# Improved control processes to sustain electricity cost savings on a mine water reticulation system

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# Abstract

Title: Improved control processes to sustain electricity cost savings on a mine water reticulation system

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Keywords: Electricity cost savings, water reticulations systems, critical component failures, failure processes, energy services company, Eskom, demand load shift.

Eskom provides the majority of South Africa's electricity. However, Eskom's maximum generating capacity might not be sufficient to meet South Africa's demand in the future. Therefore, Eskom initialised the Demand Side Management (DSM) initiative to reduce electricity consumption in South Africa. The benefit of this initiative was seen as the DSM target was achieved 10 years earlier than anticipated. The mining industry is a large energy consumer and implemented numerous demand management projects.

The deep level mining industry is a harsh environment with high humidity and temperatures in underground working areas. These conditions can lead to critical component failures that negatively affect demand management control strategies, which has a detrimental effect on electricity cost savings.

New processes and control strategies are required for load demand control projects when critical components fail. From an extensive literature review it is shown that various problems were identified and solved for water reticulation systems. At the time, no methods or processes were found that mitigated the reduction in load demand shifting when a critical component failure occurred on a mine water reticulation system. These new processes on control strategies is listed as the first novel contribution of the study.

Two prediction models were developed and used as tools in the formulation of each control strategy, namely, the dam level prediction model and the load demand prediction model. A process was developed to formulate control strategies per water reticulation system. A digital twin was used for the study. A digital twin is a term used for a verified simulation of the entire system. Each control strategy was developed per relevant component failure and simulated in the digital twin.

All possible control strategies were tested on a case study and the remaining control strategies were validated with a digital twin. Each control strategy and its effects are discussed with regard to safety and load demand reduction. Implementing each control strategy in a digital twin and evaluating the effect of a failure and a control strategy was the second novel contribution.

These control strategies were implemented on a gold mine in South Africa. For this case study, the approximate increase in annual electricity cost savings equated to R3.8 million. These electricity cost savings were achieved without requiring any capital expenditure for implementation.

The results showed that the implementation of the new electricity cost reduction control processes and strategies for failure conditions increased the electricity cost savings. These cost savings were achieved without adding additional risks.

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# Nomenclature

| **Symbol** | **Unit** |
|---|---|
| GWh | Gigawatt-hour |
| kg/s | Kilogram per second |
| kL | Kilolitre |
| kW | Kilowatt |
| L | Litre |
| L/s | Litre per second |
| Ml | Megalitre |
| MW | Megawatt |
| MWh | Megawatt-hour |

# Abbreviations

| | |
|---|---|
| 3CPFS | Three-chamber Pipe Feed System |
| BAC | Bulk Air Cooler |
| DSM | Demand Side Management |
| ESCO | Energy Service Company |
| OCGT | Open Cycle Gas Turbine |
| PCD | Precooling Dam |
| PCT | Precooling Tower |
| PRV | Pressure Reduction Valve |
| TOU | Time-of-Use |
| VSD | Variable Speed Drive |

# Chapter 1: Introduction

---

*"Science is about knowing, engineering is about doing."*

**Henry Petroski**

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## 1.1 Preamble

### 1.1.1 Electricity in South Africa

Eskom is the leader in electricity generation in South Africa. They generate approximately 95% of the total electricity used in the country [1]. The remaining 5% is generated by private users and some industrial companies [1]. In 2016/17, Eskom's electrical energy available for distribution was 237 215 GWh, which reduced from 238 599 GWh in the 2015/16 term [2], [3]. This reduction can be caused by a decrease in demand or Eskom was unable to generate the required electrical energy. In the past, Eskom has also generated electricity using other means such as open cycle gas turbines (OCGTs). The amount of liquid fuel burnt using OCGTs in 2015/16 was roughly 1 248 Ml compared with 10 Ml in 2016/17 [2], [3].

Although the amount of electricity consumed decreased from 2015/16 to 2016/17, history has shown that an increase in electricity consumption is required due the increase in consumers. Eskom is aware of this issue and is in the process of constructing coal-fired power stations to meet demand. The design and construction of coal-fired power stations are highly complex and require extensive time to complete. This leads to an increase in costs of electricity [24]. Various factors such as the cost of construction and lack of planning can cause delays in the construction of these coal-fired power stations. This may lead to insufficient electricity supply to consumers. To effectively manage electricity consumption, Eskom initiated the Demand Side Management (DSM) initiative.

Eskom initiated the DSM programme in May 2004 [4]. The DSM initiative was implemented as a short-term solution until the planned coal-fired power stations were operational. DSM includes strategies such as load shifting and peak clipping [4]. Peak clipping projects reduce energy consumption in a specific period of the day; most projects focus on the Eskom evening peak period. The load shifting strategy will be discussed later as it forms an important part of this study. The purpose of these DSM strategies is to achieve electricity cost savings.

Time-of-use (TOU) tariffs were implemented, which means that the cost of electricity is dependent on the time of day, day of week and season. Eskom implemented three time periods to which a specific tariff would be applied, namely, peak, off-peak and standard. Figure 1 shows the TOU Megaflex tariff structure used by Eskom [4].

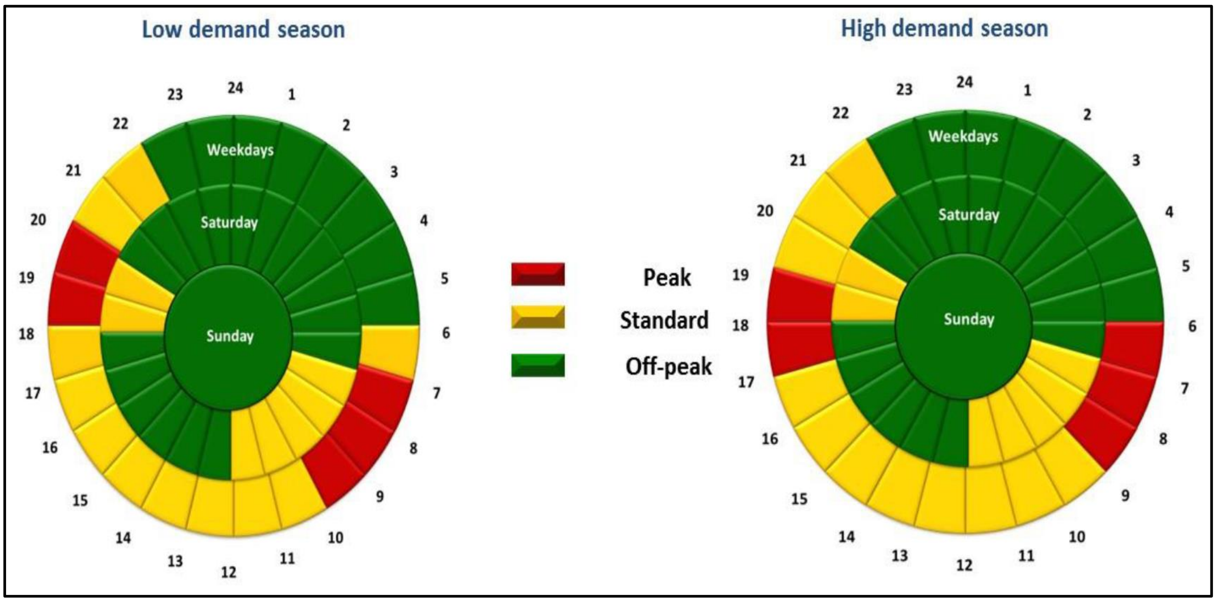


Figure 1: Megaflex tariff structure [4]

Figure 1 shows that there is a low and high demand season. The high demand season includes the winter months (June, July and August) with the rest of the year making up the low demand season. The red bars in Figure 1 represent the peak periods, the yellow bars standard periods, and the green bars off-peak periods [4].

In a high demand season, the evening peak period for each weekday is between 17:00 and 19:00. For weekdays in a low demand season, the evening peak period is between 18:00 and 20:00. From this point forward, these periods will be termed Eskom evening peak periods. The Megaflex tariff for the peak period is more than six times the off-peak period tariff. This provides energy consumers motivation to implement DSM initiatives [4].

Various strategies are used in DSM projects to reduce the load of energy consumers. The initial objective of the DSM initiative was to reduce power by roughly 4 225 MWh over a 20-year period. This equates to the energy production of a six-unit coal-fired station [5]. Figure 2 shows the target and actual peak demand saving achieved with DSM initiatives.

These savings are only applicable in the Eskom peak periods. The target set in 2004 was achieved nearly 10 years earlier than anticipated. Eskom has financed this initiative with roughly R1.36 billion [6]. It can thus be assumed that Eskom is still invested in the DSM initiative for further savings.

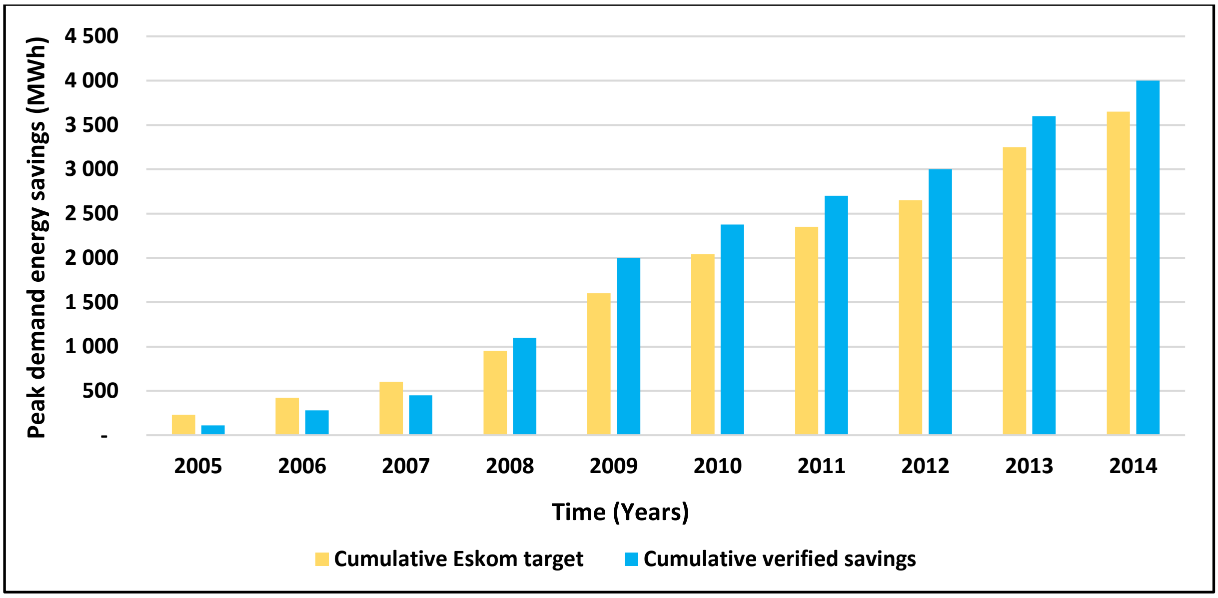


Figure 2: Cumulative Eskom target and verified energy peak savings (Adapted from [4])

These DSM initiatives are usually implemented by energy service companies (ESCOs), which are assigned to implement various DSM projects [4]. The purpose of an ESCO is to implement above-mentioned strategies, which are funded by Eskom, to reduce energy consumption. ESCOs usually implement DSM projects on large energy-consuming industries.

Figure 3 shows the total sales Eskom made in the 2016/17 term and the distribution thereof in percentage. Mining is the third-largest energy consumer in South Africa. The majority of DSM projects in South Africa were implemented in the gold and platinum mining industry [4]. The South African economy relies on the export of gold and platinum as these metals have a large influence on the gross domestic product [7], [8]. The majority of gold and platinum mining in South Africa are categorised as deep level mining [9].

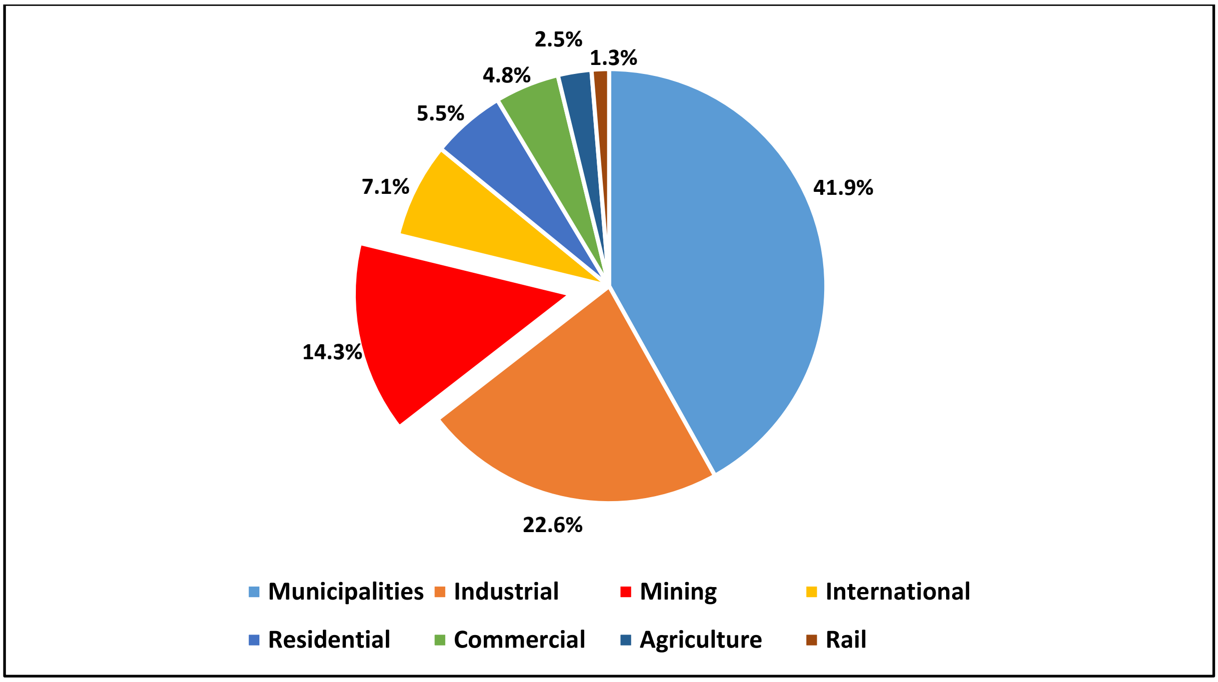


Figure 3: Eskom's total sale distribution in 2016/17 (%) [2]

## 1.2 Deep level mining

Deep level mining in South Africa contributes up to a third of the world's gold reserve [9]. South Africa has the deepest mines in the world with depths of nearly 4 000 m [9]. As these mines are so deep, the virgin rock temperature can reach up to 70°C [8], which can lead to dangerous working environments. Cooling and ventilation are required to lower temperatures to create a safe working environment for mining personnel as well as mining equipment [10]. This leads to significant energy consumption.

Furthermore, in the energy intensive mining industry of South Africa, various systems are required to enable a mine to extract precious ore including compressed air, mining, refrigeration, winders, pumping and ventilation. Figure 4 shows various energy intensive systems and how they are distributed in the South African gold mining industry. Refrigeration has the highest energy consumption and contributes 19% to the total energy consumption of a gold mine. When expanding the focus to the entire water reticulation system, which includes refrigeration, dewatering and some of the mining operations, the energy consumption increases to roughly 42% [9].

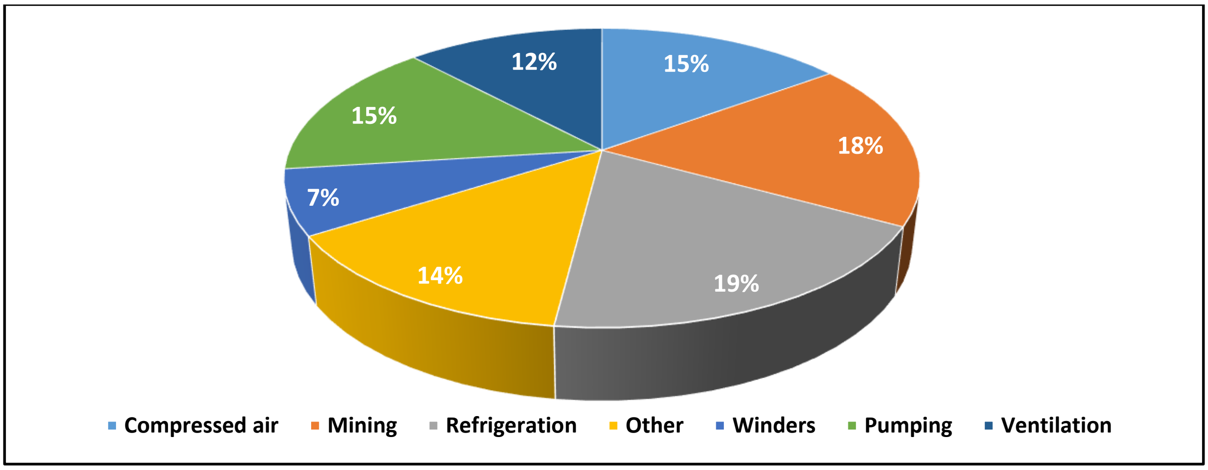


Figure 4: Energy distribution of South African gold mining industry (adapted from [11])

When the control of each mining operation system is improved, it can lead to an overall improved system efficiency. Usually these systems are controlled from a control room situated on surface where each system is controlled separately. When data is evaluated, possible operational improvements can be identified. A modern method for evaluating whether system improvements are viable is by using simulation software. Modern simulation software enables users to simulate these mining systems in detail.

Figure 5 shows a general layout of various systems in the deep level mining industry. The purpose of each system is indicated by colour and the location of each system is shown. This figure illustrates the complexity and integration of various mining systems.

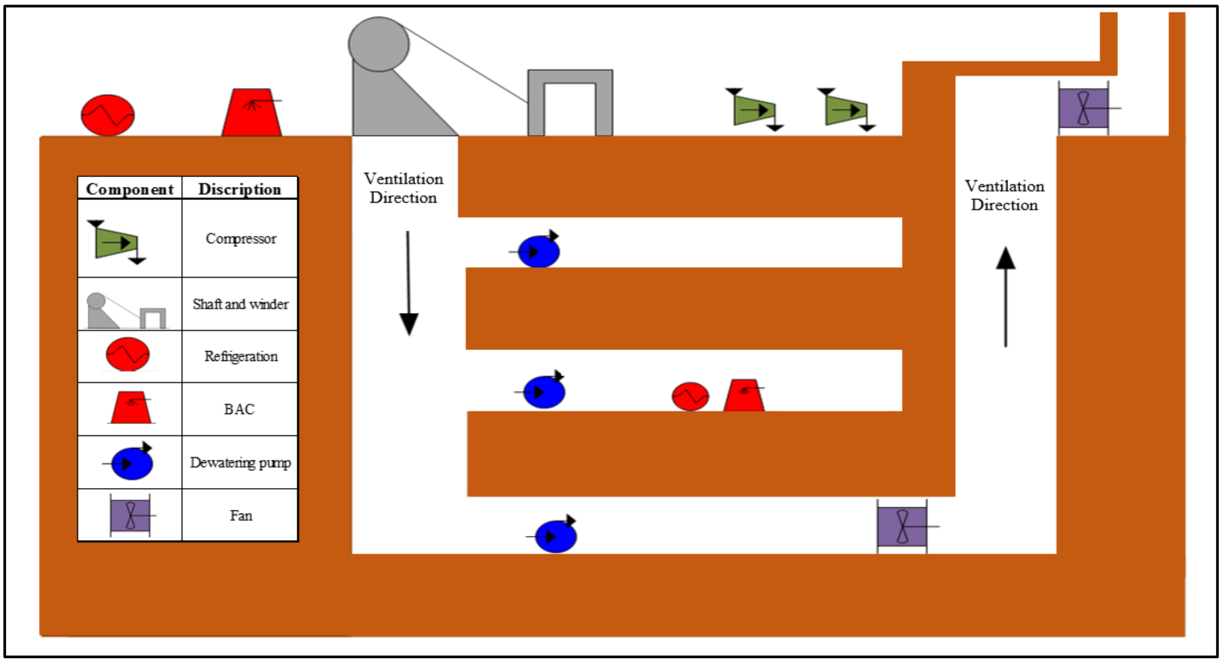


Figure 5: A simple underground operations network (adapted from [12])

As previously stated, water reticulation systems can consume up to 42% of the total energy consumption in deep level mining. Improvements in this system will have a larger impact on the total reduction in energy consumption when compared with smaller systems. This gives reason for requiring more information on water reticulation systems.

## 1.3 Water reticulation systems and modelling

Water serves various purposes in the mining environment such as cooling air in warmer underground areas with cooling cars; cooling air with bulk air coolers (BACs); cooling of drills; doing rock sweeping; and suppressing dust [14]. A water reticulation system consists of various systems such as dewatering pumps, precooling towers (PCTs), refrigeration systems and BACs. Each of these systems are considered critical in the deep level mining industry as these systems cools and dewaters a mine. If these systems fail, dangerous conditions might exist due to the flooding of dams and too high underground conditions. If components fail within each of these systems, it is seen as critical component failures for this study.

A study done by Vosloo, Kleingeld and Bolt in 2011 showed that a large contributing factor to production loss is premature critical component failures [13]. Critical component failures can lead to unsafe underground working conditions and large financial losses. Safety is considered a higher priority in the mining industry than electricity cost savings. Thus, in the event of a critical component failure, the control of the operational components will only focus on safety to reduce the associated risks. This decision means that most of all saving initiatives are ignored and little electricity cost savings are achieved. To better understand the complexity of these systems, and associated control, the different systems will be discussed in more detail.

### 1.3.1 Water reticulation components

Figure 6 illustrates a typical water reticulation systems layout, which is divided into dewatering and refrigeration systems.

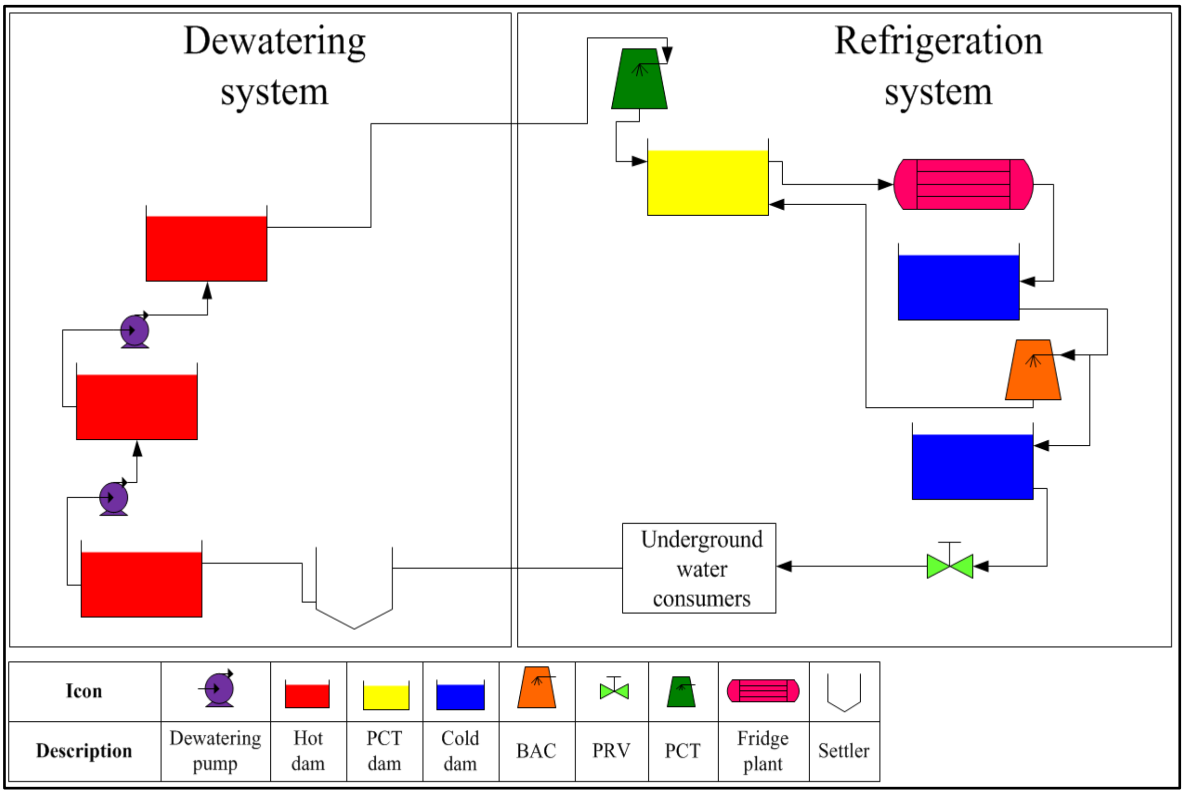


Figure 6: Basic water reticulation system layout (Adapted from [15])

The following subsystems can be found in a water reticulation system, which will be discussed in detail in the subsections that follow:

- Dewatering
- Three-chamber pipe feed system (3CPFS)
- Precooling towers (PCTs)
- Fridge plants
- Bulk air coolers (BACs)
- Dams

**Dewatering**

According to the Oxford Dictionary, *dewater* means to drain. In the mining industry, hot water is drained by pumping it to surface [97]. The purple components in Figure 6 illustrate the dewatering pumps in the dewatering system. The dewatering system is used to pump hot water from underground to surface in a cascading manner to be cooled and reused [16].

Hot dams are used as storing capacity and in emergencies such as increases in water demand, breakdowns, maintenance and power failures [17]. Hot dams can typically be found on every underground dewatering level. The difference in height between two dewatering levels can be as high as 1.3 km [18]. Multi-stage centrifugal pumps are used to overcome the large head (pressure) experienced in the mining environment [16]. Figure 7 shows a single dewatering pump setup in an actual mining environment, which includes a multi-stage centrifugal pump, pump motor and motor cooler.

