented automated control strategy, technical specifications are to be adhered to. The technical specifications for Mine A's surface cooling system are presented in Appendix A.

3.2.3. System control summary

According to Van Greunen, the simplest way to optimise an existing control system is to categorise system limitations and constraints [45]. It is therefore, suggested that to enhance existing control strategies, system parameters are categorised according to controllable and uncontrollable variables.

Similarly, before implementing an automated dynamic control philosophy, it is important to categorise control constraints and existing energy saving measures. Therefore, an overview of the variable flow control strategy implemented as an energy efficiency IDM intervention in 2011 is briefly discussed in the following subsection.

Chiller control

At Mine A, PI controllers are used to modulate a desirable evaporator outlet temperature. Signals from the PLCs are sent to the IGVs of the chillers' compressors to achieve the evaporator outlet temperature set point. A fixed temperature set point, agreed upon by the machine manufacturers, of 3°C was selected.

BAC flow control cycle

The BAC feed pumps were controlled with VSDs to maintain an air outlet (WB) temperature set point of 7.5°C. Open loop proportional (P) control logic was used to control the VSDs on the BAC feed pumps. The VSDs modulate the pump speed to meet an ambient air enthalpy set point.

Evaporator flow control cycle

The evaporator pumps were controlled with VSDs to maintain a stable CCD level of 75%. Closed loop PID control logic was used to maintain the desired temperature set point. The recycling valve from the CCD to the HCD was also decommissioned to enable complete VSD control. The dam level set points and VSD frequency set points of the evaporator pumps are illustrated in Table 3-1.

Table 3-1: Evaporator pump control parameters

Evaporator pump	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5	Pump 6
Control [-]	Closed Loop PID	Closed Loop PID	Closed Loop PID	Closed Loop PID	Closed Loop PID	Closed Loop PID
Feedback signal [-]	CCD Level	CCD Level	CCD Level	CCD Level	CCD Level	CCD Level
Set point [%]	75	75	75	75	75	75
Minimum VSD frequency [Hz]	39	37	39	36	37	36
Maximum VSD frequency [Hz]	49	49	49	45	46	46
Minimum flow [ℓ/s]	190	190	190	190	190	190
Maximum flow [ℓ/s]	253	253	253	253	250	253
Low flow alarm [ℓ/s]	185	185	185	185	185	185
Low flow trip [ℓ/s]	177	177	177	177	177	177

If the CCD level exceeds the set point of 75%, the closed loop P&ID control is initialised and the minimum VSD frequency is selected as the driving frequency for the VSDs. A minimum VSD frequency set point will decrease the pump speed. In the case where the CCD drops below the dam level set point of 75%, the maximum VSD frequency was selected to increase the pump speed.

The evaporator pumps were controlled in either manual or auto mode. During the start-up, set P&ID values were communicated via the SCADA to the VSDs. In manual mode, the existing EMS had no control of the VSDs. In auto mode, the EMS controlled the frequency set points of the VSDs. Auto mode was initialised after the pump had been running at a maximum speed for 5 minutes. Figure 3-3 illustrates the existing auto/manual control strategy for the evaporator pumps.

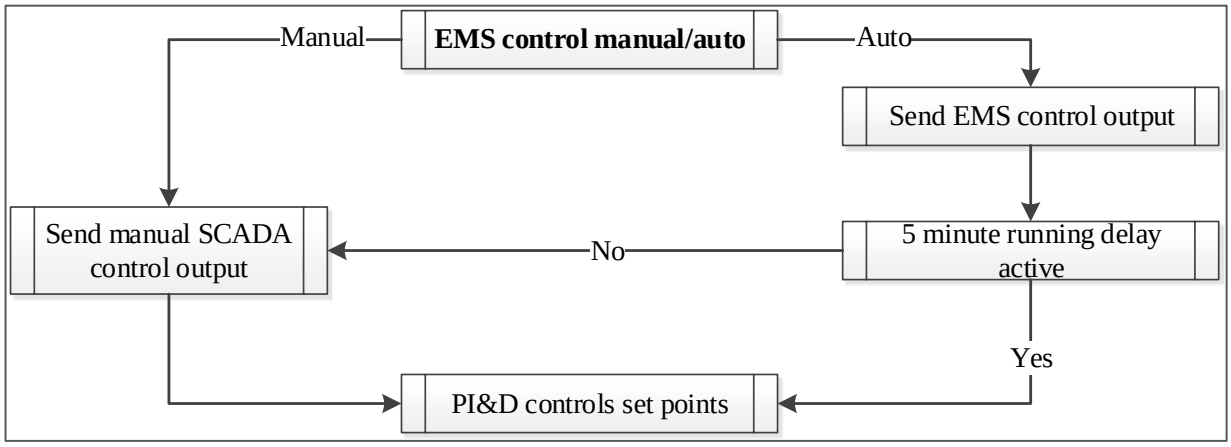

Figure 3-3: Evaporator pump auto/manual control

Condenser flow control cycle

The condenser pumps were controlled through the VSDs to maintain a condenser water temperature difference (condensers water temperature out - condenser water temperature in) of 5°C. Closed loop PID control logic was used to maintain the CCD level. Furthermore, the throttling valves were decommissioned to enable complete VSD control.

As with the evaporator pumps, the condenser pumps were controlled in either manual or auto mode. During the start-up, pre-programmed P&ID set points were communicated via the SCADA to the VSDs. After 5 minutes, auto control was initiated, and the condenser pumps were controlled by the EMS.

The condenser temperature difference set points and VSD frequency set points of the condenser pumps are illustrated in Table 3-2 below. As opposed to the evaporator pumps, only three of the six condenser pumps were controlled with VSDs. Condenser pumps 2, 3 and 4 were controlled with the use of VSDs, while condenser pumps 1, 5 and 6 were controlled with pre-programmed PLCs located at Mine A.

Table 3-2: Condenser pump control parameters

Condenser pump	Pump 1	Pump 2	Pump 3	Pump 4	Pump 5	Pump 6
Control [-]	None	Closed Loop PID	Closed Loop PID	Closed Loop PID	None	None
Feedback signal [-]	N/A	Condenser temperature difference	Condenser temperature difference	Condenser temperature difference	N/A	N/A
Set point [°C]	N/A	3.5	3.5	3.5	N/A	N/A
Minimum VSD frequency [Hz]	N/A	38	40	40	N/A	N/A
Maximum VSD frequency [Hz]	N/A	45	47	47	N/A	N/A
Minimum flow [ℓ/s]	435	350	350	350	435	435
Maximum flow [ℓ/s]	435	435	435	435	435	435
Low flow alarm [ℓ/s]	250	250	250	250	250	250
Low flow trip [ℓ/s]	238	238	238	238	238	238

If the temperature difference of the condenser pump exceeded the temperature set point, the pump speed was increased. To increase the speed, the P&ID control loop utilised the maximum VSD frequency set

point. In the case where the temperature difference was less than the temperature set point, the P&ID control loop utilised the minimum VSD frequency set point.

Pre-cooling flow control cycle

Within the pre-cooling flow control cycle, the pre-cooling tower feeder and transfer pumps were modulated with VSDs. The pre-cooling tower feed pumps were controlled with VSDs to maintain a stable pre-cooling sump level of 85%. Closed loop P control logic was used to maintain this sump level.

The pre-cooling tower transfer pumps, however, were controlled with VSDs to maintain a stable HCD level of 80%. As with the evaporator pumps, closed loop PID control logic was used to maintain a stable HCD level. In addition, the back-pass valve was decommissioned to enhance the VSD control strategy.

From the system control summary, it is obvious that the existing control is simplistic. Existing energy saving measures utilise static set points that do not accommodate for the dynamic nature of mine cooling systems. It is critical to evaluate existing control constraints and operational limits to develop a simple and practical dynamic control strategy with automated features. Therefore, the performance of existing implementation strategies is critically evaluated in the following section.

3.3. Performance evaluation of existing implementation strategies

Existing control philosophies are re-evaluated to accurately characterise potential control faults. The following section provides a detailed summary of existing implementation strategies on Mine A's cooling system. The existing control strategies are thoroughly investigated and evaluated to develop an automated dynamic control strategy for sustainable cost savings.

3.3.1. Chiller control

Evaluation

Evaluation of the chillers' control revealed the chillers were being controlled to meet a static evaporator outlet temperature set point of 3°C. It was discovered that the temperature set point had not been altered since initial installation of the chillers. Due to new design limitations and operational constraints, it is difficult to operate the chillers at design equipment manufacturer (DEM) specifications.

As a result, the mine personnel have been using outdated control philosophies to meet DEM specifications. Analysis of existing control strategies revealed that two of the six chillers' IGVs were set to operate consistently at maximum guide vane openings. Although part-load compressor conditions were active, the IGVs were set at 100% to supply maximum refrigerant. Mine A has adopted inefficient energy saving measures.

The existing control of the chillers is also old-fashioned and unrefined. The static evaporator outlet temperature of 3°C has resulted in freezing within the chiller cooling chambers. Consequently, as a safety precaution, chillers tripped during the start-up phases. Unfavourable machine operating conditions is likely to negatively impact productivity, which can result in increased financial strain on Mine A.

At Mine A, the chillers were controlled manually to meet the required cooling demand. Typically, the mine personnel decided whether it was appropriate to start or stop a chiller. As suggested by literature, manual control was a leading contributor to the underperformance of energy saving measures. Manual control of the chillers prompted irregular scheduling and cycling of chillers to meet varied cooling demands. This prompted an increase in maintenance and the costs associated thereof.

Operators typically monitored the temperature of the CCD to manually start and stop chillers so that a static CCD temperature set point of 8°C was met. This manual control did not accommodate the inclusion of ambient temperature conditions. Subsequently, seasonal changes impacted the performance of the mine cooling systems adversely. Importantly, during warmer months, maintaining favourable underground environmental temperatures is critical for optimal performance of mineworkers.

Proposed solutions

To prevent inefficient energy practises, it is suggested that the chillers' compressors are operated under partial-load conditions. The IGVs of the chillers' compressors can be adjusted (cut back) to meet these conditions. A solution to control the IGVs (refrigerant discharge flow) of the chillers' compressors is proposed. The alteration will reduce compressor power consumption; prompting improved energy efficiency practices.

To prevent overcooling, it is suggested that the static evaporator outlet temperature of 3°C be altered to 3.5°C. This change would reduce cooling loads and the duration of cooling required from operating chillers. To mitigate human intervention and the impact associated with it, an automated dynamic control model is proposed. This solution will also prevent chillers from tripping, it will improve compressor cost savings potential and reduce the prospect of scaling in chiller cooling chambers and heat exchangers.

To improve mine working conditions, the CCD static temperature set point is altered from 8°C to 6°C. Although, this change will result in increased cooling loads, the alteration will increase load management potential during the Eskom evening peak period.

It is also suggested to adopt a dynamic CCD temperature set point limit. The dynamic temperature set point will update minutely to ensure that sufficient cooling is supplied. Implementing a dynamic temperature set point will prevent false chiller start-ups to ensure that chillers operate close to DEM specifications.

An integrated control approach is adopted to improve the response of the cooling system to dynamic disturbances. Existing mine cooling infrastructure, such as thermal storage dams and auxiliary turbomachinery, will be included within the new suggested control strategy. The solution will assist in achieving the aim to develop a simple, practical and integrated control strategy for sustainable cost savings.

3.3.2. Evaporator water flow control cycle

Evaluation

Evaluation of the evaporator water flow control cycle illustrated that the variable flow control strategy was decommissioned. The VSDs installed on the six evaporator pumps were disabled due to a lack of maintenance and system optimisation.

After implementation of the energy saving measure, Mine A repeatedly experienced low evaporator flow rates. Further investigation had led to the discovery that during chiller start-ups, the evaporator flow rates were considerably lower than that of the flow rate trip limits on the chillers. As a result, and as a safety precaution, chillers tripped during the start-up phases.

Mine A disabled the existing variable flow control strategy and the evaporator pumps were set to operate at a maximum guide vane opening. Although part-load conditions were active, the IGVs were set at 100% to supply maximum water flow; therefore, preventing chiller trip conditions. Similarly, larger cooling loads can be better managed and achieved with maximum evaporator flow rates.

The throttling valves were recommissioned to achieve a stable static evaporator outlet temperature set point of 3°C. This control strategy was outdated and did not accommodate for varying cooling loads. The static evaporator outlet temperature of 3°C resulted in overcooling within the evaporator heat exchanger ducts. Consequently, due to chiller trips, a loss of production was being realised.

Proposed solutions

Similar to the proposed chiller control, it is suggested that the static evaporator outlet temperature of 3°C be altered to 3.5°C. The control of the evaporator pumps is integrated into the chiller control to achieve a static evaporator outlet temperature set point of 3.5°C.

The throttling valves will remain operational to achieve an evaporator outlet temperature of 3.5°C. This solution will reduce the risk of overcooling in the evaporator heat exchanger ducts and reduce fouling. Chillers will also operate closer to DEM specifications, which will improve evening load management potential.

The variable flow control strategy will be recommissioned and adapted to prevent chillers from tripping at low evaporator flow rates. Operating the evaporator pumps at higher flow capacities will ensure that varied cooling loads are always achieved, and that production is never compromised.

Due to a swift deterioration in water quality from mining operations, it is suggested that a bi-yearly (twice a year) maintenance schedule is developed. Although, operating the evaporator pumps under full-load conditions enhances scaling and fouling, a proactive maintenance plan will ensure that water treatment is fulfilled, and sediment build-up is reduced.

3.3.3. Condenser water flow control cycle

Evaluation

As with the evaporator water flow control cycle, an evaluation of the condenser cycle concluded that the variable flow control strategy was decommissioned. The review showed that the VSDs on the condenser pumps were disabled by mine personnel. The condenser pumps were left to operate at maximum capacity (full-load), although partial-load conditions were active.

As a part of the existing energy saving measure, condenser pumps were installed with VSDs to reduce the water flow rate through the condenser tubes. Due to monetary constrictions, only three of the six condenser pumps were installed with VSDs. To compensate for the three pumps operating at maximum capacity, the VSD-installed pumps were forced to run at reduced operating speeds (partial-load conditions).

As a result, the drive end (DE) temperature of the motor bearing increased. Coupled with a lack of proactive maintenance, the motors were damaged extensively. Similarly, the energy saving measure was disabled and the mine personnel operated the condenser pumps under maximum-load conditions.

To mitigate against extensive motor damage, the throttling valves were recommissioned to meet a desirable condenser pump flow rate. This control strategy was outdated, resulting in the inefficient operation of the condenser pumps. As a result, the DEM specifications of the condenser towers were not being met.

Due to increased condenser flow rates, condenser tube fouling was enhanced. The increased sediment build-up in the condenser tubes resulted in increased maintenance costs. Unnecessary resources were dispersed to remediate the maintenance issues effectively.

Proposed solutions

As suggested by literature in Section 2.3.3, pump speed reductions of approximately 50% have little effect on variable torque applications due to increases in temperature. It is therefore suggested that motor speed

be limited to 50% or half-load pump conditions. The half-load limit can be determined using historical discharge flow data and verified using a simulation.

It is suggested that during chiller start-up phases, the condenser pumps be operated at full-load conditions for a certain period of time. Thereafter, existing PI control logic will be utilised to maintain a stable condenser delta temperature of 5°C. A minimum time period of ten minutes was selected from performance investigations.

As a result of the optimised PI control logic used to operate the VSD-installed condenser pumps, the flow will operate closer to DEM technical specifications. Consequently, fouling may be reduced, accommodating for effective heat transfer within the condenser towers. This may also result in improved condenser tower performance. It is also suggested that a yearly maintenance agreement be set up to prevent sediment build-up within the condenser tubes.

As opposed to the evaporator water control cycle, the water quality does not deteriorate as a rapidly in the condenser cycle. The water within the condenser water flow control cycle is isolated from the water reticulation system. Hence, the need for a yearly maintenance schedule.

The existing variable flow control strategy will be re-enabled and refined to prevent chiller trip phases during start-up procedures. Larger condenser pump flow rates during chiller start-up phases will ensure that the necessary DEM specifications are met to successfully operate the chiller at the optimal load.

3.3.4. Bulk air cooler water flow control cycle

Evaluation

Similar to the evaporator and condenser water flow control cycles, the evaluation of the bulk air cooler cycle revealed that the VSD-installed pumps were decommissioned. The review showed that the variable flow control strategy on the BAC feed pumps was disabled by mine personnel. At partial-load conditions, the BAC feed pumps did not supply sufficient flow for optimal cooling of ambient air. Mine A was concerned with the increase in BAC outlet air temperature as a result of the energy saving measure. The temperature sensor measuring the BAC outlet air temperature was also malfunctioning.

The existing energy saving measure utilised an ambient air enthalpy set point to modulate the speed of the pumps. As a part of the existing energy saving measure, a weather station was installed to measure ambient DB temperature and relative humidity. Inaccurate measurements readings from the weather station led to a deterioration in system performance. Incorrect ambient air enthalpy values were communicated to the PLCs, resulting in ineffective control of BAC feed pumps.

After implementation of the energy saving measure, the mine personnel disabled the BAC pump control by removing the PLC programming. The PLC infrastructure was removed, which affected the performance of the EMS. The EMS was unable to read and write into the respective SCADA tags to execute the correct BAC pump control. Such a change negatively impacted the performance of the BACs. In addition, should the VSDs be re-installed in the future, supplementary resources will need to be deployed to recreate the necessary PLC infrastructure.

Inadequate flow through the BAC feed pumps also resulted in a decrease in BAC tower efficiency. The reduced water flow rate affected the distribution flow pattern through the BAC spray nozzles, which impacted the thermal heat transfer capabilities. Similarly, the mine personnel were concerned with an increase in underground temperatures at the refuge bays.

Motor damage, similar to that of the condenser pumps, was anticipated, resulting in the variable flow control strategy being disabled. Consequently, the BAC ducts experienced signs of increased scaling. Particle build-up within the ducts of the BAC tower resulted in unexpected maintenance costs.

Proposed solutions

It is suggested that the variable flow control strategy on the BAC feed pumps is re-enabled. As a part of the strategy, it is also suggested that the weather station is recalibrated. This will ensure that accurate ambient air enthalpy measurements are achieved. In addition, a radiation shield can be installed to prevent the external heat source from tampering with the readings measured from the weather station.

The VSD-installed BAC feed pumps should be transferred to automatic control. Similarly, with assistance from the mine personnel, the PLC infrastructure can be reformulated. The PLC programming will be documented and filed to circumvent the need for additional costs and resources to streamline previously implemented PLC infrastructure. New read and write tags will also be developed to execute precise automated control.

The PI control logic will be updated to ensure that the VSDs modulate the speed of the BAC feed pumps to meet a minimum desirable pressure and flow range. The VSD control will be updated and refined using performance tests. In addition, during summer months, the VSDs will modulate the pump speed to a maximum flow capacity for a certain period of time so as to ensure a desirable BAC outlet air temperature of 7°C (WB).

By recommissioning the VSD-installed BAC feed pumps, the flow distribution pattern will operate closer to DEM technical specifications. Consequently, fouling is reduced, accommodating for effective heat transfer within the BACs. The BAC tower efficiency is also increased adversely.

Motor damage can be effectively mitigated by adopting the solution suggested in the condenser water control cycle. Operating the BAC feed pumps under half-load conditions can mitigate increases in DE motor bearing temperatures. Adjusting the minimum frequency of the VSDs will also ensure that the required static head is achieved. Also, the VSD-equipped pumps will operate closer to design load conditions, improving pump efficiency.

3.3.5. Pre-cooling tower water flow control cycle

Evaluation

Evaluation of the pre-cooling water control cycle revealed that the variable flow control strategy was disabled. Existing energy saving measures were also decommissioned by mine personnel. In addition, the pre-cooling tower fans were operating at full-load conditions. Closer investigation revealed that although the energy saving optimisation strategy was decommissioned, the cooling duty of the pre-cooling tower was sufficient.

The existing energy saving measure modulated the speed of the pumps to maintain a stable dam level for the pre-cooling sumps and HCD. After the VSD-installed pumps were decommissioned, the pumps were operating at frequencies lower than the minimum frequency threshold. Consequently, inadequate flow meant that the pre-cooling pumps were operating well below DEM specifications.

Due to the lowered operating flow rates, the pumps were incapable of delivering a discharge pressure to meet the minimum required static head. In addition, the mine personnel expressed concern with the increase in DE motor bearing temperatures. Operating the motor at reduced speeds, posed unfavourable flow distribution patterns within the pre-cooling towers. At lower motor speeds, the pre-cooling towers did not operate efficiently to meet varied cooling demands.

After implementation of the energy saving measure, communication between the EMS and SCADA was not maintained. The control of the VSD-equipped pre-cooling pumps was disabled. The EMS was unable to read and write into the respective SCADA tags to execute the correct PLC control logic.

Furthermore, inaccurate measurement readings from the faulty dam level sensors led to a deterioration in system performance. Incorrect dam level values were communicated to the PLCs, resulting in occurrences whereby the pre-cooling sumps and HCD overflowed. Due to a lack of communication between the SCADA and EMS, the automatic control of the pre-cooling tower pumps was disabled.

At maximum pump load conditions, scaling and fouling of the pre-cooling tower fill was enhanced. The increased sediment build-up resulted in increased maintenance costs. Unnecessary resources will need to be deployed to clean spray nozzles and tubes.

Proposed solutions

It is suggested that the variable flow control strategy on the pre-cooling pumps is re-enabled. Accurate dam level measurements can be achieved by recalibrating the dam level sensor. Once calibrated, the existing VSD control on the pre-cooling pumps can be re-enabled.

The VSD-installed feed and transfer pumps should be shifted to automatic control. Similarly, the PLC infrastructure can be reconstructed. As with the BAC flow control cycle, the PLC programming is documented for prompt availability. New read and write tags are also successfully added to execute precise automatic control on the EMS.

The PI control logic for the transfer pumps will be updated accordingly. The VSDs will modulate the speed of the pumps to meet a minimum desirable frequency limit. The frequency limit will be attained through various performance tests. The results will be reviewed so as to achieve flow distribution patterns within the DEM specifications. Similarly, fouling is reduced and the pre-cooling tower efficiency is improved.

The pumps can be operated under half-load conditions to mitigate damages to the motor and pump. Adjusting the minimum frequency of the VSDs will provide sufficient pressure for optimal pre-cooling tower performance. Also, the VSD-equipped pumps will operate closer to design load conditions; improving system efficiency.

3.3.6. EMS control

Evaluation

Implementation of an integrated EMS is crucial for the success of an energy saving initiative. An EMS is used to control mine cooling system components for improved operational performance and potential energy savings.

An evaluation of the EMS revealed that the server used to communicate between the EMS and the SCADA was disabled. The OPC of the host server was disconnected. As a result of SCADA upgrades, the host server was incapable of connecting with the SCADA due to outdated software. As a part of the SCADA upgrade, existing control tags were altered. These control tags were necessary for effective execution of the energy saving measure.

During the SCADA upgrade, the PLC infrastructure was removed, which affected the performance of the EMS. The EMS was unable to read and write into the respective SCADA control tags. Previously implemented PLC code was not recorded and documented for future use. Similarly, Mine A did not consider the effects the SCADA upgrade would have on the functionality and performance of the EMS.

Such a change negatively impacted the performance of the EMS, which led to a deterioration in energy savings.

As a part of the existing energy saving measure, the EMS was configured to monitor the performance of critical mine cooling components. After the EMS was disabled, component performance deteriorated leading to a decrease in total system efficiency. An unreliable OPC connection made it difficult to monitor the operational limits and performance of critical equipment.

A centralised data storage server was integrated with the EMS to store data for performance trends. Due to OPC connectivity issues, the host server failed to send data to the centralised data storage server. Investigations revealed that the Simple Mail Transfer Protocol (SMTP) address was not operative. The software applications used to send the data were outdated. Similarly, existing data trends could not be analysed for intuitive decision-making.

Proposed solutions

The OPC between the host server and SCADA will be reconnected. This will ensure that the EMS has consistent communication with the SCADA and host server. All outdated software packages will also be upgraded and installed. The control software package will be thoroughly tested before re-implementation.

Watchdog control tags, that persistently monitor process variables in real-time, will be implemented to ensure a reliable communication network between the SCADA and EMS. These watchdog control tags will automatically reconnect the OPC to ensure active communication between the SCADA and host server. As an additional safety feature, the watchdog control tags will notify the EMS users of communication failures. The frequency thereof can be investigated by the ESCO and EMS users to mitigate communication failures. This will consequently enhance cost savings and mitigate project deterioration.

The ESCO that was responsible for the previously implemented energy saving measure will be contacted to reconstruct the PLC infrastructure. The PLC code will also be updated to adapt to new software packages. This PLC programming will be documented for prompt availability. New read and write control tags will also be redeveloped to execute precise control on the EMS.

After a stable OPC connection is re-established, the EMS can be configured and upgraded to monitor the performance of critical mine cooling components. Due to SCADA upgrades and changes, it is necessary to also incorporate new control tags. This ensures that the EMS can monitor essential operational parameters for improved communication between field equipment and PLCs.

The SMTP address is reconfigured, and the software package is upgraded to the latest version so that data can be sent from the host server to the centralised data storage server. This will enable the ESCO and

mine personnel to gather important characteristic trends for the operational performance of critical mine cooling equipment.

The EMS also serves as a crucial tool that contributes to the effective control of field instrumentation. The refined and ungraded EMS will therefore integrate existing control philosophies to develop an automated strategy for sustainable cost savings. The following section will investigate existing sustainability practices. Thereafter, the development of an automated dynamic control strategy will be discussed.

3.3.7. Sustainability practices

Evaluation

As discussed in Section 1.5, the sustainability of energy saving measures is a critical focus area for this study. An investigation into the initial project implementation revealed that a performance monitoring report was established. The report automatically monitored the operational performance of Mine A's cooling system. Due to OPC connectivity issues and SCADA upgrades, as discussed in Section 3.3.6, the report was disabled.

In keeping with the suggestions from the literature in Section 2.6.4, the sustainability of energy saving measures is enhanced by identifying and monitoring KPIs. Although, KPIs were initially identified, new post-implementation system constraints were recognised. New KPIs were therefore not considered and incorporated into the daily report. Similarly, performance deterioration of the initial energy saving measure was realised.

After the initial energy saving measure was disabled, the control of the mine cooling system was reverted to manual control. From literature, manual control was identified as a leading cause of project underperformance. In addition, the literature suggests that a deterioration in cost savings can be successfully mitigated and sustainably maintained with the implementation of an automated control system; hence, the purpose of this study.

Proposed solutions

After a stable OPC connection is re-established, the daily report can be updated and refurbished. Thereafter, new KPIs can be identified and included within the report. This enables the relevant stakeholders (ESCO and mine personnel) to analyse crucial operational parameters for sustained system performance. To mitigate human error, it is suggested that an automated dynamic control strategy is employed. Automated chiller control, which is yet to be investigated, has been recommended to reduce project underperformance and improve the sustainability of energy saving measures.

Chiller maintenance schedules will also be recommended. To guarantee the sustainability of the EMS, proactive maintenance is critical. During winter months, the demand for cooling is reduced, which provides a time period for system maintenance. Performance criteria related to the maintenance of mine cooling components can be added to the daily report, which will increase cost savings awareness adversely.

Finally, it is important to note that regardless of how many new systems and processes are put in place, it is still the mine personnel who will manage the system on an ongoing basis. For this reason, it is important to consider partnering with the Human Resources function to drive a change management approach that looks at continuous training. This is likely to provide the 'soft' support that enables the culture of Mine A to shift sustainably in the longer term.

3.3.8. Existing control strategy summary

The control philosophy of the existing energy saving measures were evaluated and reviewed to suggest a new optimised solution. Understanding the existing control and infrastructure is crucial for developing an automated dynamic control strategy. A brief summary of the original control philosophy is illustrated in Table 3-3.

Table 3-3: Audit results of existing energy saving control strategies

Existing energy saving measure	Control limit	Evaluation results
i. BAC flow control cycle - Install a VSD on each BAC feed pump. - Open loop P control logic. - Update PLC infrastructure. - Modulate VSDs to an ambient air enthalpy set point.	- - - 25 - 75 kJ/kg	- Insufficient flow for adequate cooling. - Inaccurate measurement reading from weather station. - Ineffective control of BAC resulted in increased operational temperatures. - Removed PLC infrastructure. - Reduced BAC tower efficiencies. - Scaling (sediment build-up) led to increased maintenance costs.
ii. Condenser flow control cycle - Install a VSD on three of the six condenser pumps. - Closed loop PID control logic. - Throttling valves were decommissioned. - Modulate VSDs to meet a stable condenser water temperature difference.	- - - 5°C	- Motor damage due to increased DE bearing temperatures. - Variable flow control strategy decommissioned. - Inadequate flow specifications. - Scaling (sediment build-up) led to increased maintenance costs. - Throttling valves recommissioned to meet DEM specifications.
iii. Evaporator flow control cycle - Install a VSD on each evaporator pump. - Closed loop PID control logic. - Throttling valves were decommissioned. - Modulate VSDs to maintain a stable CCD level.	- - - 75%	- Insufficient evaporator flow for chiller start-up. - Chillers tripped repeatedly. - Variable flow control strategy decommissioned. - Overcooling in heat exchanger ducts resulted in a loss in production. - Lack of proactive maintenance.
iv. Pre-cooling flow control cycle - Install a VSD on each pre-cooling tower feed pump. - Open loop P control logic. - Throttling valves were decommissioned. - Modulate VSDs to maintain a stable pre-cooling sump dam level. - Install a VSD on each pre-cooling tower transfer pump. - Closed loop PID control logic. - Throttling valves were decommissioned. - Modulate VSDs to maintain a stable HCD level.	- - - 85% - - - 80%	- Inaccurate measurement reading from dam level sensors. - Pressure is less than static head. - Reduced pre-cooling tower efficiencies. - Variable flow control strategy decommissioned. - Scaling (sediment build-up) led to increased maintenance costs. - Increased motor windage damage.

Table 3-4: Audit results of existing energy saving control strategies

Existing energy saving measure	Control limit	Evaluation results
v. Chiller control		- Chillers are not operating at DEM specifications.
- Compressor IGV control of chillers.	3°C	- Inefficient energy practises of compressor IGVs.
- Closed loop PI control logic.	-	- Freezing in chiller cooling chambers.
- Infrastructure constraints.	-	- Increased chiller trip phases.
- Manual control of chillers by operators.	-	- Irregular chiller scheduling resulted in inefficient operation of chillers.
- Start and stop chillers to maintain varied cooling demands.	-	- Increased maintenance costs.
- Start and stop chillers to maintain a stable CCD temperature.	8°C	- Unfavourable service delivery requirements.
vi. EMS control		- No OPC with the host server.
- Installed a hosting server.	-	- Names of control tags were changed and upgraded.
- Limited tag counts.	-	- Automated monitoring of process variables were disabled.
- Modulate VSDs to maintain a stable pre-cooling sump dam level.	-	- Backups of framework and existing EMS was deleted.
- SCADA integration and communication.	-	- SMTP address was not operational.
- PLC infrastructure.	-	- PLC programming was deleted.
- Installed a central server.	-	- No existing documentation.
- Log and store historical process data.	-	- Communication with the central server was terminated.
- Periodically backed-up existing frameworks.	-	
vii. Sustainability practices		- No OPC with the host server.
- Created a performance monitoring report.	-	- Automated performance monitoring report was disabled.
- Logged KPIs.	-	- Missing KPIs from existing daily report.
- Automatically sent to stakeholders.	-	- Human intervention led to underperformance of energy saving measure.
- Proactive maintenance schedules.	-	- Failed to adhere to maintenance schedules. - Increased maintenance costs.

3.4. Control philosophy development

3.4.1. Foreword

A performance evaluation of existing implementation strategies on Mine A was critically discussed in Section 3.3. An overview of each system and subsystem was thoroughly reviewed to discover control faults and/or anomalies, as summarised in Table 3-3. The evaluation results depicted that previously implemented energy saving measures were non-existent. Project deterioration was largely accredited to the problems discussed in Section 3.3.

As highlighted in Section 1.2, the mining sector is under increasing financial strain to reduce operating costs to remain financially competitive. An automated dynamic control philosophy is suggested, whereby the primary focus of the strategy will be to sustain cost savings on mine cooling systems. As a result, deep-level gold mining can lucratively contribute to the GDP and remain financially competitive globally.

This Section will therefore summarise the necessary infrastructure that is required for the implementation of an automated control system. To regain and sustain the financial benefit of the previously implemented energy saving measures, a stable communication network between the SCADA and host server is re-established.

To execute the correct control outputs to the necessary field equipment, an integrated control system is required. The integrated control strategy will use an EMS to communicate with the PLCs and SCADA. The necessary infrastructure required for this integrated control system will be discussed in the following subsections.

3.4.2. SCADA and PLC infrastructure

Mine A utilises a Wonderware™ ArchestrA SCADA system to communicate with PLCs and field instrumentation. Wonderware™ ArchestrA is responsible for receiving control inputs and relaying control outputs to the respective PLCs located on Mine A's cooling system. OPC tags are created to denote certain process parameters with read or write capabilities. This allows for the SCADA to successfully monitor control inputs and execute control outputs in real-time.

As mentioned in the literature review, mine cooling equipment is controlled by PLCs. Field instrumentation such as temperature sensors, dam level sensors and flow meters are fitted along Mine A's cooling system to read the necessary process parameters. These process parameters are conveyed to the SCADA through OPC tags. OPC represents a standardised technique for communicating between a diverse range of devices.

To optimally control the cooling auxiliaries and chillers at Mine A, real-time data is considered. The success of the automated dynamic control philosophy is largely dependent on the availability of a healthy OPC connection between the SCADA and EMS. Crucial OPC tags are required to maximise the benefit of implementing an energy saving measure. The Wonderware™ ArchestrA SCADA system and its subcomponents are fundamental for the automated control of mine equipment.

To communicate with field equipment, status control tags are required. Chiller and mine cooling auxiliaries' status control tags are utilised to communicate with the EMS and SCADA through OPC connectivity. The following status control tags are required:

- Running tag - Indicates if field equipment is running.
- Availability tag (MTR) - Indicates if field equipment is available to remotely control.
- Ready-to-start tag (RTS) - Indicates if field equipment is available to start.
- Trip tag (TR) - Indicates if field equipment has tripped or is in its trip phase.
- Start-up tag (STR) - Indicates if field instrumentation is in the start-up phase.
- Shutdown tag (STP) - Indicates if field instrumentation is in the shutdown phase.

In the event that a status control tag is not available, additional PLC programming will be required. The tags listed above are crucial for complete and safe automatic control of cooling auxiliaries and chillers. Evaluation of the existing Wonderware™ ArchestrA SCADA system indicated that the MTR status control tag was not available. The MTR status control tag is critical for the safe operation of field equipment remotely. With the assistance of the mine personnel, an MTR status control tag was formulated. The updated PLC code was also documented for future accessibility.

PLCs located on the mine cooling system are responsible for relaying the relevant status control tags to the SCADA. The EMS will then read the status control tags from the SCADA to remotely start and stop field instrumentation. These process control variables are monitored and logged for performance reporting. In the event of a communication problem, the report will notify the respective stakeholders (ESCO and mine personnel) to ensure that the issue is resolved immediately. The ability to automatically control field equipment is heavily reliant on communication with the SCADA through OPC status control tags.

3.4.3. EMS infrastructure

The sustainability of an energy saving measure is largely dependent on the use of an integrated EMS. It is therefore essential that the necessary EMS infrastructure is correctly established and configured. Similar to the SCADA system, the EMS utilises internal programmable tags to execute the desired control outputs.

The internal tags communicate the desired control outputs using an OPC connection between the host server and the SCADA. The internal programmable tags are also only available on the graphical user interface (GUI) of the EMS. Process parameters are considered and evaluated to execute the necessary control outputs through internal programmable tags.

Before creating an automated EMS, a virtual cooling network or digital twin is designed. The digital twin will log all important process variables and serves as an ideal simulation layout for Mine A's cooling system. A layout of the system is made available from Mine A and integrated with the use of Google Earth to develop the digital twin.

Thereafter, the EMS is configured and built with the integration of important component characteristics collected from Mine A's Wonderware™ ArchestrA SCADA system. The virtual cooling network is displayed on the GUI of the EMS to accurately represent the surface cooling system at Mine A. Figure 3-4 illustrates the digital twin that was configured on the GUI of the EMS for Mine A's cooling system.

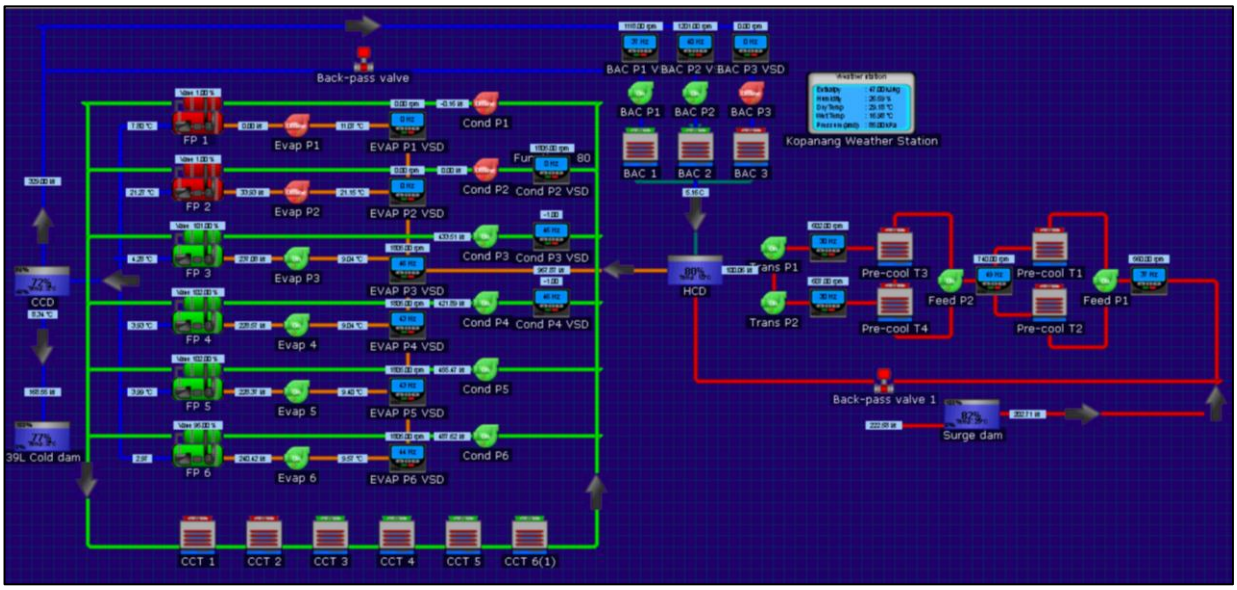

Figure 3-4: Digital twin displayed on the GUI of the EMS

Critical cooling system components that include BACs, chillers, auxiliary pumps and pre-cooling towers are represented in Figure 3-4. A component highlighted in the colour red denotes the specified component is not operational; or off. A component highlighted in green indicates that the component is currently operating; or on. Process variables that include temperatures, flows, dam levels, VSD frequencies and IGVs are indicated by white function blocks on the GUI. The green, orange, blue and red lines represent the different interconnected pipe networks. Flow direction of water is also displayed with arrows.

After the virtual cooling network is constructed, the EMS is utilised to simulate and execute the control outputs. The EMS system will execute the control strategy suggested in Section 3.5.

3.4.4. Process parameters

As previously suggested, to accurately execute the automated dynamic control strategy, important process variables are defined. Within this section, the process parameters required for the automated control strategy will be critically evaluated. Table 3-4 illustrates the process variables required to optimise and automate the control of the cooling system at Mine A.

Table 3-4: EMS process parameters

No.	Process variable description	Unit of measure
1	BAC mass flow rate	kg/s
2	Water to Underground mass flow rate	kg/s
3	Refrigerant mass flow rate	kg/s
4	Evaporator mass flow rate	kg/s
5	BAC air outlet temperature	°C
6	Outlet evaporator temperature	°C
7	Inlet evaporator temperature	°C
8	CCD temperature	°C
9	39L cold dam temperature	°C
10	Dry-bulb ambient air temperature	°C
11	Refrigerant suction temperature	°C
12	Refrigerant discharge temperature	°C
13	HCD level	%
14	CCD level	%
15	39L cold dam level	%
16	Fridge plant refrigerant compressor IGV position	%
17	Fridge plant refrigerant compressor guide vane spare	%
18	Evaporator pump running status	0/1
19	Condenser pump running status	0/1
20	BAC pump running status	0/1
21	BAC fan running status	0/1
22	38L Turbine running status	0/1
23	Fridge plant running status	0/1
24	COP	-

Table 3-4 includes all the necessary information required to develop an accurate automated control strategy. The process variables mentioned in Table 3-4 are monitored and logged on the EMS. The trends are analysed for performance monitoring and performance tracking. Excluding these process variables will make it difficult to send control commands to the new EMS. Therefore, the control logic for the EMS utilises the process variables suggested above.

3.4.5. Functional specification

This section of the EMS control philosophy describes the functional specifications of the PLCs, the SCADA, EMS and process variable. The communication associations between the relevant systems are

also discussed. Figure 3-5 illustrates the functional specification diagram of the PLCs, the SCADA and EMS.

The PLCs communicate using OPC with the field equipment and instrumentation. PLCs can be in two modes, namely; local mode or in remote mode. In local mode the PLC controls the field equipment to a set point which is pre-programmed on the PLC. In remote mode, the PLC controls the field equipment to a set point which is received from the SCADA. Typically, the EMS connects to the SCADA to send control outputs to the PLCs. The SCADA system is predominantly utilised for remote monitoring and field instrumentation control purposes.

The SCADA development necessary for the EMS will be developed by the mine personnel, as suggested in Section 3.4.2. It is required that the following control modes be made available for selection on the SCADA system: automatic control utilising EMS and manual control.

