




Optimal utilization of a three-chamber pipe feeder system

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ABSTRACT

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South African gold production is decreasing year-on-year. This can be attributed to numerous challenges faced by the gold mining industry. One of these challenges is high operating costs of which electricity forms a large portion. This is especially due to the electricity intensive nature of the gold mining industry, inefficient use of electricity and the aggressive rate of electricity price increases in South Africa. However, unlike most of the other challenges faced by this industry, this portion offers large potential for improvement.

A large number of energy savings initiatives have been implemented over the years on the electricity intensive systems of gold mines. One of these systems is the water reticulation system because of its large potential for improvement in terms of electricity consumption and cost. The problem, however, is that maximised benefits are often overseen, especially with the implementation of multiple initiatives on this system. Specific reference is made to a three-chamber pump feeder system (3CPFS), which is an energy efficiency initiative that influences the performance of the load management initiatives.

The main cause of the 3CPFS influencing the performance of load management initiatives was identified as the lack of integrated control between the sub-systems of the water reticulation system. These sub-systems include the 3CPFS, dewatering and refrigeration systems. A need was therefore identified to develop an integrated control philosophy to optimally utilise the 3CPFS to improve the performance of load management initiatives on the other two sub-systems.

A water reticulation system of a South African deep-level gold mine (Mine A) was identified for the implementation of optimised strategies. Mine A has a 3CPFS installed and load management initiatives were implemented on both the refrigeration and dewatering systems.

The performance of the load management initiatives was negatively influenced by the operation of the 3CPFS, which made the water reticulation system of Mine A an ideal case study for the implementation of optimised strategies.

A step-by-step methodology was followed to develop a control philosophy that would integrate the operation and control of the 3CPFS with the other two sub-systems. The main focus with the control philosophy was to maximise the cost savings potential on the water reticulation system without negatively affecting the operational parameters of the system, hence influencing production.

A verified simulation model proved the feasibility of the developed control philosophy in terms of complying with the operational limitations. The control philosophy was therefore implemented by incorporating it within a real time energy management system at Mine A. For redundancy, the control room operators were also provided with adequate training to manually implement the control philosophy in the case of emergencies.

Mine A realised an average load shift of 6.3 MW on its water reticulation system with the optimised control philosophy. This was an improvement of 4.8 MW from the performance prior to implementation. This accumulates to a financial cost saving of approximately R4.4 million per annum. It was also proven that the operational parameters were not influenced by the control philosophy, which also validated the accuracy of the predicted results through simulation. All in all the optimal utilisation of a 3CPFS in a water reticulation system was proven.

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LIST OF ABBREVIATIONS

Abbreviation	-	Description
3CPFS	-	Three-Chamber Pipe Feeder System
BAC	-	Bulk Air Cooler
CA	-	Cooling Auxiliaries
CL	-	Comeback Load
DSM	-	Demand Side Management
EE	-	Energy Efficiency
ESCO	-	Energy Saving Company
FP	-	Fridge Plant
L	-	Level
LM	-	Load Management
LS	-	Load Shift
Ltd	-	Limited
Max	-	Maximum
Min	-	Minimum
M&V	-	Measurement and Verification
P	-	Pumping
PC	-	Pre-Cooling
PES	-	Pressure Exchange System
PL	-	Preparation Load

PTB	-	Process Toolbox by TEMM International
Pty	-	Proprietary
R	-	South African Rand
REMS	-	Real Time Energy Management System
RFT	-	Rock Face Temperatures
RH	-	Relative Humidity
SCADA	-	Supervisory Control and Data Acquisition
TOU	-	Time-of-use
VSD	-	Variable Speed Drive

LIST OF SYMBOLS

Symbol		Description
%	-	Percentage
&	-	The word 'and'
<i>a</i>	-	Pump pressure curve coefficient
<i>C</i>	-	Partial load
CCR	-	Cooling capacity rating
COPR	-	Coefficient of performance rating
E_m	-	Pump efficiency
dP	-	Pressure difference
<i>m</i>	-	Mass flow rate
<i>N</i>	-	Pump speed fraction
<i>P</i>	-	Pressure
P_{power}	-	Power
<i>p</i>	-	Density
RefCD	-	Reference cooling capacity rating
<i>T</i>	-	Temperature

LIST OF UNITS

Unit		Description
°C	-	Degrees centigrade
g/ton	-	Grams per ton
km	-	Kilometre
kV	-	Kilovolt
kW	-	Kilowatt
ℓ/s	-	Litres per second
MVA	-	Megavolt ampere
MW	-	Megawatt
MWh	-	Megawatt hours
R/kg	-	Rand per kilogram

LIST OF TERMS

Term	Description
Electrical Energy	The electric charge that enables work to be accomplished.
Electrical Power	The rate at which electrical energy is transferred by an electric circuit.
Electricity	The flow and presence of an electric charge.
Demand Side Management	Electrical saving method that is usually implemented by an ESCO and funded by Eskom to positively influence the consumption patterns of national electrical users.
Fissure water	Water that comes from underground cracks and accumulates in the mine's water reticulation system.
Pumping head	The maximum vertical height to which a pump can displace water.
Rock face temperatures	Temperature of the underground rock surfaces.
Stopes	An incline that is formed by mining ore from vertical or steeply inclined vanes that contain valuable minerals.
Time-of-use	Structure implemented by Eskom to bill customers certain amounts during certain hours of the day.

CHAPTER 1

1 Introduction

1.1 South African gold production

South Africa was the number one producer of gold until China took the acclaimed number one spot in 2009. According to Naingo, South Africa is currently fifth in the world in terms of gold production. There are many factors to consider when establishing the exact cause of the production decline. According to research, the main contributing factor is the exhaustion of high grade gold deposits [1].

Gold ore grade in South Africa declined from 12 grams per ton (g/ton) in 1970 to approximately 5 g/ton during 2016 [2]. From 1970 to 2001, annual gold production in South Africa declined from 1000 tons to a mere 395 tons [3]. With the decline in gold production, profit margins of gold mines also narrow. Figure 1 shows the decline in gold production for South Africa from 1990 to 2014 [4].

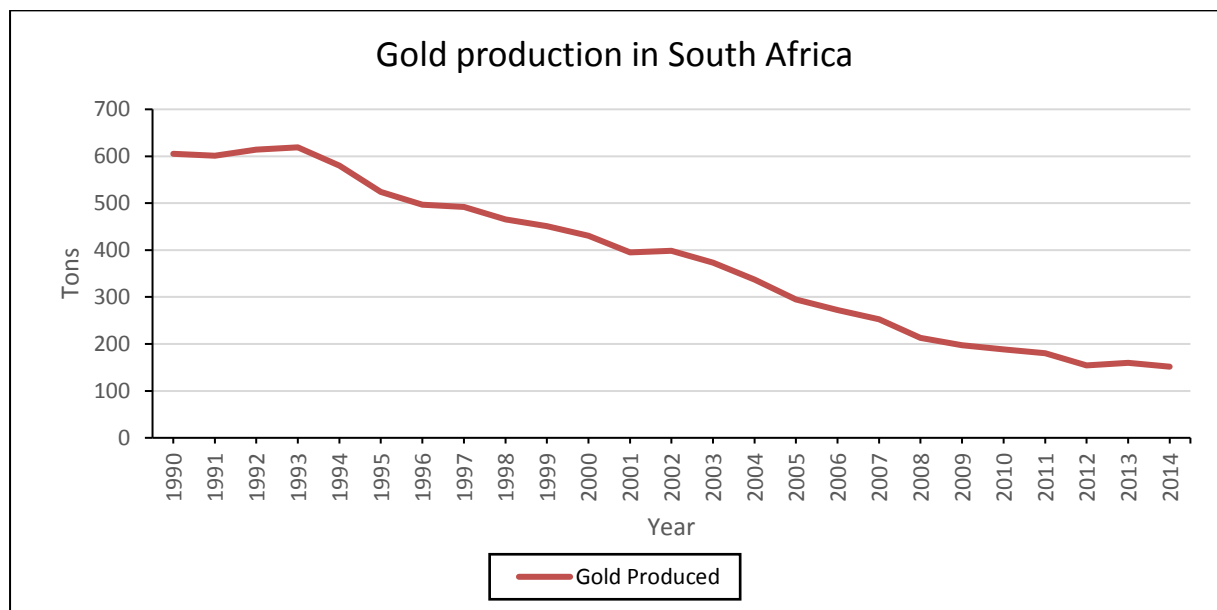


Figure 1: South African gold production trend [4]

In the past few years many other external factors played a role in the profitability of gold mines. These factors mainly include fluctuating gold prices, strikes and electricity price increases [1]. Figure 2 shows the constant fluctuation in the gold price in R/kg [5]. Although mining companies are familiar with commodity price volatility, the fluctuating gold price greatly

influences economic growth [6]. Deloitte used China as an example as it was clear how their economic growth declined with the decline in gold prices [6].

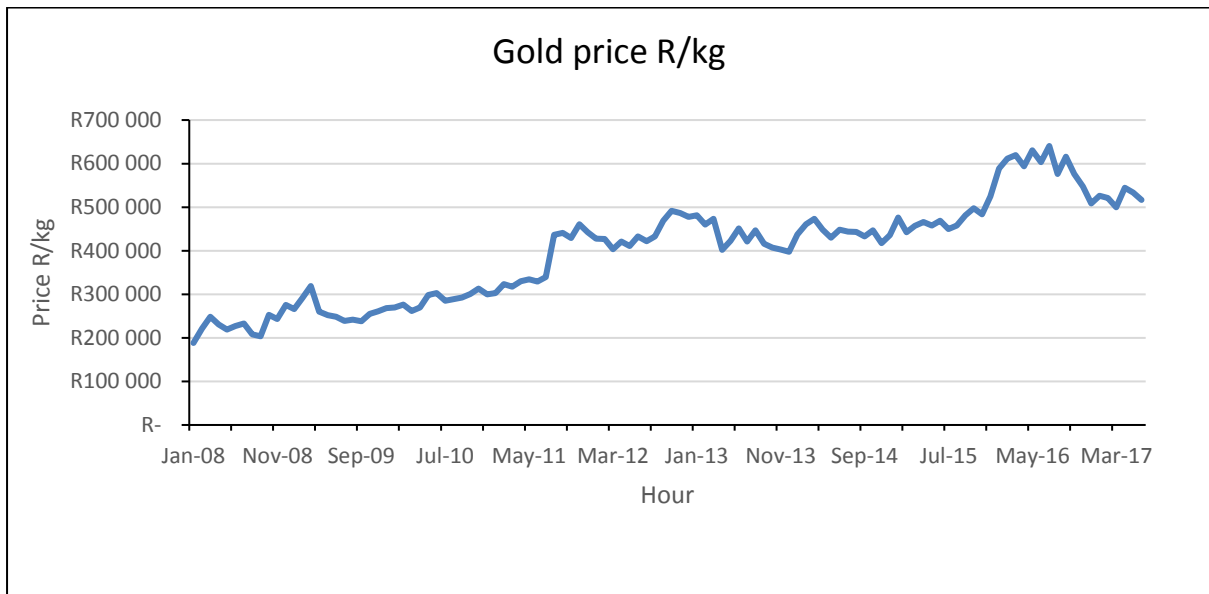


Figure 2: Gold price in R/kg [5]

Over the last few years, many miners have partaken in national strikes over salary disputes. With labour costs comprising 40-60% of the total operating costs of an underground mine, it is clear why the result of these disputes can heavily influence gold production costs [7]. This is, however, not the only concern for mines in South Africa [1].

The ever-increasing electricity prices in South Africa are causing large headaches for mines [8]. Over the last five years, the cost of electricity has increased by an average of 14% per annum [8]. This has forced mines to make cost saving initiatives a priority. Figure 3, adapted from Eskom Holdings, shows the increase in electricity costs for the mining industry in South Africa [8].

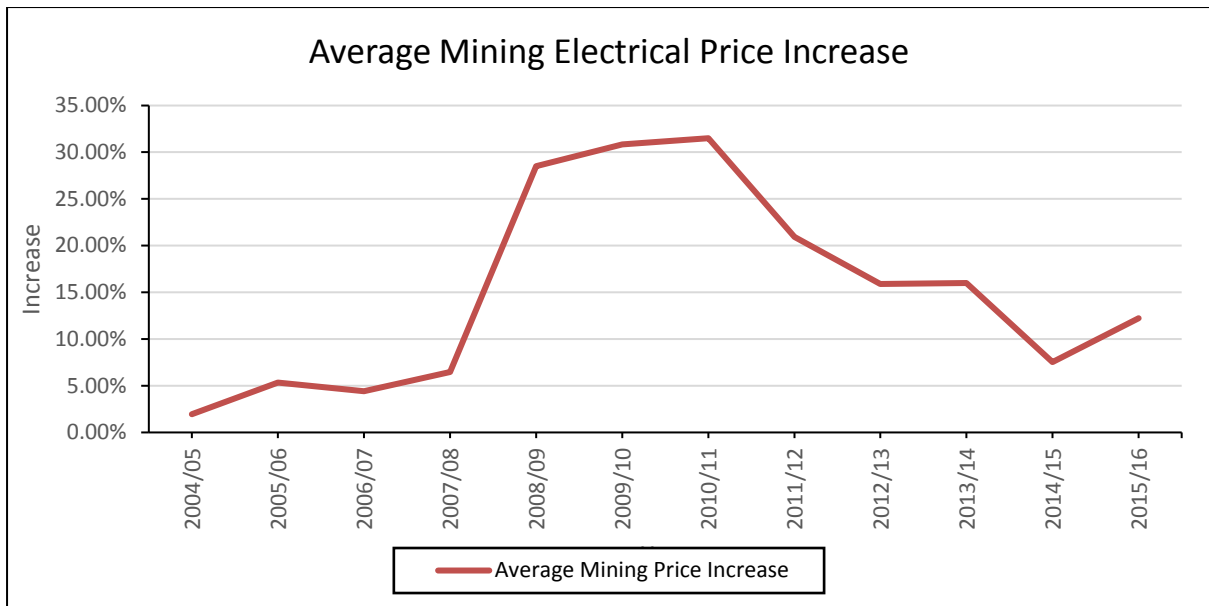


Figure 3: Average mining electrical price increase [8]

Gold mines use large equipment, which is electricity intensive. It is, therefore, natural for these mines to explore new ways to reduce electricity costs. Mines are unable to do much about gold prices, ore grades and strikes, but they can change their electrical consumption patterns. This caused mines to turn their focus to electricity usage.

The biggest consumers of electricity on a typical underground gold mine are winders, compressors, pumps, fridge plants (FP) and ventilation fans. The refrigeration and dewatering systems form part of the water reticulation system that makes up 34% of the mine's electrical demand [9]. As this is one of the largest consumers, it is the best place to start optimising.

1.2 Deep-level mine water reticulation systems

1.2.1 Preface

Deep-level mine water reticulation systems are highly important for mining activity and the health and safety of mine employees. The water reticulation system typically consists of the following integrated systems:

- Refrigeration
- Dewatering

Each system is discussed in more detail below.

1.2.2 Refrigeration

Chilled water from the refrigeration system is used to cool machinery and several mining processes. It is also used by the Bulk Air Coolers (BACs) to reduce underground temperatures. The dewatering system, on the other hand, removes used water from underground and prevents flooding [10].

The deeper an underground mine is, the higher the temperatures and risk of heat stroke for the mineworkers [11]. Current regulations state that deep-level mines should maintain wet-bulb temperatures below 32.5°C in the stopes and 27.5°C on the stations [12]. For this reason, mines use refrigeration systems to remain below these legal limits [12].

Refrigeration systems on large gold mines may typically require 1000 ℓ/s to cool underground environments to a certain set point. The amount of cooling required, however, differs from mine to mine and typically ranges between 40–50 MW [13]. It depends on different factors such as rock face temperatures (RFT), average ambient temperatures and the size of the mine. These systems consume approximately 19% of a typical gold mine's total electricity consumption [9].

1.2.3 Dewatering

Deep-level mines need to displace high volumes of water from great depths all the way to the surface [14]. This makes dewatering an extremely electricity intensive system due to the head that needs to be overcome [14]. Typically, a cascading system is used to reduce the pumping head on a single pump station stage [15]. Dewatering pumps consume approximately 15% of a gold mine's total electricity [9].

Each level usually transfers between 100 and 500 ℓ/s of water, depending on the amount of water sent underground and the amount of fissure water in the system [9]. The installed capacities of the dewatering pumps usually vary between 1 MW and 3 MW, depending on the system requirements [9].

1.2.4 Integration

The refrigeration and dewatering systems are usually interconnected (Figure 10). The chilled water from the chillers is sent to the BACs, as well as to a surface chill dam [13].

From the chill dams the water is sent underground to the required sections and transferred to the settlers after use [15]. The water is cleaned and the dewatering pumps are used to pump the water back to the surface, where the cycle repeats itself [15]. The amount of chilled water sent underground therefore directly influences the amount of water that needs to be dewatered. This in turn influences the power consumption of the dewatering pumps.

In an attempt to reduce the operating cost on the water reticulation system, numerous Load Management (LM) initiatives have been implemented on the above-mentioned systems. These initiatives mainly target the ever-increasing electricity prices [7]

The previous sections provided background on these individual systems as well as the integration to form the water reticulation system of a gold mine. Considering that the water reticulation system consumes approximately a third of the mine's total electricity, it is natural to assume that numerous methods have been investigated in the past to reduce cost on electricity consumption [9]. The next section focuses on the existing methods to achieve this.

1.3 Energy cost savings on water reticulation systems

Due to the vast amount of electricity used by mining and industrial companies, Eskom introduced the time-of-use (TOU) structure [15]. This bills customers different amounts for the quantity of electricity used at different times of the day [16]. Customers who have a notified maximum demand of more than 1 MVA fall into the Megaflex tariff structure. Mines are typical clients of this structure [16].

The Megaflex structure has three TOU periods: off peak, standard and peak. Eskom charges differ for the three periods. The charges change as the season changes, line size differs as well as with the client's distance from Johannesburg, South Africa [16]. Figure 4 indicates the prices of a Megaflex client with a 6.6 kV line within 300 km of Johannesburg [17]. Please refer to Appendix A for the winter and summer time schedules for the Megaflex tariff structure.

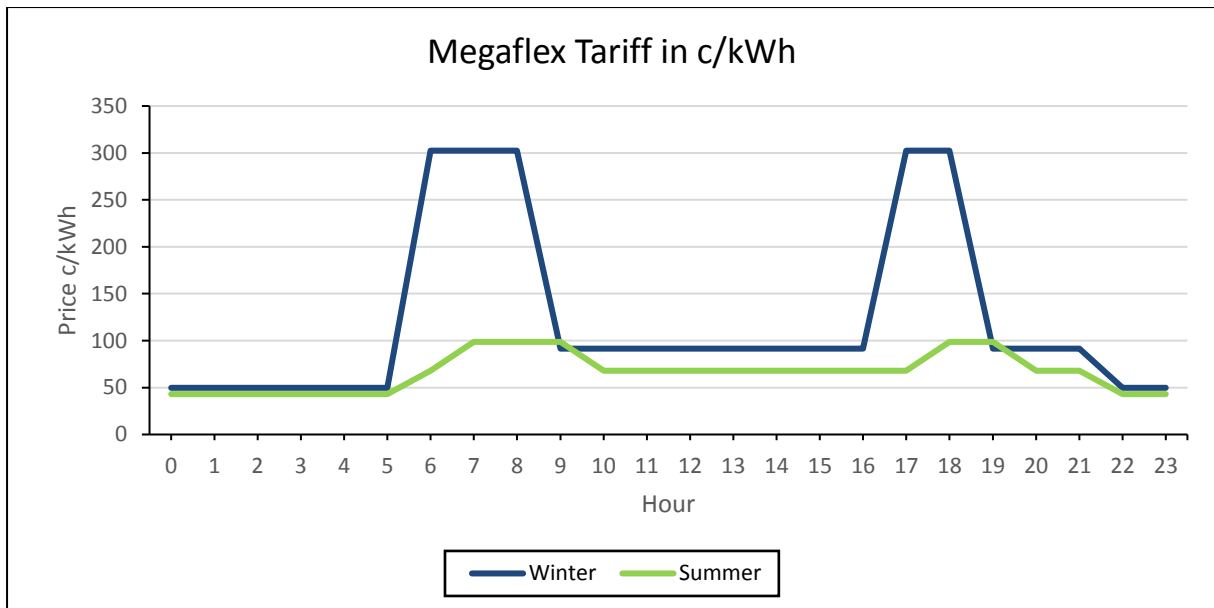


Figure 4: 6.6 kV Megaflex tariff within 300 km of Johannesburg

South Africa was in an energy crisis during 2008 due to a delayed decision by the Government to invest in new power plants [18], [19]. Demand side management (DSM) was introduced to help lighten the demand of electricity so Eskom could still supply the country [20].

1.3.1 Load management initiatives

The TOU structure was implemented to motivate industrial and mining companies to lower their electrical consumption during the peak times [15]. Load shifting was implemented as a DSM tool to assist these companies with lowering their electrical demand in peak times. The aim was not to use less electricity during the day, but rather to shift the load to less expensive times [21]. This is beneficial to both parties as Eskom will have more capacity during peak times and the client will pay less for electricity [22].

Figure 5 is an example of a load shift, with an average of 3.4 MW and 3.6 MW shifted during morning and evening peaks, respectively. The demand is reduced during the peak times and a total of 17.4 MWh has been shifted.

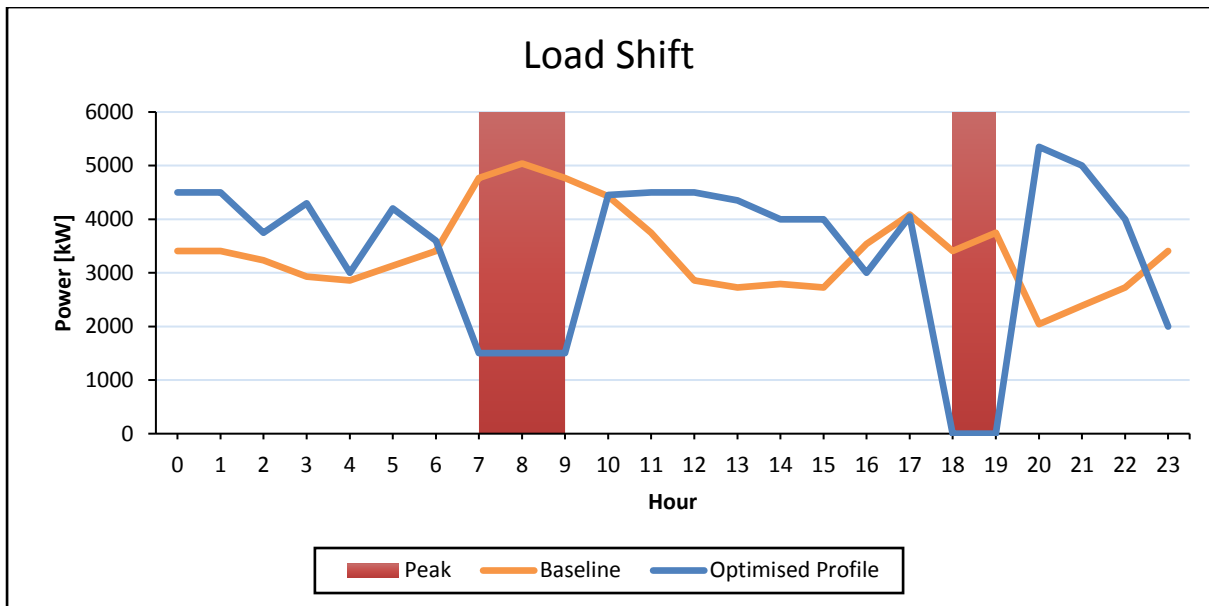


Figure 5: Load shift

With DSM initiatives to save costs identified, ESCOs were approached to implement it as the mines did not have the time, skill or resources to do it [23]. Prinsloo defines an ESCO as “a company that investigates, develops, installs and finances projects designed to improve the energy efficiency and maintenance costs for facilities over a period of seven to ten years” [24].

Before a load shift can be implemented on a dewatering or refrigeration system, the preparation load (PL) and comeback load (CL) must be investigated [15]. The increase in energy usage before peak to prepare a system for a load shift is defined as the PL. The CL is the increase in energy after the fact to get the system back to normal working conditions [15].

Dewatering and refrigeration systems usually have load shift initiatives implemented on them, as mines tend to have large dams underground and on surface. ESCOs investigate the possibility by calculating whether their dams can handle the PL and CL [24]. When refrigeration and dewatering systems are automated, they are controlled either by the mine’s SCADA (supervisory control and data acquisition) or energy management systems [15]. The energy management system is used to control the dewatering and refrigeration systems.

One example of an energy management system is a REMS (real time energy management system). There is a different REMS platform for each system. A REMS controls the pumps and fridge plants by taking the dam levels, water flows, temperatures and time of day into account. By analysing these parameters, it schedules the number of pumps or fridge plants during the

day. The REMS then send signals to start or stop the equipment to match the schedule. Figure 6 is an example of the REMS pumping platform controlling pumps on a mine.

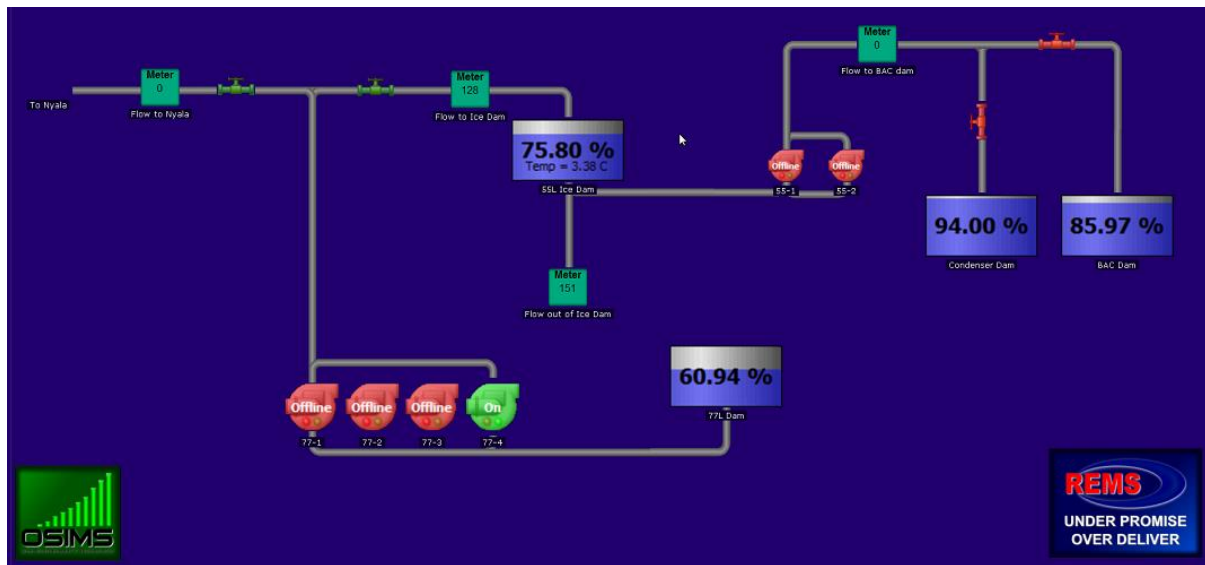


Figure 6: REMS pumping

With the background of load management, the energy efficiency (EE) components will be discussed in the section below.

1.3.2 Energy efficiency initiatives

This initiative's objective is to reduce the daily overall electrical consumption of the client [25]. This will lower the electrical demand of the client as well as cut costs. Figure 7 shows an example of an energy efficiency power profile. The decrease in power is a constant 500 kW for the entire 24-hour period.

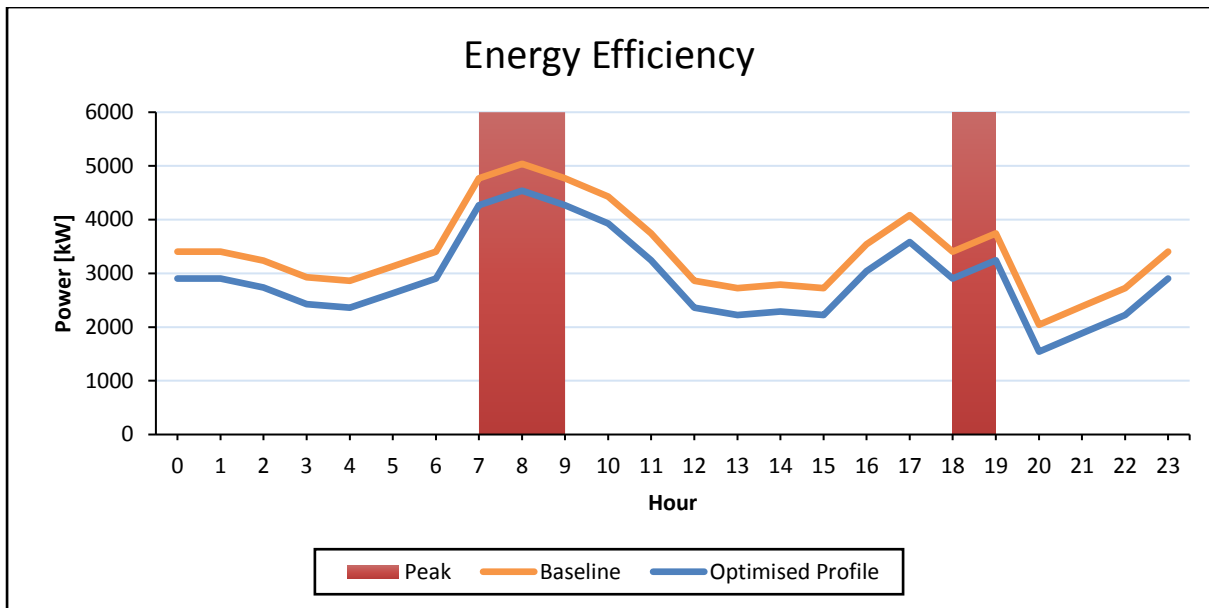


Figure 7: Energy efficiency

With a typical efficiency of 80%, dewatering pumps have always been an ideal solution for the mines [26]. But as mentioned above, dewatering pumps on deep-level mines consume high amounts of electricity [27]. With the constant increase in electricity costs, mines have been looking for a way to move greater volumes of water, but using less energy [28]. There are a few systems to increase the EE of the dewatering system, such as turbines, Pelton wheels and the 3CPFS. The 3CPFS will be discussed as it is not only important for this study, but also the best EE system for the mines [28].

Figure 8 is a schematic representation of the 3CPFS as adapted from JJ Botha [29]. The “3” in the 3CPFS comes from the number of chambers that are in the different stages of pressure [29].

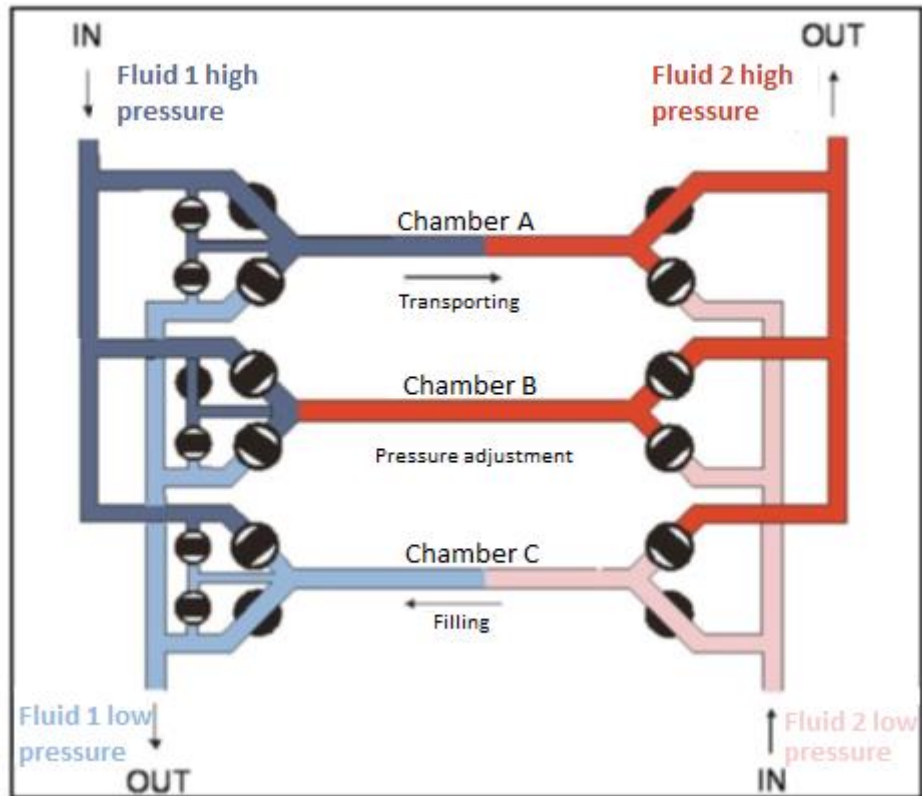


Figure 8: Schematic representation of the 3CPFS [29]

The mining industry uses the 3CPFS to circulate the water in the reticulation system [30]. Potential - or pressure energy, together with two small filler pumps, is used from the chilled water on surface to displace warm water from underground to the surface [29]. The warm water is then cleaned, pumped, cooled and reused in the system.

This specific 3CPFS displaces about 400 ℓ/s at a vertical distance of 1400 m and uses approximately 800 kW of electricity to do it [30]. The 3CPFS displaces the same amount of water as two conventional multistage centrifugal pumps with an installed electrical capacity of 2.5 MW over the same vertical distance. This can be translated to a high component of energy efficiency on the daily dewatering pumping power profile. Figure 9 displays the typical impact a 3CPFS has on a conventional dewatering pump's power profile.

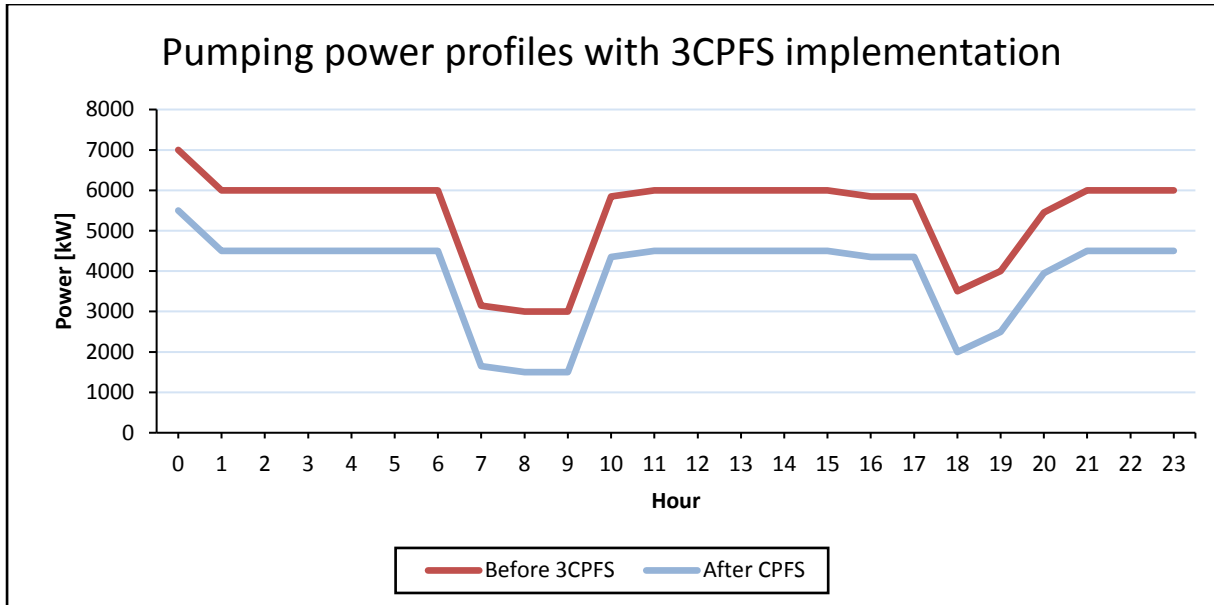


Figure 9: Pumping profile with 3CPFS implementation

To get the best results, LM and EE initiatives sometimes need to be integrated and this will be discussed in the section below.