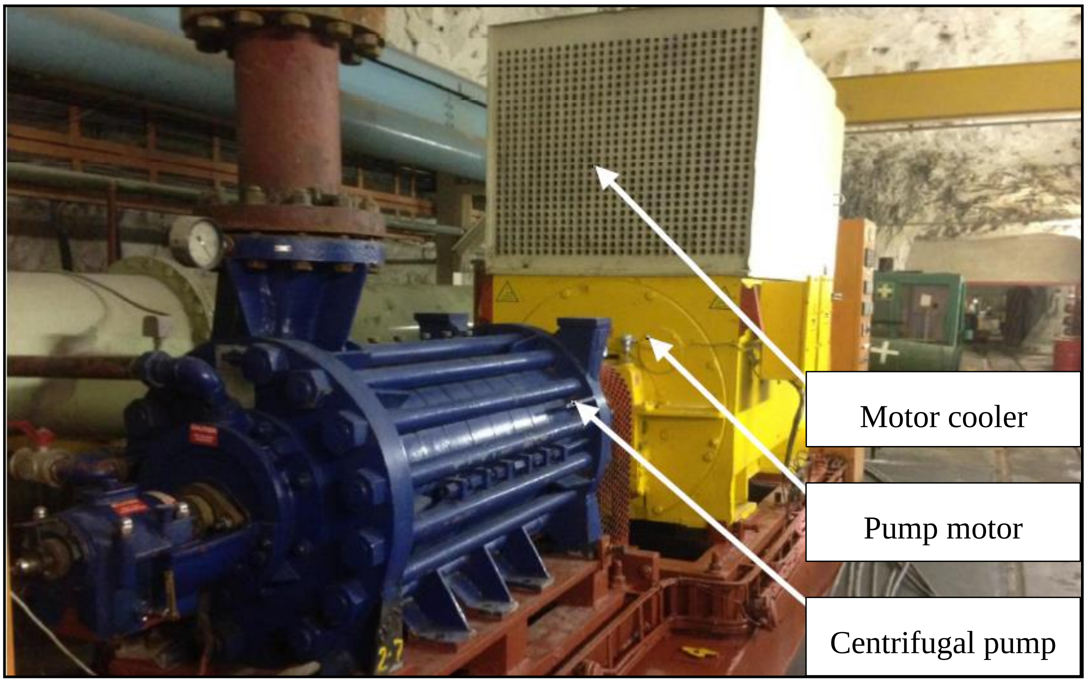


Figure 7: Dewatering pump setup [16]

As a mine's depths increase, electricity costs increase. Various projects have been implemented to reduce the electricity cost of dewatering systems. An example of such a project is implementing a real-time energy management system to optimise the scheduling of water reticulation system components [44]. Shifting load to off-peak periods was identified as a solution to reduce electricity costs in a specific dewatering system.

A study was done in which a dewatering strategy was developed and simulated to determine if it would be a feasible solution. This load was shifted without having a negative effect on production and safety. A predictive control strategy was implemented on a mine using turbines to further improve the control of the dewatering system [9].

There is a strong correlation between implementing control systems and energy efficiency [19]. Energy efficient savings can be obtained when water pumping systems are improved with an operational control model. An optimisation algorithm can be used to select the optimal pump combination to reduce energy consumption [20], [21]. An optimal scheduling algorithm using variable speed pumps was implemented [21]. When pumping control and selection are improved, a considerable amount of electricity cost savings can be achieved [22].

### Three-chamber pipe feed system

Some mines use energy recovery systems in their dewatering systems. A 3CPFS is an energy recovery system that uses high pressure caused by great mining depths to assist in draining hot mine water. The working principle is based on a U-tube system. A 3CPFS is the most efficient energy recovery system used for dewatering in the mining industry [13]. For this reason, a 3CPFS will be the only energy recovery system discussed.

Figure 8 shows the working principles of a 3CPFS. In the first step, water is pumped into the top chamber by filler pumps. The valve configuration equalises the pressure in the chamber as shown in Step 2. The water is forced out of the chamber by cold water in Step 3. This is possible as the cold water has a higher pressure due to booster pumps. Each step in Figure 8 also represents one of the three chambers.

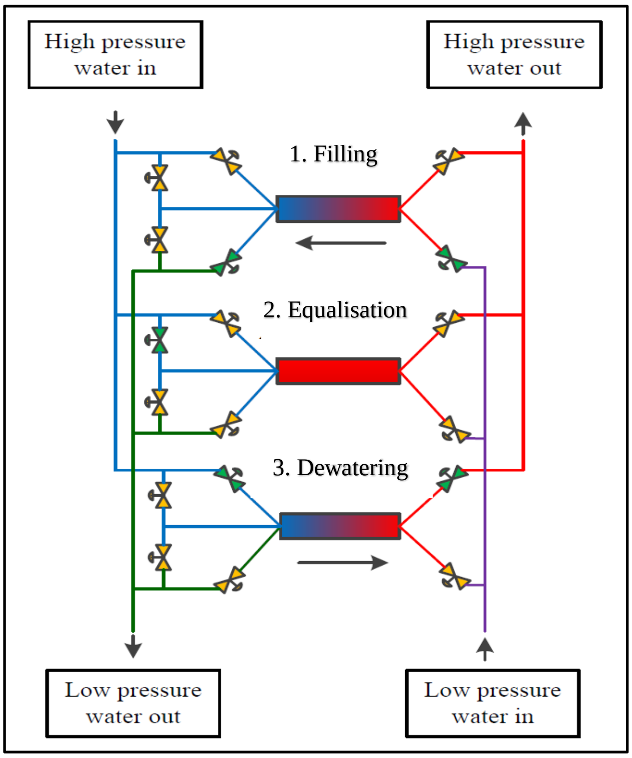


Figure 8: Working principle of a 3CPFS [23]

This process will operate continuously to drain hot water from underground hot dams. In some cases, the delivery flow of the system can be adjusted. This is possible by adjusting the valve combination speeds.

**Precooling towers**

According to the Oxford Dictionary, a cooling tower is defined as: "*A tall, open-topped, cylindrical concrete tower, used for cooling water or condensing steam from an industrial process"* [97].

PCTs are used in the mining industry to reduce water temperatures before the water is cooled further by fridge plants [24]. Water exiting the mine due to dewatering pumps has a typical temperature of between 25°C and 30°C [1]. When referring back to Figure 6, the right side of the diagram illustrates a classic refrigeration cycle. PCTs are used in the refrigeration cycle. The dark green component in Figure 6 represents the PCT. To explain PCTs in even more detail, a simplified diagram is illustrated in Figure 9.

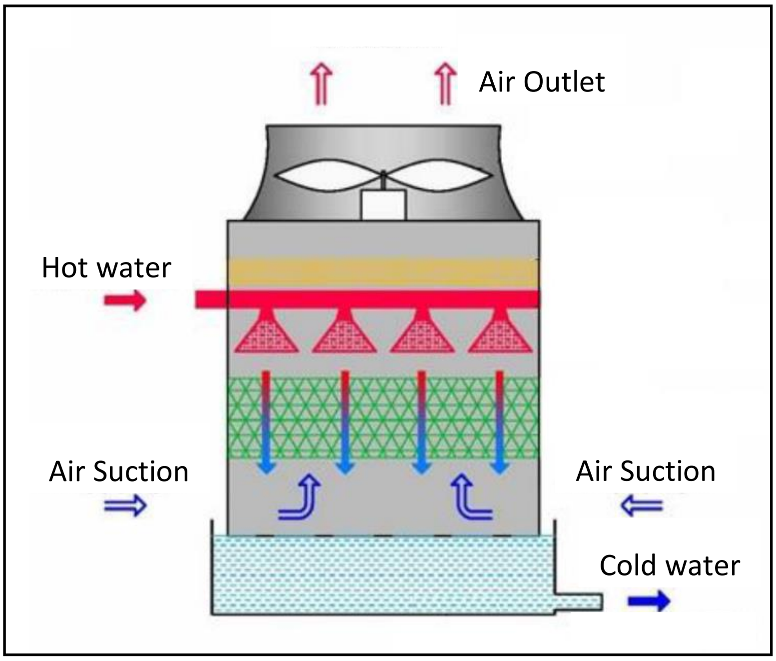


Figure 9: PCT flow diagram [25]

Hot water from underground is pumped into PCTs. Fans draw ambient air into the towers, where nozzles are used to spray warm water through each tower [26]. Heat exchange occurs between the hot water and ambient air, which reduces the water temperature to between 15°C and 20°C [27]. Water is collected in precooling dams (PCDs) where it mixes with return water from BACs [28]. The temperatures in PCDs typically range between 9°C and 12°C [28]. The cold water temperatures can be reduced by improving the operations of PCTs. This in turn reduces the energy consumption of fridge plants [25]. From PCDs, water is pumped to fridge plants for further cooling [29].

**Fridge plants**

Refrigeration is crucial as the human heat tolerance screening procedures state that underground wet-bulb temperature at the station must be below 27.5°C [30]. Figure 10 illustrates a typical refrigeration system layout and Table 1 describes the various flows.

Table 1: Figure 11 flow description

| Colour | Flow description |
| --- | --- |
| (Blue line) | Evaporative water flow |
| (Red line) | Refrigeration flow |
| (Yellow line) | Condenser water flow |

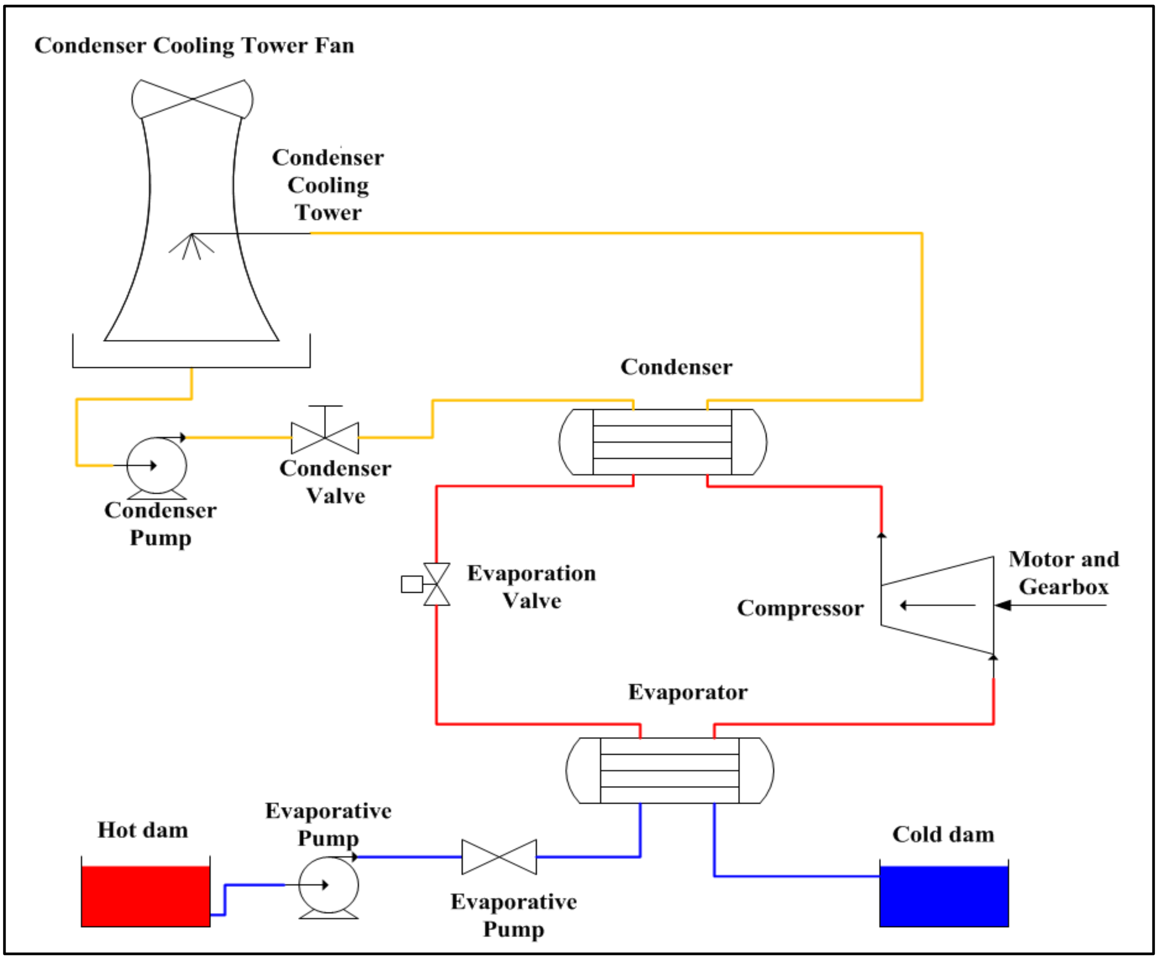


Figure 10: Typical refrigeration system (adapted from [31])

A refrigeration system consists of various components as indicated in Figure 10 [16]. These components are:

### Condenser

Heat is transferred from the refrigerant to the condenser fluid. The refrigerant is usually in a closed loop to optimise heat transfer. The refrigerant is chosen according to specific properties. Only the working principles are needed for this study, thus refrigerant properties are not discussed [24].

### Evaporator

Heat is transferred from the evaporator fluid to the refrigerant. The evaporative liquid is usually water in the mining industry. Hot water is cooled in the evaporative cycle [24].

### Compressor

The compressor is used to increase the pressure of the refrigerant, which is done before the condenser. Compressed refrigerant is usually in a liquid phase [24].

### Evaporation valve

High pressure is released over the evaporative valve. When the pressure of the refrigerant decreases, a phase transformation occurs. This phase transformation is from liquid to gas, which reduces the refrigerant temperature [24].

Mines generally require more than one fridge plant. The total fridge plant's rated power capacity can be as high as 20 MW [32]. This provides the opportunity for various fridge plant configurations [31]. For the purpose of this study, only the working principles of refrigeration are relevant.

From literature, various shortcomings were identified as the complexity of these systems increased, and various projects were implemented to improve the control of the refrigeration systems. A few of the projects that focus on reducing the energy consumption of fridge plants are discussed in the following paragraphs.

Cooling systems can be improved without any capital investment. An energy management system was used to simulate a refrigeration system to improve the control thereof. The energy consumption of the refrigeration system decreased without having a negative effect on the underground working environment [33].

Another study investigated and implemented variable speed drives (VSDs) on large mine cooling systems. These cooling systems include evaporators, condensers, BACs and PCTs. Various flow strategies were developed and implemented on these components, which resulted in electricity cost savings [32].

### Bulk air coolers

Ambient air temperatures are too high for underground usage in some cases and need to be cooled [34]. BACs extract energy from ambient air by using cold water, which results in cooler air temperatures, which is sent underground. BACs are installed on surface, although some mines have underground BACs [34].

BACs are considered the least expensive method of cooling underground air [35]. Using BACs reduces water consumption to underground areas as less water is needed for underground cooling [24]. This results in a reduction of water that needs to be drained. Figure 11 shows two types of BAC mainly used in the mining environment [16].

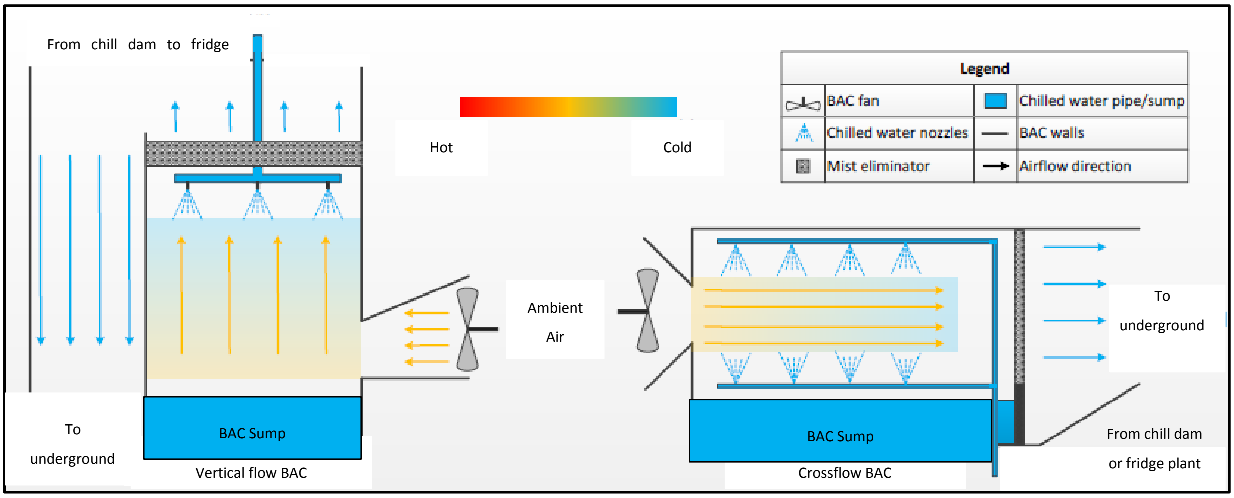


Figure 11: BAC diagram [16]

Figure 11 shows that ambient air is blown into the same chamber as cold water is sprayed to absorb heat from the air. After air is cooled, water is trapped in BAC sumps from where it is pumped to PCDs. For the purpose of this study, only the working principles are relevant.

BACs consume large amount of chilled water [34]. Load reduction on a BAC can reduce the energy consumption of both BACs and fridge plants as the total amount of cold water required is reduced [34]. Peak clipping reduces the amount of air sent to underground by either stopping one or more BACs or reducing the load of BACs. When peak clipping is done, the underground temperatures are presumed to increase, which can cause dangerous underground conditions for mining personnel. Optimal times for BAC peak clipping can be done in no-entry periods (for example, after blasting and before the first cleaning shift) as no mine personnel are allowed in underground working areas [34].

**Dams**

Dams provide a buffer to reduce the effect of varying chilled water consumption on water reticulation systems [24]. Hot dams are used for storage in dewatering systems. As discussed previously, dewatering pumps do not necessarily have the head capability to pump water directly from the lowest level to surface, thus a cascading hot dam configuration is used in most mines.

Figure 12 shows a surface cold dam and a surface hot dam. The cold dam is closed to provide thermal storage for water after it has been cooled. From this cold dam, water is sent underground and to the BACs.


Figure 12: Cold dam and hot dam [36]

This section was used to provide necessary background information on water reticulation components including how each component operates and some projects that were implemented to achieve electricity cost savings. The next section will consist of information regarding the use of water in the mining environment.

### 1.3.2 Water usage in deep level mining

As stated in Section 1.2, water reticulation systems can consume up to 42% of the total energy used in the gold mining industry [9]. Various methods have been identified to reduce the cost of electricity used by water reticulation systems. Figure 4 illustrated that fridge plants consume the largest amount of energy in a water reticulation system. Reducing water consumption in a water reticulation system will essentially reduce the energy consumption as well [10]. A method to optimise water usage in the mining industry is to match water delivered and water consumed [37].

Some mines oversupply cooling cars, which increases the underground water consumption [38]. This leads to higher energy consumption of fridge plants and dewatering systems as more water needs to be drained and cooled [38]. Electricity cost savings can be realised when less water is supplied to the cooling units. Integrating water usage distribution with cold water reticulation can also lead to large electricity cost savings [39].

Whether the water supplied to underground areas can be reduced depends on the time of day. In the peak drilling shift, more water is supplied than during the Eskom evening peak period as more water is required for drilling. An investigation was done that evaluated underground water temperatures. It was seen that less water is required for cooling purposes in the Eskom evening peak period. As water consumption was reduced, less water was required to be pumped to surface, which resulted in electricity cost savings [40].

Various mine systems and the effect these systems have on each other have been investigated. A water supply optimisation project was implemented, which reduced the amount of water supplied to underground. The total energy consumption of these various systems decreased, resulting in electricity cost savings [41].

Underground temperatures can be reduced using various equipment. Some of these equipment use water to reduce underground temperatures [37]. Water used in underground operations is typically for cooling, ventilation, washing and dust suppression [42]. Before any of the previous initiatives were implemented, the feasibility of each project was determined. A modern method to determine feasibility is by using simulation models, which will be discussed in the next section.

### 1.3.3 Water reticulation simulation models

A study was done to compare various simulation models [43]. The following simulation packages were discussed in the previously mentioned study: Environ, Flownex, VUMA3D, REMS, QUICKcontrol, VisualQEC and Process Toolbox [43]. These simulations were generally not aimed at energy management or integrated system optimisation [43]. Only the following simulation packages could have been used in this study: Flownex, QUICKcontrol, VisualQEC and Process Toolbox (QUICKcontrol and VisualQEC were used to create Process Toolbox) [43].

The remaining packages are used for ventilation purposes or only comprise steady state calculations. When using steady state calculations, it is stated that no system predictions can be made [43]. A need was identified for transient simulations, which could be used to predict energy consumption for an integrated system [43]. For this study, Process Toolbox will be used as it is a simulation package utilising transient calculations.

A critical evaluation was done that compared various simulation models. The selected simulation model is used in the mine cooling environment where all critical components are operational [43].

Various simulations were done to provide necessary information regarding pumping systems. It was seen that shifting load on pumping systems is possible if water storage capabilities are sufficient [17].

When a simulation is calibrated, the simulation is referred to as a digital twin, which will be discussed later. It should be noted that a digital twin will not always be available. More information regarding a digital twin will be discussed in Chapter 2.

Table 2: Effect of failures on water reticulation systems

| System | DSM project type | Type of failure | Effect of failures on system | Effect of failure on savings | Risk |
|---|---|---|---|---|---|
| Dewatering | Load shift | Dewatering pump failure | Flooding or emptying of dams | Medium | High |
| | | Burst in pumping column | | | |
| | | Valve malfunction | | | |
| Fridge plant | Peak clip | Fridge plant failure | Increasing underground temperatures | Medium | High |
| | Load shift | Condenser cooling tower failure | Increasing underground temperatures | Medium | High |
| BAC | Peak clip | BAC failure | Decreasing cool air to underground | Low | Medium |
| | | Blocked nozzles | | | |
| PCT | Peak clip | PCT failure | Increasing water temperature towards fridge plants | Medium | Low |
| | | Blocked nozzles | | | |

Table 2 discusses each water reticulation subsystem and shows the effect of a failure on the system, the effect of the failure on the savings and, finally, the associated risks. Failures within dewatering and fridge plant systems have high risks due to safety reasons. When an underground dam floods or underground temperatures are too high, it could be harmful to underground mining personnel. These risks should be avoided. More information is required from previous studies to obtain the necessary information regarding problems that have been identified and how each problem has been solved. A further requirement is to identify any problems that have been detected but have not been addressed by previous studies.

## 1.4 Relevant studies

The following subsections consist of studies that were done in the mining sector and other industries. These studies extend the literature review to identify deficiencies in existing methods and validate the need for the study.

### 1.4.1 Mine dewatering

The following paragraphs discuss studies that were done within the mine dewatering field. Each study will have a summary of what was discussed in the study and what need exists from this study.

**Gunson et al.** [37]

A method to reduce unnecessary water usage on mines was introduced. Water balance calculations were done to ensure that each water consumer received the required amount of water. The model included all water sources and compared their location with water consumers, thus improving underground water usage. This method reduced water consumption significantly, which reduced the dewatering energy consumption.

No focus was given to scenarios where dewatering pumps fail; however, it will be beneficial if less water is required to be pumped to surface. No processes were put in place to maintain load shift savings in case of failures.

**Van Rensburg and Liebenberg** [44]

Improving dewatering pump scheduling led to electricity cost savings on deep level mines. Load shifting projects were identified and implemented to achieve these electricity cost savings. Automating the dewatering system of a mine was used to improve the system efficiency and achieve required load shifting [45].

In this study, it seems as if the assumption was made that all dewatering pumps are available and operational. No mentions were made in the event of a dewatering pump failure.

**Groenewald, Stols and Van Rensburg** [70]

Load shifting project performance tends to deteriorate after ESCOs are no longer involved with the projects; even automated project performance deteriorated. This was seen as an opportunity to investigate the possibility of maintaining projects. A strategy was developed to mitigate problems and regain possible electricity cost savings.

There was no mention regarding the reasons for deterioration in load shifting performance. Further investigations could be done to identify these reasons. A reason for the deterioration in load shifting performance might be failures of dewatering pumps, although a process was not discussed how to proceed in such scenarios.

**Vosloo et al.** [13]

Various energy recovery systems were investigated to use in deep level mining. It was seen that implementing energy recovery systems could be beneficial to energy efficiency savings. The study shows that the use of a 3CPFS was an optimal energy recovery system at the time.

The focus of this study was to identify the optimal energy recovery system at the time; for this reason, no failure strategies were discussed. This study did not discuss how to proceed in the event of a dewatering pump failure.

**Schoeman, Pelzer and Vosloo** [46]

Focus was given to valve selection and valve combinations. The aim of the study was to reduce friction losses within a dewatering system while avoiding water hammering and backflow. The study also included the effect that discharge isolation valves have on specific pumps. These techniques were used to improve the dewatering system and achieve electricity cost savings.

The main focus of this study was to improve the dewatering system. It seems as if an assumption was made that all dewatering pumps were available and operational, thus no focus was given to a process to follow in the scenario of such a failure.

**Schoeman** [47]

Investigations were done on a mine with various shafts. It was seen that load shifting could be implemented on the entire water network. It was simulated and tested to prove the benefits of transferring water to other shafts to obtain load demand shifting, which leads to electricity cost savings.

The improvements that were investigated in this study were done when all dewatering pumps were available and operational. No focus was given to a process to follow in the case of a dewatering pump failure.

**Van Rensburg** [48]

Water management improvements can be implemented on deep level mines. Various techniques have been identified to reduce water supply to mines. It was seen that less water is needed and load shifting is possible in some cases. This led to energy efficient savings combined with load demand shifting, which led to electricity cost savings.

This study did not discuss a process to follow in the case of a dewatering pump failure. It is beneficial to lower the amount of water that needs to be pumped to surface, although energy savings in scenarios where failures occur were not included in this study.

**Vosloo** [49]

The study focused on an integrated water reticulation system, which included dewatering systems and refrigeration systems, as well as supplying cold water to underground levels. The integration of these systems improved the control to reduce electricity costs of deep level mines. It was seen that all components were operational and no processes were in place for scenarios where component failures occur.

### 1.4.2 Cooling

The previous subsection focused on studies done specifically on mine dewatering. The next subsection will focus on cooling and projects that were implemented in the mining industry. Each of the following studies will include the focus of the study and the needs that still exists.

**Buys, Kleingeld and Cilliers** [50]

Improving cooling systems can reduce energy consumption without affecting service delivery when VSDs are installed to match underground cooling supply. Installing VSDs gave the opportunity to achieve energy efficiency savings.

This study focused on obtaining energy savings on a mine cooling system, although all components were operational and available. This study did not focus on a process that is required in the case of a component failure.

**Uys, Kleingeld and Cilliers** [26]

An investigation was done that compared the electricity consumption of ice storage systems with chilled water systems. Ice storage systems were converted to chilled water systems where the water flow was varied. Water flow variations were made possible by installing VSDs on condenser and evaporator pumps.

Two cooling methods were compared, although it was assumed that all components within this study were operational and available. The study did not include scenarios where component failures occur.

**Maré, Marais and Van Rensburg** [51]

Existing strategies at the time did not account for the deterioration of cooling system performance, which provided the opportunity to develop new strategies to address this issue. Implementing these new strategies resulted in energy efficient savings on a mine cooling system.

These new strategies can be implemented when all components are operational. None of these new strategies included a scenario where component failures occur. This study also did not discuss a process to follow in a scenario where a component fails.