In the case that the EMS's automated control is enabled, and the SCADA is in Automatic mode, the EMS will send simulated control set points and outputs to the PLCs. This ensures redundancy during emergencies, as suggested by Du Plessis *et al.* [71]. If the EMS is disabled and the SCADA is in remote mode, the SCADA will send a set of pre-determined control outputs to the PLCs. In the case that EMS is disabled, and the SCADA is in manual mode, the PLCs are controlled with user entered control values (manual inputs) on the SCADA. In the event of a communication failure between the SCADA and PLCs, pre-programmed set points on the PLCs will be executed.

To ensure consistent communication between the EMS and the SCADA, a changing parameter called a heartbeat signal is established. This ensures that during a loss of communication between the SCADA and EMS, default set points are executed by the PLCs. Therefore, as suggested by Maré [36] and Du Plessis [37], the automated control system had built in redundancy features that were considered practically viable for automating mine cooling systems.

As illustrated in Figure 3-5, when the EMS is in manual and the heartbeat signal is not being sent, an alarm message is sent to the SCADA to notify the stakeholders (mine personnel and ESCO) to switch the SCADA into manual control. Until a stable communication network between the EMS and SCADA is restored, manual user inputs from the operator will be required.

Utilising the functional specification diagram, the optimised EMS control system will have the capability to; optimise and automatically control the chillers in automatic control mode; communicate with the SCADA system using OPC; communicate with the PLCs via SCADA to start and stop chillers and auxiliary equipment; log important process parameters for performance monitoring and performance assessment; display critical mine cooling functional parameters; achieve an Eskom evening peak load shift saving; enable user security levels; and install alarm notifications.

Figure 3-5 indicates that a centralised data storage server communicates with the EMS, as a part of an integrated approach, to store data for performance trends. An SMTP is incorporated to make communication secure and private as suggested by Banday [206].

As part of the EMS, a watchdog control tag was also programmed to monitor process variables in real time. These tags automatically reconnected the OPC to ensure active communication between the SCADA and host server. Thereby, providing a robust and safe control system.

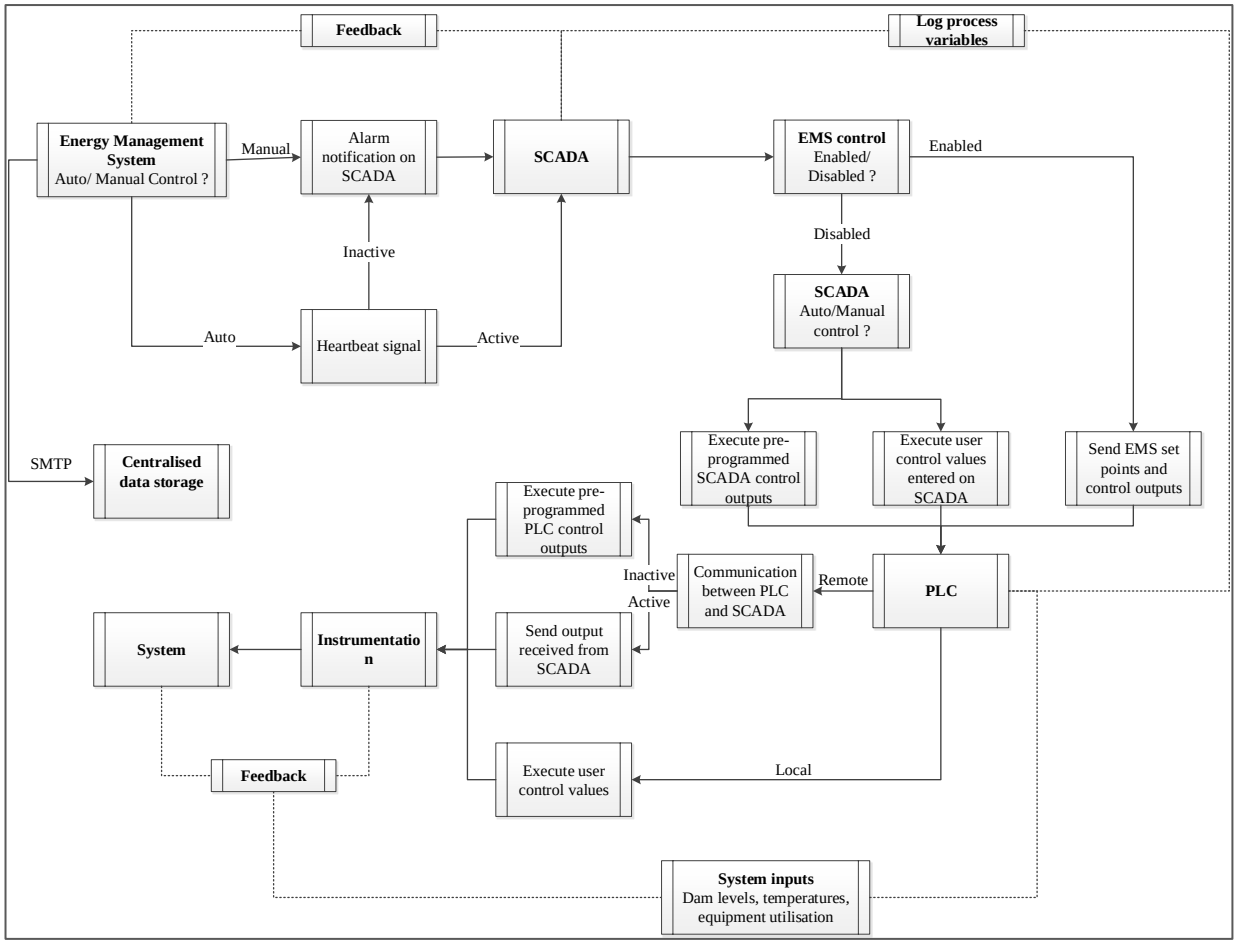

Figure 3-5: PLC, SCADA and EMS functional specification

The functional specifications and integrated communication networks, as described in Figure 3-5, are established prior to the control philosophy development stage. The integration of the PLCs, SCADA and EMS will form the back-bone for the successful implementation of the automated dynamic control strategy. Therefore, prior to implementation of the suggested control strategy, the PLC, SCADA and EMS functional specification will be tested and reviewed.

3.5. Implementing an automated dynamic control strategy

3.5.1. Introduction

Existing energy saving measures on Mine A's cooling system were thoroughly investigated and evaluated in Section 3.3. The evaluation revealed that the previously implemented energy saving measures were decommissioned, which negatively impacted cost savings potential. The sustainability of the original implementation control strategy was investigated and revealed to be non-existent.

Crucial KPIs were discussed and compared to the original energy saving measure. Project deterioration was exhibited and accredited to system modifications. In this section, an automated dynamic control philosophy for sustainable cost savings will be developed. The fundamental control infrastructure and process parameters, discussed in Section 3.4, will be included to form an integrated EMS. Mine A was selected as a suitable case study to re-implement a sustainable energy saving measure.

The control techniques discussed in this section will be verified with a calibrated simulation model. The performance of the energy saving measure will be tested and reviewed before the strategy is commissioned at Mine A.

The control philosophy for the automated cost saving measure is summarised into four control categories. The following control strategies will be integrated to automate the chillers and their respective auxiliaries:

- Flow balance control;
- Auxiliary turbomachinery control;
- Temperature control; and
- IGV control.

This section will discuss fundamental control parameters. These process parameters were identified through detailed investigations. The process parameters will be continuously revised to accommodate for dynamic system changes. A detailed characterisation of the process parameters will be established to sufficiently evaluate Mine A's cooling requirements. This will be achieved by integrating the four control categories. The EMS will also simulate the predicted ambient temperature conditions to estimate future cooling requirements. Thereafter, an accurate dynamic energy saving measure can be implemented.

3.5.2. Automated dynamic control model

Figure 3-6 summarises the requirements for the implementation of an automated dynamic control model. This model begins with *distinguishing mine cooling requirements*. This ensures characteristics of chillers, heat- absorption and rejection towers, auxiliary turbomachinery and thermal storage capacities are considered. This section of the model combines the technical specifications of components with the dynamic responses of these components to external factors, so as to develop the dynamic control strategy. These system components are integrated to develop an EMS in order to execute the dynamic control remotely.

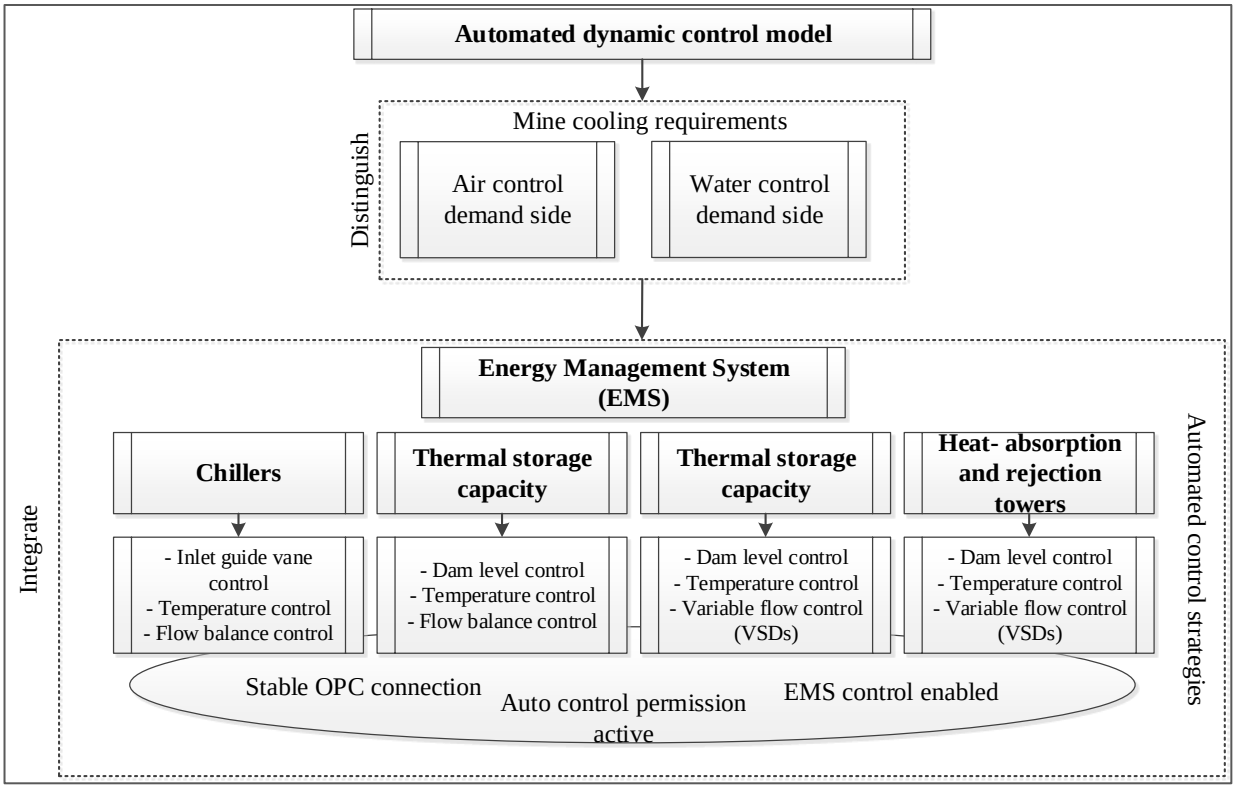

Figure 3-6: Automated dynamic control model for mine cooling systems

Each component within the EMS section of the model was categorised by automated control strategies. To achieve optimal chiller control, dynamic control techniques including IGV control, temperature control and flow balance control were considered. Ambient DB air temperature, which was identified as an uncontrollable variable by Vakiloroaya *et al.* [166], was included in this model to optimise the chiller control. Variable flow control strategies were also considered for the optimal control of auxiliary turbomachinery such as pumps, as illustrated in the control model and suggested by Du Plessis *et al.* [71]. Thereby, providing an integrated control strategy for deep-level mine cooling systems.

Factors including a stable OPC connection, auto control permission and EMS control were enabled to execute the dynamic control of the EMS. These three factors are illustrated in an ellipse to denote that the dynamic control strategies are interrelated and interdependent. The model provided a holistic and

practical approach to integrating mine cooling components for sustainability as suggested in the literature by Chao and Yeo [196].

The ultimate objective of the control model is to dynamically control subsystems, holistically, for power demand reductions on a deep-level mine cooling system in South Africa. This was completed simply and timeously with an EMS for sustainable energy savings. The control model identified temperature control, IGV control, flow balance control and variable flow control to be suitable control techniques. The variable flow control strategy incorporates VSD-installed motors for reduced motor energy consumption. This was implemented on auxiliary pumps and water supply valves.

Integrating these automated control strategies was essential for enhancing system control. This model is also versatile for underground cooling systems but should be adapted for other mine processes like pumping and compressed air. The remaining control techniques will be discussed in the next subsections.

3.5.3. Flow balance control

Flow balance refers to the balance of flow within the CCD from the chillers to the BACs and 39L cold dam. Flow meters are placed along the cooling system to measure delivery flow from the chillers in ℓ/s. The EMS utilises flow balance control to prevent flooding or draining of the CCD and HCD.

To ensure sufficient flow balance is achieved, the EMS will evaluate the flow to the BACs and water sent to underground (UG) end-users. Inlet and outlet water flow, to- and from the chillers, is also monitored. The EMS will then automatically start and stop chillers to maintain the flow balance. Figure 3-7 displays the necessary flow instrumentation required to regulate the flow for optimal flow balance control.

Upstream and downstream flow is utilised to achieve optimal flow balance control. The upstream flow meters represent the total flow from the evaporator pumps to the CCD. The downstream flow meters represent the total flow supplied to the BAC's and the water sent to UG end-users from the chillers. Both upstream and downstream flow is utilised by the EMS to automatically simulate the desired chiller combination. To ensure constant flow from the chillers to the CCD, a stable CCD level must be maintained.

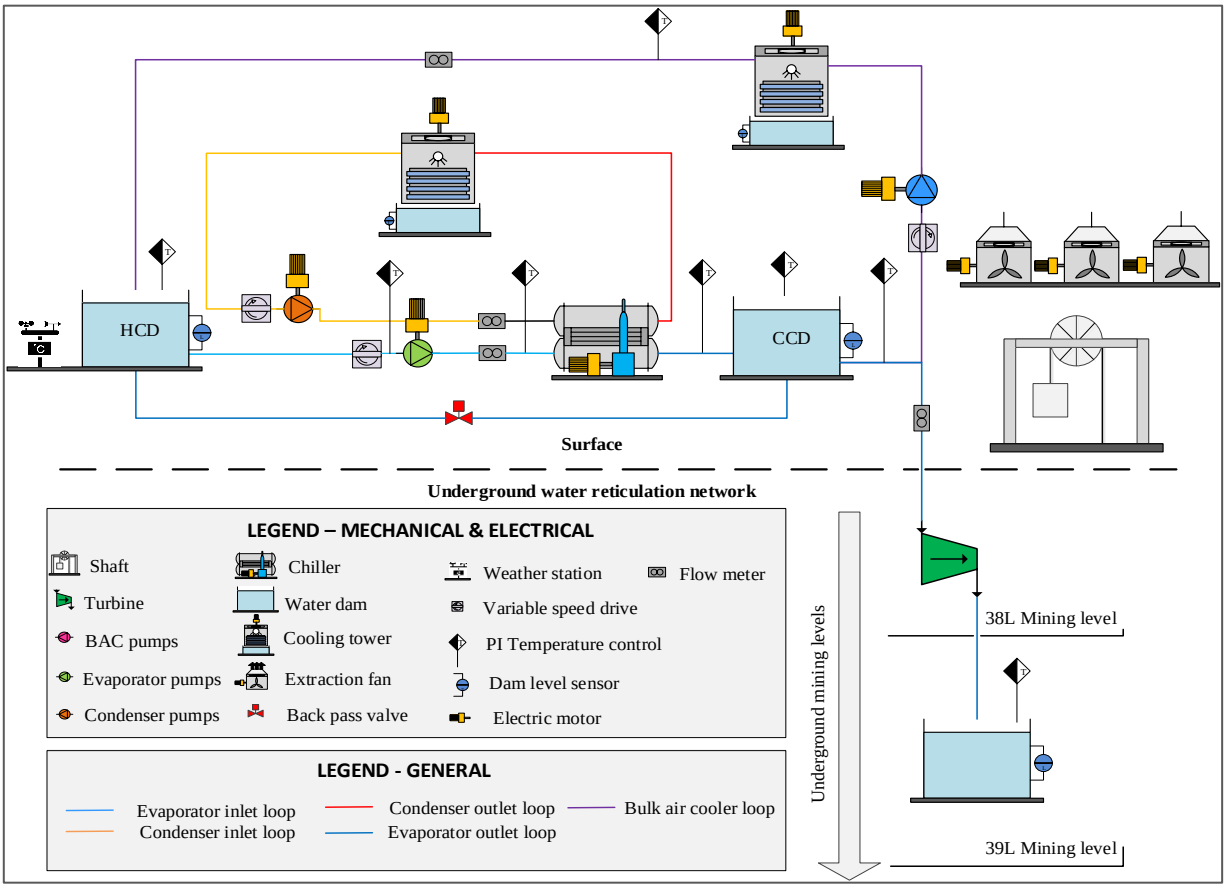

Figure 3-7: Instrumentation required to regulate temperatures and flow at Mine A

Flooding and draining of water dams is of paramount importance when automating chillers. As a precautionary safety measure, the EMS will never schedule less than the minimum number of chillers required to maintain a stable CCD level. The minimum number of chillers is established through detailed system investigations and testing. The investigation revealed that the EMS will not schedule less than three chillers to run at any given time during weekdays. The flow balance within the CCD is therefore maintained by utilising Equation 3-1.

Equation 3-1: Mass flow balance

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \qquad [kg/s]$$

$$\dot{m}_{in} = \dot{m}_{BAC} + \dot{m}_{UG} \qquad [kg/s]$$

Where:

$\dot{m}_{in} = average\ flow\ into\ the\ cold\ confluence\ dam$ $[kg/s]$

$\dot{m}_{BAC} = average\ flow\ of\ water\ to\ the\ BACs$ $[kg/s]$

$\dot{m}_{UG} = flow\ of\ water\ sent\ underground$ $[kg/s]$

By utilising Equation 3-1, the required flow into the CCD can be calculated. Assuming the CCD can be represented as a control volume system, the CCD level should remain stable, provided Equation 3-1 is utilised. To prevent flooding or draining, the EMS schedules chillers to start and stop to maintain the CCD level. By maintaining a constant CCD level, the flow demand to the BACs and 39L CD is also met.

Knowing the required flow into the CCD, the VSDs are able to control the evaporator pumps to match the water demand. The VSDs must be controlled according to the optimised control strategy in section 3.5.4. In addition, the demand flow will be further satisfied utilising an EMS to schedule a chiller to start or stop, should the water demand exceed the pumping capacity.

During introductory investigations, it was discovered that the maximum flow capabilities of the evaporator pumps are 253 ℓ/s. Through integrating a new set of control parameters with the existing VSD control, the flow demands can be better met. Table 3-5 illustrates the suggested number of chillers required to maintain a stable CCD ($\dot{m}_{BAC} + \dot{m}_{UG}$) level.

The suggested control ranges in Table 3-5 are to be re-evaluated to accommodate for system changes or alterations and to ensure that the evaporator pumps operate close to DEM specifications.

Table 3-5: Scheduled number of chillers for a specified CCD outlet flow rate

CCD outlet flow rate [ℓ/s]	**Suggested number of chillers**
≥200	3
≥400	4
≥600	5
≥800	6

To accurately meet the desired flow demands, the trip statuses of the following components are considered: chillers, BAC feeder pumps and the 38L turbine. The component trip statuses are configured with OPC status control tags on the EMS. During a chiller and/or BAC trip phase, the CCD runs the possibility of running dry or flooding. As a safety precaution, the EMS will continue to schedule the same number of chillers prior to the trip, after which a time delay is activated. If the proposed fridge plant schedule is not met after 40 minutes, the schedule will return the fridge plant running status to prevent components from cycling.

In the case that the 38L turbine trip phase is activated, the flow of water sent to UG is terminated. Similarly, the flow of water delivered to the 39L cold dam and underground water users is reduced. As a result, the temperature of the CCD decreases as the cool water entering into the CCD is allowed to circulate.

The EMS also utilises dam level control to accurately control the demand of water. The EMS automatically schedules the chillers to stop and start according to HCD and CCD levels. The EMS considers low and high dam level control set points. During low level control, the EMS automatically

controls the chillers to start and stop according to a minimum dam level set point. During high level dam control, the EMS automatically control the chillers to start and stop to a maximum dam level set point.

Two scenarios for high dam level control exist. If the CCD is above its maximum limit during or prior to the evening peak period, the EMS will automatically switch off the chillers and its cooling axillaries to ensure that the CCD does not over flow. During or prior to the Eskom evening peak period, if the dam level of the HCD is at a maximum, the EMS will automatically start a chiller and its cooling auxiliaries. The EMS will then re-evaluate the scheduled number of chillers. If necessary, the EMS will then start an additional chiller to increase the water flow from the HCD to underground end-users.

In the case of low level dam control, if the dam level of the CCD is below its minimum limit, the EMS will automatically start a chiller and its cooling auxiliaries. The EMS will evaluate the scheduled number of chillers to execute the correct control commands. During or prior to the Eskom evening peak period, if the dam level of the HCD is at a minimum, the EMS will automatically stop a chiller and its cooling auxiliaries to ensure that mud is not pumped through the water reticulation system.

Table 3-6 illustrates the high-level and low-level dam set points selected for the CCD and HCD. The dam level set points are unique and are designed to be altered depending on mining requirements. The dam level set points are aligned with standards set up by the mining personnel at Mine A.

Table 3-6: Dam level parameters

Dam	High level dam set point	Low level dam set point
HCD	90%	40%
CCD	90%	40%

If either the HCD or CCD level exceeds the dam level set point and a chiller has not been automatically started or stopped, an alarm notification is activated. The alarm notification will be activated to notify the operator to switch from automated control to manual control. Automated control will be re-established after the operator is satisfied with the HCD and CCD level.

3.5.4. Auxiliary turbomachinery control

As part of an integrated control approach, the control and utilisation of auxiliary turbomachinery for improved system performance is considered. The methodology for the improved control of auxiliary turbomachinery is therefore discussed and reviewed in this section. The suggested operation of the 38L turbines is discussed below.

Turbines

To develop an integrated control strategy, the automated EMS will start and stop the 38L gravity turbines. The gravity turbines harness downward gravitational potential energy and converts it to rotary energy.

The rotary energy is converted to mechanical shaft power which is utilised to power the 38L pumps at Mine A.

The turbines are manually controlled by operators. In manual control mode, the operator manually starts and stops the turbines to maintain a stable 38L hot dam and 39L cold dam level. The operation of these turbines are inefficient and outdated. It is, therefore, suggested that these turbines are remotely controlled to improve the dynamic control of the mine cooling and water reticulation systems.

If automatic control is provided, the EMS will supply temperature and dam level parameters to the SCADA and PLC. The turbines will then be scheduled to start and stop according to these parameters. The turbine control logic requires the following process parameters via OPC tags:

- Chiller evaporator outlet temperature [°C]
- CCD temperature [°C]
- Water to underground (UG) temperature [°C]
- 39L cold dam temperature [°C]
- BAC outlet air temperature [°C]
- CCD level [%]
- 39L cold dam level [%]
- Turbine running status tag [1/0]
- Turbine RTS tag [1/0]
- Turbine TR tag [1/0]
- STR and STP tags [1/0]

The EMS will log the SCADA OPC tags and write permissions into the STR and STP tags of the turbine to start and stop the turbine. This is achieved with start and stop permissions that are programmed using a turbine tag controller and internal programmable tags.

In the case of a communication failure between the EMS and the SCADA, the EMS will be overridden to allow for manual control by the operators. As an additional safety precaution, the EMS will display an alarm notification. The alarm notification will be sent to an email recipient list agreed upon by the ESCO and mine personnel.

In the case where the turbines are not operational, the flow of water to underground is terminated. As a result, the total flow of water from to the CCD to the relevant consumers is reduced. Because of reduced

water flow to underground consumers, the temperature of the CCD decreases as the cool water in the CCD is allowed to circulate. In addition, depending on the water demand requirements at the mine, the 39L dam level is reduced.

Mines are extremely volatile and periods where the mining demands and requirements fluctuate will occur. To accommodate for such changes, a dynamic control strategy is employed to control the 38L turbine effectively. The control strategy is displayed in Figure 3-8.

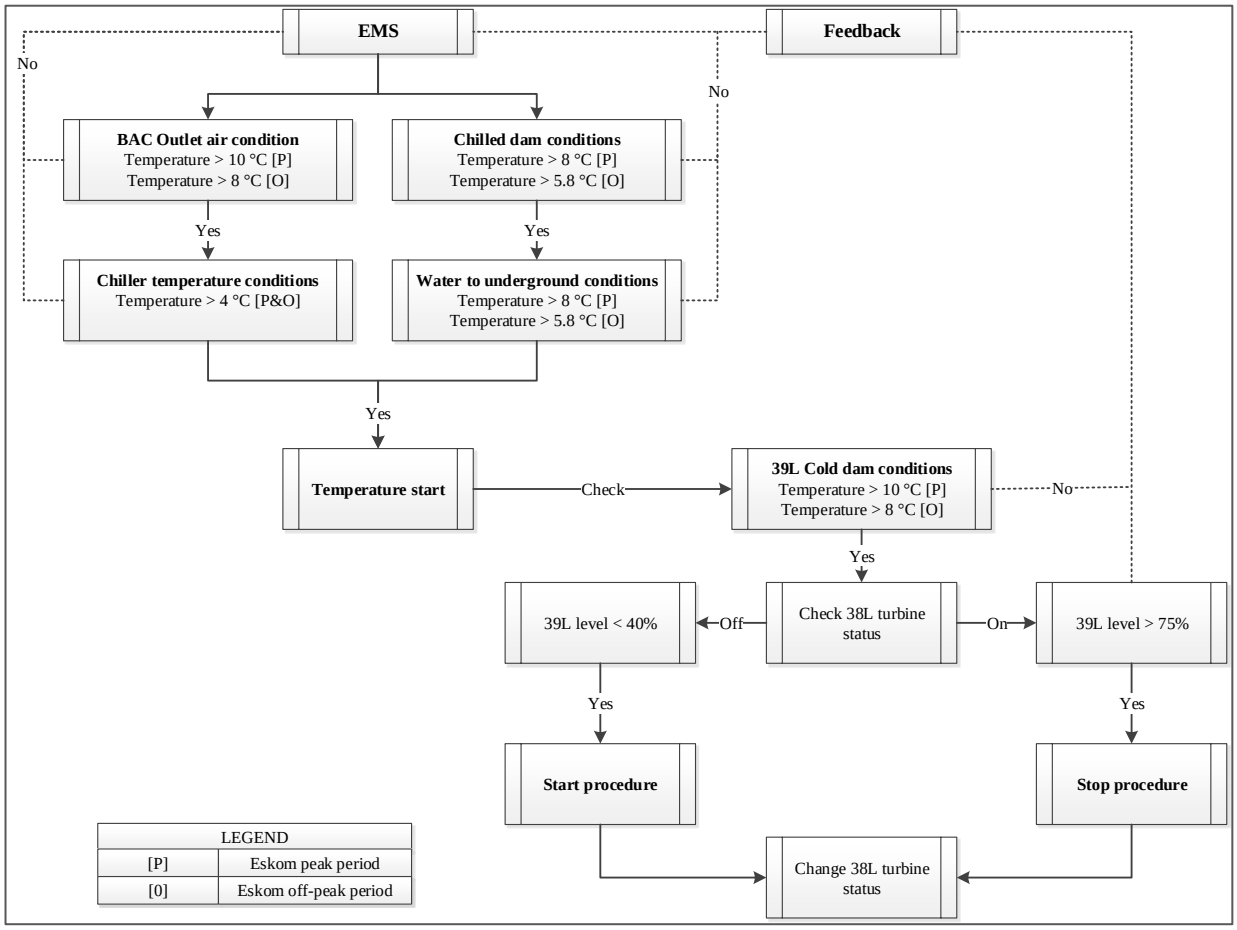

Figure 3-8: 38L turbine control strategy

Evaluation of the original 38L turbine control logic revealed that the operators would manually stop the turbine during the Eskom evening peak period. During the Eskom evening peak period, the demand for water is considerably reduced, as suggested by the literature. Although the demand is reduced, the turbine is necessary for maintaining a stable 38L hot dam and 39L cold dam level.

In addition, to reduce unnecessary pumping costs during the Eskom evening peak period, it is more favourable to start the 38L turbine as opposed to a 38L pump powered by a motor. This limitation was included in the 38L turbine control logic, as displayed in Figure 3-8, to ensure optimal turbine control for maximum cost savings.

As previously mentioned, certain temperature and dam level parameters will be monitored to accurately execute the control logic for the turbine. It should be noted, that the conditions utilised for the control strategy can be updated and altered as cooling requirements or control systems change.

During the Eskom evening peak period, if the dam level of the 39L cold dam is at a minimum, the EMS will prioritise the 38L turbine to start. The turbine will be started to prevent unnecessary pumping costs. This will also prevent mud being pumped up through the pipe networks. Draining of tanks is detrimental to the safety and longevity of pumps and could cause pipe impasses and cavitation. In the case that the dam level of the 39L is at a maximum, the EMS will prioritise the 38L turbine to stop.

Similarly, the EMS will prioritise the turbine to stop when the 39L cold dam temperature parameter is within its desired temperature set point. The EMS will stop the turbine to allow the temperature of the CCD to cool. After the EMS prioritised the turbine to stop, the EMS will reanalyse the temperature and dam level conditions to schedule a turbine to start.

The 38L turbine is important for maintaining a stable 39L cold dam level. When prioritising a 38L turbine to start or stop, the EMS will consider the 39L cold dam level of greater importance. In the case where the dam level is depleted and the CCD temperature parameter is not within its temperature set point, the EMS will prioritise the 38L turbine to start. Similarly, a chiller will be scheduled to start, as illustrated by the control logic in Figure 3-20.

The control strategy for the 38L turbine is critical for ensuring sufficient water distribution to different water users. Figure 3-9 displays the start/stop control logic used for the safe automatic control of the 38L turbine at Mine A.

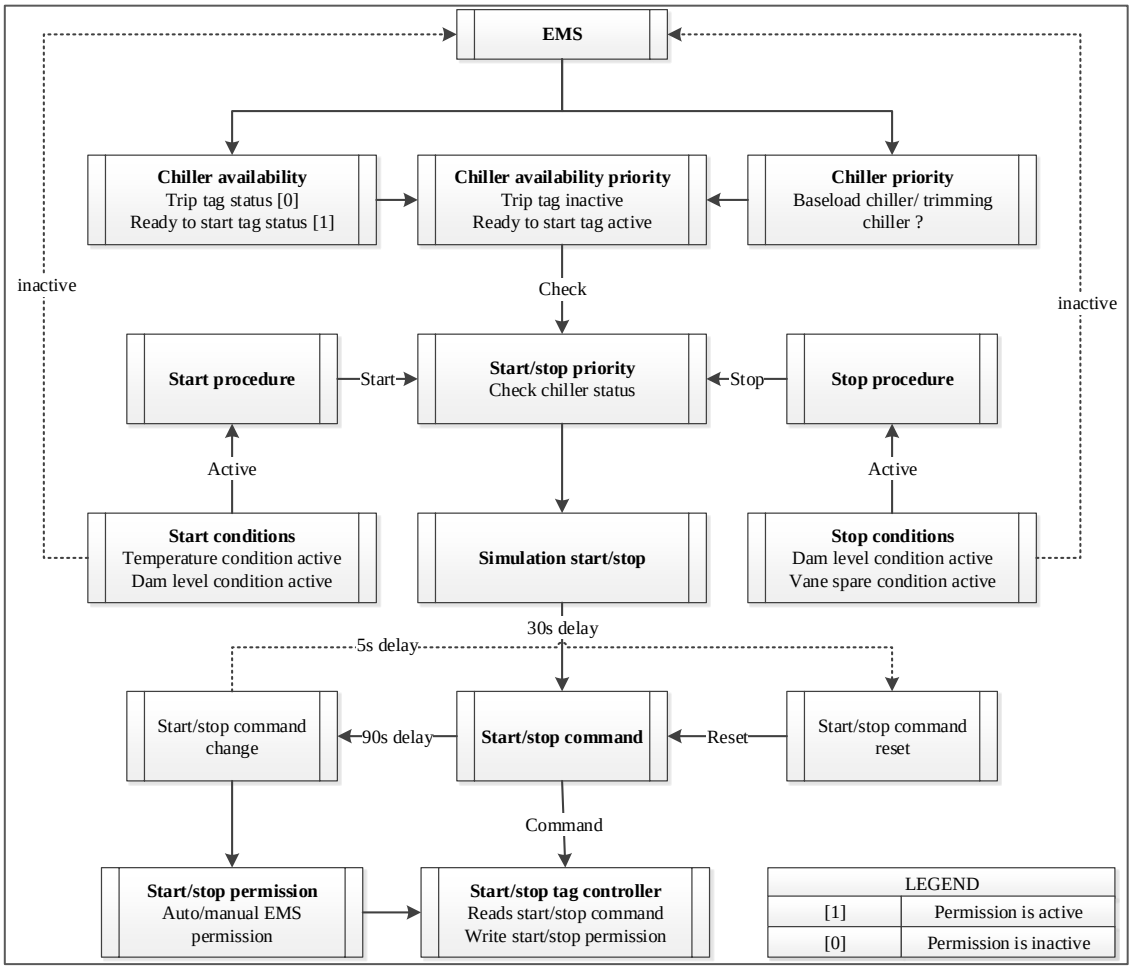

Figure 3-9: Start/stop controller for 38L turbine

To correctly automate the 38L turbine control outputs, the EMS will read and write into the STR and STP OPC tags of the 38L turbines. As a safety precaution, the 38L turbine is only controlled if the turbine control permission is active. The turbine control permission represents an auto to manual switch that is controlled by the operators.

The EMS will only execute start/stop control commands and permissions to the PLCs when the turbine control permission is set to auto or enabled. In the case of a communication failure between the EMS and the SCADA, the turbine control permission will be set to manual (disabled). Thereafter, the control outputs simulated by the EMS will be overridden to allow for manual control by the operators. Also, the EMS will notify the relevant stakeholders with an automated alarm notification.

Heat absorption and heat rejection towers

Proposed solutions for the optimisation of the pre-cooling towers and BACs variable flow control was thoroughly discussed in Section 3.3. Figure 3-10 summarises the control strategy to be followed when implementing an optimised energy saving measure on the cooling towers' (BAC and pre-cooling) auxiliaries.

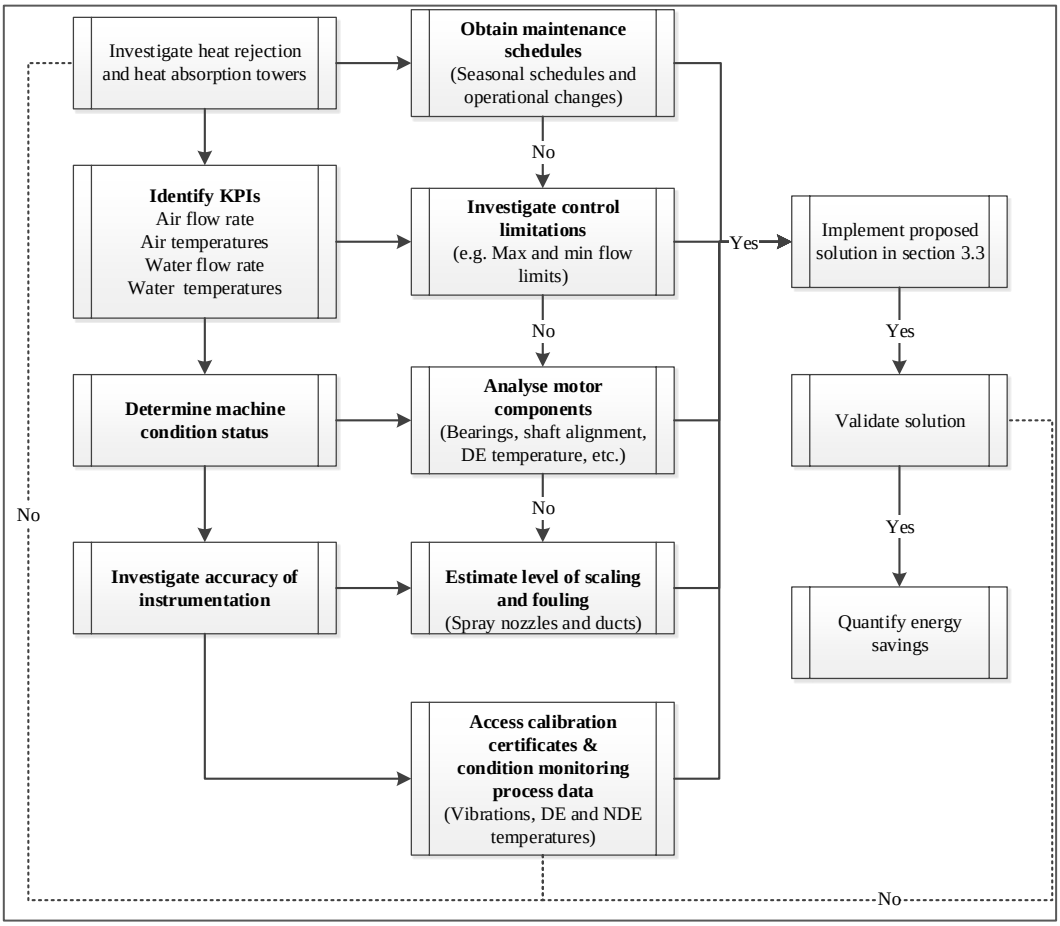

Figure 3-10: Heat absorption and heat rejection tower control strategy

To effectively execute the proposed solutions in Sections 3.3.4 and 3.3.5, it is necessary to obtain or create a feasible maintenance schedule. The maintenance schedule must be determined prior to the implementation of the energy saving measure. It is also essential that the maintenance schedule is agreed upon by all stakeholders (ESCO and client).

All operational changes must be included within the maintenance schedule. Furthermore, prior to the implementation of the energy saving measure, component maintenance periods must be critically defined. Depending on operational requirements, a seasonal maintenance schedule is preferred. Therefore, to accommodate for system disturbances, the maintenance schedule will be reviewed quarterly.

During the pre-implementation phase, crucial KPIs are identified. The KPIs must be reviewed throughout the project life cycle to ensure the sustainability of the energy saving measure. Control limitations (minimum flow restriction, maximum air outlet temperature, etc.) must also be determined. The control restrictions and limitations will be included within the programming of the EMS to execute the desired control.

The condition status of the cooling towers must be thoroughly investigated. The physical condition of the motors, spray nozzles, ducts and bearings must be healthy. It is critical that the mechanical components are also regularly inspected after the implementation of the energy saving measure.

Control instrumentation must be healthy and in good working order. Calibration certificates must be made available to the ESCO for thorough review and investigation. All condition monitoring process data must be accurately verified and documented. It is essential that the ESCO communicate with the necessary instrumentation technicians to ensure the feasibility of the energy saving measure.

Unlike the 38L turbine, the BACs are not automatically started and stopped with a start/stop controller. As requested by Mine A, two of the three BACs should be operating continuously. Therefore, it is not required to automatically start and stop the BACs. Mine A, however, agreed to implement the variable flow control strategy discussed in Section 3.3.4.

Similar to the control of the BACs, Mine A requested that the pre-cooling towers operate continuously. Therefore, it is not required to implement an automatic start/stop controller to control the pre-cooling towers. The proposed variable flow control strategy for the pre-cooling towers will be executed with the EMS. Mine A requested that the variable flow control strategy on the pre-cooling towers does not affect the service delivery requirements.

The condenser towers will be automatically started and stopped together with the chillers. The automated control of the chillers and condenser towers will be critically discussed and evaluated in Section 3.5.7.

Pumps

Proposed solutions for the optimisation of the auxiliary pumps was critically evaluated in Section 3.3. A variable flow control strategy was suggested. Figure 3-11 summarises the control strategy when implementing an optimised energy saving measure on the auxiliary pumps.

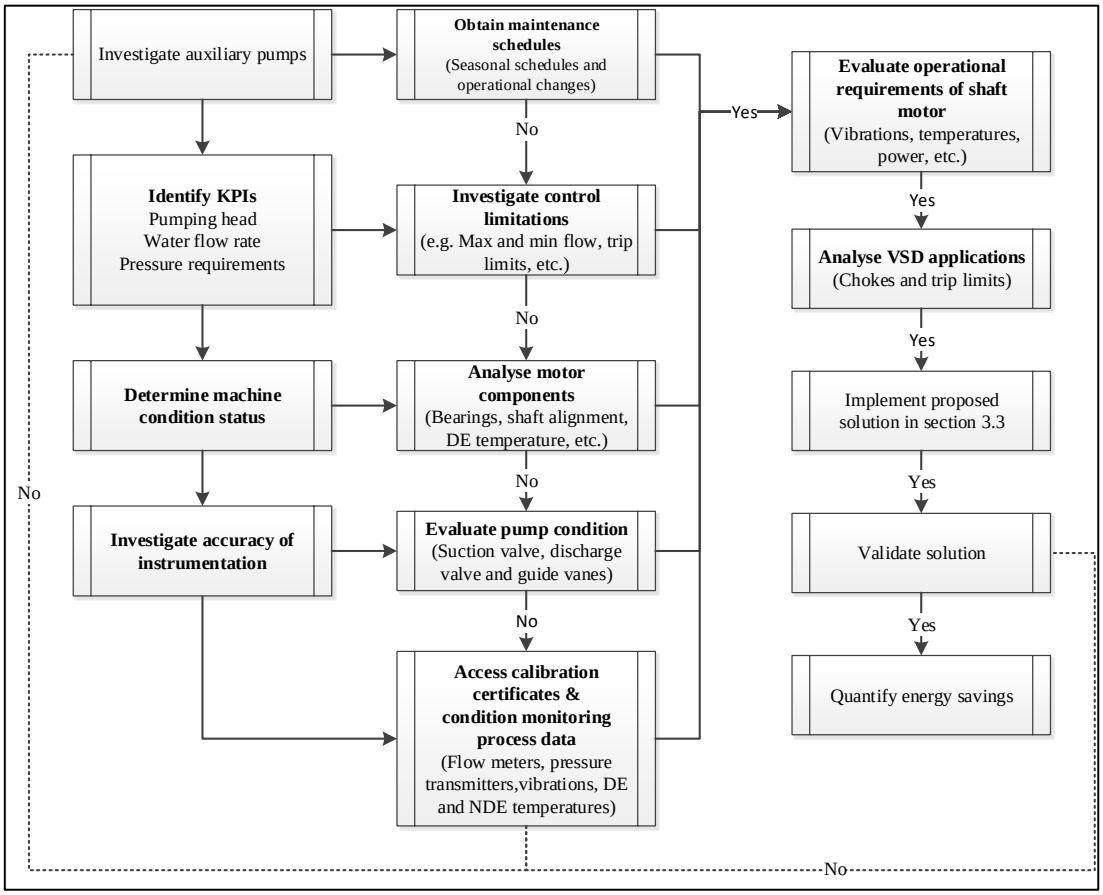

Figure 3-11: Auxiliary pump control strategy

The suggested control of the auxiliary pumps was critically discussed in Sections 3.3.2 to 3.3.5. To re-establish a feasible variable flow control strategy, it is critical that the control strategy in Figure 3-11 is followed. The auxiliary pump control strategy must be constructed prior to the implementation of the energy saving measure.