1.3.3 Integration of initiatives

The dewatering and refrigeration systems both form part of the integrated water reticulation system on a mine as they use the same water. As discussed in 1.2.4, the water reticulation system is more complicated than it seems. With so many parts influencing each other, it is evident that the control of the water reticulation system is more complex than just switching on and off certain machines at certain times. This is especially difficult when the focus is to save costs with DSM projects and there is a 3CPFS in the middle of the system. Figure 10 shows how intricately the systems can be interconnected and thus drastically influence each other on a mine.

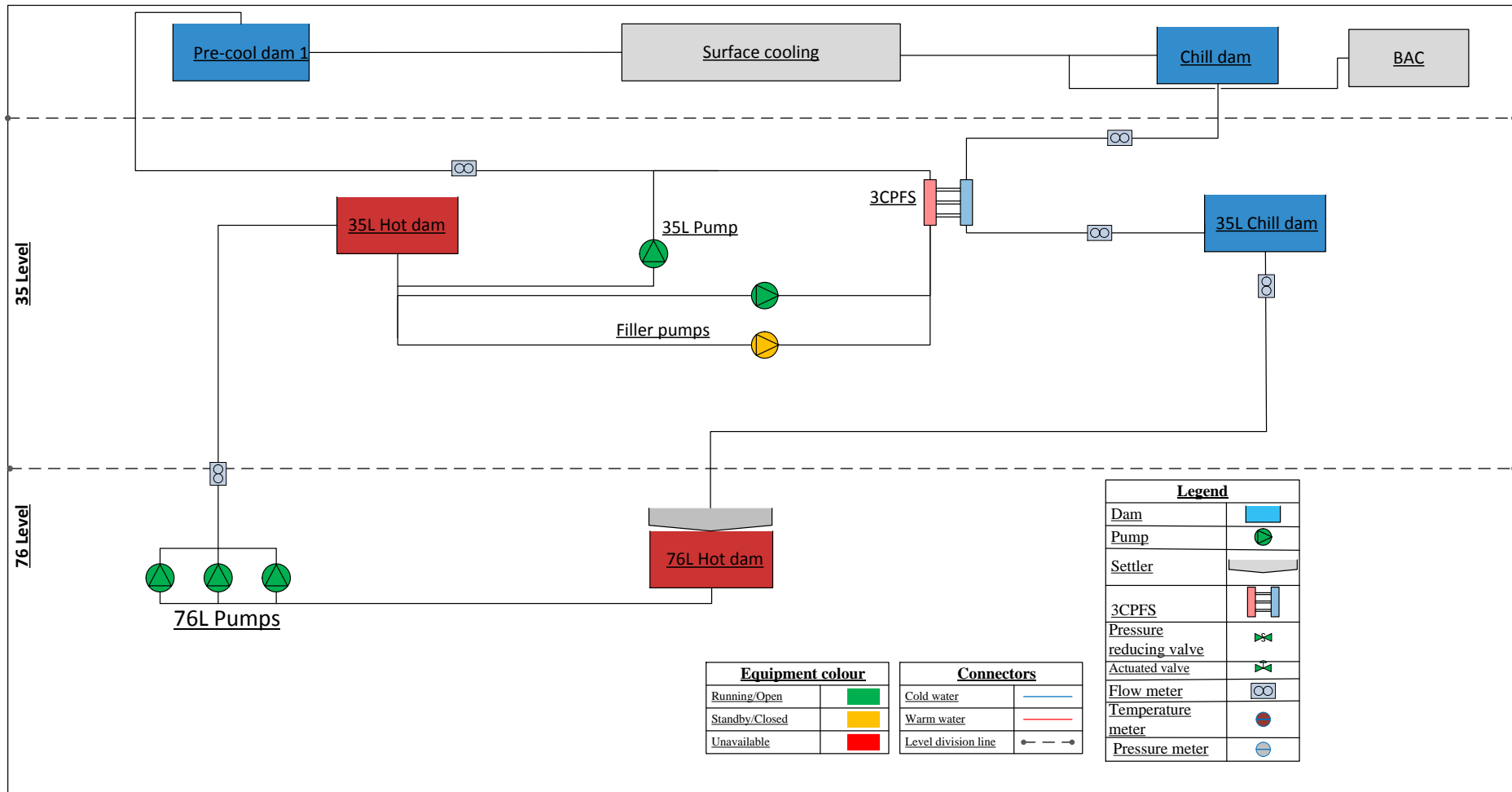


Figure 10: Water reticulation layout

With a capacity to move 300 ℓ/s and a recorded efficiency as high as 93% [31], it is hard to believe that the 3CPFS can have any negative aspects. The negative side to the 3CPFS in this case is, however, one of the characteristics that make it so appealing. The high volumes of water can influence the DSM initiatives to the point where the control and performance are negatively influenced.

Dam levels change too drastically in short periods of time where LM is done and the 3CPFS is controlled independently. This is true for the chilled water demand as well when the FPs are offline and the 3CPFS needs chilled water.

All the aspects mentioned above will now be formulated in a problem statement or need for the study. Objectives will then be given to solve the problem that is identified.

1.4 Problem statement, need and objectives

South African gold mines are struggling to remain profitable. It can be mainly attributed to challenges such as gold price fluctuations, decline in gold ore grade, labour unrests and ever-increasing operating costs. Gold mines do not have much control over fluctuating gold ore grades, gold prices or strikes. One challenge that can, however, be addressed is that of operating costs.

A large portion of a gold mine's operating costs is ascribed to electricity consumption, especially with the higher-than-inflation electricity tariff increases in South Africa. For this reason, mines do not hesitate to implement energy and cost savings initiatives on the major electricity consuming systems. One of these systems is the water reticulation system as it typically consumes approximately 34% of a gold mine's total electricity consumption.

A large number of energy and cost savings initiatives have been implemented in the past on gold mine water reticulation systems in an attempt to reduce operating costs. Load management and energy efficiency initiatives were, however, individually implemented on the individual sub-systems without considering the impact thereof on the other systems [23]. This proved to be successful in the past, but problems occurred when mines wanted to combine the load management initiatives on the dewatering and refrigeration systems with the operation of a 3CPFS.

The main cause of the 3CPFS influencing the performance of load management initiatives was identified as the lack of integrated control between the sub-systems of the water reticulation system. These sub-systems include the 3CPFS, dewatering and refrigeration system. A need therefore exists to develop an integrated control philosophy to optimally utilise the 3CPFS to improve and maximise the performance of load management initiatives on the other two sub-systems. Load management would also be expanded to the 3CPFS itself to further maximise cost savings.

The objectives for this study are therefore formulated as follows:

- Integrate the control of the dewatering, refrigeration and three-chamber pipe feeder systems (3CPFS) in an optimised control philosophy.
- The integrated control philosophy must improve the performance of cost saving initiatives and maximise the cost savings potential of the water reticulation system.
- The operational parameters of the water reticulation system may not be influenced to such an extent that production is negatively influenced.

1.5 Chapter overview

Chapter 1

Background on South African gold mining production is given with key challenges influencing its profitability. The high electricity usage of gold mines and consequently the high related costs is discussed. Numerous energy savings initiatives that were implemented in the past to reduce electrical costs are presented. Challenges with integrating cost saving initiatives on deep-level mine water reticulation systems are identified. The problem statement is defined, from which the need and objectives of the study are formulated.

Chapter 2

This chapter provides an overview of deep-level mine water reticulation system operation and components. Energy recovery systems are discussed as part of the water reticulation system with detailed focus on the functionality of a 3CPFS. Previously implemented studies are critically analysed with specific focus on integrated control of water reticulation sub-systems.

Finally, different simulation packages are investigated to identify the most suitable package for the purposes of this study.

Chapter 3

The information gathered from the previous chapters was used to develop a step-by-step methodology to optimise the utilisation of 3CPFS in a water reticulation system. The steps of the methodology are discussed and include scope identification, characterising the systems, defining objectives, collecting data, optimising the control of the 3CPFS, and simulating different scenarios for testing.

Chapter 4

This chapter describes how the developed methodology is implemented on the water reticulation system of a South African gold mine, referred to as Mine A. Scenarios were simulated and tested with very positive results on the implemented control philosophy. The results are presented in terms of maximised cost savings and the impact of the control philosophy on the operational parameters of the water reticulation system. Finally, the results are discussed based on the objectives formulated in Chapter 1.

Chapter 5

The study is summarised with the main results reiterated to prove the viability of optimally utilising a 3CPFS. Recommendations for further studies are provided to conclude the study.

CHAPTER 2

2 Water reticulation systems in the mining environment

2.1 Introduction

An integrated solution for this underperformance can only be developed if one thoroughly understands the functionality and integrated nature of deep-level mine water reticulation systems. Specific focus is placed on incorporating a three-chamber pump feeder system as an energy recovery initiative on these systems, as well as the cascading impact thereof.

It is also important to investigate previously implemented studies regarding cost saving initiatives on water reticulation systems, with specific focus on the positive- and negative aspects and the shortcomings of each study. Finally, simulation packages capable of simulating the integrated sub-systems as part of the water reticulation system must be investigated. A suitable simulation package will simplify the solution development process as manual modelling of such a system could be a complex and tedious process. All of the above-mentioned information and literature will be discussed in Chapter 2, which will lay the foundation to develop a research methodology in Chapter 3.

2.2 Water reticulation operation and components

2.2.1 Typical operation

As mentioned in Chapter 1, the water reticulation system consists of a refrigeration- and dewatering system, which are referred to as the sub-systems [14]. Each of these systems contributes to establish safe working conditions for the workers underground [14], [15], [32]. Figure 11 illustrates a simplified layout of a typical water reticulation system on a deep-level mine. The hot and cold water are indicated by the red and blue lines, respectively.

Figure 11 is a simple drawing of a typical water reticulation system. The hot and cold water is indicated by the red and blue lines, respectively. The numbered sub-systems' functions will be discussed.

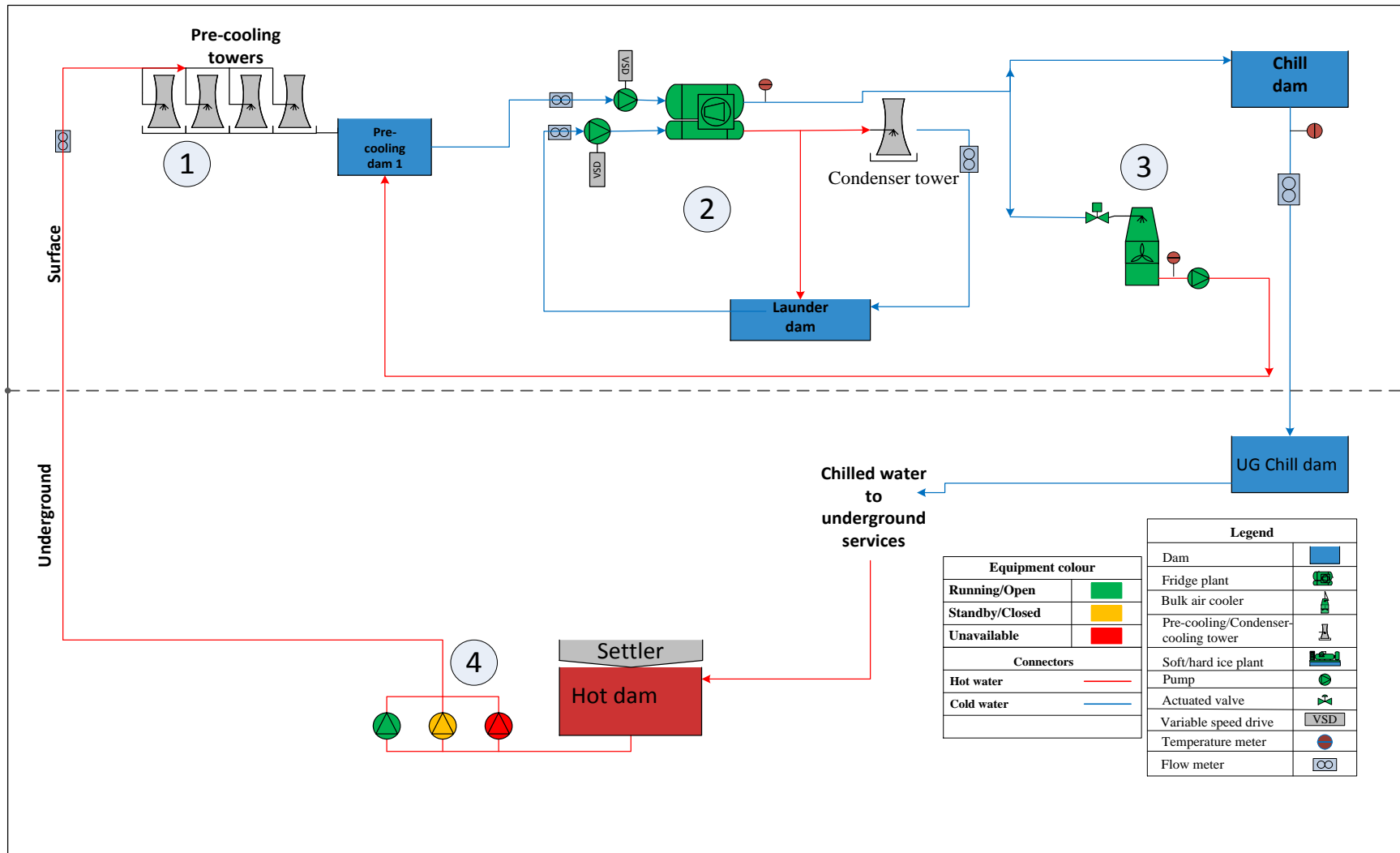


Figure 11: Typical deep-level mine water reticulation system

The process usually starts at the pre-cooling (PC) towers on the surface (labelled with the number 1 on Figure 11). The hot water from underground is pumped to the PC towers, which pre-cools the water for the chillers. From the PC towers, the water is transferred to a warm water dam. The warm water dam provides storage capacity for the water to ensure a constant water supply to the chillers [23].

The chillers (labelled number 2) cool down the water to a set temperature, from where it is transferred to a chill dam or a BAC (labelled number 3) on the surface. The chill dam is used as a storage mechanism to ensure an uninterrupted supply of cold water to mining operations. The BAC uses the supplied chilled water to cool down the air sent underground. From the BAC, the warmer water is returned to the pre-cooling dam.

The chilled water is gravity fed from the surface chill dam to an underground chill dam from where it is distributed to be used for services [13], [15]. The used service water is then channelled and cascaded to the settlers to separate the mud from the clear water. The clear water is then pumped (labelled number 4) to the surface via cascading dewatering pump stations, from where the cycle repeats itself [13].

With a better understanding of the operation of a deep-level mine water reticulation system, the next step is to investigate the main components of the sub-systems. The next section presents the basic operation of these components.

2.2.2 System components

2.2.2.1 Refrigeration systems

The refrigeration system consists of five main components, namely, chillers, cooling towers, BACs, transfer pumps and dams. Each component is discussed in the following sections:

Chillers (labelled number 2 in Figure 11)

The chiller machines on most South African gold mines use tube-in-shell heat exchangers and work on the principles of the vapour-compression cycle [33]. This is basically due to simplicity and relatively low operating cost. The pressure vessel acts as the shell, with tubes installed on the inside. The refrigerant passes over the tubes in the vessels, which are filled with the water from the evaporator and condenser pumps [34]. Heat is rejected from the warm water in the

evaporator vessel to cool it down. The heat from the gas is then rejected to the water in the condenser vessel [35].

Figure 12 shows a schematic representation of a tube-in-shell heat exchanger working on the principles of the vapour-compression cycle [33].

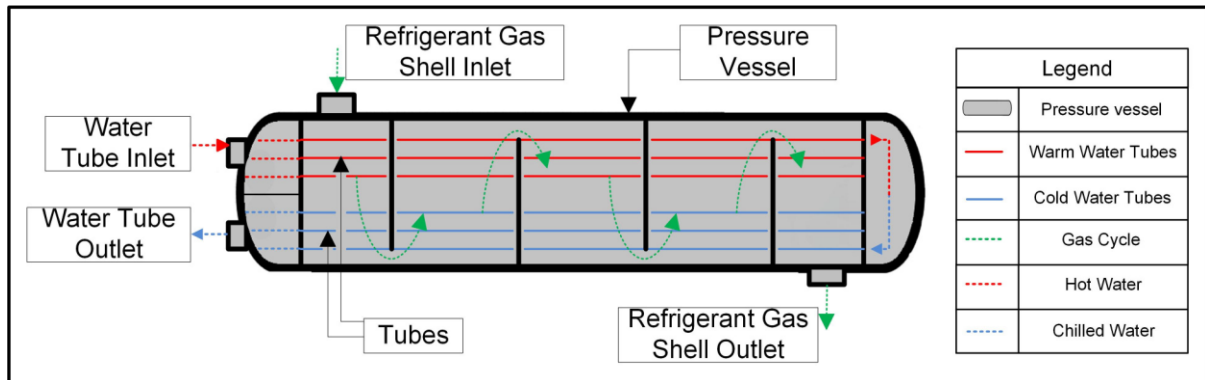


Figure 12: Schematic of a tube-in-shell heat exchanger [33]

Figure 13 is an example of a refrigeration plant installed at a mine. The compressor, motor and pressure vessels are visible in the picture.



Figure 13: Practical example of a chiller machine

The chillers are the most electricity intensive components in the refrigeration cycle, consuming approximately 66% of the total system's load [34]. For this reason, load management initiatives are most likely to be implemented on these components.

Cooling towers (labelled number 1 in Figure 11)

Pre-cooling towers comprise mechanical force draft towers, made from steel or concrete, that are used to cool down the hot water from underground. Mechanical suction fans are typically mounted on the top of the towers to force ambient air through the hot water mist inside the tower [36]. The water can be cooled down to 2°C above the ambient temperature when performing at maximum efficiency [37]. The decrease in temperature is realised by latent and sensible heat transfer [34]. Due to the design, the cooling tower performance is dependent on the ambient psychometric conditions and water temperatures [34].

The condenser cooling towers are designed to work on the same principle as the PC towers. The hot water leaving the condenser side of the chiller is cooled by blowing ambient air through the water mist. The colder water from the tower outlet accumulates in the sump dams of the condenser towers from where it is returned to the condenser vessel of the chiller [34].

Figure 14 represents a practical example of a cooling tower used in the refrigeration system of a South African gold mine [13].



Figure 14: Practical example of cooling towers [13]

BACs (labelled number 3 on Figure 11)

BACs basically operate on the same principle as cooling towers, except that they use the chilled water to cool down and dehumidify the ambient air before it is sent underground [33]. The chilled water flows through the fill and extracts the heat from the ambient air blowing through it. The heated water is pumped back to the pre-cooling dam to be cooled by the chillers [38]. Figure 15 is a picture of a bulk air cooler used on a mine.

¹ Photo taken by Corné Momberg



Figure 15: Practical example of a bulk air cooler

Transfer pumps

Transfer pumps are a collective name for all the small pumps that displace the water between the different chilled water users within the refrigeration system. These pumps typically vary in size between 30 – 400 [kW] each. Configurations can differ as they are dependent on the specific system on each mine. [33]

These pumps are basically smaller versions of the dewatering pumps discussed in the dewatering system in 2.2.2.2 hereafter. The only differences are the size and the amount of stages in the centrifugal impeller.



Figure 16: Single stage centrifugal pump

Dams

Dams in the refrigeration systems are typically used to collect and store water on the surface or underground. From here the water is sent to different stages of the cooling process and then underground for service delivery purposes.

Dams are used in the dewatering system as well, but that will be discussed in the dam component of the dewatering system in the next section.

2.2.2.2 Dewatering system

The dewatering system typically consists of three main components, namely, settlers, dams and the dewatering pumps. The components are discussed as follows:

Settlers

The first step in dewatering a mine is to accumulate all the service and fissure water [15]. The accumulated water underground, however, contains small mud particles and is often referred to as “dirty water”. Underground settlers are therefore required to remove these particles from the water to prevent excessive damage to the dewatering pumps [9], [39]. Figure 17 shows a practical example of an underground settler.

² Photo by direct industry.com



Figure 17: Practical example of a settler [31]

Chemicals are added to the water entering the settlers. This ensures that suspended solid particles stack together [40]. The larger particles (sediment/sludge) settle at the bottom of the settlers from where they are drawn off and transferred to mud dams [41]. Clear water (separated from particles) spills from the settler into columns and is transferred to clear water dams. From the clear water dams the water is pumped with the dewatering pumps.

Dams

Dams are a necessity as they are used to accumulate all the water sent underground (Fissure, cooling & service). Without dams, the mines will flood and that can lead to closing of certain levels, closing of mines or even loss of lives. The settlers are used to remove dust & rock particles and water is then sent to the dams underground. [15].

These dams usually have large capacities to ensure mines can store water underground if it cannot be removed immediately [9], [15]. Mining personnel explained that these dams are usually cylindrical and can hold around 3.7 Mℓ of water. Typically, dams are built with significant vertical height to provide substantial head pressure for the dewatering pumps that will be discussed in the next section.

Dewatering pumps

On a typical gold mine, high volumes of water are pumped from underground to the surface with the help of dewatering pumps [42]. Depending on the water volumes and size of the mine, a pumping station may comprise up to twelve dewatering pumps [9], [15], [43].

The pumps can be categorised as dynamic or displacement, depending on the energy added to the fluid [42].

Dynamic pumps are further sub-divided into centrifugal and special effect pumps. Displacement pumps are sub-divided into reciprocating and rotary pumps [42]. In most cases, deep-level mines make use of multistage centrifugal pumps as they are designed to displace water over a large vertical distance (head) [14], [44], [45], [46]. Figure 18 shows a photo of a multistage centrifugal pump used at an underground mine



Figure 18: Multistage dewatering pump

The operation and different components of a typical deep-level mine water reticulation system have been discussed in detail. In some instances, additional systems may, however, form part of the water reticulation system. These usually are in the form of energy recovery systems, which have components of their own. The next section therefore focuses on incorporating energy recovery systems with specific focus on the benefits in terms of electricity consumption.

2.3 Incorporating energy recovery systems

As mentioned in Chapter 1, deep-level mine water reticulation systems consume large amounts of electricity. With the ever-increasing electricity price in South Africa, deep-level mines investigated the opportunity to utilise the vertical displacement of water as an energy recovery medium [26]. The water, however, cannot recover the energy on its own and equipment is usually required.

2.3.1 Energy recovery systems

In the mining industry, three types of energy recovery systems are typically installed, namely, Pelton turbines, pump-turbines, and three-chamber pipe feeder systems (3CPFS) [47]. More background and information on these systems are provided in the following sections.

2.3.1.1 Pelton turbines

Since 1978, South African deep-level mines have installed between 50 and 60 Pelton turbines [47]. Literature proved that around eighteen of them are still in operation, but with low energy recovery performance [47]. These Pelton turbines are recovering less than 50% of the available energy in the head due to inefficient centrifugal pumps installed in the system before it [48].

Figure 19 depicts an illustration of a Pelton wheel turbine [49].

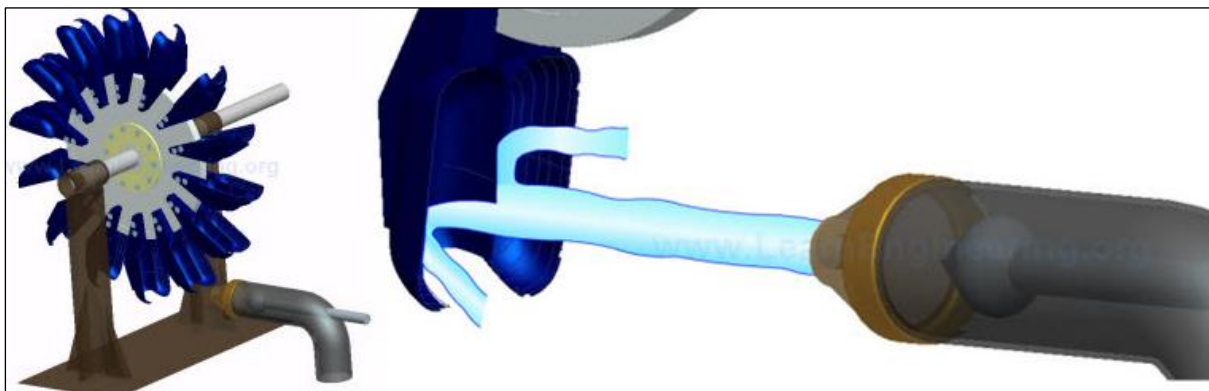


Figure 19: Pelton wheel turbine [49]

The Pelton turbine uses the energy of water at high speed to generate electricity. The high-pressure water is sprayed into the buckets of the Pelton wheel, which induces impulsive forces to rotate the turbine. The turbine is connected to the generator, which in turn generates electricity. Optimum power is extracted from the turbine when the product of the impulsive

force and the bucket velocity is at maximum. There are Supervisory Control and Data Acquisition, however, disadvantages to this turbine [49].

With the harsh underground conditions, it is natural to assume that dust particles will negatively influence the bearings and block spray nozzles [50]. If the Pelton wheel is not able to rotate, zero power will be transferred. Another disadvantage is that no power will be transferred if the bucket and water speed is the same. This is due to the absence of impulsive forces [49].

With the inner workings of the Pelton turbine better understood, another energy recovery device, pump-turbines, will be discussed in the next section.

2.3.1.2 Pump-turbines (PT)

Pump-turbines are used to recover energy by using the pressure head from the incoming water column. The Francis turbine is the most common turbine used in the mining industry and uses the back pressure to convert it into kinetic energy [47]. Figure 20 shows a photo of a Pump turbine with a motor generator.



Figure 20: Pump turbine with motor generator

Water passes through a set of stationary guide vanes to convert a small amount of the total head into kinetic energy. The water is then guided into the runner as the guide vanes accelerate to

³Picture from <http://www.hfm.tugraz.at/en/references/turbine/examination-of-pump-turbines-on-test-rig-acc-to-iec-60193.html>

displace the water at the correct angle. Kinetic energy is then generated by converting the pressure energy inside the runner. The drop-in system pressure is controlled by the configuration of the impeller, angle of the guide vanes and the rotational speed of the impeller. [47].

Turbine-pump configurations can cost between R8 000 000 and R10 000 000 for a depth ranging from 600 m to 800 m [26], [31], [51]. A study concluded that the payback period can be around three years [47], [52]. With a total efficiency of 68% for the turbine-pump system and the long manufacturing time, it is understandable why this system is not usually chosen [31].

The previous two energy recovery devices that were discussed are rather old technology and are not often used. In the next section the latest, and more favourable, three-chamber pipe feeder system energy recovery device will be discussed.

2.3.1.3 Three-chamber pipe feeder systems (3CPFS)

The three-chamber pipe feeder system is the latest technology, in terms of energy recovery systems, used on South African deep-level mines [47]. Potential energy from cold water fed to the mine is utilised to displace large volumes of hot water from the mine [15], [31], [53]. Figure 21 shows a photo of an installed 3CPFS on a deep-level gold mine [30].



Figure 21: Three-chamber pipe feeder system [30]

The 3CPFS was initially designed to displace the slurry in a pressurised chamber by utilising high-pressure water [47]. It was then further developed into an energy recovery system and installed for the first time on a South African deep-level mine in 1994 [47], [54]. Thereafter numerous mines in South Africa introduced the use of a 3CPFS in their water reticulation systems. With an efficiency of 80%, installation cost of approximately R5.5 million (in 2014) and a payback period of three months, it becomes clear why this system is the most feasible option for the mines [26], [31], [47], [55].

There are, however, reasons why the 3CPFS cannot replace the current dewatering systems. This is because it operates in a closed loop system and external water, such as fissure water, cannot be displaced by the 3CPFS [15] [30]. Another reason is that no water can be displaced if no water is entering the 3CPFS and vice versa [47].

From this section, it becomes evident that a 3CPFS is the most practical solution when it comes to energy recovery in deep-level mines. This is mainly due to high efficiency and high return-on-investment. As this study focuses on the optimal use of a 3CPFS, the next sections will provide more detail on the components, functionality and operation of these systems.

⁴ Photo by A Janse van Rensburg

2.3.2 3CPFS components and functionality

A typical 3CPFS comprises a booster pump, filler pump and the pressure exchange system (PES). The PES again comprises three chambers with an intricate set of valves to control the water flow [15] [30].

The small booster pump is installed on the high-pressure side to overcome friction in the column [30]. The chilled water feed column is on the one side, the PES underground (bottom) and the delivery column (outgoing) on the other side of the “U-tube” [47].

The filler pump fills the three chambers with low-pressure warm water when required. These two pumps control the flow at which the 3CPFS operates [30]. The PES enables alternate in- and outflow of fluids as it moves from the high to the low-pressure system [30]. The three chambers alter between filled and pressurised and empty and depressurised, as low-pressure and high-pressure mediums pass through it. Each one of these chambers are seen as a PES.

To understand the flow of the water, a single PES will be explained by means of an example. Figure 22 shows a simplified schematic representation of a PES [30]. The letters A and B represent regular control valves, whereas D and E represent non-return valves.

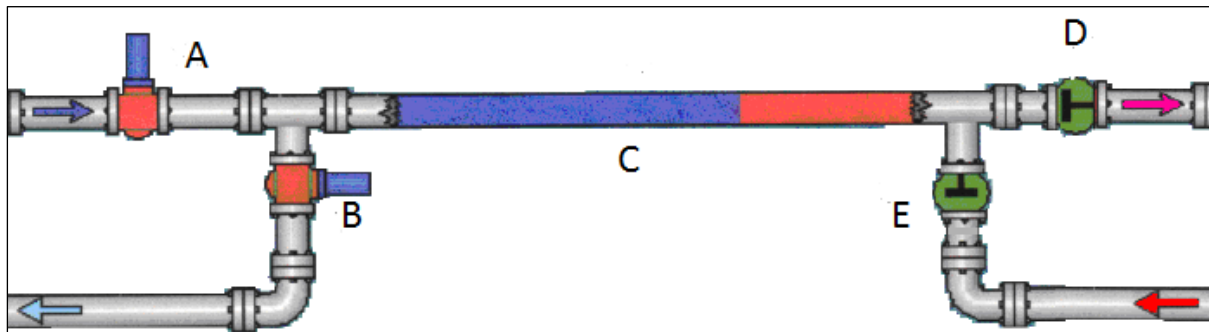


Figure 22: Single pressure exchange system [30]

Valve A will open and the horizontal chamber C will be filled with high-pressure cold water. At the same time, valve D will open and E will close, which forces the hot water through D. After C is filled with cold water, A and D will close and B and E will open. The cold water will then flow through B due to the low-pressure hot water filling up C through E. If C again is filled with hot water, A will open and B will close and the process will repeat itself.

The 3CPFS is just three pressure exchange systems combined. This configuration is designed to ensure continuous flow of water [47]. Figure 23 represents a simplified schematic of the

3CPFS with the cold water entering at 1 and exiting at 2 [30]. The booster and filler pumps are situated at the sides of 1 and 2, respectively.

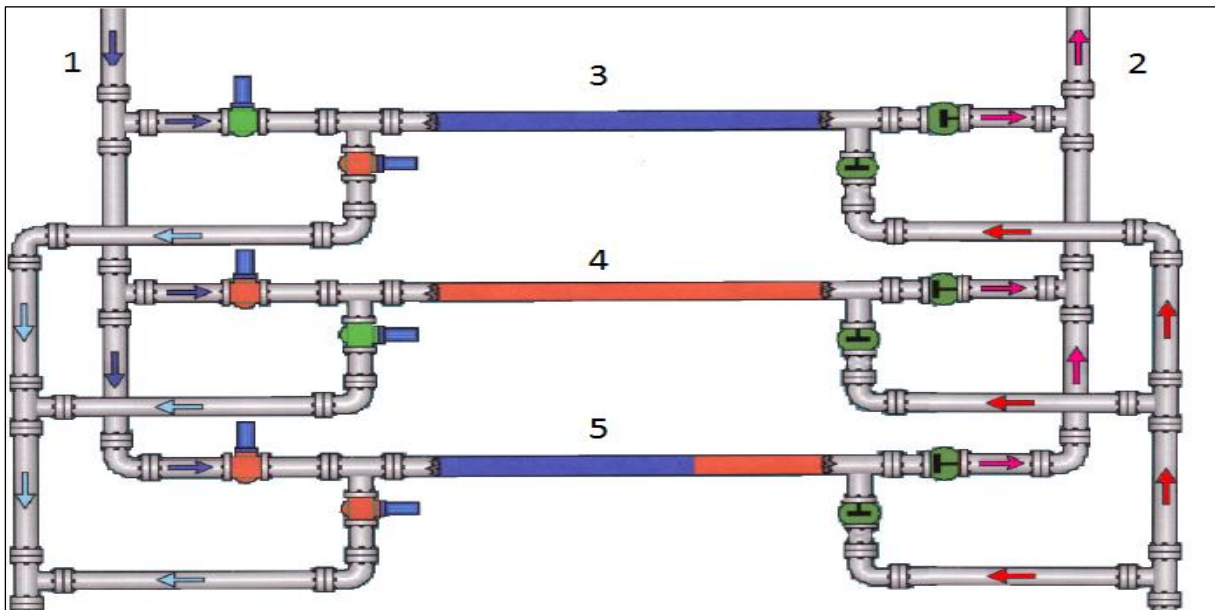


Figure 23: Three-chamber pipe feeder system schematic representation [30]

With the functionality and components of the 3CPFS discussed and better understood, the integration with the water reticulation can be discussed.

2.3.3 Integrating the 3CPFS in the water reticulation system

For the 3CPFS to function properly, it requires a significant head, chilled water and hot water [30], [47]. The head is sufficient at depths of approximately 1 km [47]. The refrigeration system provides the chilled water that is used to displace the hot water. As mentioned earlier in the section, the dewatering pumps cannot be replaced by the 3CPFS. The integration of the three systems is therefore very important to realise the potential efficiency.

Figure 24 shows an example of an integrated water reticulation system, including the dewatering system, refrigeration system and the 3CPFS connecting the two.