**Schutte, Kleingeld and Van der Zee** [52]

Mine ventilation and refrigeration systems were operated separately, thus the integration of these systems was investigated. Various projects were suggested; some of which were implemented. It was seen that integrating systems in the mining environment is possible and electricity cost savings can be obtained.

Two mining systems were integrated to improve the overall control, although it was assumed that all components are operational and available. No scenarios were discussed on how the integration of these systems would be affected in the case of component failures.

**Schutte, Pelzer and Mathews** [33]

Investigations were conducted that established that the efficiency of precooling could be improved. The water quality was improved and PCT fans were cleaned. This resulted in an energy efficient improvement on a mine cooling system.

At the time, no studies were found that developed strategies in the case of failures on dewatering or cooling systems in the mining industry. This is seen as an opportunity to develop and select new control strategies in the industry as failures in the mining industry are common occurrences. No study was found where focus was given to a process to follow in a scenario where a component failure occurs.

### 1.4.3 Dewatering simulations

The previous two subsections focused on studies done in the mining industry, specifically in the dewatering and cooling sections of mining. This subsection will be used to discuss studies that were done on simulations for mine dewatering systems. This section will also briefly discuss the need that still exists after each study.

**Gao et al.** [54]

A model was designed with various objectives, which were categorised as follows: water input, water output, water task, treatment plant and dissolved salt balance. A case study on an Australian coal mine was done where seven water management strategies were simulated. When combining a process-based simulation with these objectives, various management strategies were analysed to implement an optimal solution.

This study focused on a system where all components were operational. No scenarios were simulated where a component was turned off (to simulate a failure). This study also did not discuss a process to follow on how to adjust the simulation to include a component failure.

**Rautenbach, Krueger and Mathews** [55]

Effective control is the most cost-effective solution to improve the running cost of a 3CPFS. A simulation tool was used to predict the influence of a pumping schedule, control parameter and dam level set points on each 3CPFS. An optimal strategy was simulated and implemented to achieve load demand shifting on a deep level mine.

This simulation was developed for scenarios where all 3CPFSs and water reticulation components were operational. This study was also done in a scenario where all other components were operational.

**Appuhamillage and Senadhire** [56]

A model was developed for a medium-depth graphite mine. The model included water seepage and mining water filling underground sumps. Various underground pump combinations were implemented to improve the efficiency of a mine dewatering system.

This study focused on simulating various pump combinations to improve the mine efficiency, although all dewatering pumps were operational and available. This study did not discuss simulations where components were turned off (to simulate a failure).

**Smith, Joubert and Van Rensburg** [57]

Electricity cost savings were realised by implementing an automated control on a deep level mine’s dewatering pumps. The potential for implementing a load shifting project was investigated using simulation software. Load shifting projects were implemented for the Eskom morning and Eskom evening period.

These simulations were developed for ideal scenarios; thus, all dewatering pumps were assumed to be operational and available. This study did not mention how to adjust the automated control in the scenario of a dewatering pump failure.

**Schoeman** [47]

A study was done to improve the energy usage of dewatering systems for multiple shafts. The study included integrating five interacting shafts. The operations of the dewatering systems were improved by using simulation software to determine a feasible solution.

This study did not consider dewatering pump failures and how these would influence the integration between the shafts. This study also did not develop processes to adjust control strategies in scenarios where failures take place. From literature novel contributions can be formulated, where the next section will be used to do so. A literature review table will also be included to identify novel contributions (Table 3).

### 1.4.4 Need for the study

A number of studies focus on mine simulations [43], [47], [54], [55], [56], [58], [59]. No studies were found that focus on simulating the effects of critical component failures in the deep level mining industry. Table 3 shows a novel contribution table. This table shows previous work done with relevant topics to this study, which are used to motivate the novelty in this study.

Table 3: Literature review table

| | **Field of study** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reference** | **Water usage** | **Water reticulation** | **Dewatering/pumping** | **Fridge plant/cooling** | **Precooling towers** | **Bulk air coolers** | **Mine simulation** | **Critical component failures** | **Failure strategies** | **Automation** | **Maintenance** | **Preventative maintenance** | **Selection of failure strategy** |
| [37, 46, 48, 61] | x | | x | | | | | | | | | | |
| [26, 39, 49, 51, 52, 71, 72, 76–78, 93–95] | | | | x | | | | | | | | | |

| | **Field of study** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reference** | **Water usage** | **Water reticulation** | **Dewatering/pumping** | **Fridge plant/cooling** | **Precooling towers** | **Bulk air coolers** | **Mine simulation** | **Critical component failures** | **Failure strategies** | **Automation** | **Maintenance** | **Preventative maintenance** | **Selection of failure strategy** |
| [62–66] | | | | | | | | | x | | | | |
| [55, 56] | | | x | | | | x | | | | | | |
| [12, 17, 20, 70, 73, 80] | | | x | | | | | | | | | | |
| [82, 83] | | | | | | | | | | | | x | |
| [81, 84] | | | | | | | | | | | x | | |
| [85, 86] | | | | x | | | x | | | | | | |
| [58, 92] | x | | | | | | x | | | | | | |
| [59, 67] | | | | | | | x | | | | | | |
| [45, 54] | | | x | | | | | | | x | | | |
| [46] | x | | x | | | | | | | | | | |
| [47] | | x | | | | | x | | | | | | |
| [50] | | x | | | | | | | | | | | |
| [53] | | | | | x | | | | | | | | |
| [43] | | | | x | | | x | | | | | | |
| [60] | | | | x | x | | | | | | | | |
| [50] | x | | | | | x | | | | | | | |
| [66] | x | | | x | | | | | | | | | |
| [67] | x | x | | | | | | | | | | | |
| [68] | | | | | | | | x | | | | | |

A few studies focus on failures from various other industries. These studies include failures that occur in space [62], slope failures in open pit mining [63], detecting failures using safety instrument systems in industries containing hazardous subsistence [64], and risk strategies [65].

At the time, no studies were found that focused on sustaining electrical cost savings while critical component failures occur in deep level mining. This is seen as a problem, as the mining industry and Eskom is affected negatively by these failures [1]. The client is affected negatively as their electricity costs will increase since energy is more expensive periods due to TOU.

Eskom is affected negatively as it does not necessarily have the capacity to generate the required demand. Thus, sustaining electricity cost savings is beneficial for both parties.

Literature also shows that it is the client's responsibility to maintain the infrastructure of a DSM project [1]. This includes ensuring that all critical components are in working condition, otherwise the project performance might deteriorate. Not achieving the savings could also lead to penalties being imposed.

Additionally, no studies were found on a specific process to follow in the case of critical component failures. From this section a problem arises in the mining industry. The next section will be used to discuss the problem.

## 1.5 Problem statement

The mining industry is experiencing financial pressure as electricity costs are increasing. In addition to this, mining equipment are more prone to failures due to the environment they are used in. These failure occurs in the dewatering and cooling sections within the mining industry.

From experience it was seen that dewatering pump failures are common in dewatering systems. This is a cause for concern as this system is capable of dewatering a reduced amount of water to surface. This may result in flooding of underground areas, leading to unsafe working environments for mining personnel.

In the cooling section within the mining industry, fridge plants, BACs and PCTs fail. Each of these components is used to reduce water or air temperatures. This results in cooler underground areas. Should a cooling component fail, water or air temperatures may increase, leading to unsafe underground working environments for mining personnel.

These failures lead to the neglect of electrical cost reduction control strategies. The result is a decrease in electrical cost savings and an increase in the risk associated with the mining industry. These risks include the increase of underground dam levels and underground temperatures. This rise in temperatures can result in hazardous, life-threatening situations.

As the risks increase with critical component failures, little attention is given to strategies to reduce electrical consumption. This applies to most systems, which include water reticulation systems. The following needs exist:

- Sustain achievable electricity cost savings despite component failures.
- Implement control strategies for failure conditions without incurring additional risk.
- Develop a simulation model to determine the effect that critical component failures have on safety and electricity cost savings.

## 1.6 Contributions of this study

The novelty of this study lies in developing processes that could be implemented when a critical component fails in a mine water reticulation system. These processes include developing load management control strategies to be implemented in a scenario where a critical component fails in order to still safely achieve a portion of the load demand shifting that would otherwise be lost. Two contributions are discussed in detail in the following paragraphs.

**1. Develop a process to create and select unique water reticulation control strategies to sustain electricity cost savings when a failure occurs**

**Why are current methods insufficient?**

In many cases, a mine water reticulation component failure compromises the opportunity to prepare for load shifting in the evening peak. This has a negative impact on the potential electricity cost savings. In addition, when using manual control, the human factor can result in lost saving opportunities.

**How does the system currently work?**

Automated control is used in normal conditions when all water reticulation components are operational. In the event of a failure, control reverts back to manual control and saving opportunities are neglected.

**What needs to be done?**

New strategies are required to maximise the achievable load shifting saving opportunities when critical component failures occur in a mine water reticulation system. Each new control strategy should be implemented without incurring additional safety risks. These control strategies must manage common combinations of water reticulation component failures. In addition to creating these new strategies, a new process needs to be developed that will identify a control strategy on a water reticulation system when a failure occurs. These control strategies will aim to maximise achievable load demand shifting despite the critical component failure.

**How does this study solve the problem?**

The new control strategies will enable a mine to better sustain load demand shifting over a longer period by improving load demand shifting opportunities if a critical component failure occurs. The process will also identify the failure and ideal control strategy that could sustain the achievable electrical cost savings on the water reticulation system.

**2. Application of digital twin methodology to implement improved control processes when failures occur**

**Why are current methods insufficient?**

Current simulations do not consider the effect that failures have on a mine water reticulation system.

**How does the system currently work?**

No such integrated simulation exists as simulations are not set up to accommodate failures.

**What needs to be done?**

A water reticulation simulation that combines electricity cost saving strategies with safe operations is needed in the event of critical components failing. This will be used to identify the risk and viability of control strategies for failure conditions.

**How does this study solve the problem?**

This simulation will be used when a critical component fails to evaluate control strategies. The modification to simulate failure conditions allows control strategies specific to each failure condition to be evaluated.

## 1.7 Thesis layout

**Chapter 2**

The methodology of the thesis will be discussed in this chapter. This includes developing a control strategy, which contains different models that will be used. Each model along with the processes that are required to develop and select a control strategy for a given scenario will be discussed. A process will also be included to modify a simulation to accommodate critical component failures combined with control strategies. This will be done to determine the effect of the control strategy when failures occur.

**Chapter 3**

In Chapter 3, the methodology will be applied to a case study. The results of each developed control strategy will be discussed where most strategies were implemented on a practical case study. The simulation will be verified by comparing actual data with simulated data. Each strategy will be validated by means of practical case studies. The probability of each type of failure will be discussed and combined with possible annual electricity cost savings. This chapter will also include the results obtained with the selection process to ensure that the ideal control strategies are selected for failure conditions combined with real-time variables.

**Chapter 4**

The study will be concluded in Chapter 4. The conclusion will include recommendations for possible future work. A discussion will be done to confirm that each contribution was proven in the thesis.

## 1.8 Conclusion

Chapter 1 discussed background regarding the electricity situation in South Africa. The current state of the DSM model was also discussed and background information was given on deep level mining. Background information was provided regarding water reticulation systems. Each water reticulation component was discussed in detail, which included the basic operations of each component. A literature review was done, which discussed previous studies that focused on mine water reticulation systems. A literature review table was included where the novelty of the study was proven.

From the literature it was gathered that critical component failure of mining equipment is inevitable and can result in higher energy consumption as risks increase. To assist with this problem, two novel contributions to the study were identified. The contributions include sustaining a portion of electrical cost savings despite critical component failures on mine water reticulation systems. The implementation of control strategies without incurring additional risk to the mining environment. The second contribution includes using a simulation model to determine the effect of critical component failures on safety and electricity cost savings. This chapter therefore gives a clear motivation for the study as well as the proposed solutions.

The next chapter will focus on the methodology of this study, which will include various processes that will be discussed. These processes will include the development of two prediction models, which will be used as tools in the development of each control strategy. A selection process will also be discussed, which will select an ideal control strategy for failure conditions. Processes will also be developed regarding the use of the simulation, which will determine the effect of failure conditions and control strategies.

# Chapter 2: Water reticulation control process development

*"There is nothing I believe in more strongly than getting young people interested in science and engineering, for a better tomorrow, for humankind."*

**Bill Nye**

## 2.1 Preamble

Chapter 1 gave background information regarding water reticulation systems. Chapter 1 also consisted of a literature review to identify work that was done on water reticulation systems. From the literature review the problem statement was discussed, which also led to the development of the two novel contributions.

Control strategies are required to obtain electricity cost savings safely in scenarios where critical components fail. Prediction models will be developed in this chapter to aid strategy development. These models will be used as a tool for developing each control strategy. A selection process will be discussed to select control strategies for failure scenarios. These control strategies will be implemented into a digital twin to determine the effect of the control strategy while the failure is occurring. Figure 13 shows the main process to be followed.

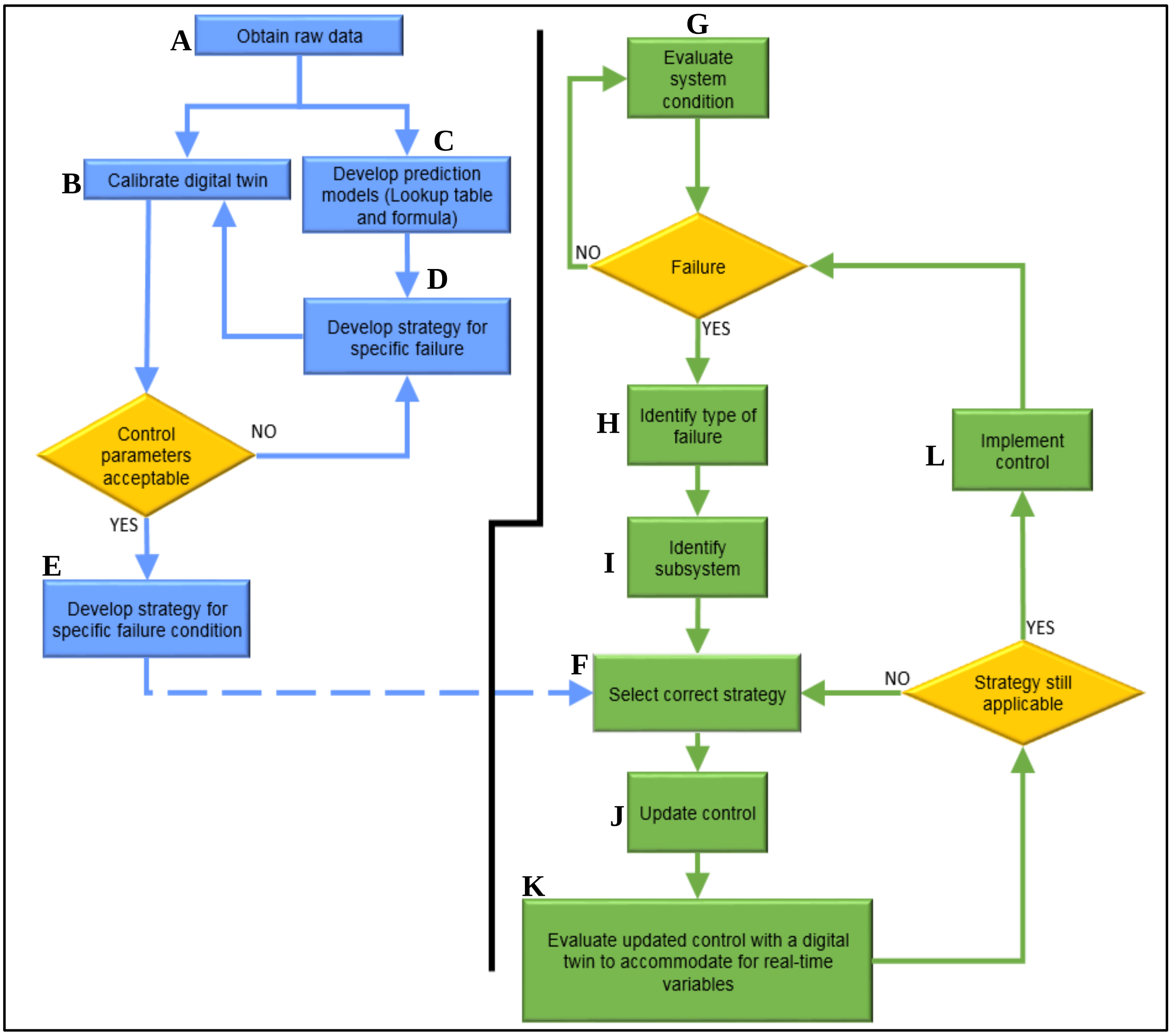


Figure 13: Failure process diagram

The left-hand side (blue blocks) of Figure 13 shows the once-off process, which is used to develop strategies for mine water reticulation systems. The number of strategies depends on the number of critical components; thus, it is site-specific. The right-hand side (green blocks) of Figure 13 shows the continuous process, which commences once all control strategies have been developed. Figure 14 forms part of the once-off steps (shown in blue as Step A–E in Figure 13).

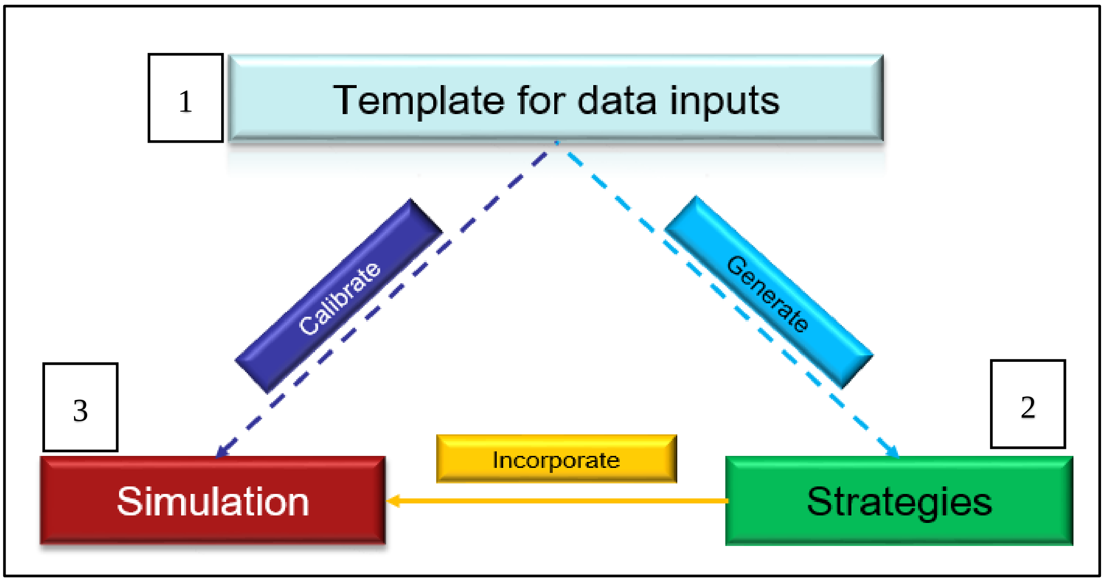


Figure 14: Once-off process per water reticulation system

The following steps are used to explain the process followed in Figure 14:

**Step 1: Obtain data using a template**

The first step in the development of these new control strategies is obtaining data (Step A, Figure 13). Data can be obtained from site personnel. It should be noted that reliable data is required. Determining how these measurements are taken as well as determining the reliability of the data do not form part of this study.

Information that does not necessarily change over time is required. A generic template ensures that all required information is obtained, which includes dam sizes, pump flow capabilities, locations etc. The data obtained in this step will be used to calibrate the simulation at a later stage. Table 4 shows a generic template for the basic information that is required. It is beneficial if this information is accompanied by site layouts as they could help improve the control strategies. This information combined with site layouts will be used with the prediction models to develop control strategies.

Table 4: Generic site information template

| Parameters: | | Fridge Plant | PCT | Dewatering | BAC |
|---|---|---|---|---|---|
| Machines | Location | x | x | x | x |
| | Number | | | x | |
| Max flow per machine | | x | x | x | x |
| Required temperature out | | x | x | | x |
| Dam capacities | | x | x | x | x |
| Min dam level | | x | x | x | x |
| Max dam level | | x | x | x | x |

**Step 2: Generate control strategies**

Step 2 as depicted in Figure 14 is using the data obtained in Step 1 to generate the various required control strategies for a water reticulation system. These control strategies are unique per water reticulation system. The process of developing these models will be discussed at a later stage.

**Step 3: Calibrate the simulation**

The final step is calibrating the simulation and incorporating the various control strategies derived in Step 2. For this study, it is assumed that there is a calibrated simulation.

When this process (Step 1 to Step 3) has been completed, each simulated control strategy should be a feasible option that should ensure that dangerous situations do not occur. Dangerous situations include, for example, too high or too low dam levels, or high underground temperatures. A risk assessment is deemed unnecessary as the development of control strategies includes avoiding risks. When these control strategies are proven to be feasible, the diagram shown in Figure 13 can be implemented on a water reticulation system.

## 2.2 Digital twin simulation

The purpose of verifying the simulation is to prove the accuracy of the digital twin [43], which is an important aspect as all control strategies will be simulated. The feasibility of each control strategy will be determined using the digital twin.

### 2.2.1 Digital twin (Step B in Figure 13)

A study was done on an integrated transient response simulation [43], which created a digital twin of the mine that focused on managing mine cooling systems. The purpose of the digital twin was to simulate future projects to improve mine efficiency and identify the validity of each future project. The study calculated an average percentage error of 3.2% [43]. This simulation also had an average combined accuracy of 96.7% [43].

The simulation software used for creating the digital twin of the mine is Process Toolbox. This software is component-based and was developed from other simulation software, namely, VisualQEC and QUICKcontrol [43]. Literature showed that this software are used to simulate integrated mining systems [43].

For the purpose of this study, a digital twin is used to simulate the effect that each control strategy has on the water reticulation system of a mine in case of critical component failures. The novelty thereof lies in reusing the current digital twin and implementing the failures and control strategies on the simulation.

The implementation of these failures and control strategies is as follows: First, data is required. The process of obtaining data was discussed previously. Second, the data is used to validate the accuracy of the simulation by comparing the simulated results with the actual results. The validated simulation (digital twin) should be adjusted to incorporate failures, which is done by switching the component off in the digital twin. The process of calibrating the digital twin is shown in Figure 15.

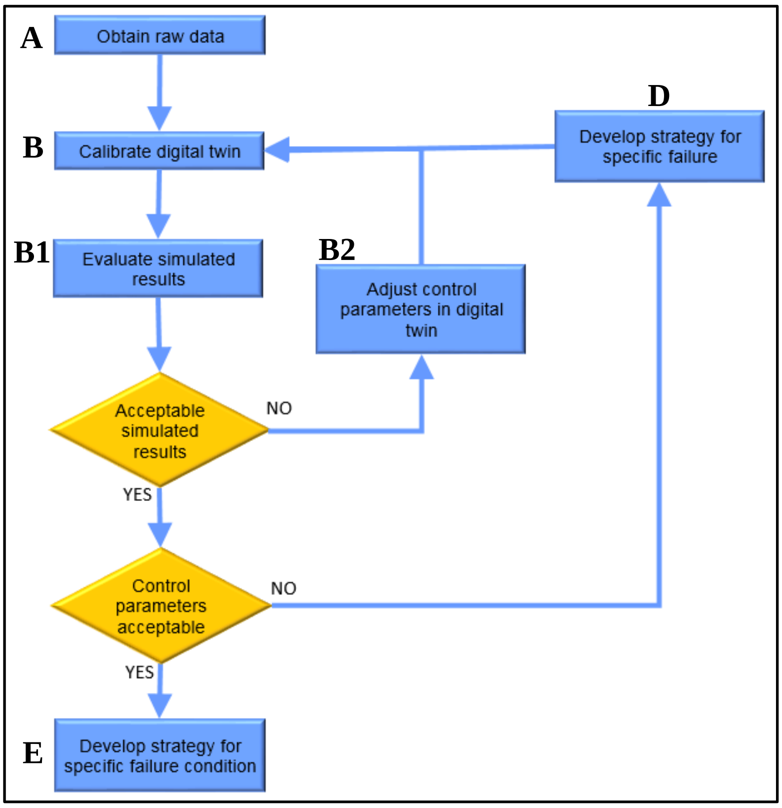


Figure 15: Calibrate digital twin process

The following steps are used to discuss the process of calibrating the digital twin shown in Figure 15:

**Step A: Obtain raw data**

The template for data inputs is described by Figure 14 and Table 4. This data is used to calibrate a simulation to create a digital twin and to develop the prediction models.

**Step B: Calibrate digital twin**

A calibrated simulation is referred to as a digital twin. In Step B, real-time data is used to simulate current conditions in a water reticulation system using a digital twin. The effect that various failures have on the water reticulation systems is also evaluated.

## Step B1: Evaluate simulated results

The simulated results of the digital twin are obtained after the raw data for a specific water reticulation system has been implemented. These results are evaluated to ensure that the predicted results correspond with the actual data for the water reticulation system. All predicted data is evaluated, for example, all water reticulation components' energy consumption and all refrigeration components' outlet temperatures.

### Step B2: Adjust control parameters in digital twin

Step B2 is used when the simulated results are not acceptable, i.e. when the percentage error between the simulated results and actual results is too high. In this case, control parameters should be changed in the digital twin to obtain accurate simulated results. This step will be in a loop until acceptable results have been obtained.

The next decision block evaluates if the control parameters of the control strategy are acceptable, and forms part of the failure process diagram shown in Step F–L in Figure 13. The remaining steps (Step F–L) also form part of the failure process; however, it is necessary to include these steps to keep track of the failure process.

The next step (Step B) includes simulating the adjusted digital twin to predict the effect of each failure on the water reticulation system. In most cases, dangerous scenarios will be predicted due to the critical component failure. The next step (Step B2) is to adjust the operational components in the digital twin according to the developed control strategies (discussed in Section 2.4). Finally, the effect of the implemented control strategy can be simulated to evaluate if the dangerous scenarios have been mitigated.

## 2.2.2 Simulation model integration with achievable savings and safety results

The simulation model is interlinked with a real-time system to monitor the water reticulation system continuously. These parameters could also decrease the response time to take action when a failure occurs. It will therefore be beneficial to the mining system to reduce the time it takes to react when a failure occurs as it leads to a longer preparation time and could reduce the risk of dangerous underground working conditions. It should be noted that there is a point in the number of failures that all remaining operational components should operate constantly until some components are fixed.

Figure 16 shows the failure process that needs to be followed specifically when selecting a control strategy and how the digital twin is used to aid in this selection.