A practical maintenance schedule must be developed and agreed upon by the ESCO and the client. All operational changes must be included within the maintenance schedule. The maintenance schedule will be reviewed quarterly to evaluate the conditional status of the pumps.

Prior to the implementation of the energy saving measure, KPIs are identified. The KPIs will be continuously reviewed throughout the project performance periods. Control limitations will be determined and programmed into the programming of the EMS. The control restrictions will be determined during the project pre-implementation phase.

The health status of the control instrumentation will be evaluated and reviewed. Calibration certificates will be collected and filed for future evaluation. The physical condition of the motors, suction and discharge valves must be evaluated and in good working order. The mechanical components will be regularly inspected after the implementation of the energy saving measure to enhance sustainable cost savings.

To ensure the feasibility of the variable flow control strategy, the motor choke and trip limits must be determined and documented. This is done through data analysis and investigations. The health status of the motor must also be in good working condition. As suggested in the literature, a minimum threshold frequency must be determined and tested. Depending on the mechanical efficiency of the motor, the minimum threshold frequency should be continuously re-evaluated and updated.

3.5.5. Temperature control

Temperature control is of paramount importance to provide safe mining conditions. The EMS will utilise dynamic temperature set points to automatically schedule chillers to start and stop. To determine the optimal chiller combination and configuration, the EMS evaluates temperature process variables and their corresponding dynamic temperature set points. The EMS then writes the required chiller schedule to the PLCs to maintain temperatures aligned with mining requirements. The following temperature process variables will be evaluated:

- Water temperature to UG;
- CCD temperature;
- BAC air outlet temperature;
- 39L CD temperature;
- Average outlet fridge plant temperature; and
- DB ambient air temperature.

Each temperature process variable is evaluated in terms of the temperature measured from the temperature sensors displayed in Figure 3-7. Static temperature limits are established to account for heat loads and auto-compression. The EMS analyses and logs the temperature process variables to create an adjusted dynamic temperature set point. The chillers schedule is then controlled automatically to meet the adjusted dynamic temperature set point.

The CCD temperature is considered the driving temperature for the temperature control strategy. Therefore, the remaining temperature process variables are dependent on the CCD temperature. Subsequently, if the temperature requirement of the CCD is achieved, the temperature requirements of the 39L cold dam, BAC and water sent to UG is met.

Figure 3-7 illustrates the upstream and downstream temperature sensors. The upstream temperature represents the temperature of the water leaving the HCD through the evaporator pumps. The downstream temperature sensors represent the temperature of water being sent underground, the 39L cold dam temperature and the BAC air outlet temperature. In an optimised system, the average temperature of water

exiting the chillers should be slightly lower than the remaining temperature process variables. This will ensure that all temperature conditions are within the desired limits.

As previously mentioned, dynamic temperature set points are established to optimally control the chillers. The EMS will automatically start and stop chillers when temperature process variables are not aligned with the dynamic temperature set points.

Peak and off-peak static temperature set points are defined to correctly analyse temperature process variables. Eskom's TOU period differs depending on the season. For a typical summer production day, the Eskom evening peak period is defined as the evening period between 18:00 and 20:00. Winter Eskom peak periods are between 17:00 and 19:00. The remaining 22 hours are considered the off-peak period for this control strategy. The EMS utilises a peak and an off-peak set of static temperature set points.

Peak and off-peak static temperature limits were established to account for heat loads, auto-compression and temperature increases during the different TOU tariff periods. The off-peak temperature set points were reduced to rapidly stabilise the temperatures after the evening load shift period. The static temperature set points can be customised to adapt to new system requirements and applications. Multiple static temperature set points can be established depending on the design and control specifications of integrated mine cooling systems. Table 3-7 illustrates the static peak and off-peak temperature set points.

Table 3-7: Peak and off-peak static temperature set points

Temperature parameter	Peak temperature limit [°C]	Off-peak temperature limit [°C]
Water temperature to underground	8.5	6.25
CCD temperature	8.5	6.25
BAC air temperature	10	7
39L CD temperature	10	8
AVG outlet fridge plant temperature	4	4

To accurately quantify the dynamic temperature set point, a chiller rate of change (ΔT_{rate}) was considered. The chiller rate of change represents the rate at which the chilled water dam temperature changes per unit time in °C/min. This rate is utilised in Equation 3-2 to compute the dynamic temperature set point, which was used to improve chiller control and utilisation. Regression analysis and measured data modelling served as an accurate tool to determine the chiller rate of change.

Figure 3-12 illustrates a combination plot of the CCD temperature and chiller running status for a certain production weekday. The chiller running status was included to incorporate the effect of utilising different chiller combinations on the chiller rate of change. Data displayed in Figure 3-12 was averaged for a three-month period to ensure accurate results. The areas highlighted in grey on Figure 3-12, represent time periods at which the CCD temperature decreases from the start-up of an additional chiller.

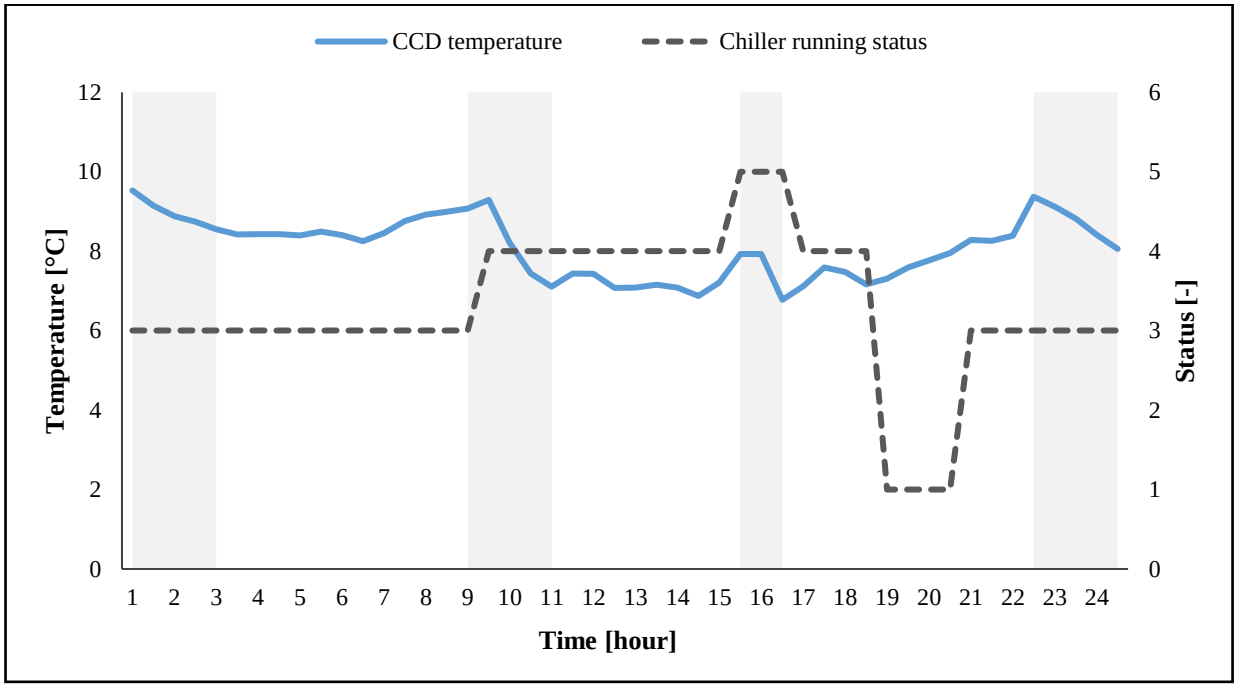

Figure 3-12: CCD temperature and running status for a three-month period

It becomes apparent from Figure 3-12 that the CCD temperature decreases more significantly when more chillers are operating. Therefore, a fixed control model to calculate the chiller rate of change cannot be assumed. Otherwise, the estimated chiller rate of change will be inexact. This could result in ineffective scheduling of chiller combinations.

Therefore, to determine the chiller rate of change accurately, the number of chillers running will be taken into consideration. This is achieved by establishing control equations (straight line profiles) as displayed in Table 3-8. The gradient (m) of the control equation represents the chiller rate of change (°C/min) for a certain chiller running status. Table 3-8 lists the gradient (m) of the control equations.

Table 3-8: Chiller rate of change [°C/min]

Number of chillers	y =mx + c		R^2
	m	m (per single chiller)	
1	-0.62	-0.6	0.98
2	-1.3	-0.65	0.93
3	-1.8	-0.61	0.84
4	-2.5	-0.63	0.97
5	-3.1	-0.62	0.93
6	-3.8	-0.63	0.89
Average [Absolute]		**0.63**	**0.9**

An average chiller rate of change of 0.63°C/min was approximated. The R^2 value of 0.9 illustrated in Table 3-8 indicates the precision of the control equations. It therefore accurately computes the chiller rate of change for chilled dams on integrated mine cooling systems. Equation 3-2 presents the dynamic temperature set point algorithm used to optimise the temperature control of the chillers.

Equation 3-2: Dynamic temperature set point formula

$$T_{dynamicsetpoint} = T_{actual} - T_{staticsetpoint} + (\Delta T_{rate})t \qquad [°C]$$

Where:

$T_{dynamicsetpoint} = dynamic\ temperature\ set\ point$ $[°C]$

$T_{actual} = actual\ temperature\ process\ variable$ $[°C]$

$T_{staticsetpoint} = static\ temperature\ set\ point$ $[°C]$

$\Delta T_{rate} = temperature\ rate\ of\ change$ $[°C/min]$

$t = time$ $[min]$

To ensure optimal chiller control, it is assumed that the chiller rate of change for each chiller is the same. In addition, it is assumed that the chiller rate of change remains constant. Using Equation 3-2 and the relevant assumptions, the response of the chiller on the designated temperature parameter can be better analysed.

The dynamic temperature set point will analyse the temperature parameter to determine whether it is decreasing within the calculated chiller rate of change (as calculated using Equation 3-2). If the temperature parameter is below the calculated dynamic temperature set point, no chillers will be scheduled to start. It is, therefore, suggested that the temperature parameter is reducing at the desired rate of change. The EMS will continue to evaluate the temperature parameter before automatically starting and stopping a chiller.

If the temperature parameter has stabilised below the static temperature set point, the dynamic temperature set point control is deactivated. At this stage a chiller could be scheduled to stop because the temperature parameter has met the static temperature set point. The chiller stop procedure is discussed thoroughly in Section 3.5.7.

When the temperature parameter starts to exceed the static temperature set point, the dynamic temperature set point control is activated; prompting the start-up of an additional chiller. The temperature parameter is continuously evaluated to analyse the response of the additional chiller to the temperature parameter.

During the Eskom evening peak period, the static temperature set point is adjusted to 8.5°C to accommodate for the evening load shift. The dynamic temperature set point control is applicable throughout the weekday (Eskom off-peak and peak periods).

Each temperature parameter, as discussed in Table 3-6, was dynamically monitored as it exceeds its static temperature set point. The EMS will utilise individual controllers to control the chillers to the desired dynamic temperature set points.

Therefore, the dynamic temperature set point formula adjusts in real time to meet variable cooling loads, as suggested by Fong *et al.* [165]. This ensures practical chiller management and control utilisation. Furthermore, adopting this control feature guarantees that chillers are scheduled effectively. A stable system performance was anticipated with enhanced dynamic system response features. Thereby, proving to be a unique model for variable applications in industrial cooling systems.

As a part of an integrated control strategy approach, a future DB ambient temperature was also considered. Unlike Lambrechts [198] that developed an empirical formula to compare VRTs to underground ambient temperatures, this strategy determined an empirical formula to relate ambient temperatures to surface chilled dam temperatures for integrated mine cooling systems. Equation 3-3 shows the adjusted ambient air temperature after 120 minutes. A time frame of 120 minutes was selected to minimise prediction errors, as recommended by Zhang *et al.* [199].

Equation 3-3: Calculating the required ambient temperature after 120 minutes

$$T_{adjusted@120min} = T_{actual} - T_{average@0min} + T_{average@120min} \quad [°C]$$

Where:

$T_{adjusted@120min} = adjusted\ temperature\ after\ 120\ minutes$ $[°C]$

$T_{actual} = actual\ measured\ ambient\ DB\ temperature$ $[°C]$

$T_{average@0min} = predicted\ temperature\ after\ 0\ minutes\ (Real\ time)$ $[°C]$

$T_{average@120min} = predicted\ temperature\ after\ 120\ minutes$ $[°C]$

The EMS continuously calculates the average DB ambient temperature profiles for weekdays, Saturdays and Sundays. These average values are logged on the EMS and can be used to predict future ambient DB temperature requirements. Equation 3-3 continuously calculates the adjusted predicted ambient DB temperature. The predicted ambient DB temperature profiles are used to determine the following temperature values:

- Current predicted DB ambient temperature; and
- Predicted temperature at 120 minutes.

To ensure an accurate prediction model, the predicted ambient DB temperature at 120 minutes is adjusted according to the difference between the actual measured ambient DB temperature and the current predicted DB ambient temperature in real time. Interpolation was used to get an accurate temperature

prediction every half-hour. This facilitates accurate data prediction for improved automatic chiller scheduling. Figure 3-13 illustrates the method used to adjust the predicted ambient DB temperature at 120 minutes, according to the actual measured ambient DB temperature.

These adjustments are made due to the dynamic nature of temperature requirements. If the predicted ambient DB temperature profiles are scaled according to the actual measured ambient DB temperature, an accurate predicted temperature model can be estimated.

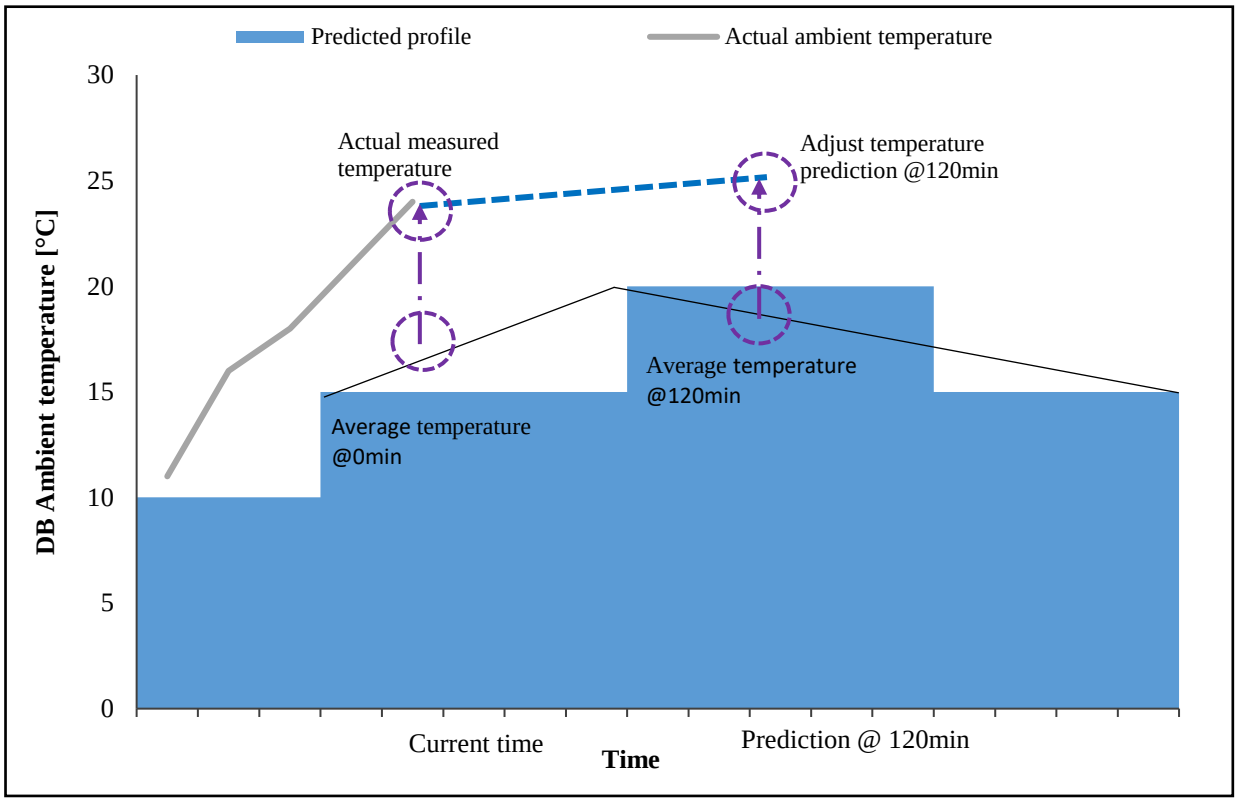

Figure 3-13: 120 minute predicted ambient DB temperature adjustment

In a typical scenario where the predicted ambient DB temperature is decreasing over the next 120 minutes, the EMS will automatically stop a chiller. To determine if a chiller can be automatically stopped, the following (previously discussed) requirements will be evaluated:

- Predicted ambient DB temperature over the next 120 minutes;
- Temperature parameters and dynamic temperature set points;
- HCD and CCD levels; and
- Turbine control parameters

3.5.6. IGV control

The IGVs of the chillers' compressors at Mine A are controlled with P&ID control logic. The P&ID variables are programmed to adjust the IGVs to maintain a chiller outlet temperature set point of 3°C. As part of the dynamic control strategy, the temperature set point to which the chillers' compressor IGVs are controlled, was increased by 15% to 3.5°C. This solution reduced compressor power consumption and refrigerant discharge flow, and prevented overcooling in the heat exchanger ducts. Therefore, the chillers' compressors were able to operate at partial-load conditions to provide variable cooling requirements, whilst maintaining an optimal temperature set point of 3.5°C.

To evaluate whether the chillers' compressors can operate at partial-load conditions, the refrigerant discharge flow of each compressor was considered. Compressor characteristic curves were developed to approximate the refrigerant discharge flow at different guide vane angles. To prevent the chillers' compressors from surging, a minimum guide vane angle was determined. Existing IGV control utilises this minimum guide vane angle to ensure that the compressor does not operate near the surge line. A minimum guide vane angle of 25° was calculated to prevent surging.

After the minimum guide vane of the chillers' compressors was computed, the compressor characteristic curve was determined. Figure 3-14 illustrates the compressor characteristic curve for chiller 4. To accurately characterise the different operating points of the compressor, data filtering was considered. Operating data points equal to or below the minimum guide vane angle were not considered for the compilation of the characteristic curves. This ensured that the IGVs were not operating close to the compressor surge line.

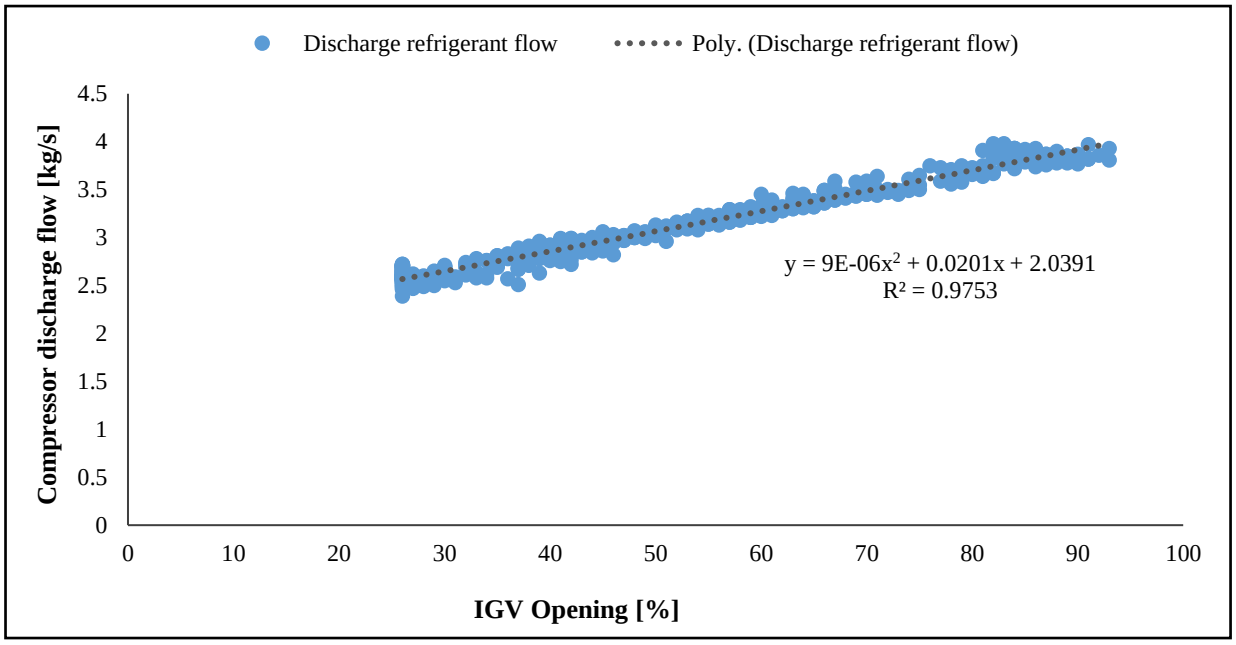

Figure 3-14: Characteristic curve of chiller 4

Utilising the characteristic curve, a trend line was determined. The compressor discharge flow was represented by a quadratic equation, as depicted in Figure 3-14. The quadratic formula characterised the refrigerant discharge flow at different guide vane angles. A R^2 value of 0.98 indicated an accurate estimation of actual conditions. It is, therefore, deemed a feasible model for estimating chillers' compressor IGVs.

Unfortunately, no flow meters were installed on Mine A's chillers to measure the compressor discharge refrigerant flow. Compressor theory, discussed in Section 2.3.2, was therefore utilised to reverse engineer the discharge refrigerant flow. It was suggested that the regression models be regularly updated to adapt with changes in compressor efficiency ratings. This ensured that accurate compressor discharge flow rates were estimated. The quadratic equation coefficients for each chiller are listed in Table 3-9.

Table 3-9: Summary of chiller regression models

Chiller	**Quadratic formula coefficients**			**Accuracy**
	a	**b**	**c**	R^2
Chiller 1	−0.0001	0.027	1.9	0.97
Chiller 2	−0.00008	0.024	2.1	0.98
Chiller 3	−0.00002	0.015	1.8	0.94
Chiller 4	0.00009	0.020	2.4	0.98
Chiller 5	−0.0000002	0.012	2.3	0.92
Chiller 6	−0.00006	0.023	2	0.98

R^2 values between 0.92 and 0.98 were approximated for the six chillers. The compressor flow regression models presented in Table 3-9 were feasible for approximating the chillers' compressor guide vanes. The chillers' compressor discharge flow was continuously determined, in real time, with the flow regression models presented in Table 3-9.

As discussed previously, the compressors guide vanes were not operated below the minimum guide vane position. Therefore, once a stable chiller outlet temperature of 3.5°C was met, the guide vanes of the chillers' compressor were cut back. This control was executed with the PLCs through the EMS. This enhanced compressor power reduction savings and enhanced system performance.

However, in the event of a communication failure or an unexpected system disturbance, the IGV control was reverted to P&ID control. After the system stabilised, the operator re-enabled automatic control to adjust the guide vanes to the optimal position. The chillers' compressor guide vanes were only controlled if the following conditions were true:

- Automatic control permission was active; and
- Heartbeat signal was active.

As previously discussed, the required flow was conjointly utilised with the characteristic curve equation to engineer the optimal guide vane opening. The quadratic equation was rearranged and solved to determine the optimal guide vane position, as illustrated in Equation 3-4.

Equation 3-4: Compressors quadratic flow formula

$$F = aG^2 + bG + c \qquad [kg/s]$$

The required refrigerant discharge flow is utilised to calculate the optimal guide vane position which is represented by the following equation:

$$0 = aG^2 + bG + c - F \qquad [kg/s]$$

The quadratic equation can be rearranged and solved to determine the optimal guide vane position:

$$G = \frac{-b \pm \sqrt{b^2 - 4a(c - F)}}{2a} \qquad [\%]$$

Where:

$F = required\ \ discharge\, refrigerant\, flow$ $[kg/s]$

$G = compressor\ guide\ vane\ position$ $[\%]$

$a, b, c = quadratic\ formula\ coefficients$ $[-]$

Figure 3-15 demonstrates the control logic utilised to determine the required discharge refrigerant flow. The calculated discharge flow represented the optimal mass flow rate of refrigerant necessary to meet the chiller outlet temperature set point of 3.5°C. This required discharge refrigerant flow utilised Equation 3-4 to engineer the optimal guide vane opening. Thereafter, the compressor guide vanes were adjusted variably, as part of a dynamic control approach, to match an outlet chiller temperature set point of 3.5°C. This enhanced compressor power reduction savings for enhanced system performance.

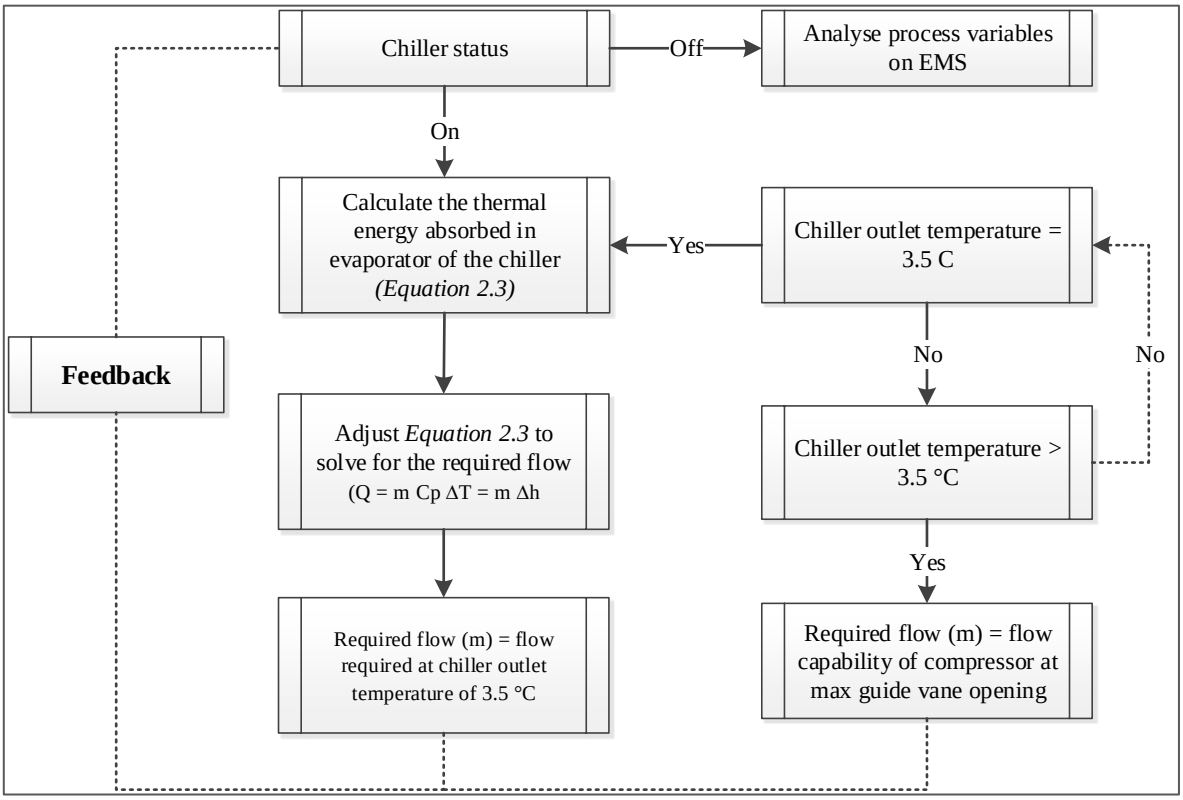

Figure 3-15: Control logic to determine the required refrigerant discharge flow

In addition to the new IGV control strategy, a chiller was stopped when a certain IGV spare was achieved. Guide vane spare is defined as the total unused guide vane percentage during an active phase of a chiller. The maximum guide vane percentage of a chiller was 100%. At 100% the chiller was operating at full-load conditions to supplying maximum cooling. Therefore, for a chiller operating at a guide vane position of 80%, the vane spare of the chiller was 20%. The chillers' vane spare was continuously monitored to correctly schedule the chillers. Figure 3-16 illustrates the guide vane angle control during start, stop and trip phases.

The EMS ensured that a total vane spare percentage of 110% was recognised and maintained before scheduling a chiller to stop. Therefore, if the IGVs of the current chiller combination were cycling, the control included a small buffer zone to prevent ineffective cooling and chiller utilisation.

Once the vane spare was maintained for 30 minutes, the EMS sent a stop signal to the SCADA to stop the desired chiller. Thereafter, the EMS continued to monitor the chillers' outlet temperatures. After a chiller was stopped or started, a gap in the cooling capacity range of the new compressor-chiller combination was recognised. The guide vane positions of the active chillers were then adjusted to 100% to accommodate for this loss in cooling capacity.

In the event that a chiller tripped, the PLCs set the IGVs of the chillers to 100% to accommodate for the loss in cooling capacity. After the system stabilised, the IGV angles of the chillers' compressors were

adjusted to match the desired chiller outlet temperature. The baseload chillers, which are more efficient, operated at higher IGVs. The selection of the baseload chillers is discussed in Section 3.5.7.

The IGV position of the chillers' compressors will be controlled using an EMS. The compressor guide vanes will be adjusted to match an outlet chiller temperature set point of 3.5°C. In the scenario of a chiller start, stop or trip, the following control logic is used by the EMS and relayed to the PLCs to determine the guide vane angle on the chillers compressor.

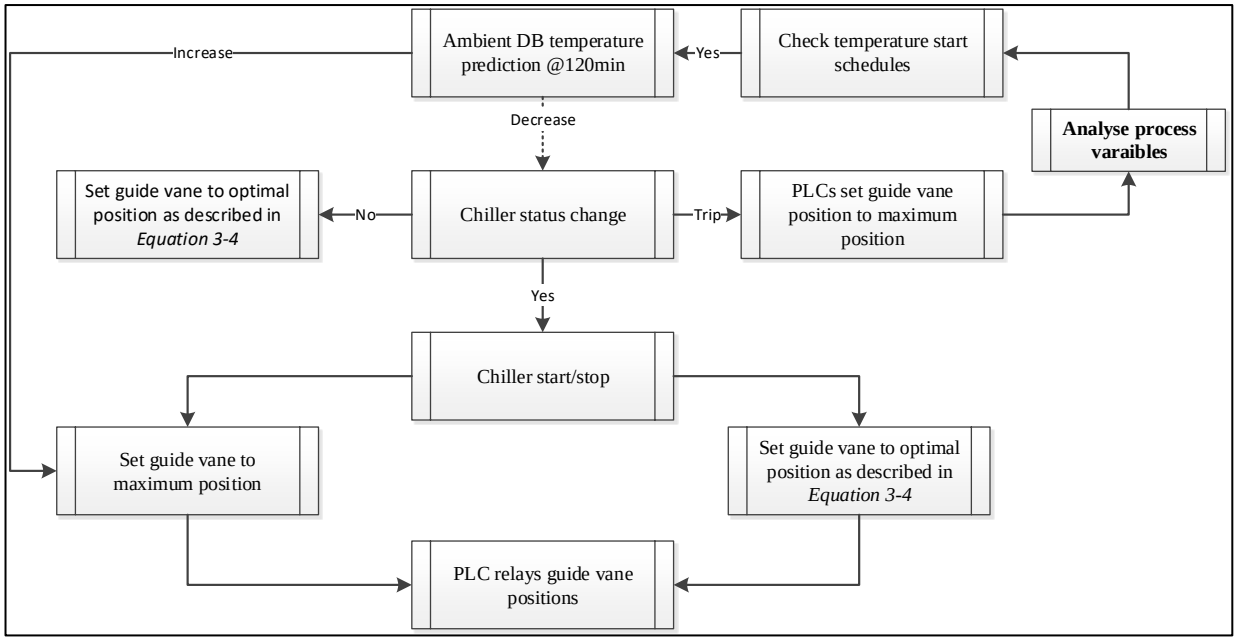

Figure 3-16: Guide vane angle control during start, stop and trip phases

When a chiller is started, the EMS will monitor the chiller outlet temperature and log the IGV of the chillers. When the desired chiller outlet temperature set point is met, the guide vanes will start to cut back. Throughout this process, the IGVs are controlled by the EMS. Once the temperature set point is met and sustained, the EMS will calculate the vane spare percentage. If the vane spare percentage exceeds 110%, the scheduled chiller is automatically stopped.

3.5.7. Chiller control

The EMS will divide the chillers into two groups, namely; baseload chillers and trimming chillers. The baseload chillers are the chillers that operate throughout the day, while the trimming chillers are started and stopped as the temperature variables change. Factors such as the availability of the chillers and the operating hours of each chiller, can have an influence on which chillers are allocated as baseload chillers.

After a feasible temperature control strategy was developed, the COP of each chiller is considered. The chillers' COP at certain guide vane angles is evaluated and compared. The COP is calculated by determining the cooling capacity per unit electrical power of the chiller. The chillers COP was computed at different guide vane angles for each compressor, as shown in Figure 3-17.

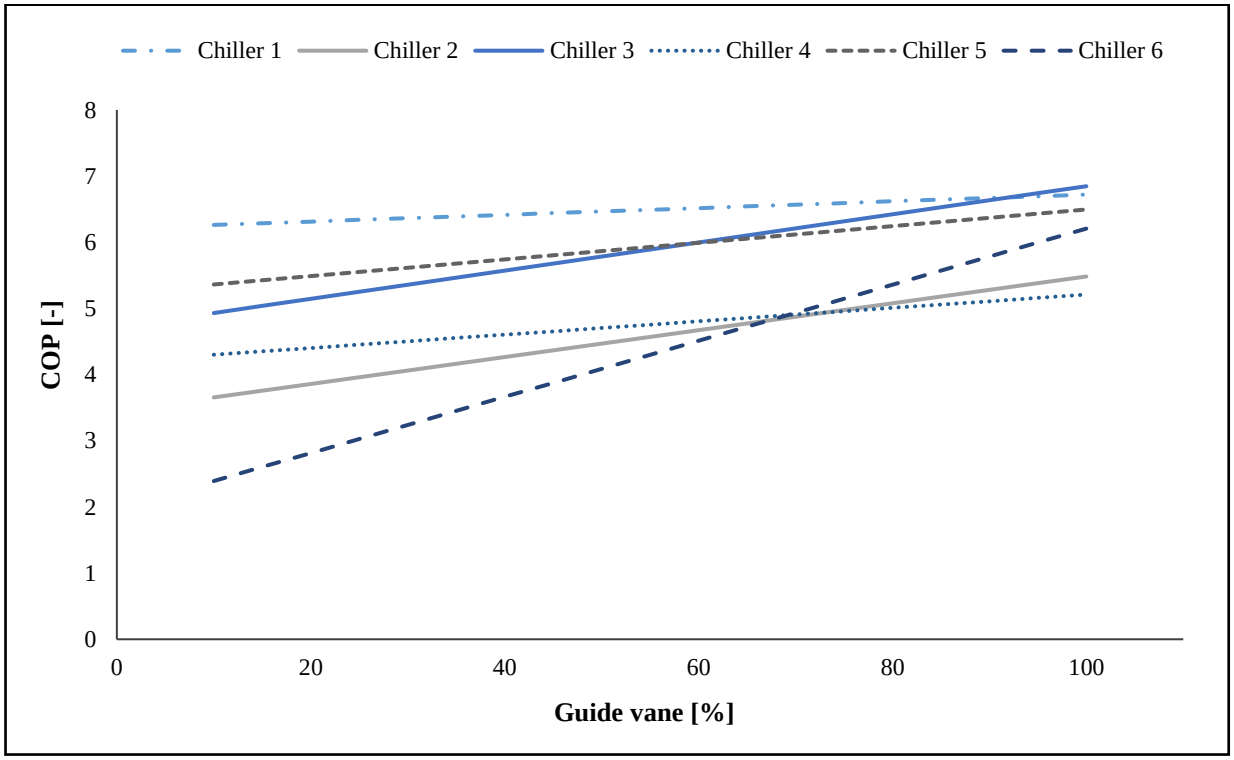

Figure 3-17; Chillers' COP at different guide vane angles

It is evident from Figure 3-17 that the COP of the chillers increases as the guide vane increases. The COP of Chiller 3 is the highest at maximum guide vane. To ensure stable dam levels, a minimum of three chillers are required to run. With normal operating conditions, the EMS will allocate Chiller 1, Chiller 3 and Chiller 5 as baseload chillers. This ideal chiller baseload combination may change as the system fluctuates. The system will, therefore, be constantly re-evaluated to determine the optimal baseload chiller combination.

The chillers not allocated as baseload chillers will be used as trimming chillers. Chiller 6 is allocated as the chiller with the first start priority. Chiller 6 has a higher COP at higher guide vanes compared with Chiller 2 and Chiller 4. To evenly spread the operating hours between the remaining trimming chillers, the priority of Chiller 2 and Chiller 4 will be alternated with every stop or start.

The EMS will then allocate Chiller 6 as the first trimming chiller to be started and alternate the start and stop priorities between Chiller 2 and Chiller 4. It should be noted that depending on the chiller availability and mining requirements, the trimming chillers' start and stop priorities are subject to change.

In the event that one of the baseload chillers is not available, the EMS will allocate the chiller with the highest start priority as a baseload chiller. Figure 3-18 illustrates the procedure the EMS will execute if a baseload chiller is not available to operate.

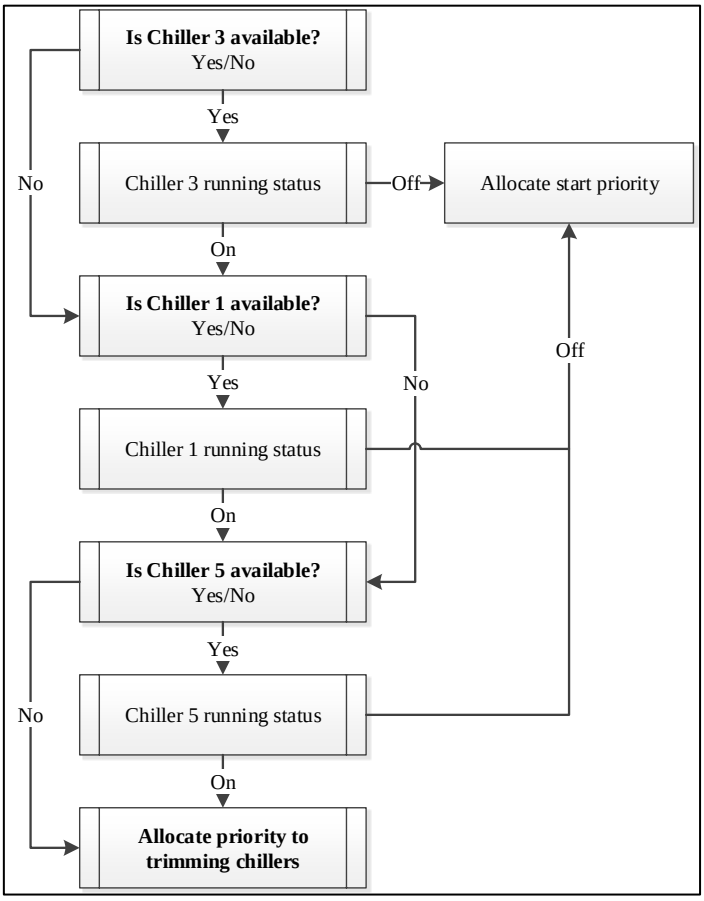

Figure 3-18: Baseload chiller selection - the EMS decision block

The EMS will then automatically change the start and stop priorities of trimming chillers as they are stopped or started. The EMS evaluates the following parameters to determine the optimal running schedules of the trimming chillers:

- Cold and HCD level limits;
- 39L cold dam level limit;
- Guide vane angles of the chillers' compressors in operation;
- Actual temperature parameters (BAC outlet air temperature, chiller outlet temperature, CCD temperature, 39L cold dam temperature and water to underground temperature);
- Real-time and predicted ambient DB temperature after 120 minutes;
- Dynamic temperature set points; and
- Turbine status.

The EMS will determine when it is required to stop and start trimming chillers. To determine if a chiller should be stopped or started, the parameters above are evaluated. Ultimately, the chillers will be stopped and started to maintain a CCD temperature set point of 6.25°C (system driving temperature).

The next section will discuss the strategy that will be used to automatically schedule an effective chiller combination to ensure that the driving temperature set point limit is maintained. Figure 3-19 illustrates the procedure to be followed when stopping a trimming chiller. Only the trimming chillers will be considered in the stop procedure.

During the Eskom evening peak periods, the baseload chillers will be automatically stopped. The control logic displayed in Figure 3-19 is not considered for the baseload chillers. The Eskom evening load shift control strategy is critically discussed and reviewed in the section below.