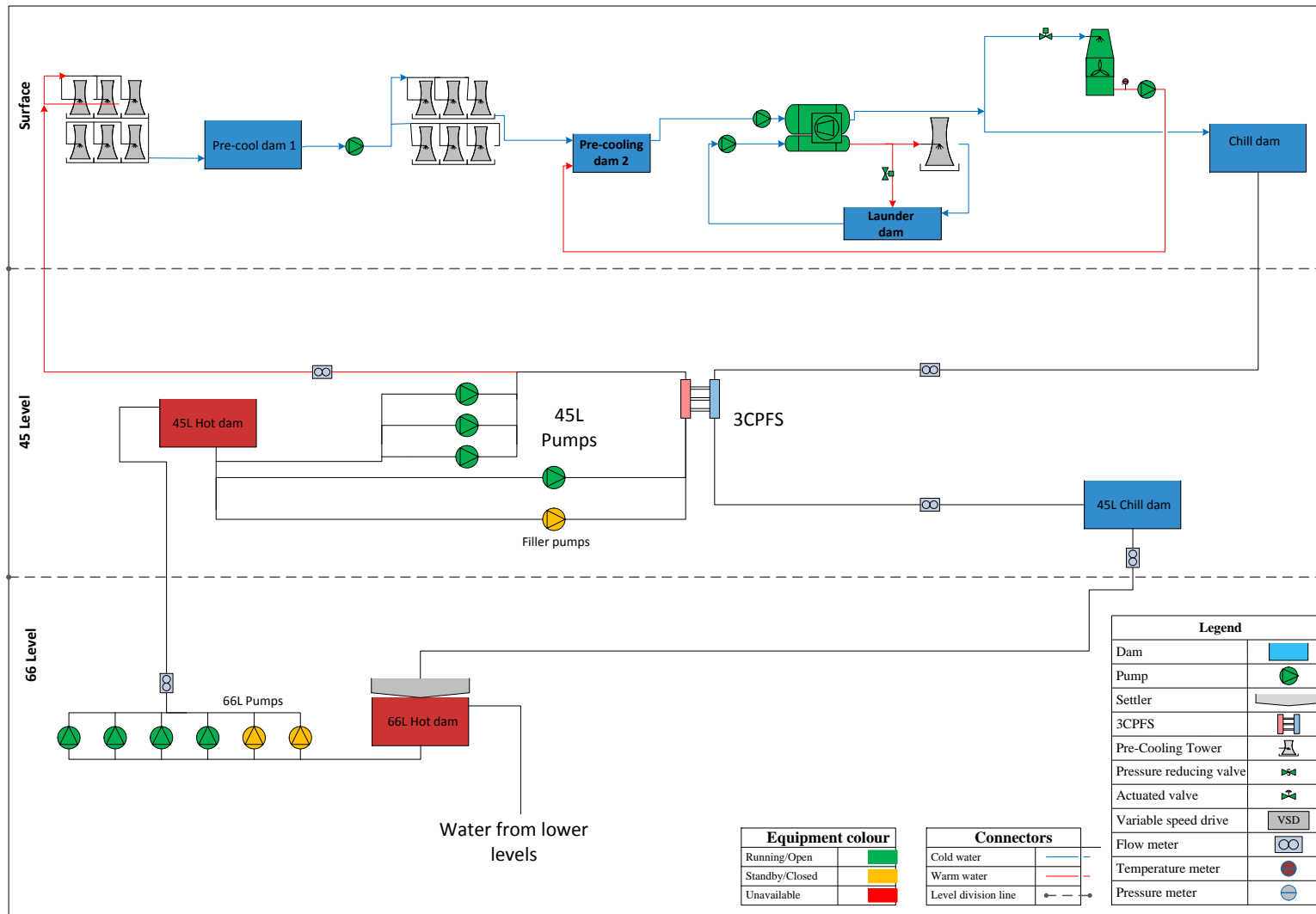


Figure 24: Integrated water reticulation system

The 3CPFS is directly influenced by the surface chill dam. If the refrigeration system is performing well and the chill dam full, the 3CPFS effectively uses the potential energy of the cold water to displace the hot water from underground to the surface. However, on the negative side, if the refrigeration system is not able to supply the demand, the 3CPFS cannot be used. This nullifies the advantages of the 3CPFS as the conventional pumps will be needed to displace the hot water to surface.

As with the refrigeration system, the 3CPFS is also influenced by the dewatering system as it is connected to the hot dam. If the dewatering pumps are inefficient or unavailable, the hot dam supplying the 3CPFS empties and the 3CPFS cannot operate.

There are many benefits from integrating the 3CPFS in the water reticulation system; for example, electricity consumption will decrease when 3CPFSs are utilised in the place of conventional dewatering pumps [30], [53]. But, with ineffective control of the 3CPFS, the benefits can be nullified. This emphasises the importance of optimising the control of the 3CPFS, especially when integrated with the water reticulation system. The following section will focus on initiatives that were implemented on deep-level mine water reticulation systems with a 3CPFS.

2.4 Critical analysis of research relevant to the study

2.4.1 Study analysis

The importance of previously implemented studies, particularly on optimising the control of a 3CPFS in a deep-level mine water reticulation system, is relevant to the study. It is important to understand what has been accomplished in this particular field of research, as well as to critically analyse the shortcomings in terms of optimal utilisation. The specific focus is on utilising the 3CPFS in such a manner that it would complement load management initiatives implemented on the other 2 systems, namely, dewatering and refrigeration

Incorporating the findings of previous studies would enable one to develop an effective solution to optimise the control of a 3CPFS in the water reticulation system. The information from the studies identified for critical analysis therefore needs to be strategically extracted and

interpreted to accomplish this task. For this reason, the following studies are analysed to the following criteria:

1. Research focus
2. Outcomes of the study
3. Shortcomings of study
4. Recommendations

Study One: The integrated effect of DSM on mine chilled water systems [56].

1. Research focus

Schoeman researched the effect of reducing the chilled water demand on a mine's refrigeration, dewatering and energy recovering systems. He compared the financial gains of cost saving initiatives with the financial losses on the components due to the reduced chilled water supply.

2. Outcomes of the study

The study proved the viability of realising cost savings by reducing the chilled water demand. It was, however, found that the effectiveness of cooling provided to the mines decreased. The cost saving benefit is, however, far greater than the small financial losses caused by incomplete load shifts. Schoeman further proved the importance of dam level control as it negatively influences the operation of the 3CPFS.

3. Shortcomings of the study

Only the integration between the 3CPFS and refrigeration system was investigated. The effect of optimised control of the integrated water reticulation system, which includes the dewatering system, was neglected

4. Recommendations

Schoeman recommended that more possibilities to decrease water consumption must be investigated as deep-level mines have many different consumers on each level. Another recommendation was to investigate installing cooling units on each level instead of surface refrigeration.

Study Two: Best practices for automation and control of mine dewatering systems [9]

1. Research focus

Oberholzer studied the best practices for automation on the dewatering systems. He accomplished this by investigating the main root causes of automated pump failures.

2. Outcomes of the study

Oberholzer improved practices to prevent failures due to cavitation and overheating. This in turn also increased pumping reliability and availability. A control philosophy was also developed for integrated control between the 3CPFS and the dewatering system.

3. Shortcomings of the study

The main goal of the study was to optimise the load shift on the dewatering pumps by incorporating the operation of the 3CPFS. As with Schoeman's study, the integral effect of including the refrigeration system was neglected.

4. Recommendations

It was recommended that automated dewatering systems must be controlled from a centralised system. This will help the operator to make an informed decision quickly if needed as all the relevant information can be accessed from one point.

Study Three: Optimising The savings potential of a new three-pipe system [30]

1. Research focus

The goal of Janse van Vuuren's research was to optimise the savings potential of a new 3CPFS. This was done by simulating the dewatering system after a new 3CPFS was installed on a dewatering system to optimise LS capabilities.

2. Outcomes of the study

He created a control philosophy that will incorporate a single or multiple 3CPFSs. From his results, it was found that there is a possibility to get a LS as well as EE on the dewatering system.

3. Shortcomings of the study

His study was successful, but like Oberholzer, Janse van Vuuren did not include the refrigeration system in his control philosophy.

4. Recommendations

Janse van Vuuren recommended that a LS should also be performed on the 3CPFS and the performance should be investigated to check for cost savings.

Study Four: Reducing the electricity cost of a Three-Pipe Water Pumping System – a case study using software

1. Research focus

Rautenbach studied the possibilities to reduce costs of the 3CPFS with the focus on the LS during Eskom peak periods. He created a new simulation tool (QUICKcontrol) to simulate the performance of the 3CPFS on a mine.

2. Outcomes of the study

The study was successful with a predicted saving of R195 000 per annum and a 3.5 MW LS during the Eskom evening peak periods.

3. Shortcomings of the study

The study was very successful, but just like Janse van Vuuren and Oberholzer, he did not include the refrigeration in the control of the 3CPFS.

4. Recommendations

Rautenbach recommended that a study should be done to investigate increasing the availability of the 3CPFS as it will increase the savings potential.

With previous studies analysed, the findings can be summarised and discussed in the following section.

2.4.2 Critical analysis summary

The key aspects of the analysis done in the previous section is summarised in Table 1:

Table 1: Critical analysis summary

Critical analysis summary				
Aspects	W. Schoeman	P. J. Oberholzer	A. Janse van Vuuren	W. Rautenbach
Cost saving initiatives	✓	✓	✓	✓
Automated control	X	✓	X	✓
Integrated control of 3CPFS, refrigeration & dewatering systems	X	X Only 3CPFS and dewatering	X Only 3CPFS and dewatering	X Only 3CPFS and dewatering

All the research discussed in 2.4.1 was successful with documented savings, but none of these researchers integrated the control of the 3CPFS with the dewatering and refrigeration systems. This study will fill the gap by integrating the 3CPFS in the control of the refrigeration and dewatering sub-systems.

Table 1 shows that the main focus of all the studies was to save costs due to the increase in electrical costs. This study will also focus on cost saving and all the findings from these studies will be kept in mind.

Automatic control was not a main focus in most of the analysed studies, but Oberholzer did a thorough study with very useful conclusions. He concluded that automatic control will be easier to implement from a central point and will speed up troubleshooting as all the information is available on one system.

The next step after the critical investigation is to analyse the different simulation packages that are available to use. These packages will be discussed in the next section.

2.5 Simulating mine water reticulation systems

The use of simulations has become more common practice in recent times. This is mainly due to the availability of suitable packages for certain applications and the accuracy with which a theoretical analysis can be conducted for practical systems. There are approximately 45 simulation packages available to simulate deep-level mine water reticulation systems. [13]

In the past, simulation software packages were not as user-friendly or accurate as the most recent packages [33] [57]. This is basically due to advanced technologies of the modern-day era. Modern simulation packages can generate fast and accurate answers without requiring long tedious manual calculations. These packages can dynamically optimise the system when you have a theoretical representation of the aforementioned system.

To be able to choose a suitable package for the purposes of this study, it was required to analyse the most commonly available packages on the market. The following section provides an overview of the analysis.

2.5.1 Simulation software overview

The first step in choosing a suitable simulation package is to define the key characteristics the software must adhere to. These characteristics mainly include compliance with the purpose of use, accuracy of outputs and ease of use.

The simulation package that is best for this study must be able to simulate a refrigeration system, a dewatering system and the 3CPFS, individually. Secondly, the package must be able to simulate the integrated configuration of these three systems. The package must also be able to provide outputs in terms of power consumption of each component, as well as selective operational parameters such as temperatures. Finally, it must have control capabilities over the theoretical models to test the feasibility of optimisation strategies.

The simulation packages that will be discussed are the following:

- KYPipe,
- ENVIRON,

- Real time Energy Management System (REMS), and
- Process Toolbox (PTB).

The characteristics identified above are summarised for each simulation package in Table 2.

Table 2: Simulation characteristic summary

Simulation characteristic summary				
	Simulation packages			
Aspects	KYPipe	ENVIRON	Real time Energy Management System (REMS)	Process Toolbox (PTB)
Simulate refrigeration	X	X	✓	✓
Simulate dewatering	X	X	✓	✓
Simulate 3CPFS	X	X	✓	✓
Simulate integrated water reticulation system	X	X	X	✓
Calculate operational parameters	✓	✓	✓	✓
Can apply controlling capabilities	X	✓	✓	✓

KYPipe

This steady-state simulation package is a powerful hydraulic simulator that focuses on the distribution of different fluids including refrigerant, water and air. A system's optimal pipe configuration can be determined with this package, but it is not able to simulate a system in real time. Fridge plants, dewatering pumps and 3CPFSs cannot be simulated by this package and thus it cannot be used. [33]

ENVIRON

Due to its ability to simulate airflow underground it aids the mine with designing a ventilation network. The purpose of ENVIRON is to calculate the cooling capacity required to effectively cool down a mine [13]. This simulation package will not be adequate for this study as it cannot simulate FPs or dewatering pumps.

REMS

REMS is a real time energy management system that has a simulation feature that can be used. REMS comes in different packages like the Cooling Auxiliaries (CA), Pumps (P), Fridge Plants (FP) etc. REMS-CA can control the mine's cooling equipment and REMS-P can control the dewatering pumps. The main objective of REMS is to control and monitor the mine's installed equipment. REMS has been validated, but it will not be viable for this study as it cannot integrate different systems [13], [33].

Process Toolbox (PTB)

PTB is a dynamic thermal hydraulic simulation package. It can simulate the three required systems separately or integrated [58]. It can enable the user to optimise a designed system's performance by determining the optimal operation of components [58]. This simulation package can predict possible power saving and control individual components [33].

Motivating the use of Process Toolbox (PTB)

From Table 2 and the discussion above it is clear that PTB has all the characteristics that are needed for this study. PTB has also been validated by Oberholzer, Peach, Van Niekerk and Rautenbach [13] [33] [53] [59] for simulating cost saving initiatives in deep-level mines. All three the required systems were used during these studies and therefore it can be concluded that PTB is an accurate simulation package. PTB is thus a viable simulation package for this study.

Although PTB has been identified as the most suitable simulation package for the purposes of this study, it is still important to understand the mathematical modelling behind the interface. This enables one to not just simulate feasible solutions, but to fundamentally understand and interpret the outputs thereof. The mathematical modelling is discussed in the following section.

2.5.2 PTB mathematical modelling

PTB uses fundamental principles in its calculations for every component. To simplify the discussion behind the mathematical modelling of PTB, the discussion is divided into the three systems of the water reticulation system, namely:

- The dewatering system,
- The refrigeration systems, and
- The three-chamber pipe feeder system.

It is important to note that focus is placed on the main components of each system.

2.5.2.1 Dewatering pumps

PTB acknowledges a dewatering pump as a device that induces water flow through a network due to the pressure differences it creates. Due to inefficiencies, the heat added to the fluid by the component is also anticipated for. The following assumptions are, however, made:

- No heat is transferred between the ambient air and the water inside the pump.
- The motor efficiency of the pump remains constant at partial and full loads.

The user is required to provide the following inputs to calculate the power (P_{ower}) consumption, pressure difference (dP) and pump efficiency (E_p):

Table 3: Symbol descriptions for the dewatering pumps

Symbol	Description
m	Water mass flow rate (kg/s)
a	Pump pressure curve coefficients
N	Pump's speed fraction
p	Water density (kg/m ³)
E_m	Motor efficiency

The following equations are solved using the inputs:

$$P_{ower} = \left(\frac{m}{p}\right) \times \frac{dP}{E_p/E_p}$$

Equation 1: Calculating electrical power

$$dP = (a_2m^2 + a_1m + a_0) \cdot (N^2)$$

Equation 2: Calculating pressure difference

$$E_p = b_2 \times (m/N)^2 + b_1(m/N) + b_0$$

Equation 3: Calculating pump efficiency

To be able to accurately simulate the flow, PTB generates the pump pressure curve automatically. All it requires is three pressure difference readings at different points. PTB automatically plots a quadratic curve through the three points to generate an equation. Figure 25 is an example of a pump pressure curve generated in PTB.

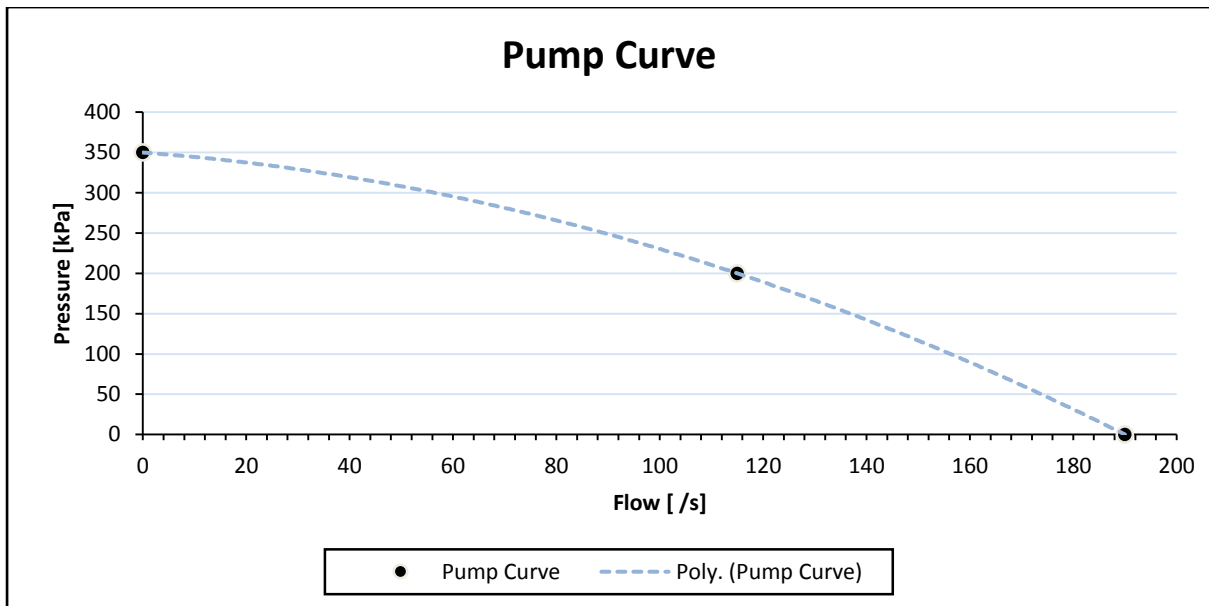


Figure 25: PTB pump pressure versus flow curve

By providing the pressure differences the curve is plotted to show the corresponding flows.

2.5.2.2 Refrigeration system

The water chiller component (FP) in PTB removes the heat from the water that is connected to the evaporator side. This heat, along with the heat generated by the compressor, is transferred to the water connected to the condenser side.

The following assumptions are made:

- The compressor of the chiller is driven by an open drive motor system.
- The compressor motor of the chiller has a constant efficiency of 93%.
- The compressor motor of the chiller rejects heat to the atmosphere.
- No heat is transferred between the ambient air and the water inside the chiller.
- The water has a constant density of 1000 kg/m^3 throughout.

The user is required to provide the following inputs to calculate the evaporator cooling duty (Q_e), condenser heating duty (Q_c), chiller cooling duty (CD), coefficient of performance (COP), and Power (P_{ower}) consumption.

Table 4: Symbol descriptions for the refrigeration system

Symbol	Description
T_{ei}	Evaporator inlet water temperature (°C)
T_{ci}	Condenser inlet water temperature (°C)
C	Partial Load (between 0 and 1)
CCR	Cooling capacity rating (kW)
$COPR$	Coefficient of performance rating
T_{eor}	Evaporator outlet water temperature rating (°C)
T_{eir}	Evaporator inlet water temperature rating (°C)
T_{cor}	Condenser outlet water temperature rating (°C)
T_{cir}	Condenser inlet water temperature rating (°C)
Internal variables	
T_{er}	Average evaporator water temperature rating (°C)
T_{cr}	Average condenser water temperature rating (°C)
T_e	Average evaporator water temperature (°C)
T_c	Average condenser water temperature (°C)
$RefCD$	Reference cooling capacity rating (kW)

$$Q_e = -CD$$

Equation 4: Evaporator cooling duty

$$Q_c = CD + CD / COP \times 0.93$$

Equation 5: Condenser heating duty

$$CD = RefCD \times C$$

Equation 6: Calculating chiller cooling duty

$$COP = COPR \times ((T_e - T_{er}) \times 0.03 + 1) \times ((T_{cr} - T_c) \times 0.03 + 1) \times (-1.331C_2 + 2.369C - 0.038)$$

Equation 7: Calculating COP

$$P_{ower} = CD/COP$$

Equation 8: Calculating compressor electrical power

2.5.2.3 Three-Chamber pipe feeder system

PTB defines the 3CPFS as a device that utilises the hydrostatic pressure of the chilled water to transfer hot water from underground to the surface.

The following assumptions are made:

- Water inlet density (p_w) is 1000 kg/m³.
- Water mass flow down is equal to the water mass flow up.
- No heat transfer occurs between the hot and cold water.

The following inputs are used to calculate the water mass flow rate (m_w) and flow admittance (k):

Table 5: Symbol descriptions for the 3CPFS

Symbol	Description
P_u	Upstream node water total pressure (kPa)
P_d	Downstream node water total pressure (kPa)
P_i	Water inlet pressure (kPa)
P_o	Water outlet pressure (kPa)
m_w	Water mass flow rate (kg/s)

$$m_w = (kp_w (P_u - P_d))^{0.5}$$

Equation 9: Calculating water mass flow rate

$$k = m^2 / (p_w (P_i - P_o)) k_v$$

Equation 10: Calculating admittance

With the mathematical modelling analysed, the user now has a better understanding of how the simulation simulates the major systems. The other smaller components are dependent on the outputs of these major systems and their mathematical modelling will not be discussed.

With all the aspects of PTB discussed and the mathematical modelling better understood, PTB can now be used to develop an optimised solution. The literature review is concluded in the next section.

2.6 Conclusion

An overview of a deep-level mine water reticulation system was discussed with specific focus on the integration of a 3CPFS. Information was presented on individual components, their functionality and their integrated nature to comprise the water reticulation system.

Energy recovery systems used in deep-level mine water reticulation systems were investigated. It was found that the 3CPFS is the most effective solution in terms of efficiency and return-on-investment. The inner detail of the 3CPFS was therefore discussed and presented to obtain a better understanding on the operation of the 3CPFS within the water reticulation system.

Previously implemented studies regarding cost saving initiatives on water reticulation systems were investigated and critically analysed. Specific focus was placed on the positive-, negative aspects and shortcomings of each study. The critical analysis revealed that there is no strategy for integrated control between the three sub-systems, namely, dewatering, refrigeration and the 3CPFS. The recommendations found in these studies will, however, be used during the development of a new control philosophy.

Finally, simulation packages capable of simulating the integrated sub-systems as part of the water reticulation system were investigated. It was proven that the PTB simulation package is

the most suitable software to use due to its sound mathematical modelling. The modelling of the components behind the software interface was discussed.

All of the above-mentioned information and literature lay the foundation to develop a research methodology. The methodology is developed and discussed in the following chapter.

CHAPTER 3

3 Optimising a deep-level mine 3CPFS

3.1 Introduction

The information gathered in Chapter 2 was used to develop a step-by-step methodology to optimally utilise a three-chamber pump feeder system in a deep-level mine water reticulation system. The goal is not only to keep the 3CPFS from negatively influencing the LM initiatives, but also to perform a LS on the 3CPFS itself. Figure 26 illustrates a layout of the step-by-step methodology.

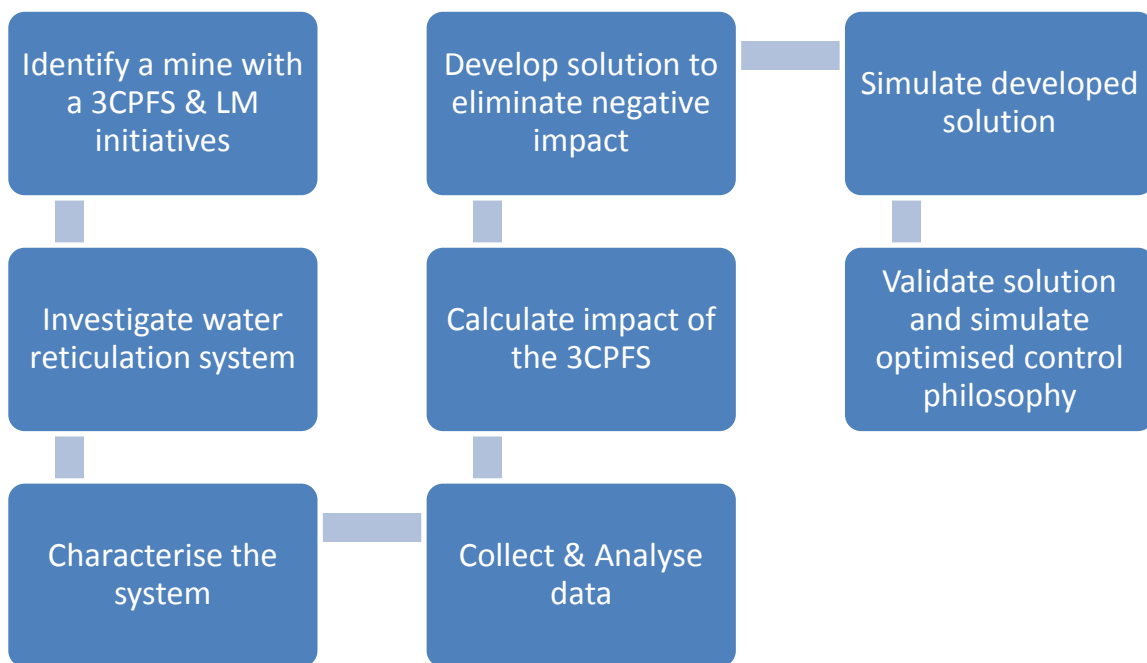


Figure 26: Research methodology

A mine must be identified with a 3CPFS, dewatering pumps as well as refrigeration plants. An investigation is then required to thoroughly understand the integrated system. Data must be collected, analysed and the impact of the 3CPFS on the other sub-systems characterised. A verified simulation of the water reticulation system is then developed with the gathered data, which serves as a theoretical model of the system.

The next step is to develop a solution to optimally utilise the 3CPFS and water reticulation systems. These steps will be discussed in more detail in the following sections.

3.2 Identifying the water reticulation system

3.2.1 Preface

In this step, a deep-level mine water reticulation system comprising the three sub-systems is identified. The presence of LM initiatives and the possible influence as a result of these initiatives are also identified. Scope for optimisation typically exists on such a system.

3.2.2 Identifying possible scope

Table 6 can be used to identify a deep-level mine water reticulation system comprising dewatering, refrigeration and 3CPFS systems.

Table 6: Water reticulation system identification

MINE NAME:		
Systems	Yes	No
Dewatering system		
Refrigeration system		
3CPFS		

With the mine identified, the next step is to identify the scope for improvement. As the main objective is to reduce operating costs, the LM opportunities on the water reticulation system are investigated. Underperforming LM initiatives are the focus, but if there are none implemented, possible implementation should be investigated.

All the LM initiatives identified on the specific water reticulation system should be investigated to monitor the performance. Load shifting on dewatering and refrigeration systems usually becomes an issue when the 3CPFS is not incorporated in their control philosophies. Possible room for improvement of the performance of the water reticulation system should be identified.

Typical causes for underperformance include the following:

- Chilled dam levels decreasing due to BACs or the 3CPFS draining the dams during Eskom peak times. This results in more fridge plants starting in an attempt to increase the chilled water dam level.
- Underground hot water dam levels decreasing due to the 3CPFS continuing to displace water during the Eskom peak times. This results in the dewatering pumps to start in an attempt to fill the emptying dams.
- Lack of maintenance may result in the underperformance of critical equipment and even lead to breakdowns. Breakdowns during critical periods may lead to flooding of underground levels.

Figure 27 shows an example of a typical dewatering system power profile, indicating the influence of the 3CPFS during Eskom evening peak periods (red areas). All dewatering pumps were off at 18:00, but some pumps were started before 19:00. The pumps were started due to emptying dams. This caused the load shift to underperform.

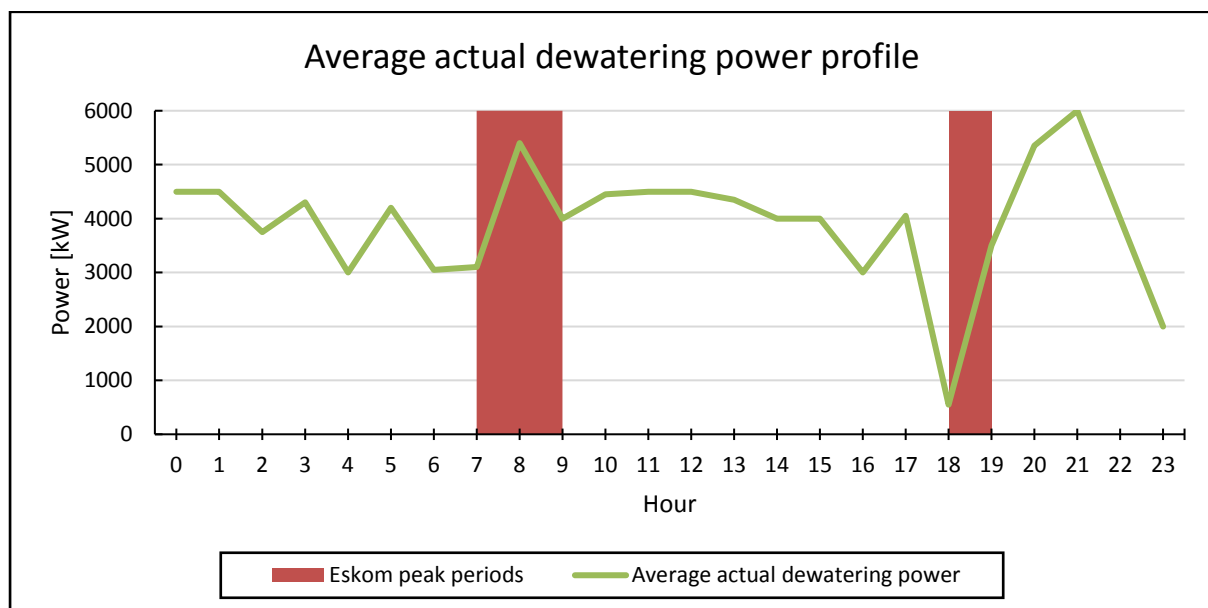


Figure 27: Affected dewatering power profile

Failing initiatives can typically be identified when little or no reduction in power consumption is noticed during the Eskom peak times. This is displayed visibly over the Eskom morning peak period in Figure 27. Another characteristic of failing initiatives is large spikes in the power profiles, visible during the evening peak period in Figure 27. Targets are set when LM

initiatives are implemented and these targets are used as reference when failing initiatives are being identified.

Table 7 should be used as a checklist to summarise failing LM initiatives on the sub-systems of the water reticulation system. These failing initiatives will be the focus as it can have a cascading effect on the cost savings potential of the system.

Table 7: Failing LM initiative checklist

MINE NAME:		
Systems	Yes	No
LM initiatives implemented on the water reticulation system		
Dewatering systems		
Refrigeration systems		
3CPFS		
Failing LM initiatives		
Dewatering systems		
Refrigeration systems		
3CPFS		

Once the information in Table 7 is available and depending on the outcome, possible scope can be identified. The next step is to characterise the water reticulation system in detail. This provides a thorough understanding of the system and its components to fully address the identified scope for optimisation.

3.3 Characterising the system

3.3.1 Preface

In this step the layouts of the sub-systems are analysed and the integrated nature of these systems are investigated. From the layouts, component and equipment lists can be generated which should include installed capacities, quantities etc. From all the information gathered, the constraints of the sub-systems can be identified.

3.3.2 Evaluating system layouts

Refrigeration

To fully understand the system, the layout must first be thoroughly investigated. Figure 28 is an example of a typical refrigeration layout on a deep-level mine.

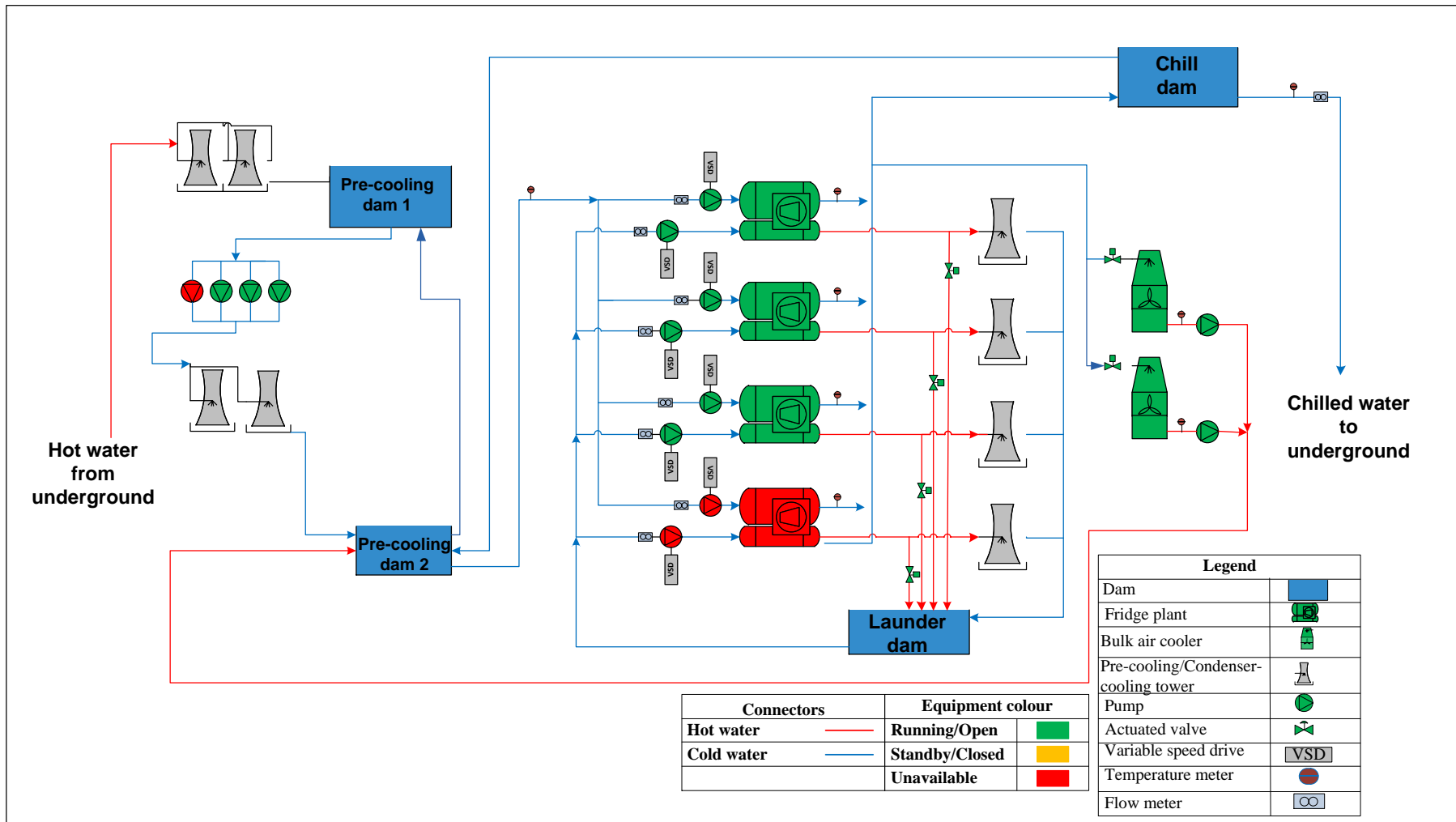


Figure 28: Typical refrigeration layout

From the layout one can determine the number of FPs, BACs, cooling towers, installed capacities and the system flow. Points can be identified where measurements should be taken when data collection starts if there is no desirable instrumentation installed.