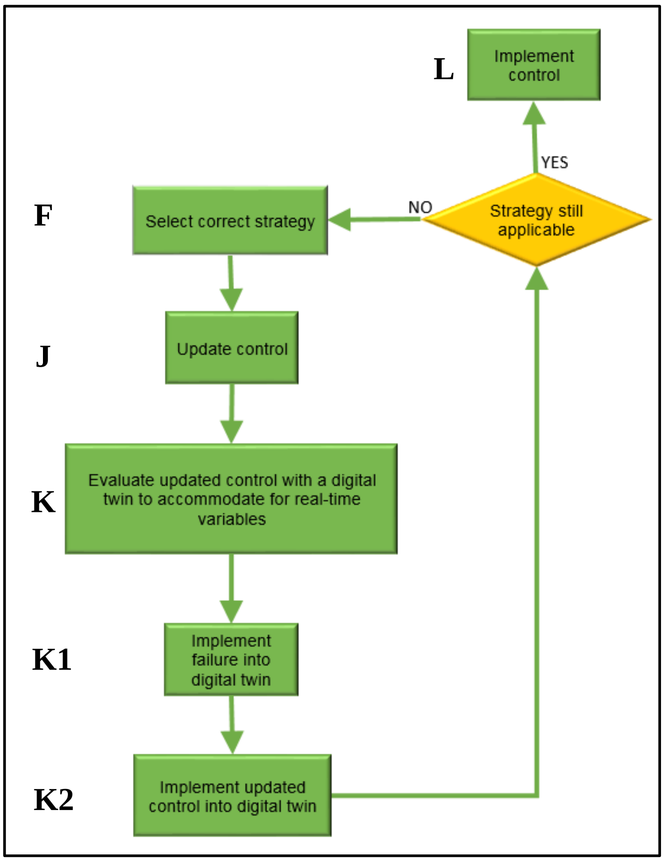


Figure 16: Digital twin failure process

The following steps are used to discuss the process that uses the digital twin in the continuous section (Figure 16):

**Step F: Select correct strategy**

Step F forms part of the continuous step that selects a control strategy according to the specific failure within the system. All developed control strategies (developed with the once-off process) are available for selection.

**Step J: Update control**

Step J identifies the control adjustments for the strategy after the control strategy has been selected in Step F.

**Step K: Evaluate updated control**

The identified control adjustments acquired in Step J are implemented into the digital twin. Step K is divided into two additional steps:

### Step K1: Implement failure into digital twin

Step K1 first implements the identified failure into the digital twin.

### Step K2: Implement updated control into digital twin

Step K2 implements the updated control parameters into the digital twin. When this has been completed, the simulated results are evaluated to determine if the control strategy selected for the given failure still applies to the current scenario, which includes real-time variables. If the strategy is not applicable to the given scenario, the process forms a loop back to Step F. If the control strategy is applicable, it is implemented (Step L).

The simulation model integration (the integration between the digital twin and the continuous section of the failure process) is also used to determine the achievable load demand shifts in the event of a failure and to determine if safe conditions are maintained. The next step in the failure process is developing prediction models (Step C, Figure 13).

## 2.3 Prediction models

Prediction models (Step C, Figure 13) are used in this study to help develop control strategies for two reasons: First, it is beneficial to have a model to predict the effect on dam levels if a number of critical components fail. Second, it is beneficial if control strategies achieve electricity cost savings. Thus, a prediction model is required to predict load demand shifting for a control strategy. These models are beneficial to use as they can ensure a first draft control strategy to account for safety and Eskom evening peak load shifting electricity cost savings. This can reduce the development time of control strategies.

### 2.3.1 Dam level prediction model

The effect on dam levels should be predicted in the case of a critical component failure. If a critical component fails, a control strategy is required to achieve load demand shifting safely. This model is used to predict the effect that a control strategy has on dam levels (i.e. whether dams will flood or not). If the strategy could lead to a dam flooding, the control strategy should be adjusted. These adjustments should continue until the predicted dam levels are acceptable.

The following steps are required to develop the dam level prediction model:

- Step 1: Obtain reliable historical data.
- Step 2: Calculate hourly averages for component statuses and dam levels.
- Step 3: Calculate dam level differences for consecutive hours.
- Step 4: Calculate average dam level differences per number of operational components.
- Step 5: Use the number of operational components and actual dam levels to predict dam level.

Each of these steps will be discussed in more detail:

**Step 1: Obtain reliable historical data**

Step 1 entails obtaining reliable historical data. It is suggested that a minimum of one year's data be used to develop this model to ensure that the data is representative of the water reticulation system's control. The accuracy of the model could increase if more data is used. As stated in Section 2.1, the data obtained should be reliable.

**Step 2: Calculate hourly averages for component statuses and dam levels**

Step 2 entails calculating the hourly average component statuses and dam levels. A variety of calculations are required for each dewatering dam level.

**Step 3: Calculate dam level differences for consecutive hours**

Step 3 of the dam level prediction model entails calculating the differences in dam levels for consecutive hours. This is required to enable the prediction model to determine a predicted profile.

**Step 4: Calculate average dam level differences per number of operational components**

Step 4 is to calculate the average dam level differences per number of operational components. Dam levels change each hour due to the number of operational components and underground operations. These operations usually change according to mining shifts. The dam levels can be predicted according to the number of operational components per hour; therefore, predicted values are used in the model.

**Step 5: Predict dam levels**

Step 5 of the dam level prediction model entails using the number of operational components and actual dam levels to predict the dam levels. The model should therefore be tested by predicting dam levels using component statuses and the prediction model. Predicted values are used with actual pump statuses to predict the effect on the dam levels. These values are compared with actual dam levels from historical data to determine the accuracy of the model.

It might be argued that only water pumped from the dam is considered to predict dam levels. This is not the case as the average dam level differences are used. These calculations include the total flows in and out of each dam.

This prediction model will be implemented on all water reticulation components. Each model can be improved over time when more data is available and the model is updated. The dam level prediction model focuses on safety as dam levels are predicted. An example of this model will be discussed in Section 3.3.1. As the purpose of this study is to achieve electricity cost savings safely, a model is required to predict load demand shifting regardless of critical component failures.

### 2.3.2 Load demand prediction model

The method used to develop the dam level prediction model is not sufficient for the load demand prediction model as the electricity cost saving calculations are more complex. The steps that follow are required to develop a load demand prediction formula. A simplified example will be discussed afterwards.

- Step 1: Obtain reliable historical data.
- Step 2: Create a standard savings formula.
- Step 3: Create applicable parameters.
- Step 4: Create preliminary formulas.
- Step 5: Solve unknown parameters in preliminary formulas.
- Step 6: Create load demand prediction formula.
- Step 7: Determine accuracy of formula.

**Step 1: Obtain reliable historical data**

Step 1 of the load demand prediction model is the same as Step 1 of the dam level prediction model. In order to ensure that the data is representative of the water reticulation system's control, it is suggested that a minimum of one year's historical data be used to develop this model. The accuracy of the load demand prediction model could increase if more data is used during development as this ensures that the average control on the water reticulation system is used. It should be noted again that all data obtained should be reliable.

**Step 2: Create standard load demand formula**

Step 2 is to create a standard load demand formula. The standard savings formula is developed and presented in Equation 1.

$$\text{Load demand shifting} = \text{ax} + \text{by} + \text{cz}$$

Equation 1: Standard load demand formula

This formula has three constants and three parameters. Symbols a, b, and c are constants, which will be calculated in an example (discussed in Section 3.3.2). Symbols x, y and z are parameters, which will be defined in Step 3. The number of constants and parameters are dependent on the user. The formula should be more accurate if more constants and parameters are used, although it increases the time required to calculate the constants significantly. The load demand shown in Equation 1 will be calculated by conventional methods. These methods may include a known method to calculate the actual load demand shift savings of an initiative. These methods do not form part of this study, thus will not be discussed. The actual load demand shifting will be required to calculate the constants.

**Step 3: Create parameters**

Step 3 of the load demand prediction model entails creating applicable parameters defined in Equation 1. Great care should be given to creating these parameters as they influence the accuracy of the formula. The purpose of this formula should be considered as it influences the creation of the parameters.

The purpose of this formula is to predict the evening peak load demand. The factors that influence load demand shifting should be considered, for example, power consumed within the evening peak period and power consumed outside the evening peak period.

If the power outside the period is higher than usual, and the power within the evening peak period is lower, the electricity cost savings achieved increase. This is due to baseline scaling, which is used to adjust the initial baseline to take the current operations into account when calculating the project electricity cost savings. To reduce the difficulty of using the formula, operational hours are used as they influence the power consumed directly.

The three possible parameters created are the following:

- x: Total running hours from 00:00 to 17:59
- y: Total running hours from 18:00 to 19:59
- z: Total running hours from 20:00 to 23:59

**Step 4: Create formulas**

Step 4 of the load demand prediction model entails constructing the preliminary load demand formulas. The parameters defined in Step 2 and Step 3 ($x$, $y$ and $z$) are used in order to solve the constants ($a$, $b$, and $c$) and create a savings formula. It should be noted that it is necessary to create the same number of preliminary formulas as number of parameters. Thus, three preliminary formulas are created.

To construct the preliminary formula, reliable historical data is used to set up the daily matrices of the total component running hours. Using these matrices and reliable historical data, the preliminary formulas are created. It is suggested that a large amount of reliable historical data is used for each preliminary formula. Each preliminary formula should, however, use approximately the same number of data points to ultimately increase the accuracy of the formula.

**Step 5: Solve unknown parameters**

Step 5 of the load demand prediction model is solving the constants ($a$, $b$, and $c$), which are shown in the standard load demand formula (Equation 1).

**Step 6: Create load demand prediction formula**

When the constants ($a$, $b$, and $c$) have been solved, they are inserted into the standard load demand formula (Equation 1). This forms the load demand prediction model.

**Step 7: Determine accuracy of formula**

Step 7 tests the load demand shifting prediction model. It should be noted that the accuracy of the formula increases with the increase in parameters ($x$, $y$ and $z$) and constants ($a$, $b$, and $c$). As the number of parameters and constants increase, more detail regarding the load demand shifting of a power profile is used.

The goal of this formula is to aid in the process of developing control strategies. Since mining operations are not constant and change constantly, it is beneficial to update the load demand prediction model over time, which can be done when more data becomes available. It is suggested that all data is logged and stored for this purpose. An example of this model will be discussed next to eliminate any uncertainties.

## Simplified example

### Step 1: Obtain reliable historical data

As discussed in the development of this formula, the first step is to obtain reliable historical data. As this is only a simplified example of developing the formula, this step will not be done in this section, although it will be discussed in Section 3.3.2.

### Step 2: Create standard savings formula

Creating the standard formula is fairly generic. As stated in the method discussion, the standard formula for this example will be the same as stated in the previous section, namely, Equation 1.

### Step 3: Create applicable parameters

The same parameters will be selected as discussed in the previous section.

- x: Total running hours from 00:00 to 17:59
- y: Total running hours from 18:00 to 19:59
- z: Total running hours from 20:00 to 23:59

### Step 4: Create preliminary formulas

From the reliable historical data obtained, data should be split into time periods. Three time periods were selected, which depends on the number of parameters that were created in Step 3. These time periods should obtain the same number of data points to aid in the accuracy of this model.

Table 5: Summarised data matrix for simplified example

| | **Actual load demand shifted** | **x** | **y** | **z** |
|---|---|---|---|---|
| **Time period 1** | 2.75 | 9 | 2 | 7 |
| **Time period 2** | 3 | 10 | 3 | 5 |
| **Time period 3** | 3.25 | 12 | 1 | 10 |

Table 5 is an example of the summarised data per time period. These parameters (x, y and z) are the average running hours of each parameter for each time period. The actual load demand shifted represents the actual load demand shifted for each time period. From Table 5, each preliminary formula can be derived, as follows:

$$2.75 = 9x + 2y + 7z$$

Equation 2: Preliminary formula 1, for example

$$3 = 10x + 3y + 5z$$

Equation 3: Preliminary formula 2, for example

$$3.25 = 12x + 1y + 10z$$

Equation 4: Preliminary formula 3, for example

**Step 5: Solve unknown parameters in preliminary formulas**

The three equations created in Step 4 should be used to determine the three unknowns. The "solver" function in Excel™ was used to determine the three unknowns.

From the solver function, the following values were determined:

- a: 0.162
- b: 0.291
- c: 0.101

**Step 6: Create load demand prediction formula**

When these unknowns are inserted into the standard savings equation, the following equation can be derived:

$$\text{Load demand shifting} = 0.162x + 0.291y + 0.101z$$

Equation 5: Example load demand formula

**Step 7: Determine accuracy of formula**

Equation 5 represents the final formula for this example. The final step is to determine the accuracy of this formula. This is done by using all the reliable historical data obtained in Step 1. All parameters should be calculated daily and inserted into the calculation. The load demand shift determined by the formula should be compared with the actual load shifted for each day. These prediction models will be used as tools in the development of control strategies. These models will further be combined with processes to develop control strategies. In Section 3.3.2, this method to be used for the case study is shown again.

## 2.4 Process for developing new strategies

New control strategies are required to safely obtain electrical cost savings in case a critical component fails in a water reticulation system. Each water reticulation system has unique control strategies as water reticulation systems are usually unique.

A generic method is required to develop control strategies per water reticulation system to enable the process to be used for various water reticulation systems (Step D in the failure process shown in Figure 17). Figure 14 shows a basic diagram for constructing a generic method. This diagram is further divided into three sections that act as three steps within the overall method.

The once-off section of the failure process will be discussed first, and is shown in Figure 17.

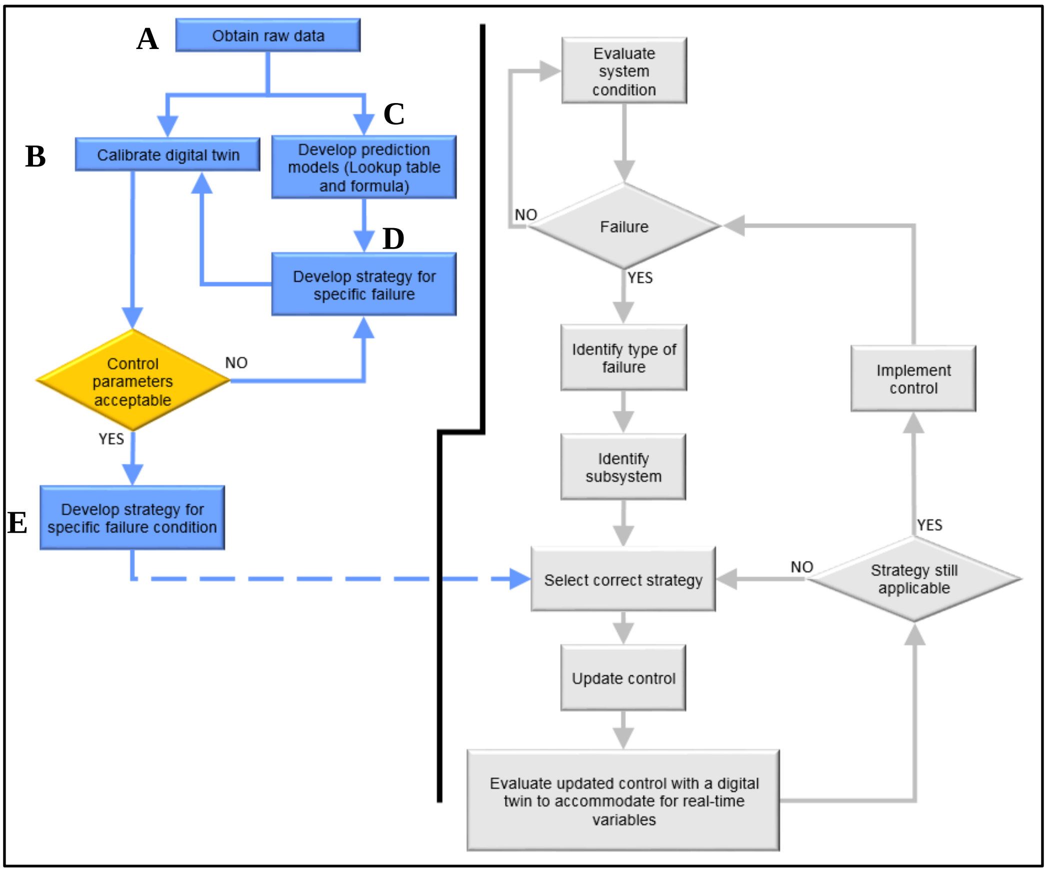


Figure 17: Failure process diagram – once-off section

The following steps are used to discuss the once-off section of the failure process shown in Figure 17.

**Step A: Obtain raw data**

The template for data inputs are described in Figure 14 and Table 4. This data is used to calibrate a simulation to create a digital twin and develop the prediction models. It is important to note that all data used should be reliable.

**Step B: Calibrate digital twin**

As discussed in Section 2.2, a calibrated simulation is referred to as a digital twin. In this step, real-time data is used to simulate current conditions in a water reticulation system with a digital twin. The effect that the various failures have on the water reticulation systems is also evaluated.

**Step C: Develop prediction models**

Two prediction models are required, which include the dam level prediction model (Section 2.3.1) and the load demand prediction model (Section 2.3.2). These models should be used to determine the effect that the failure has on the water reticulation system.

**Step D: Develop strategy for specific failure**

A control strategy is developed for a specific failure to mitigate the effect of the failure on the water reticulation system. As stated previously, this is only done once per water reticulation system. This control strategy is evaluated using the digital twin. If the control strategy is not acceptable, this step is repeated by adjusting the control of the operational components to mitigate the effect of the failure. If possible, load demand shifting should be implemented into the control strategy.

**Step E: Develop strategy for specific failure**

If the control strategy is acceptable to mitigate the effect of the failure and obtain load demand shifting, it is used as a control strategy. Each control strategy forms part of the continuous process when the specific failure occurs. The following section will discuss the continuous section of the failure process, which is shown in Figure 18.

## 2.5 Process to obtain an improved strategy

The once-off process is used to develop each control strategy, which was done in the previous section. The next step, according to the failure process, is to discuss the continuous process. Figure 18 shows the continuous section of the failure process.

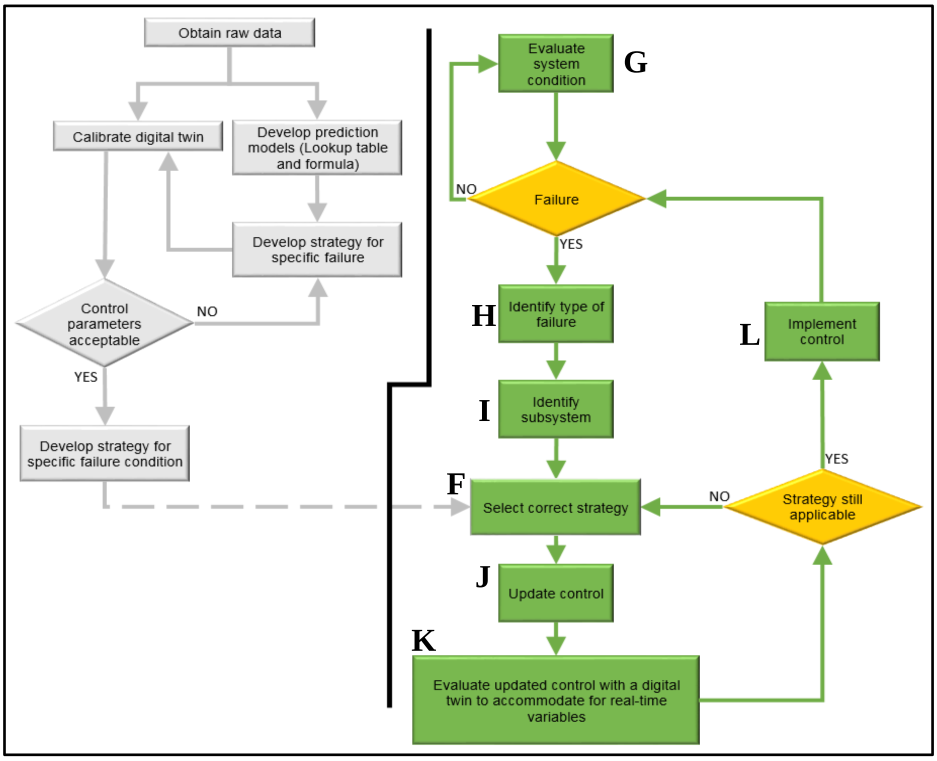


Figure 18: Failure process diagram – continuous section

The following steps are used to discuss the continuous section of the failure process shown in Figure 18.

### Step F: Select correct strategy

Once all control strategies have been developed, it is possible to select a control strategy for specific failures.

### Step G: Evaluate system condition

Step G includes using real-time data to evaluate the condition of the water reticulation system. This evaluation includes identifying when a failure occurs. If no failure occurs, this evaluation step remains in a loop. When a failure does occur, the failure is identified and Step H follows.

### Step H: Identify type of failure

After a failure has been identified, it is important to identify which component has failed.

**Step I: Identify subsystem**

When the failure has been identified, the specific subsystem should also be identified (dewatering, refrigeration, BAC or PCT).

**Step J: Update control**

Step F listed the control strategies after the once-off process has been completed. In Step J, a control strategy is selected for the given failure. The control strategy contains various control adjustments, which should be implemented on operational components.

**Step K: Evaluate updated control**

Step K involves implementing the control adjustments combined with the failure (identified in Step H) into a digital twin. These control adjustments are evaluated to determine if the selected control strategy is applicable to real-time variables due to the specific scenario.

If the control strategy is not acceptable, a loop is built in to where a control strategy should be identified. When the control strategy is acceptable for a current real-time scenario, Step L commences.

**Step L: Implement control strategy**

The control changes provided in the selected control strategy are suggested and implemented in the water reticulation system. A loop was built into this process to identify where a failure occurs in the water reticulation system. The reason is to continually monitor and evaluate the water reticulation system to ensure that the correct control strategy is implemented.

When a failure occurs within a water reticulation system, control strategies are required to achieve electricity cost savings safely in a specific scenario. Various control strategies are required as various possible failures exist. This leads to a need to obtain an improved control strategy for a given scenario, which will be done by developing selection processes.

This process (continuous section) is developed to work within the failure process seen in Figure 13. Step F in the failure process lists all the developed control strategies, whereas Step J is used to select the improved control strategy for a specific failure.

Each water reticulation system has a similar process for selecting a control strategy for a given scenario. The dewatering system's process will be discussed in the following section. This process is an extension of Step J that has already identified the type of failure. A dewatering pump failure has been identified to show the process of selecting a control strategy and the process shown in Figure 19 will be used.

Using the selection process (shown in Figure 19), an improved control strategy can be selected for a scenario. The next step continues the failure process shown in Figure 13, Step H. The selection process of the dewatering system is the only water reticulation group that will be discussed. The selection processes for other groups (fridge plant, BAC and PCT) are similar with other applicable control strategies. The other selection processes are shown in Appendix B.

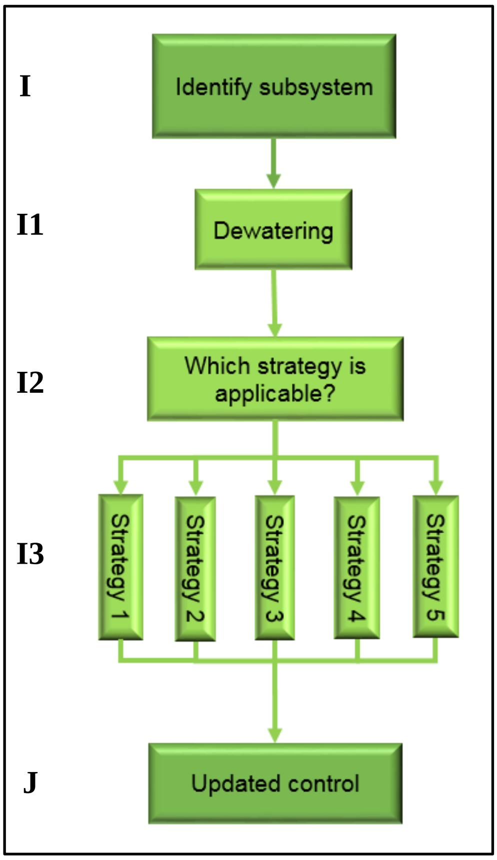


Figure 19: Dewatering selection process

The dewatering selection process will be discussed in more detail in the following paragraphs. The number and letter combinations depicted in Figure 19 indicate the steps to follow.

**Step I: Identify subsystem**

The type of failure is identified in the failure process (discussed in Figure 13). The dewatering selection process is an extension of Step H in the failure process.

### Step I1: Dewatering

This step shows the water reticulation group where the failure has occurred. In the example given in Figure 19, the failure occurred in the dewatering subsystem.

### Step I2: Which strategy is applicable?

A control strategy has to be selected from all the developed control strategies. The selection is based on the specific component that has failed. A control strategy will be discussed in Chapter 4, and the remaining control strategies (dewatering, fridge plant, BAC and PCT) will be discussed in Appendix D.

### Step I3: Possible strategies

Step I3 lists all the possible control strategies applicable to the water reticulation group.

#### Step J: Update control

Step J updates the selected control strategy into the digital twin discussed in Section 2.5, Step J. This step is used to illustrate where this process is linked with the failure process (shown in Figure 13).

A selection process is required per water reticulation system (dewatering, refrigeration, BAC and PCT). The remaining selection processes are shown in Appendix B. These processes follow the same steps; the only differences between these processes are the different control strategies.

Each of these control strategies is implemented into a digital twin to determine its feasibility. This also gives reason to provide more information regarding the use of a digital twin: A digital twin was available for this study and could therefore be used in the processes; however, the construction of the digital twin will not be discussed. The focus of the study is therefore to simulate the effect of failures and control strategies.

## 2.6 Conclusion

Chapter 2 discussed the methodology of the study. This methodology included two prediction models, which were used as tools in the development of control strategies. The first prediction model is used to determine the future dam level according to the number of operational components. Reliable and historical data is used to formulate this prediction model. An example will be discussed in Chapter 3. The second model consists of predicting the load demand shifted according to the number of operational components. A simplified example was included in Chapter 2. Chapter 3 will discuss a more complex and realistic example.

Developed processes were also discussed, which were used to develop and select a control strategy for a given scenario. Another process was discussed to ensure the concept of using a digital twin is understood. This process focused on the method to be followed to calibrate the digital twin, which is a necessity as it is used to verify results.

The first and second need for the study, as discussed in Section 1.5, led to the first contribution discussed in Section 1.6. This objective requires a process to be developed, which will, firstly, be used to create and, secondly, to select a unique water reticulation control strategy to be used in case of component failures, which will sustain electricity cost savings. This first section of this process was discussed in Section 2.4. This process will be used to create new control strategies in the case of critical equipment failures.

The second section of the process was discussed in Section 2.5. Firstly, this process will be used continually to determine whether a water reticulation system has a critical component failure and, secondly, process real-time information to determine the best-suited control strategy for the given scenario.