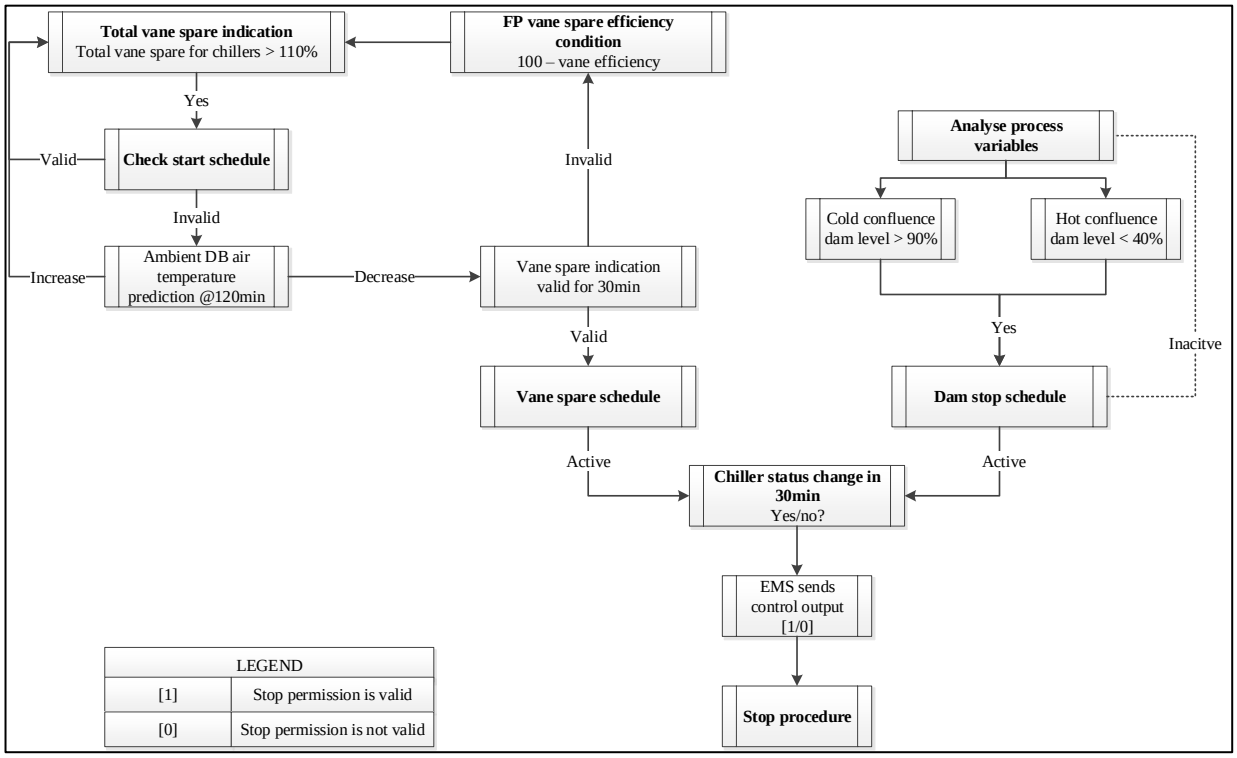

Figure 3-19: Conditions evaluated for the chiller stop procedure

The following conditions will be evaluated to determine if a chiller should be stopped:

1. The chiller start schedule and ambient DB temperature prediction model will be evaluated. If the start schedule is not active and the ambient temperature is to decrease in the next 120 minutes, the chiller stop procedure will be continued.
2. The vane spare indication will be evaluated. If the vane spare is equal or greater than the vane spare limit of 110%, the chiller stop procedure is continued. If the vane spare is less than 110%, the chiller stop procedure will not be considered and the process will start at the beginning.
3. If the vane spare condition is active for 30 minutes, the chiller stop procedure will be continued.

4. The EMS will also evaluate the dam stop schedule. If the CCD is greater than the max dam level limit of 80%, the chiller stop procedure will be continued. In the case that the HCD is less than the low dam level limit of 40%, the chiller stop procedure will be continued.
5. Only the dam level schedule and vane spare schedule will be considered for scheduling a chiller to stop.
6. Finally, the chiller running status will be evaluated. If a chiller was recently stopped or started within 30 minutes, the EMS will not schedule a chiller to stop. In such occurrences, the process will start at the beginning of the stop procedure where the stop procedure is re-evaluated. If there was no chiller status change within 30 minutes, the EMS will automatically stop a chiller. Thereafter, the chiller stop procedure will be re-evaluated.

If the chiller stop procedure is active, the EMS will stop the prioritised chiller. When a chiller is stopped there will be a noticeable increase in temperature parameters. PLCs on the chillers' compressor guide vanes will be adjusted to meet an outlet chiller temperature set point

The guide vanes of each chiller are continuously logged and monitored. An optimal guide vane angle for each compressor will also be continuously calculated. In a scenario where the relevant temperature parameters are exceeding their dynamic temperature set point, PLCs will control the trimming chillers guide vanes to a maximum. Thereafter, the EMS will consider starting an additional trimming chiller. Figure 3-20, illustrates the procedure that will be followed to start a chiller.

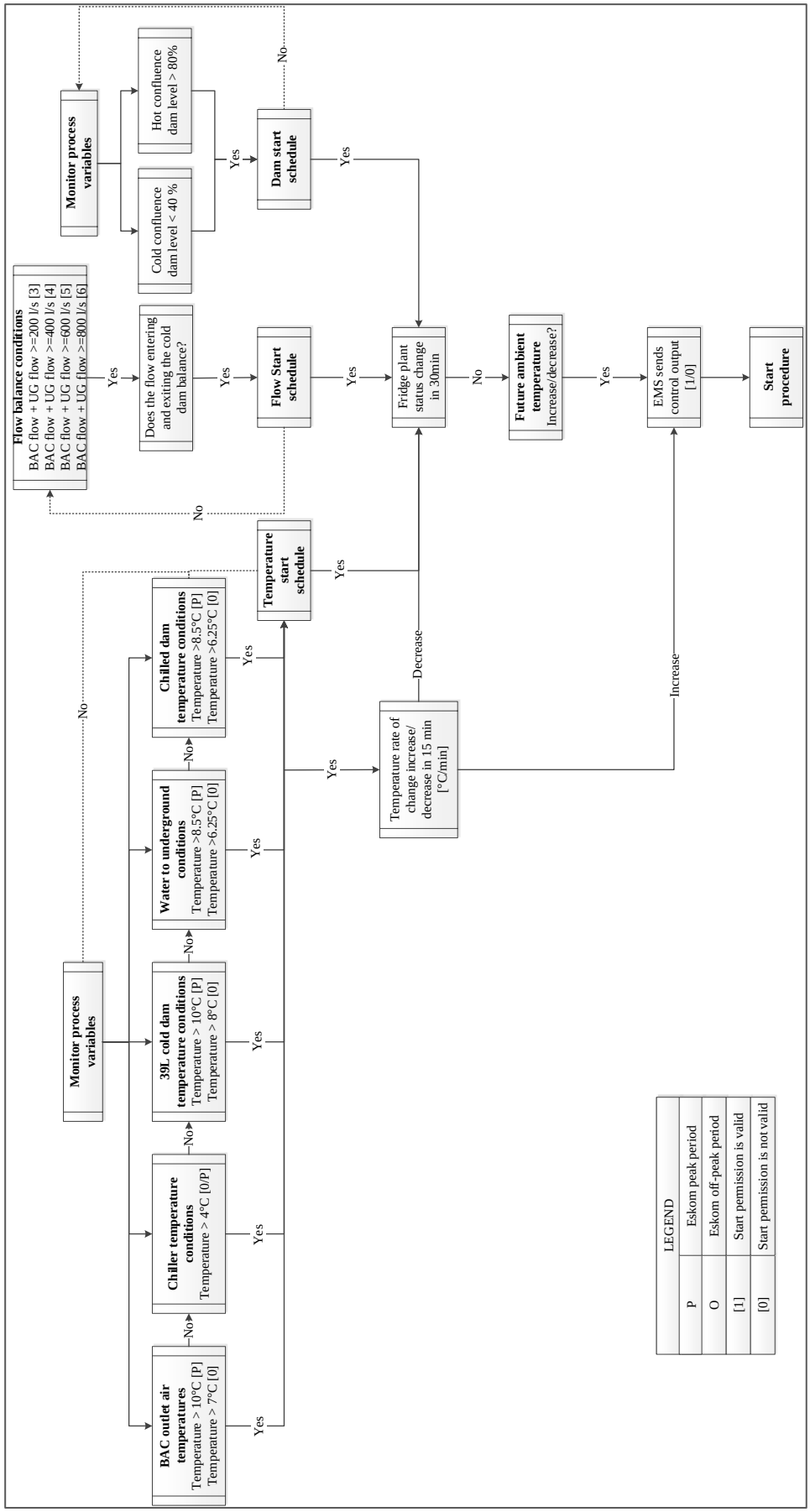

Figure 3-20: Conditions evaluated for the chiller start procedure

The following conditions will be evaluated to determine if a chiller should be started, as illustrated in Figure 3-20:

1. The following temperature conditions will be evaluated: chiller outlet temperature, CCD temperature, water to underground temperature, 39L cold dam temperature and the BAC outlet air temperature. If any of the temperature parameters are greater than the static temperature set points, the chiller start procedure will be continued.
2. The dynamic temperature set points will be evaluated. If either of the temperature parameters are greater than the dynamic temperature set points, the chiller start procedure will be continued. If either of the temperature parameters are equal to or below the dynamic temperature set points, the chiller start procedure will not be considered and the process will start at the beginning.
3. The EMS will evaluate the flow schedule. If the flow exiting the CCD is increasing, the chiller start procedure will be considered. In the case that an additional BAC is started, the CCD level will start to decrease. In this scenario, an additional chiller is required to re-stabilise the dam. The chiller start procedure will be continued.
4. The EMS will also evaluate the dam start schedule. If the HCD is greater than the max dam level limit of 80%, the chiller start procedure will be continued. In the case that the CCD is less than the low dam level limit of 40%, the chiller stop procedure will be continued.
5. Only the dam level schedule, flow schedule and temperature schedule will be considered for the chiller start procedure.
6. Finally, the chiller running status will be evaluated. If a chiller was stopped or started within 30 minutes, the EMS will not schedule a chiller to start. In such occurrences, the process will start at the beginning of the start procedure where the start procedure is re-evaluated. If there was no chiller status change within 30 minutes, the EMS will start a chiller. Thereafter, the chiller start procedure will be re-evaluated.

If the chiller start procedure is active, the EMS will automatically start the prioritised chiller. In ideal conditions, Chiller 1, Chiller 3 and Chiller 5 will not be considered in the start procedure. However, unforeseen circumstances do occur at times. If a baseload chiller trips and the temperatures, dam levels, flows and vane spare conditions are met, an available trimming chiller or baseload chiller will be started immediately.

When all the conditions are valid, an available trimming chiller will be started. If the baseload chiller is made available to start again, the baseload chiller will be started when required. The chiller start procedure must be satisfied before the baseload chiller is started. The chillers will be automatically started and stopped with a start/stop tag controller. The chiller start/stop control logic is presented in Appendix B.

3.5.8. Peak period control strategy

As part of the project implementation, an evening load shift strategy was agreed upon by the relevant stakeholders (ESCO and client). To accurately execute the desired control during the Eskom evening peak period, the control logic displayed in Figure 3-21 is utilised.

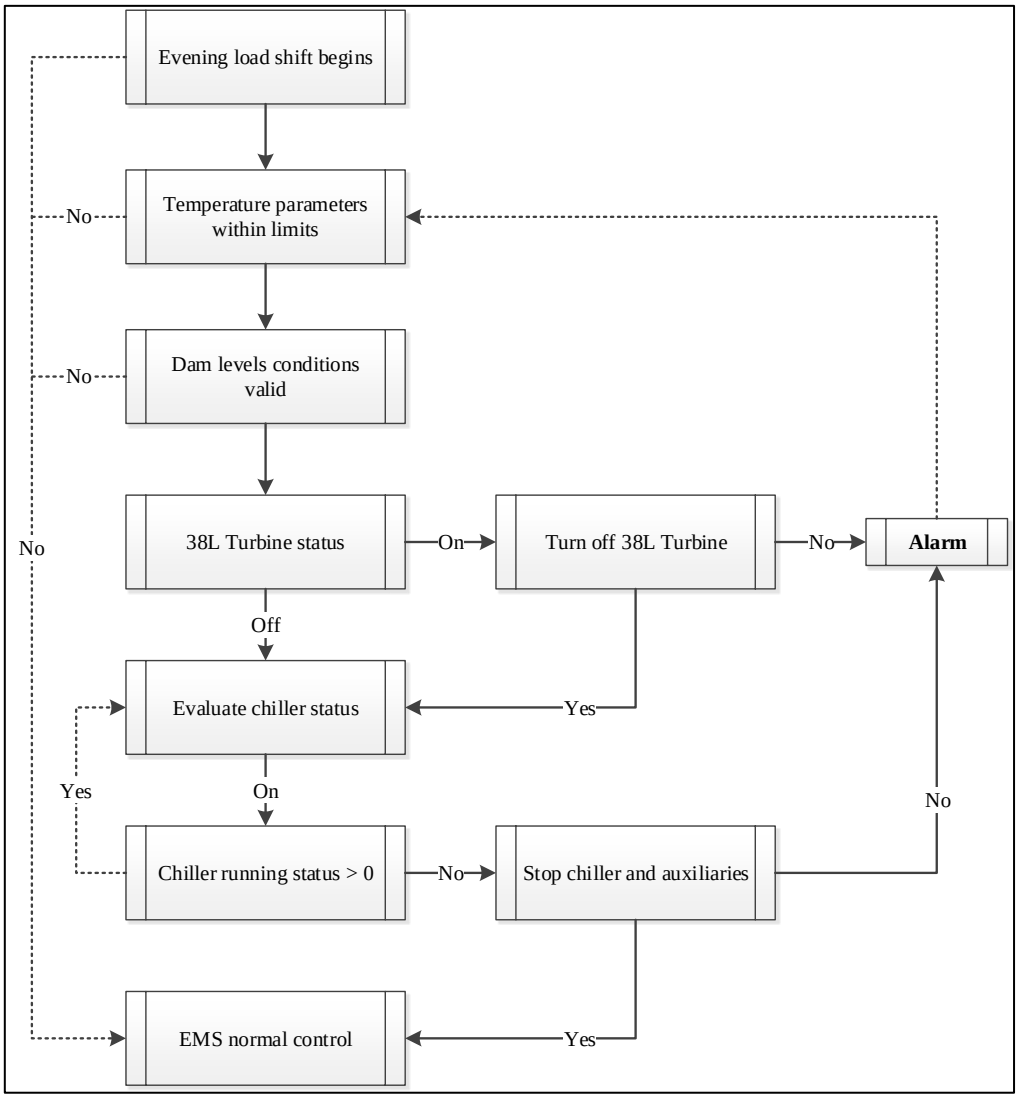

Figure 3-21: Load shift start procedure

When the Eskom evening peak period is initiated, the EMS will evaluate the process parameters discussed in Section 3.4.4. If the process parameters are within acceptable limits, as discussed in Figure 3-21, the running chillers (baseload chillers) will be considered to stop. The EMS will evaluate the running status of the turbine and schedule the turbine to stop. A stop signal will be sent to the 38L turbines start/stop controller.

An alarm will be activated on the SCADA if the EMS is unable to stop the turbine. In the event that the EMS is unable to stop the turbine, the load shift will not be initiated, and the EMS will continue with normal control (as discussed in Section 3.5). It is important that no water is sent underground during the

evening load shift period. This will reduce the cooling demand significantly; prompting a feasible load shift saving.

During the load shift, the control parameters will be continuously evaluated. If the chiller start procedure, as discussed in Figure 3-20, is active, a baseload chiller will be prioritised to start. After the evening load shift period is initiated, normal chiller control will be activated. The control logic illustrated in Figure 3-22 is utilised at the end of the Eskom evening load shift period to schedule a chiller to start.

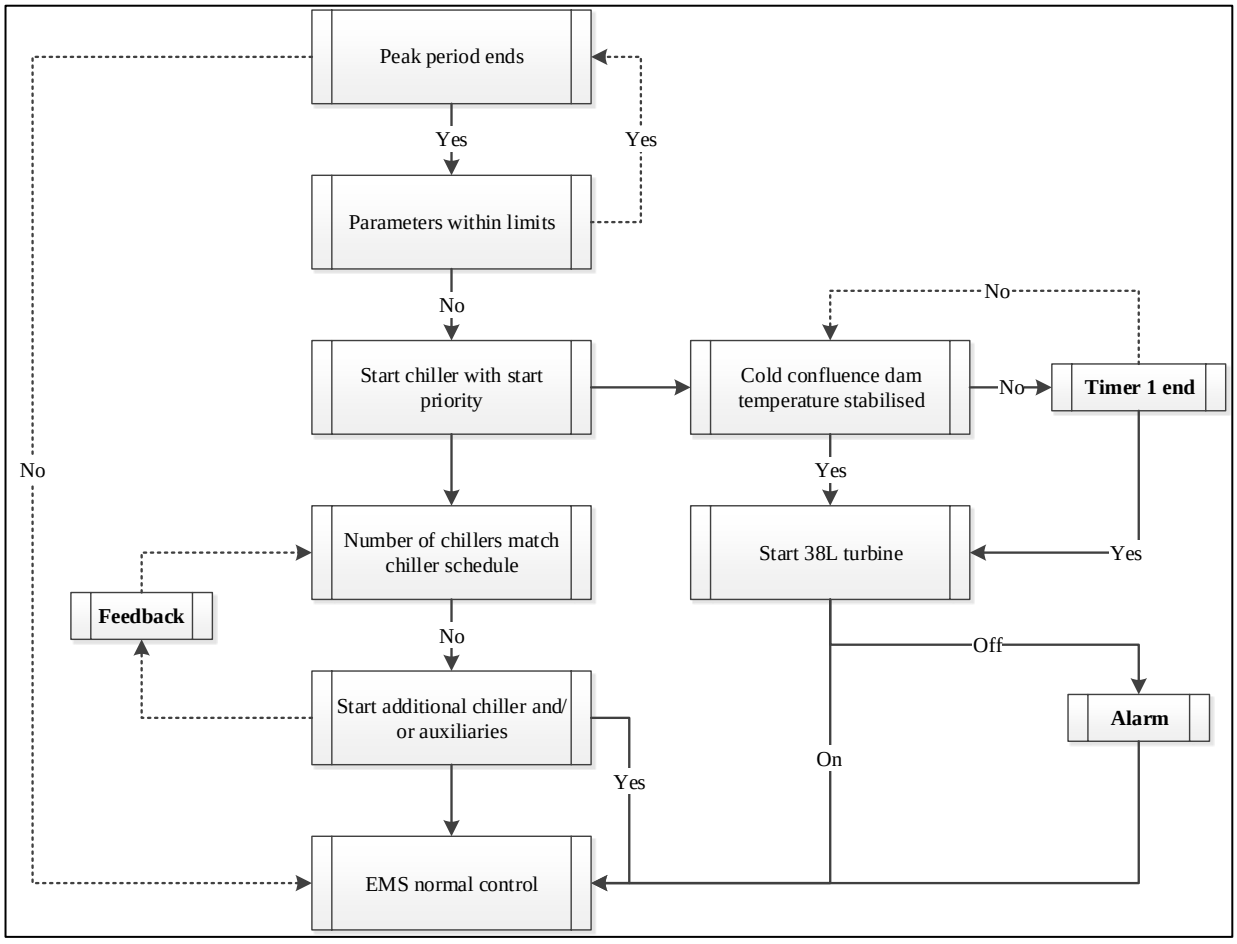

Figure 3-22: Load shift stop procedure

During the evening load shift period, the EMS will continuously evaluate whether the control parameters are within the desirable limits. In the case that a chiller is required or scheduled to start, the EMS will start the chiller with the lowest start priority (baseload chiller). After the first chiller is started, the EMS will evaluate the proposed chiller schedule and if necessary start an additional chiller.

Once the first chiller is started, the EMS will activate a timer. The timer is valid for a period of 20 minutes. After the timer has ended, the EMS will prioritise the 38L turbine to start. Thereafter, the CCD's temperature will be evaluated to ensure the dam temperature is within its dynamic temperature set point.

In the event that the EMS is unable to start the 38L turbine, an alarm on the SCADA will be activated. The operator will then be notified to start the turbine manually on the SCADA.

3.5.9. Sustainability and reporting

As discussed in Section 1.5, the sustainability of energy saving measures is of critical focus for this study. Figure 3-23 indicates the reporting and sustainability strategy for implementing an automated dynamic control strategy on mine cooling systems.

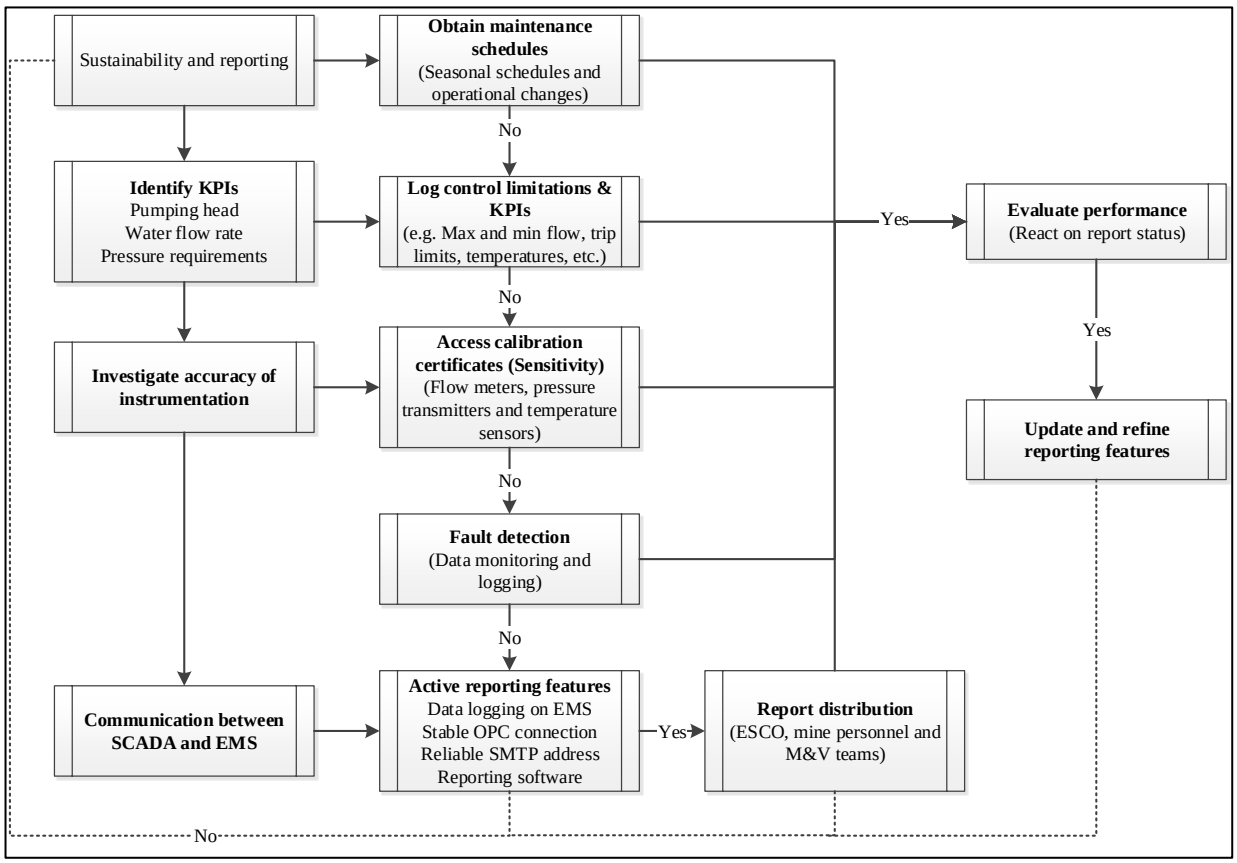

Figure 3-23: Summarised reporting and sustainability strategy

The application of reporting serves as a crucial tool for improved sustainability on mine cooling systems. The reporting and sustainability system strategy, presented in Figure 3-23, is described in four core mechanisms. Firstly, a practical maintenance schedule must be developed and reviewed. All operational changes must be considered for the feasibility of the maintenance schedule. The maintenance schedule will be reviewed quarterly to document large system disturbances that may affect the suggested schedule.

Secondly, KPIs such as the chiller's COP, service water to underground end-users and chilled water dam temperatures were quantified for the implementation period. KPIs will be identified and reviewed throughout the project performance periods. Control limitations will be included within the reporting features. The control restrictions will be determined during the project pre-implementation phase. New control restrictions will be added to the report to enhance sustainability.

The above-mentioned KPIs were considered to compare the total operational performance impact as a result of the developed strategy. The total system power results were also quantified to validate the sustainable impact of the control model. The sustainable impact for this study represents the period of time for which the study attained improved load demand reduction savings. Moldan *et al.* [207] suggested that sustainability is quantified by selecting a target. Therefore, these savings were recorded for a target period of 14 months to evaluate the sustainable economic impact of this study.

Thirdly, the accuracy of the control instrumentation will be assessed and reviewed. Calibration certificates will be collected and filed regularly to ensure accurate and sensitive data logging. Fault detection mechanisms will be established and recorded. A condition monitoring section within the report will be established to ensure trip limits (fault detection mechanisms) are included.

Lastly, a stable communication between the SCADA and EMS must be ensured. Reliable data-logging and data transfer measures must be employed. A centralised database is set u-tip to store the relevant process data. Reporting software is developed to process and interpret the data. Finally, the report is distributed to the relevant stakeholders to evaluate the performance of the cooling system.

The control strategies discussed in Section 3.5 provide an easy, practical and adaptable approach to verify and validate the sustainability of an optimised dynamic control strategy for mine cooling systems. The control strategies will be tested and validated through implementation. The suggested solutions are simulated and verified in the following section.

3.6. Performance assessment and verification

3.6.3. Introduction

An automated dynamic control strategy for sustainable cost savings on mine cooling systems was developed. The solution formed part of a simple, practical and robust control strategy with the potential to be implemented on other gold mines as part of a case study. The impact of the suggested control strategy was evaluated with a comprehensive simulation model.

During the project proposal, the mine personnel were hesitant to implement the automated control strategy. To convince the mine personnel, the automated control strategy was verified with the use of a calibrated simulation. The calibrated simulation model enabled the ESCO to convince the mine personnel of the benefits of the energy saving measure.

The simulation model quantified the effects of an automated control strategy for improved operational performance and sustainable cost savings. A detailed report proposal was compiled and distributed to the relevant mine personnel to illustrate the impact of such a strategy. The suggested solution was approved, tested and implemented.

3.6.4. Solution overview

To accurately control the cooling components, an integrated control strategy was developed. The system control strategies for the energy saving measure is summarised in Section 3.5. The pre-cooling pumps, BAC pumps and evaporator pumps will be controlled with a variable flow control strategy. VSD-installed pumps will be utilised to modulate the speed of the pumps to improve service delivery requirements and enhance sustainable energy savings.

The chiller control strategy system was divided into four control categories; flow balance, auxiliary turbomachinery, temperature and IGV. A unique dynamic temperature set point algorithm and ambient air temperature prediction model was developed. The four system control strategies were combined for maximum cost savings potential.

A standardised reporting control strategy was developed. Important KPIs were logged and reported to ensure mechanical components were operating close to DEM specifications. The reporting strategy is employed to enhance sustainability and improve intuitive decision-making.

3.6.5. Simulation modelling

A calibrated simulation model is necessary to evaluate the impact of the system control strategies. A simulation provides a viable solution to accurately predict system responses, disturbances and effects. Thereafter, a detailed project proposal is provided to the mine personnel for soft-commissioning tests.

Before the control strategies are verified, a baseline simulation is developed. As suggested in the literature in Section 2.4.6, Process Toolbox (PTB) serves as a feasible simulation package to verify the automated cost saving measure. The baseline will be compared to the simulated results to determine the accuracy of the simulation software package.

PTB represents a component-centred simulation software package. Several multi-variable components are integrated to determine dynamic system responses. The simulation model, therefore, adheres to dynamic system boundary conditions. The simulation software package also provides comprehensive results that can be analysed at a component-based level.

Before a simulation model is developed and calibrated, important process data is collected. The relevant process data is used as simulation inputs to accurately represent system dynamics. The relevant data is logged with the EMS and stored on the centralised database. Once the necessary data is available, the simulation model is developed and calibrated. Thereafter, the results are analysed and discussed.

3.6.6. Verification of simulation

A calibrated baseline simulation model was developed to verify the accuracy of PTB. Historical process data was obtained from Mine A's SCADA to calibrate the simulation. A baseline period agreed upon by all the relevant stakeholders (ESCO, client and M&V team) was selected.

Due to the nature of cooling systems and the adverse effects from seasonal changes, a summer and winter baseline was formulated. Historical data for the winter period of 01 July 2014 to 31 August 2014 and the summer period of 01 September 2014 to 31 December 2014 was used to develop the baseline for the energy saving measure. The development, characterisation and adjustment of the baseline will be discussed in Section 4.2.

The calibrated simulation model for Mine A's cooling system is depicted in Appendix C. The results from the simulation will be evaluated and reviewed in this section. The accuracy of the simulation package, PTB, will be verified to simulate the automated cost saving measures. Due to reduced cooling loads in winter months, the summer baseline period was simulated.

The accuracy of the simulation package, PTB, will be verified to simulate the implementation control strategies. Thereafter, a detailed project proposal is delivered to the mine personnel to review the impact of the implementation control strategies.

To evaluate the accuracy of the baseline simulation model, various process variables are considered. These process variables will be compared to the simulation, to predict the accuracy of the simulation software package. Power, temperatures and dam levels were considered.

Figure 3-24 illustrates the baseline and simulated power profiles for the summer baseline period. The energy cost savings potential is largely reliant on the reduction in power. The baseline and simulated power profiles depict a strong correlation with an average percentage accuracy of 99%.

As suggested by the literature in Section 2.4.6, an average percentage accuracy of 90% and greater is considered feasible. Although, the baseline and simulated power profiles indicated a strong correlation, it was important to evaluate the impact of the simulation on service delivery. Therefore, an integrated model was established to accurately verify the dynamic responses of the simulation model.

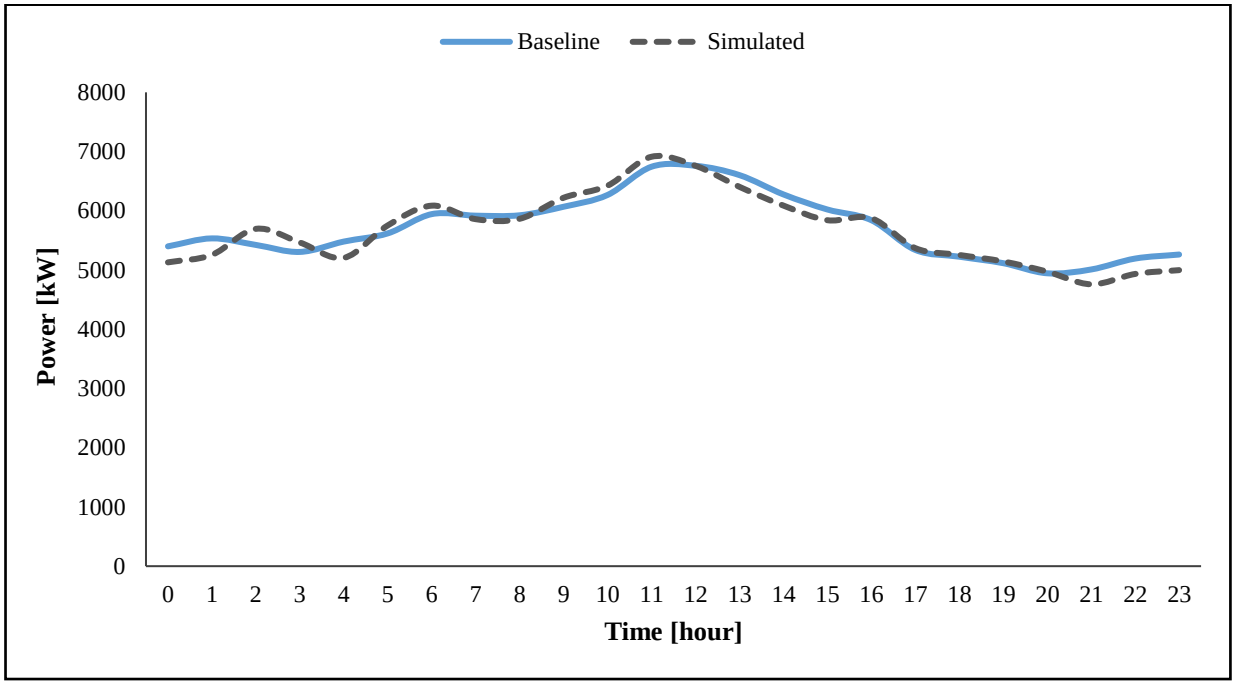

Figure 3-24: Power profile verification - Baseline

In Figure 3-25, the cold dam temperatures are compared to the simulated dam temperatures from the calibrated simulation model. For a holistic perspective, both the 39L cold dam and the CCD were selected. As mentioned in Section 3.5.5, the CCD temperature was considered as the system driving temperature. Therefore, the temperature of the CCD adversely affects mine cooling demand requirements. The chilled water dam temperatures also greatly impact the productivity and safety of underground mineworkers, as discussed in Section 1.3.

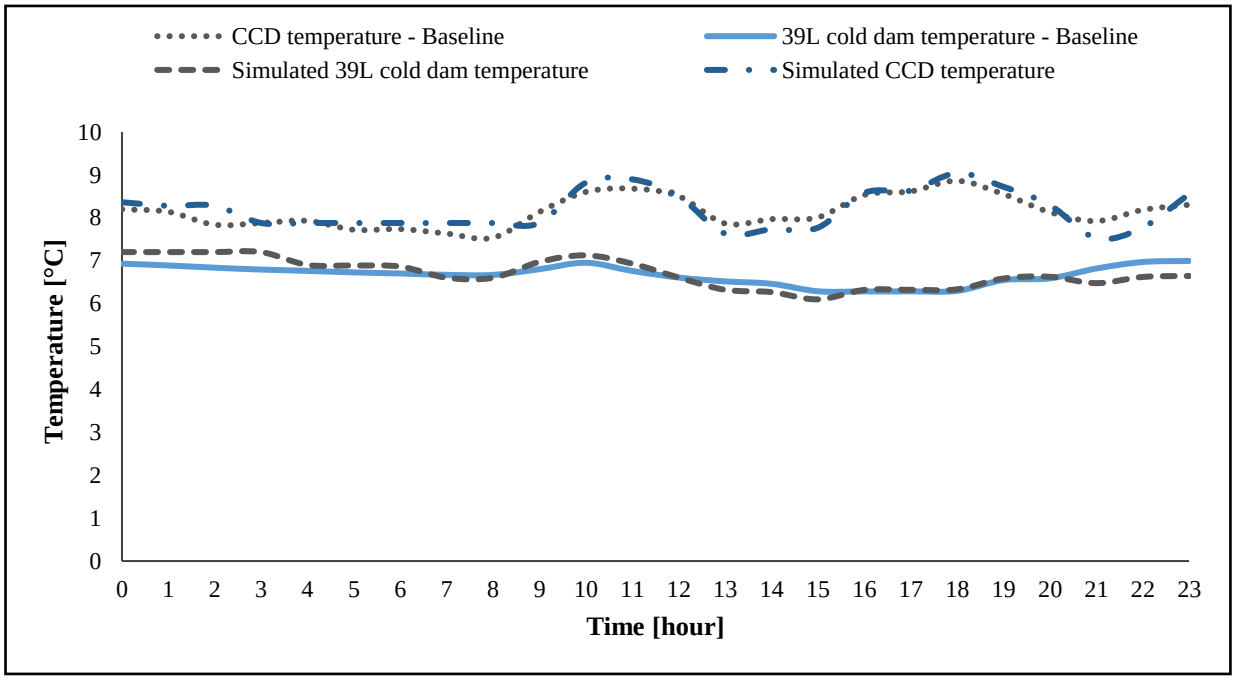

Figure 3-25: Cold dam's temperature verification - Baseline

From Figure 3-25, it is apparent that a strong correlation exists between the baseline and simulated cold dam temperatures. The 39L cold dam is approximately 2°C lower than that of the CCD temperature. The temperature sensor measuring the CCD temperature is located along the CCD wall, which is heated by external heat sources. The CCD temperature and 39L cold dam temperature profiles have an average percentage accuracy of 98% and 94% respectively, when compared to the calibrated simulation model.

To supply the mine with cool dehumidified air, a BAC is utilised. The BAC outlet air temperature (WB) is crucial for the fulfilment of underground mining activities. Chilled water from the CCD is pumped through spray nozzles in the BACs to supply 7.5°C (discussed in Section 3.2.2) of sufficient cool air.

Although the CCD temperature is considered the main driving temperature, the conditional status of the BAC is also crucial. Inadequate flow through the BAC feed pumps can result in a decreased water-side efficiency. The reduced water flow rate affects the flow distribution pattern through the BAC spray nozzles. The thermal heat transfer capabilities are adversely affected. The baseline and simulated BAC outlet air temperature profiles are presented in Figure 3-26.

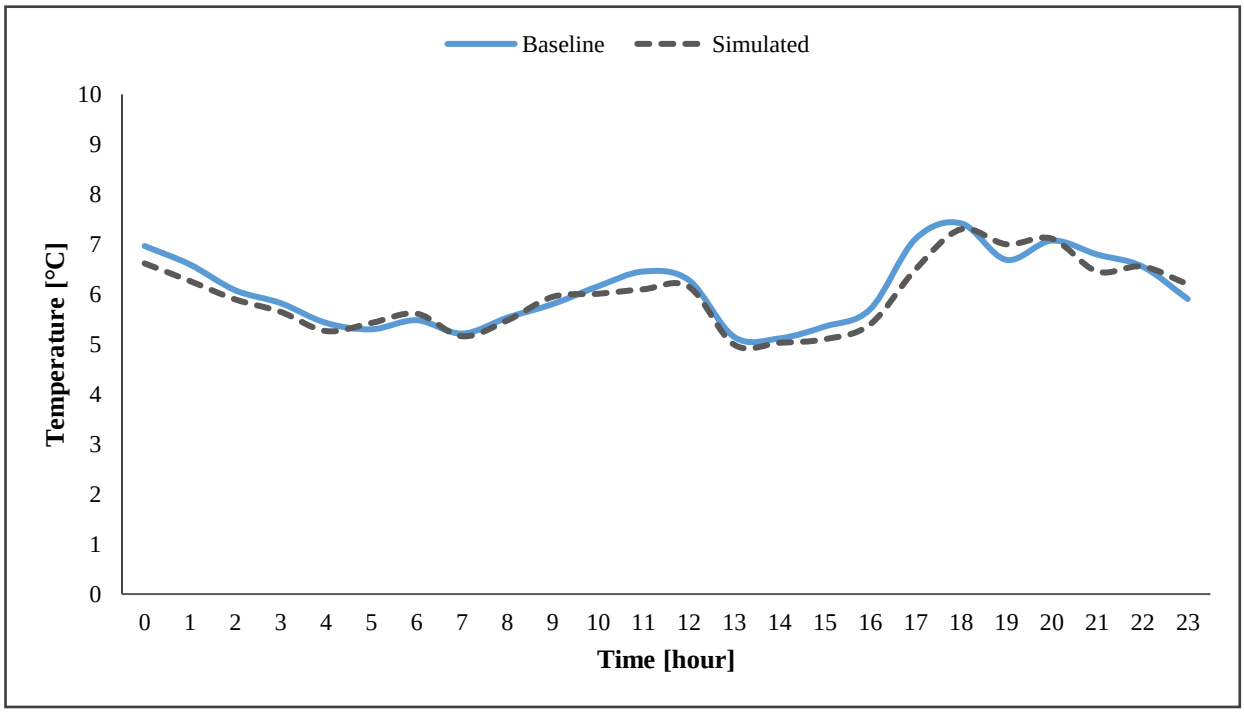

Figure 3-26: BAC air outlet temperature verification - Baseline

As anticipated, the baseline BAC air outlet temperature (in Figure 3-26) and CCD water temperature (in Figure 3-25) have a strong correlation. The system driving temperature (CCD temperature) largely impacts the cooling demands of the BAC. Comparing the baseline and simulated BAC air outlet temperature profiles yielded an average percentage accuracy of 98%. The BAC air outlet temperature accuracy of the calibrated simulation model is above the threshold of 90%. The simulation model is considered accurate and viable.

Thermal storage capacity is essential for the implementation of energy saving measures. The success of load management and variable flow control strategies are dependent on thermal storage capacity. It is, therefore, critical to analyse the capacity of the HCD and CCD. Figure 3-27 compares the baseline and simulated dam levels. For improved accuracy, both the HCD and CCD are selected.

The CCD level and HCD level profiles have an average percentage accuracy of 93% and 98% respectively, when compared to the calibrated simulation model. Although the simulated dam levels are considered accurate, the dam levels fluctuate irregularly. Stable dam levels will be achieved after the implementation of the energy saving measure.