For the refrigeration system, the temperatures of the chill dam as well as the evaporator temperatures of all the FPs are important. For the BACs, the inlet and outlet air and water temperatures are important. The water flows from the chill dam and to the FPs are also needed. Finally, the electrical consumption of every component is needed to calculate the LM performance.

With a better understanding of the refrigeration system, one can move on to the dewatering and 3CPFS layout.

Dewatering and 3CPFS

The dewatering and 3CPFS systems can be analysed under the same layout due to the integrated nature of these 2 sub-systems. As with the refrigeration system, the dewatering and 3CPFS layouts must be investigated to better understand the configuration. Figure 29 is an example of a typical integrated layout of the dewatering and 3CPFS.

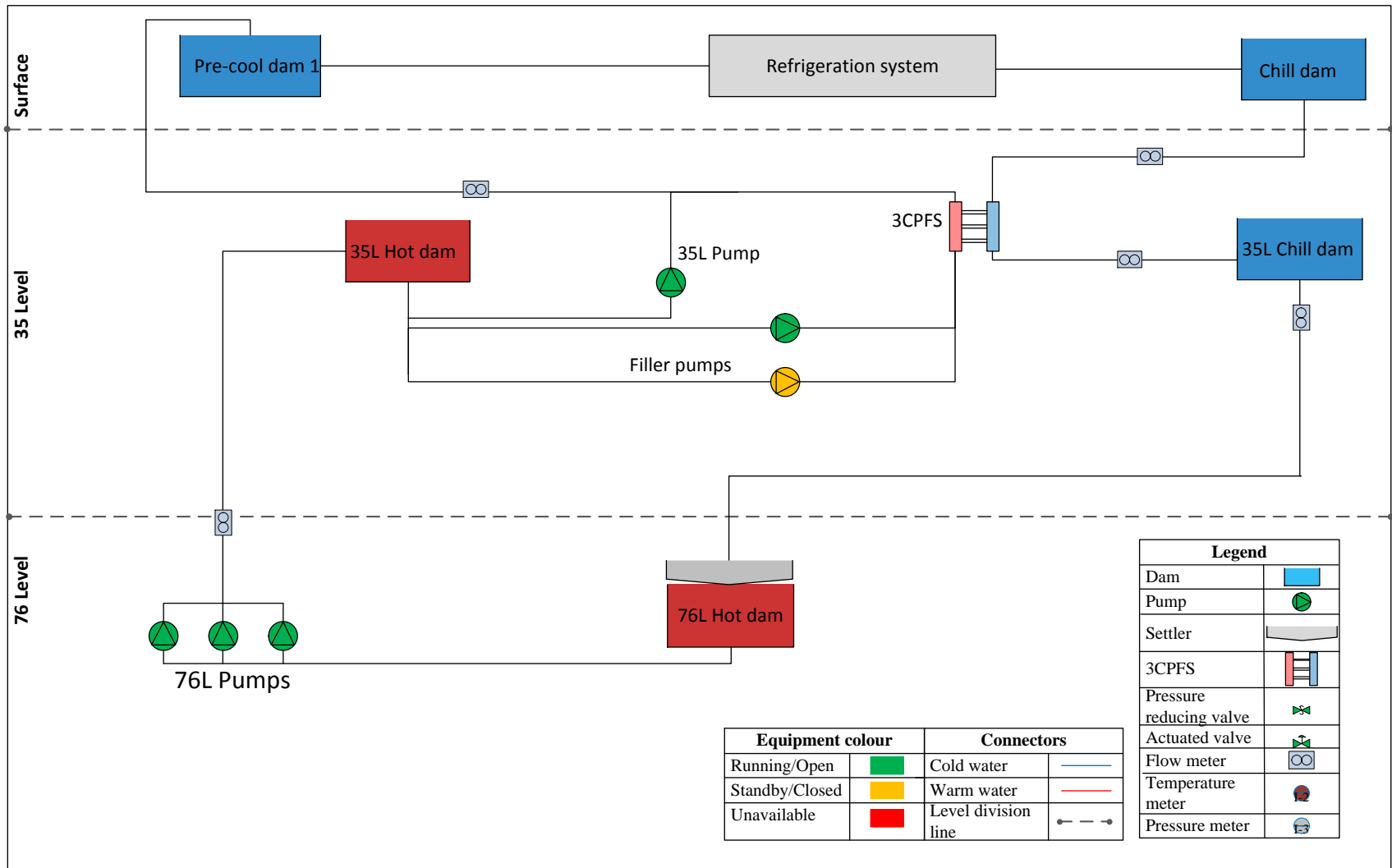


Figure 29: Typical dewatering layout with 3CPFS and refrigeration

From Figure 29 one can determine the number of pumps on each level, dams on each level and the system flow. Points can again be identified where measurements should be taken when data collection starts if there no desirable instrumentation is installed.

On the dewatering side, it is important to know how many pumps there are, the power consumption of each and the amount of water each can displace.

The most important part of the methodology is to familiarise oneself with the integrated nature of the systems at the particular mine under investigation.

Integrated systems

As this study aims to create a control philosophy for the integrated system, it must be investigated how these systems influence each other.

For example, Figure 29 shows a typical integrated layout of the dewatering, 3CPFS and refrigeration systems. The 3CPFS influences the 35L hot dam level, which is the parameter used to control the 35L pump. The surface and 35L chill dams are also influenced by the 3CPFS as it fills the 35L chill dam from the surface chill dam that is filled by the FPs.

With the integrated water reticulation system influences investigated, the next step is to characterise the systems.

3.3.3 System constraints

It is important to characterise the water reticulation system to have a thorough understanding of the entire setup and related integrated operation. The first step of characterisation is to identify the constraints of the sub-systems and related components. For reference purposes the main sub-systems are:

- dewatering,
- refrigeration, and
- 3CPFS.

The constraints for every sub-system are tabulated as follows:

Table 8: Sub-system constraints example

Constraints		
Dewatering	Refrigeration	3CPFS
<ul style="list-style-type: none"> • Max and min dam levels • Pump availability • Total number of pumps • Columns pressure threshold • Automatic control capabilities • Water demand of the mine • Efficiencies of pumps • Dam level restrictions • Dam sizes 	<ul style="list-style-type: none"> • Max and min dam levels • Fridge plant availability • Total number of fridge plants • Columns pressure threshold • Chilled water demand • Ambient temperature • Max temperature of chilled water dam • Dam level restrictions • Dam sizes 	<ul style="list-style-type: none"> • Chilled water demand • Hot and chilled water dam levels • Columns pressure threshold • Reliability • Potential energy that can be generated (minimum distance for optimal efficiency) • Dam level restrictions • Dam sizes

To ensure the solution will not influence the production of the selected mine negatively, the constraints that must be met should be tabulated. These values can be obtained from mining personnel by discussing the areas that will be influenced with them. For example; if the refrigeration system is being investigated, certain temperatures are required for instruments to function properly. It is therefore important to discuss these values with the relevant personnel.

All the collected constraints can then be summarised and tabulated as shown in Table 9. This table will form the basis of the study and therefore it is extremely important that the information is correct.

Table 9: Constraints summary example

Constraints summary			
	Maximum	Minimum	Check
Dam Levels %			
Surface chill dam	100	30	
Surface hot dam	95	30	
Underground dam	100	30	
Pre-cooling dam	95	30	
Dam Temperatures °C			
Surface chill dam	8	4	
Surface hot dam	N/A	N/A	
Underground dam	N/A	N/A	
Pre-cooling dam	28	15	
Number of Pumps			
Surface	4	0	
Underground	4	0	
Number of Fridge Plants			
Surface	5	0	
Underground (UG)	2	0	
Other Temperatures °C			
Chilled water to UG	12	4	
Air to UG	15	N/A	

With the constraints and objectives identified, the focus can shift to the automation of the systems. Most mines tend to prefer automatic control in the last few years [9].

Automation

Automation of mining equipment and operations is a very popular and effective method to optimise cost savings potential by eliminating the influence of human error [9].

LM initiatives are usually controlled by automated systems due to higher reliability. It is, however, possible to control the water reticulation system without automated infrastructure, but it becomes labour intensive. The control room operators will be required to monitor the systems more intensively and may neglect other responsibilities. It will therefore be ideal to optimise the use of a 3CPFS with the availability of automated infrastructure.

Once the systems have been characterised the next step is to collect the relevant data to analyse and evaluate the general operation of the systems. The data analysis would also aid in revealing the scope for optimising the systems.

3.4 Data collection and analysis

3.4.1 Preface

Data plays an important role in any investigation and it is therefore essential that sufficient and credible data is available to make sensible decisions. The data integrity is important as it will be used to change operations that control conditions underground. Baselines will also be developed from the data, which will be used to measure the performance of optimised solutions.

3.4.2 Data collection

Table 10 and Table 11 summarise the data required for all the parameters on the water reticulation system. The requirements for all three sub-systems are tabulated.

Table 10: Refrigeration data requirement table example

Refrigeration data	
Parameter	Measurement Point
Dam levels [%]	<ul style="list-style-type: none"> • Surface chill dams
Temperature [°C]	<ul style="list-style-type: none"> • Surface chill dams • BAC water inlets • BAC water outlets • BAC air inlets • BAC air outlets
Flows [ℓ/s]	<ul style="list-style-type: none"> • FP condensers • FP evaporators • Water to BAC • Water from BAC
Electrical power [kW]	<ul style="list-style-type: none"> • FP chillers • BAC fans • Condenser pumps • Evaporator pumps

Having identified the crucial measurements in the refrigeration system, identifying the crucial measurements in the dewatering and 3CPFS systems is the next step.

Table 11: Dewatering and 3CPFS data requirement table example

Dewatering and 3CPFS data	
Parameter	Measuring Point
Dam levels [%]	<ul style="list-style-type: none"> • Dams on dewatering levels • Surface chill dam
Temperatures [°C]	<ul style="list-style-type: none"> • Surface chill dam
Flows [ℓ/s]	<ul style="list-style-type: none"> • All dewatering pumps • 3CPFS
Electrical power [kW]	<ul style="list-style-type: none"> • All dewatering pumps • All 3CPFS filler & friction pumps

With all the crucial measurements identified, the data collection process can begin. There are numerous methods to obtain the data for the parameters stipulated in Table 10 and Table 11. The different options and methods are discussed in the following sections.

3.4.2.1 SCADA system data

Most mines make use of a supervisory control and data acquisition (SCADA) system to control the equipment and processes. Most of these systems have the capability to store historical data for all the measured parameters, including that of the water reticulation system. For this reason, SCADA data is usually the ideal option in obtaining data. Figure 30 is an example of a mine's water reticulation system on the SCADA.

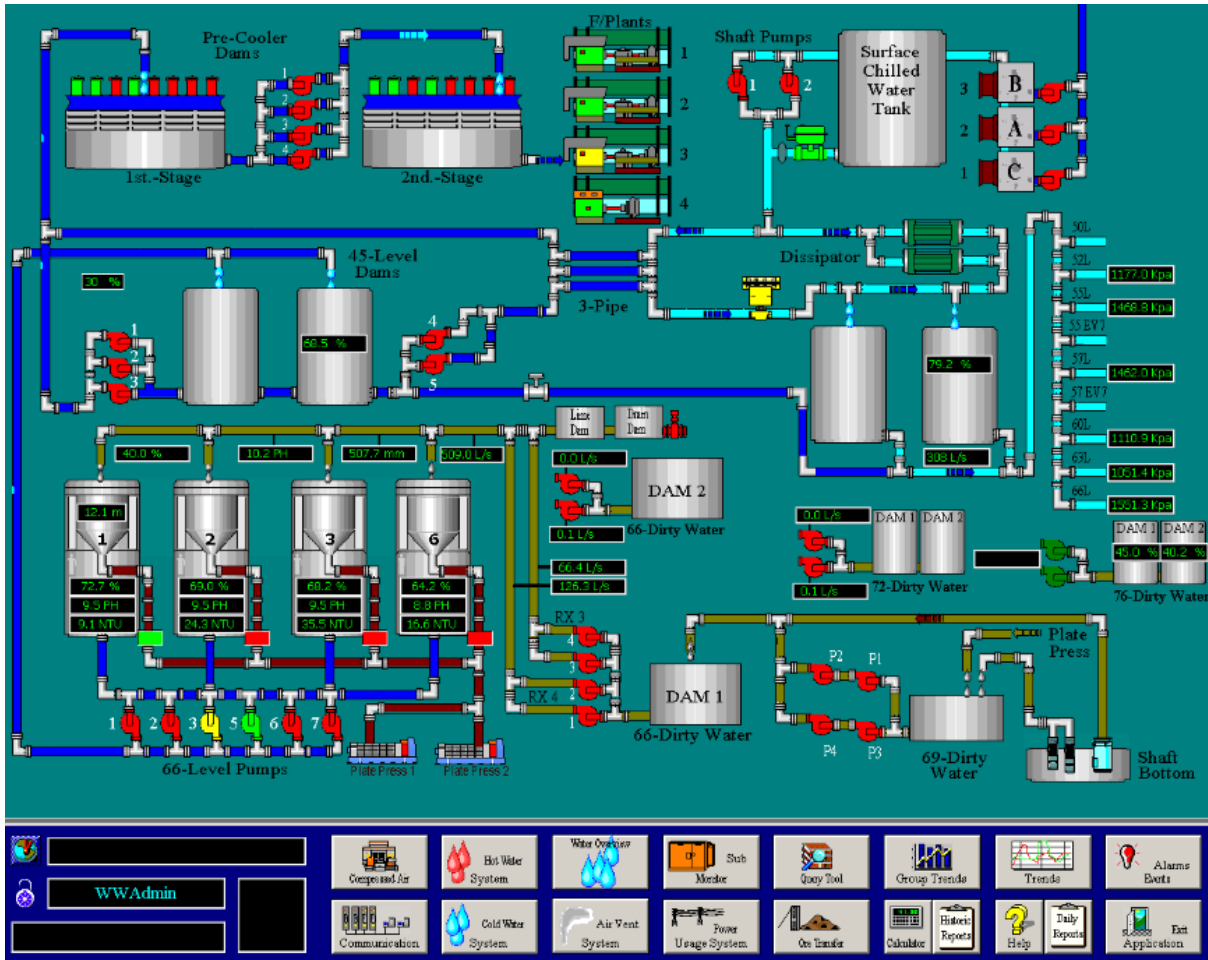


Figure 30: Mine SCADA

In some instances, the measurements on the SCADA system need to be verified. The calibration certificates of the measuring equipment must be requested in such instances to eliminate the factor of faulty instrumentation. Alternative options are, however, available to obtain data in the case of faulty instrumentation or if no data is available on the SCADA system. These options come in the form of log sheets and manual readings.

3.4.2.2 Log sheets

Some mines use log sheets if their instruments are not connected to a SCADA system for monitoring purposes. This is a manual process where readings are written down on a piece of paper. These sheets typically contain all the important information that one would also find on the SCADA.

As it is a manual process, the readings are exposed to the factor of human error and not always trustworthy. Log sheets should therefore be considered a last resort when collecting the required data. It would be more reliable to manually measure the required data with calibrated portable equipment.

3.4.2.3 Manual readings

There are numerous types of measuring instruments that can be used for different applications. It is very important to note that one must familiarise oneself with the use of these instruments to ensure accurate readings are taken. For the purposes and relevance to this study the following are discussed:

Water flow measurements

An ultrasonic flowmeter can be used to measure the water flow in the pipes. This instrument is clamped onto the pipe and uses ultrasonic pulses to determine the flow of the water in the pipe. Figure 31 is an example of an ultrasonic flow meter. The logger can be seen in the top left corner with the “clamp-on” sensors at the right and the connection cables at the bottom



Figure 31: Ultrasonic flow meter

Electrical power measurements

A power logger can be used to measure and log the required power data. An example of such a device is a DENT instrument logger which is displayed in Figure 32 on the right. The yellow, blue & red clips are the voltage lead clips for each phase. The black and white twisted cables are the respective current leads.



Figure 32: DENT logger

Dam level measurements

A level pressure transmitter can be used to determine the level of the dam. This sensor determines the level of the dam by measuring the pressure the water exerts on the installed sensor. Figure 33 is an example of such a level pressure transmitter.



Figure 33: Level pressure transmitter

Temperature measurements

Tinytag temperature loggers can be used to measure the temperatures on a wide set of applications. The dry-bulb temperature, relative humidity (RH) and pressure can be measured, depending on the probe used on the instrument. If it is a requirement the RH and dry-bulb temperature can then be used to calculate the wet-bulb temperature. Figure 34 is an example of a Tinytag with a wired temperature probe.



Figure 34: Tinytag with temperature probe

Once all the data sources and methods to obtain the data from these sources have been identified, the next step would be to collect the data for the analysis phase.

3.4.3 Data analysis and evaluation

Analysing the data would reveal the general operation of the water reticulation system and identify the influence of the 3CPFS on LM initiatives. The outcome of the analysed data will influence the development of a solution to optimise the use of the 3CPFS in the water reticulation system. Finally, baselines will be developed to measure and quantify the impact of optimisation strategies implemented on the systems.

3.4.3.1 Analysing the data

The first step is to analyse the power profile of all three sub-systems and see whether the LM initiatives are being implemented successfully. Figure 35 is an example of the power profile of the dewatering system with Eskom peak periods in red.

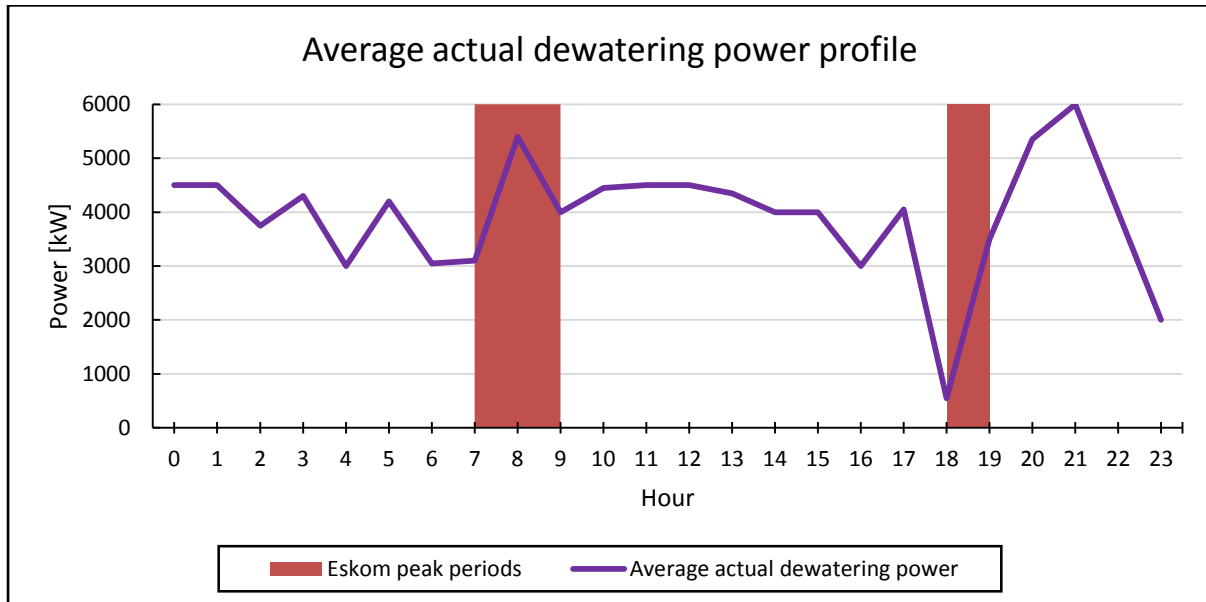


Figure 35: Average dewatering power profile

From Figure 35 it is clear that the dewatering system's LS was unsuccessful as there were pumps running during the Eskom peak periods. To establish the cause of the failed LS, the relevant dam levels should be investigated as well as the systems that can cause dam levels to be influenced.

For example, the level of the 35L dam is shown in Figure 36 with the min dam level limit in red. The dewatering pumps on 76L needed to start to increase the dam levels during Eskom peak periods as the limit was reached.

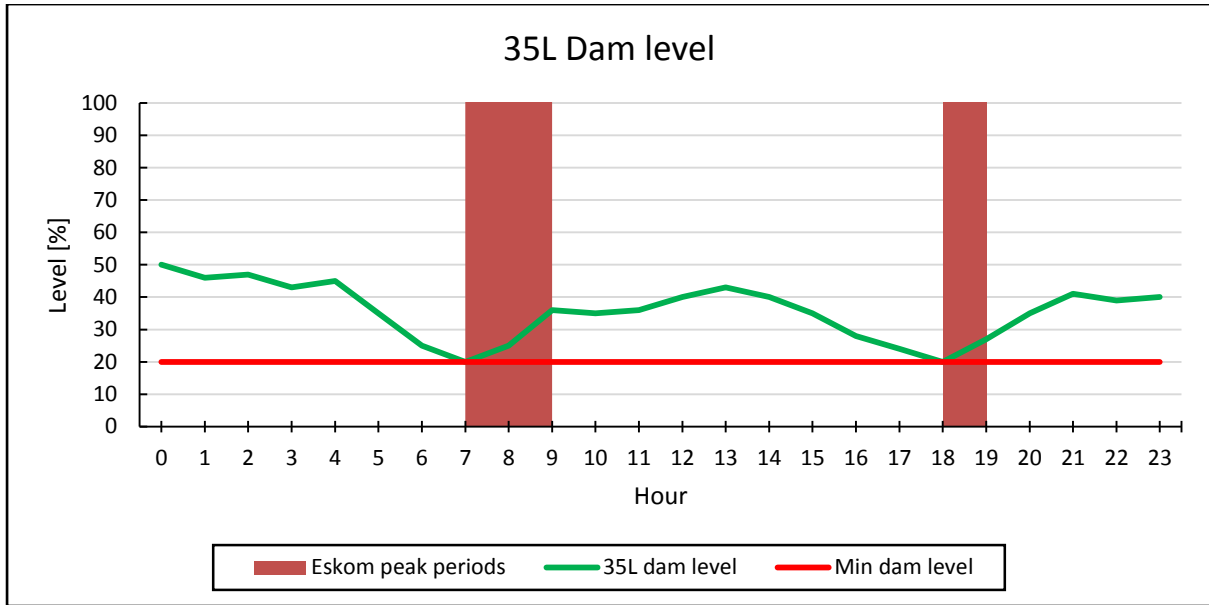


Figure 36: Dam level analysis example

With the dam levels investigated, the focus can shift to the cause of the dam being drained. The 3CPFS and the 35L dewatering pumps are the only systems that pump water out of the 35L dam. Therefore, the power profile of the 3CPFS and the 35L dewatering pumps should be investigated to see whether they were running during the periods in question.

Figure 37 shows the power profile of the 3CPFS in blue and the 35L dewatering pumps in orange for the same day. From the figure one can see that only the 3CPFS was running that day and that it caused the 35L dam level to dip below the limit. This in turn caused the 76L pumps to start and the LS failed.

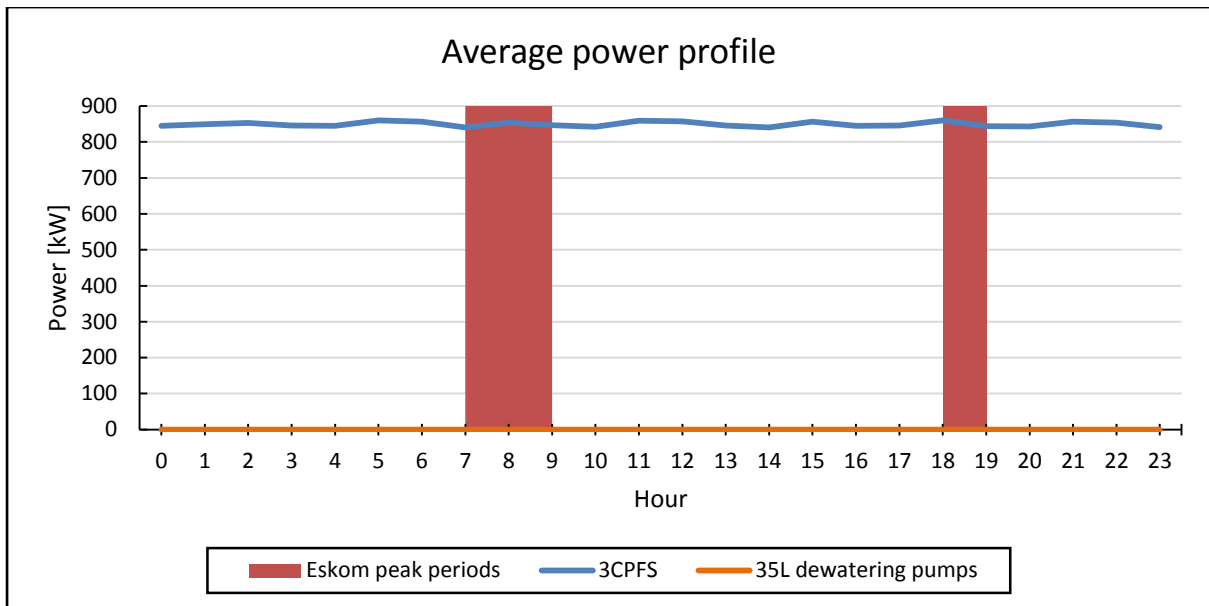


Figure 37: Average power profile example

This step should also be repeated for the refrigeration system to determine whether the LM initiatives are being negatively influenced.

With the data from the dewatering and refrigeration systems analysed, the focus can shift to the performance calculation steps. To calculate the performance, baselines should be generated.

3.4.3.2 Baseline development and adjustment

Baselines are developed and used to measure and quantify the performance of implemented initiatives. Baselines are developed with data gathered over a period of three months and averaged into hourly intervals. The three-month period ensures credibility and a true reflection of the typical operation of the systems. This procedure will be applied to all three sub-systems.

Figure 38 shows an example of a typical power baseline for a dewatering system on a deep-level gold mine. The Eskom summer peak times are highlighted in red.

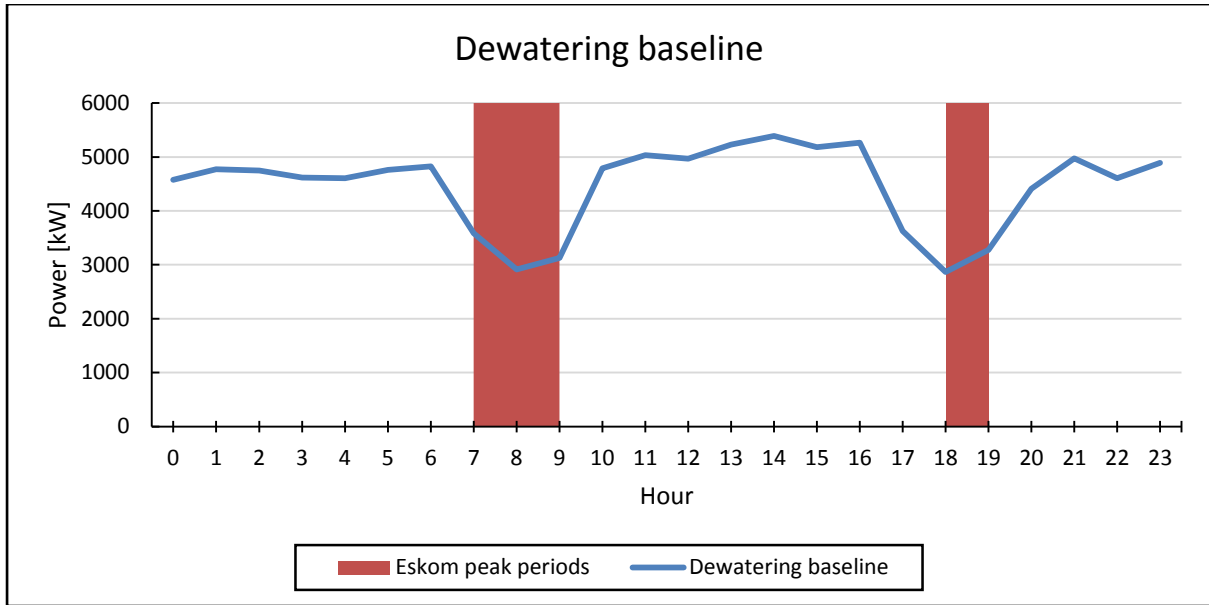


Figure 38: Dewatering baseline example

Baselines are adjusted to ensure the performance can be calculated accurately. Since the study focuses on optimal use of a 3CPFS to improve the load shifting potential on the dewatering pumps and fridge plants, only energy neutral baseline adjustments will be relevant. The baseline example mentioned earlier in this section is used as an example to explain the concept of an energy neutral baseline adjustment.

To calculate the performance the average power profile is compared with the adjusted power profile baseline. The current performance is then compared to the contracted performance to see how far off the target it is. The difference is the impact that inefficient control has on the mine.

The baseline will be adjusted using this formula:

$$E_{baseline_{adj}} = B * E_{Baseline_{M\&V}}$$

Equation 11: Baseline adjustment

Where $E_{baseline_{adj}}$ is the newly adjusted baseline value, B is the factor that is multiplied by the old baseline $E_{Baseline_{M\&V}}$ to ensure that the scaling is done according to the stipulated contract. B can be calculated by using Equation 12 where $\sum Actual\ Power$ is the total of the average power profile and $\sum Baseline_{M\&V}$ is the total of the M&V baseline power profile.

$$B = \frac{\sum Actual\ Power}{\sum Baseline_{M\&V}}$$

Equation 12: Baseline adjustment factor

Figure 39 shows a typical hourly averaged power profile of a dewatering system of the selected mine with the M&V baseline and adjusted scaled baseline next to it. Eskom summer peak times have been marked red for illustrative purposes. Eskom’s peak periods differ during the summer (September – May) and winter (June – August) times:

- Summer peak – 7am to 10 am and 6pm to 8pm
- Winter peak – 6am to 9 am and 5pm to 7pm

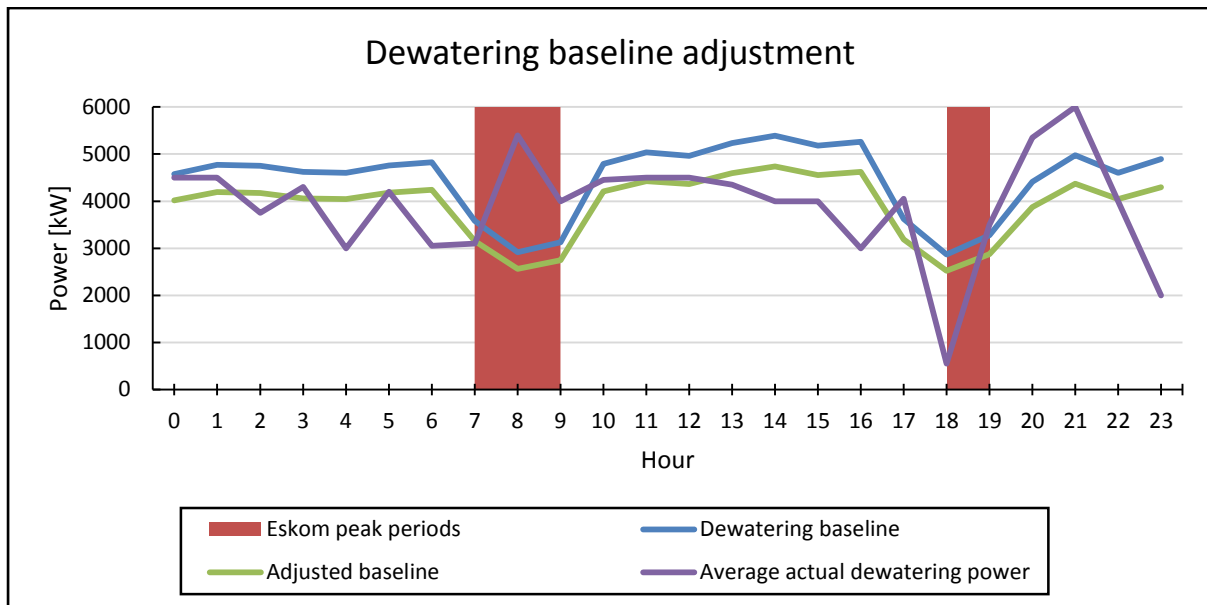


Figure 39: Dewatering baseline adjustment example

With the baseline adjustment procedure discussed, the performance calculation will be discussed in the following section.

3.4.3.3 Calculating project performance and missed opportunities

Using the baseline adjustment technique, the performance can now be calculated. Figure 40 shows the average power profile (blue) of a typical dewatering system on a gold mine. A baseline (red) that was approved by the M&V team and the adjusted baseline (green) are also plotted on the same graph for comparison. From the graph, it appears that the LM initiative is

not performing optimally as there are still large amounts of power being consumed during the Eskom peak periods. To determine whether the target is being reached, the load shift must first be calculated and then compared to the target of the contract.

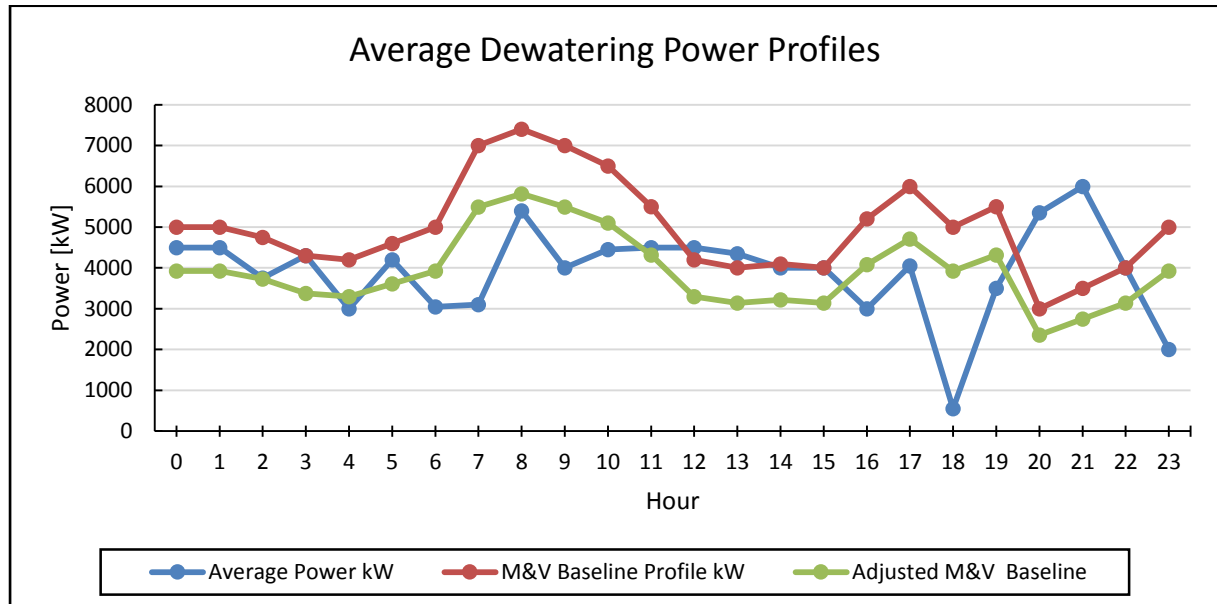


Figure 40: Dewatering power profiles and baselines

To calculate the load shift, Equation 13 can be used:

$$LS = \text{Average adjusted power}_{\text{evening peak}} - \text{Average actual power}_{\text{evening peak}}$$

Equation 13: LS performance calculation

Applying Equation 13 to the data in Figure 40:

The average of the adjusted power during evening peak is $(3926.93+4319.62)/2 = 4123.28$ [kW]. The average of the actual power during evening peak is $(550+3500)/2 = 2025$ kW. Therefore, the load shift is 2100 kW. If the target for this project is 2500 kW, then the project is not performing to target as it was 400 kW below target.