The final need for the study led to the final contribution, which was discussed in Section 1.6. This contribution uses a digital twin and critical component failures combined with selected control strategies (obtained through the use of the process discussed in Section 2.4 and Section 2.5) to predict the conditions of the water reticulation system. The use and calibration of the digital twin were discussed in Section 2.2.

Finally, the effect of failures on a water reticulation system was discussed. These effects were simulated in the digital twin. The digital twin will be verified in Chapter 3. The processes developed in this chapter will be implemented and validated in Chapter 3. Chapter 3 will be used to discuss the results of this study.

# Chapter 3: Practical application of improved control strategies

*"Engineering is the art of directing the great sources of power in nature for the use and convenience of man."*

**Thomas Tredgold**

## 3.1 Preamble

The methodology developed in this study was discussed in Chapter 2. These discussions included the development and selection of control strategies. The method to develop a control strategy was also discussed, which included the development of two prediction models (dam level prediction model and load demand prediction model). The purpose of these prediction models are to aid in the development of the control strategies.

Chapter 4 will be used to discuss the results of this study. The methodology will be implemented on a case study. The first step of the methodology, mentioned in Chapter 3, would be the implementation of the Step A of the once-off section in the failure process. This process in shown in Figure 20.

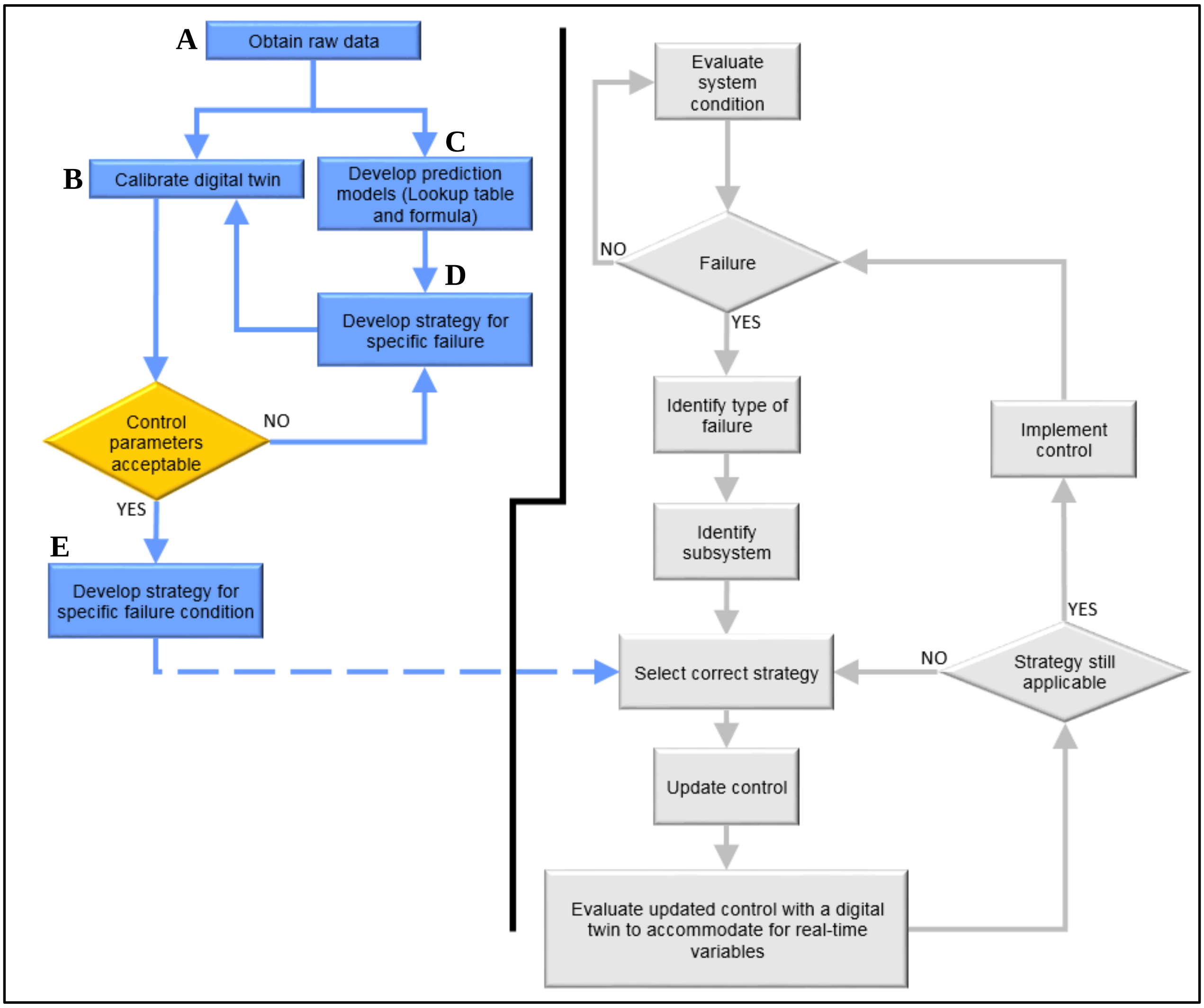


Figure 20: Failure process diagram – once-off section for the case study

Figure 20 shows the once-off section of the failure process, which is used to develop and evaluate control strategies to ensure that each control strategy has acceptable control adjustments in case of critical component failures. Before these control strategies can be developed, it is necessary to obtain raw data and the water reticulation layouts for the case study, which forms part of Step A in Figure 20.

Figure 21 shows the refrigeration layout for the case study. This layout includes three PCTs, five fridge plants, three BACs and the surface chill dam.

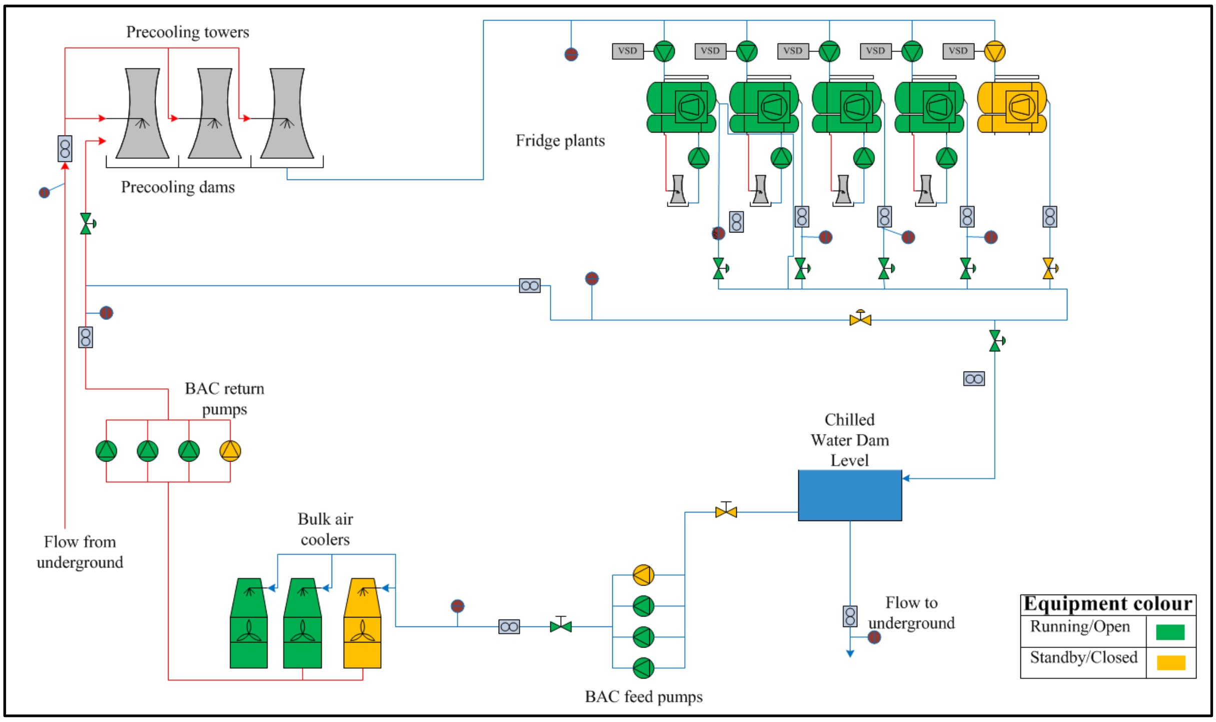


Figure 21: Surface refrigeration layout for the case study

Figure 22 shows the dewatering layout for the case study. This includes four 3CPFSs, nine dewatering pumps and all relevant dams. Finer details are also illustrated in the layout; for example, the mining levels and the U-tube system near Pumping Level 3.

These layouts for the case study are shown to give background on the water reticulation system. This background is necessary to illustrate the complexity of the case study mine's water reticulation system, which is part of Step A in Figure 20. This step shows the once-off process required for developing a control strategy.

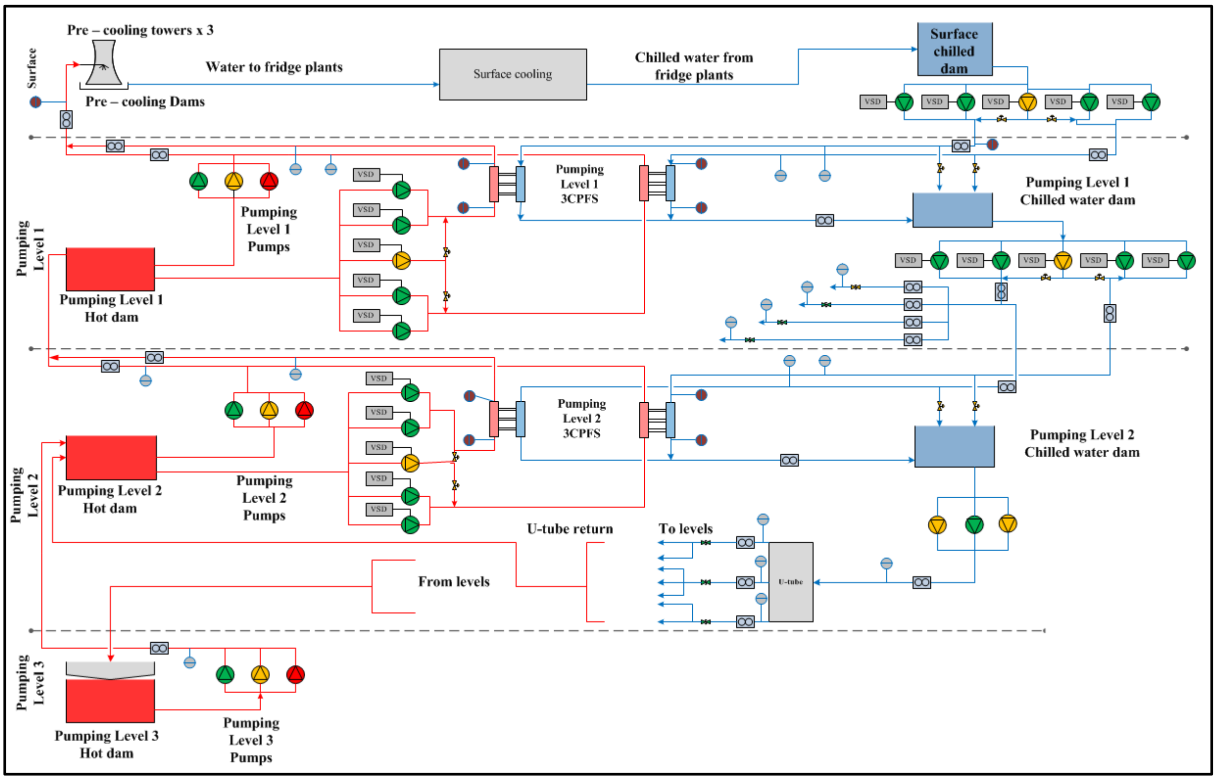


Figure 22: Dewatering layout for the case study

Information needed for the case study is shown in Table 6. The information includes constant parameters for the specific mining operation including dam sizes, locations, number of BACs, etc. If some of the information in Table 6 changes, the process shown in Figure 18 should be started from this point in the once-off process (failure process, shown in Figure 13). The water reticulation system layouts (Figure 21 and Figure 22) and Table 6 form part of the raw data obtained, which is Step A in Figure 20.

Table 6: Site information

| **Parameters:** | | **Fridge Plant** | **Precooling Tower** | **Dewatering** | | | **Bulk Air Cooler** |
|---|---|---|---|---|---|---|---|
| **Machines** | **Location** | 5 | 3 | **Pumping level 1** | **Pumping level 2** | **Pumping level 3** | 3 |
| | **Amount** | | | 3 | 3 | 3 | |
| **Max flow per machine (L/s)** | | 300 | 267 | 180 | 180 | 180 | 105 |
| **Temperature out (°C)** | | 6 | 17 | | | | 12 |
| **Dam capacities (kL)** | | 5 | 9 | 7 | 11 | 6.7 | 9 |
| **Min dam level (%)** | | 25 | 25 | 25 | 25 | 25 | 25 |
| **Max dam level (%)** | | 90 | 90 | 90 | 90 | 90 | 90 |

Table 6 is used to capture the specific site information that is required to calibrate the simulation. This information is also required to develop prediction models, verify the digital twin and develop control strategies. Each control strategy will be discussed together with the discussion on safety and demand load shifted from the Eskom evening peak period in Section 3.4.2. Actual and simulated results will be discussed per control strategy. The simulated results will be obtained using a digital twin. For this reason, it was deemed necessary to verify the digital twin before use.

## 3.2 Verification of digital twin

The digital twin used to simulate the developed control strategies had to be verified (Step B in failure process). The process discussed in Section 2.2.1 (Figure 15) was used to calibrate the simulation to ensure that the simulated results of this study were accurate. The total power of the water reticulation system and the total simulated power were compared to determine the accuracy of the digital twin. Power was used to determine the accuracy of the simulation as load demand shifting would be evaluated thereon.

Figure 23 compares the total power of the water reticulation system and the simulated power for a three-day period.

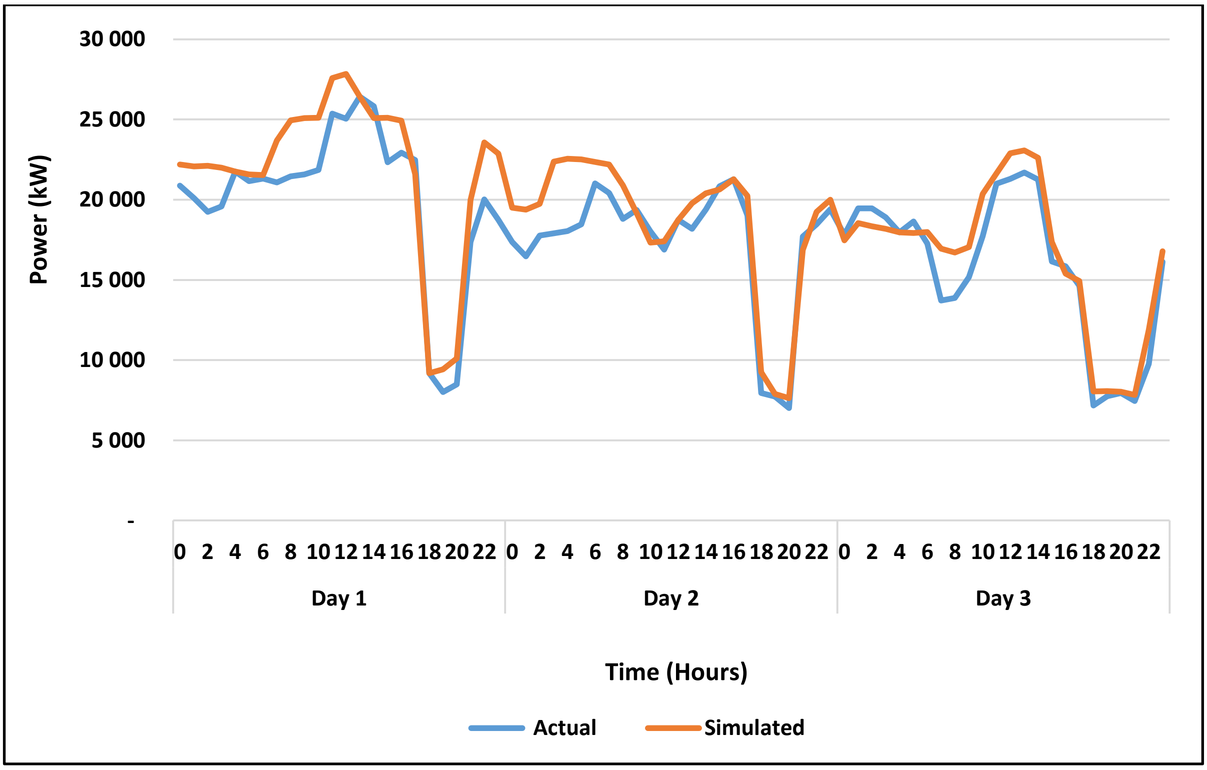


Figure 23: Digital twin calibration

The average percentage error was calculated to be 6.77% when these power profiles were compared. Power could not be the only parameter used to verify the simulation, thus BAC outlet temperature was also used. BAC outlet temperature is also an important variable, which is shown in Figure 24, as BACs are used to provide cooler underground conditions for mining personnel. If the underground temperatures are too high, it causes hazardous underground working conditions.

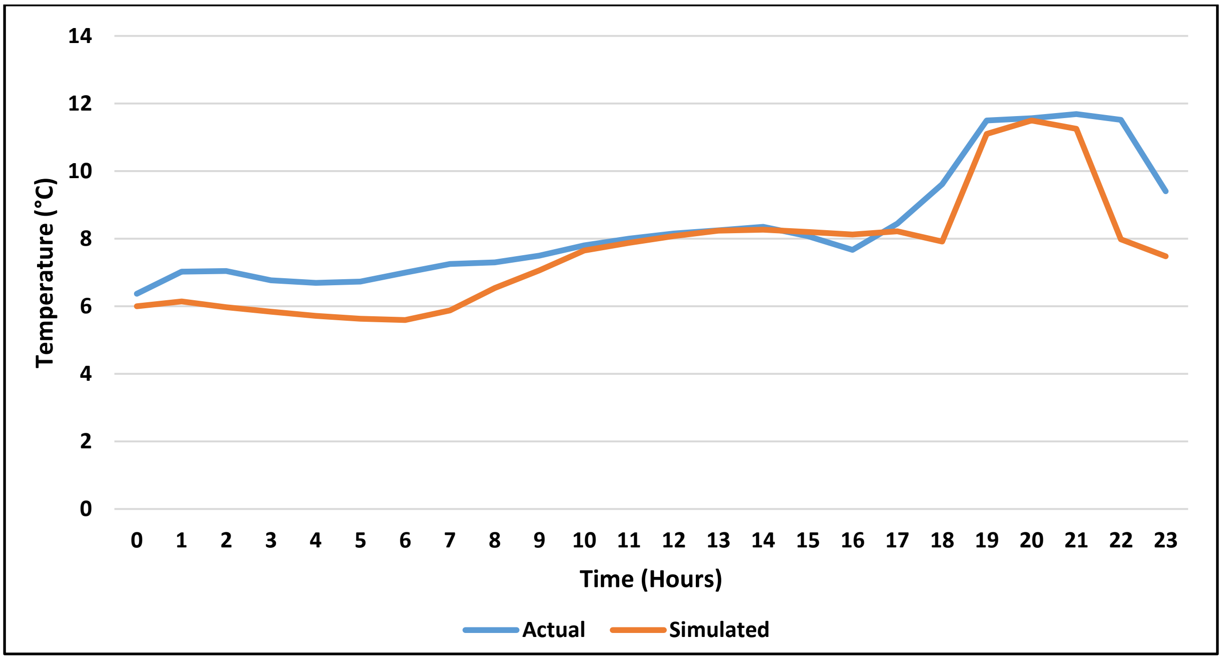


Figure 24: BAC temperature validation

Figure 24 shows the actual and simulated BAC outlet air temperatures to verify the simulated results. The same time period was used to verify the BAC outlet temperature comparison and the power consumption verification. An average BAC outlet temperature was used to verify the BAC outlet temperature. The average percentage error between these temperature profiles was 8.76%, thus proving that the simulated BAC outlet air temperature had an acceptable accuracy.

The total power consumption and BAC outlet air temperatures were used to verify the digital twin's simulated results. The digital twin was used to determine if the control strategies were safe before it was implemented in the digital twin.

## 3.3 Developing control strategies for water reticulation system in case of a failure

New control strategies are required to safely shift demand from the Eskom evening peak period in the case a failure occurs on a mine's water reticulation system. This section will include developing prediction models and using processes to develop a control strategy. As a control strategy requires a fair amount of calculation, only the development of a single control strategy will be discussed in this chapter. This control strategy will include a single dewatering pump failure on a mine's top dewatering level.

The remaining control strategies will follow the same steps and will be discussed in Appendix D. The once-off section of the failure process (discussed in Section 2.4, Figure 17) will be used to develop each control strategy. Each step will be discussed for the case study.

As discussed in the methodology (Section 2.3), the prediction models should be developed per water reticulation group. The first prediction model (dam level prediction model) will be developed and discussed in Section 3.3.1 while Section 3.3.2 will include the development of the second prediction model (load demand prediction model). The methodology of both prediction models was discussed in detail in Section 2.3.

### 3.3.1 Dam level prediction model verification (Step C)

When a critical component fails, it is likely unknown how the failure will influence the dam levels over time. Therefore, it is beneficial to predict dam levels should a critical component fail. This was done for one strategy on the case study.

The dewatering system consisted of three pumping levels with three dewatering pumps on each level. The strategy was developed for one dewatering pump failure on Pumping Level 1. Table 7 shows the results of the calculations that were done. The table shows that each pumping level had a maximum of two pumps. Although a third pump was available, it was not operated in the historical data used to develop this model. In this specific system, a third pump would be used in case of failures or maintenance on other pumps.

Table 7: Dam level predictions for Strategy 1

| **Dewatering level** | **Number of pumps** | **Dam level percentage difference (%)** |
|---|---|---|
| Pumping Level 1 | 0 | 2.95 |
| | 1 | −3.95 |
| | 2 | −7.77 |
| Pumping Level 2 | 0 | 1.15 |
| | 1 | 0.17 |
| | 2 | −0.98 |
| Pumping Level 3 | 0 | 5.50 |
| | 1 | 0.07 |
| | 2 | −2.83 |

The values shown in column three of Table 7 indicate the percentage that the dam level changed in one hour per pumping level using the number of operational pumps. Figure 25 shows the actual and predicted dam levels for a period of five days.

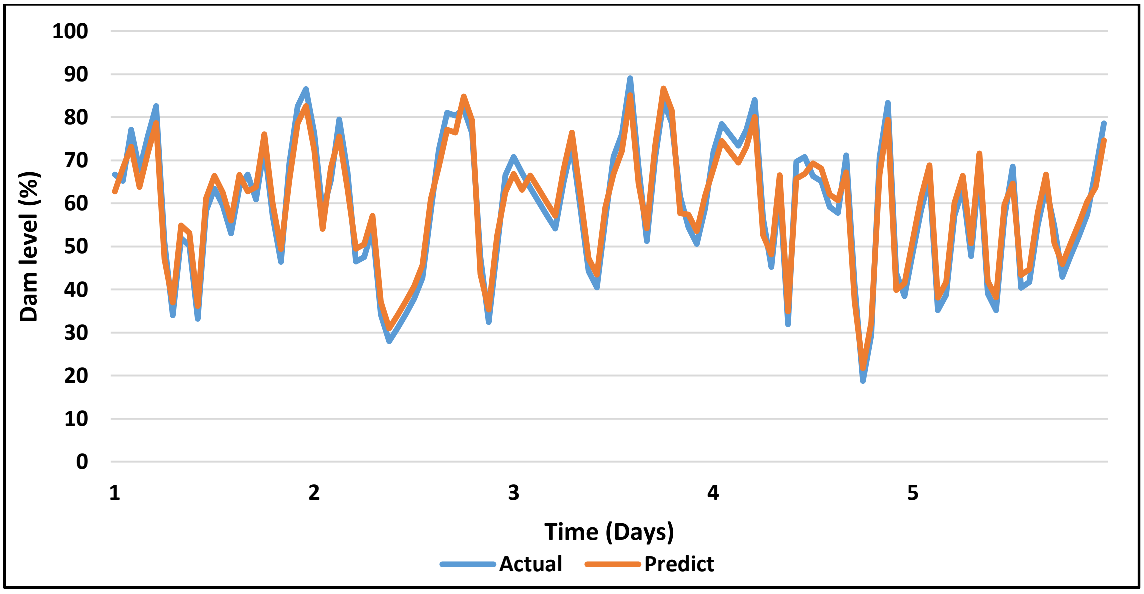


Figure 25: Dam level prediction model comparison for Strategy 1

This model can be considered accurate as the average percentage error over the five-day period, shown in Figure 25, was calculated to be 0.71%. Literature confirms that 10% is an acceptable percentage error [28], [68]. This model could therefore be used in the development of control strategies corresponding with specific pumping levels. It should be noted that a digital twin will not always be available, thus this method is used to ensure redundancy of predicted results.

### 3.3.2 Load demand prediction model verification (Step C)

A load demand prediction model was required to aid in the development of control strategies. In the development of this prediction model, a load demand formula was developed. During the development, it was noticed that the number of parameters influenced the accuracy of the formula. When the number of parameters increased, the amount of time spent to solve each unknown also increased. A formula with five parameters and five constants were used.

**Step 1: Obtain reliable historical data**

In the first step of creating a load demand formula, reliable historical data is required. The method of obtaining data is not part of this study. As suggested in the methodology of developing the prediction formula (Section 2.3.2), it is suggested that a minimum period of one year be used. This is recommended to ensure data is representative of the system's control.

**Step 2: Create a standard savings formula**

Equation 6 shows the standard load demand prediction formula. The steps discussed in Section 2.3.2 were used to create a load demand prediction formula for the relevant system. Relevant parameters were required for the next step, in developing the formula.

$$\text{Savings} = \text{ax} + \text{by} + \text{cz} + \text{dw} + \text{ev}$$

Equation 6: Standard load demand prediction formula for Strategy 1

**Step 3: Create applicable parameters**

The parameters should be created keeping the purpose of the formula in mind. More information regarding this step was mentioned in Section 2.3.2. The purpose of this formula was to predict the load demand shifting achieved in the Eskom evening peak period. The power consumed within this period and the power consumed for the rest of the day were used. The following five parameters were used:

- x: Total running hours between 00:00 and 17:59
- y: Total running hours between 18:00 and 19:59
- z: Total running hours between 20:00 and 23:59
- w: 24 − y
- v: x + z

**Step 4: Create preliminary formulas**

The next step was to create five preliminary formulas. The development of the preliminary formulas was discussed in the development of this model in Section 2.3.2. As discussed in the mentioned section, various equally spaced time periods should be chosen. The defined parameters as well as the actual load demand shift savings achieved should be calculated for each time period, and daily matrices should be set up. As five parameters were defined for this model, five time periods are required combined with all calculated values.