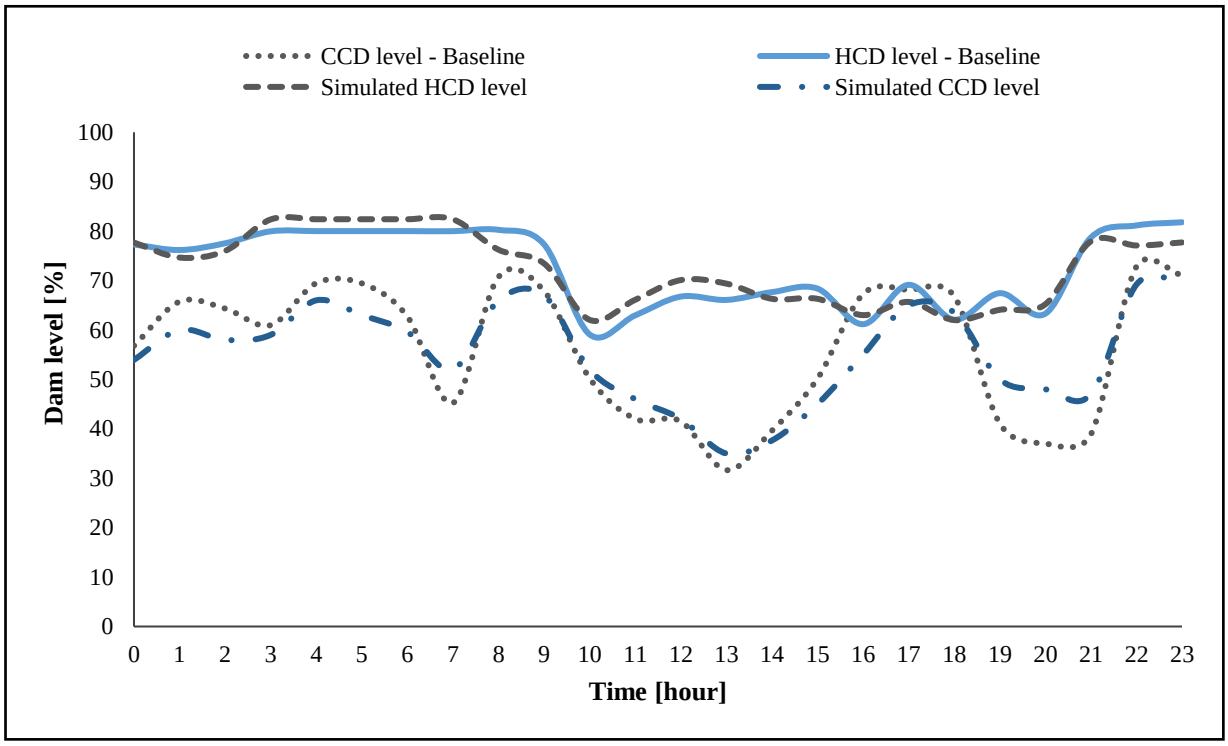

Figure 3-27: CCD and HCD level verification - Baseline

A baseline simulation verification summary is presented in Table 3-10. The average percentage accuracies are within the threshold limit of 90% and greater. PTB is considered feasible for accurately estimating Mine A's process parameters.

Table 3-10: Simulation verification - Baseline

No.	Description	Baseline results	Simulated results	Accuracy [%]
1	Total system power [kW]	5717	5686	99
2	CCD Chilled water temperature [°C]	8.1	8.3	98
3	39L cold dam chilled water temperature [°C]	6.7	7.1	94
4	BAC air outlet temperature [°C]	6.1	6	98
5	CCD level [%]	57	53	93
6	HCD level [%]	73	72	98
Average				**97**

3.7. Conclusion

A deep-level mine cooling system at Mine A, with previously implemented energy saving measures, was identified. Due to performance deterioration and no maintenance agreement in place, power savings were no longer being attained. Underperformance of existing implementation strategies prompted the opportunity to investigate a sustainable cost-effective solution.

Existing control strategies on Mine A's cooling system were critically evaluated and reviewed. Important KPIs were identified and analysed. A systematic approach to conduct a project performance investigation was developed. This ensured that critical problem areas were recognised and resolved.

A detailed summary of existing control optimisation techniques on Mine A's cooling system were recognised. System control faults were identified and documented. The control faults were mitigated with proposed solutions. Consequently, an automated dynamic control strategy for sustainable cost savings was developed. Mine A's technical specifications were thoroughly investigated, which ensured that the proposed control strategy was aligned with best practices. A project proposal was provided to the client, Mine A, for detailed analysis and review.

The simulation software package, PTB, was utilised to develop a calibrated simulation model of Mine A's cooling system. A summer baseline simulation model for 01 September 2014 to 31 December 2014 was selected. Historical input data was collected and stored on the centralised database for development and calibration of the baseline simulation model.

The accuracy of the simulation package, PTB, was verified. The calibrated simulation model accurately predicted the total system power usage and service delivery parameters. The baseline and simulated profiles were compared; an overall average percentage accuracy of 97% was attained. PTB was considered a feasible software package for estimating the performance of a mine cooling system.

The automated cost saving measure will be simulated, tested and implemented. The implementation results are verified and validated in Chapter 4. The control strategy will be commissioned in alignment with the ethos and safety requirements of Mine A.

CHAPTER 4: STRATEGY IMPLEMENTATION AND ASSESSMENT MONITORING

[4]

The chapter discusses the results obtained from implementing an automated dynamic control strategy. Strategy assessment and verification is discussed to prove the feasibility of the study. Post-implementation results are thoroughly discussed to validate the energy saving measure. This chapter serves as a performance assessment tool on the automated control strategy.

[4] *Photograph courtesy of Planet KB, http://www.planetkb.co.za/portfolio-detail.php?Mining-Photography-4*

4.1. Preamble

An automated dynamic control philosophy for sustainable cost savings on mine cooling systems was discussed in Chapter 3. The performance of PTB was determined by developing a calibrated baseline simulation model. The automated cost saving measures will be simulated to verify the impact of this study.

Mine A was selected as a suitable case study to implement the automated control strategies. Previously implemented energy saving measures were employed at Mine A, but project underperformance was found to be the principle factor to unsustainable savings. To mitigate this, the automated cost saving measures were implemented and thoroughly discussed in this chapter.

The simulated results will be discussed and critically analysed. The viability of the automated cost saving measures will be determined by commissioning the automated strategy. The formulation and adjustments of the baseline will be discussed to accurately quantify cost savings.

This chapter will include the baseline development, improved strategy implementation results, strategy verification and sustainability of the automated cost saving measures. The impact of the automated implementation strategy will be critically discussed and reviewed.

4.2. Measurement and Verification (M&V) procedure

To accurately quantify the benefits of an automated cost saving measure, a baseline model was developed. The baseline model represents the performance of the cooling system without the intervention of an energy saving measure.

Before implementation of the energy saving measure, the total power demand load (kW) for Mine A's cooling system was quantified. Power data was measured in half-hourly intervals to calculate the average demand load (kW) for the baseline periods. An external M&V team developed the demand load baseline. Summer (September to December) and winter (July to August) baseline profiles were considered. Figure 4-1 illustrates the M&V approved summer and winter baseline profiles.

As depicted in Figure 4-1, the winter baseline profile was an average of 83% lower than that of the summer profile. This is attributed to lower ambient temperature conditions during the winter periods. In the summer period, between 10:00 and 12:00, ambient temperatures increase from approximately 15°C to 25°C (DB), resulting in an increase in power consumption. Therefore, giving rise to an inflated summer baseline profile, as depicted in Figure 4-1.

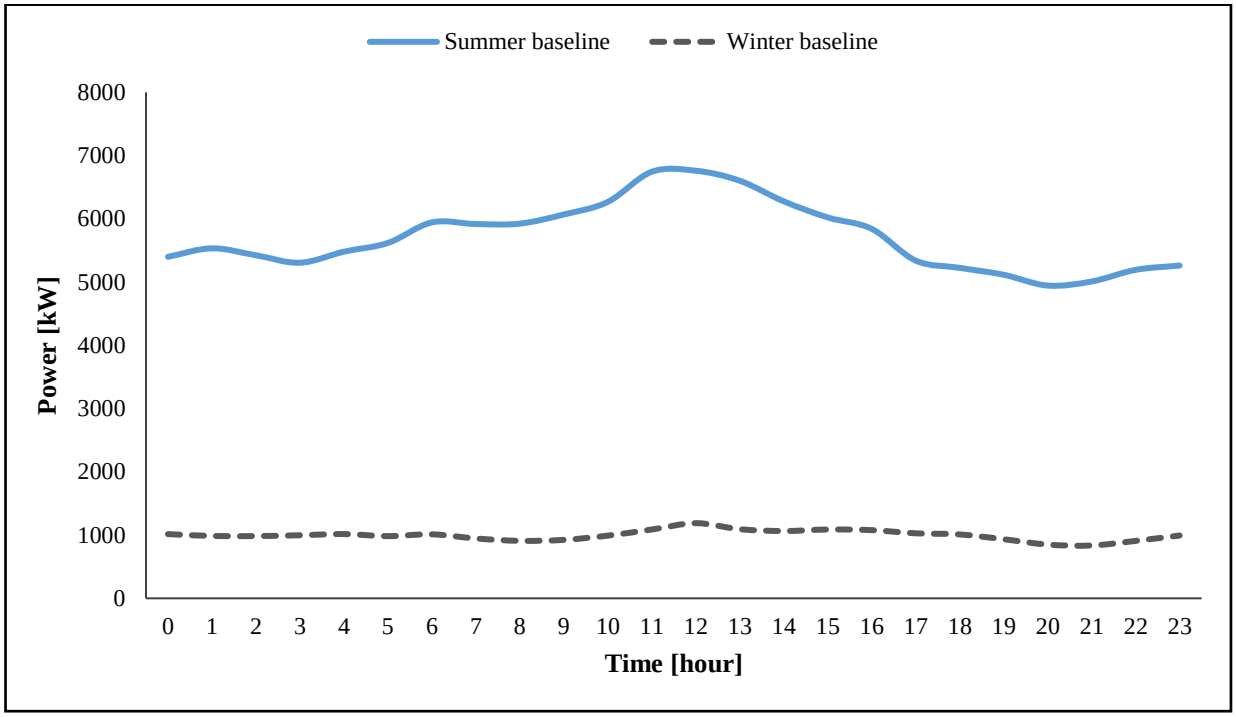

Figure 4-1: Summer- and winter unscaled baseline - Mine A

To accurately quantify the impact of the automated cost saving measure, a Service Level Adjustment[5] (SLA) was considered. The SLA accommodated for large system disturbances that were not included during the development of the baseline. The SLA factor was calculated using Equation 4-1.

Equation 4-1: SLA scaling factor

$$SLA_i = \sum_{i=1}^{48} \frac{kWh_{actual_i}}{kWh_{baseline_i}} \qquad [-]$$

The SLA scaling factor is utilised to calculate the scaled baseline which is represented by the following equation:

$$Adjusted_{baseline_i} = SLA_i \; x \; Unscaled_{baseline_i} \qquad [kW]$$

Where:

$SLA_i = half - hourly\ SLA\ factor$ $[-]$

$kWh_{actual_i} = half - hourly\ actual\ energy\ usage$ $[kWh]$

$kWh_{baseline_i} = half - hourly\ unscaled\ baseline\ energy\ usage$ $[kWh]$

$Adjusted_{baseline_i} = half - hourly\ adjusted\ baseline\ power\ usage$ $[kW]$

$Unscaled_{baseline_i} = half - hourly\ unscaled\ baseline\ power\ usage$ $[kW]$

[5] *M&V protocol for accurately quantifying energy savings*

The SLA ensures that accurate savings are quantified and reported by the ESCO. For the purposes of this study, an energy neutral scaling method was adopted by the M&V team. Therefore, a fixed unscaled weekday baseline was utilised, but adjusted daily using the SLA factor. Incorporating the SLA factor ensured that the scaled baseline was representative of what energy usage would have been without automated cost saving measures.

The difference between the actual power usage and the adjusted baseline power usage was utilised to calculate the actual demand savings (kW). The actual demand savings were averaged half-hourly between 18:00 and 19:30 in summer TOU periods. These savings were verified by an M&V team and reported accordingly in a performance assessment report. The energy savings were calculated using Equation 4-2.

Equation 4-2: Energy savings

$$Demand_{impact_i} = Adjusted_{baseline_i} - Actual_{impact_i} \qquad [kW]$$

Where:

$$Demand_{impact_i} = half - hourly\ actual\ demand\ savings \qquad [kW]$$

$$Adjusted_{baseline_i} = half - hourly\ adjusted\ baseline\ power\ usage \qquad \{kW]$$

$$Actual_{impact_i} = half - hourly\ actual\ power\ usage \qquad [kW]$$

Baseline models are essential for representing the performance of mine cooling systems. An SLA factor was incorporated to accurately quantify energy savings. The demand savings are accurately quantified and discussed in Section 4.5. The implementation results of the automated cost saving measures are analysed in the next Section.

4.3. Improved performance strategy implementation

4.3.1. Preamble

The implementation of automated cost saving measures, as discussed in Section 3.6.6, requires approval from the mine personnel. This was achieved by simulating the proposed control strategies. After the system control strategies were approved, the automated cost saving measures were implemented and tested. The results from the commissioning tests of the automated cost saving measures were compared to the simulation results to verify the effect of the strategy.

In this section the implementation results are also thoroughly reviewed and discussed. Implementation results were compared to the baseline period results to quantify the total impact of automated cost saving measures. This section will, therefore, evaluate KPIs to quantify total system performance improvements.

4.3.2. Simulated strategy performance

As discussed in Section 3.6.5, a summer baseline period was used to compare the impact of the automated cost saving measures. A calibrated baseline simulation model was developed to verify the accuracy of PTB. PTB accurately estimated the system responses of Mine A's cooling system with an overall average percentage accuracy of 97%.

During the baseline period, the mine cooling system was controlled in 'manual' by the operators with previously implemented energy saving measures disabled. The manual control implemented by the operators was used to develop the baseline simulation model. After quantifying the accuracy of PTB, the automated cost saving measures were simulated. The simulation was accurately modelled with the procedures discussed in Section 3.6.5.

The simulated results from the automated cost saving measure are tabulated in Table 4-1. Table 4-1 compares the impact of the simulated energy saving measures to the baseline. For comparison purposes, 23 facets were included to holistically quantify the total impact of the automated cost saving measures.

Table 4-1: Summary of the simulated energy savings results

No.	Description	Baseline	Simulated energy saving measures	Impact [%]
1	Total system power [kW]	5717	5954	−4%
2	Auxiliary component power [kW]	1582	1986	−20%
3	Chiller compressor power [kW]	4135	3986	4%
4	BAC air outlet temperature [°C]	6.1	5.6	7%
5	39L Chilled water temperature [°C]	6.7	6.3	5%
6	CCD Water temperature [°C]	8.1	6.7	21%
7	Chilled water sent to underground [°C]	8.1	6.7	21%
8	Chiller outlet temperature [°C]	6.1	4.3	3%
9	Evaporator inlet water temperature [°C]	11.4	10.7	6%
10	Evaporator outlet water temperature [°C]	6.1	4.3	3%
11	Evaporator delta water temperature [°C]	5.2	6.4	−22%
12	Chiller vane opening [%]	81.2	64.9	20%
13	Chiller vane spare opening [%]	57.6	63.7	−11%
14	CCD Level [%]	56.3	69	−23%
15	HCD Level [%]	72.7	75.5	−4%
16	Evaporator water flow rate [ℓ/s]	232.8	203.6	13%
17	Condenser water flow rate [ℓ/s]	426.3	382.3	10%
18	BAC Water flow rate [ℓ/s]	422.4	411.5	3%
19	Chilled water flow sent to underground [ℓ/s]	158.3	118.8	25
20	Chiller status [-]	3.3	3.5	−9%
21	Number of chiller start-ups [-]	5	6	−20%
22	38L Turbine shutdowns [-]	1	2	100%
23	Chiller COP [-]	4.98	5.49	10%

The results were reviewed and approved. The mine personnel suggested the automated cost saving measures are soft-commissioned to identify system- control and integration issues. Thereafter, the system control strategies can be completely automated through hard-commissioning.

4.3.3. Commissioning results

To successfully implement the automated cost saving measures, the control strategies were commissioned. Complete implementation involves two commissioning stages: soft-commissioning; and hard-commissioning.

Soft-commissioning includes implementing the energy saving measures manually. The results from the soft-commissioning tests will be reviewed and evaluated. After the conclusions are reviewed by the section engineer, the hard-commissioning phase can commence. During the hard-commissioning phase, energy saving measures are executed in complete automatic control.

Five successive weekdays were scheduled to conduct the soft-commissioning tests. The mine personnel operated the mine cooling system in manual, but in accordance with the control strategies discussed in Section 3.5. The cost saving measures were enabled but controlled manually. Although significant cost savings were achieved, operator negligence lead to inaccurate control. The control would be timeously executed by implementing the control in complete automated control.

The cost savings were calculated on the performance of the energy saving measures and provided to the mine personnel for critical review and evaluation. Operational parameters were within design constraints and limitations, deeming the control strategies feasible.

After approval of the soft-commissioning test from the mine personnel, the energy saving measures were automatically implemented. Results from the calibrated simulation model indicated that the mine cooling system was balanced after three consecutive days. Therefore, the automated system control strategies were implemented for a further five-day period to ensure complete system stabilisation. During this phase, Mine A’s cooling system was operated automatically with the system control strategies discussed in Section 3.5.

During the implementation of the automated cost saving measures, the EMS controlled all the necessary field instrumentation and mine cooling components. During one of the test days, the EMS lost communication with the SCADA due to an unstable OPC connection. The EMS, however initiated all the correct alarms and warning notifications. Once a stable OPC connection was realised, the automated control continued.

The performance of the tests were categorised, logged and evaluated. All the necessary process- and power data was captured on the EMS and sent to the centralised database. A daily feedback report for the mine personnel was also compiled and distributed.

Boundary conditions were considered and established to precisely compare the impact of automated cost saving measures on the performance of mine cooling systems [36]. The following system boundary conditions were identified and evaluated: Ambient air enthalpy; and Ambient air temperature (DB). A suitable test day during the consecutive five-day hard-commissioning test period was selected to compare these conditions. The comparable boundary conditions for the M&V baseline and actual hard-commissioning tests are presented in Figure 4-2.

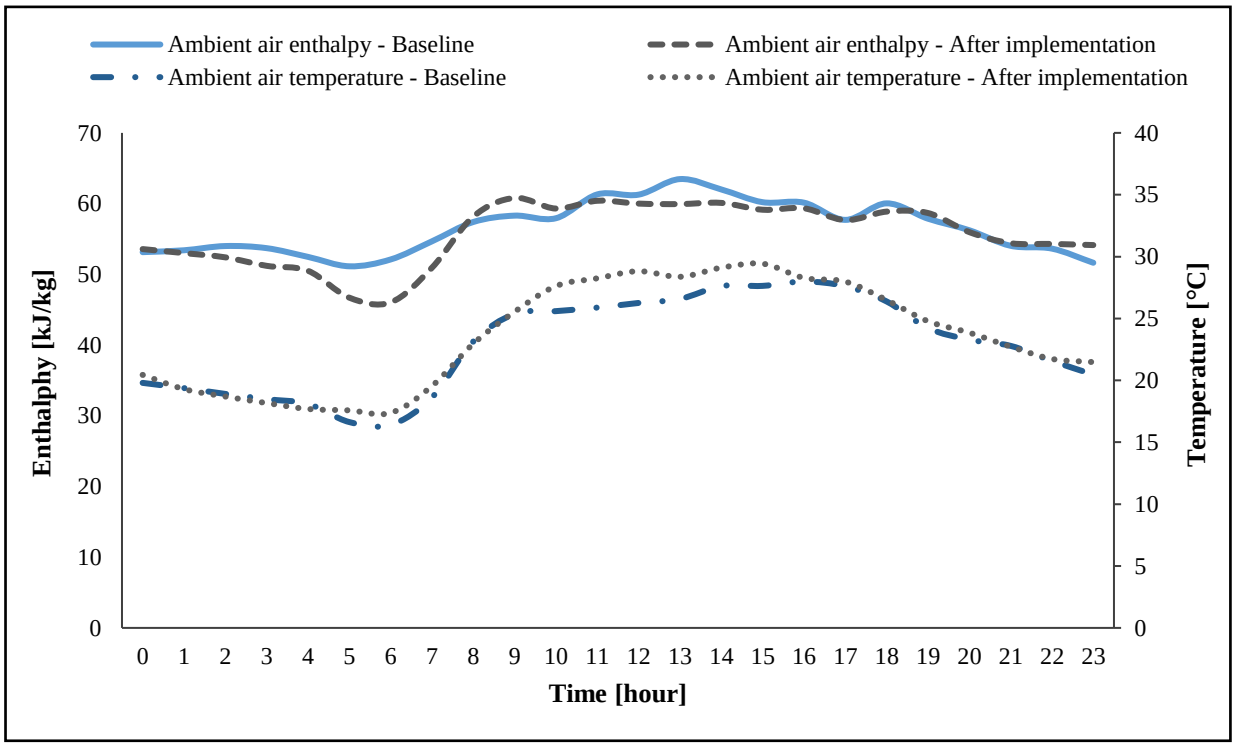

Figure 4-2: Comparable system boundary conditions

The ambient air temperature (DB) was listed as a comparable boundary condition due to the temperature of the CCD being largely dependent on the ambient air temperature. The difference in ambient air temperature (DB) for the two periods are presented in Figure 4-2. The average percentage ambient air temperature difference is 0.73°C. Similarly, the overall percentage error of the ambient air enthalpy for the two test periods is 2%. These differences are considered extremely small, making the test day results viable for comparisons.

After comparable boundary conditions for the two test periods have been established and considered feasible for comparisons, the performance of the cooling system, as a result of the automated cost saving measures, can be compared and analysed. The impact of the automated cost saving measures for a particular test day with feasible conditions will be discussed in the following subsection.

Interpretation of hard-commissioning results

Two comparable periods have been established; an M&V baseline and hard-commissioning test period. A test day with similar comparable boundary conditions to that of the baseline period was identified. These two periods are critically discussed and compared in this section. The total system performance is compared to holistically quantify the impact of automated control strategies on mine cooling systems.

A comparison between the total power consumption of the mine cooling system for the two periods is presented in Figure 4-3. Analysing the systems' power curve of the automated energy strategy, it can be realised that between 18:00 and 20:00 the total system power is reduced significantly. This is typical of a load management strategy.

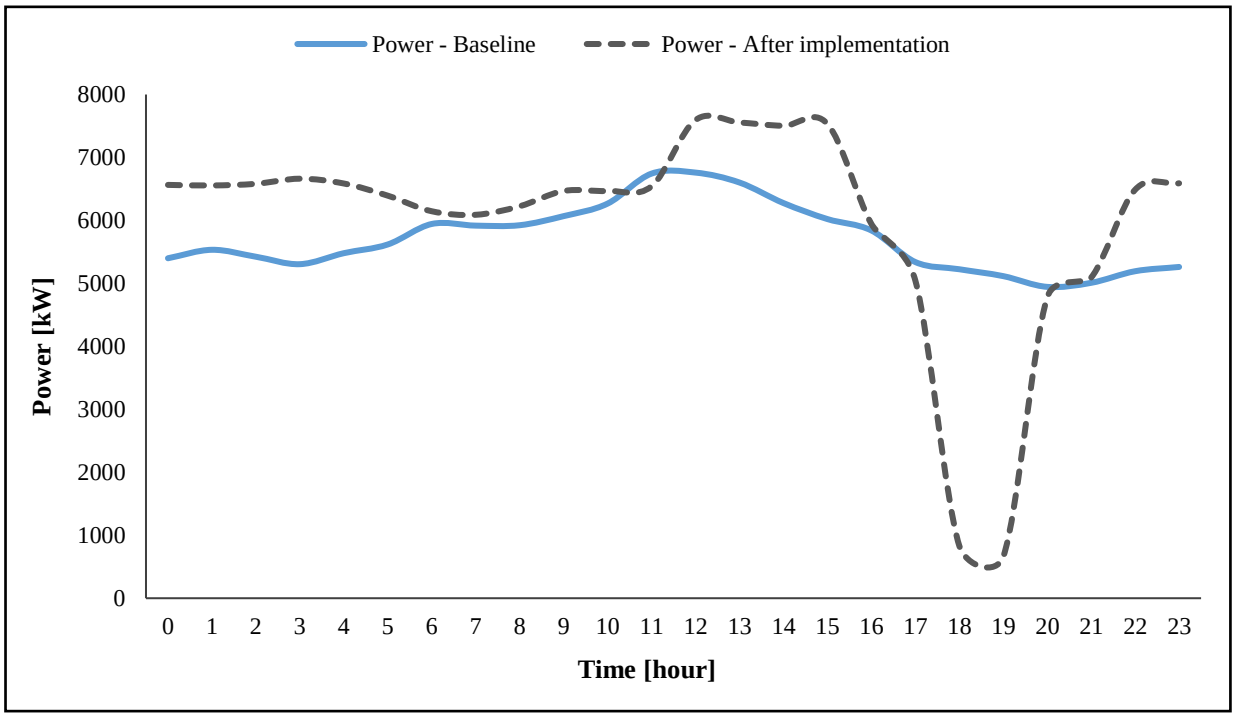

Figure 4-3: Total power consumption - Mine A

The automated strategy attained an evening load shift saving of 4.7 MW, which resulted in an 86% reduction in total power consumption between 18:00 and 20:00 for the particular test day. The average power consumption for the selected test day was 6123 kW. This represents a 3% discrepancy from the anticipated simulation results of 5954 kW tabulated in Table 4-1. The sustainability of this evening load demand reduction will be critically discussed in Section 4.6.

Figure 4-4 illustrates the relationship between the total compressor chiller power for the two test periods. The test results indicate a reduction of 3.8 MW in chiller compressor power consumption during the evening peak period. The chillers compressor power was reduced by 4135 kW to 3986 kW for the particular test day. This resulted in a 4% reduction in compressor power, which was attributed to the IGV control discussed in Section 3.5.6.

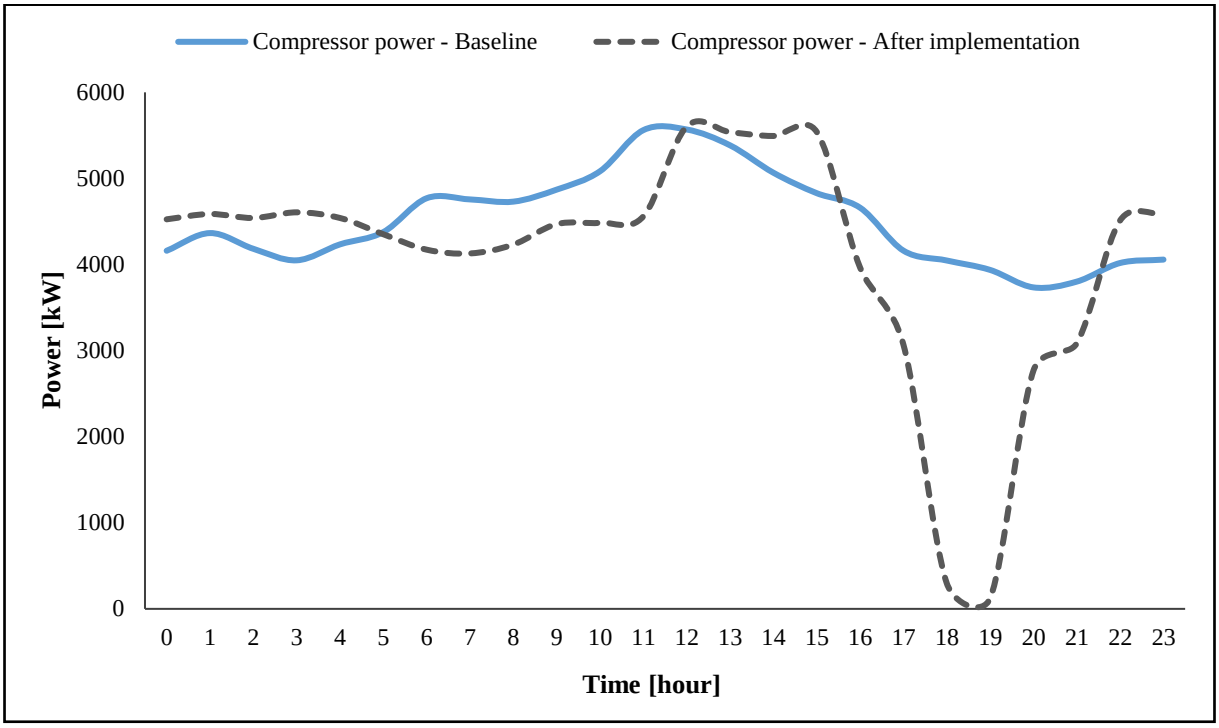

Figure 4-4: Total compressor power consumption - Mine A

To accurately investigate the complete impact of IGV control, the guide vane openings are critically evaluated in the sections that follow. Although the IGV control strategy resulted in a 149 kW power reduction, the evaporator water outlet temperature was also evaluated to determine the impact of increasing the static evaporator temperature set point to 3.5°C.

Due to the detriment of manual control on the performance of mine cooling systems, the control strategies discussed in Chapter 3 were developed to enhance chiller control and utilisation. This was developed to reduce chiller cycling and to select efficient baseload and trimming chillers for variable cooling loads. Therefore, the chillers utilisation was critically evaluated and reviewed. Figure 4-5 displays the running status of the chillers for the particular test day.

During the baseline period, an average of five chiller starts and six chiller stops occurred daily. Figure 4-5 indicates improved chiller utilisation, but an increase of 17% in chiller start-ups for the test day. This increase is attributed to a total load demand reduction during the evening peak periods. Therefore, the impact of automated cost saving measures on the maintenance costs of chillers prompts further investigation.

Although the two periods yielded no significant reduction the number of chiller starts and stops, the strategies attained an average load demand reduction of 4.7 MW during peak periods. In addition, the chillers operated for increased periods of time without being cycled. The chillers were operated for a minimum of five hours with the automated strategy; compared to a minimum operating time of two hours during the baseline metering period.

This realised a 60% improvement in the operating time of chillers. The chillers were also operating closer to DEM specifications, as outlined in the proposed solution outcomes in Section 3.3.1.

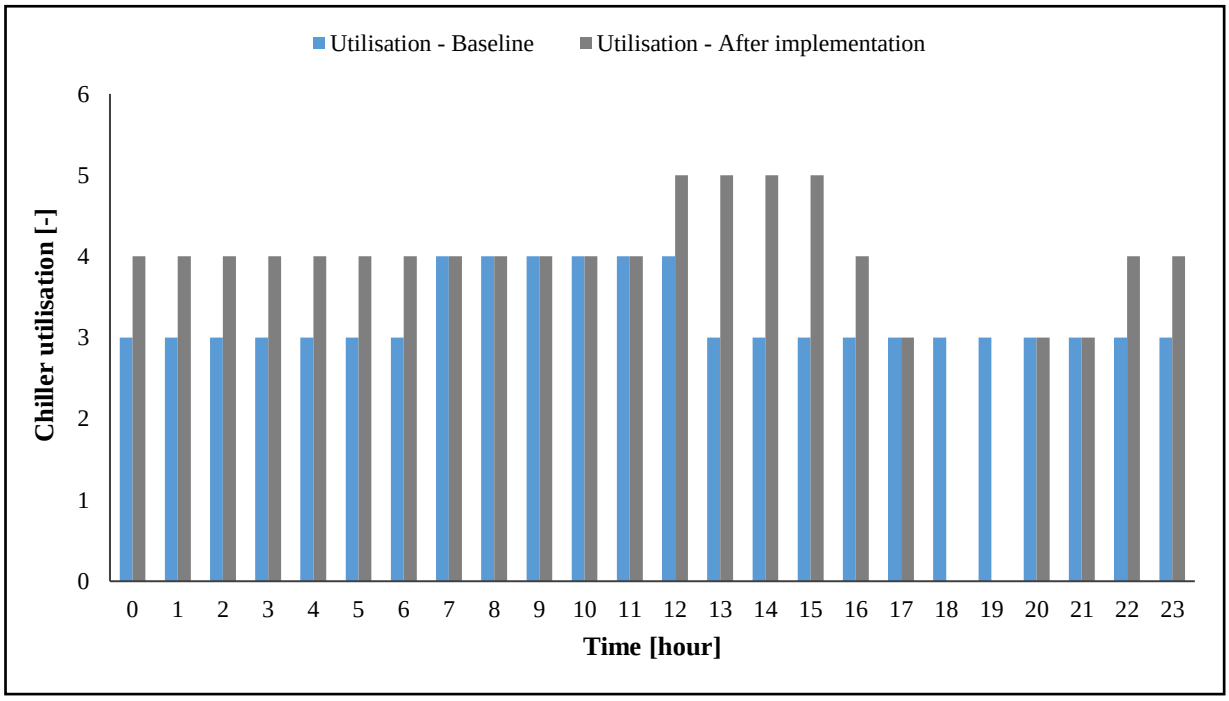

Figure 4-5: Chiller utilisation - Mine A

The cold dam temperature profiles are illustrated in Figure 4-6. The 39L cold dam and CCD are critically compared and evaluated. As mentioned in Section 3.5.4, the CCD temperature is considered the system driving temperature. Therefore, the temperature of the CCD adversely affects mine cooling requirements. An average CCD temperature difference of 1.7°C was calculated by comparing the two periods. This resulted in an average chilled dam temperature improvement of 21%.

Figure 4-6 reveals an average 39L cold dam temperature of 6.7°C for the test day. The results indicate that the 39L cold dam temperature reduced from 7.7°C, resulting in a 13% dam temperature improvement. This ensured that the water sent to underground end-users was cooler, which also suggests that underground working conditions have been greatly improved. A further study that evaluates the impact of cooler underground chilled dams on productivity and thermal fatigue should be investigated.

From the literature, it was suggested that the surface chilled dam temperature influences the BAC air outlet temperature adversely. Therefore, the BAC air outlet temperature is compared and critically discussed. The BAC air outlet temperatures for the two comparative periods are depicted in Figure 4-7. The 1.7°C CCD temperature reduction, resulted in enhanced heat transfer capabilities within the BAC tower and a BAC air outlet temperature improvement of 1.3°C.

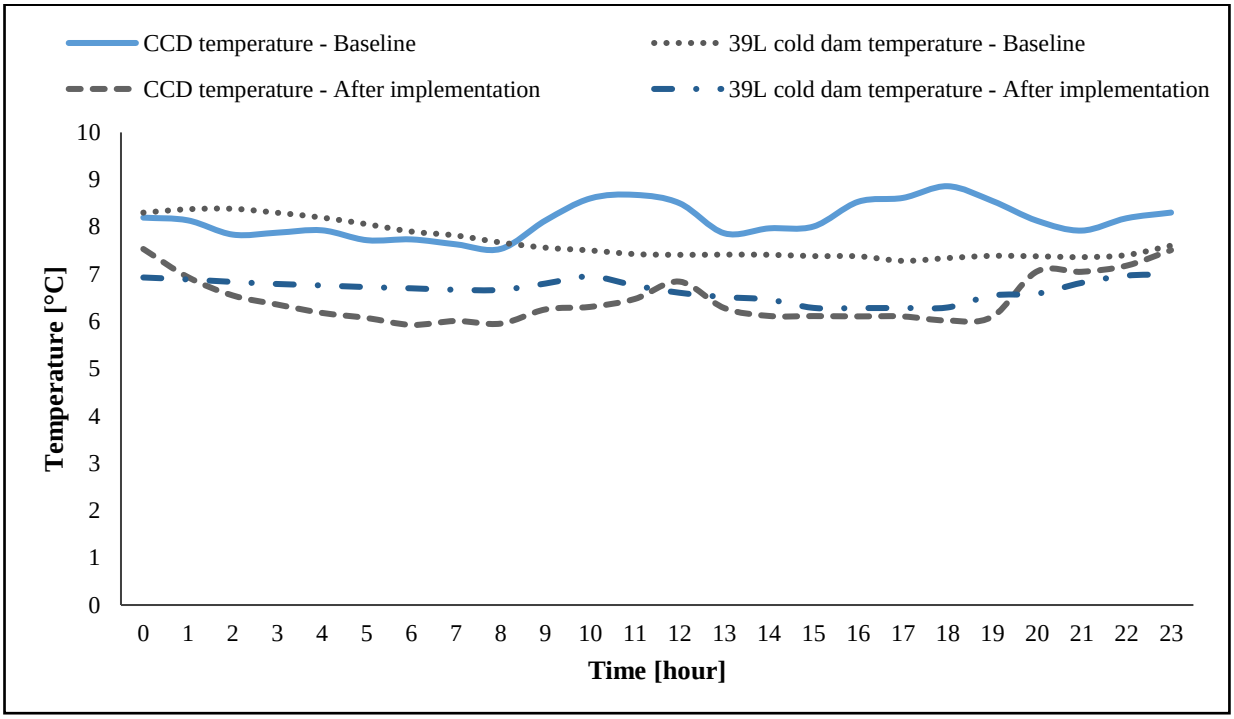

Figure 4-6: Chilled dam's temperatures - Mine A

The BAC air outlet temperature of 5.6°C is approximately 1.6°C below the BAC temperature limit, as illustrated in Figure 4-7. Figure 4-7 also reveals a temperature difference of 4.6°C for the two periods between 18:00 and 20:00. This indicates that the BAC air outlet temperature was 46.3% below the limit during the evening load management period. Therefore indicating an improved supply of chilled air to underground consumers as a result of automated control strategies.

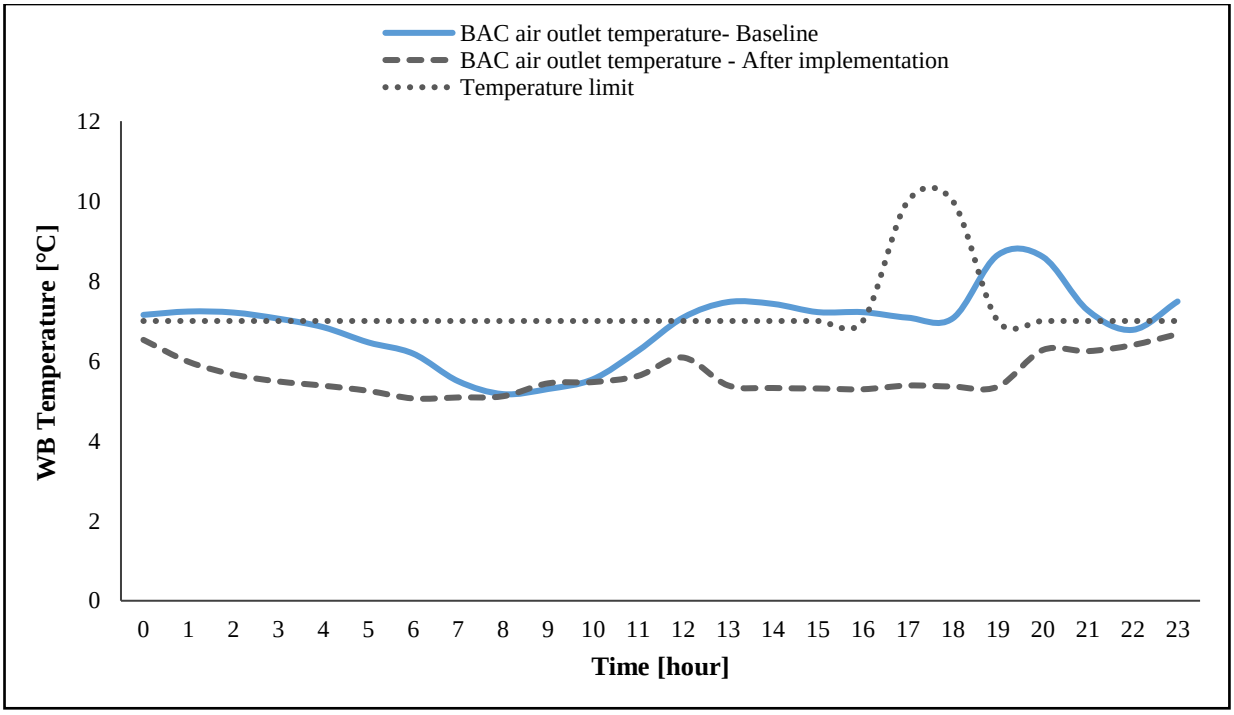

Figure 4-7: BAC wet-bulb air outlet temperature - Mine A

Being well below the BAC air temperature limit also prompts scope for additional cost savings. Therefore, the enthalpy control limits can be inflated to reduce BAC auxiliary power consumption. This could negatively impact productivity but positively impact cost savings. This can be discussed with the relevant mine personnel or investigated in another study.

Results from Figure 4-7 reveal small fluctuations between 5.1°C and 6.7°C for the BAC air outlet temperature. This indicates the value an automated cost saving measure has in providing a stable BAC air outlet temperature. The automated control strategies have also provided a suitable solution that aids in circumventing BAC machine component trips.

The average evaporator outlet chiller temperatures for the two periods is illustrated in Figure 4-8. An average evaporator outlet temperature of 4.1°C was realised after the implementation of automated control strategies. Figure 4-8 indicates the evaporator outlet temperature spikes from 3.2°C to 6°C between 16:00 and 20:00. This temperature spike is accredited to the implementation of an automated cost saving measure and is compensated with significant load shift savings as presented in Figure 4-3.