With the performance under target, the missed opportunities can now be determined. Missed opportunities can be calculated by changing the actual power to zero during hour 18 and 19 (ideal scenario/perfect load shift) and calculating the load shift again. By taking that load shift

value and subtracting the actual load shift value, the missed opportunities are calculated. This results in a 1.8 [MW] missed opportunity which would have resulted in a 187.51 [%] target achieved if all the pumps were off during evening peak.

With the entire system now understood and baselines generated, the optimal solution to improve the performance of these three systems can now be created. The procedure to develop the solution will be discussed in the following section.

3.5 Optimising control of 3CPFS

3.5.1 Preface

With the water reticulation system evaluated through the data analysis, the next step is to develop solutions to optimise the system. The solutions are mainly focused on optimising the utilisation of the 3CPFS to improve cost savings potential on the water reticulation system without negatively influencing the production output of the mine.

Optimisation starts off by identifying numerous feasible solutions that can be investigated. These solutions are then simulated and compared with actual test results. An optimal solution is then derived from the results and implemented on the system.

3.5.2 Solution development

Different possible solutions must be listed, simulated, validated and tested on the mine's system. This should ensure that an optimised solution is implemented and decreases the chances of negatively influencing the mine's production. For example, the following presents possible solutions:

- Switch off all the pumps, fridge plants, BACs, including the 3CPFS during Eskom evening peak periods.
- Switch off all the pumps, BACs, 3CPFS and run one FP during Eskom evening peak periods.
- Switch off all the pumps, 3CPFS and run one BAC and FP during Eskom evening peak periods.

To test these possible solutions, they must be simulated to see if they will meet the constraints set earlier. The process to develop and validate the simulation will be discussed in the next section.

3.5.3 Simulation verification

As discussed in Chapter 2, the simulation package used for this study is Process Toolbox (PTB). The data gathered, as illustrated in section 3.4, is used as inputs for the simulation. A simulated replica of the mine's water reticulation system could then be developed.

The simulation model should be verified to ensure high accuracy of simulated solutions. This is accomplished by identifying key parameters to be used as a baseline to compare with the simulation. The outputs of an actual day's operation are compared to the simulated operations of that same day. The outcome of this comparison determines the accuracy of the simulation model and whether there is a need for further calibration.

Table 12 serves as a checklist that can be used during the simulation verification for the water reticulation system.

Table 12: Verification checklist

Verification checklist			
Parameter	Simulation	Actual	Difference [%]
Dam Levels %			
Surface chill dam			
Surface hot dam			
Underground dam			
Pre-cooling dam			
Dam Temperatures °C			
Surface chill dam			
Surface hot dam			
Underground dam			
Pre-cooling dam			
Number of Pumps			
Surface			
Underground			
Number of Fridge Plants			
Surface			
Underground			
Other Temperatures °C			
Chilled water to UG			
Air to UG			

Figure 41 shows a simplified layout on the PTB simulation package containing dams, FPs and pipes. This is for illustration purposes and, as mentioned before, the investigated mine must be replicated in the simulation.

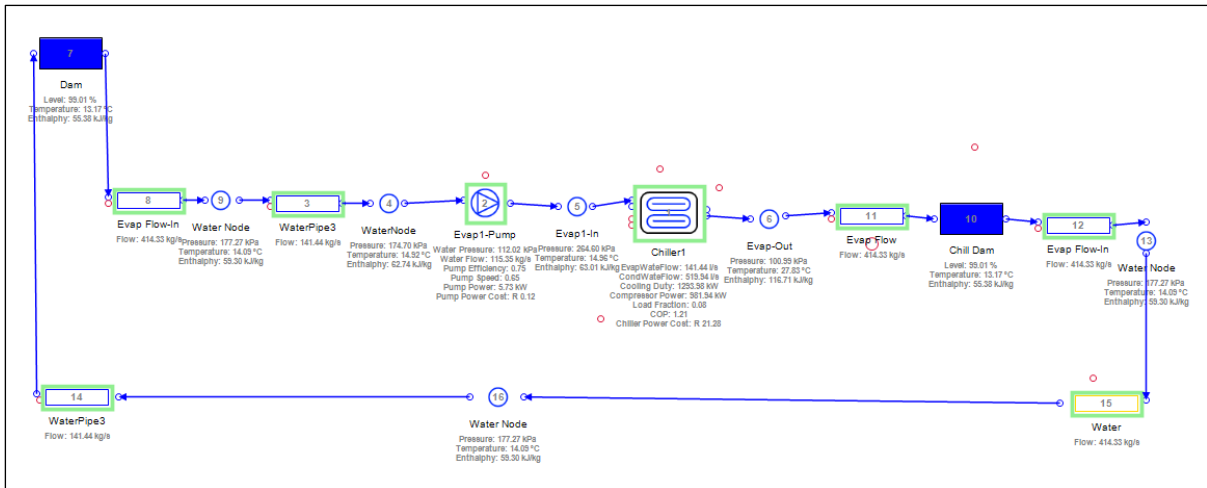


Figure 41: Simplified PTB layout

The simulation is verified if the overall differences of the verification checklist parameters are below 10%. The verified simulation model can be used to simulate the different developed scenarios to identify the most suitable solution. The procedure to develop the solution will be discussed in the next section.

3.5.4 Solution implementation

If the optimised solution has been developed, simulated and approved by the mine, the control philosophy can be implemented and validated by comparing the results to the objectives set. This will show whether the control philosophy is successful.

3.5.4.1 Feasibility and testing

The solutions developed in 3.5.2 are simulated with the help of the verified simulation model. It is important to note that the developed solutions should comply with the operational constraints identified for the system as discussed in section 3.3.3. Solutions not complying with the identified criteria should be eliminated.

With authorisation from relevant mining personnel, the most viable solutions can be implemented and results noted. The results are summarised in Table 13 for validation. Results that are outside of the constraints should be highlighted and investigated to ensure the solution will not negatively influence production.

For example, if the scenario was tested with everything switched off during the evening peak the table could look as follows:

Table 13: Constraints checklist example

Constraints checklist							
	Maximum	Minimum	Daily average actual maximum	Daily average actual minimum	Simulated Maximum	Simulated Minimum	Compliance to constraints
Dam Levels %							
Surface chill dam	100	30	90	17	89	20	
Surface hot dam	100	30	87	42	87	42	✓
Underground dam	95	30	92	44	93	43	✓
Pre-cooling dam	100	30	93	45	93	45	✓
Dam Temperatures °C							
Surface chill dam	8	4	6	4	6	4	✓
Surface hot dam	N/A	N/A	-	-	-	-	✓
Underground dam	N/A	N/A	-	-	-	-	✓
Pre-cooling dam	28	15	20	17	20	17	✓
Number of Pumps							
Surface	4	0	4	0	4	0	✓
Underground	4	0	4	0	4	0	✓
Number of Fridge Plants							
Surface	5	0	5	0	5	0	✓
Underground	2	0	1	0	1	0	✓
Other Temperatures °C							
Chilled water to UG	12	4	8	7	8	7	✓
Air to UG	15	N/A	12	10	12	10	✓

The red cells in Table 13 represent values not within the pre-set margins. This is where the optimisation comes in. By changing the scenario, for example keeping one FP running, the chill dam will not drain so quickly which will resolve this issue. The scenarios, however, must be tested to quantify the optimal solution.

If the constraints checklist is completed with all the values within the set parameters, the solution can then, with mining personnel’s permission, be implemented on the mine. The solution implementation will be discussed in the next section

3.5.4.2 Optimal solution implementation

Implementing the control philosophy can be done by programming it into the management system program if the equipment is automatically controlled. If the equipment is not automatic, ensure that the control room operator shuts off the desired components at the times specified by the control philosophy. With the control philosophy implemented, the results can be compared to calculate the performance. The process to analyse the results will be discussed in the next section.

3.5.4.3 Analysing the results

With the optimised solution implemented, the important parameters to keep in mind are the following:

- chill dam temperatures and levels;
- BAC incoming and outgoing air temperatures;
- BAC incoming and outgoing water temperatures;
- relevant dam levels; and
- number of components (FPs or pumps) that can run at the same time.

Table 14 is an example of a completed operational objective checklist containing the actual results.

Table 14: Completed constraints checklist for optimised solution

Constraints checklist for optimised solution					
	Maximum	Minimum	Actual Maximum	Actual Minimum	Check
Dam Levels %					
Surface chill dam	100	30	90	32	✓
Surface hot dam	100	30	87	42	✓
Underground dam	95	30	92	44	✓
Pre-cooling dam	100	30	93	45	✓
Dam Temperatures °C					
Surface chill dam	8	4	6	4	✓
Surface hot dam	N/A	N/A	-	-	✓
Underground dam	N/A	N/A	-	-	✓
Pre-cooling dam	28	15	20	17	✓
Number of Pumps					
Surface	4	0	4	0	✓
Underground	4	0	4	0	✓
Number of Fridge Plants					
Surface	5	0	5	0	✓
Underground	2	0	1	0	✓
Other Temperatures °C					
Chilled water to UG	12	4	8	7	✓
Air to UG	15	N/A	12	10	✓

The next step is to calculate the performance of the systems with the baselines generated and then validate the results of the implementation with the simulated results.

3.5.4.4 Solution validation

The starting conditions of the implemented day are programmed into the simulation and the results from this simulation are summarised below in Table 15.

Table 15: Completed simulation validation checklist

Simulation validation							
	Maximum	Minimum	Actual Maximum	Actual Minimum	Simulated Maximum	Simulated Minimum	Check
Dam Levels %							
Surface chill dam	100	30	90	32	89	31	✓
Surface hot dam	100	30	87	42	87	42	✓
Underground dam	95	30	92	44	93	43	✓
Pre-cooling dam	100	30	93	45	93	45	✓
Dam Temperatures °C							
Surface chill dam	8	4	6	4	6	4	✓
Surface hot dam	N/A	N/A	-	-	-	-	✓
Underground dam	N/A	N/A	-	-	-	-	✓
Pre-cooling dam	28	15	20	17	20	17	✓
Number of Pumps							
Surface	4	0	4	0	4	0	✓
Underground	4	0	4	0	4	0	✓
Number of Fridge Plants							
Surface	5	0	5	0	5	0	✓
Underground	2	0	1	0	1	0	✓
Other Temperatures °C							
Chilled water to UG	12	4	8	7	8	7	✓
Air to UG	15	N/A	12	10	12	10	✓

With the solution developed, the results analysed, and the simulation validated, the chapter can be concluded.

3.6 Conclusion

To be able to develop an integrated control philosophy, the water reticulation system must be thoroughly investigated. All the constraints and characteristics of the system need to be analysed and tabulated. The different data collection procedures to follow were discussed.

From the collected data, the system performance and operation can be analysed. Baselines can also be generated to quantify the performance of optimised strategies.

The development of a simulation model was discussed along with the verification process. The process to develop and test different scenarios with the simulation model was presented. After the optimal solution has been developed, the steps to implement and analyse the results were discussed. With all the results available, the conclusion can be made on the feasibility of optimising the utilisation of a 3CPFS.

The developed methodology was tested on a practical case study, which is discussed in the following chapter.

CHAPTER 4

4 Implementing optimised control strategies

4.1 Introduction

The methodology developed in Chapter 3 was implemented on the water reticulation system of a South African deep-level gold mine. Chapter 4 presents the results of optimally utilising the 3CPFS in the integrated water reticulation system of this mine. For confidentiality reasons, the mine is referred to as Mine A.

4.2 Identifying the water reticulation system

4.2.1 Identify possible scope

It was found that the water reticulation system of Mine A comprises all three sub-systems. Table 16 presents the completed water reticulation system identification table.

Table 16: Completed water reticulation system identification

MINE NAME: Mine A		
Systems	Yes	No
Dewatering system	✓	
Refrigeration system	✓	
3CPFS	✓	

The sub-systems could be investigated to determine the scope for improvement. Through investigation it was found that LM initiatives were implemented on both the dewatering and refrigeration systems of Mine A. The focus was therefore on the performance of these initiatives and not to investigate the feasibility of implementing new LM initiatives.

The power profiles of both systems were analysed. Figure 42 and Figure 43 show the profiles of the dewatering and refrigeration system, respectively. These profiles were developed with data ranging over the same period.

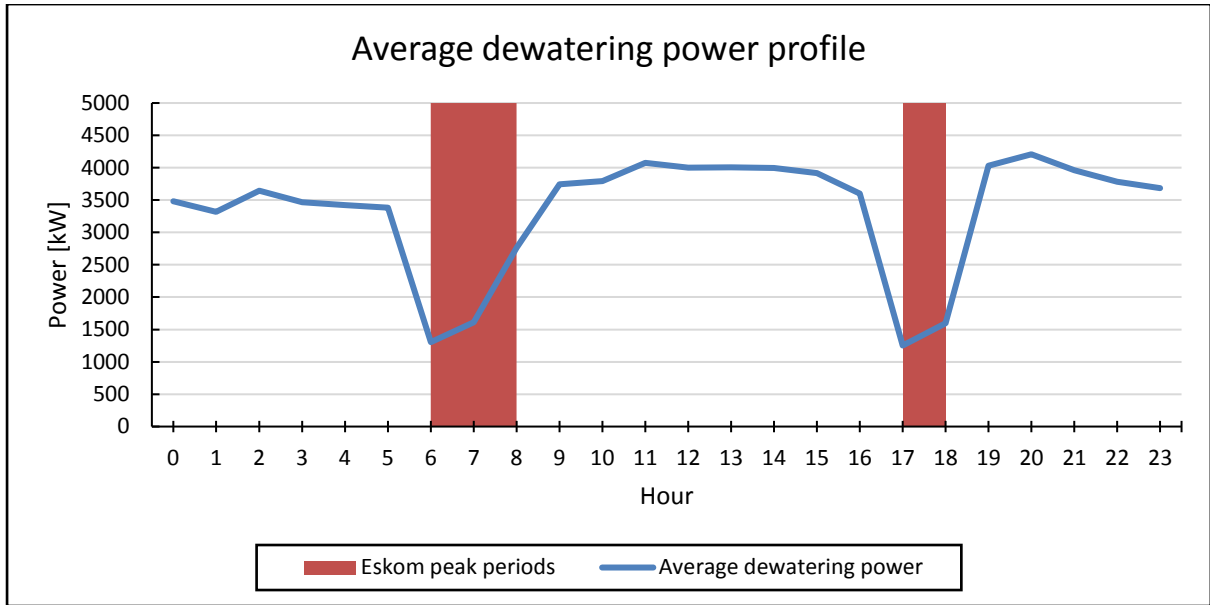


Figure 42: Dewatering power profile

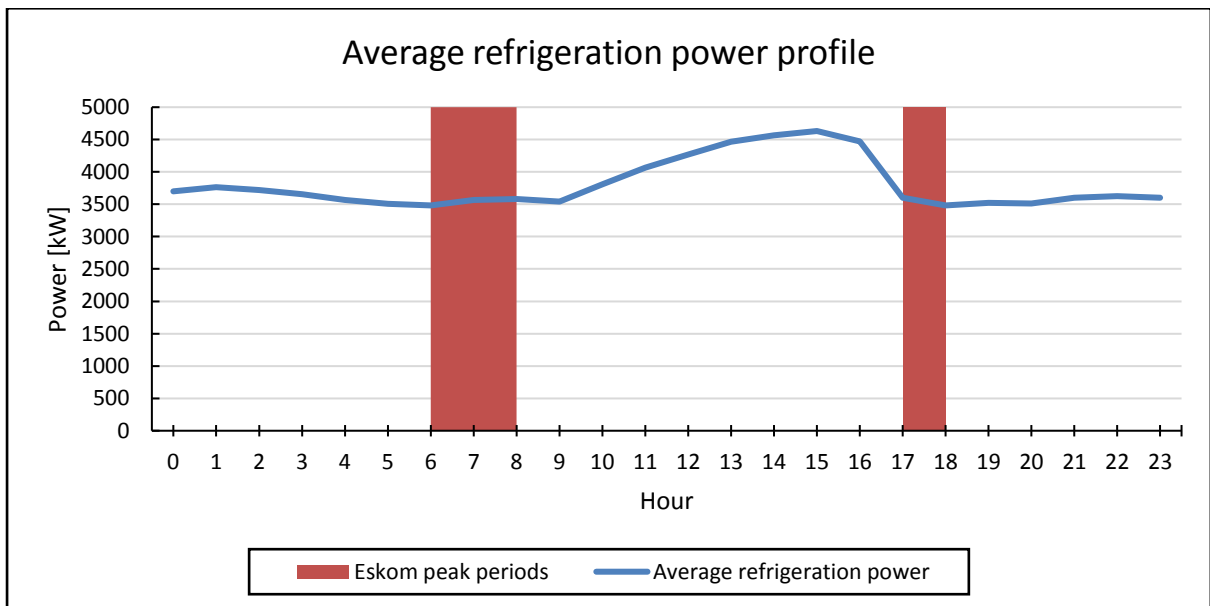


Figure 43: Refrigeration power profile

From Figure 42 & Figure 43 it seems as if there is scope to improve the performance of the LM initiatives. From the dewatering power profile, approximately 1.3 MW remains during load shifting over the Eskom peak periods, which indicates that optimal load shifting is not occurring. Figure 43 indicates that load shifting is non-existent on the refrigeration system.

The next step was to determine the root causes of the underperformance. After an in-depth investigation, which included several consultations with relevant mine personnel, it was concluded that the underperformance can mainly be attributed to the following:

- Chilled dam levels becoming too low due to the BACs and 3CPFS emptying the dams during the Eskom peak periods. This results in the fridge plants being started to recover the levels of the chilled dam.
- Hot water dam levels becoming too low due to the 3CPFS continuing to transfer water during the Eskom peak periods. This results in the dewatering pumps being started to recover the hot water dam levels.
- Unavailability of the 3CPFS and dewatering pumps, especially during critical periods of the day. This is mainly due to lack of maintenance.
- Inefficient dewatering pumps resulting in lower volumes of water being transferred.
- Lack of an effective control philosophy to accommodate the above-mentioned constraints.

It was further found that the main factor contributing to the underperformance of the LM initiatives on both systems is the ineffective use and control of the 3CPFS. Table 17 is the completed failing LM table for the water reticulation system of Mine A.

Table 17: Completed failing LM table

MINE NAME: Mine A		
Aspects	Yes	No
LM initiatives implemented on the water reticulation system		
Dewatering systems	✓	
Refrigeration systems	✓	
3CPFS		✓
Failing LM initiatives		
Dewatering systems	✓	
Refrigeration systems	✓	
3CPFS	N/A	N/A

Table 17 shows ample scope for optimisation as the performance of the LM initiatives on the dewatering and refrigeration systems is low. One of the main reasons for this is inefficient control of the 3CPFS. Mine A therefore met all the requirements that were set out in Chapter 3. The next step was to characterise the water reticulation system of Mine A.

4.3 Characterising the system

4.3.1 Evaluating system layouts

Refrigeration

Figure 44 depicts the detailed layout of Mine A’s refrigeration system. The main components include four fridge plants installed on surface, four condenser cooling towers, three BACs, and first and second stage pre-cooling towers.

The hot water, displaced by the 3CPFS from underground, goes through the pre-cooling stages and accumulates in pre-cooling dam 2 before it enters the fridge plants. The water from the fridge plant outlet is sent to the BACs or the surface chill dam. From the surface chill dam, the water enters the 3CPFS where the potential energy of the water is used to displace the warm water to the surface.

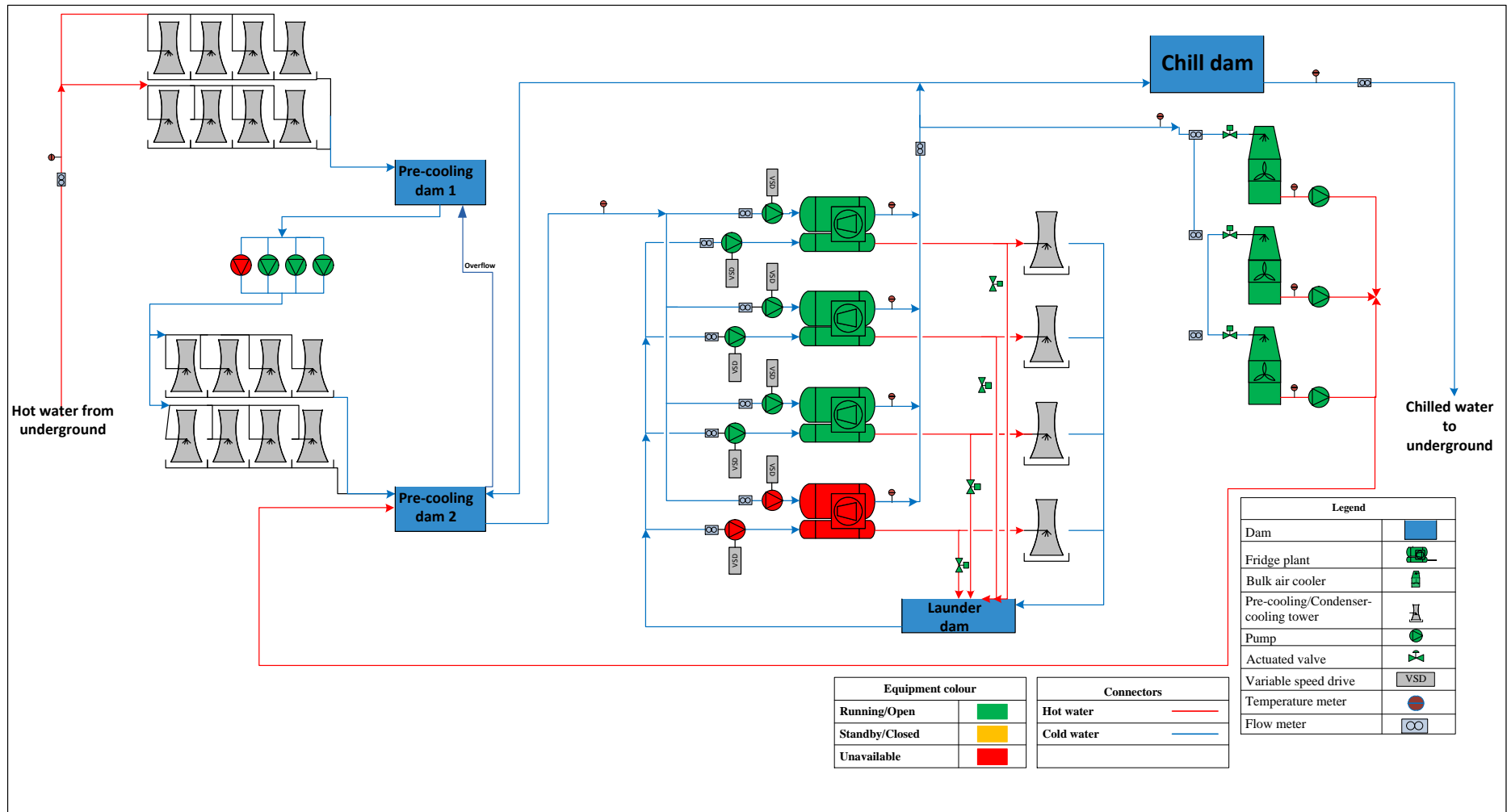


Figure 44: Mine A refrigeration system layout

From Figure 44 it can be seen that the refrigeration system is rather intricate and small changes may influence the system negatively. Therefore, the important measurements on the refrigeration system are as follow:

- the surface chill dam level;
- the evaporator outlet temperature;
- the evaporator water flow rate;
- the power consumption of the chillers;
- the surface BAC water inlet and outlet temperatures;
- the surface BAC air inlet and outlet temperatures; and
- the pre-cooling dam sizes and levels.

The next step was to evaluate the dewatering and 3CPFS layout.

Dewatering and 3CPFS

Figure 45 depicts the detailed layout of the dewatering system at Mine A, including the 3CPFS. Mine A has four pumping stations, but the focus will be on the 45L and 66L pumping stations. These pumping stations handle the clear water and not dirty water as the two remaining levels.

Chilled water is moved from the surface to the 45L chilled dam via the 3CPFS. From here the water is gravity fed to the working places through extensive pipe networks. The dirty water (used water) is then pumped to the settlers on 66L where it is cleaned and pumped to the 45L hot dam. The 3CPFS then uses two filler pumps on 45L and the potential energy of the chilled water to fill the 45L chilled dam and displace the hot water in the 45L hot dam to surface.

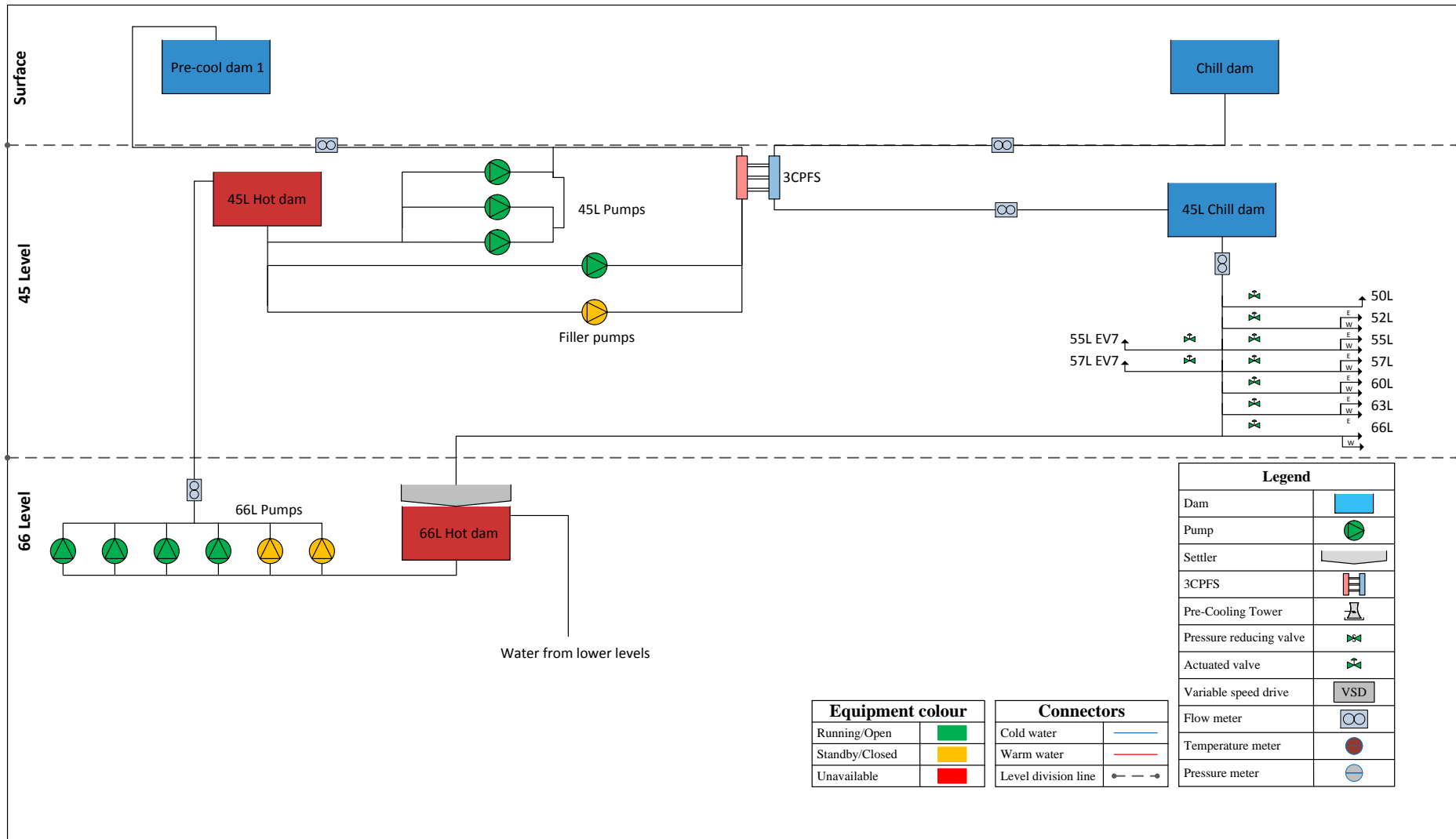


Figure 45: Mine A dewatering system layout

From Figure 45 it can be seen that the dewatering pumps and 3CPFS are intricately connected. The important measurements are as follow:

- the 45L chilled dam levels and sizes;
- the 66L hot dam levels and sizes;
- the water flow rate from 45L to surface;
- the water flow rate from 66L to 45L;
- the 3CPFS water flow rate from and to underground; and
- the power consumption of every pump and 3CPFS.

The final step during the evaluation phase is to investigate the entire integrated system and characterise the influence of the 3CPFS on both the dewatering and refrigeration system

Integrated system

A simplified integrated layout is depicted by Figure 46, which includes the surface refrigeration, 3CPFS and dewatering systems. The 3CPFS inter-connects the other two systems to form the entire water reticulation system. This also means that the 3CPFS has a direct influence on both the refrigeration and dewatering system.

The 3CPFS uses the water in the surface chill dam (refrigeration system) to displace the hot water on 45L. The 3CPFS influences the refrigeration system as it requires a constant water feed from the surface chill dam. When the FPs are switched off during the Eskom peak periods, there is no chilled water feeding the chilled dam which consequently results in the 3CPFS emptying the dam. This results in the FPs to be started and influences the load management initiatives.

The 3CPFS also influences the dewatering system as it displaces water directly from the 45L hot dam when it is running. If the 45L hot dam level decreases, the 66L pumps are started to maintain the required dam level for the 3CPFS to continue functioning. This directly influences the load management initiative on the dewatering system as in some instances the pumps need to be started during the Eskom peak periods.

With a thorough understanding of the entire water reticulation system and how the 3CPFS influences the other systems, the focus can shift to baseline generation.

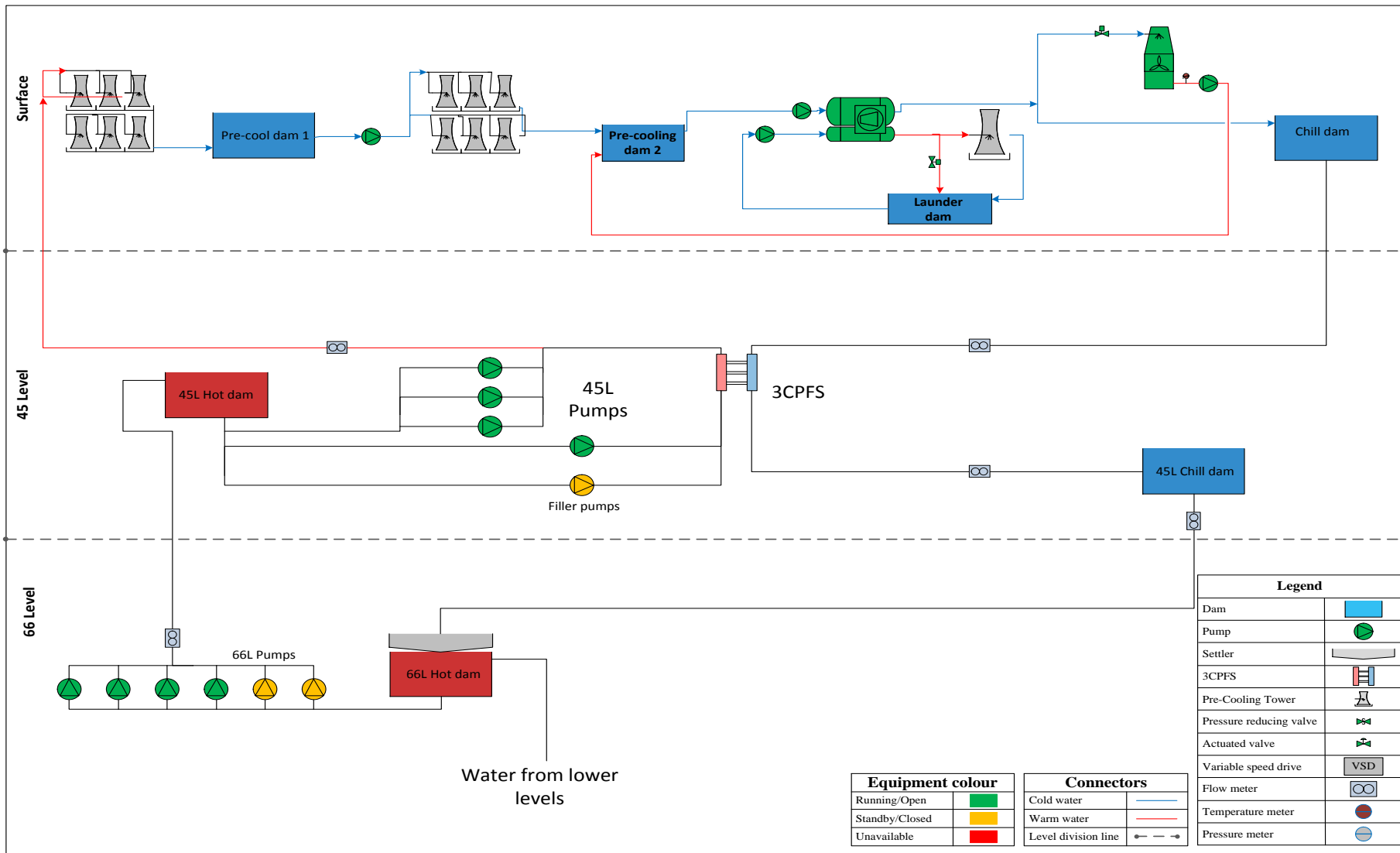


Figure 46: Simplified layout of the integrated water reticulation

With the entire water reticulation system evaluated and understanding how the 3CPFS influences the other two systems, the focus moves to identifying the system constraints.

4.3.2 System characteristics and constraints

Identifying the system characteristics and constraints is very important as it forms the boundaries for the solution development phase. The constraints formulated for the three sub-systems are tabulated in Table 18:

Table 18: Sub-system constraints

Constraints: Mine A		
Dewatering	Refrigeration	3 CPF system
<ul style="list-style-type: none"> • Max and min dam levels • Pump availability • Total number of pumps • Columns pressure threshold • Automatic control capabilities • Water demand of the mine • Efficiencies of pumps • Dam level restrictions • Dam sizes 	<ul style="list-style-type: none"> • Max and min dam levels • Fridge plant availability • Total number of fridge plants • Columns pressure threshold • Chilled water demand • Ambient temperature • Max temperature of chilled water dam • Dam level restrictions • Dam sizes. 	<ul style="list-style-type: none"> • Chilled water demand • Hot and chilled water dam levels • Columns pressure threshold • Reliability • Potential energy that can be generated (minimum distance for optimal efficiency) • Dam level restrictions • Dam sizes

Table 19 shows the completed constraints checklist for the relevant information gathered to ensure that production related activity is not influenced.