An example of this is shown in Appendix A, Table 21. Using these matrices, the parameters can be calculated. The parameter matrices are summarised in Appendix A, Table 22. Using the matrices shown in Table 22, the average values per parameter are calculated for each time period. The average actual load demand shifting achieved for the same time period is also calculated. The parameters presented in Table 22, Appendix A, are used to create the preliminary equations. These preliminary equations are shown in Appendix A (Equation 10, Equation 11 and Equation 12). There are three constants (a, b, and c) that need to be solved within these three equations.

Appendix C is used for developing the load demand shift formula for the case study. Equation 7 provides the first preliminary formula developed for Strategy 1. Five equations were required as there were five unknowns. The other four equations are shown in Appendix C.

$$1.44 = 49.92\mathrm{x} + 1.62\mathrm{y} + 10.77\mathrm{z} + 22.38\mathrm{w} + 60.67\mathrm{v}$$

Equation 7: Preliminary formula 1 for Strategy 1

**Step 5: Solve unknown parameters in preliminary formulas**

As stated in Section 2.3.2, the method of solving these parameters are not part of this study. The solver function in Excel was used to do so. When all values are calculated per time period, it should be inserted into the standard savings equation, Equation 6.

**Step 6: Create load demand prediction formula**

Equation 8 shows the formula that was developed to predict the load demand shifting for the dewatering system.

$$\mathrm{Savings} = -0.247\mathrm{x} - 1.060\mathrm{y} + 0.245\mathrm{z} - 0.191\mathrm{w} + 0.282\mathrm{v}$$

Equation 8: Load demand formula for Strategy 1

**Step 7: Determine accuracy of formula**

Figure 26 shows the actual and predicted load demand shifting for a period of 55 days. There were large discrepancies between the actual and predicted load shift profiles. This load demand model is used to develop a good first iteration control strategy for a failure scenario. Further development is required to improve this first iteration strategy. This first iteration control strategy can be used to reduce the development time for each control strategy.

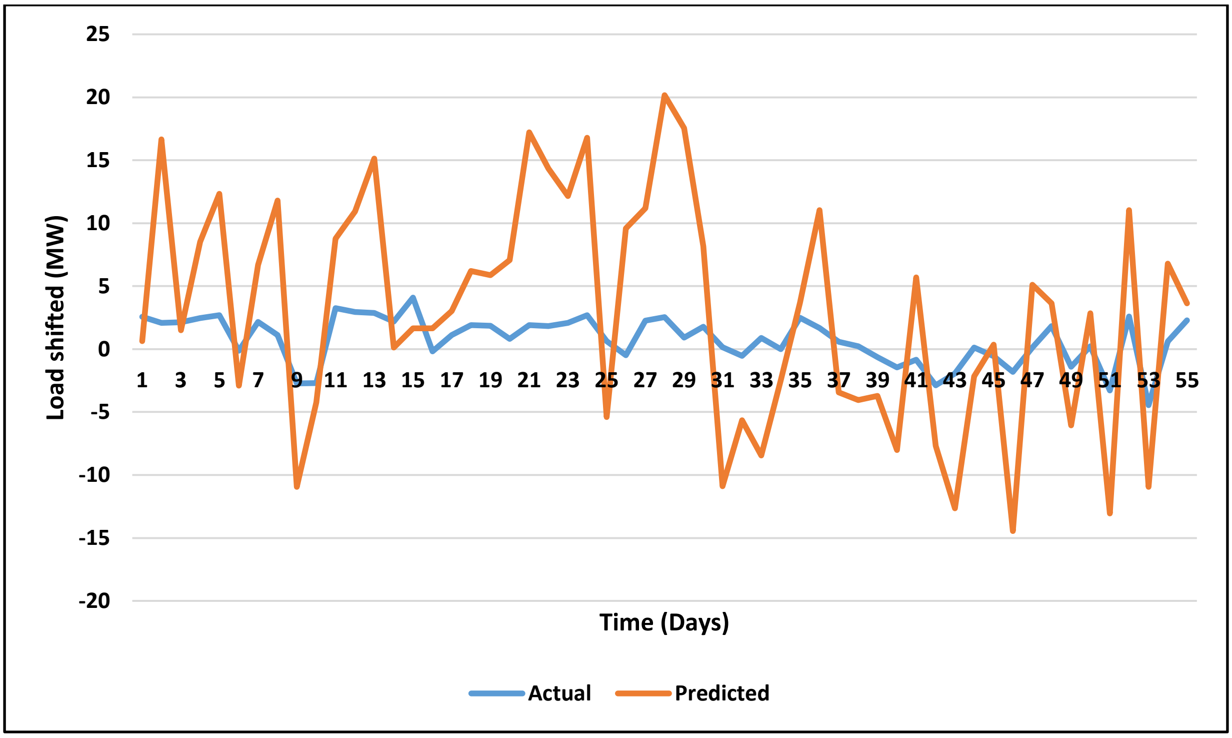


Figure 26: Load prediction model for Strategy 1

The negative values were calculated when there was a reduction in load demand shifted, which negatively affected electricity cost savings. It should be noted that some of the percentage errors were fairly large. When the average actual and the predicted load demand shifting for the period were compared, a percentage error of 12% was calculated. It should be noted that this model was used as a tool in the development of control strategies to develop a good first iteration control strategy.

## 3.3.3 Effect of failure and adjusting simulation

The next step was evaluating the effect of a failure on a system, which forms part of Step C in Figure 20. The developed dam level prediction model was used to predict possible dam levels due to the failure. A dam level was predicted for a period of five days. Figure 27 compares the actual dam levels without a failure with the predicted dam levels due to a dewatering pump failure on Pumping Level 1.

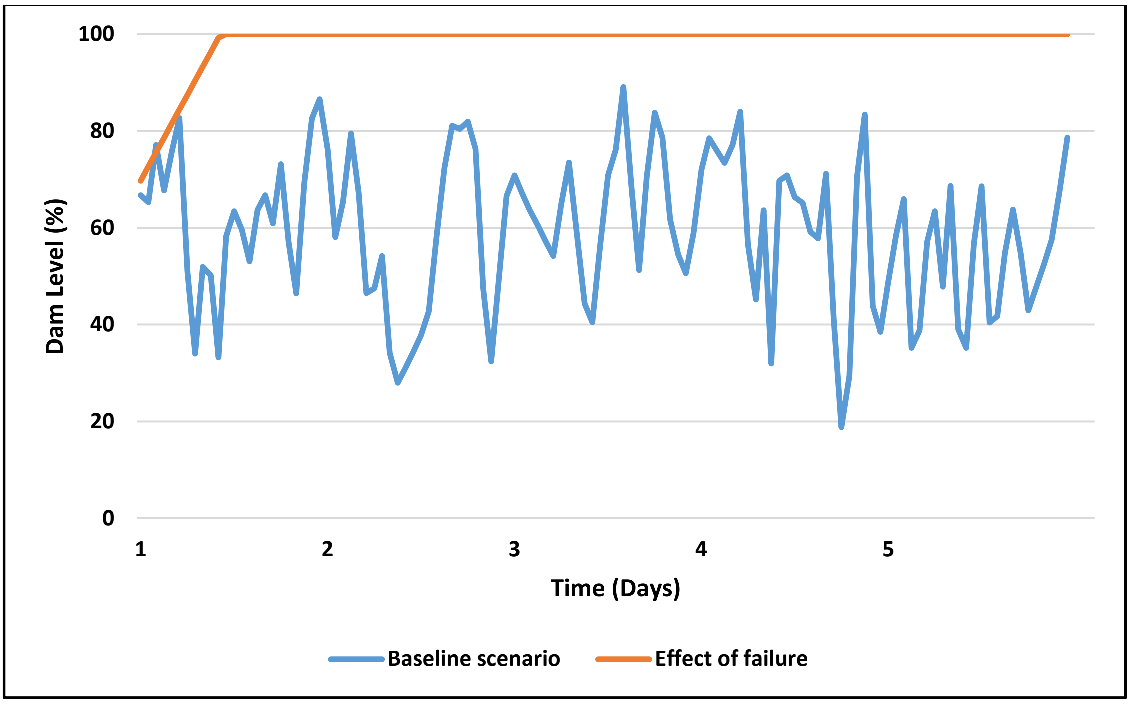


Figure 27: Effect of failure for Strategy 1

It should be noted that this prediction was done without attempting to mitigate the failure, as shown in Figure 27. It was calculated that the dam should flood within twelve hours after the failure occurring. It is clear that a control strategy is required to ensure this prediction be avoided.

Numerous adjustment and evaluation steps (discussed in Section 2.4, Figure 17, Step D) were required to ensure that no dangerous situations were predicted when using the digital twin. When this process was completed, the next control strategy could be developed. In this case study, the mine had four 3CPFSs. Two were located on each pumping level (1 and 2), which can be seen in Figure 22. The control for this strategy was done only on the dewatering system to reduce the critical component's effect on the rest of the water reticulation system. Table 8 shows the control adjustments for Strategy 1.

Table 8: Control adjustment for Strategy 1

| Number | Control adjustment |
|---|---|
| **I** | Increase 3CPFS set points on Pumping Level 1 to high. |
| **II** | Decrease 3CPFS set points on Pumping Level 2 to low or medium depending on Pumping Level 1's dam level. |
| **III** | Stop Pumping Level 2's dewatering pumps depending on Pumping Level 1's hot dam. |
| **IV** | Stop Pumping Level 3's dewatering pumps depending on Pumping Level 2's hot dam. |

Number I:

- Change the set points of both 3CPFSs on Pumping Level 1 to high. The level of Pumping Level 1's hot dam will decrease due to this adjustment.
- If the level of Pumping Level 1's hot dam is lower than 30%, change both set points to medium.

Number II:

- Change the set points of both 3CPFSs on Pumping Level 2 to low or medium. This setting is dependent on Pumping Level 1's hot dam level:
    - If the dam level is above 85%, set it to low.
    - If the dam level is below 85%, set it to medium.

Number III:

- Adjust the dewatering pump control of Pumping Level 2 according to the Pumping Level 1 hot dam.
- If the level of Pumping Level 1's hot dam is above 85%, Pumping Level 2's dewatering pumps will stop.

Number IV:

- Control the dewatering pumps of Pumping Level 3 according to the hot dam on Pumping Level 2 and Pumping Level 3.
- If the level of Pumping Level 2's hot dam is too high (above 85%), stop these pumps.
- If the level of Pumping Level 3's hot dam is above 85%, use one dewatering pump to avoid flooding this dam.

When this control strategy was implemented in the digital twin, improvements in dam levels were seen compared with the predicted dam level with no mitigation strategy shown in Figure 27. In the case of this failure, Strategy 1 predicted that no dangerous situation would occur due to the underground dams flooding. It should be kept in mind that load demand shifting was achieved safely during the evening peak period. The results of each strategy will be discussed in Section 3.4, which forms part of Step E in Figure 17 (discussed in Section 2.4).

## 3.4 Analysing results of strategies on achievable savings and safety

In the event of a failure in the water reticulation system, electricity cost savings are usually neglected. In this section, the control strategies that were implemented show that load demand shifting could be achieved in the case of critical component failures. The method to follow for developing each control strategy will be discussed using the steps in Figure 17.

### 3.4.1 Analysing control strategy savings

This section will focus on the dewatering and fridge plant water reticulation groups. These groups have the highest power consumption in a water reticulation system as illustrated in Figure 4. Energy saving initiatives will typically focus on these groups. This section will include different types of failure and load demand shifting achieved before and after control strategies were implemented.

**Dewatering**

Five control strategies were developed for the dewatering system. The number of required control strategies was set up according to the number of dewatering pumps. If more dewatering pumps were part of the dewatering system, extra control strategies would be required. A control strategy was developed per failure. Table 25 in Appendix D shows the control strategies developed for specific failures.

A 30-day period was identified within the initial one-year analysis where dewatering failures occurred before the control strategies were implemented, it should be noted that this data should be reliable. The pump availability was compared with the power consumption of the dewatering system within this specific period. This was done to evaluate the correlation between the pump availability and power consumption. Figure 28 shows the comparison. The average daily power consumption in the Eskom evening peak period before the control strategies were implemented was calculated to be 7.49 MW. Component availability is an important aspect in this study as a lower availability reduces the load demand shifting potential. This study aims to mitigate this loss in electricity cost savings with control strategies.

Figure 28 compares the pump availability with the power consumption of dewatering. The purpose of this study is to decrease the power consumption within the Eskom evening peak period in spite of a low pump availability.

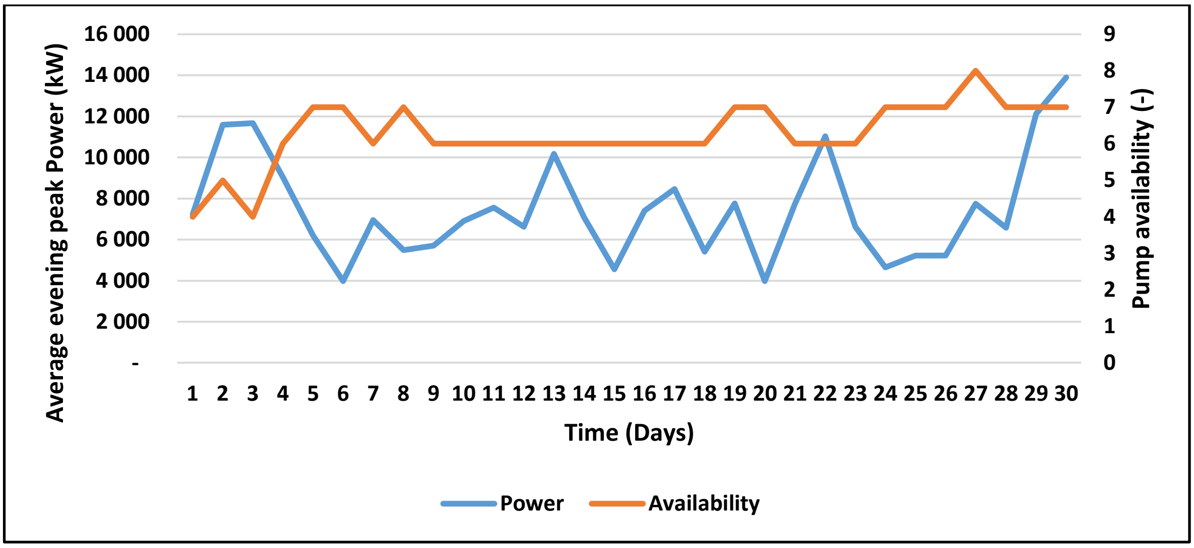


Figure 28: Dewatering pump availability and power before control strategies

An additional period of 30 days was used to analyse the effect of these control strategies. Figure 29 compares the dewatering pump availability with the total power consumption after implementing these control strategies. The average power for this period was calculated to be 4.19 MW.

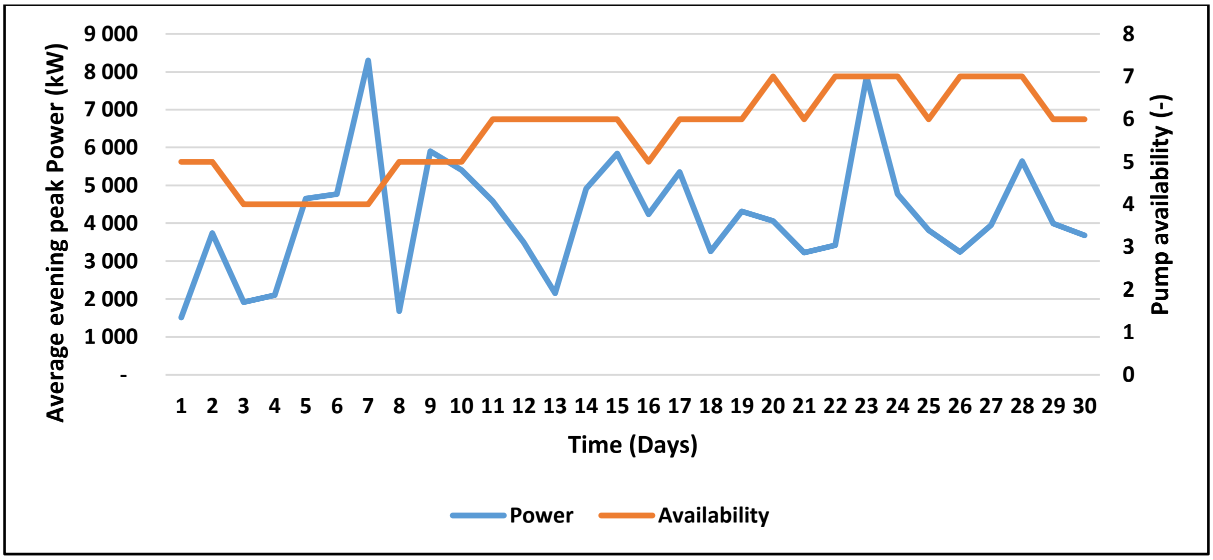


Figure 29: Dewatering pump availability and power after control strategies

Table 9 summarises the information discussed above and compares the pump availability and Eskom evening peak power consumption before and after control strategies were implemented. The average power decreased by 3.29 MW in the Eskom evening peak period. This is relevant as a similar number of dewatering pump failures was recorded as the average pump availability reduced by 9%.

Table 9: Dewatering strategy comparison

| **Before savings** | | **After control strategies** | |
|---|---|---|---|
| **Power (MW)** | **Availability (–)** | **Power (MW)** | **Availability (–)** |
| 7.49 | 6.27 | 4.19 | 5.70 |

Table 9 shows that the power decreased in the Eskom evening peak period after the control strategies were implemented. This provides proof that the implementation of these control strategies has a significant influence on reducing the Eskom evening peak period power consumption on the dewatering system.

**Fridge plants**

Two control strategies were developed for the fridge plant system as a third fridge plant failure is a rare occurrence and a very limited to no load demand shifting is possible. Should a third fridge plant fail, all remaining fridge plants are required to operate. These two failures are in the case that one or two fridge plant fail.

The actual fridge plant availability was compared with the Eskom evening peak power consumption for a period of 30 days before the control strategies were implemented. This was done to establish the correlation between fridge plant availability and power consumption within the Eskom evening peak period. Fridge plant availability is an important aspect (also discussed in this section under dewatering) as a decrease in fridge plant availability can lead to a decrease in the evening peak load demand shifting.

Figure 30 shows the 30-day period, within the initial one-year analysis, before control strategies were implemented. Figure 30 shows the fridge plant availability, which shows that fridge plant failures were common in this case study. Power in the Eskom evening peak periods could be reduced in spite of fridge plant failures (reduction in fridge plant availability). This is however not a common occurrence, thus implementing control strategies could sustain lower power consumption in the Eskom evening peak periods.

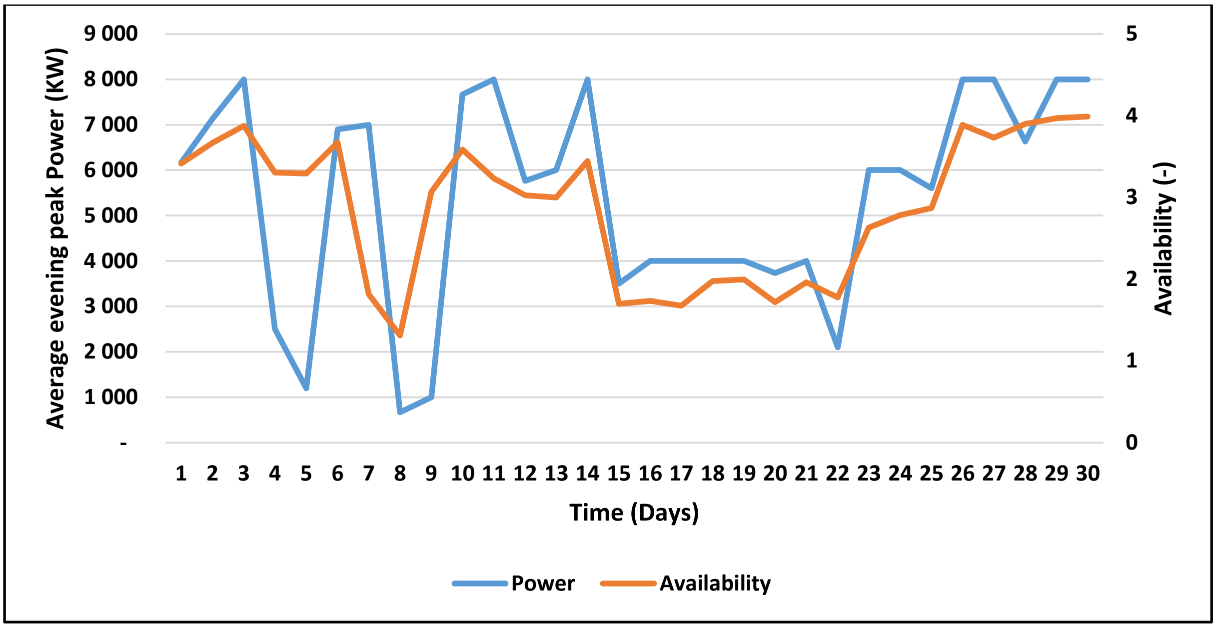


Figure 30: Fridge plant status and power before control strategies

Figure 31 shows the fridge plant availability and compares it with the Eskom evening peak power for a 30-day period after the control strategies were implemented. This was done to evaluate if these control strategies are beneficial in spite of fridge plant failures.

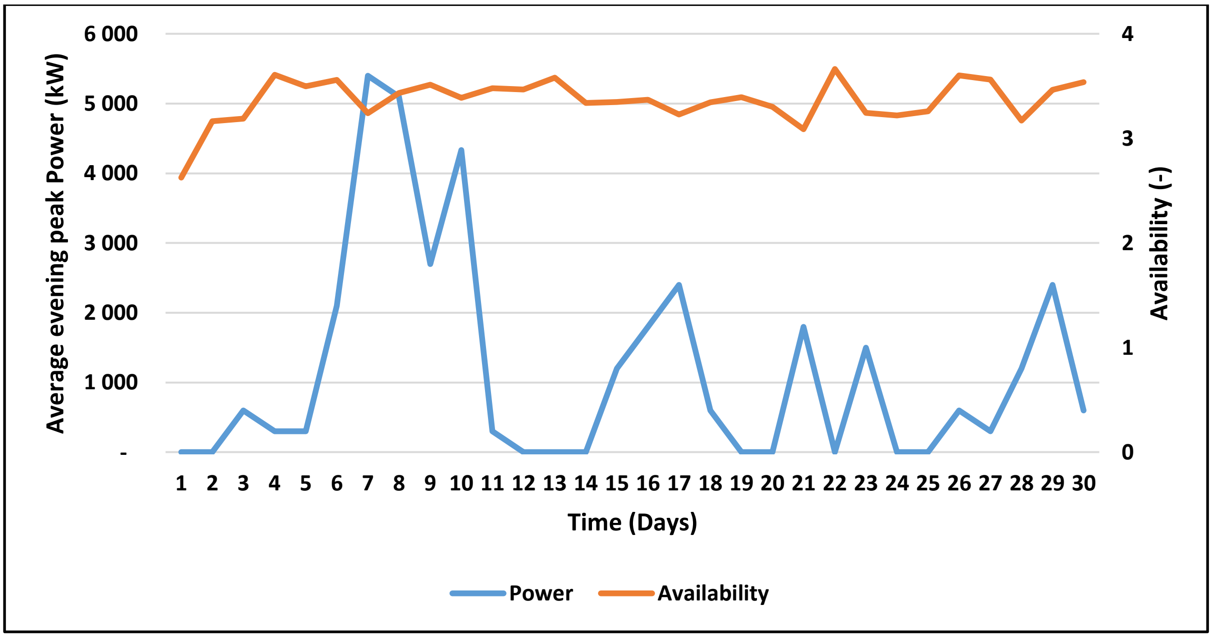


Figure 31: Fridge plant status and power after control strategies

Figure 31 shows that the fridge plant power in the Eskom evening peak period decreased after implementing the control strategies developed in this study. The purpose of this study is to decrease the power within the Eskom evening peak period in spite of failures. Table 10 summarises the information discussed above.

Table 10: Fridge plant strategy comparison

| **Before strategies** | | **After strategies** | |
|---|---|---|---|
| **Power (MW)** | **Availability (–)** | **Power (MW)** | **Availability (–)** |
| 8.68 | 2.88 | 3.55 | 3.32 |

The Eskom evening peak period's power decreased by 5.12 MW after strategy implementation. The average fridge plant availability increased by 13.8%, which means that in similar scenarios, a reduction in power could be achieved even in the event of fridge plant failures. This provides proof and validates that the control strategies decreased power within the Eskom evening peak period. The following sections will focus on each control strategy where safety and load demand shifting will be analysed.

### 3.4.2 Validation through analysing strategy results

This section will be used to validate the safety and achievable load demand shifting that was obtained per control strategy developed. This analysis included comparing the actual data, predicted data and simulated data. The analysis was used further to evaluate whether each strategy was feasible to be implemented. In some cases, strategies were not tested as the failures to implement the strategy did not occur in the testing period of one year. In these cases, the simulated and predicted results will be discussed. Each control strategy was developed according to specific failures for the case study. Table 25, Appendix D, shows the failures with corresponding control strategies. Total load demand shifting was determined per control strategy, thus the load demand for all water reticulation systems (dewatering, refrigeration, BAC and PCT).

The following power profiles will be compared per control strategy: actual, baseline and predicted. The actual power profile is obtained by using the actual data for the specific day each strategy was required: data reliability is important. The baseline period chosen for this comparison is the year before these strategies were implemented (the year 2017), which included all weekdays. The predicted value is calculated by the load demand prediction model, which is done per control strategy.

**Strategy 1: Dewatering pump failure on Pumping Level 1**

A period was identified where a failure occurred that required Strategy 1. Strategy 1 was developed specifically for dewatering failures. It was deemed necessary to illustrate the section of the dewatering system where the failures occurred. Figure 32 shows the location of the failures (shown by the red block) where Strategy 1 was required. It can be seen that an additional dewatering pump failure occurred on Pumping Level 1. Safety will be discussed first as it is considered a high priority in the mining industry. The unsafe scenario associated with a dewatering failure is usually dams that flood.