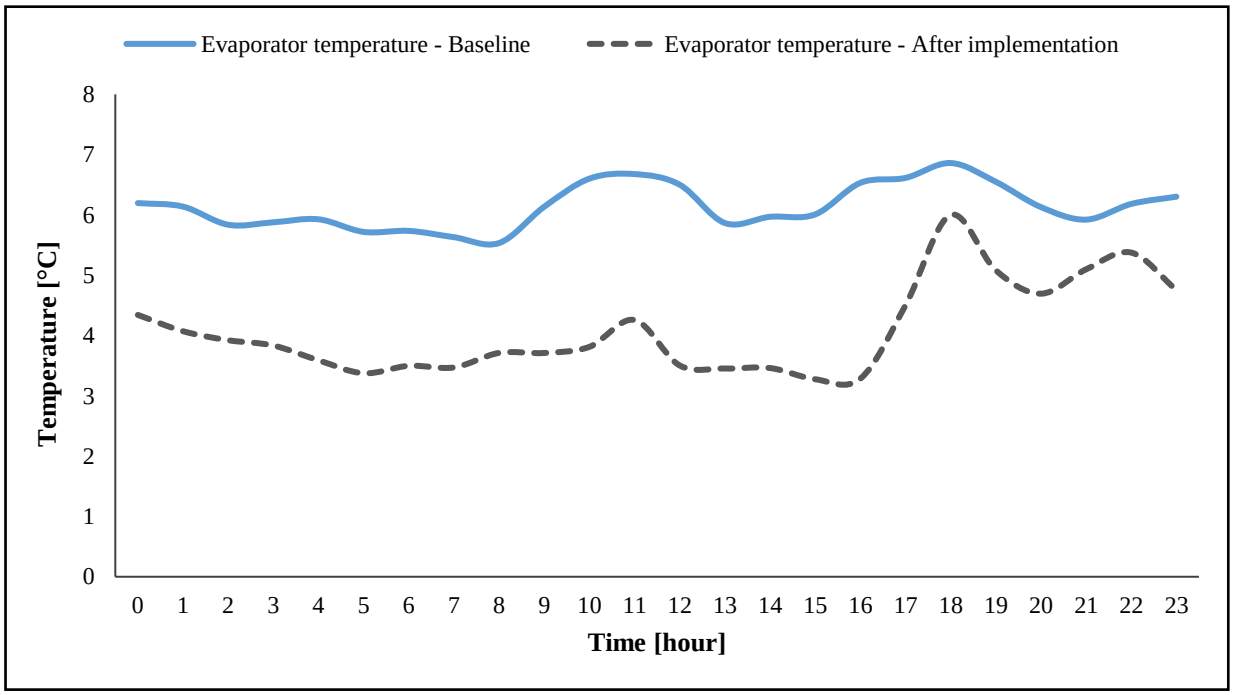

Figure 4-8: Chiller's evaporator outlet temperature - Mine A

Due to the automated cost saving measure, an improved evaporator outlet temperature of 33% was observed. The static evaporator temperature set point, as discussed in Section 3.3.1, of 3.5°C was almost met. It could be suggested that the static evaporator outlet temperature set point be increased to 4°C because the chillers are already operating close to DEM specifications. This change will also enhance energy efficiency practises.

Due to the need for varied cooling requirements, it was suggested that the auxiliary turbomachinery be controlled to vary the chilled water flow to underground. This ensured that the underground 39L cold dam temperature requirements were met. The chilled water flow to underground is illustrated in Figure 4-9.

Figure 4-9 shows that the chilled water flow sent underground reduced by 36 ℓ/s, or 23%, which is well within the design flow of 173.6 ℓ/s. Although, there is a supply reduction in service water, the 39-level chilled dam still has significant dam capacity to supply underground end-users. A reduced storage dam capacity also enhances the chilled water supply temperature, because a lesser volume of water is being stored for a shorter period of time. This reveals a significant improvement in operational efficiency.

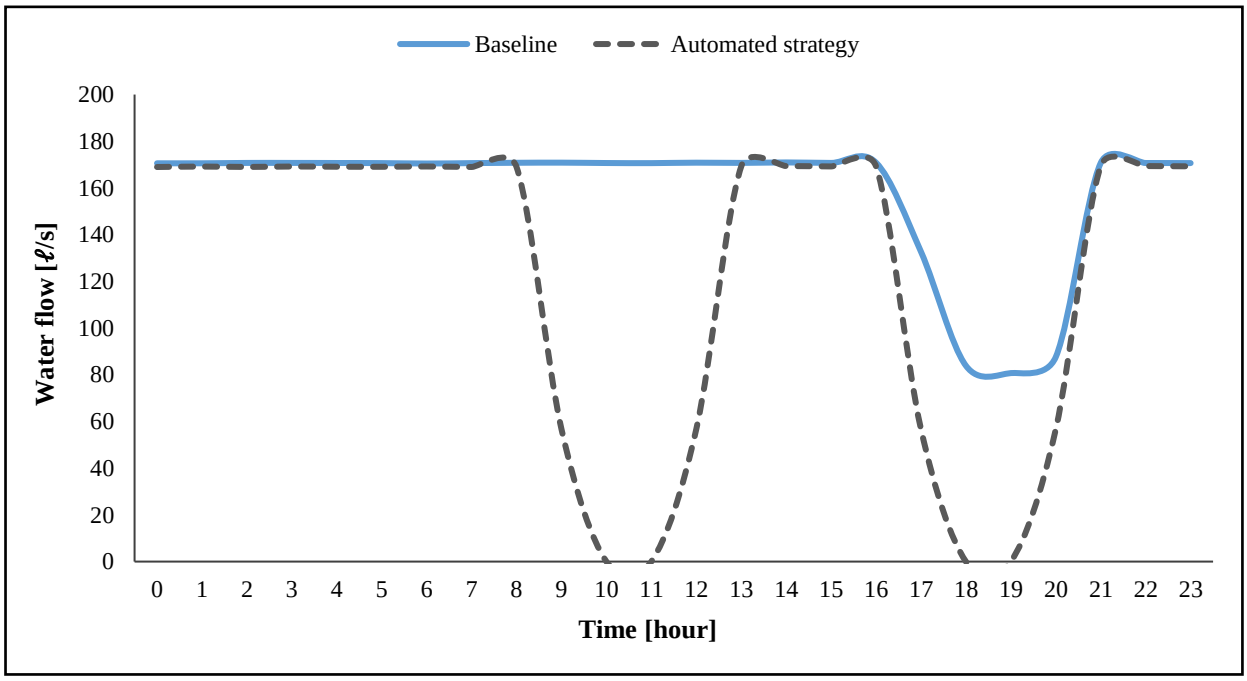

Figure 4-9: Chilled water flow to underground - Mine A

The reduction in underground chilled water demand not only recognised improved underground chilled dam temperatures, but also significant energy savings on dewatering pumps. The exact details pertaining to the achievable energy savings on dewatering pumps is beyond the scope of this study and is recommended to be investigated in further studies. It should be noted that although the demand for underground chilled water varies day-to-day, the results from the 38L turbine control have positively impacted service delivery requirements.

A summary of the BAC water flow profiles for the two comparative periods is illustrated in Figure 4-10. It is evident that the BAC pumps were operating at full-load conditions, or 408 ℓ/s during the baseline period. Utilising the variable flow control strategies discussed in Section 3.5.4, the BAC water flow was reduced to 309 ℓ/s. This resulted in a BAC water flow demand reduction of 24%. This improvement significantly improved BAC transfer pump utilisation.

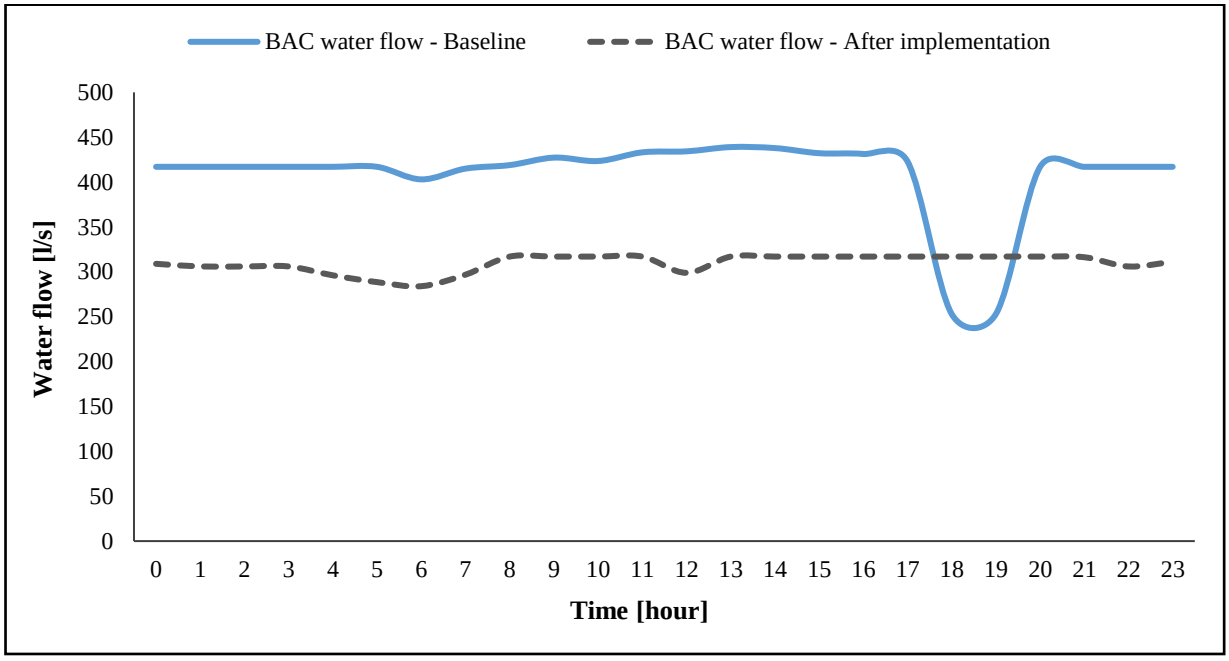

Figure 4-10: Total chilled water flow to the BAC's - Mine A

As part of the new control strategies, during the evening peak period of between 18:00 and 20:00, the BACs are completely operational to compensate for the chiller reduction. This results in a stable BAC water flow of 317 ℓ/s compared to the reduction from 423 ℓ/s to 253 ℓ/s of the baseline profile during the evening peak period.

It should be noted that operating the BAC pumps under partial-load conditions did not negatively impact the BAC air outlet temperature. The BAC air outlet temperature was still well below the temperature limit of 7°C WB, as depicted in Figure 4-8. Therefore, even at partial-load conditions, the BAC supply requirements were met. This suggests that the underground cooling requirements were met. Consequently, the BAC flow control cycle can be optimised for further energy savings.

As thoroughly discussed in Section 3.3.3, the variable flow control strategy for the condenser flow control cycle was decommissioned. The evaluation revealed that the VSDs on the condenser pumps were disabled by mine personnel. Only three of the six condenser pumps were controlled with VSDs. The VSD-installed control was recommissioned as a part of the integrated dynamic control approach. The total condenser tower water flow and condenser temperature difference for the two periods is displayed in Figure 4-11.

The motor VSDs on the condenser pumps were modulated to maintain a constant condenser water temperature difference (condensers water temperature out - condenser water temperature in) of 5°C. In the implementation period, a condenser temperature difference of 4.8°C was achieved. This represents a discrepancy of 4% when compared to the control set point of 5°C; illustrating the benefit automated control has on the accuracy of control. Implementation results revealed a delta temperature reduction of

19% or 1.1°C. Therefore, adjusting the closed loop PI control to allow the condenser pumps to operate at partial-load conditions resulted in favourable temperature control.

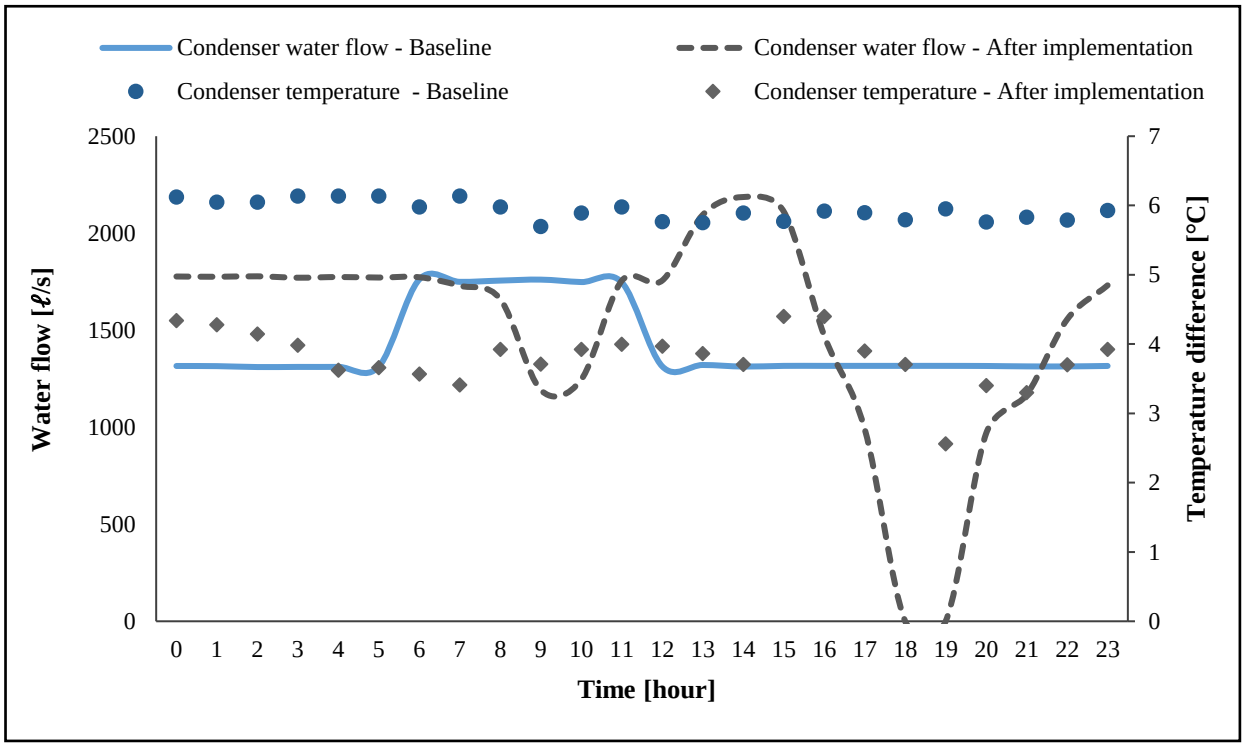

Figure 4-11: Total condenser flow and condenser temperature difference - Mine A

From Figure 4-11, it is revealed that the condenser pumps were operating at full-load conditions, an average of 438 ℓ/s, during the baseline period. The throttling valves were enabled to achieve the required flow. After implementation, however, an average flow of 375 ℓ/s was realised. This represents a reduction of 63 ℓ/s, or 14%.

Although the total flow after implementation is 1501 ℓ/s compared to 1424 ℓ/s during the baseline period, this is mitigated by improved chiller control and utilisation as a result of load management during the evening peak period. It can be suggested that as a result of operating the condenser pumps at partial-load conditions, the thermal heat transfer capabilities in the heat exchangers were enhanced.

The evaporator pumps were controlled with VSDs to maintain a stable CCD level of 75%. In the past, the mine personnel disabled the VSDs and the variable flow control strategy was decommissioned. After implementation of the automated dynamic control model, the evaporator pumps realised significant control improvements. Figure 4-12 illustrates the evaporator flow and CCD water temperature for the two particular periods.

Re-commissioning of the variable flow control strategy realised an average water demand reduction of 31 ℓ/s, from 233 ℓ/s to 201 ℓ/s for the test period. The automated cost saving measures ensured that the chillers did not trip. In addition, although the evaporator pumps were operating 49 ℓ/s, or 19% below the

technical specification of 250 ℓ/s for the evaporator pumps, the control revealed significant improvements in chilled water temperatures. The chilled water temperature improved from 8.1°C to 6.5°C after implementation.

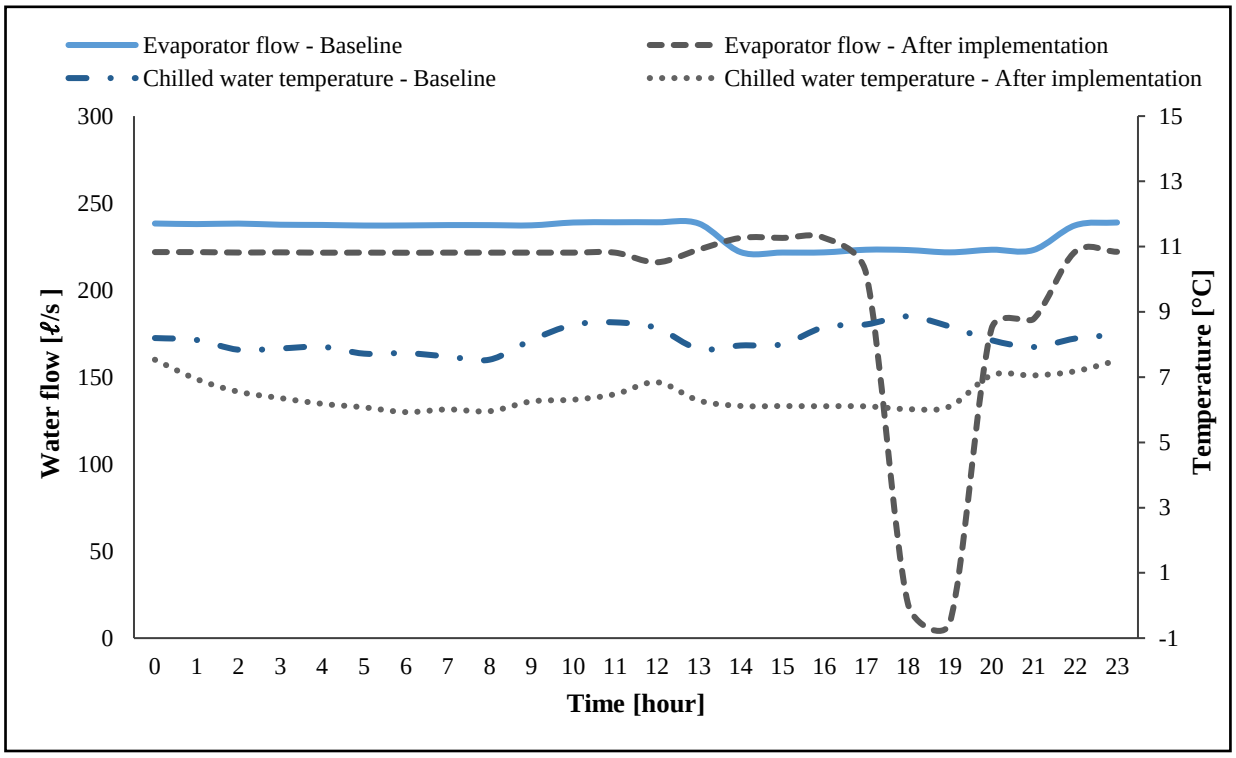

Figure 4-12: Average evaporator flow and CCD water temperature - Mine A

The delta temperature over the evaporators for the two comparative periods is depicted in Figure 4-13. An average delta evaporator temperature of 6.4°C was realised after the implementation of the automated strategy. This represented a 9% temperature difference improvement from the delta temperature of 5.9°C during the baseline period. Higher delta temperatures over the evaporator resulted in improved heat transfer in the evaporator, which enhanced the chiller COPs. This meant that the mine was making complete use of the chillers' cooling power.

Analysis of the baseline chiller COPs revealed an average COP of 4.98. The automated strategy resulted in an average COP improvement of 7%, which meant that the chillers were operating closer to the design COP rating of 5.5. Figure 4-13 also reveals that between 18:00 and 19:00 the COP of the chillers decreased. This can be expected from the implementation of an automated load management strategy.

The evaporator inlet temperatures between the two comparative periods differed by 1.3°C. This decrease in evaporator inlet water temperature is accredited to the implementation of the automated cost saving measures on the pre-cooling flow control cycle. Although the inlet evaporator temperature decreased, an increase in chiller COP and improved chiller utilisation resulted in significant operational efficiency improvements.

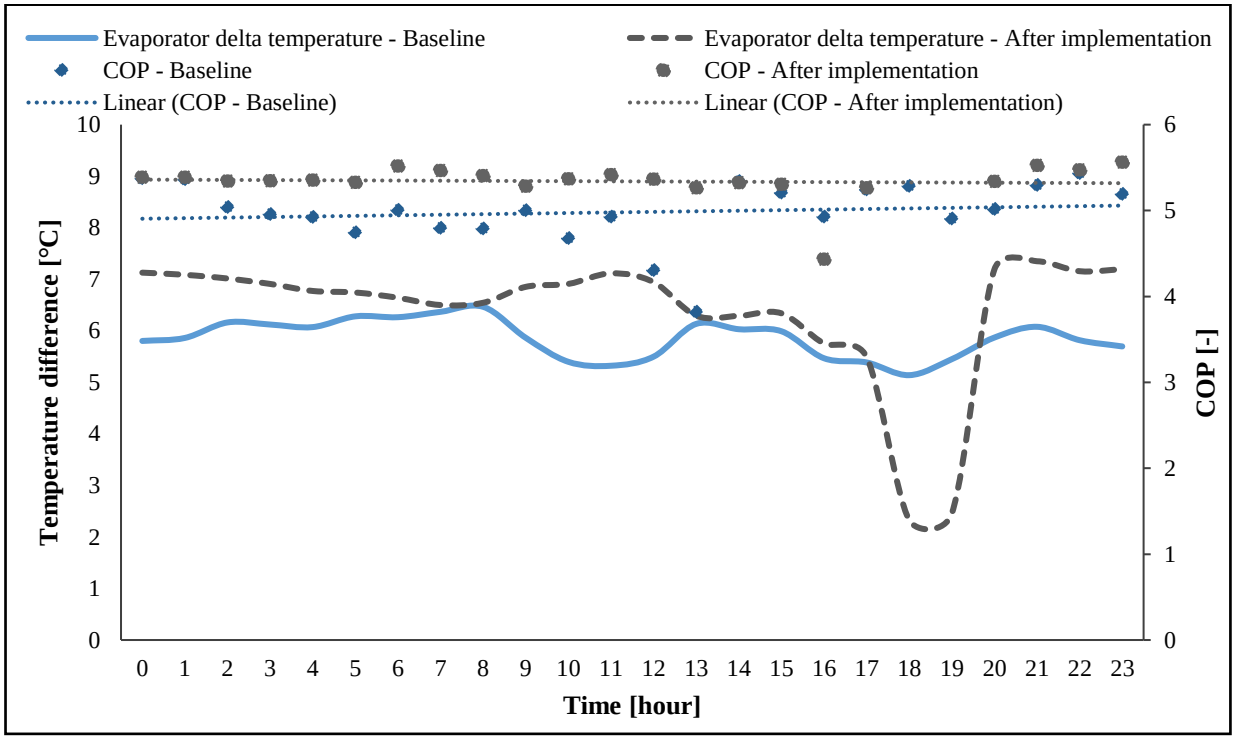

Figure 4-13: Delta evaporator temperature and chiller COP - Mine A

The IGV control strategy was systematically discussed in Section 3.5.6. The strategy suggested that the discharge refrigerant flow and, consequently, the IGV opening can be reduced by increasing the static evaporator temperature set point from 3°C to 3.5°C. The average chiller IGV opening is therefore presented in Figure 4-14.

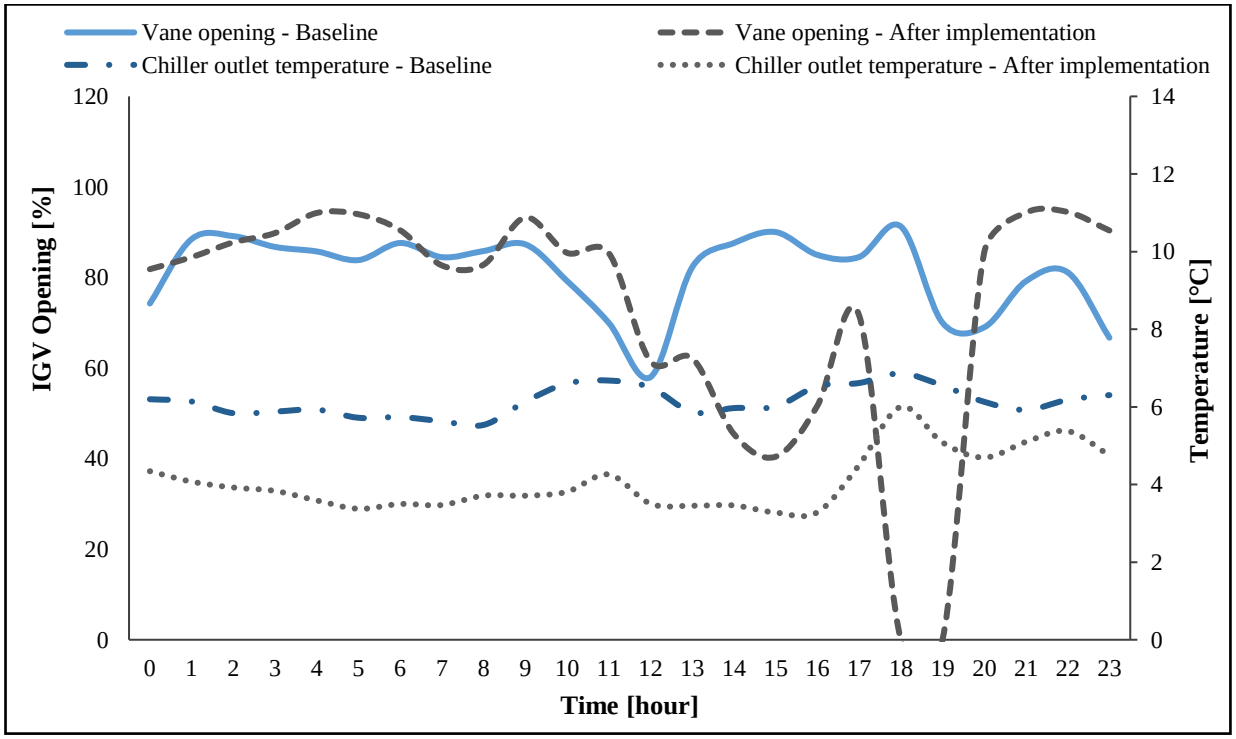

Figure 4-14: Average chiller IGV opening and chiller outlet temperature - Mine A

The IGV openings depict an overall average difference of 8% between the two periods. The implementation of the automated cost saving measures has resulted in an IGV opening of 73% compared with 82% during the baseline period. This, in turn, resulted in higher operating COPs as illustrated in Figure 4-13. The average refrigerant discharge flow reduction as a result of the IGV control strategy will be discussed in Section 4.4.

Figure 4-14 also reveals a stable chiller outlet temperature of 4.1°C after implementation of the IGV control strategy. This indicates an average discrepancy of 17% when compared to the required temperature set point of 3.5°C. This reveals that the IGV strategy accurately controlled the refrigerant discharge flow to meet the required temperature set point.

In addition, Figure 4-14 indicates an average chiller outlet temperature of 6.1°C for the baseline period. This represents a 3.1°C temperature difference from the static set point of 3°C. This contributed to poor chiller control and utilisation during the baseline period. The lack of an automated dynamic control philosophy, with sustainability as the principle focus point, lead to poor chiller performance.

Between 18:00 and 19:00, the IGV opening after implementation was 0%. This was a result of improved chiller control and utilisation from automated control strategies during the Eskom evening peak period. Figure 4-3 indicates the achievable energy savings from such strategies. The vane spare opening profiles for the respective test periods are illustrated in Figure 4-15.

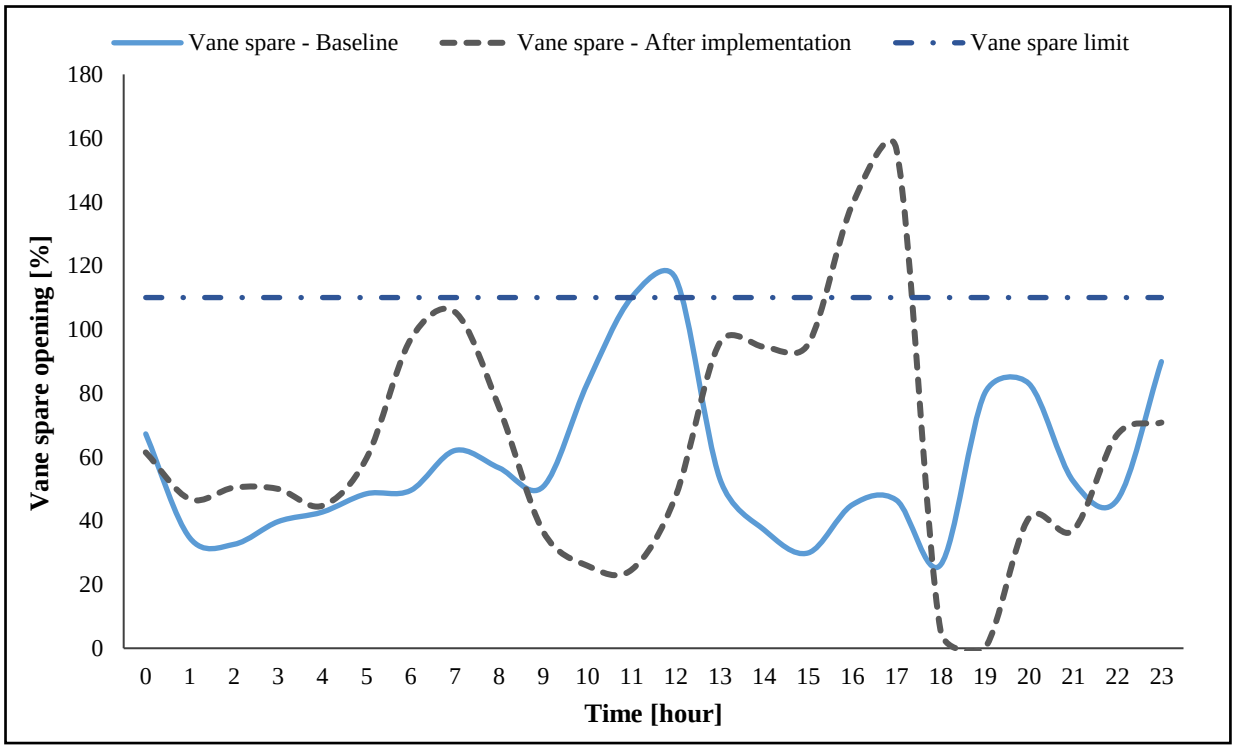

Figure 4-15: Average chiller IGV spare opening - Mine A

The vane spare opening increased by 6% as a result of the implemented control strategies. This ensured that variable cooling requirements were continuously met through improved control and utilisation of chillers.

Between 15:00 and 17:00, the vane spare opening increased from 95% to 156%. This exceeded the vane spare limit of 110% by 46%. This indicates that a chiller should be stopped, as suggested by the control philosophy in Chapter 3. This was confirmed by a chiller stop at 16:00 during the baseline period, in Figure 4-5. Therefore, verifying the accuracy of the control philosophy.

Flow balance control was employed to ensure that the HCD and CCD did not overflow or run dry. The HCD and CCD levels are illustrated in Figure 4-16. The HCD and CCD levels differ by approximately 10% and 16% for the two periods respectively.

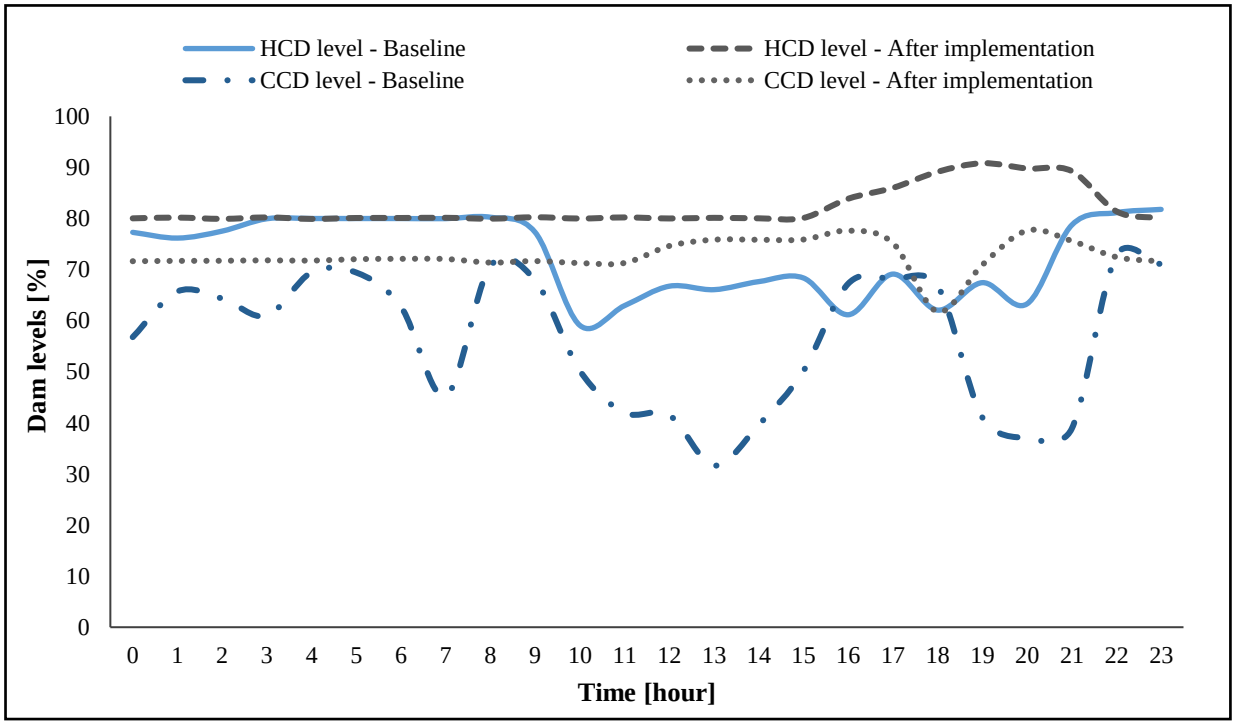

Figure 4-16: HCD and CCD levels - Mine A

Improved flow balance control has resulted in stale HCD and CCD levels. Figure 4-16 illustrates that the dam levels fluctuate irregularly between 37% and 80%, revealing inefficient control of the chillers and cooling auxiliaries during baseline periods. After implementation, however, the HCD levels stabilised between ranges of 80% and 91%, which represents a dam level range improvement of 74%. Also, the CCD level ranges improved by 68%. Figure 4-16 reveals that the CCD and HCD levels are operating close to the dam level limits of 75%. Sufficient thermal storage capacity has ensured sufficient load shift savings.

Figure 4-17 illustrates the COP versus total system power for the two comparative periods. Although the total system power increased from 5717 kW to 6123 kW, or 3% after implementation, the chillers COP increased slightly from 4.98 to 5.3. This suggests that the thermal heat transfer in the heat exchangers increased.

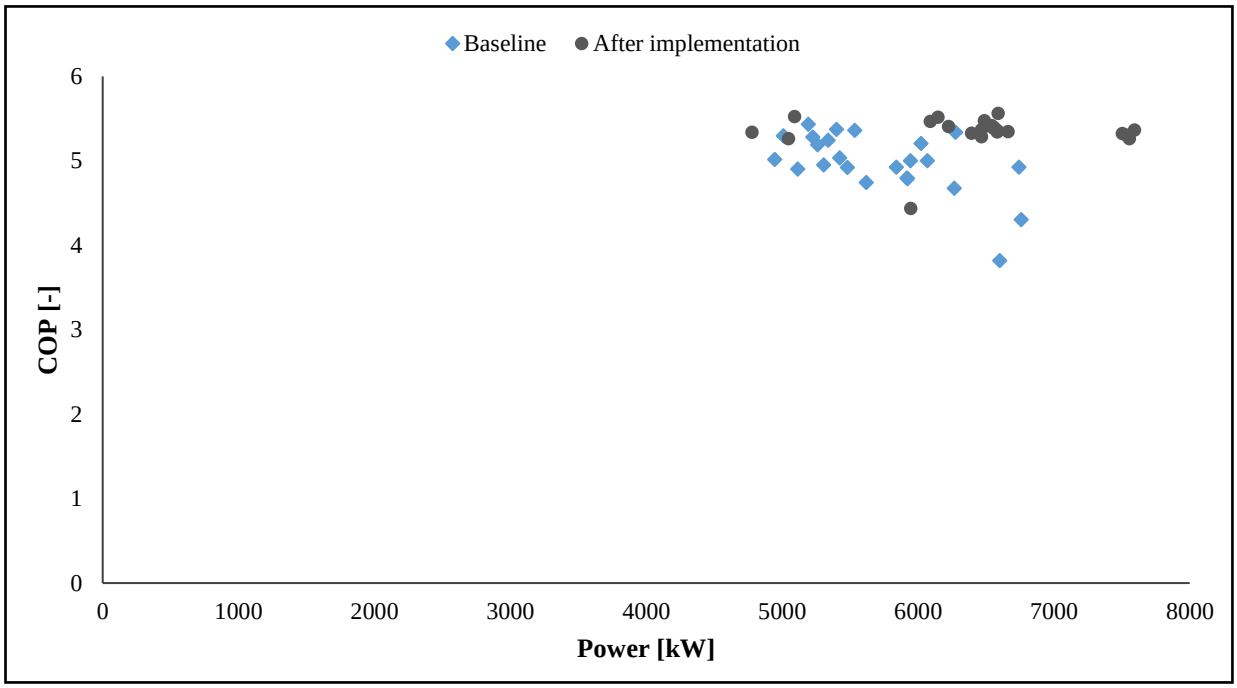

Figure 4-17: Chillers COP versus power - Mine A

Figure 4-18 illustrates the COP for the individual chillers. The individual chiller COPs are operating close to the DEM specification of 5.5. Chiller 6 realised a COP improvement from 3.5 to 4.7, or 26%.

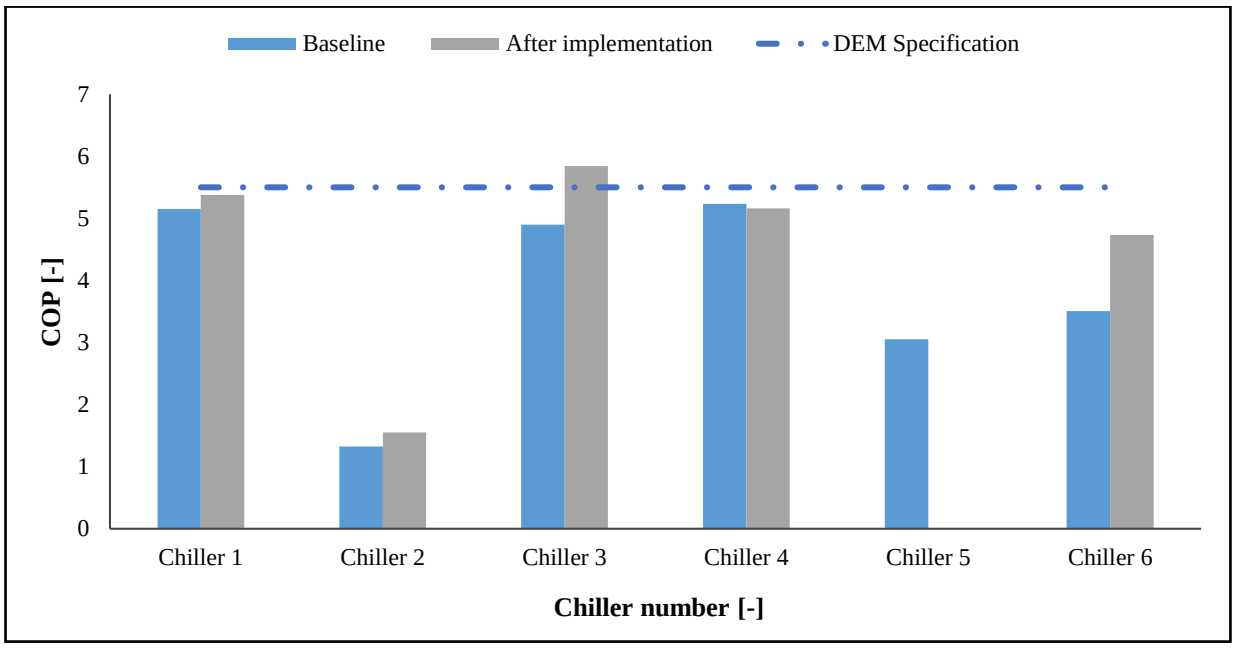

Figure 4-18: Individual chiller COPs - Mine A

The test periods were analysed, compared and reviewed in Figure 4-1 to Figure 4-18. A summary of these commissioning test results are presented in Table 4-2. These results indicate a 15% improvement in operational efficiency. This improvement is attributed to the implementation of an automated and integrated dynamic control strategy.

In addition, Table 4-2 indicates that the DB ambient temperature increased by an average temperature of 0.7°C after implementation. This resulted in an increase in total system power from 5717 kW to 6123 kW. Although this anomaly occurred, the newly proposed method attained a chiller COP and compressor power improvement of 7% and 4% respectively. These improvements can be increased during days with cooler ambient temperature conditions.

Table 4-2: Summary of test period results - Baseline and Hard-commissioning

No.	Description	Baseline	Hard-commissioning test	Error difference [%]
1	Total system power [kW]	5717	6123	−7%
2	Auxiliary component power [kW]	1582	2137	−35%
3	Chiller compressor power [kW]	4135	3986	4%
4	BAC air outlet temperature [°C]	6	5.6	7%
5	39L Chilled water temperature [°C]	7.7	6.7	13%
6	CCD Water temperature [°C]	8.2	6.5	21%
7	Chilled water sent to underground [°C]	8.2	6.5	21%
8	Chiller outlet temperature [°C]	6.1	4.1	33%
9	Evaporator inlet water temperature [°C]	12	10.5	11%
10	Evaporator outlet water temperature [°C]	6.1	4.1	33%
11	Evaporator delta water temperature [°C]	5.9	6.4	9%
12	DB Ambient air temperature [°C]	22.9	23.6	−3%
13	Chiller vane opening [%]	81.2	72.9	10%
14	Chiller vane spare opening [%]	57.6	63.7	−11%
15	CCD Level [%]	56.3	72.7	29%
16	HCD Level [%]	72.7	82.2	−13%
17	Evaporator water flow rate [ℓ/s]	233	201	14%
18	Condenser water flow rate [ℓ/s]	438	375	14%
19	BAC Water flow rate [ℓ/s]	408	309	24%
20	Chilled water flow sent to underground [ℓ/s]	158	122	23%
21	Ambient air enthalpy [kJ/kg]	56.7	55.7	2%
22	Chiller status [-]	3.3	3.7	−12%
23	Number of chiller start-ups [-]	5	6	−20%
24	38L Turbine shutdowns [-]	1	2	−100%
25	Chiller COP [-]	4.9	5.3	7%

The specific test day will be simulated to verify the accuracy of the test day results. The simulated strategy verification will be briefly discussed and reviewed in Section 4.3.4 below.

4.3.4. Simulated strategy verification

A calibrated baseline simulation model was developed to verify the accuracy of the test results from the implementation of the automated cost saving measures. PTB simulation software was deemed to be a feasible solution. The simulation methodology discussed in 3.6.5 was used to verify the accuracy of the test results.