Table 19: Constraints checklist for Mine A

Constraints summary			
	Maximum	Minimum	Check
Dam Levels %			
Surface chill dam	95	50	✓
Surface hot dam	100	35	✓
45L Chill dam	100	35	✓
66L Hot dam	90	35	✓
Pre-cooling dam	100	30	✓
Dam Temperatures °C			
Surface chill dam	10	2	✓
Number of Pumps			
45L	1	0	✓
66L	4	0	✓
Number of Fridge Plants			
Surface	4	0	✓
Other Temperatures °C			
Chilled water to UG	11	3	✓
Air to UG	16	N/A	✓

After the constraint values have been identified and stipulated, the next step is to investigate the automation capabilities of Mine A's systems. In some instances, it may also be seen as a constraint, especially when limited automated infrastructure is available.

Automation

The dewatering and refrigeration systems at Mine A are fully automated and the load management initiatives are controlled by REMS. The 3CPFS is also automated, but not automatically controlled due to its unreliability. The automated control of the LM initiatives on the dewatering and refrigeration systems does not take the operation of the 3CPFS into account. This influences the performance of the initiatives.

With the water reticulation system fully characterised and all the constraints identified, the next step is to collect the relevant data for analysis.

4.4 Data collection and analysis

4.4.1 Data collection

Table 20 & Table 21 summarises all the parameters from which the data will be required.

Refrigeration

Table 20: Mine A refrigeration data requirement table

Refrigeration data	
Parameter	Measurement point
Dam levels [%]	<ul style="list-style-type: none"> • Surface chill dam
Temperature [°C]	<ul style="list-style-type: none"> • Surface chill dam • BAC water inlets • BAC water outlets • BAC air inlets • BAC air outlets
Flows [ℓ/s]	<ul style="list-style-type: none"> • FP condensers • FP evaporators • Water to BAC • Water from BAC
Electrical power [kW]	<ul style="list-style-type: none"> • FP chillers • BAC fans • Condenser pumps • Evaporator pumps

Table 21: Mine A dewatering and 3CPFS data requirement table

Dewatering and 3CPFS data	
Parameter	Measuring Point
Dam levels [%]	<ul style="list-style-type: none"> • Dams on 45L and 66L • Surface chill dam
Temperatures [°C]	<ul style="list-style-type: none"> • Surface chill dam
Flows [ℓ/s]	<ul style="list-style-type: none"> • All dewatering pumps on 45L and 66L • 3CPFS
Electrical power [kW]	<ul style="list-style-type: none"> • All dewatering pumps on 45L and 66L • All 3CPFS filler and friction pumps

Mine A has all the required data available on the local SCADA system, except for the power consumption of the 3CPFS (refer to 4.4.2.2 for 3CPFS power readings). This is advantageous as no manual readings or measurements need to be taken as historical data can easily be obtained.

4.4.2 Data analysis and evaluation

4.4.2.1 Analysing the data

The data of a random day was selected for analysis to obtain a general overview on the operation of the water reticulation system at Mine A. Average profiles were constructed for the power consumption of the major components as well as for the operational parameters. The developed profiles are presented in this section.

Figure 47 shows the average power consumption profile of the dewatering pumps. It can be seen that the LS during the Eskom peak periods was unsuccessful. The large concern is during the evening peak period as there was a drastic increase in power consumption.

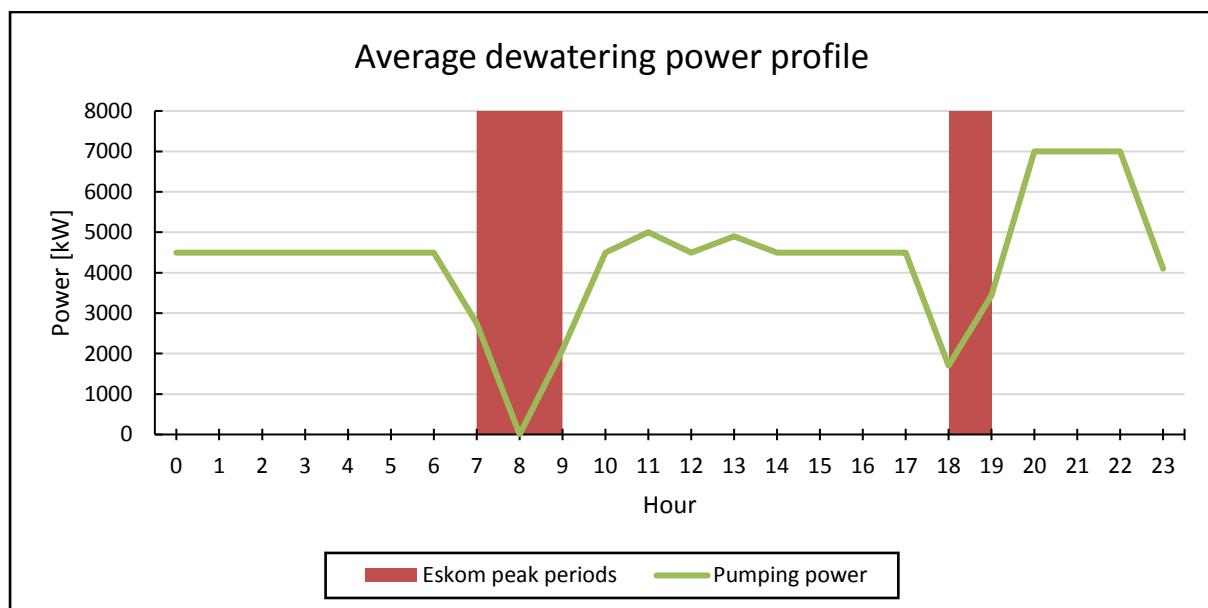


Figure 47: Average dewatering power profile

To determine the cause of the underperformance, the dam level of the 45L hot dam was analysed. The 66L dewatering pumps will only start when the 45L hot dam reaches its minimum level. Figure 48 shows the dam level reaching the minimum level of 35% and the 66L pumps had to be started to increase the dam level.

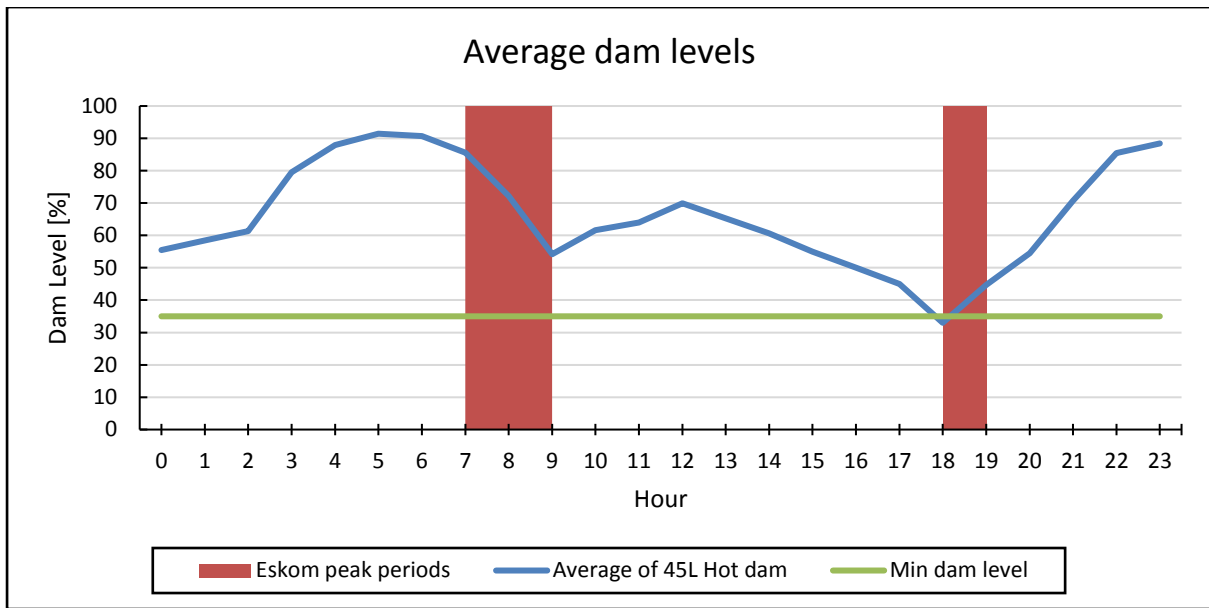


Figure 48: Average 45L dam level

Figure 49 depicts the running statuses of the 3CPFS and 45L dewatering pumps as these are the only components that could empty the 45L hot dam. On this particular day the 3CPFS was running the whole day until 20:00, with no 45L dewatering pump used. The influence of the 3CPFS in emptying the 45L hot dam becomes clearly visible.

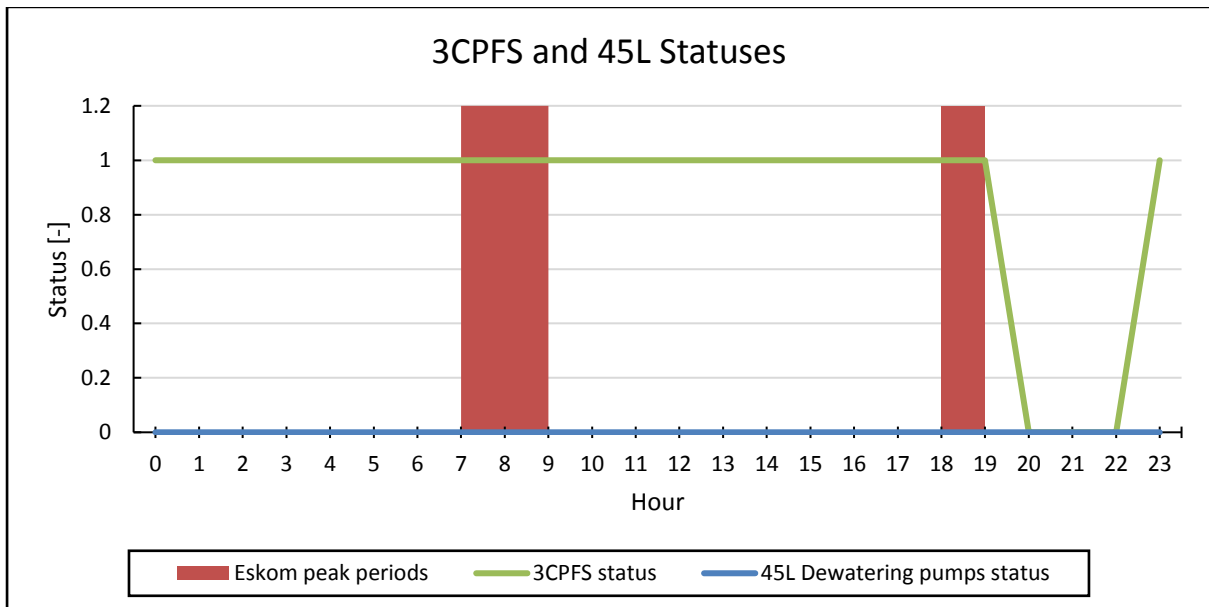


Figure 49: Average 3CPFS and 45L dewatering pumps statuses

Figure 50 depicts the refrigeration power profile of the same day and the findings for the failed LM initiatives were very similar. The FPs were switched off too early to perform a LS during the evening peak period and at 18:00 the power consumption increased dramatically.

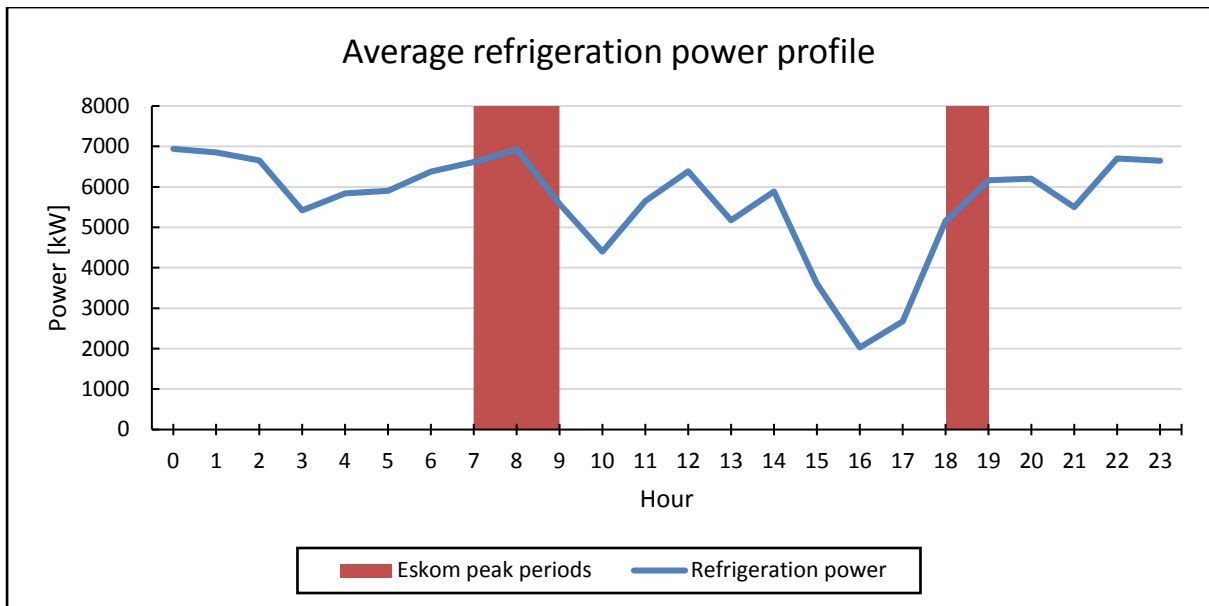


Figure 50: Average refrigeration power profile

The surface chill dam level and temperature were analysed to determine the exact cause of the fridge plants start-up. Figure 51 shows that the surface chill dam level reached its minimum level of 50[%] and the FPs were started to recover the dam level. The temperature also started to increase drastically from 15:00 due to the early shut down and this also played a big part in starting the FPs at 18:00.

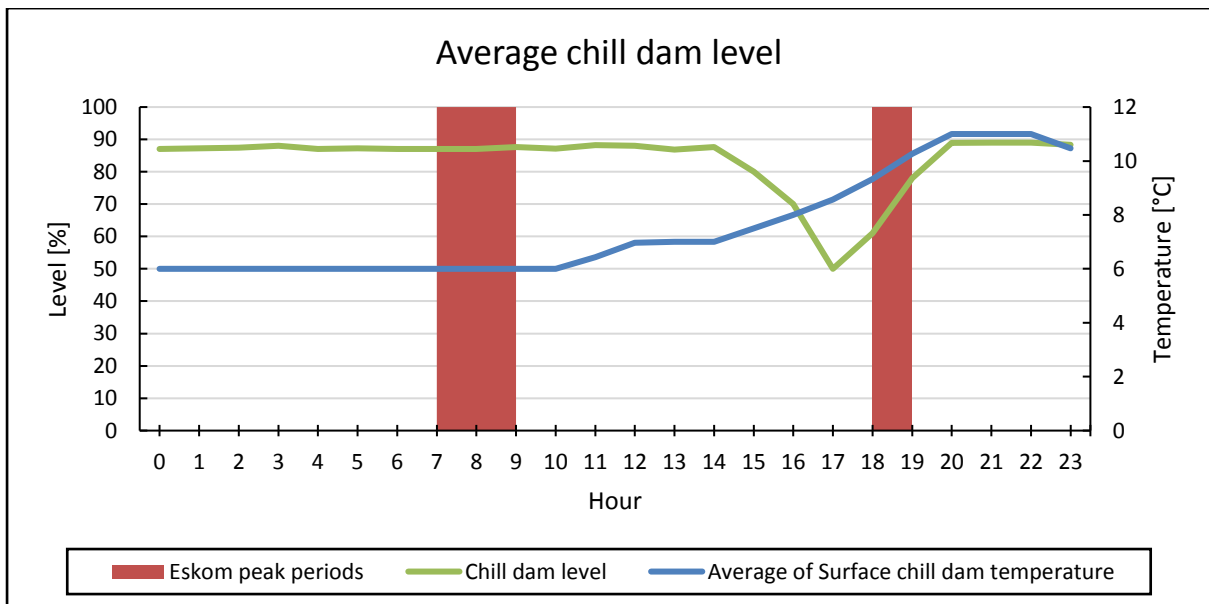


Figure 51: Average surface chill dam level and temperature

The surface chill dam can only be emptied by the 3CPFS or a valve that can be opened when the 3CPFS is out of order. Figure 49 indicated that the 3CPFS was running on this particular day and thus the cause of the failed load shifts.

From the analysed data it is clear that the 3CPFS is negatively influencing the LM initiatives implemented on both the refrigeration and dewatering systems of Mine A. There is thus a need to develop a solution to optimally utilise the 3CPFS to accommodate these initiatives without compromising the service delivery of these systems. It is, however, important to develop baselines of the existing performance to quantify the impact of any improvement strategies implemented on the water reticulation system.

4.4.2.2 Baseline development

The power consumption baselines were developed for the sub-systems with data over a consecutive three-month period. There are no power meters installed on the 3CPFS' pumps and limited access prohibited the capture of manual measurements. The running status of the 3CPFS was, however, available and with the help of the installed ratings of the pumps, a power profile could be derived.

Figure 52 depicts the power consumption baselines of the sub-systems.

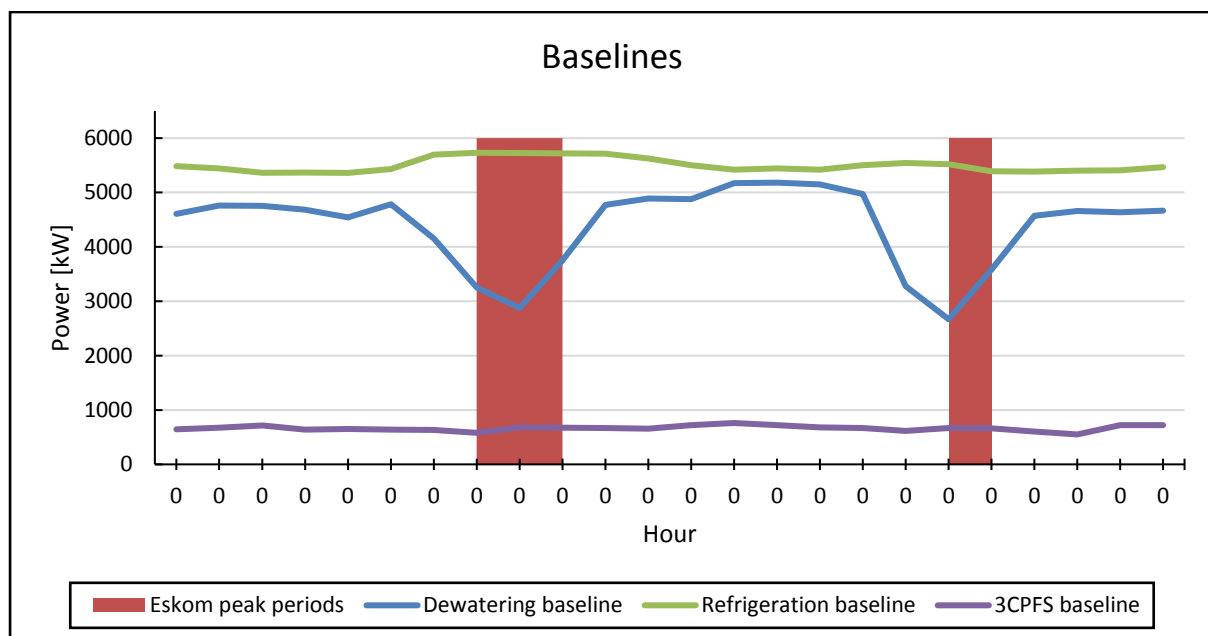


Figure 52: Sub-system baselines

Energy neutral baseline scaling was applied to the baselines of all three systems after implementation of optimisation strategies. The next section focuses on the performance and missed opportunities of the load management initiatives.

4.4.2.3 Calculating project performance and missed opportunities

According to mining personnel, the Eskom peak period targets for the load management initiatives implemented on the dewatering and refrigeration systems are:

- Refrigeration – 810 [kW] (Evening peak daily average)
- Dewatering – 2 100 [kW] (Morning and evening peak daily average)

No initiative was implemented on the 3CPFS and therefore no target was assigned. The performance of the remaining two sub-systems, averaged over the three-month baseline period, was calculated as follows:

Table 22: Sub-system average performance

Sub-system performance	
Refrigeration	Dewatering
779 kW (Month 1)	1690 kW (Month 1)
184 kW (Month 2)	444 kW (Month 2)
31 kW (Month 3)	1220 kW (Month 3)

From Table 22 it can be seen that the systems are clearly underperforming compared with the allocated targets. This is due to the ineffective control and operation of the 3CPFS. If the control had been effective, the performances of the initiatives would have been much higher than what was achieved. This deficit is referred to as the missed opportunities and was calculated as follow:

Table 23: Sub-system average missed opportunities

Sub-system missed opportunities	
Refrigeration	Dewatering
4350 kW (Month 1)	2228 kW (Month 1)
3000 kW (Month 2)	2736 kW (Month 2)
2600 kW (Month 3)	2140 kW (Month 3)

It is important to note that the missed opportunities were calculated for the ideal scenario where everything is switched off during the Eskom peak periods. With proper dam preparation and optimal utilisation of the 3CPFS, it is possible to completely switch off the dewatering system during the Eskom peak times. The refrigeration system is different as the mine depends on chilled water for its operations. It is, however, possible to optimise the load shifts to realise the maximum benefit during Eskom evening peak times.

The next section focuses on the development of a solution to optimally utilise the 3CPFS to realise maximised cost savings on the water reticulation system of Mine A.

4.5 Optimising control of 3CPFS

4.5.1 Solution development

The following solutions were identified for possible optimisation of Mine A's water reticulation system:

- Switch off all the dewatering pumps, fridge plants, BACs and the 3CPFS during the Eskom evening peak periods.
- Switch off all the pumps, BACs, 3CPFS and run one FP during the Eskom evening peak periods.
- Switch off all the pumps, 3CPFS and run one BAC and FP during the Eskom evening peak periods.

The feasibility of these solutions was simulated to determine the theoretical impact on the system. It was, however, first required to verify the accuracy of the simulation model developed for Mine A.

4.5.2 Simulation verification

An integrated simulation model was developed for Mine A, including the 3CPFS, dewatering and refrigeration systems. Refer to Appendix B: Simulation, for the inner detail on the developed simulation model.

To verify the simulation, a random day was simulated by using the actual data from the water reticulation system as inputs. The outputs of the simulation were then compared to the actual outputs of the system. For the purposes of this study, an overall error margin of 10 % was determined to be acceptable.

Table 24 shows the tabulated results comparing the actual and simulated parameters. The parameters with an error higher than 10 % were highlighted in red

Table 24: Completed verification checklist for Mine A

Verification checklist			
	Daily average (Actual)	Daily average (Simulated)	Average Difference [%]
Dam Levels [%]			
Surface chill dam	83	80	4
45L chill dam	46	44	4
66L hot dam	55	64	18
Dam Temperatures [°C]			
Surface chill dam	9	6	30
Other Temperatures [°C]			
Chilled water to UG	6	7	17
Air to UG	8	8.5	7
Power Usage [kW]			
Dewatering	4180	4190	>1
Refrigeration	4480	4438	>1

The simulation model proved to be accurate, except for irregularities found on the chill dam temperature, 66L hot dam level and chilled water to underground temperatures. After extensive investigations, the irregularities could be explained, and the simulation was credibly verified. Refer to Appendix C for detailed information on the verification process.

The next step was to simulate the feasibility of the different possible solutions and validate the results with actual tests.

4.5.3 Solution implementation

4.5.3.1 Feasibility and testing

The first scenario of switching off all the FPs, pumps, 3CPFS and BACs during the evening peak will be investigated as it is the best-case scenario in terms of cost saving. By switching off all the components mentioned, it should ensure that the relevant dams will not drain or fill too fast and cause the FPs or pumps to start during the evening peak period.

Everything off

With the ambient conditions, dam levels and certain starting temperatures assumed, the scenario was simulated. The assumptions were made from averaging historical data to get a good starting point. Switching off all the fridge plants, dewatering pumps and BACs during Eskom peak times in the simulation delivered the following results:

Table 25: Completed operational objective checklist for all systems off

Operational objective checklist for Mine A					
	Maximum	Minimum	Daily average simulated maximum	Daily average simulated minimum	Compliance to constraints
Dam Levels %					
Surface chill dam	95	50	87	62	✓
45 Chill dam	100	35	81	64	✓
66L Hot dams	90	35	71	53	✓
Dam Temperatures °C					
Surface chill dam	12	2	9	5	✓
Number of Pumps					
45L	2	0	1	0	✓
66L	4	0	4	0	✓
Number of Fridge Plants					
Surface	4	0	2	0	✓
Other Temperatures °C					
Chilled water to UG	11	3	10	6	✓
Air to UG	16	-	22	7	X

From Table 25 the sudden increase in the outlet air temperature to UG is noted (highlighted in red). After numerous investigations it was found that PTB immediately assumes the BAC outlet air temperature will be equal to the ambient temperature after it has been switched off. In practice, this is not exactly the case as the negative draft in the shaft sucks ambient air through the BACs, of which the fill is still wet after it has been switched off. As a result of this occurrence the outlet temperature systematically increases after the BAC shutdown.

Figure 53 shows the simulated profile for the BAC outlet air temperature. It must be noted that the simulations were compiled with winter data, which means the Eskom evening peak periods are an hour earlier.

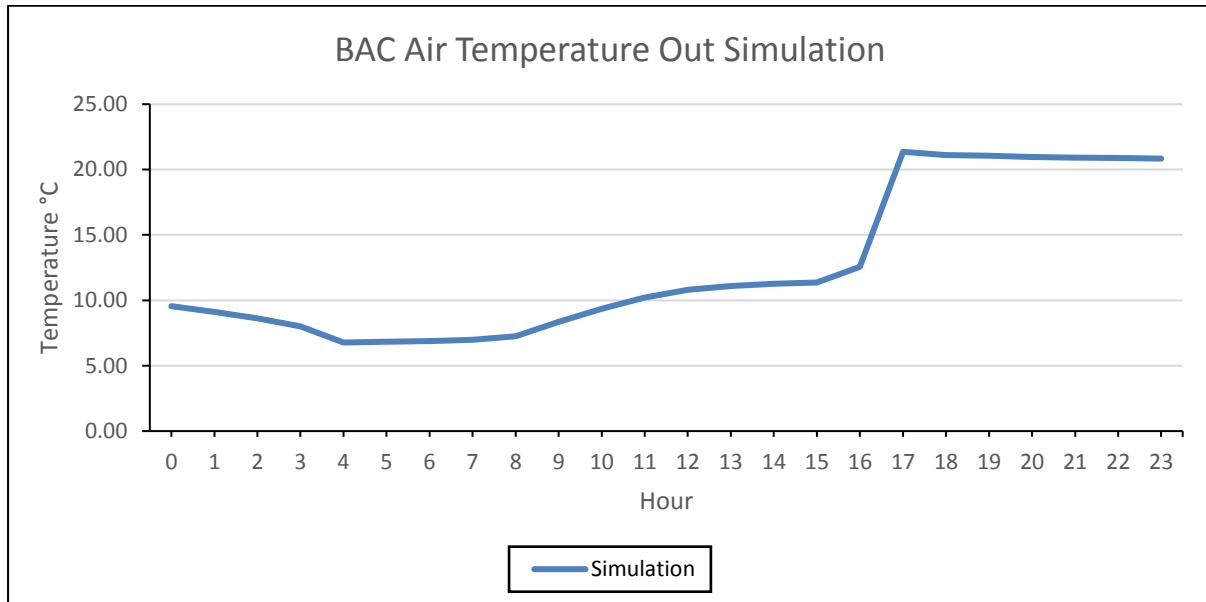


Figure 53: BAC air temperature to UG simulation

The positive results, together with the fact that the hot air on the outside is not sent underground, as the BAC fan is off during this time, means that the anomaly can be explained, and it is not a concern.

The next step should be to test the remaining scenarios, but due to the results from scenario one, the other two scenarios will not be tested due to the following reasons:

- Scenario two will keep one FP running only to keep the chill dam level above the minimum mark. Scenario one proved that the chill dam level was sufficient and thus this scenario would only result in less saving and will therefore not be tested.
- The third scenario runs one BAC to decrease the temperature of the air sent underground and one FP to feed the BAC. Again, scenario one proved that this should not be a concern and thus the BAC and FP will be running unnecessarily.

With the results of the first scenario a success, the scenario can be seen as the optimal solution. The next step is to implement the optimised solution which is discussed in the next section.

4.5.3.2 Optimal solution implementation

The control philosophy for the optimal solution was programmed into the REMS systems of the FPs and dewatering pumps. The BAC and 3CPFS could not be automatically controlled and the control room operators were instructed to manually control the equipment according to the control philosophy.

The implementation results are analysed and presented in the following sections.

4.5.3.3 Analysing the results

As mentioned in the previous sections, the key parameters were analysed to determine the feasibility of the solution. For reference purposes, the following parameters were analysed in detail:

- surface chill dam level and temperature;
- 45L chill dam level;
- 66L hot dam level;
- number of FPs running;
- number of dewatering pumps running on 45L and 66L; and
- BAC incoming and outgoing air temperatures.

The control philosophy was implemented and Table 26 presents the results realised:

Table 26: Solution implementation results

Constraints checklist					
	Maximum	Minimum	Actual Maximum	Actual Minimum	Compliance to constraints
Dam Levels %					
Surface chill dam	95	50	88	63	✓
45L chill dam	100	35	89	59	✓
66L hot dam	90	35	66	42	✓
Dam Temperatures °C					
Surface chill dam	10	2	10	6	✓
Number of Pumps					
45L	1	0	1	0	✓
66L	4	0	3	0	✓
Number of Fridge Plants					
Surface	4	0	2	0	✓
Other Temperatures °C					
Chilled water to UG	11	3	10.67	7.26	✓
Air to UG	16	-	15.4	6.18	✓

Table 26 shows the test to be successful with all the actual temperatures and levels below the prescribed set points with the equipment off during the Eskom evening peak period. The performance will now be discussed in the next section.

Load shift performance

The load shift performance for the refrigeration system was calculated at 3.1 MW during the evening peak period. This is an immense improvement seeing that the operational parameters also remained within the limitations. Figure 54 shows the refrigeration baseline, scaled baseline and actual power profile after implementation.

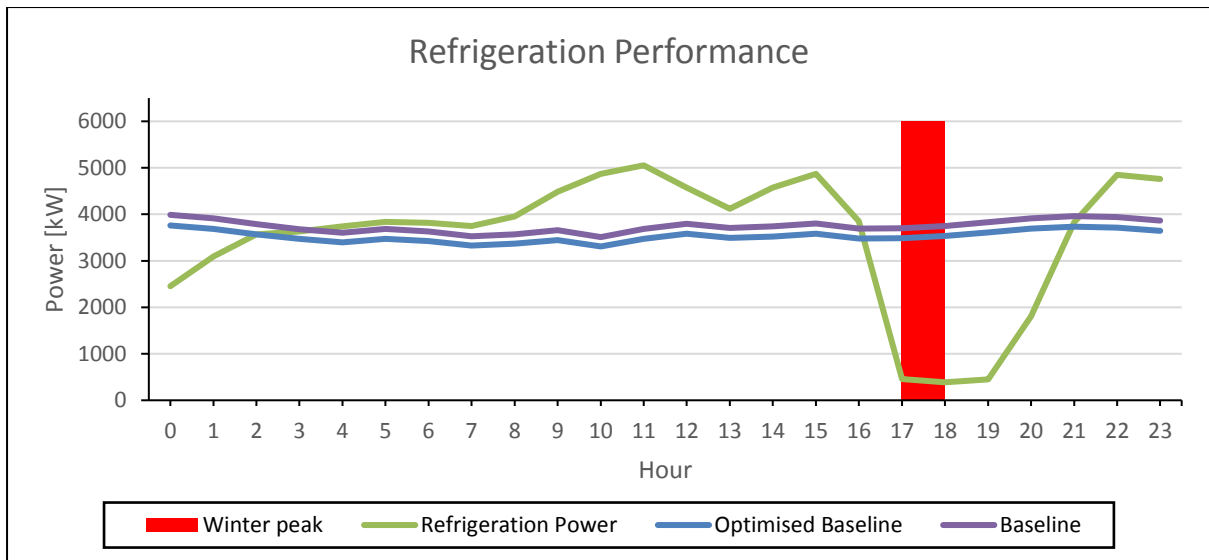


Figure 54: Refrigeration performance after implementation

Figure 55 shows the baseline, scaled baseline and actual power profiles for the dewatering system. A 2.51 MW load shift was achieved during the Eskom evening peak period

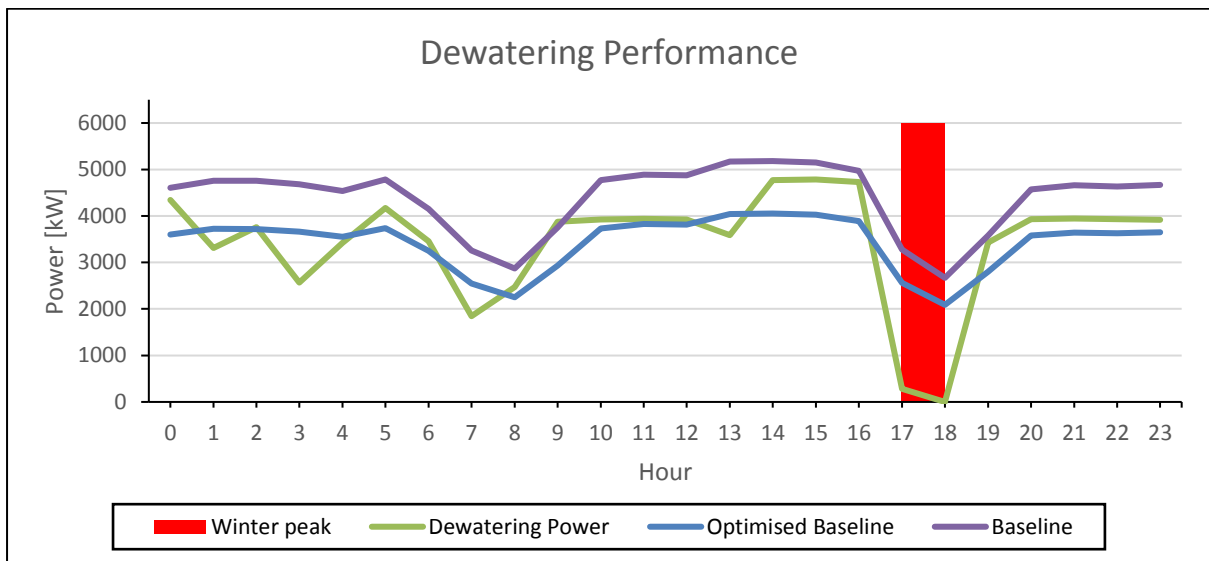


Figure 55: Dewatering performance after implementation

Figure 56 shows the baseline, scaled baseline and actual power profiles for the 3CPFS. The 3CPFS achieved a load shift of 0.67 MW during the Eskom evening peak period.