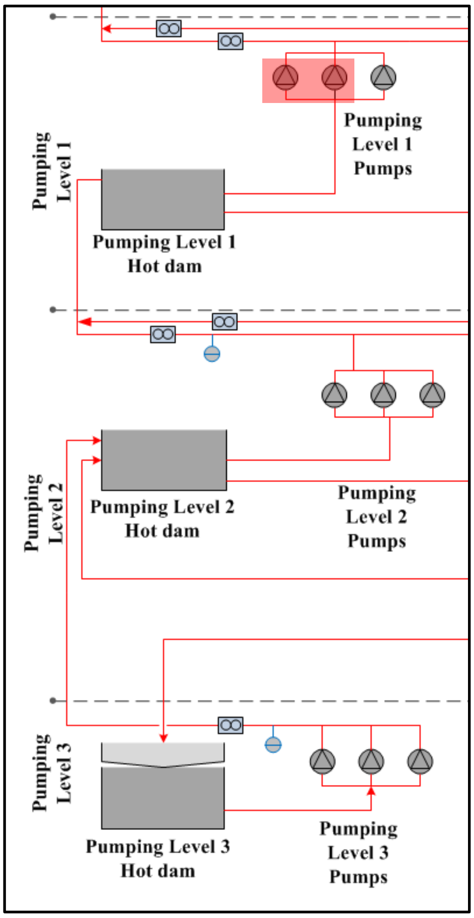


Figure 32: Strategy 1 failures

Figure 33 shows the actual dam levels, simulated dam levels and predicted dam levels for the period during which Strategy 1 was implemented. The failure occurred at the beginning of Day 1. The dewatering pump failure was on Pumping Level 1. The hot dam on Pumping Level 1 will be discussed.

Figure 33 shows that the dam levels from all three data sources were low (below 50%). These low dam levels did not cause concern since normal operational control used the 3CPFS to empty the dam. When the dam level reached a minimum, the 3CPFS set point was lowered, which increased the dam level.

The actual dam level was obtained by calculating the average dam level for each instance Strategy 1 was used. The percentage error between the actual dam levels and the simulated dam levels was 11.09%, which was just outside the preferred percentage error of 10%. However, the dam level prediction model was only used to aid in the development of the control strategy.

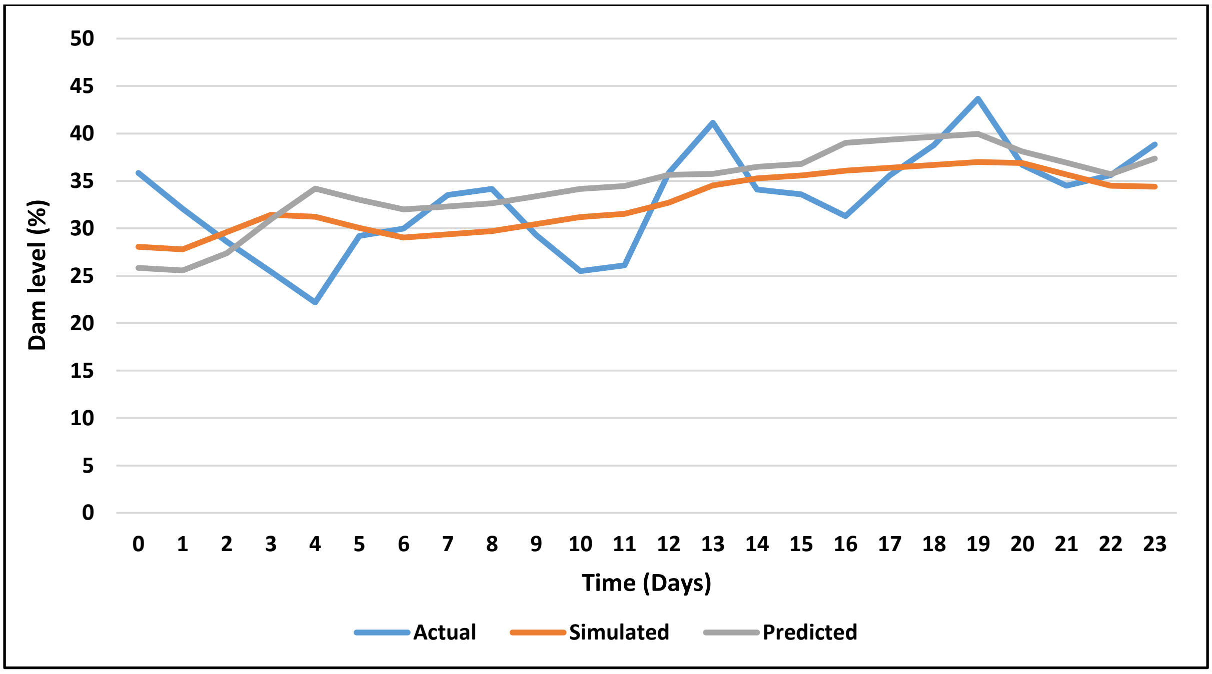


Figure 33: Dam levels for Strategy 1

In order to develop the control strategy effectively, dam level predictions were required. The predictions were done before the control strategy was implemented in order to predict the future dam levels while the dewatering pump failure occurred. The average percentage error between the predicted dam levels and the simulated dam levels was 6.85%.

The simulations did not identify any dangerous scenarios for Strategy 1 since the dam levels could be regulated by adjusting the control as stated in the development of the control strategy (Section 3.3.3). The next step was to evaluate whether the control strategy would be able to achieve load demand shifting while maintaining safe working conditions. Using

Equation 8 in Section 3.3.2, the average load demand shifting could be predicted for the period during which Strategy 1 was required. Table 11 shows the average parameters for Equation 8.

Table 11: Average parameters for Strategy 1

| **Parameter** | **Value** |
|---|---|
| $v$ | 30 |
| $w$ | 12 |
| $x$ | 24 |
| $y$ | 0 |
| $z$ | 6 |

The predicted demand in load shifting was calculated as 3.43 MW in the evening peak period. The period during which Strategy 1 was implemented shifted a demand load in the Eskom evening peak equating to 3.26 MW. The prediction model was fairly accurate for this period as the percentage error equated to 4.85%. This percentage error was within the preferred limit, although the accuracy of this prediction model may be improved over time if more data is used. The improvement can be done when more data is available and the model is updated.

Figure 34 illustrates the power profiles for Strategy 1, which includes the actual, baseline and predicted power profiles. Strategy 1's profile was obtained by calculating the average power profile for each day the control strategy was implemented. The same procedure was used to obtain the baseline power profile. The load demand shifting prediction model predicted a single value representing the predicted load demand shifting for a specific scenario. The predicted load demand shifting is presented as the green block in Figure 34.

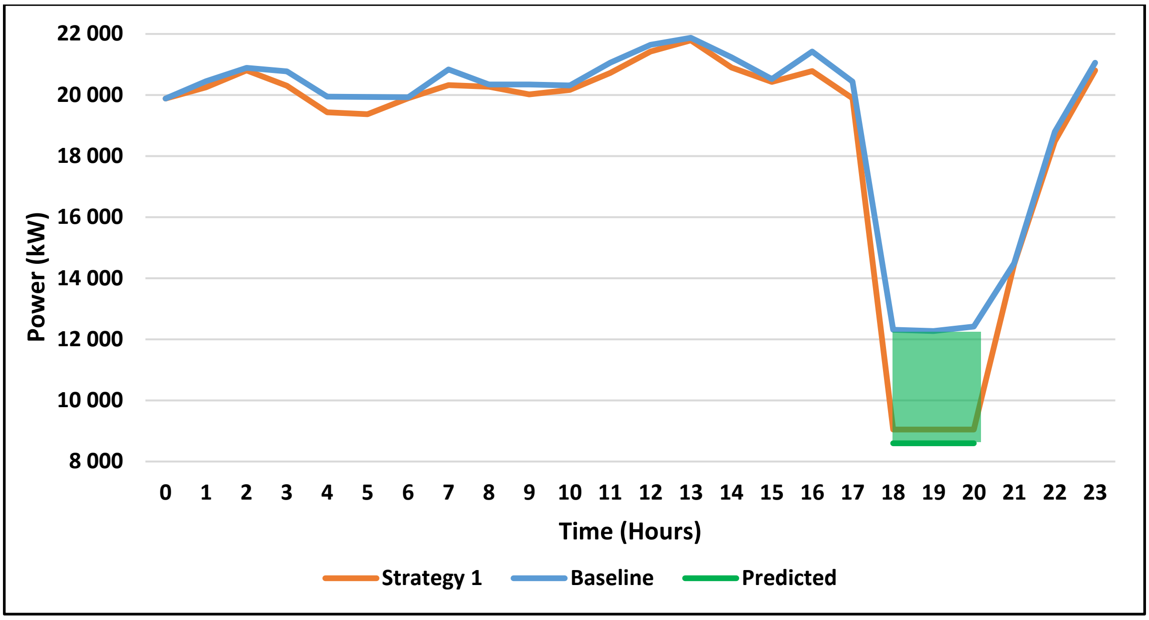


Figure 34: Power profiles for Strategy 1

The predicted load demand shifting in the Eskom evening peak period equated to 3.43 MW. This can be compared with the actual demand shift, which equated to 3.26 MW during the Eskom evening peak period. It therefore validated that Strategy 1 could be implemented on the load shifting demand in the Eskom evening peak period while maintaining safe underground working conditions.

**Strategy 2: Dewatering pump failure on Pumping Level 2**

Strategy 2 was implemented for the scenario where a dewatering pump failed on Pumping Level 2. It was deemed necessary to illustrate a section of the dewatering system where the failures occurred. Figure 35 shows the location of the failures (shown by the red block) where Strategy 2 would be required. It can be seen that an additional dewatering pump failure occurred on Pumping Level 2. As with Strategy 1, safety will be discussed first. Dam flooding presents the most common risk. For this reason, dam levels on Pumping Level 2 in the specific mining environment will be discussed.

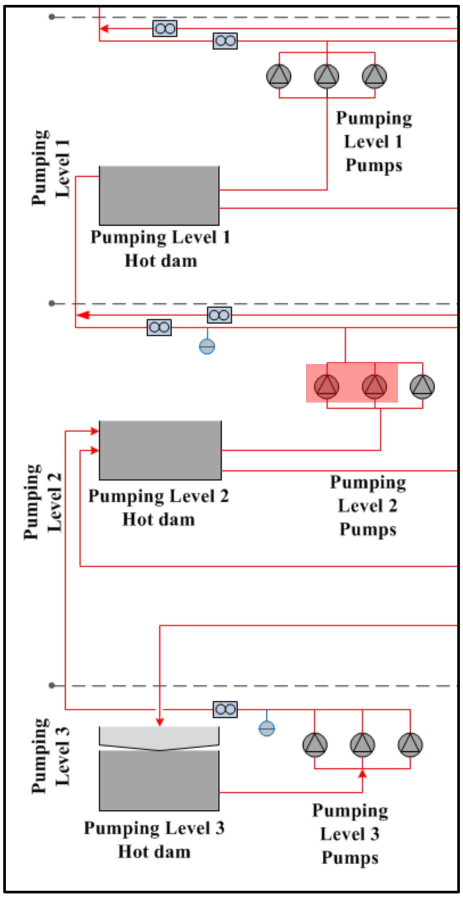


Figure 35: Strategy 2 failures

Figure 36 shows the dam levels obtained to provide proof of the safe control of Strategy 2. This figure shows the actual, simulated and predicted dam levels for the period during which Strategy 2 was implemented. No dangerous scenarios were identified since the dam neither flooded nor did it empty (relative constant dam level of ±40%). This pumping level used a 3CPFS system to aid in the dewatering and furthermore to regulate dam levels in order to avoid dangerous scenarios such as dam flooding. As the strategy did not present dangerous dam levels, load demand shifting could be achieved.

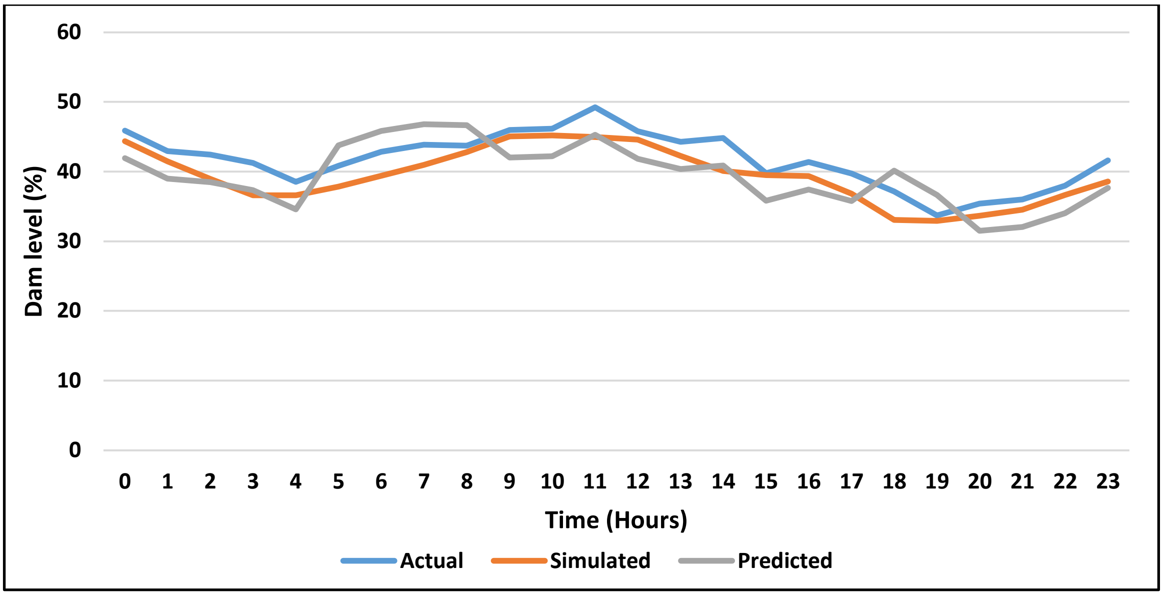


Figure 36: Dam levels for Strategy 2

Equation 8 was used again to predict load demand shifting for the specific dewatering operations. Table 12 presents the average values used to calculate the predicted load demand shifting for Strategy 2. The predicted load demand shifting for this period was calculated as 3.14 MW for the Eskom evening peak period.

Table 12: Average parameters for Strategy 2

| **Parameter** | **Value** |
|---|---|
| *v* | 33 |
| *w* | 12 |
| *x* | 28 |
| *y* | 0 |
| *z* | 6 |

In the period during which Strategy 2 was implemented, an actual load shifting demand of 2.99 MW was achieved. The percentage error between the predicted and the actual load shifting demand was 4.80%. As previously discussed, the accuracy of this prediction model could be increased with an increase in data used in the model. Figure 37 shows the actual, baseline and predicted power profiles for Strategy 2. The predicted load shifting demand is presented as a green block in Figure 37.

The predicted load shifting demand in the Eskom evening peak period equated to 3.14 MW. This can be compared with the actual load shifting demand that equated to 2.99 MW during the Eskom evening peak period. Strategy 2 was thus validated by load shifting demand in the Eskom evening peak period while maintaining safe underground working conditions.

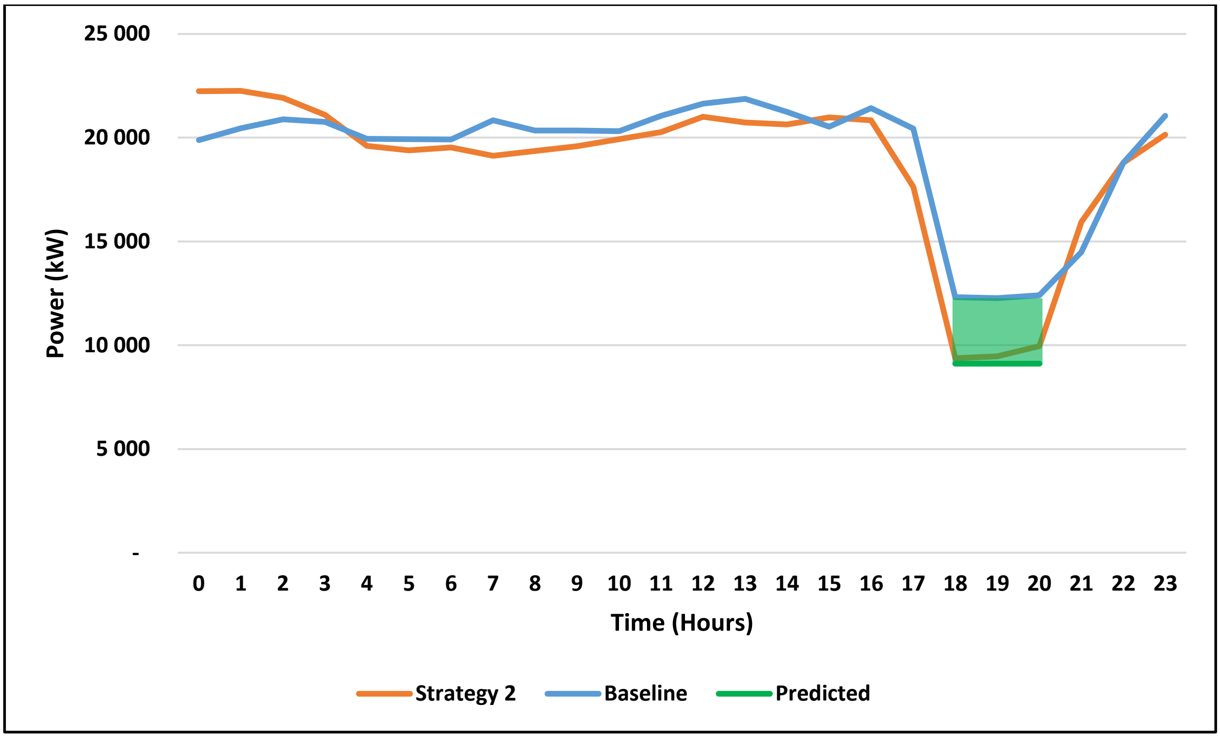


Figure 37: Power profiles for Strategy 2

**Strategy 3: Second dewatering pump failure on Pumping Level 2**

Another strategy was required in the event of a second dewatering pump failing on Pumping Level 2, which means that all dewatering pumps have failed on Pumping Level 2. Unfortunately, this strategy could not be tested as this scenario did not occur within the testing period. It was deemed necessary to illustrate a section of the dewatering system where the failures occurred. Figure 38 shows the location of the failures (shown by the red block) where Strategy 3 was required.

It can be seen that all the dewatering pump failures occurred on Pumping Level 2. The simulation model and prediction models were proved accurate in the previous control strategies and were used to predict the outcome of other scenarios. Pumping Level 2 had a 3CPFS, which means that water could be drained without using dewatering pumps. The 3CPFS could not drain water quickly enough to remove all the water that enters the dam. This presented a possible risk as dams could flood. This risk would therefore be evaluated first.

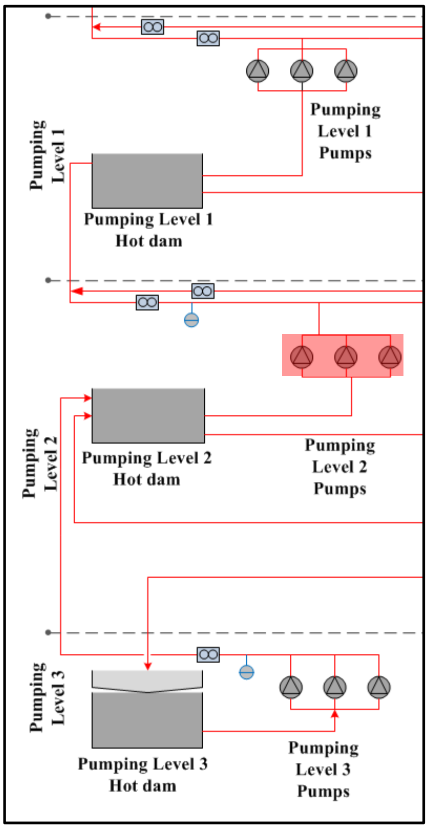


Figure 38: Strategy 3 failures

The first aspect that had to be evaluated was the safety of the strategy as dam flooding is a possible dangerous situation. Figure 39 presents the average simulated and predicted dam levels for a period of 24 hours. The y-axis was adjusted to show the difference between these dam level profiles. The red blocks are used to show periods during which the simulation and prediction model indicated the dam would flood.

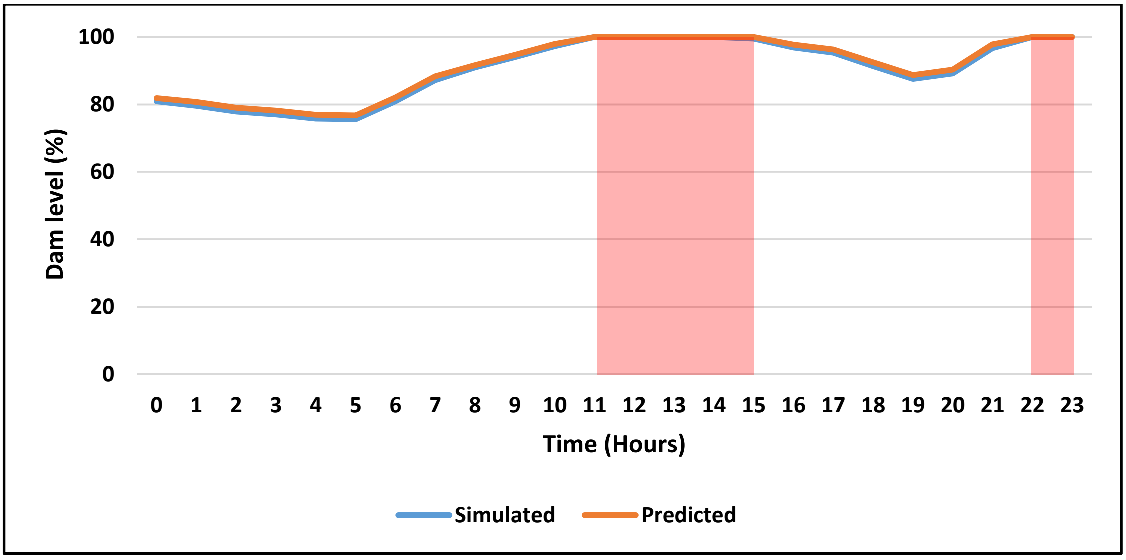


Figure 39: Dam levels for Strategy 3

As the simulated and predicted dam levels were shown to flood, further evaluations were required. Figure 40 shows the simulated dam level profile for a period of four days. The failures were initiated at the first hour of the first day.

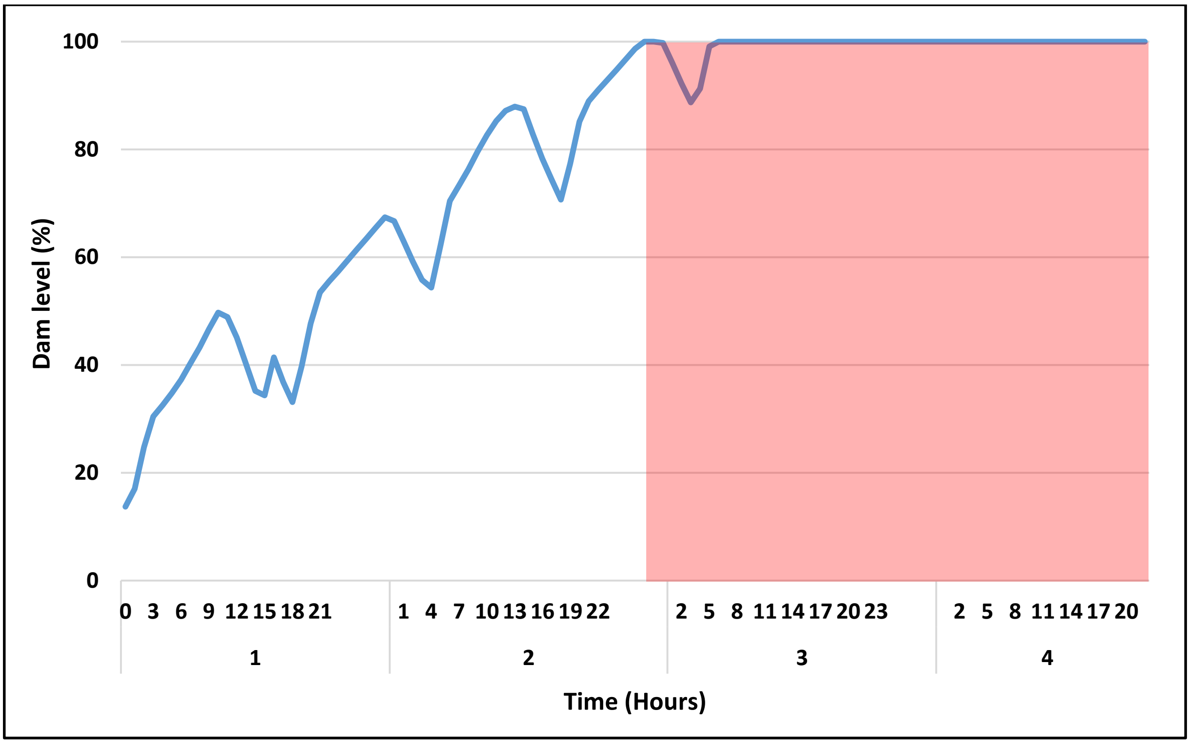


Figure 40: Simulated dam level for Strategy 3

Figure 40 shows that the dam levels increased from the initialisation of the failure. The dam levels were reduced in the simulation in the evenings as water consumption decreases in the Eskom evening peak periods. The red block shows that the dam is predicted to flood at the end of the second day. Therefore, the problem should be mitigated within 48 hours of the failures occurring otherwise the dam will flood and the safety of underground mining personnel will be compromised.

Should the dams flood, load demand shifting could still be realised in spite of the failures because the dewatering system's control are adjusted around the failures. As no pumps were operational on the pumping level where they were needed, the pump controls of other pumping level were adjusted and reduced to limit the dangerous situation. As the possible load demand shifting could be achieved while other dewatering levels experienced failures, the predicted load demand shifting was calculated using Equation 8.

Table 13 shows the parameters used to predict the load demand shifting that could be achieved using Strategy 3. The predicted load demand shifting equated to 2.14 MW. As stated, there were no actual results for Strategy 3 that could be used for comparison purposes.

Table 13: Average parameters for Strategy 3

| Parameter | Value |
|---|---|
| $v$ | 35 |
| $w$ | 15 |
| $x$ | 30 |
| $y$ | 0 |
| $z$ | 6 |

The simulated load shifting demand achieved using this control strategy was calculated as 1.98 MW. The predicted load demand shifting was 2.14 MW. Thus, the percentage error calculated between the simulated and the predicted load demand shifting equated to 7.35%. The power profiles shown in Figure 41 include the baseline, simulated power profile and predicted load demand shifting.