To evaluate the accuracy of the automated strategy test results, various process variables were considered: power consumption, CCD and BAC air outlet temperatures. Figure 3-23 illustrates the simulated power profile for the automated cost saving measures.

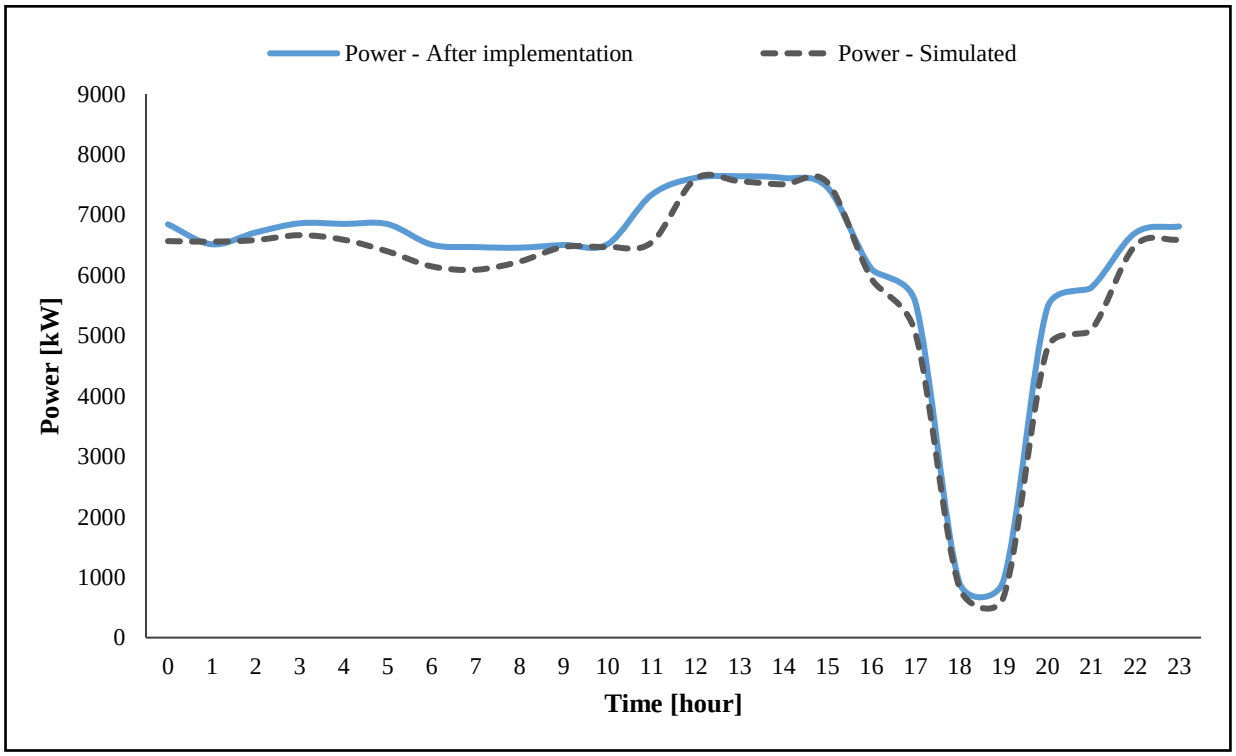

Figure 4-19: Power profile verification - Automated strategy

The baseline and simulation attained an average difference of 169 kW. PTB accurately simulated the power response profile of the automated strategy with an error of 3%. The load shift savings attained from the automated strategy were also correctly simulated. The simulation proved that a sustainable load shift saving is possible from the implementation of an automated control strategy.

In Figure 4-20, the CCD and BAC air outlet temperatures are depicted. The CCD temperature was considered as the system driving temperature and therefore adversely affects mine cooling demand requirements. The CCD temperatures differ by an average of 0.24°C for the two profiles. The BAC air outlet temperature, which is responsible for significant underground cooling and ventilation, revealed an average error of 8%.

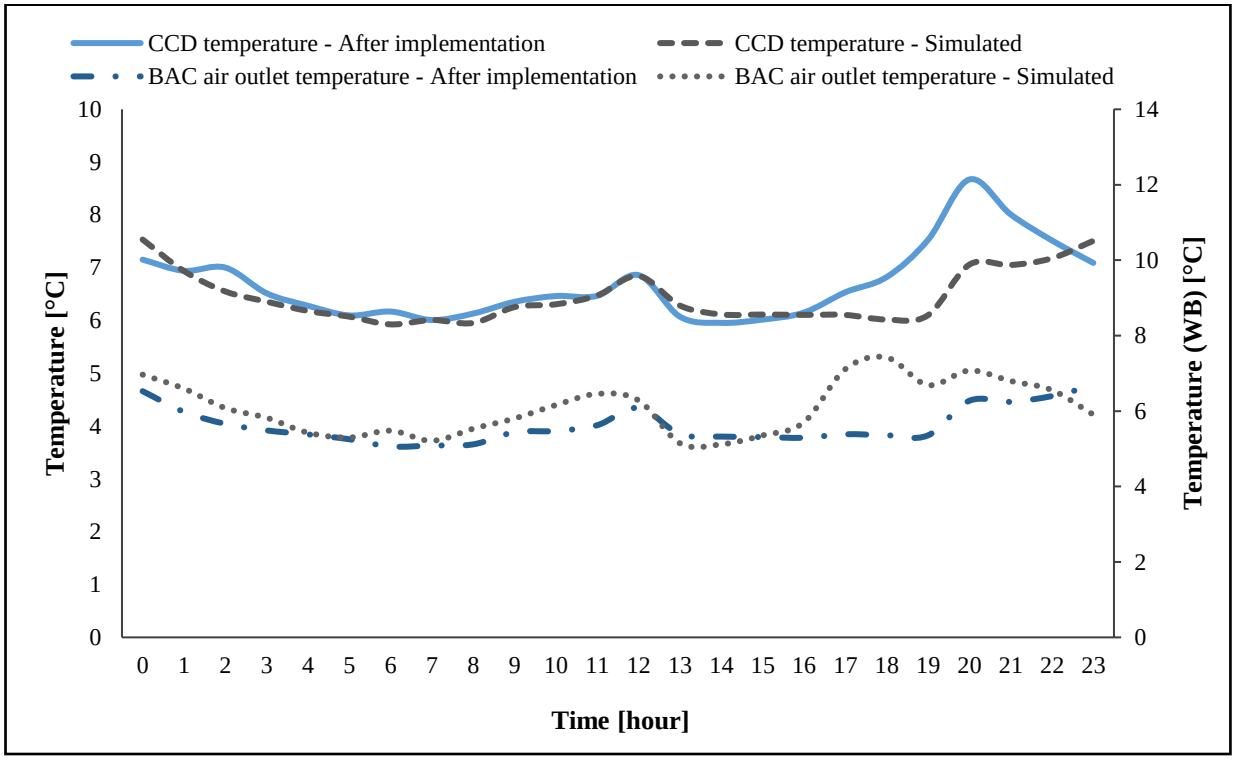

Figure 4-20: CCD- and BAC temperature verification - Automated strategy

Figure 4-20 reveals that between 17:00 and 20:00, the CCD temperature spiked from 6.2°C to 8.7°C, which is characteristic of a load management strategy. Although a temperature difference of 1.5°C between 17:00 and 20:00 for the two profiles is present, PTB accurately modelled the period's CCD temperature with an accuracy of 96%.

An automated strategy simulation verification summary is illustrated in Table 4-3. The simulation revealed that PTB is considered feasible for accurately estimating the impact of the automated strategy.

Table 4-3: Simulation verification summary - Automated strategy

No.	Description	Automated strategy results	Simulated results	Accuracy [%]
1	Total system power [kW]	5954	6123	97%
2	CCD Chilled water temperature [°C]	6.5	6.7	96%
3	BAC air outlet temperature [°C]	5.6	6.1	92%
Average				**96%**

The simulation verification summary revealed an overall average accuracy of 96%. The average percentage accuracies are within the threshold limit of 90% and greater. PTB is deemed a viable simulation package.

The implementation results of the automated cost saving measures were meticulously investigated and discussed in this section. Comparisons between the automated cost saving measures and the baseline were completed. The automated dynamic control strategies are verified in the following section.

4.4. Control strategy verification

4.4.1. Overview

The automated strategy was commissioned, implemented and evaluated. A calibrated simulation model was constructed to verify the impact of the automated strategy. Within this section the control strategies are verified to support the impact of automated control. Data from the EMS was collected to verify the study. This will ensure the development of an accurate and practical strategy that can be implemented on other mine cooling systems.

4.4.2. Chiller characterisation and control

To maintain the required HCD and CCD levels and temperatures, the chillers were automatically stopped and started with control schedules. The control logic displayed in Figure 3-19 and Figure 3-20 were evaluated to schedule the optimal chiller configuration. The chiller start and stop simulation schedules are illustrated in Figure 4-21.

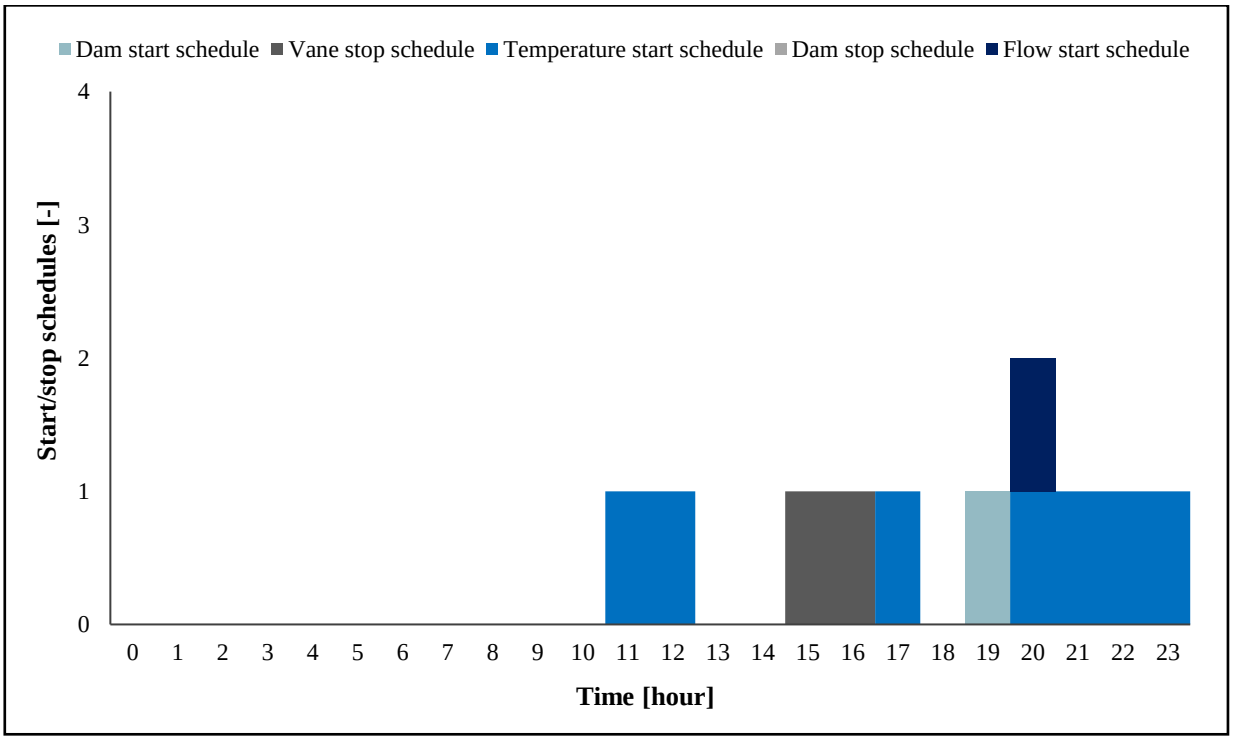

Figure 4-21: Chiller start and stop schedules - Verification of automated strategy

Figure 4-21 reveals that between 10:30 and 12:00 the temperature start schedule is active. This suggests that the trimming chiller with the start priority will be automatically started by the chiller start/stop controller, as confirmed by the start-up of chiller 6 at 12:00 in Figure 4-22. Also, Figure 4-21 indicates that between 14:30 and 16:30, the vane stop schedule is active. This is emphasised in Figure 4-15 when the vane spare surpasses the vane spare limit of 110%. At 15:00, Figure 4-22 reveals that the chiller with stop priority, chiller 4, was automatically stopped because of the active vane stop schedule.

At 18:00, the load shift strategy was executed. Therefore, as depicted in Figure 4-22, revealing a total load demand reduction between 18:00 and 20:00. At 19:00 the temperature start schedule was active. This was due to the evaporator outlet temperature increasing to 6°C at 20:00, as illustrated in Figure 4-8. Although this schedule was active, the ambient temperature was decreasing. Hence, no chiller was automatically started.

The chillers were systematically started and stopped throughout the day with the start/stop controller in Appendix B. The chillers running status for the particular test day is illustrated in Figure 4-22. Figure 4-22 reveals that the start and stop schedule indications interlink with the daily chiller utilisation, thereby confirming the accuracy of the automated chiller control strategies.

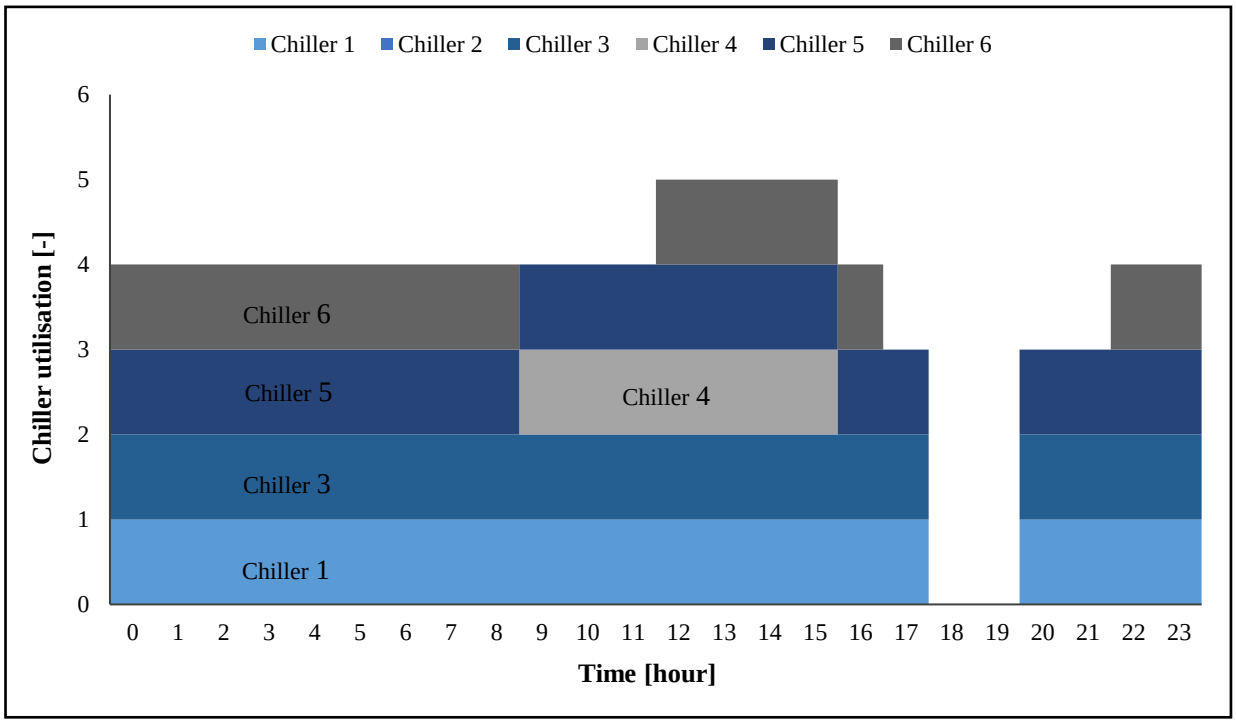

Figure 4-22: Baseload- and trimming chiller utilisation - Verification of automated strategy

These control strategies realised significant improvements in the operating time of chillers. The chillers were also operating closer to DEM specifications, as discussed in Section 4.3. Figure 4-21 and Figure 4-22 reveals that the chillers were successfully started and stopped automatically as different mine cooling requirements or conditions were required. This verified the accuracy and precision of the control.

4.4.3. Temperature control

An integral facet of the automated cost saving measures was temperature control. An ambient air temperature (DB) prediction model was formulated to optimally control the chillers. Key principles and methodologies describing the prediction model were discussed in Section 3.5.5.

The ambient air temperature prediction results for the test day are illustrated in Figure 4-23. From these results, the accuracy of this unique model was quantified and verified. The prediction model attained an average difference of 0.19°C between the predicted and actual ambient temperatures. The ambient temperature prediction model accurately predicted the actual ambient temperature conditions to improve the control, utilisation and performance of a mine cooling system with a predication error of 6%. This result was aligned with a research paper compiled by Zhang *et al.* [199] that achieved a mean absolute error of less than 1K for a duration of 120 minutes.

Disparities in daily predictions were recognised due to the variable nature of ambient temperature conditions. Therefore, the accuracy of the model and extent to which subsystems can be dynamically controlled was affected. Although the prediction model revealed accurate results, to mitigate the effect of these variable conditions, a smaller prediction interval like 60 minutes can be utilised. This can be investigated in an additional study.

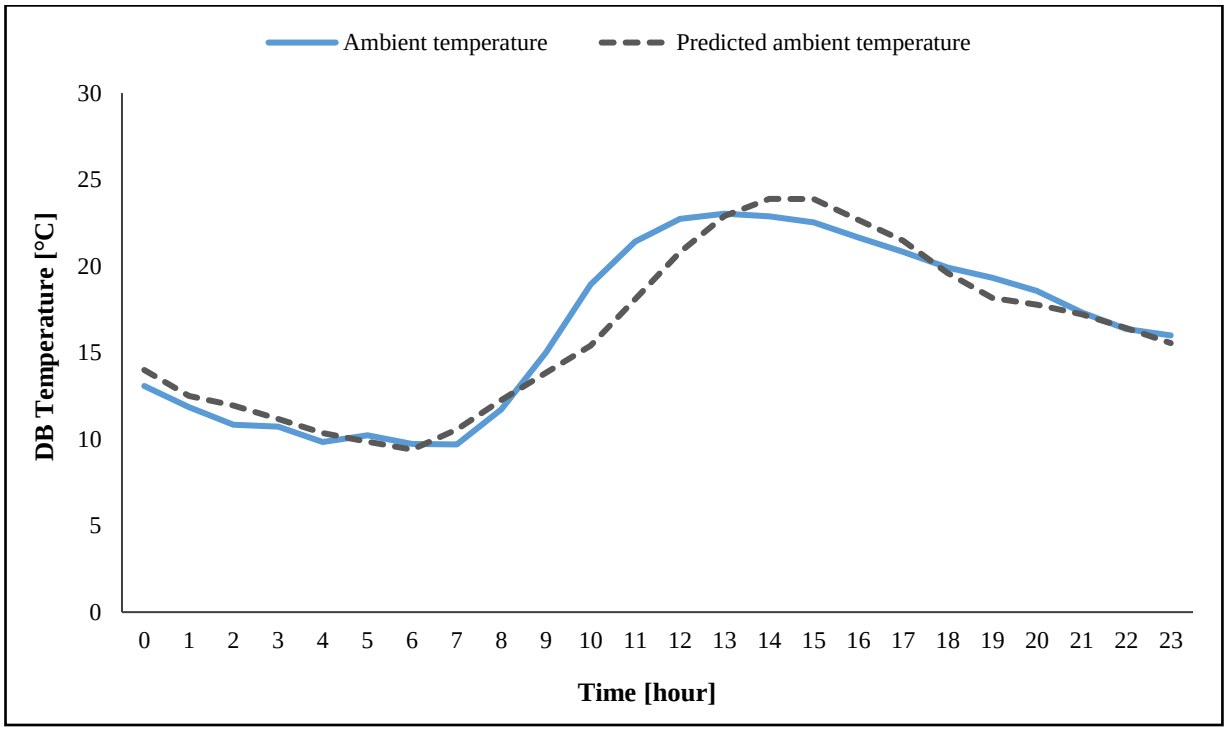

Figure 4-23: Ambient DB air temperature - Verification of automated strategy

Between 06:00 and 10:00, Figure 4-23 reveals that the predicted ambient temperature model increases by approximately 24% more than that of the actual ambient DB temperature. This was due to the steep increase in actual ambient conditions from 08:00 to 12:00. The suggested interpolation assumptions can be modified to mitigate this discrepancy in the future.

Figure 4-24 demonstrates the implementation results of the dynamic temperature set point algorithm. The dynamic temperature set point adjusts in real time to meet the chilled dam temperature parameter. The daily average chilled water temperature decreased from 8.1°C to 6.5°C after implementation. This was ultimately due to improved chiller control and utilisation as a result of dynamic temperature set point

control. This chilled water temperature reduction was less than the target temperature limit established by the mine personnel, resulting in an improved service delivery.

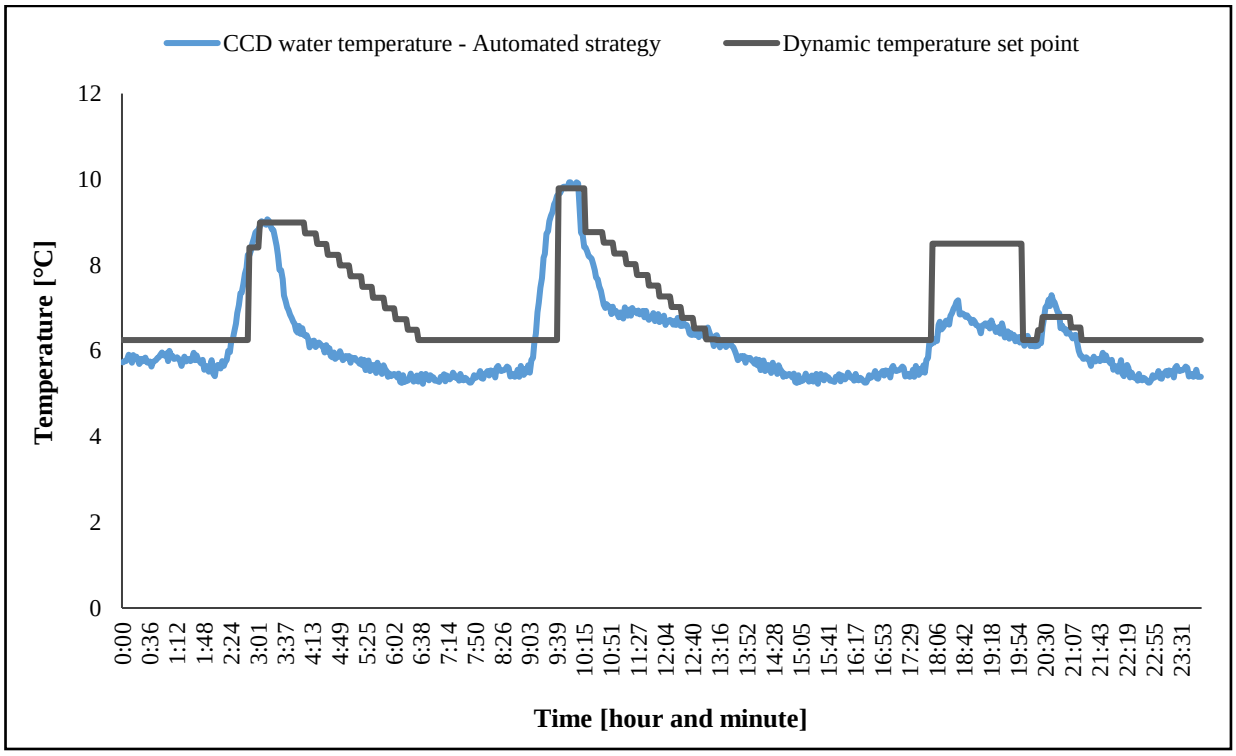

Figure 4-24: CCD dynamic temperature set point - Verification of automated strategy

As depicted in Figure 4-24, the dynamic temperature set point analyses the temperature parameter to determine whether it is decreasing within the calculated chiller rate of change. At 03:00 and 09:15, the chilled dam temperature exceeded the static temperature set point of 6.3°C by 29.2% and 35.6% respectively.

Also, the static temperature set point was adjusted to 8.5°C to accommodate for the evening load demand reduction between 18:00 and 20:00. During this period, the chilled dam temperature increased to 7.14°C, which was 19.1% below the temperature set point of 8.5°C. This increase is marginal and suites mine operating conditions. After the load demand reduction period, the dam temperature stabilised within one hour, deeming the control strategy feasible by mining standards.

The dynamic temperature set point algorithm substantially improved the performance of chillers on the case study. From Figure 4-24, it is evident that the temperature rate of change of 0.63°C accurately emulated the chilled dam water temperature parameter. Therefore, the incorporation of a dynamic temperature set point algorithm, as opposed to a static temperature set point adopted by Sen Huang *et al.* [162], controlled the chillers optimally with a chilled dam temperature improvement of 21%, from 8.2°C to 6.5°C. This is ultimately due to improved chiller control and utilisation as a result of dynamic temperature set point control. This chilled water temperature reduction was less than the temperature limit established by the mine personnel, resulting in an improved operational efficiency.

This temperature improvement, as a result of the dynamic temperature set point, also compared well with similar results obtained by Du Plessis *et al.* [71] where a mine cooling system was optimised through the use of an EMS to obtain a chilled dam water temperature of 6.4°C. It is, therefore, apparent that the chiller rate of change optimised the chiller capacity control to improve service delivery. It is worth noting that the temperature rate of change can be increased to provide improved load management of the chillers. However, this is likely to compromise improved service delivery.

The temperature control strategies were successfully tested, compared and verified. The temperature prediction model was able to accurately predict the ambient air temperature within an average error of 11.9%. The dynamic temperature set point algorithm adjusted accordingly to meet the desired chiller rate of change.

4.4.4. IGV control

As suggested in Section 3.5.6, the IGVs of the chillers' compressors were controlled to meet a chiller outlet temperature of 3.5°C. The compressors, therefore, operated at partial-load conditions to reduce compressor power consumption.

Figure 4-25 shows the test days actual and calculated refrigerant discharge flow for Chiller 1 utilising the IGV control strategy in Figure 3-15. The quadratic regression model, as tabulated in Table 3-9, precisely modelled the actual refrigerant flow; revealing an average accuracy of 97%. It is clearly evident that the calculated flow emulates the actual flow pattern.

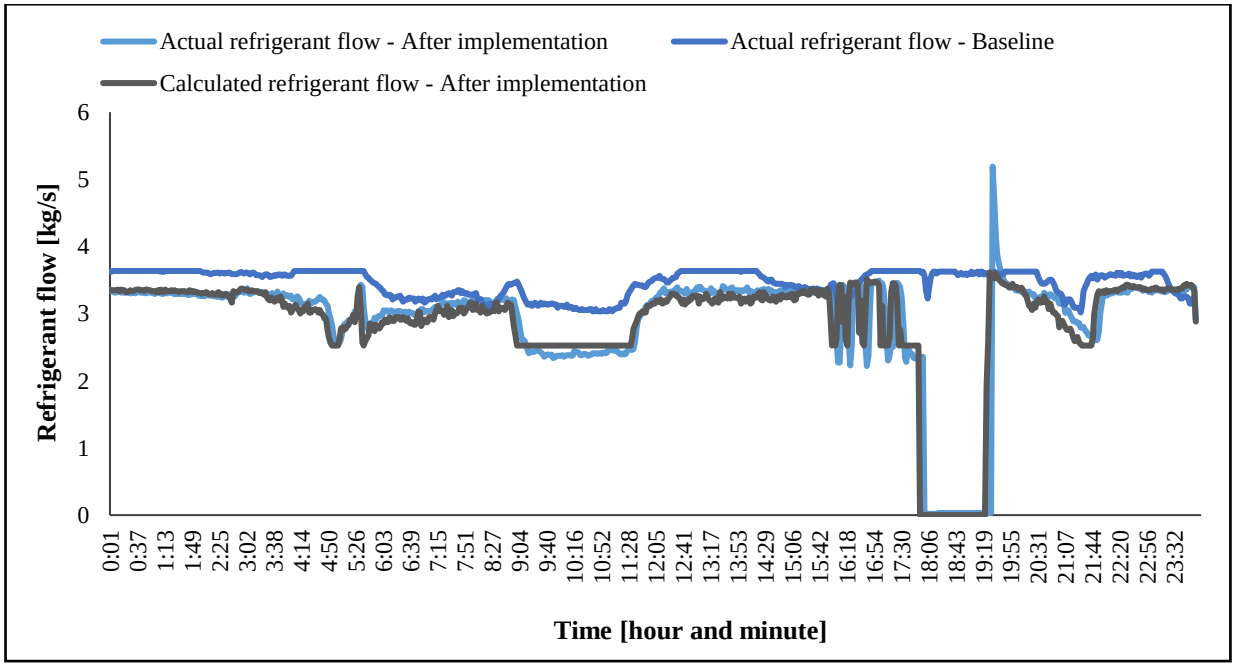

Figure 4-25: Chiller 1's compressor discharge flow - Vaerification of automated strategy

Figure 4-25 reveals that the refrigerant discharge flow was reduced by 0.25 kg/s after implementation to achieve a chiller outlet temperature of 3.6°C. This was marginally above the limit of 3.5°C resulting from

the variable flow control strategy. This alteration influenced the chiller control and heat transfer capabilities in the heat exchanger ducts significantly.

The reduction in refrigerant discharge flow between 18:00 and 20:00 is attributed to optimal chiller control and utilisation during the high electricity costs periods. Substantial dam storage capacity enabled remote chiller stoppages during this period.

As depicted by the actual refrigerant flow for each chiller in Table 4-4, it can be seen that Chiller 1, Chiller 3 and Chiller 4 operate with higher discharge refrigerant flows. Chiller 1, Chiller 3 and Chiller 5 operate with an average actual flow of 2.9 kg/s, 2.5 kg/s and 2.8 kg/s respectively. This, therefore, validates the baseload chiller selection in Section 3.5.7. Also, the discharge refrigerant flow as a result of the IGV control strategy for the six chillers varied between 2.1 kg/s and 2.9 kg/s with a design flow of 2.7 kg/s. This range is directly translated to compressor power reduction as a result of partial-load control.

Inaccurate regression models will result in inexact IGV control. It is suggested that the regression models be regularly updated to adapt with changes in compressor efficiency ratings. This will ensure that accurate compressor discharge flow rates are estimated.

Table 4-4: Chillers' compressor flow regression verification summary

No.	Chiller	Actual flow	Calculated flow	Accuracy [%]
1	Chiller 1	2.9	3	97%
2	Chiller 2	2	2.1	98%
3	Chiller 3	2.5	2.4	94%
4	Chiller 4	2.4	2.6	93%
5	Chiller 5	2.8	2.9	95%
6	Chiller 6	2.1	2.1	98%
Average				**96%**

It should be noted that although Chiller 4 was inoperable during the test period, the actual and calculated flows for Chiller 4 were populated with data that was outside the testing period.

After 14 months of evaluation, it was reported that the IGV opening reduced from 81.2% to 72.9% after implementation. This translated to a 10% compressor power reduction. It is therefore possible to obtain substantial compressor energy savings, while maintaining mine operating requirements.

The performance of the automated cost saving measures were successfully verified using simulations and calculations. The dynamic temperature control regimes adjusted accurately to meet the desired chiller rate of change. An accurate ambient temperature prediction model was formulated and compared, showing little- to no deviation when compared to the actual ambient temperature. The chiller control and characterisation were compared. The chillers were automatically started and stopped to match the start/stop simulation schedules.

4.5. Cost savings impact

4.5.1. Introduction

As mentioned in Chapter 1, South Africa is faced with a challenging socio-economic crisis. To sustain profitability and competitiveness, mines are forced to curtail operational costs. The measures discussed in this study shows lucrative cost savings potential; providing a cost-effective strategy to mitigate some economic challenges. This section will analyse the energy and cost savings impact of such a measure.

4.5.2. Cost-benefit analysis

The hard-commissioning test day results attained an evening load shift saving of 4.7 MW. This translates into a 45.7% load demand reduction between 18:00 and 20:00. This reduction must be deemed economically viable to determine the feasibility of automated cost saving measures. This will ensure that the challenges described in Section 1.5 are mitigated. Table 4-5 illustrates a cost-benefit analysis for the particular test day.

Table 4-5: Summary of electricity cost saving - Test day

Time [hour]	Baseline power [kW]	Power profile [kW]	Scaled baseline power [KW]	Baseline electricity cost [ZAR]	Electricity cost [ZAR]	Cost saving [ZAR]	Cost saving [%]
0	5400	6734	5783	2257	2628	−371	−14%
1	5534	6726	5927	2313	2624	−312	−12%
2	5424	6752	5809	2267	2635	−368	−14%
3	5306	6833	5682	2217	2666	−449	−17%
4	5480	6757	5869	2290	2637	−347	−13%
5	5619	6563	6018	2348	2561	−213	−8%
6	5944	6470	6366	3916	3980	−64	−2%
7	5918	6260	6338	5663	5594	70	1%
8	5924	6395	6344	5669	5715	−45	−1%
9	6069	6638	6500	5808	5932	−124	−2%
10	6268	6638	6713	4129	4083	46	1%
11	6744	6712	7222	4443	4129	314	8%
12	6760	7775	7240	4453	4782	−329	−7%
13	6602	7736	7070	4349	4758	409	−9%
14	6276	7683	6721	4134	4726	−592	−13%
15	6022	7714	6449	3967	4745	−778	−16%
16	5841	6126	6255	3848	3768	80	2%
17	5340	5227	5719	3518	3215	303	9%
18	5225	685	5596	5000	612	4388	717%
19	5116	638	5479	4896	570	4326	759%
20	4945	5183	5296	3257	3188	69	2%
21	5009	5273	5364	3300	3243	56	2%
22	5194	6668	5562	2170	2602	−431	−17%
23	5261	6770	5634	2198	2642	−443	−17%
Avg.	**5717**	**6123**	**6123**	**3684**	**3501**	**4376**	**56%**

The cost-benefit analysis was completed by considering the most recent Eskom Megaflex tariff structure (2017/2018). The summer and winter Eskom Megaflex tariff structures are presented in Appendix D. The electricity cost saving for the particular test day are tabulated in Table 4-5.

Typically, the baseline and power profiles were utilised with the SLA factoring to develop a scaled baseline power profile. The scaled baselines electricity costs were compared with the power profiles electricity costs to calculate the daily costs saving. To calculate accurate cost savings, an average electricity tariff cannot be assumed. Utilising the hourly summer tariff structures, a cost saving of R4 376[6] was calculated. This translated to a 56% cost saving improvement. The seasonal savings can be calculated using a similar method to that described in Table 4-5.

Assuming an average calculated power saving during peak periods of 2.1 MW and 1.8 MW for autumn and spring respectively, typical weekday cost savings can be approximated. These power savings will result in a weekday autumn and spring cost saving of R2 299 and R1 590 respectively.

During winter months, the demand for cooling is significantly reduced. Although, the need to supply chilled water is reduced, the mine cooling system at Mine A is still operational. Mine A is obliged to maintain habitable underground conditions for enhanced productivity. Using a calculated demand saving of 1 MW during peak periods for winter, an estimated weekday cost saving of R4,312 can be realised. The potential cost savings for winter periods is inflated due to the increased Eskom winter tariffs.

The annual seasonal electricity cost savings are tabulated in Table 4-6. The Eskom tariff structures, as discussed in Appendix D, were used to estimate the seasonal cost savings. Due to the implementation of the automated cost saving measures, a total annual cost saving of R900 110 is approximated.

Table 4-6: Summary of seasonal electricity cost savings - Mine A

Season	Peak demand savings [MW]	Electricity cost savings [ZAR]
Summer (Dec - Feb)	2.5	217 784
Autumn (Mar -May)	2.1	190 719
Winter (Jun - Aug)	1	318 445
Spring (Sep - Nov)	1.8	173 162
Total		**900 110**

The implementation of automated cost saving measures requires hardware, software, equipment and specialised labour [36]. These costs are considered to determine the payback period for cost saving initiatives. Therefore, to ensure this strategy is considered viable for implementation on other large-scale industrial cooling applications, a small payback period is preferred. In addition, a strong return on

[6] *Calculated from the Eskom 2017/2018 tariff structure*

investment for the relevant stakeholders will ensure feasible implementation of automated cost saving measures on multiple case studies.

As previously mentioned, the implementation of the automated cost saving measures requires no additional equipment. This, in turn, necessitates no specialised intensive-labour. The automated cost saving measures were implemented with existing mechanical equipment. Therefore, no initial costs were incurred.

As critically discussed in Section 3.3.6, existing hardware was disconnected and disabled. The costs incurred to re-enable the host server and reconnect the OPC connection were negligible. Deleted software was also re-installed at no additional expense. Therefore, no costs were incurred to implement the automated cost saving measures. Machine maintenance, and the costs thereof, can be considered in another study and was therefore not considered for the calculation of the payback period.

Due to no expenses and capital outlay, a payback period of 0 months was established, that is, no payback period is required. This assisted in proving the financial benefit of automated cost saving measures. The automated cost saving measures proved viable for implementation as a generic strategy on other industrial cooling applications with no capital expenditure.

A cost-benefit analyses was successfully compiled. The results were compared to quantify significant cost savings as a result of the automated cost saving measures. No payback period was identified, enhancing the need for such a study in other industries. The sustainability of the cost savings will be discussed in Section 4.6 below.

4.6. Sustainability analysis

4.6.1. Introduction

The sustainability of automated cost saving measures is a critical focus area of this study. The literature suggested that the sustainability of energy saving measures is enhanced by identifying KPIs. KPIs are reported and logged for improved transparency between ESCOs and the client. Therefore, important KPIs will be identified and discussed in the following sections.

The sustainability of automated cost saving measures is a continuous process. Sustainability is therefore considered throughout the project lifespan. Factors leading to performance deterioration or reduced cost saving were continuously evaluated and compared throughout the project lifespan. The sustainability of implementing an automated strategy will be discussed and evaluated.

Performance monitoring and reporting practices will be evaluated. As previously explained, reporting promotes data-driven and thought-provoking decision-making. Effective reporting and monitoring will

enable the stakeholders to identify operational inefficiencies. Performance monitoring and sustainable practices will be investigated to enhance the sustainability of automated control strategies.

4.6.2. Sustainability of automated cost saving measures

Mine A's total cooling system power consumption was observed and reported for a period of 14 months. The reported savings are representative of the actual achieved savings from the automated cost saving measures. The accumulated electricity cost savings and demand savings for the lifespan of the project are indicated in Figure 4-26. The load shift savings represent the combined cooling system savings as a result of the automated cost saving measures. Figure 4-26 also proves the sustainable impact of the automated strategies.

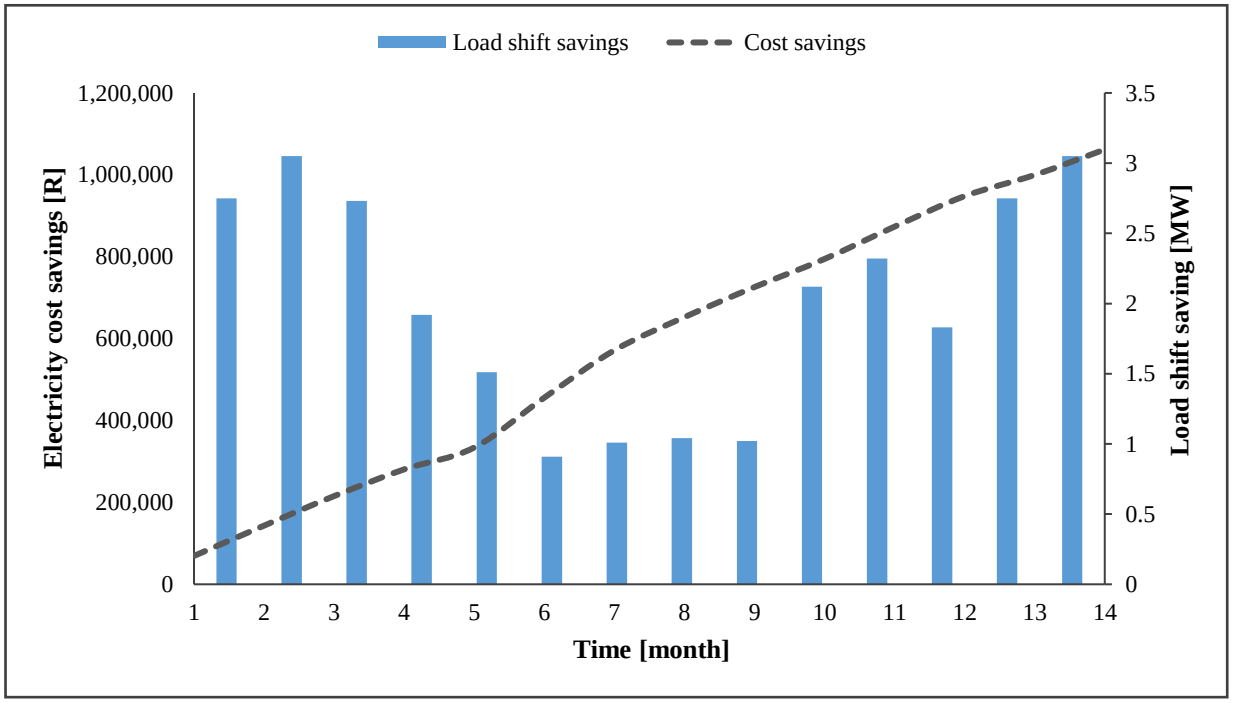

Figure 4-26: Accumulative performance summary of automated cost saving measures

Although the demand savings were reduced significantly during the winter seasons, the automated cost saving measures attained an average power reduction of 1960 kW. This load shift saving was sustained for a period of 14 months. An annual electricity cost saving in excess of R1.1 million, or 13% was attained over a period of 14 months. Coupled with no payback period, a sustainable solution to mitigate operational expenses on mine cooling systems was developed.

A performance assessment (PA) summary from the implementation of an automated dynamic control strategy are tabulated in Table 4-7. An average demand saving of 1960 kW during the peak periods translated to an average electricity cost savings of R227 072 for the five PA periods.