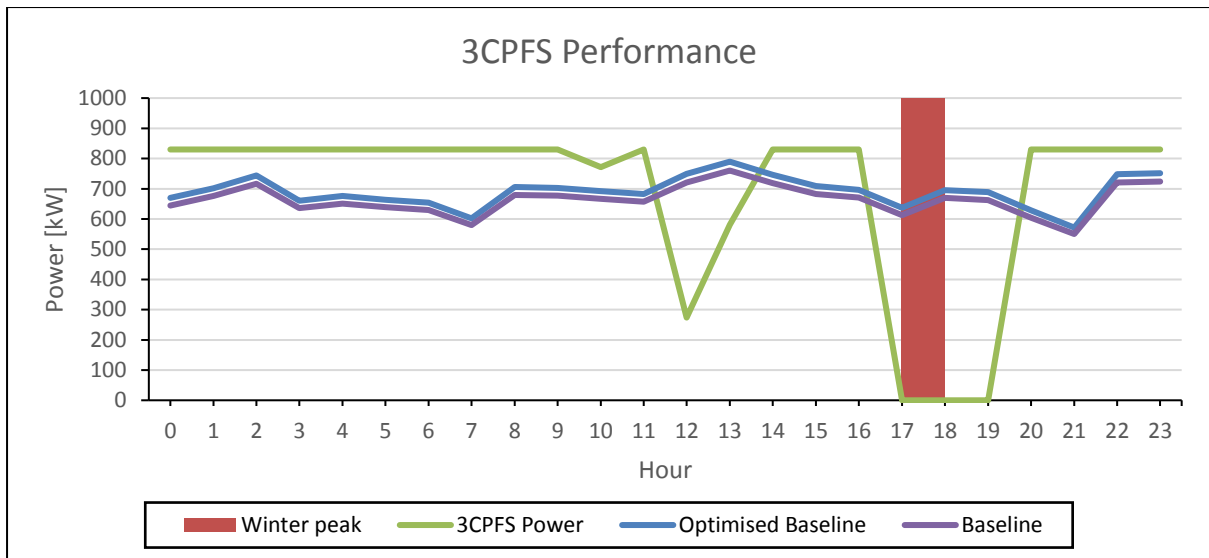


Figure 56: 3CPFS performance after implementation

Figure 57 shows the combined baseline, scaled baseline and actual power profile of the entire water reticulation system.

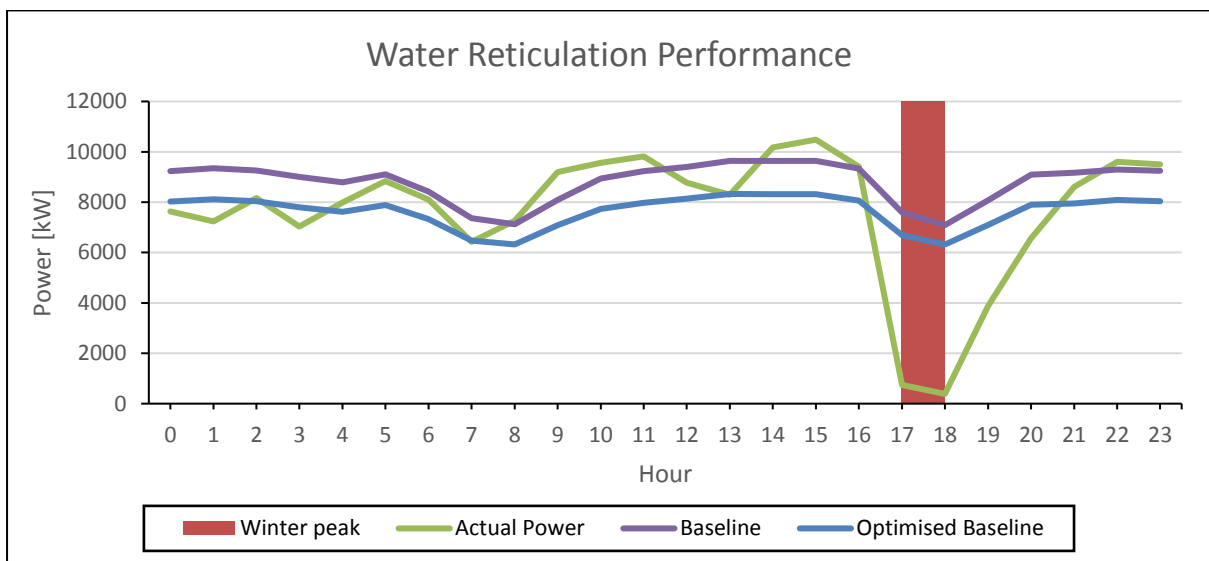


Figure 57: Water reticulation performance

The total load shift was calculated at 6.3 MW. This figure accumulates to a financial cost saving of approximately R4.4 million per annum⁵. This is a significant improvement from the combined average 1.5 MW LS that was realised before by the refrigeration and dewatering systems.

⁵ The savings were calculated with the 2017/2018 Eskom Megaflex tariffs.

A significant improvement was realised in terms of energy cost savings. The next step was to validate the simulated results by inserting the starting conditions from the actual implementation day in the scenario one simulation.

4.5.4 Solution validation

To validate the simulation, the actual inputs from the implementation day were entered into the simulation and results were simulated again. Table 27 gives us the actual and simulated minimum and maximum results and the errors between them for the parameters on the left-hand side.

Table 27: Solution validation checklist

Solution validation							
Parameters	Maximum	Minimum	Actual Maximum	Actual Minimum	Simulated Maximum	Simulated Minimum	Average error
Dam Levels %							
Surface chill dam	95	50	88	63	87	68	1.83
45L chill dam	100	35	89	59	84	63	3.8
66L hot dam	90	35	66	42	70	47	7.5
Dam Temperatures °C							
Surface chill dam	10	2	10	6	9	5	16
Number of Pumps							
45L	1	0	1	0	1	0	
66L	4	0	3	0	4	0	
Number of Fridge Plants							
Surface	4	0	2	0	2	0	
Other Temperatures °C							
Chilled water to UG	11	3	10.67	7.26	9	5	16
Air to UG	16	-	15.4	6.18	22	6	22

The error for the chill dam temperature was above 10%. However, with the design specifications and explanations given in Appendix D: Solution validation, together with the fact that the temperature did not exceed 10 °C it can be excused. The simulation predicted that the air to UG temperature would rise to 22 °C, however, it remained below the 16°C set point and is thus acceptable.

With all but three parameters below the 10% margin and with those parameters explained, this can be seen as the optimal cost saving solution for Mine A. Refer to Appendix D: Solution validation for the parameter discussions. The implementation of optimised control strategies can then be concluded in the next section.

4.6 Conclusion

Mine A was identified as an ideal case study as its water reticulation system comprises three sub-systems and load management initiatives were implemented on the refrigeration and dewatering systems. It was further identified through investigation that the operation and control of the 3CPFS influenced the performance of the load management initiatives on the other two systems. The step-by-step methodology, developed in Chapter 3, was therefore applied to develop an optimised control philosophy to integrate the control of the sub-systems for maximised performance.

Three possible solutions were developed, and the feasibility of the solutions was tested with the help of a verified simulation model. The optimal solution was implemented on the water reticulation system of Mine A as it proved maximised cost savings potential, while remaining within the operational limitations. The control philosophy was incorporated into a real time energy management system for automated control. For redundancy, the control room operators were adequately trained to manually implement the control philosophy.

Mine A realised an average Eskom evening peak load shift of 2.5 MW on the dewatering system, 3.1 MW on refrigeration and 0.7 MW on the 3CPFS with the optimised control philosophy. This accumulates to a combined performance of 6.3 MW on the water reticulation system. The performance was therefore improved with 4.8 MW from the performance prior to implementation. The optimised performance equates to a financial cost saving of approximately R4.4 million per annum.

It was further proven that the operational parameters, coupled with the production output of Mine A, were not influenced by the implementation of the control philosophy. This also validated the accuracy of the predicted results through simulation. It can therefore be safely concluded that the optimal utilisation of a 3CPFS in a water reticulation system to maximise the performance was proven.

CHAPTER 5

5 Conclusion and recommendation

5.1 Executive summary

With the gold production in South Africa ever decreasing, gold mines have been struggling to remain as profitable as they were in the 1990s. This can be attributed to many challenges such as high operating costs of which electricity forms a large portion. However, unlike most of the other challenges faced by this industry, this portion offers large potential for improvement.

A large number of energy savings initiatives have been implemented over the years on the electricity intensive systems of gold mines. One of these systems is the water reticulation system. Maximised benefits are often overseen, especially with the implementation of multiple initiatives on this system. The 3CPFS is an energy efficiency initiative that influences the performance of load management initiatives.

Lack of integrated control is the main cause of the 3CPFS influencing the LM initiatives. A need was therefore identified to develop an integrated control philosophy to optimally utilise the 3CPFS to improve the performance of load management initiatives on the other two sub-systems. Objectives were set to integrate the control of the dewatering, refrigeration and 3CPFS to improve the savings without influencing the production negatively.

A literature study was conducted to fully understand the workings of the components of the water reticulation system. Previously implemented studies were also analysed to focus on their positive aspects and determine their shortcomings. Finally, simulation packages capable of simulating the integrated sub-systems as part of the water reticulation system were investigated.

A methodology was developed to integrate the controls of the sub-systems and to improve cost saving potential. Mine A was identified, and the methodology was followed to develop a control philosophy to optimally utilise the 3CPFS.

A simulation of the mine's water reticulation system was developed, validated and finally verified with implemented results. The developed control philosophy was implemented and an average load shift of 6.3 MW was realised, which accumulates to a saving of R 4.4 million per annum. All of this was realised without negatively influencing the production of Mine A.

The study showed that it is possible to integrate the control of these systems and reduce operating costs without influencing production negatively. All the objectives stated were answered and thus the study was successful.

5.2 Recommendation for further work

5.2.1 Recommendations to improve this study

The possibility of incorporating morning load shifts in the integrated system should be investigated as this study only focused on the Eskom evening peak periods. To further increase savings, the LS can also be extended beyond the Eskom peak periods for as long as the operational constraints allow.

The simulation software used was designed to use hourly time intervals. To increase the accuracy of the results, the data must be analysed in shorter intervals.

The power consumption of the 3CPFS could not be measured and assumptions had to be made. It is recommended that power meters be installed on the filler and booster pumps to ensure accurate saving calculations.

The feasibility of optimising the control of the water reticulation system for energy efficiency initiatives should be investigated. With the installation of VSDs on the 3CPFS and refrigeration system, the energy efficiency component on the 3CPFS and refrigeration systems can be investigated.

5.2.2 Recommendations for the use of the methodology

Expand optimal control to other electricity intensive systems to make sure initiatives do not influence each other, but are integrated to maximise performance in terms of energy and cost savings without compromising service delivery.

This study showed promise and thus the methodology could also be used to optimise a larger system. It can be investigated to integrate the sub-systems within to optimise the performance and increase cost savings.

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Appendix A: Eskom peak periods

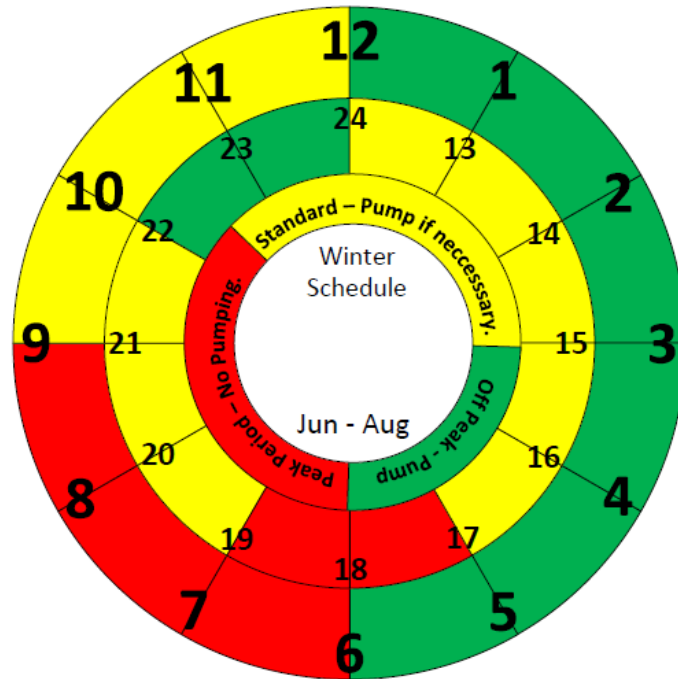


Figure 58: Mega flex winter schedule

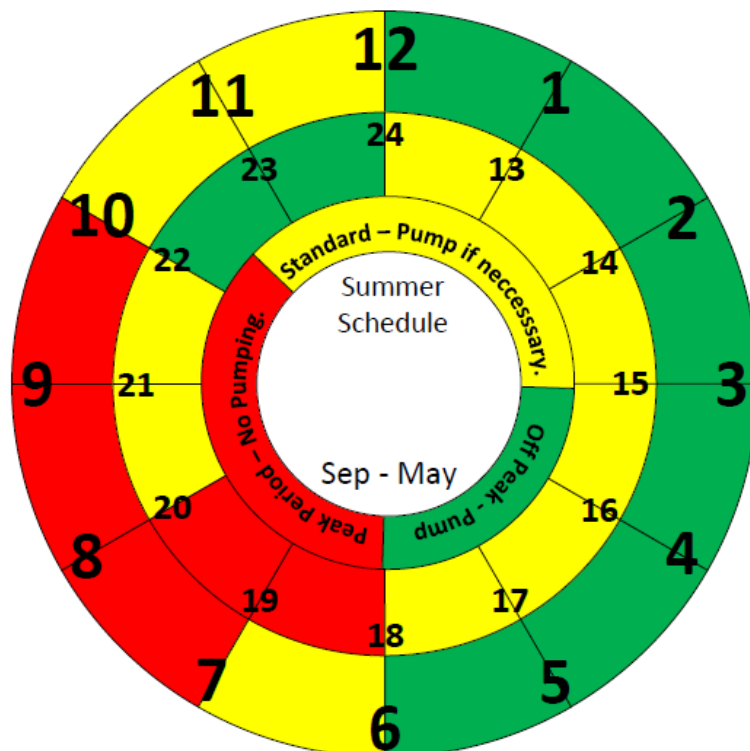


Figure 59: Mega flex summer schedule

Appendix B: Simulation

As mentioned in 4.5.2, the simulation had to be split into two parts due to the design window space restrictions. The simulations were still connected by linking node A in the refrigeration simulation to node A in the dewatering simulation. The same was done for node B in the respective simulations.

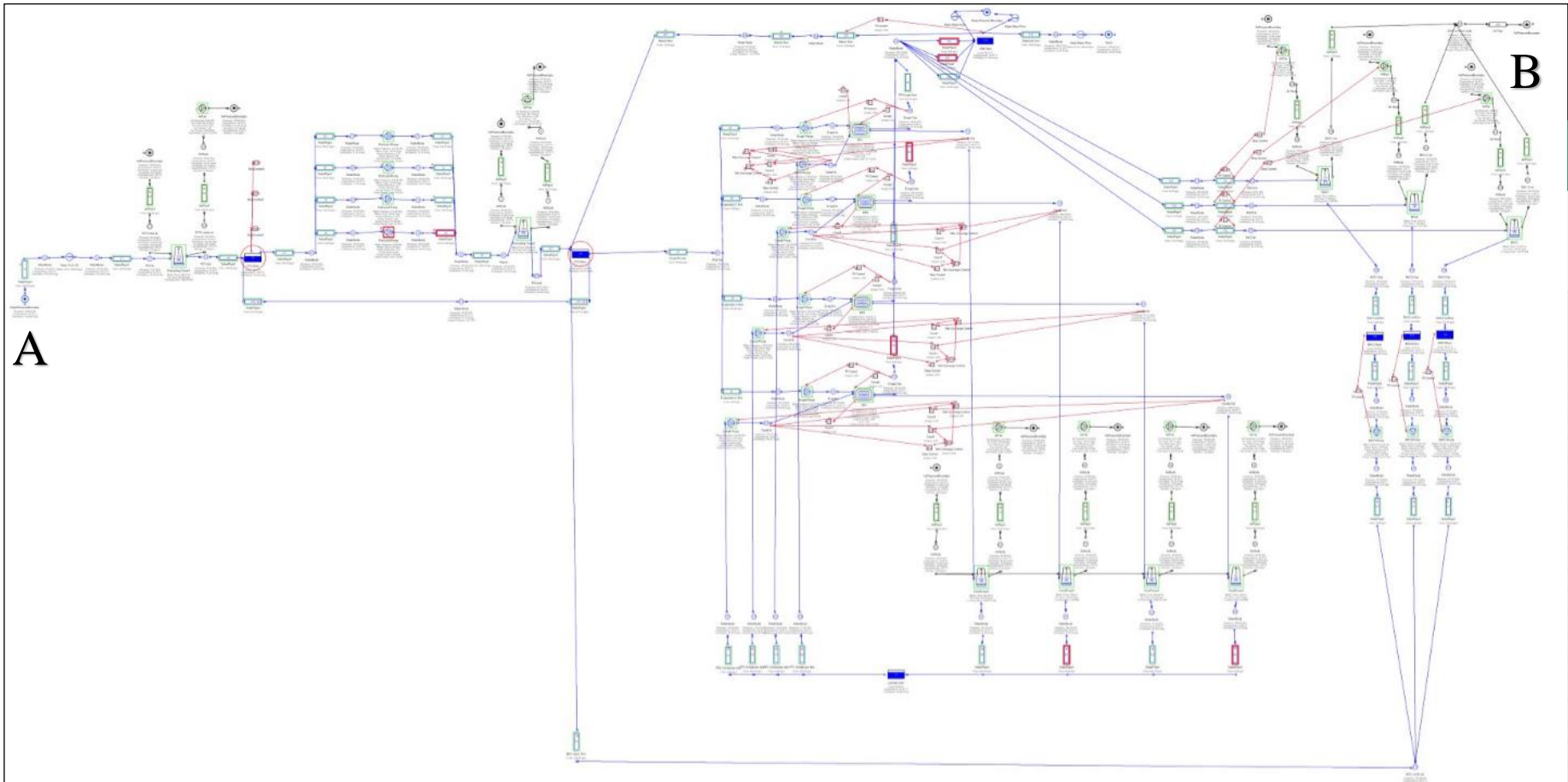


Figure 60: Refrigeration simulation

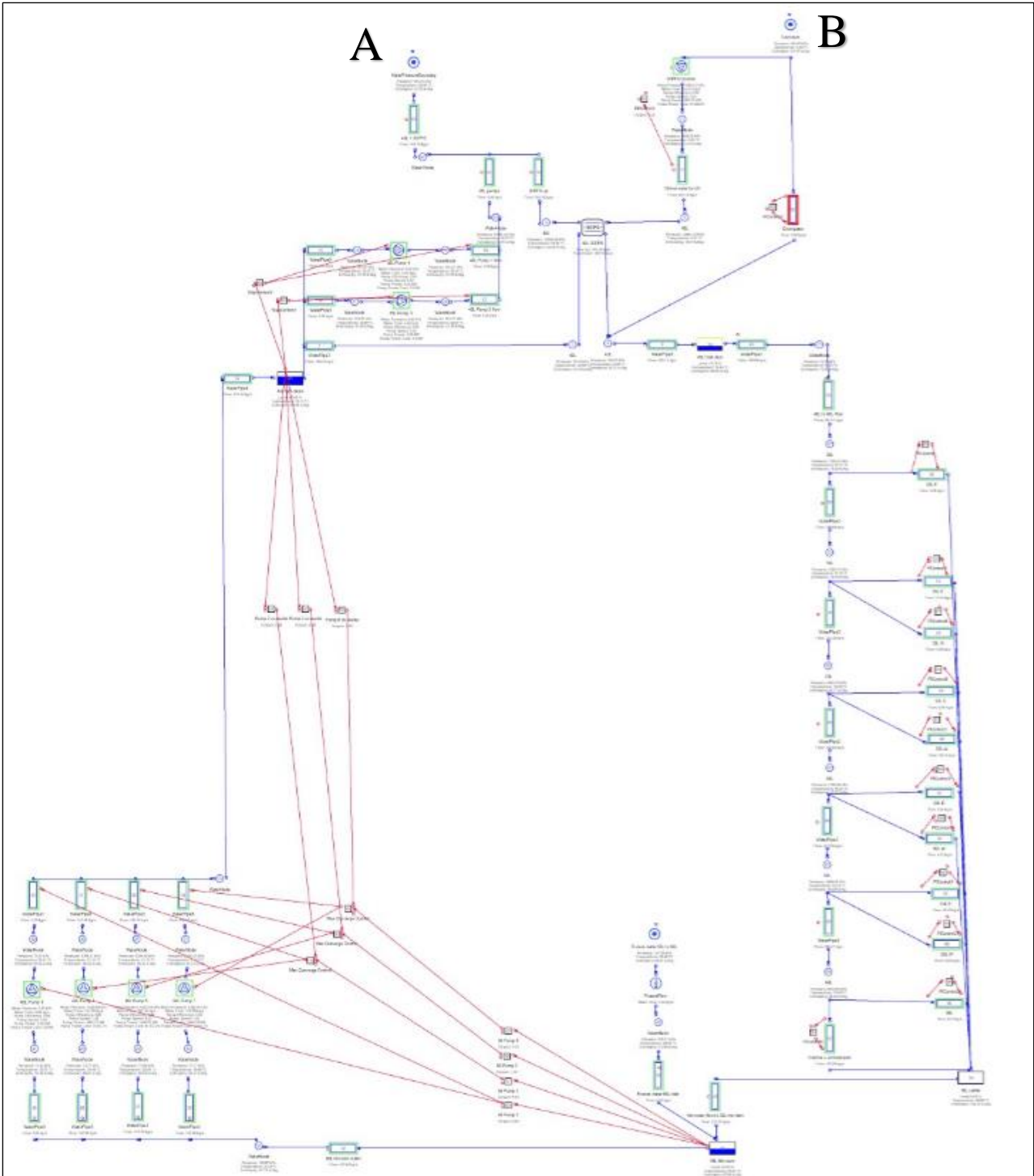


Figure 61: Pumping simulation

Appendix C: Simulation verification

The verification of the important parameters will be discussed in this appendix. The dam levels of the surface chill dam, 45L chill dam and 66L hot dam have been analysed. After the levels have been discussed, the surface chill dam, chilled water to UG and air to UG temperatures will be discussed. Finally, the power consumption of the refrigeration and dewatering systems will be discussed.

Figure 62 shows the average surface chill dam level for the actual and simulation results. There is a visual difference between the actual and simulated levels of the chill dam in the early hours of the day. There are a few factors that can cause this difference:

- The procedure followed in the simulation process. The refrigeration simulation has a 24-hour period built in before the actual simulation to allow the simulation to sort out small imperfections.
- Small instrumentation errors in the level sensors can contribute to the difference between the simulation and actual results.
- The simulation assumes the pumps displacing the water are constantly at the same efficiency and this is not the case with actual machines.

However, with the average level of the actual results at 83.17 % and the simulated average at 80.02 %, the overall difference is 3.79 %, which is lower than the acceptable 10% error defined earlier in the study. The parameter is thus verified.

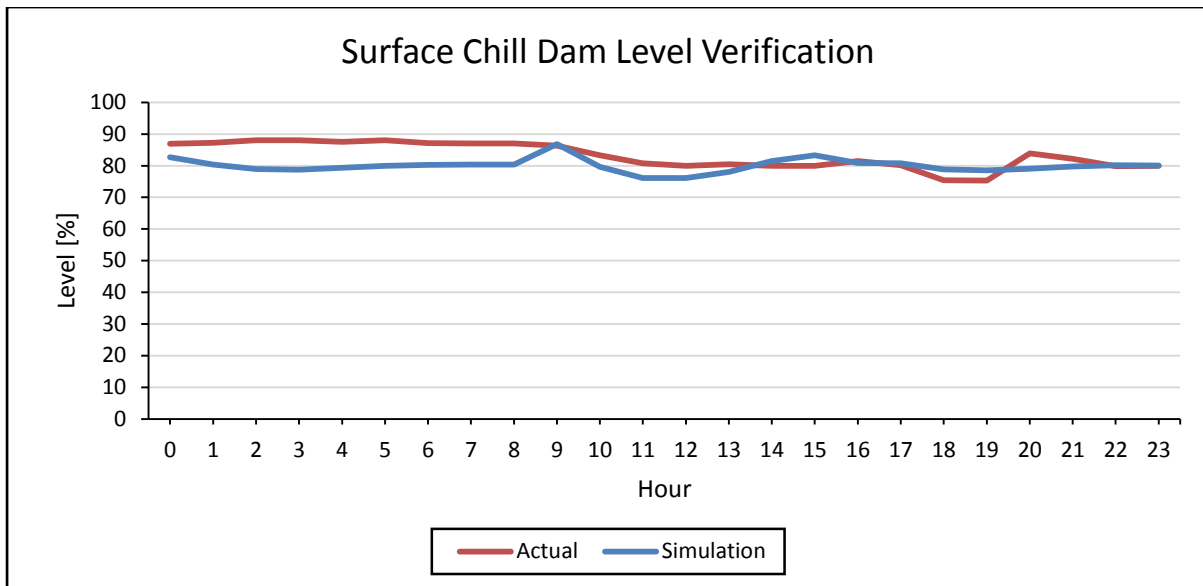


Figure 62: Surface chill dam level verification

Figure 63 shows the 45L chill dam level for the actual and simulated results. Once again, there is a visual difference between the actual and simulated results. The slight difference in the results can be explained by a few factors:

- There are two dams on 45L and the level reading that is logged is the average of these two readings.
- Small errors in the level sensing instruments can cause the average to differ from the actual levels.
- Water flow meters installed to measure the flow going into and out of the mine can be defective and this will influence the simulation as these values are used to calculate the amount of water being displaced.

With possible variances explained and the two results following the same trend with an overall average difference of 3.89 %, this parameter is verified.

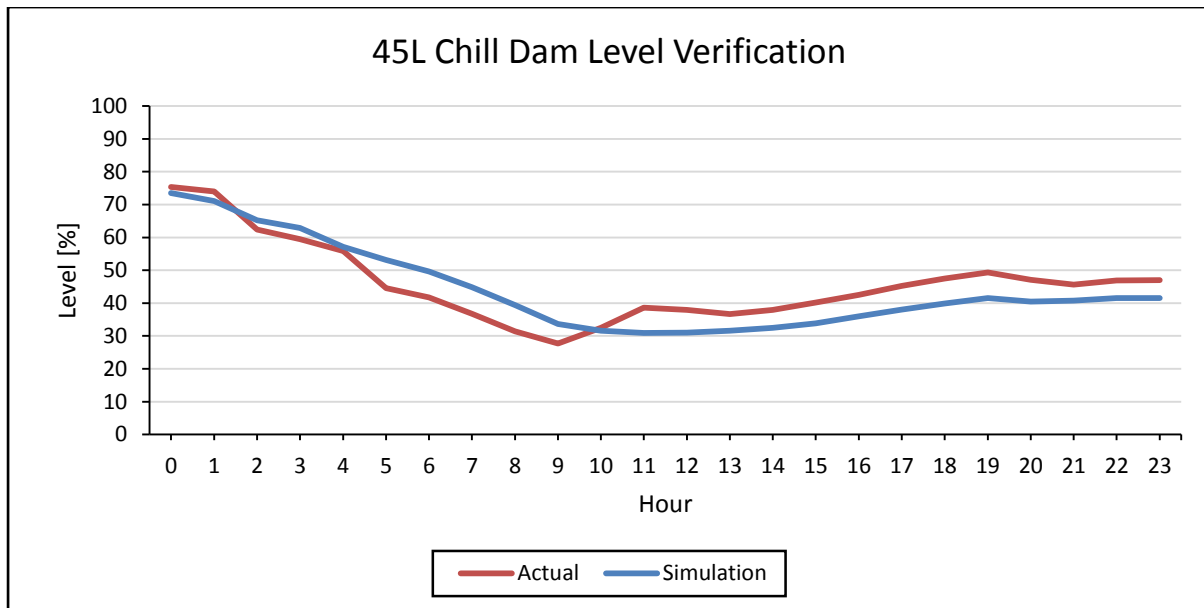


Figure 63: 45L Chill dam level verification

Figure 64 compares the average level of the 66L hot dam for the day of validation. Up until hour six the dam levels for the actual and simulated results are extremely similar and then it starts to vary. This can possibly be explained by the following:

- 66L has four hot dams and the logged actual reading is an average of the four level readings in each dam. This parameter is also coded to show the lowest of the four readings if they differ by more than 10 %. This was introduced as a safety measure to keep the dams from being pumped dry as they are not always filled and emptied by the same rate.
- Water flow meters can be slightly faulty and false readings could have been used to simulate the flow to and from the dam.
- Fissure water is also present on this level and it is difficult to quantify the exact amount of fissure water coming into the system.
- It is possible, although unlikely, that one or more of the level sensors was damaged after hour six, which would cause the readings to differ from actual results.

The overall average difference between the actual and simulated results is 17.57 %. This required further investigation to pinpoint the problem as the error is more than the acceptable limit mentioned earlier in the study. Investigations revealed that the big difference in the results is contributed to the average actual reading of the dam level. One of the hot dams reached the

10% mark mentioned above and the average level reading assumed the value of that specific dam for the rest of the day.

With the reason for the difference explained and approved by the mine, the focus could move on to the next parameter as this one has been verified.

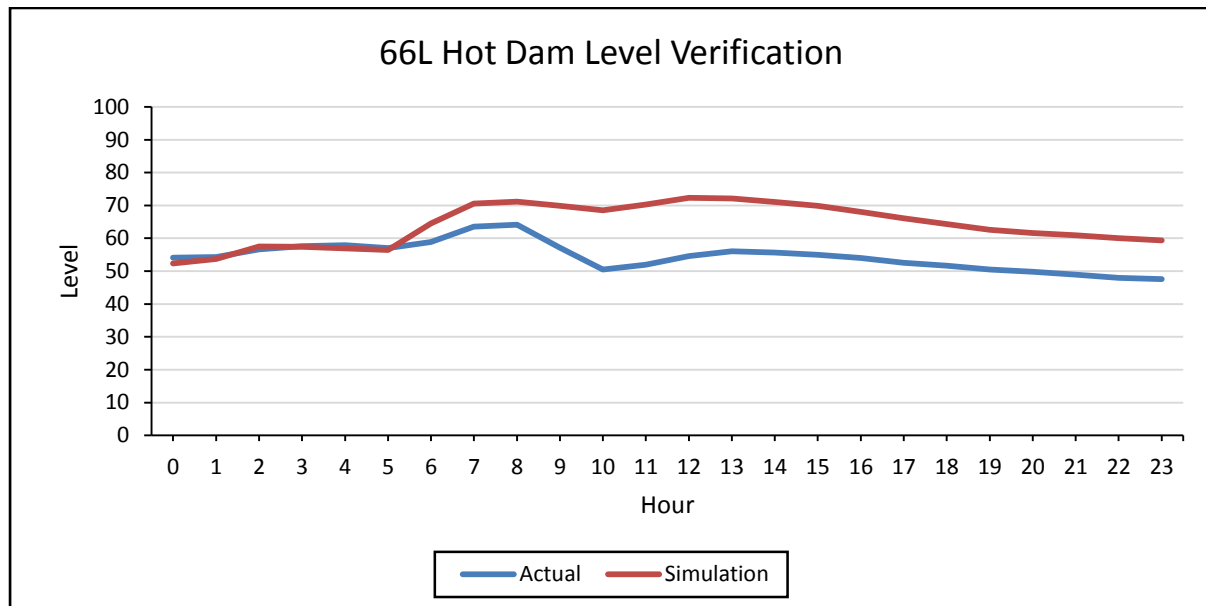


Figure 64: 66L Hot dam level verification

Figure 65 shows the hourly surface chill dam temperature for the validation day. The figure shows that the simulated temperature follows the trend of the actual results, but the difference between the two results is 29.9 %. The difference can be explained by the following:

- The design of the chill dam is not considered in the simulation. The dam consists of four separate sections with each flowing over into the next and the temperature probe is installed in the last section (Figure 66). The simulation assumes the temperature of the surface chill dam distributes evenly.
- The chill dam assumes no heat transfer takes place and this is not the case in real life.
- The simulation can control to exact set points due to the very good control, but actual systems cannot control so finely and thus temperatures will differ.
- Not all the pipes have insulated cladding and the pipes in direct sunlight will be affected by the ambient conditions. The simulation assumes no heat transfer across pipe sections.
- The relative humidity (RH) of the area was assumed as there is no instrumentation at Mine A to get the actual reading. The RH of a nearby mine was used (as Mine A did

not have a measurement for this) and this can influence the efficiency of the chillers as pre-cooling temperatures might differ significantly.

- Chillers are simulated to perform with a constant efficiency and actual machinery is not that constant as certain factors constantly change.
- Temperature probes being used may be slightly inaccurate and cause temperatures to differ.

Taking into effect the design of the dam, the insulation of the pipes and the relative humidity of the area, it is fair to assume that the chill dam temperature discrepancies are explained. The parameter is thus verified.