Table 4-7: Performance assessment summary - Mine A

Performance assessment	Peak demand savings [MW]	Cost savings [ZAR]	Saving % of target
PA 1	2.4	215 374	34%
PA 2	2.1	240 457	14%
PA 3	1	270 064	−45%
PA 4	1.8	221 073	1%
PA 5	2.5	188 392	41%
Average	**1.9**	**227 072**	**9%**

Excluding the performance of the project during the winter months would result in an additional demand saving of 492 kW (22% improvement). The project performed over the expected target of 1.8 MW by approximately 9%. Reasons for the project over-performance can be accredited to automated control strategies and improved chiller control and utilisation. The results obtained from the implementation of the automated cost saving measures has attained favourable and sustainable results.

4.6.3. Sustainable system performance

In Section 4.6.2, the sustainability of cost savings from the implementation of automated control strategies was discussed. The effects, however, on the impact of service delivery requirements must be quantified. Performance parameters such as dam levels, flow rates and temperatures were considered. The performance parameters were compared to ensure optimal working conditions. The automated control strategies were required to sustain habitable working conditions at reduced life cycle expenses to remain financially feasible.

Table 4-8 tabulates the impact of the automated strategies on certain operational parameters. An average over-improvement of 11% was calculated. The operational parameters were operating close to DEM specifications. Implementation of the automated cost saving measures has revealed a sustainable improvement in service delivery requirements.

Table 4-8: Combined sustainable system performance - Mine A

PA	CCD temp [°C]	39L cold dam temp [°C]	BAC air outlet temp [°C]	HCD level [%]	CCD level [%]	Flow to underground [ℓ/s]	Average % of design limit
PA 1	6.3	6.3	5.7	74.2	78.3	132.3	10%
PA 2	6.5	6.8	6.1	73.8	81.7	120.7	8%
PA 3	5.4	5.5	5.3	79.3	75	128.5	15%
PA 4	5.8	5.9	5.6	76.8	74.4	164.4	9%
PA 5	6.2	6.2	5.6	72.5	77.4	124.3	12%
Avg.	**6.1**	**6.1**	**5.7**	**75.3**	**77.4**	**134**	**11%**

It is suggested that an additional study be conducted to investigate the monetary value of improved service delivery improvements (%/ZAR). This does not form part of the scope of this study and will not be discussed in this dissertation.

4.6.4. Performance monitoring and sustainable practices

The application of reporting serves as a crucial tool for improved sustainability on mine cooling systems. As suggested in the literature, KPIs are identified, monitored and reported to reduce underperformance. Integrated sustainable practises must be adopted by the relevant stakeholders to ensure the sustainability of the project. Although, automated control on mine cooling systems (Mine A) has resulted in sustainable savings (as illustrated in Sections 4.6.2 and 4.6.3), it is essential to maintain theses automated systems.

Changes in system constraints or technical specifications must be communicated to the ESCO to make the necessary alterations to the EMS. The control inputs will affect the control outputs to the relevant PLCs. Automated control, however, realised sustainable savings without reporting and monitoring. This is a huge milestone for the industrial sector.

As part of the requirement from the mine personnel, a daily report was established. The daily report provided essential information that assisted the section engineers and control technicians in making ad hoc decisions. The daily report was also utilised for M&V purposes by the independent M&V team. The M&V only requires the report to verify the reported load shift savings to Eskom.

As a part of the new DSM model, the ESCO is also responsible for maintaining the performance of the project for a three-year period. This pre-requisite of the newly adapted DSM model is utilised to promote sustainability. The daily report will assist the ESCO in sustaining the performance of the automated cost saving measures. The ESCO will also be informed of control issues that can be promptly mitigated.

Although the reporting requirements for each stakeholder varies considerably, a daily report that includes the needs of all stakeholders was prepared. The daily report was set up to automatically notify all of the user recipients. The daily report was set up to include:

- Operational KPIs (chiller COP, pump efficiencies, cold dam temperatures, machine flow rates and dam levels);
- Maintenance schedules and methodologies;
- Demand impact (load shift savings);
- Cost savings; and the
- Health status of EMS (OPC connection, automatic control permissions, etc.).

The application of performance monitoring and sustainable practises is important for maintaining the performance of automated cost saving measures. KPIs will be continuously re-evaluated to ensure the correct and accurate content is reported. A daily report provides a unique solution to ensure sustainable

practises are implemented. The impact of no sustainable reporting can be investigated in an additional study and therefore does not form part of the scope of work for this dissertation.

Automated control has lucratively impacted sustainable savings on mine cooling systems. Although, the automated strategies over-performed without a daily report, a daily report will assist in identifying system changes. The integrated daily report was deemed beneficial for the client, ESCO and independent M&V team.

In summary, the sustainability of the automated cost saving measures were investigated. A daily report was compiled to evaluate daily KPIs. Mine A's combined sustainable system performance was evaluated and compared.

4.7. Conclusion

The automated cost saving measures were implemented, tested and critically compared. M&V of the implementation results was performed to formulate an applicable baseline and SLA factor. The sustainability of implementing this automated dynamic control strategy on mine cooling systems was also assessed and investigated.

The simulation software package, PTB, verified the impact of the automated cost saving measures. The test- and simulated profiles were compared; an overall average error of 4% was realised. PTB accurately predicted the impact of the automated cost saving measures. The implementation results were verified and validated.

A systematic approach to implement automated cost saving measures on mine cooling systems was discussed. The performance results of the automated cost saving measures were thoroughly evaluated and compared. The results revealed sustainable load shift savings for a period of 14 months.

An average load shift savings of 1960 kW was attained for the performance assessment periods. This equated to an accumulative electricity cost saving of R1.1 million. The project performed over the expected target by approximately 10%, resulting in an operational efficiency improvement of 15%. The automated dynamic control model, when compared to existing control practises, also attained a chiller COP improvement and compressor power reduction of 7% and 4% respectively. A sustainable solution to mitigate operational expenses with improved mine cooling system performance was developed.

The sustainable impact of automated cost saving measures on mine cooling systems was quantified. Sustainable reporting requirements were also established to ensure complete transparency between all of the stakeholders. The impact thereof was also investigated.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

[7]

This chapter serves as a conclusion that summarises the findings of the study. Recommendations are provided to assist with future research and improvements to the automated control strategy. Herein includes a set of limitations and future research objectives that can be investigated and evaluated.

[7] *Photograph courtesy of Planet KB, http://www.planetkb.co.za/portfolio-detail.php?Mining-Photography-4*

5.1. Preamble

An automated dynamic control philosophy for sustainable cost savings on mine cooling systems was developed, implemented, tested and commissioned. The automated cost saving measures were verified and validated to evaluate the sustainable impact. The strategies realised significant sustainable load shift savings and improved operational performance.

This chapter summarises and reviews the study findings. The limitations of the study are exposed, and recommendations for future studies are suggested and discussed.

5.2. Summary of this study

Financial instability in the mining sector was identified as a significant motive for reduced productivity. Coupled with increased operational costs (labour and electricity), South Africa was faced with a challenging socio-economic crisis. To remain financially competitive, mines were forced to restructure and retrench employees.

Mine cooling systems were recognised as the largest energy-intensive consumer. Ventilation and refrigeration consume approximately 28% of the total allocated electricity for deep-level gold mines. Therefore, mine cooling systems were identified as an important system to consider for cost savings.

The implementation of cost saving policies was proven to be a viable solution. These initiatives revealed prosperous peak time reductions in electricity demand, but with very little focus to the sustainability thereof. It was found that a need existed for an automated dynamic control strategy, utilising a simple and practical control approach on energy-intensive deep-level mine cooling systems. The dynamic control model was developed by utilising a holistic systems approach to achieve sustainable cost savings and improved mine cooling system performance.

A deep-level mine cooling system, at Mine A, with previously implemented energy saving measures was identified. A detailed summary of existing control optimisation techniques on Mine A's cooling system were recognised. The automated dynamic control strategy for sustainable cost savings was developed, tested, simulated and implemented.

The dynamic control strategy attained a weekday evening load shift saving of 4.7 MW. This represented an 86% reduction in power consumption between 18:00 and 20:00. The simulation software package, PTB, was utilised to develop a calibrated simulation model of Mine A's cooling system. The accuracy of the simulation package, PTB, was quantified. PTB accurately predicted the impact of the automated cost saving measures. The test- and simulated profiles were compared; an overall average error of 4% was realised.

Implementation of the automated cost saving measures achieved an average summer load shift saving of 2.5 MW. Various performance KPIs were evaluated and monitored to quantify the performance impact of implementing automated cost saving measures. The strategy revealed a compressor power reduction and COP improvement of 4% and 7% respectively.

Integrated performance monitoring and sustainable reporting practises were recognised and considered. Important KPIs were identified and included in a daily report. Integration of the daily report and the automated cost saving measures revealed sustainable load shift savings for a period of 14 months. A sustainable solution to mitigate operational expenses on mine cooling systems was developed.

The average weekday load shift savings of 1960 kW achieved during the performance assessment periods translated to an electricity cost saving of R1.1 million. Case study results revealed a 15% improvement in operational efficiency; an added benefit of this control strategy.

Implementation of an automated dynamic control strategy facilitated mines to reduce operating costs and sustain profitability for improved competitiveness. There was a need to reduce operational costs to mitigate long-term challenges such as underperformance and sustainability.

The strategy was demonstrated to be simple and likely adaptable to other industrial sectors. It is apparent that an integrated dynamic control approach, with sustainability as the core focus point, shows significant potential in the South African mining industry.

5.3. Limitations of this study

The principle limitation of this research study was that the control strategy was only implemented on one mine through a single case study. The research study findings and results are only true for Mine A. Other mines have diverse characteristics, components and limitations that may result in different behaviours. However, implementation of the automated control model can be extrapolated to other case studies for thorough comparisons to validate the impact of an automated dynamic control model.

The secondary limitation of this study is the type of cooling system used. The automated dynamic control model was only applied to a surface cooling system. This study did not examine the impact of automating underground mine cooling systems. Underground cooling systems operate independently of surface cooling systems and often include dewatering. Although previous studies have been completed on underground mine cooling systems, there is scope to examine the implementation of automated cost saving measures on underground mine cooling systems.

A further limitation of this study is the broadness of the scope. Although mine cooling systems are considered energy-intensive, other industrial cooling systems require investigation. This study did not

analyse the impact of implementing an automated dynamic control model to other industrial cooling systems. It is suggested that the control model, as discussed in Figure 3-6, be utilised to achieve sustainable cost savings on other industrial cooling systems. Although most cooling systems display similar traits and operating principles, this research study did not investigate trends pertaining to other industrial cooling systems.

5.4. Recommendation for future work

State-of-the-art initiatives have been developed to sufficiently meet different cooling demands. The literature revealed that many research studies have focused on energy efficiency practices and the implementation of load shift strategies during Eskom's evening peak period. A research study should be performed to investigate the impact of a morning load shift strategy during Eskom's morning peak period of 07:00 to 10:00 in summer and 06:00 to 09:00 in winter.

Although this study dynamically analysed the cooling system requirements, as discussed throughout the strategy compilation, the impact of the strategy on the morning peak period was not included within the scope of study and therefore not discussed in the results.

Other deep-level gold mines tend to operate differently with diverse system constraints and limitations. Implementation of the automated cost saving measures can be extrapolated to other case studies for thorough comparisons to validate the impact of the study. Development of a generic control strategy that is compatible to a diverse range of case studies can be explored and reviewed. The results can be compared to this study to further validate the impact and versatility of this automated control strategy.

It is suggested that the automated dynamic control model be extrapolated for use on other industrial cooling systems. This study did not investigate the sustainable impact of automating other industrial cooling processes, equipment and systems.

The methodology described in this paper fell short of investigating optimisation techniques centred around the condenser process. A need for an integrated control approach to improve the condenser performance temperature range still exists, without increasing the compressor lift and reducing the COP.

Furthermore, the literature revealed, that although the implementation of automated cost saving measures on mine cooling systems has realised lucrative cost savings, a research study that investigates the impact of automating integrated mine operations has not been considered. It is therefore suggested that the sustainable impact of automating compressed air operations, water supply networks and dewatering systems be explored for integrated control management.

The focus of this study was to develop an automated dynamic control philosophy and methodology for sustainable cost savings on mine cooling systems. The results from the study attained significant service delivery improvements. It is suggested that a research study be compiled to investigate the monetary value of service delivery improvements (%/ZAR) as a result of the implementation of automated cost saving measures.

The literature also revealed that the application of performance monitoring and sustainable practises is important for maintaining the performance of cost saving measures. A daily report provided a unique solution to ensure sustainable practises were implemented. Although a daily report was established, the impact of the daily report was not quantified. A study or model quantifying the value of reporting can be explored for completeness.

As a part of the control strategy, a maintenance schedule was considered. Component maintenance periods were evaluated and agreed upon by the relevant stakeholders. Addressing maintenance costs, however, was not considered within the scope of this dissertation. It is suggested that the impact of implementing an automated dynamic control strategy and the maintenance costs associated thereof, be explored and quantified.

To alleviate increasing operational costs throughout the industrial sector, it is suggested that industry adopts automated cost saving measures. This will contribute to alleviating the growing financial instability in the sector. Reducing operational costs will, therefore, ultimately support the economy by increasing the GDP and proactively contributing to the socio-economic development of South Africa.

5.5. Recommendation to stakeholders

Recognising the value of automated cost saving measures, not only in the mining industry but also in South Africa, is critical for the sustainability and competitiveness of the industrial sector. Implementing such strategies has equipped the mine personnel with opportunities to reduce operational expenditure, free up labour capacity by increasing automation, and providing overall improvements in productivity.

The implementation of automated cost saving measures, with sustainability as the critical focus point, has surfaced opportunities to enhance service delivery and has driven thought-provoking decision-making. Adopting the recommended system strategies can equip stakeholders with the ability to pre-empt dynamic system responses and to act proactively to circumvent them.

In conclusion, although this control strategy was validated on one case study, it is apparent that there is scope for the implementation of this strategy on other mine cooling systems and even other industrial cooling sectors. Given the significant cost savings (in excess of R31 million for 30 deep-level gold mines in South Africa), there should also be an appetite to implement the recommended measures and invest in

further research or additional case studies. As these optimisations reach critical mass, South Africa's industrial sector can begin to compete at the global level required of successful enterprises.

Although, gold is considered a finite resource, the ability to mine this resource in a profitable manner will improve South Africa's income revenue and credibility globally. People involved in the industrial sector should align their objectives with reducing operating costs and maximising profitability. Implementation of automated cost saving measures has realised significant potential in this regard.

CHAPTER 6: LIST OF REFERENCES

[8]

This chapter provides a summary of the various citations used within this dissertation. The list of references summarises the relevant authors, titles and locations that will assist the reader in finding the sources.

[8] *Photograph courtesy of Planet KB, http://www.planetkb.co.za/portfolio-detail.php?Mining-Photography-4*

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CHAPTER 7: APPENDICES

Appendix A: Technical specifications

Table A-1: Mine A's surface cooling system specifications

Combined cooling system	
CCD temperature [°C]	5
HCD temperature [°C]	20
CCD level [%]	75
HCD level [%]	75
Water sent underground [Mℓ/day]	15
Combined cooling capacity [kW]	39 000
Combined nominal COP [-]	5.7
Chillers (individual units)	
Compressor type [-]	Centrifugal
Refrigerant type [-]	R-134a
Evaporator outlet temperature [°C]	3
Condenser inlet temperature [°C]	25
Evaporator water flow rate [ℓ/s]	250
Condenser water flow rate [ℓ/s]	450
Nominal cooling capacity [kW]	6 500
Nominal COP [-]	5.5
Heat absorption towers	
BACs	
Water outlet temperature [°C]	9
Water inlet temperature [°C]	5
Air outlet wet-bulb temperature [°C]	7
Air inlet wet-bulb temperature [°C]	22
Water flow rate [ℓ/s]	250
Air flow rate [kg/s]	250
Number of BACs [-]	3

Auxiliary pumps	
Evaporator pump motor rating [kW]	110
Condenser pump motor rating [kW]	160
BAC return pump motor rating [kW]	75
Pre-cooling pump motor rating [kW]	70
Transfer pump motor rating [kW]	40
Number of evaporator pumps [-]	6
Number of condenser pumps [-]	6
Number of BAC return pumps [-]	3
Number of pre-cooling pumps [-]	2
Number of transfer pumps [-]	2
Heat rejection towers	
Pre-cooling towers	
Water outlet temperature [°C]	25
Water inlet temperature [°C]	30
Air inlet wet-bulb temperature [°C]	22
Water flow rate [ℓ/s]	360
Air flow rate [kg/s]	300
Number of pre-cooling towers [-]	2
Condenser towers	
Water outlet temperature [°C]	27.5
Water inlet temperature [°C]	31
Air inlet wet-bulb temperature [°C]	22
Water flow rate [ℓ/s]	450
Air flow rate [kg/s]	270
Number of condenser towers [-]	6

Appendix B: Automated start/stop control logic for a trimming chiller

Figure B-1 illustrates the start and stop control logic for the automated cost saving measures. This sequence of control inputs was programmed into the EMS to initiate correct control outputs to the PLCs. It is essential that the chiller start and stop procedures are valid before a chiller is automatically started or stopped. An alarm notification will be initiated if a chiller did not automatically start or stop.

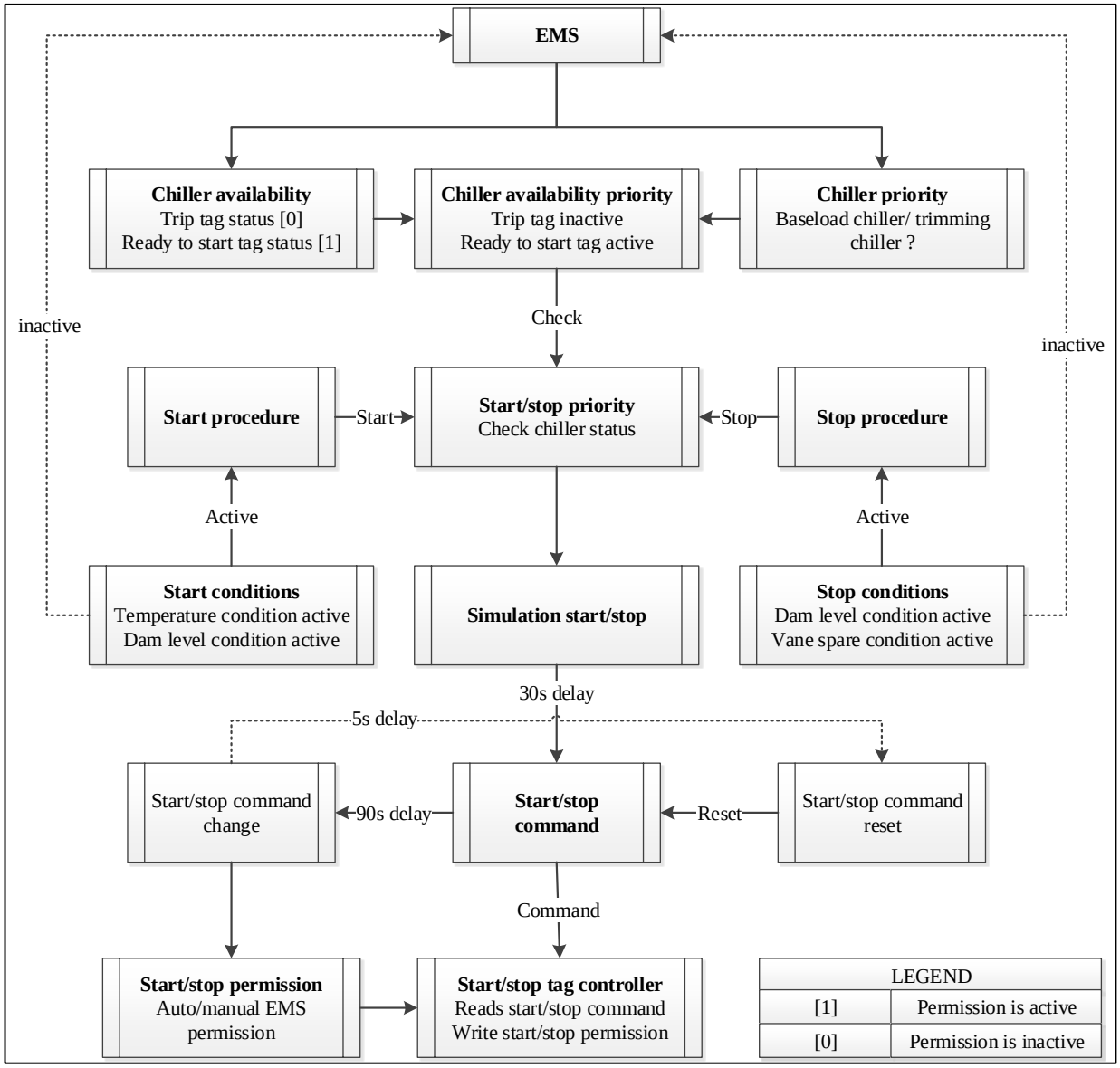

Figure B-1: Start/stop control logic for a trimming chiller

Appendix C: Calibrated PTB simulation model

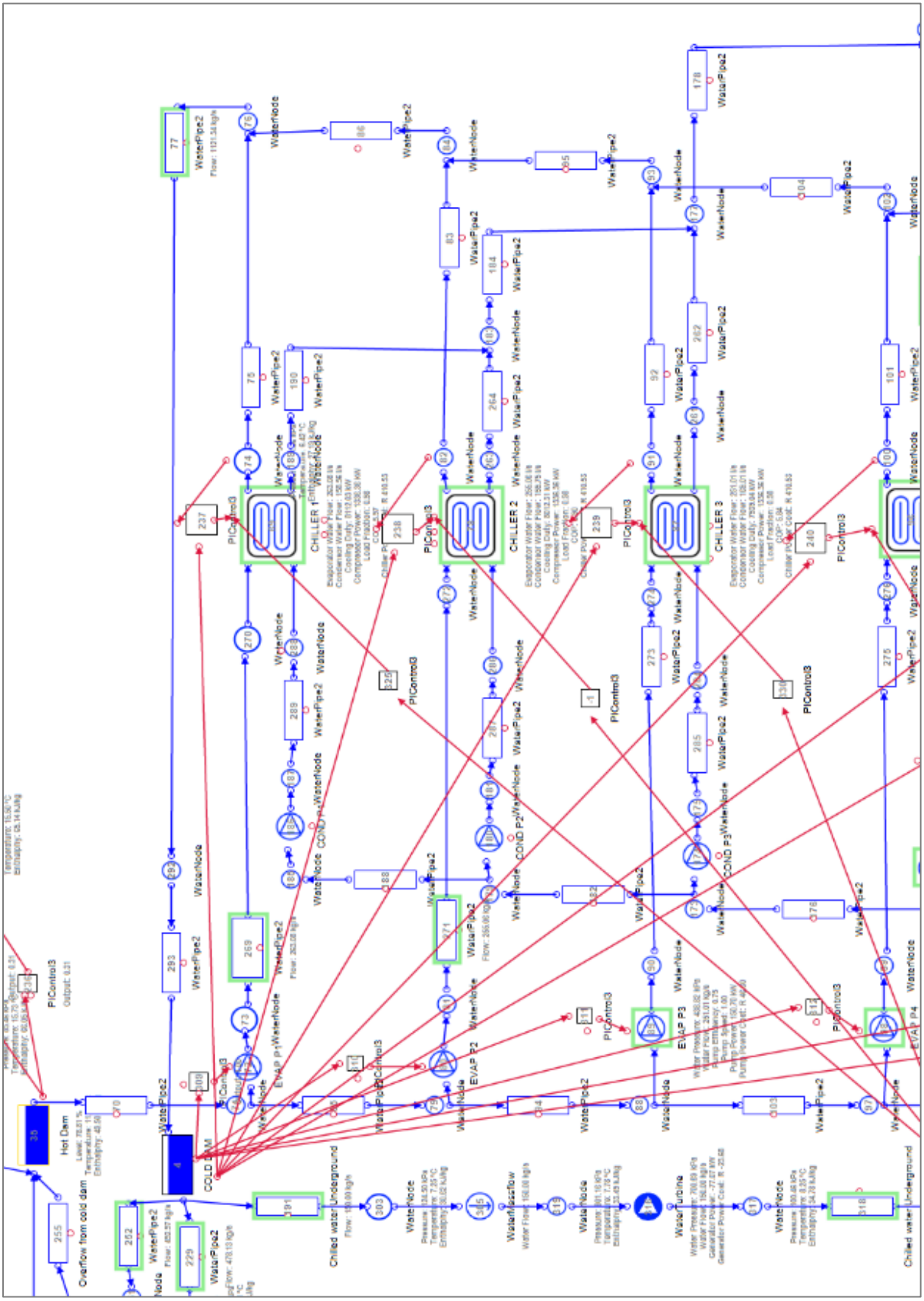

Figure C-1: Mine A's calibrated PTB simulation - Chillers configuration

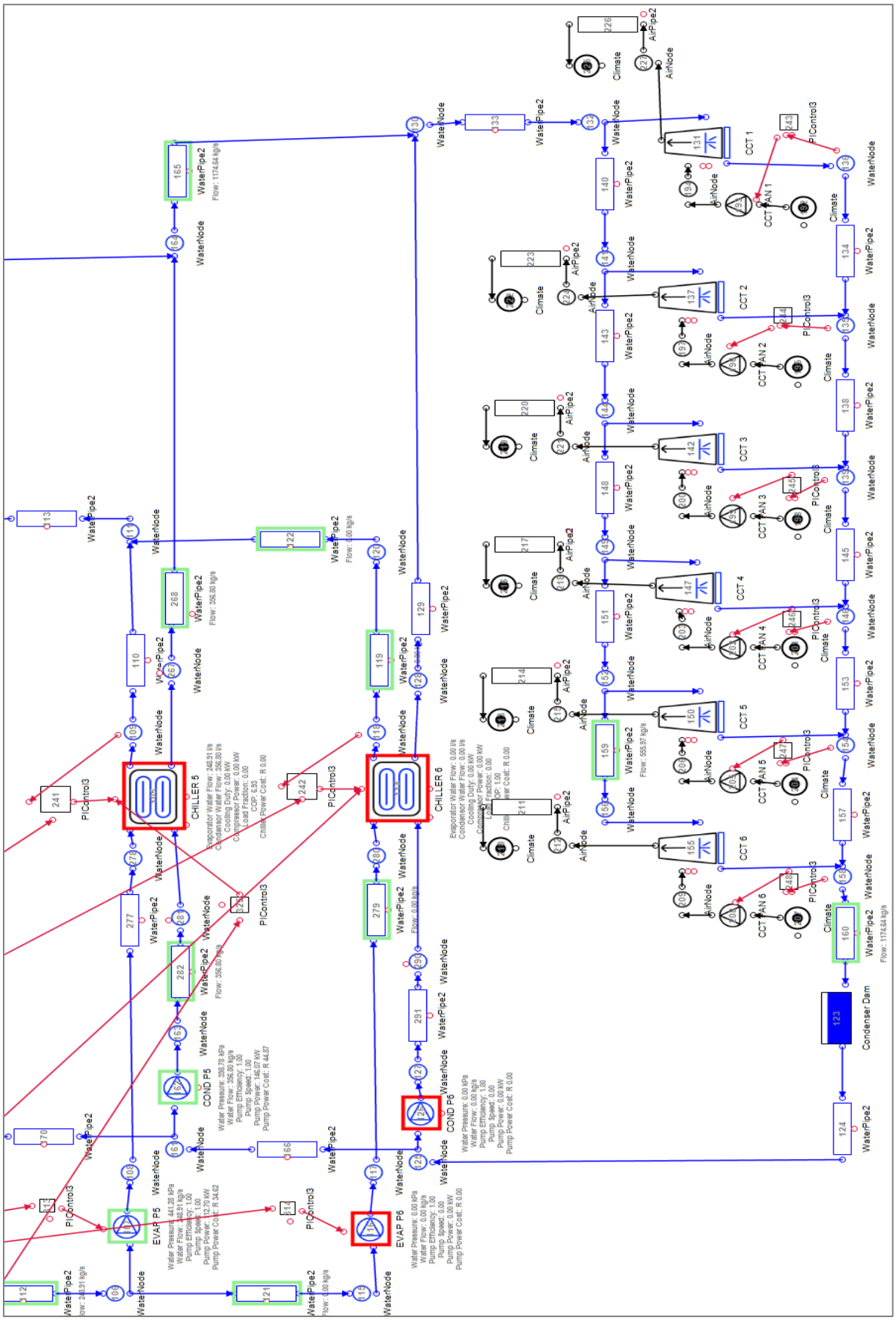

Figure C-2: Mine A's calibrated PTB simulation - Condenser towers configuration

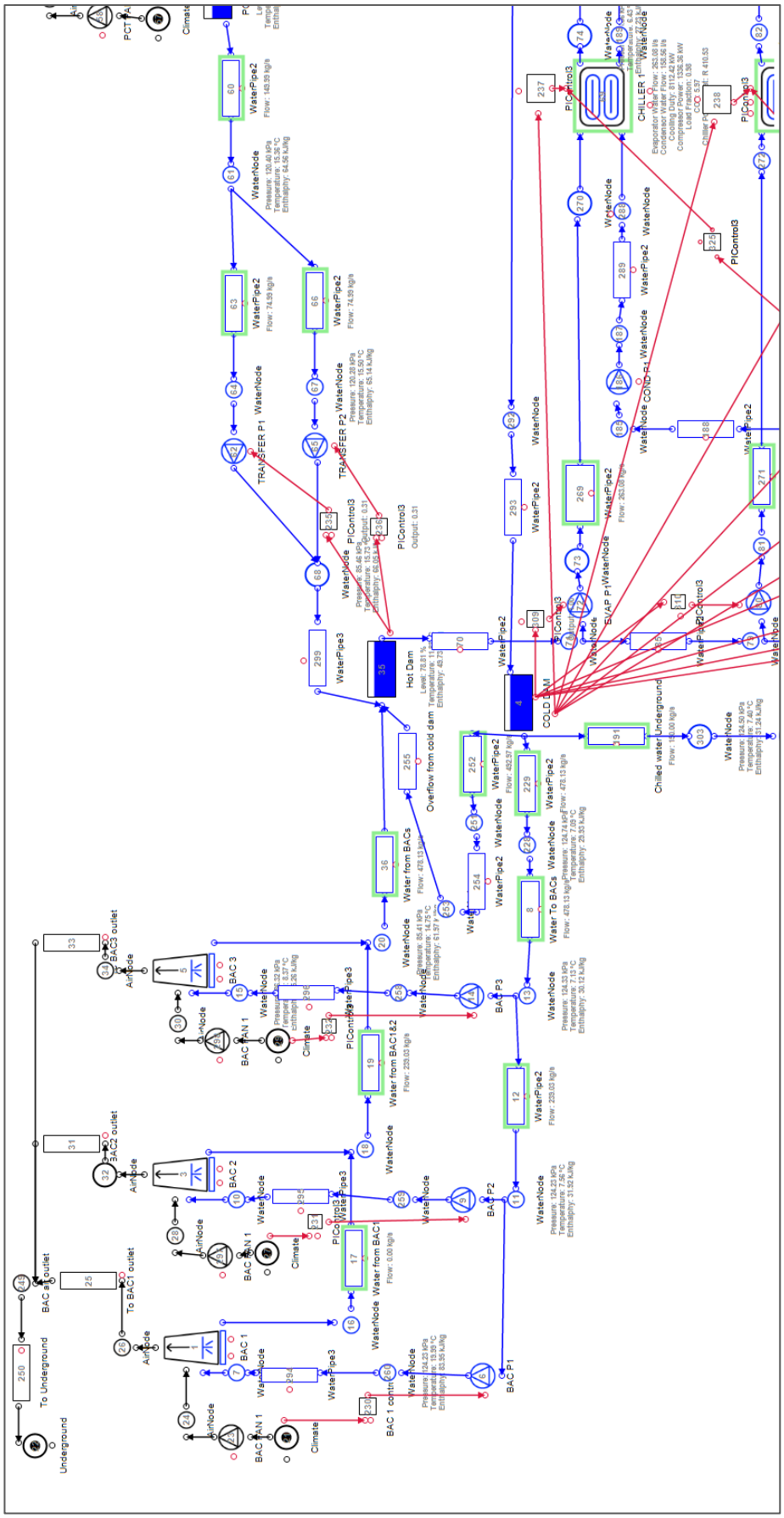

Figure C-3: Mine A's calibrated PTB simulation - BACs configuration

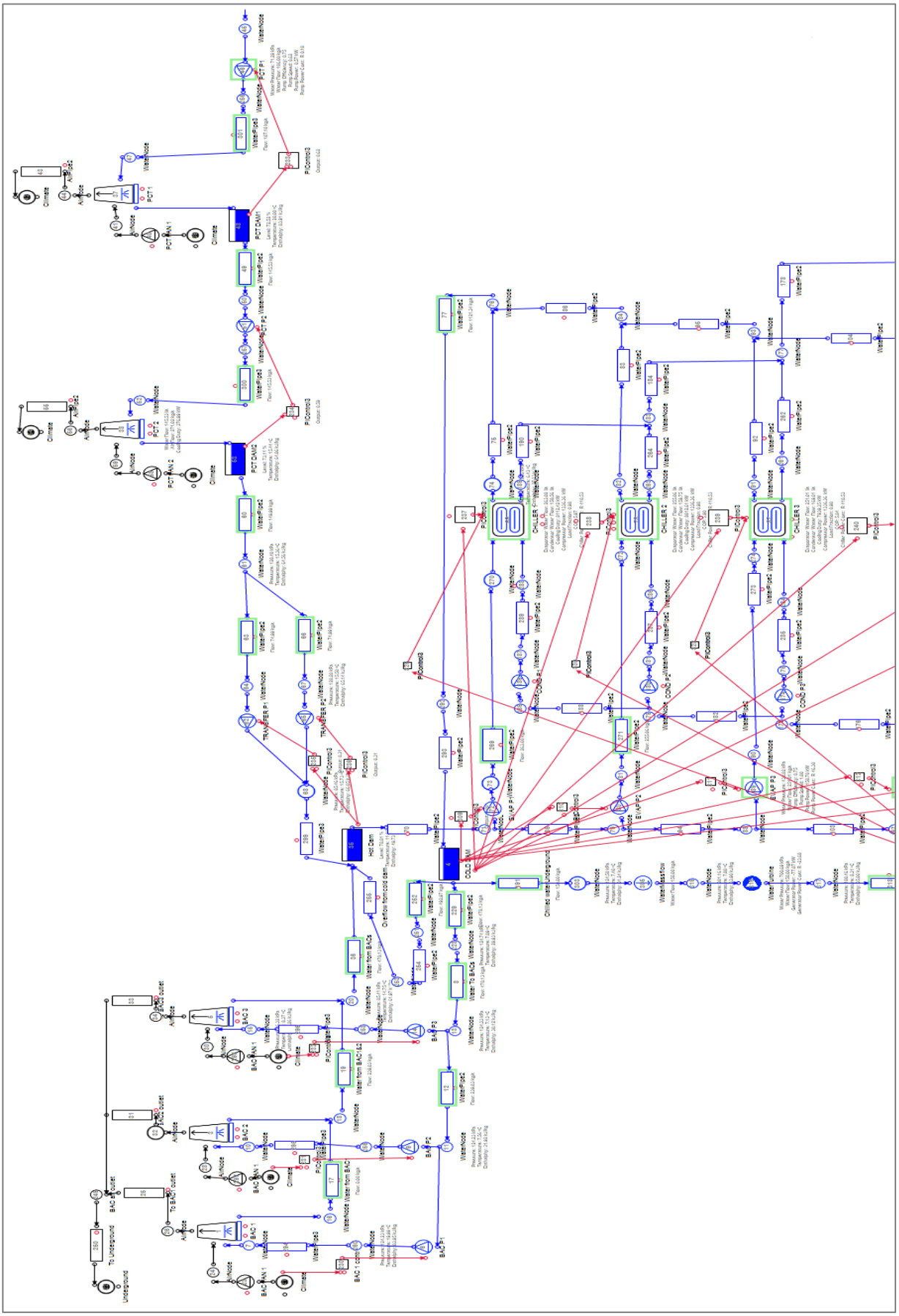

Figure C-4: Mine A's calibrated PTB simulation model - Part 1

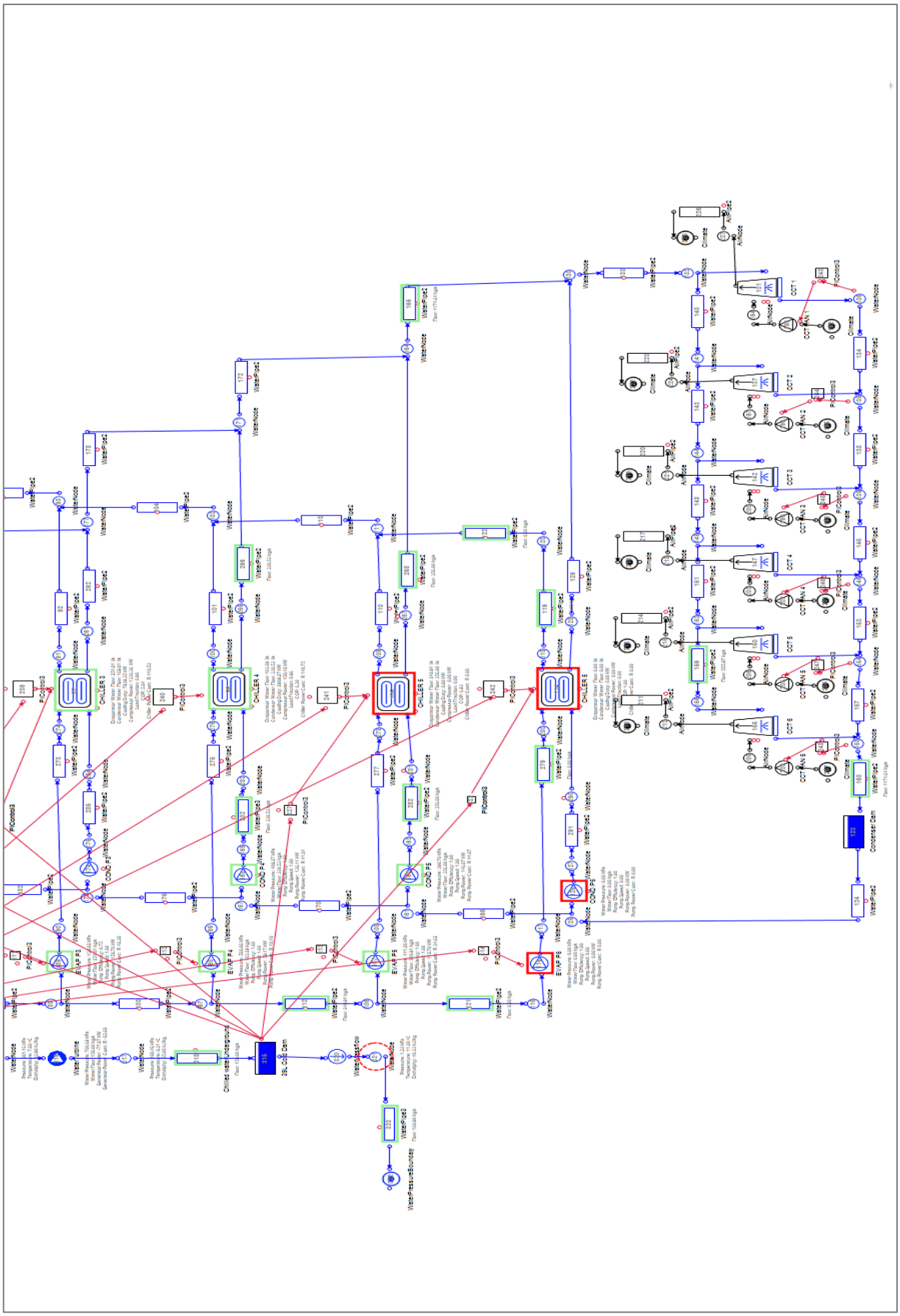

Figure C-5: Mine A's calibrated PTB simulation model - Part 2

Appendix D: Eskom's Megaflex tariff structure

Eskom's seasonal 2017/2018 Megaflex tariff structures are tabulated in Table D-1. The tariff structure is altered depending on the weekday TOU period. The electricity cost savings (seasonal or test day) for the automated cost saving measures are calculated from the electricity tariff structure presented in Table D-1.

The tariff structure is determined by identifying the distance of the transmission zone and the voltage range of the substation. The tariff structures utilised a transmission zone and voltage range of ≤ 300 km and between ≥ 500 V & < 66 kV respectively. It should also be noted that the most up-to-date tariff structures was utilised.

Table D-1: Eskom's seasonal 2017/2018 Megaflex tariff structure and TOU

Time [Hour]	Summer electricity tariff [c/kWh]	Summer TOU [-]	Winter electricity tariff [c/kWh]	Winter TOU [-]
0	39.02	Off-peak	45.07	Off-peak
1	39.02	Off-peak	45.07	Off-peak
2	39.02	Off-peak	45.07	Off-peak
3	39.02	Off-peak	45.07	Off-peak
4	39.02	Off-peak	45.07	Off-peak
5	39.02	Off-peak	45.07	Off-peak
6	61.51	Standard	273.96	Peak
7	89.36	Peak	273.96	Peak
8	89.36	Peak	273.96	Peak
9	89.36	Peak	83	Standard
10	61.51	Standard	83	Standard
11	61.51	Standard	83	Standard
12	61.51	Standard	83	Standard
13	61.51	Standard	83	Standard
14	61.51	Standard	83	Standard
15	61.51	Standard	83	Standard
16	61.51	Standard	83	Standard
17	61.51	Standard	273.96	Peak
18	89.36	Peak	273.96	Peak
19	89.36	Peak	83	Standard
20	61.51	Standard	83	Standard
21	61.51	Standard	83	Standard
22	39.02	Off-peak	45.07	Off-peak
23	39.02	Off-peak	45.07	Off-peak