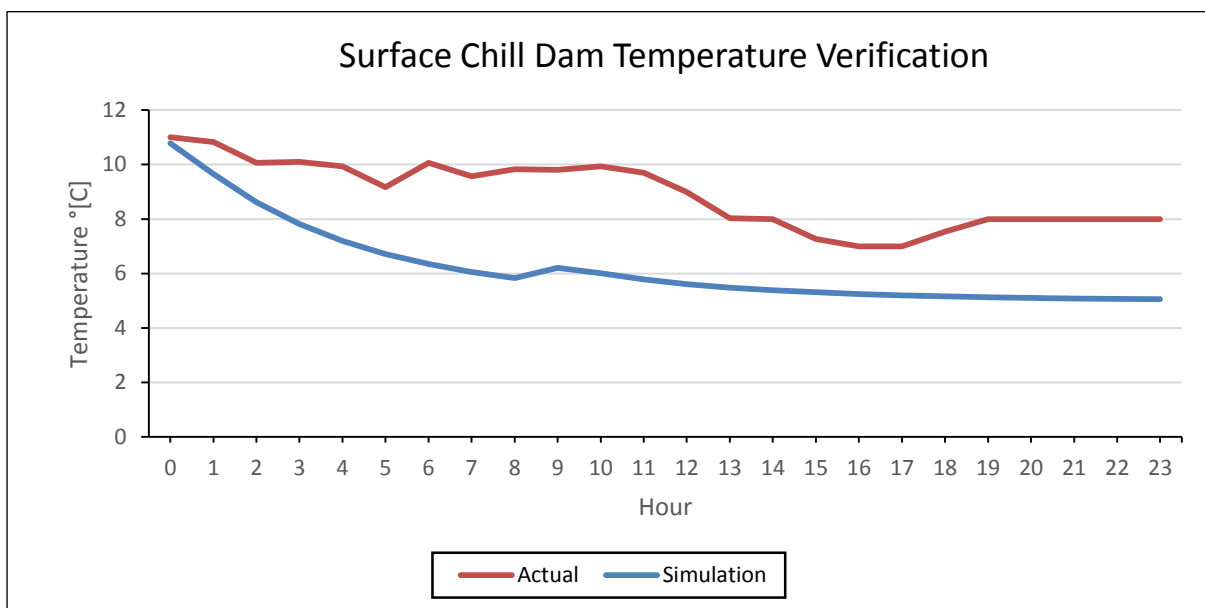


Figure 65: Chill dam temperature verification

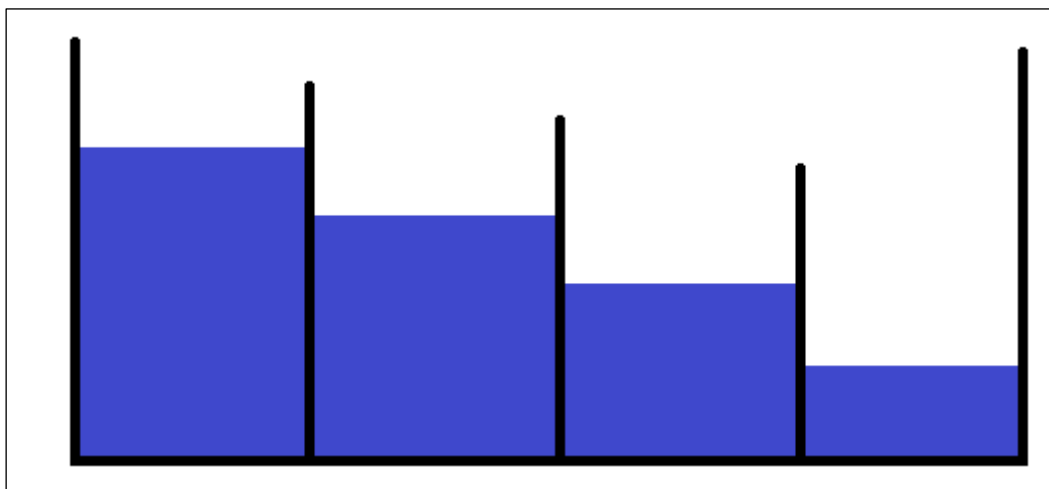


Figure 66: Cascading surface chill dam representation

The hourly chilled water to underground temperatures are compared in Figure 67. This is the temperature of the water leaving the BACs. From the graph, we see the actual temperature is lower than the simulated temperatures and, with an overall difference of 14.73 %, investigations are needed. Investigations revealed that the differences could be explained by the following:

- The efficiency of the BACs is not as high as assumed. This is clear as the actual outflowing water temperature of the BACs is much colder than that of the simulation. This indicates that less heat was transferred from the air to the water.
- The RH assumption will also play a role as the simulation uses the RH to calculate the heat transferred.
- All BACs were given the same efficiency as their design specifications are the same. The machines could differ dramatically, and this can influence the results.
- The ambient temperature probe could be damaged and inaccurate readings will influence results.

With the two results following the same trend, the differences in results explained and the maximum temperatures still well below the set value of 11 °C, the parameter is verified.

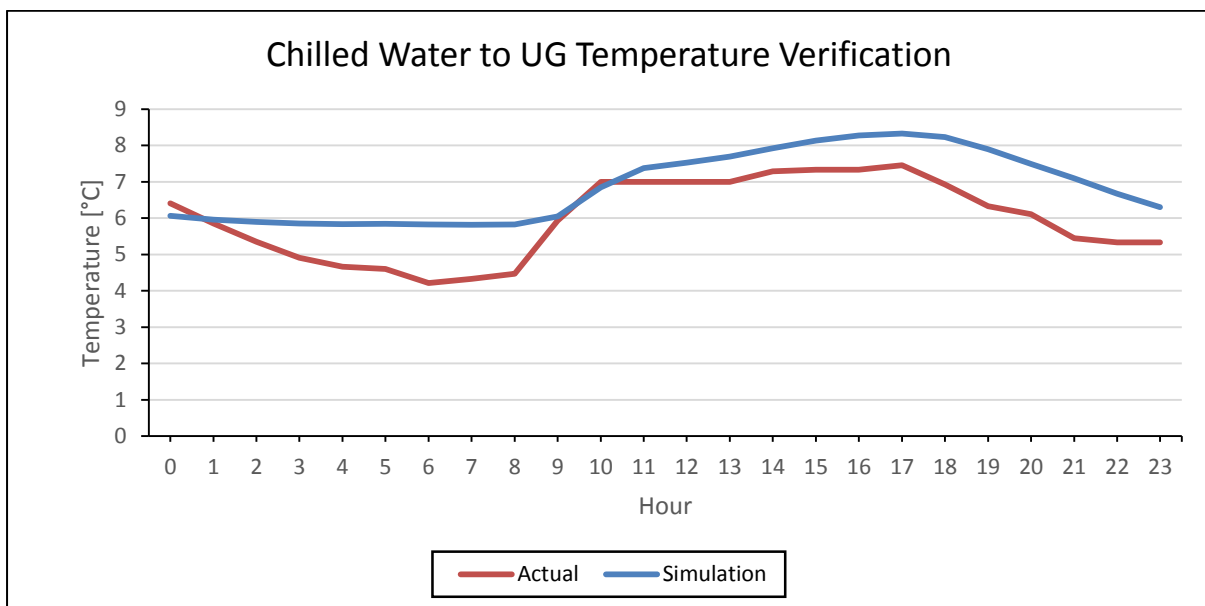


Figure 67: Chilled water to UG temperature verification

Figure 68 shows the BAC air temperature going underground on the day of verification for the simulation and actual results. With an overall accuracy of 9.82 %, the parameter is accurate enough for the study, but the differences could be explained by the following:

- The RH was assumed for this study due to lack of instrumentation and this can contribute to the difference in readings.
- The temperature probe measuring the air temperature could be inaccurate and cause readings to differ.

With possible explanations for the differences given, the parameter is verified and the study can move on to the power usage of the system.

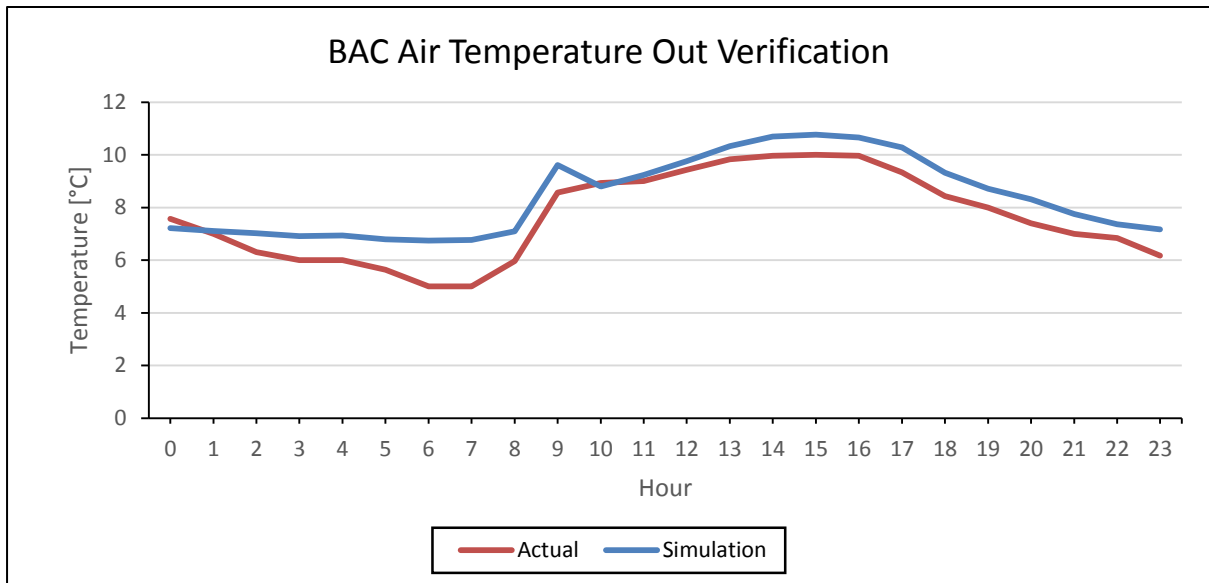


Figure 68: BAC air temperature to UG

From Figure 69, the simulated and actual power profiles match up almost perfectly and with an overall average difference of less than 1%, this parameter is verified.

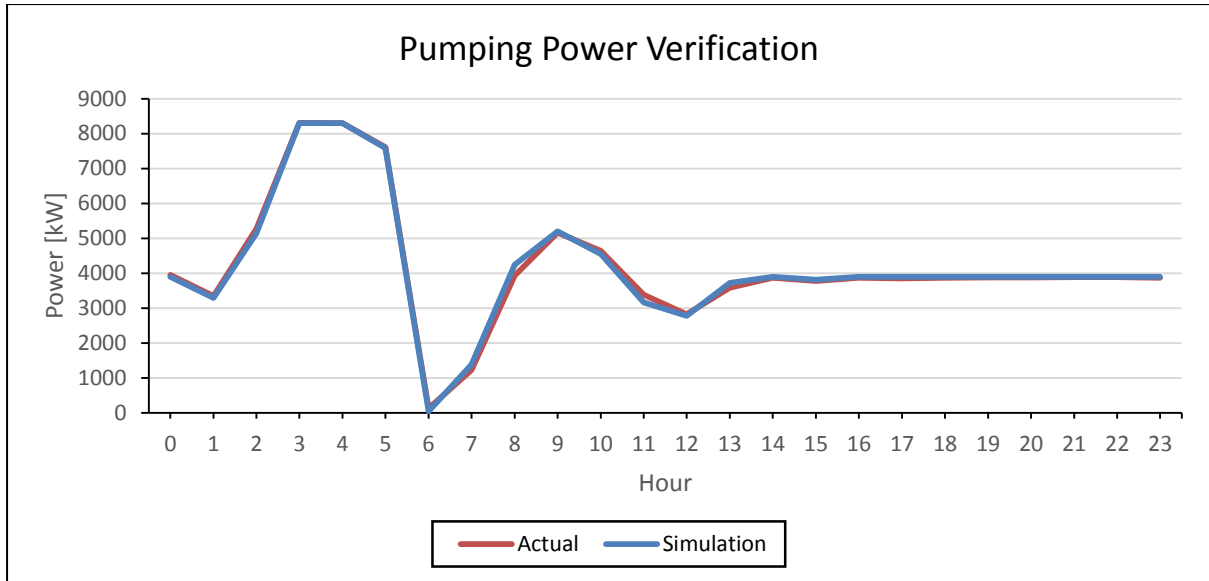


Figure 69: Pumping power verification

Figure 70 shows the power consumption of the refrigeration system. The ‘bump’ at around 12pm was caused due to the hot ambient conditions causing the actual system to ramp up power usage. With an overall average difference of less than 1%, this parameter is also verified.

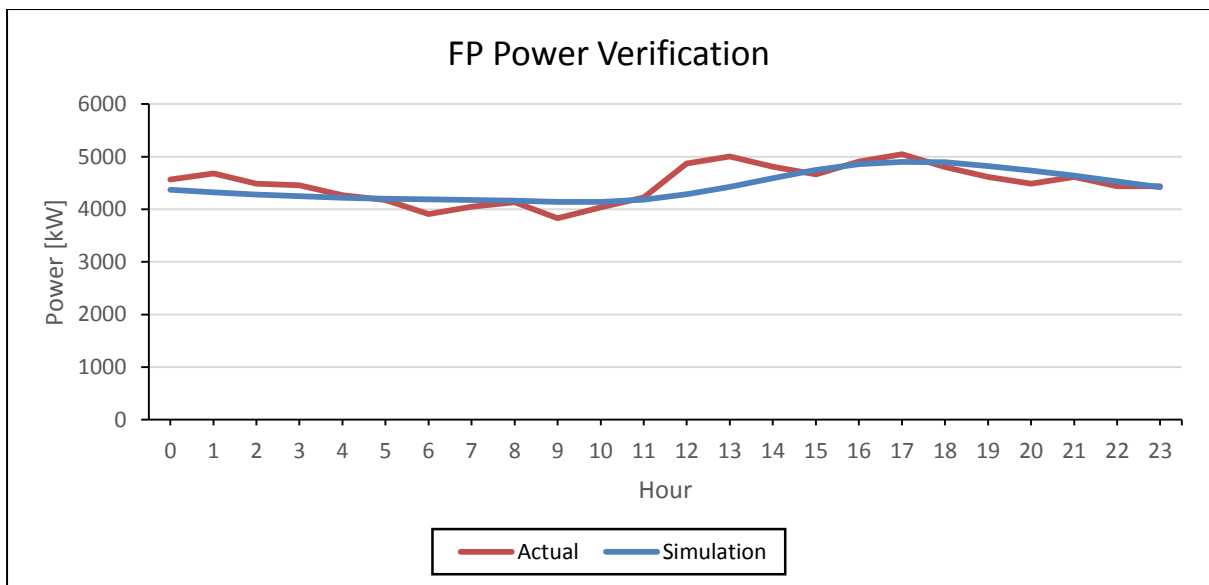


Figure 70: Refrigeration power verification

Appendix D: Solution validation

Figure 71 shows the simulated and actual chill dam level profile comparison. The small differences can be explained by possible errors in level sensing instruments.

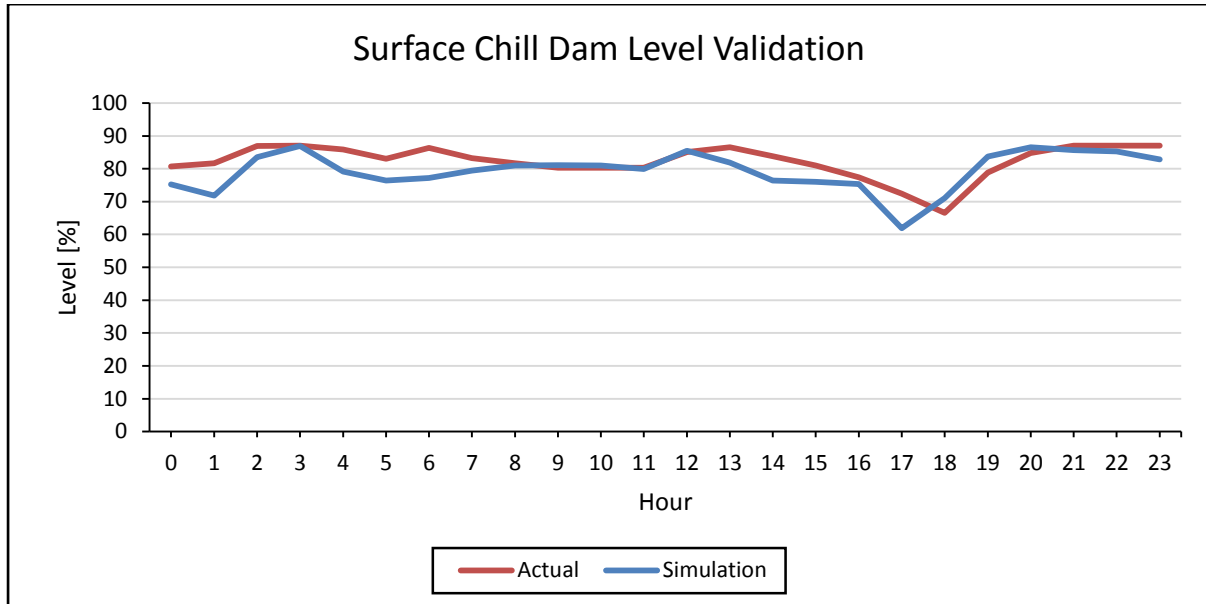


Figure 71: Chill dam level validation

The correlation between the two profiles are 0.88, which indicates a strong correlation and with an overall difference of 1.83 % the parameter is validated.

Figure 72 shows the comparison for the 45L chill dam level. The differences are ascribed to reading errors in the flowmeter and level indicating instrumentation.

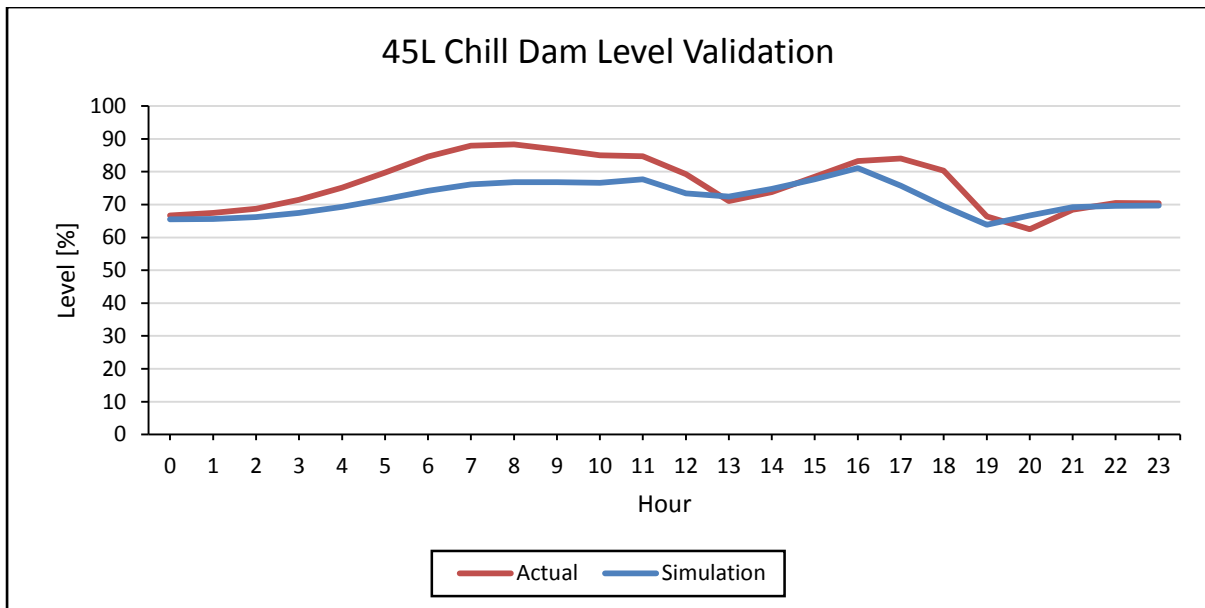


Figure 72: 45L Chill dam level validation

The correlation was calculated at 0.95, which is very strong. The overall error was calculated at 3.8%.

Figure 73 shows the comparison for the 66L hot dam. Errors can be ascribed to pumps not being as efficient as defined and instrumentation errors as the mine's instruments are not finely calibrated.

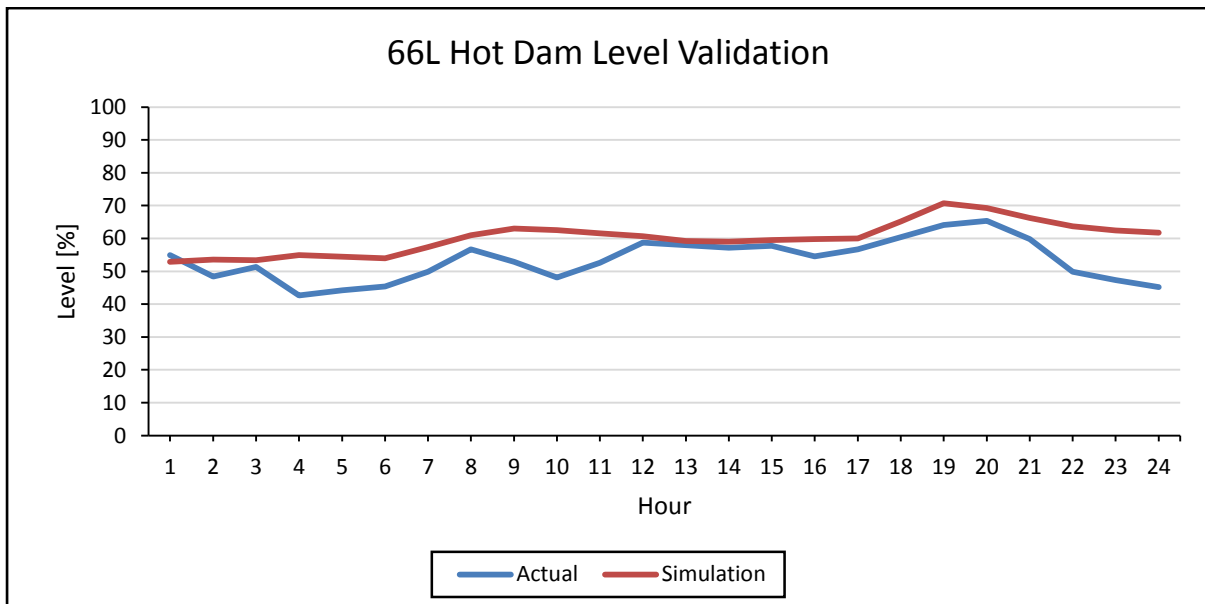


Figure 73: 66L Hot dam level validation

The correlation was calculated at 0.9, which is again very strong. The average difference was calculated at 7.5 %.

Figure 74 shows the hourly average comparison for the surface chill dam temperature. From the figure it is noticed that the actual temperature increases after the load shift, while the simulated temperature decreases. This is because the simulation assumes the FPs will immediately perform to its efficiency after start-up, which in actual practice is not the case. The fridge plants go through a start-up procedure and only begin to perform optimally after a while.

This delay in optimal performance of the fridge plants results in warmer water being dumped into the chill dams. Another main reason for the difference was explained in Appendix C: Simulation verification.

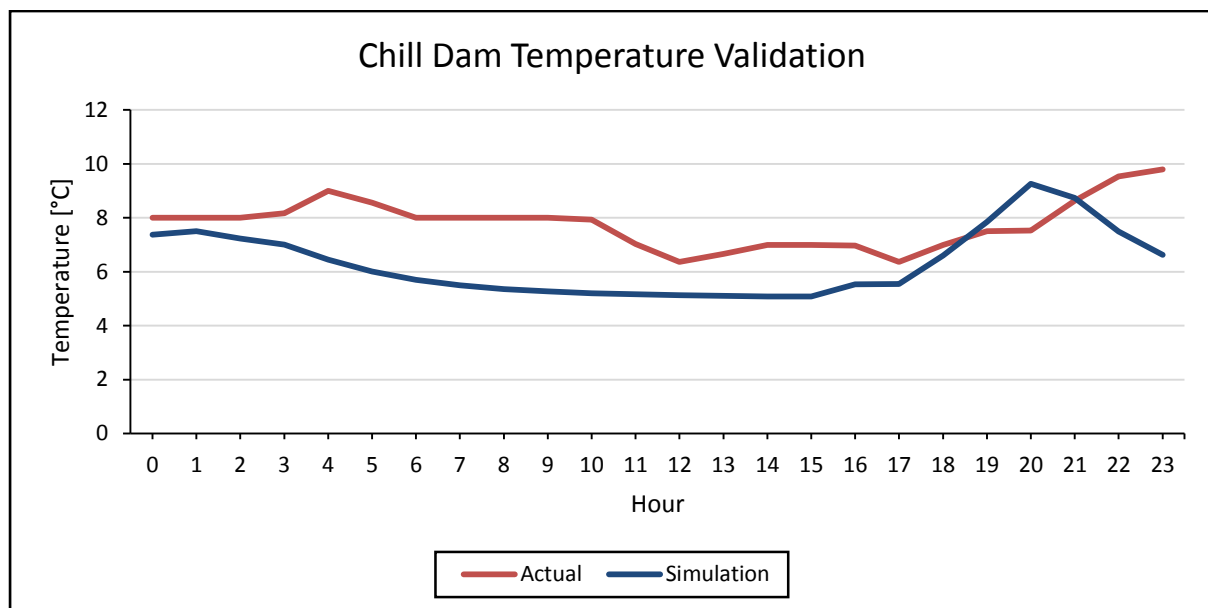


Figure 74: Surface chill dam temperature validation

The correlation was calculated at 0.51, which is not good at all, but with the reasons mentioned above, this can be overlooked. The difference was calculated at 16%.

Furthermore, the temperatures remained within the limits set by mining personnel. There is, however, a concern that the chill dam temperature may rise above the 10°C threshold if the control philosophy is not properly implemented. It is therefore crucial that the control room operators understand the control philosophy and immediately take over when any problems arise.

Figure 75 shows the chilled water to UG temperature comparison for the simulated and actual results. The differences can be caused by many factors as discussed in Appendix C: Simulation verification.

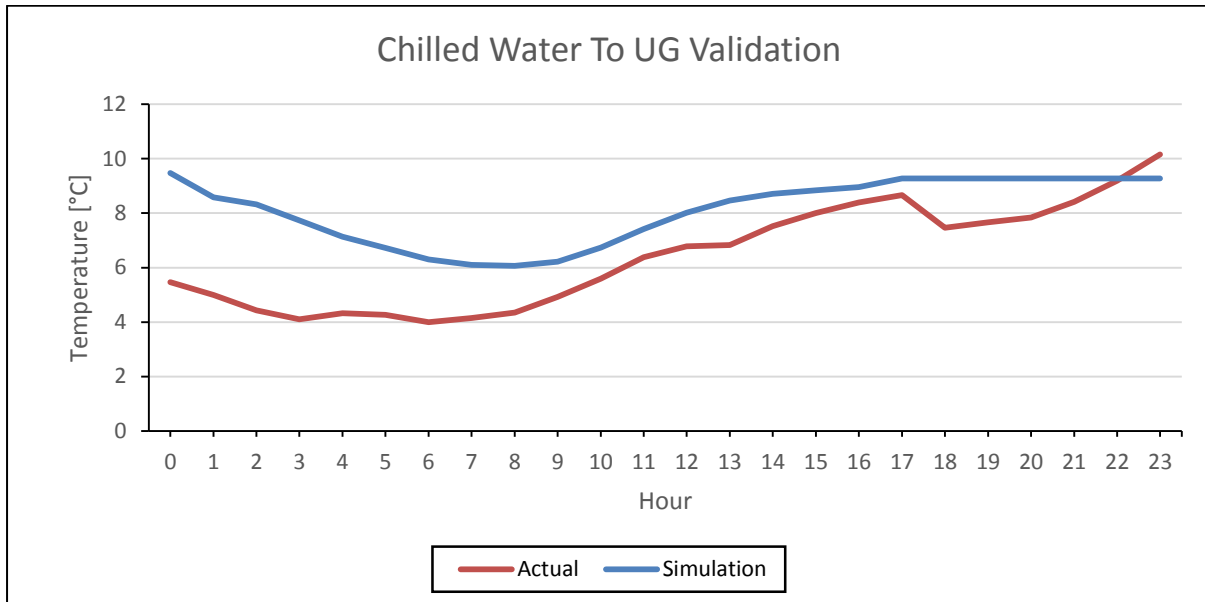


Figure 75: Chilled water to UG validation

The correlation between the two sets of data is 0.78 and the error was calculated at 16%. The actual temperatures remained within the limits, but it should be noted that the temperature increased when the hotter water was dumped into the chill dam. This should be strictly monitored by the control room operators.

Figure 76 shows that the simulation still predicts that the temperature will rise above 20°C. The simulated temperature profile follows the actual profile until the BACs are stopped at 16:00. As explained, this is due to the design specifications of PTB.

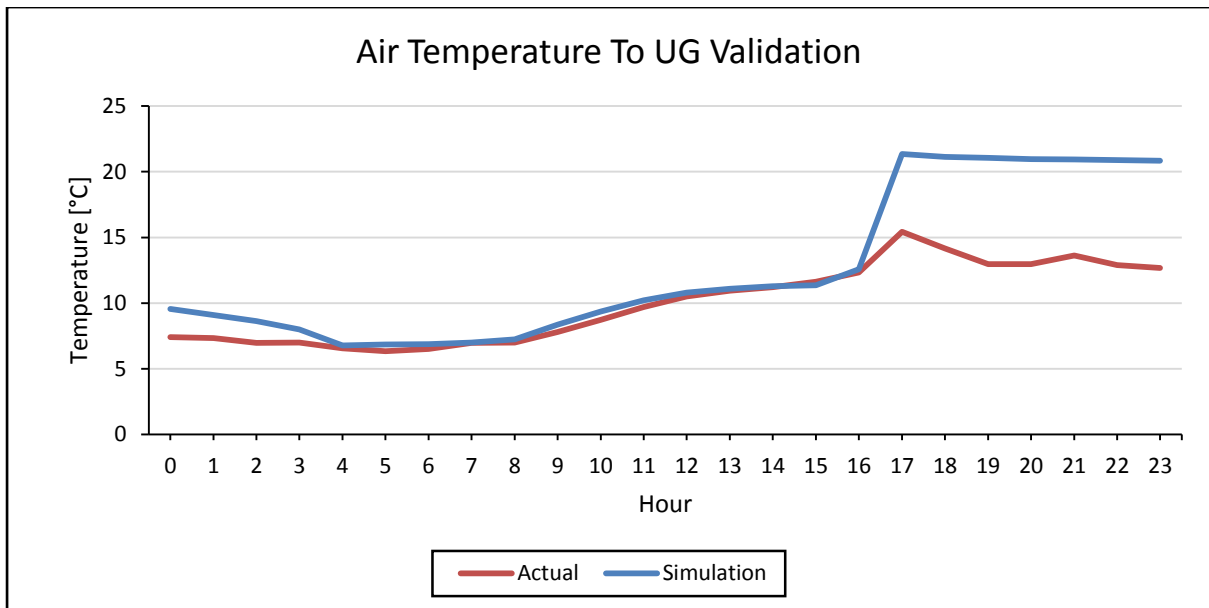


Figure 76: BAC air temperature out validation

The correlation between the two profiles is 0.78 with an error of 22%, which indicates that the trends follow similar paths even if the temperatures started to differ vastly at 16:00. This parameter is thus validated, and the focus can now shift to the performance calculation section.

From Figure 77, it is clear that the actual power profile reacted as the simulation predicted as the correlation between them is 0.94. The overall power difference is 8.76 %. This small error can, however, be explained by the following:

- Simulations always assume that efficiency is constant and there is no start-up time, which is not the case in actual machinery.
- Small inefficiencies on the power meters on all the components can equate to a big difference as there are multiple components consuming electricity to consider.

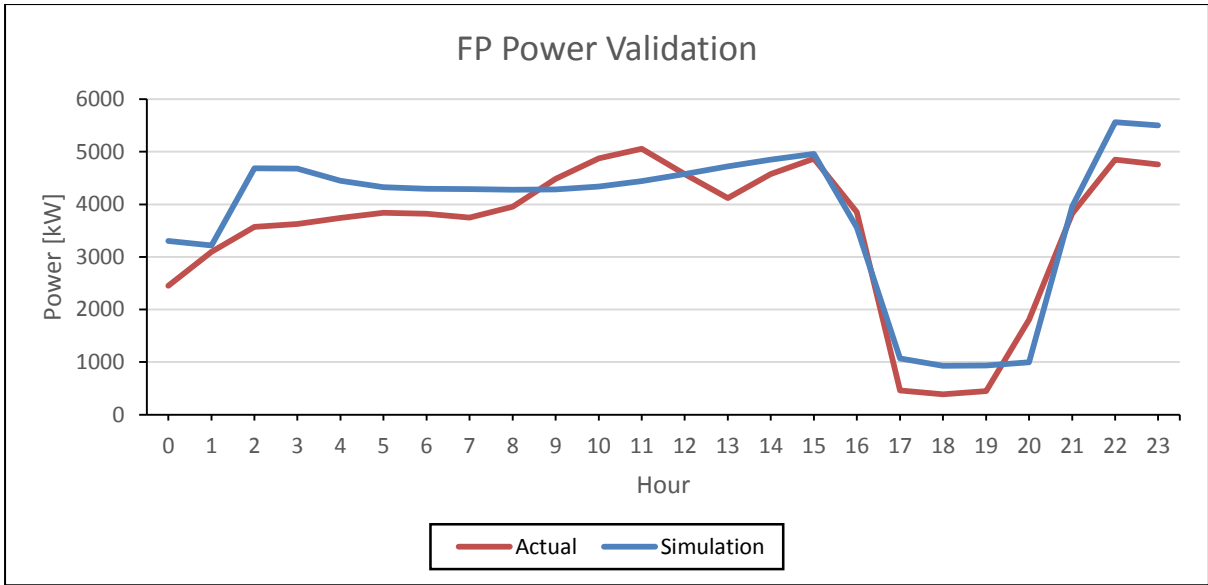


Figure 77: FP Power validation results

Figure 78 shows the power profiles of the dewatering system for the simulation and actual results. It is clear that the pumps reacted almost exactly like predicted with a correlation of 1 and an overall average difference of less than 1%.

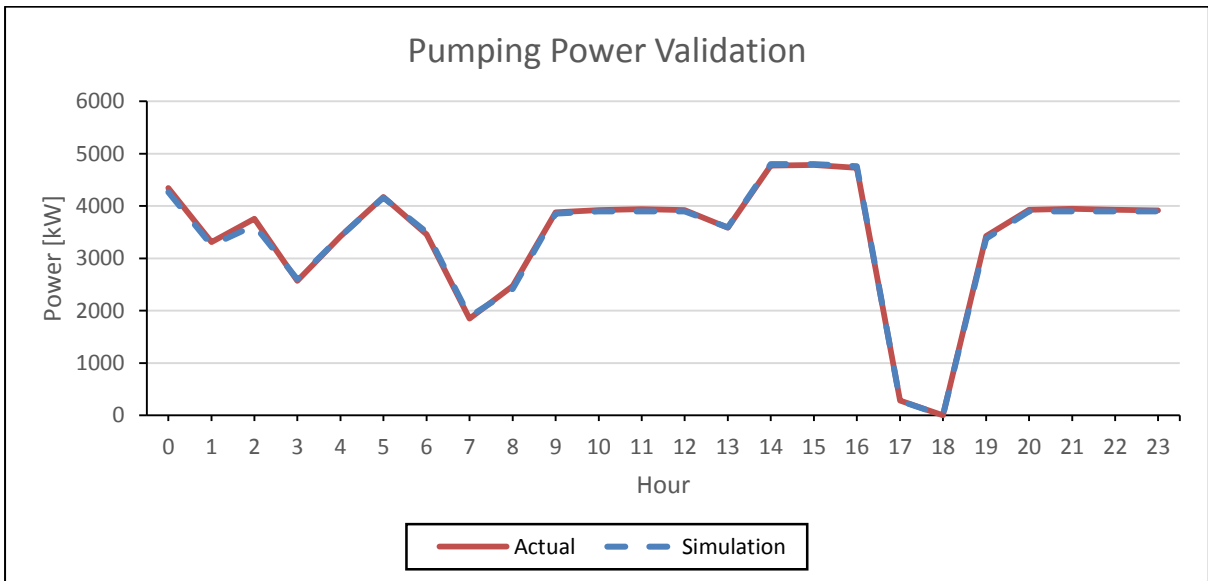


Figure 78: Pumping power validation results