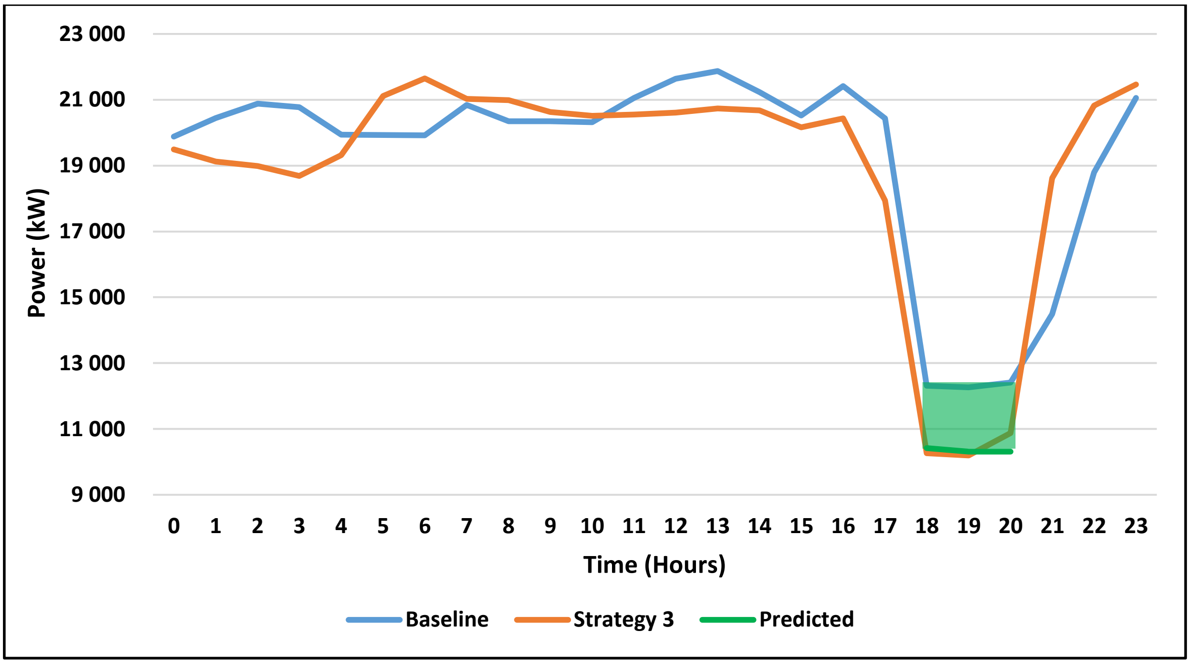


Figure 41: Power profiles for Strategy 3

This control strategy was not required in the testing period of one year. These failures are not likely to occur as all three dewatering pumps would have to fail on Pumping Level 2 before this control strategy would be required. If this failure occurs, Strategy 3 should be implemented.

It should be noted that this strategy would only be possible for 48 hours. After this period, the dam would probably flood according to the simulation.

### Strategy 4: Dewatering pump failure on Pumping Level 3

If a single dewatering pump fails on Pumping Level 3, a strategy is required to obtain electricity cost savings safely. It was deemed necessary to illustrate the section of the dewatering system where the failures occurred. Figure 42 shows the location of the failures (shown by the red block) where Strategy 4 would be required.

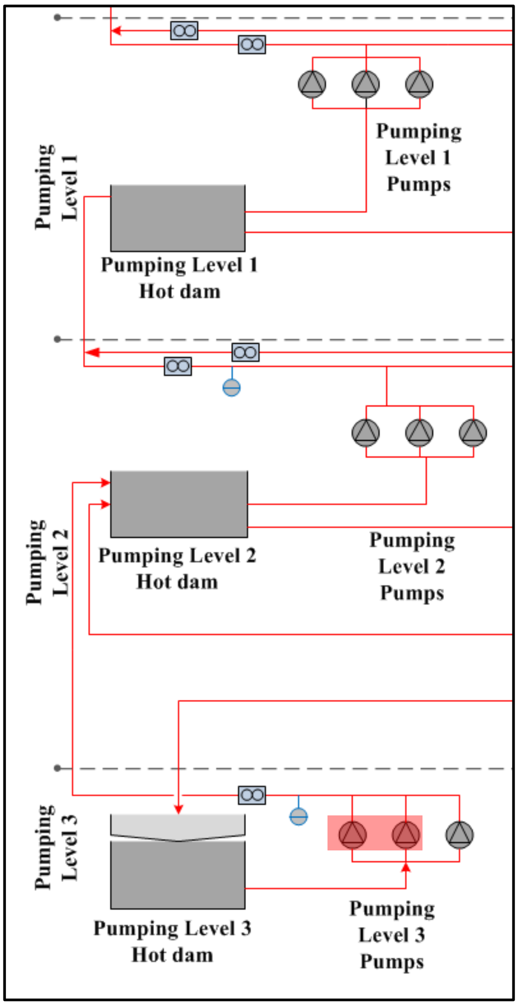


Figure 42: Strategy 4 failures

It can be seen that an additional dewatering pump failure occurred on Pumping Level 3. Strategy 4 was developed for this purpose. Figure 43 shows the actual, simulated and predicted dam levels in the case where Strategy 4 was implemented.

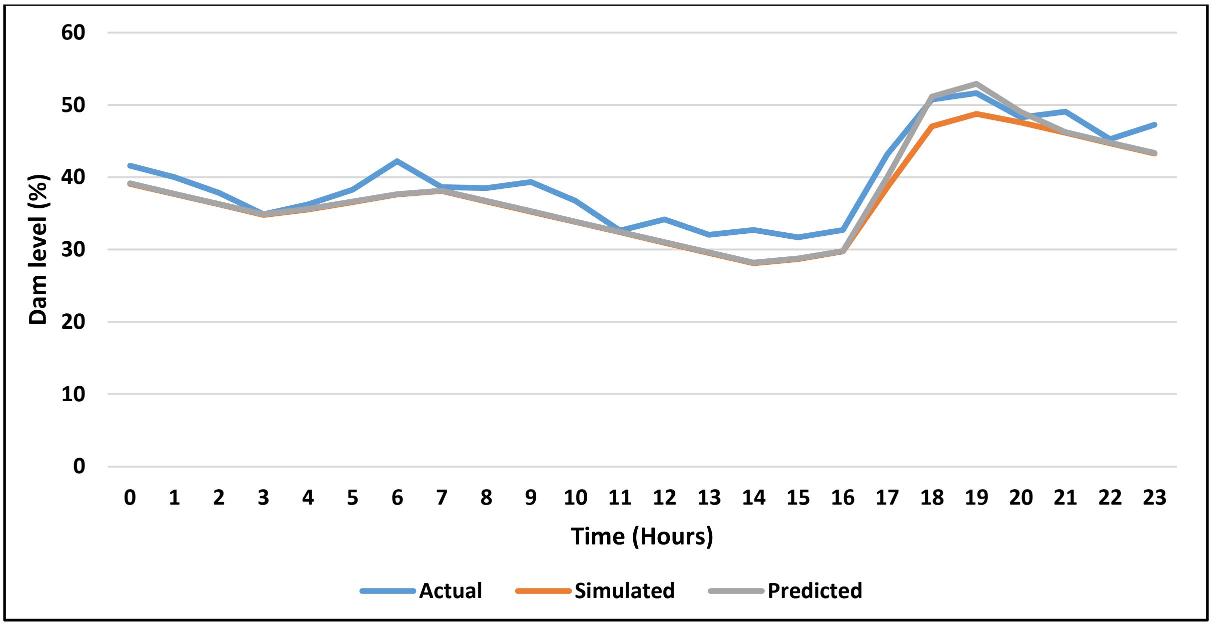


Figure 43: Dam levels for Strategy 4

Strategy 4 did not present dangerous dam levels in the actual, simulated and predicted scenarios (less than 25%), thus load demand shifting could be analysed. First, load demand shifting was predicted using Equation 8. Table 14 shows the parameters used to predict the load demand shifting for Strategy 4. The predicted load demand shifting equated to 2.19 MW.

Table 14: Average parameters for Strategy 4

| Parameter | Value |
|---|---|
| *v* | 32 |
| *w* | 13 |
| *x* | 29 |
| *y* | 0 |
| *z* | 7 |

The actual load shifting demand achieved when Strategy 4 was implemented equated to 2.05 MW. The percentage error calculated between the predicted and actual load shifting in demand was 6.38%. Figure 44 shows the power profiles obtained by implementing Strategy 4. The baseline, actual power profile and predicted load demand shifting are shown for Strategy 4. The green block again illustrates the predicted load shifting demand from the baseline.

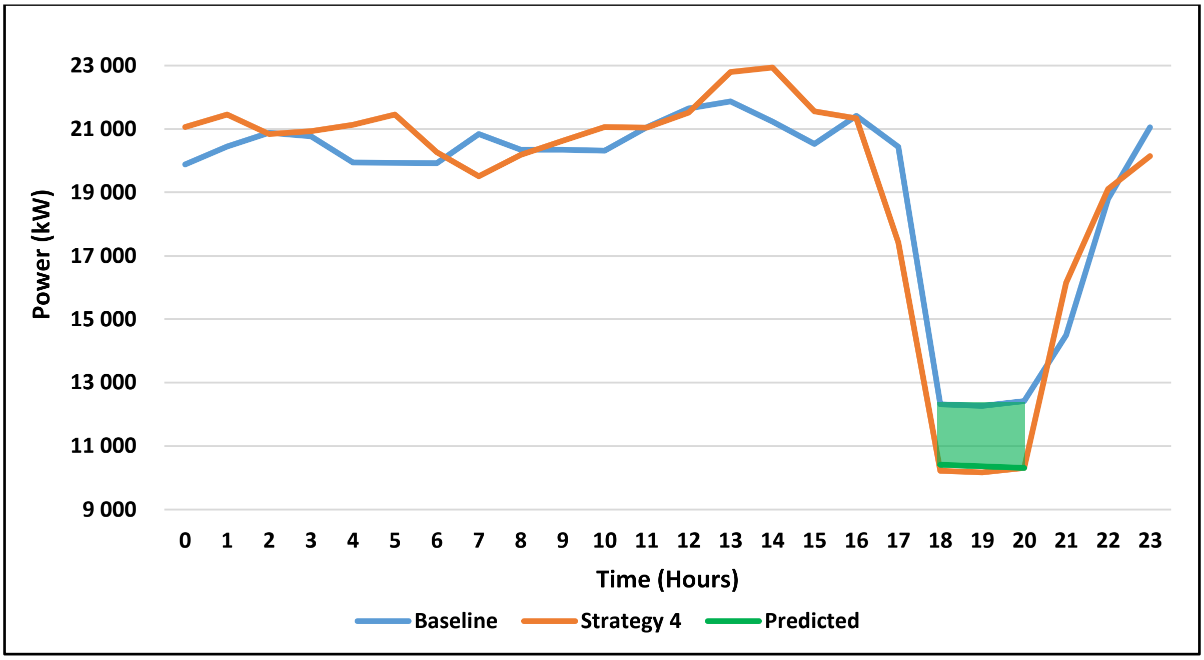


Figure 44: Power profiles for Strategy 4

Figure 44 shows that the predicted load demand shifting in the Eskom evening peak period equated to 2.19 MW. This can be compared with the actual load demand shifting, which equated to 2.05 MW during the Eskom evening peak period. Therefore, Strategy 4 could be implemented to shift load demand in the Eskom evening peak period. This strategy was validated as load demand shifting was achieved safely.

**Strategy 5: All dewatering pumps failing on Pumping Level 3**

A control strategy is required should all dewatering pumps fail on Pumping Level 3. The only method of pumping water from the bottom dewatering dam in this case study is by using dewatering pumps. Unfortunately, this scenario did not occur within the testing period of one year. It was however deemed necessary to illustrate the section of the dewatering system where the failures occurred. Figure 45 shows the location of the failures (shown by the red block) where Strategy 5 would be required.

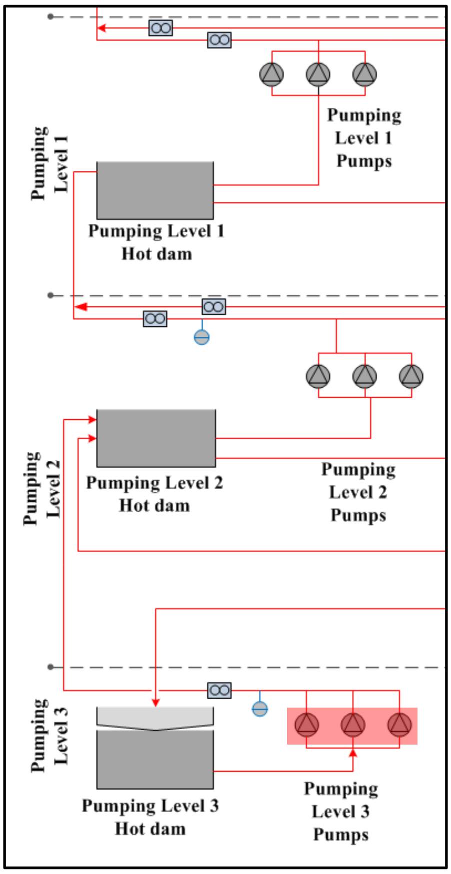


Figure 45: Strategy 5 failures

Figure 46 shows the simulated and predicted dam levels when all the dewatering pumps on Pumping Level 3 failed. Unfortunately, there are limited control adjustments that can be done to reduce the risk of all dewatering pumps failing on Pumping Level 3.

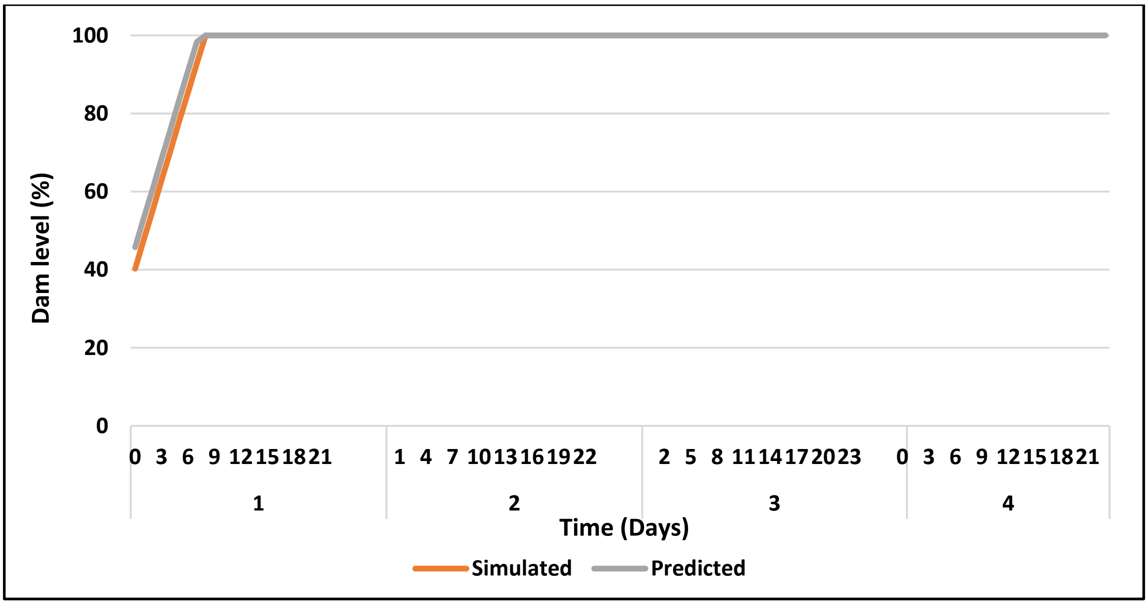


Figure 46: Dam levels for Strategy 5

Figure 46 shows that both the simulated and predicted dam would flood within a few hours (seven hours) because there was no method for pumping water from this dam in this specific scenario. Fortunately, this has not occurred and is unlikely as there are three dewatering pumps on this level. There is a method for reducing the water towards the dam. However, this was not a viable option as it included reducing the water towards active mining levels. This would have a negative effect on production as less water would be supplied. It would also have a negative effect on the safety of mining personnel.

As discussed in Strategy 3, electricity cost savings could be obtained in this scenario as no pumping was possible on the dewatering level experiencing these failures. Once the failures have been fixed, the priority would be to reduce the dam level until load demand shifting can be achieved safely. Table 15 shows the parameters used to predict the load demand shifting for Strategy 5.

Table 15: Average parameters for Strategy 5

| **Parameter** | **Value** |
|---|---|
| *v* | 35 |
| *w* | 17 |
| *x* | 28 |
| *y* | 0 |
| *z* | 15 |

Figure 47 shows the power profiles obtained for Strategy 5. As previously stated, this scenario could not be tested; therefore, simulated power profiles were compared with the baseline and predicted load demand shifting. Figure 47 clearly illustrates the load demand shifting achieved between the predicted power and the baseline power profiles. The simulated load demand shifting was calculated to be 3.05 MW. The predicted load demand shifting was calculated to be 3.34 MW. The percentage error between the simulated and predicted load demand shifting equated to 8.77%. The green block in Figure 47 again illustrates the predicted load demand shifting.

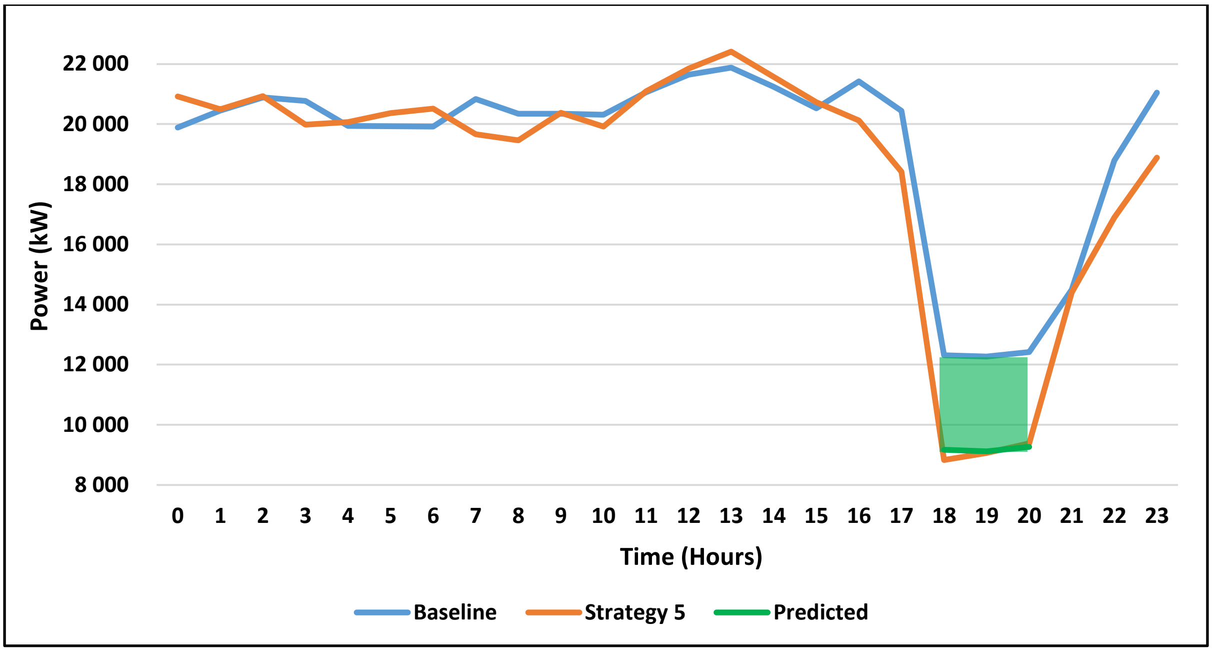


Figure 47: Power profiles for Strategy 5

Comparing the power profile of Strategy 5 with previously discussed control strategies shows that the load demand shifting is higher than the previous strategies, because the upper dam level should be as empty as possible. When the failures are fixed, these dewatering pumps should be operated to reduce the dam level. This can only be done safely when the upper dam levels are low. Thus, the upper dewatering levels will operate for longer periods. An increased load demand shifting opportunities exist as the baseline will be scaled higher.

**Strategy 6: Single fridge plant failure**

Strategy 6 and Strategy 7 were developed for fridge plant failures. Strategy 6 consists of a single fridge plant failure. It was deemed necessary to illustrate a section of the refrigeration system where the failures occurred. Figure 48 shows the location of the failures (shown by the red block) where Strategy 6 would be required. A one-year period was identified during which Strategy 6 would be required. Safety will be discussed first as it is a priority in the mining industry.

Possible dangerous scenarios related to fridge plant failures include low surface chill dam levels and high surface hot dam temperatures. When the surface chill dam level is too low (less than 25%), less water is available for cooling, which could lead to dangerously high underground temperatures. When the hot dam water temperature is too high, the same dangerous situation could occur.

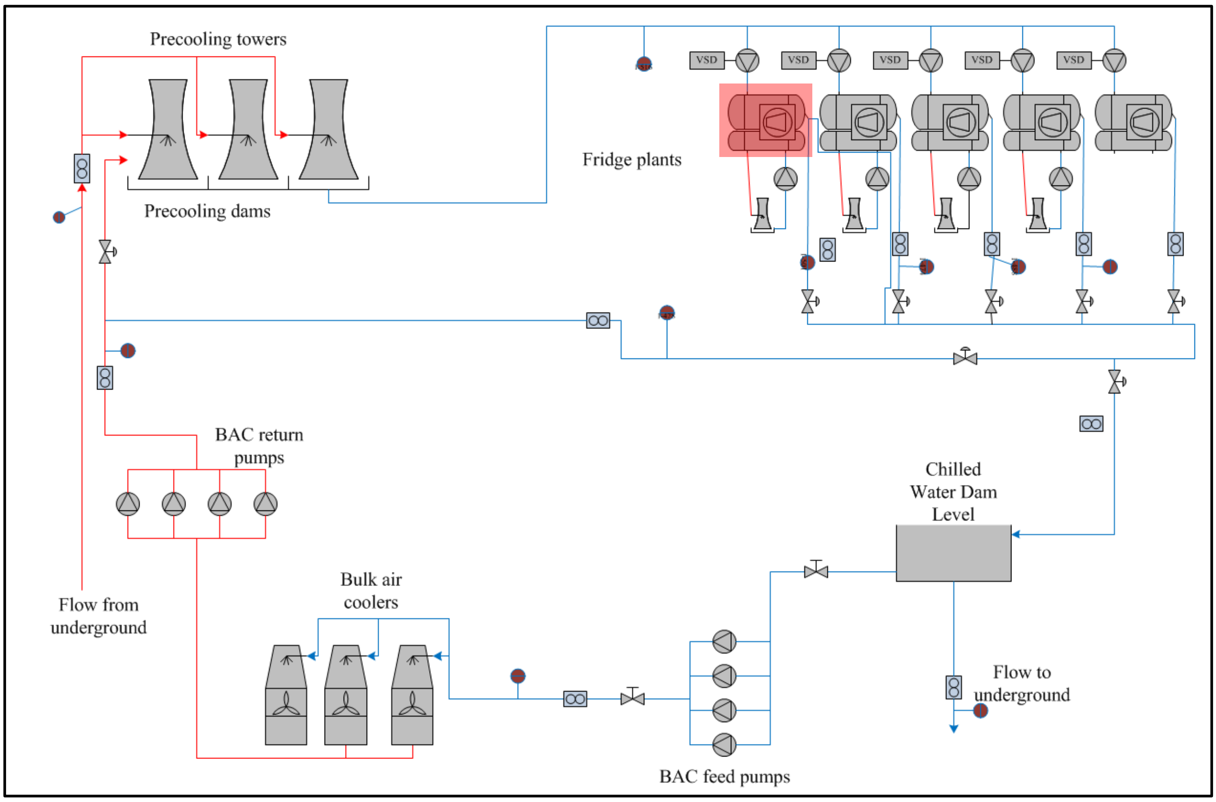


Figure 48: Strategy 6 failures

Figure 49 shows the average actual, simulated and predicted chill dam levels for the period during which Strategy 6 was required. The dam levels were high although no dangerous situations occurred. The dam levels did not reach dangerously low or high levels. The lower chill dam levels in the Eskom evening peak period (indicated by the blue block) were caused by stopping fridge plants during this period.

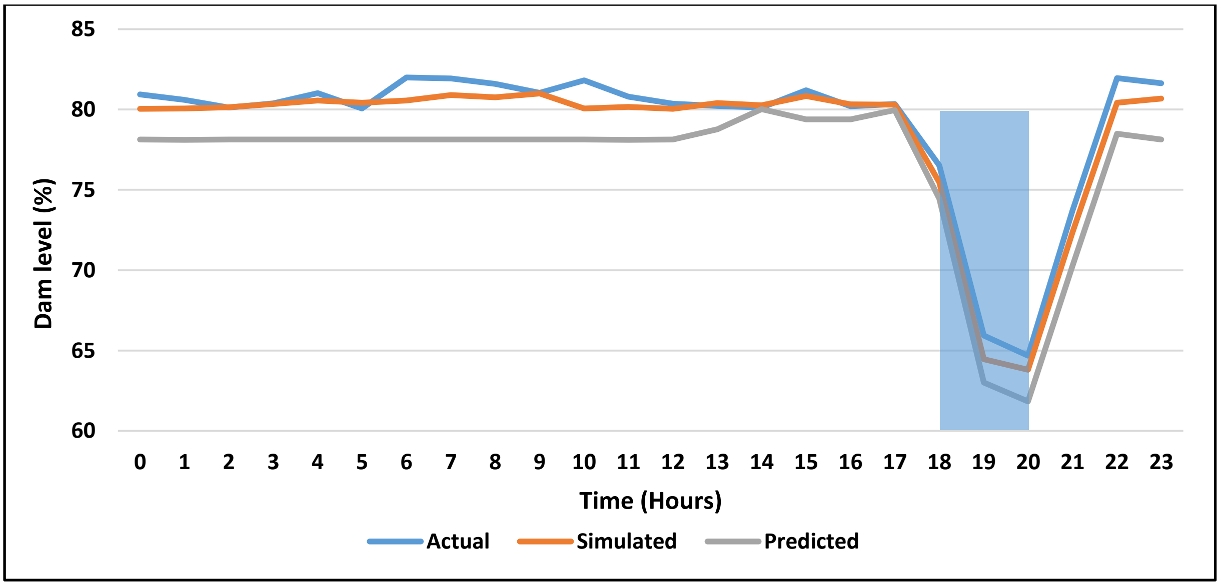


Figure 49: Dam levels for Strategy 6

Figure 50 shows the actual and simulated surface chill dam temperatures. During the drilling shift (from 07:00 to 14:00), these temperatures should not exceed 9°C as it leads to high underground temperatures. This limit was set by mining personnel, so the limit may differ for other case studies.

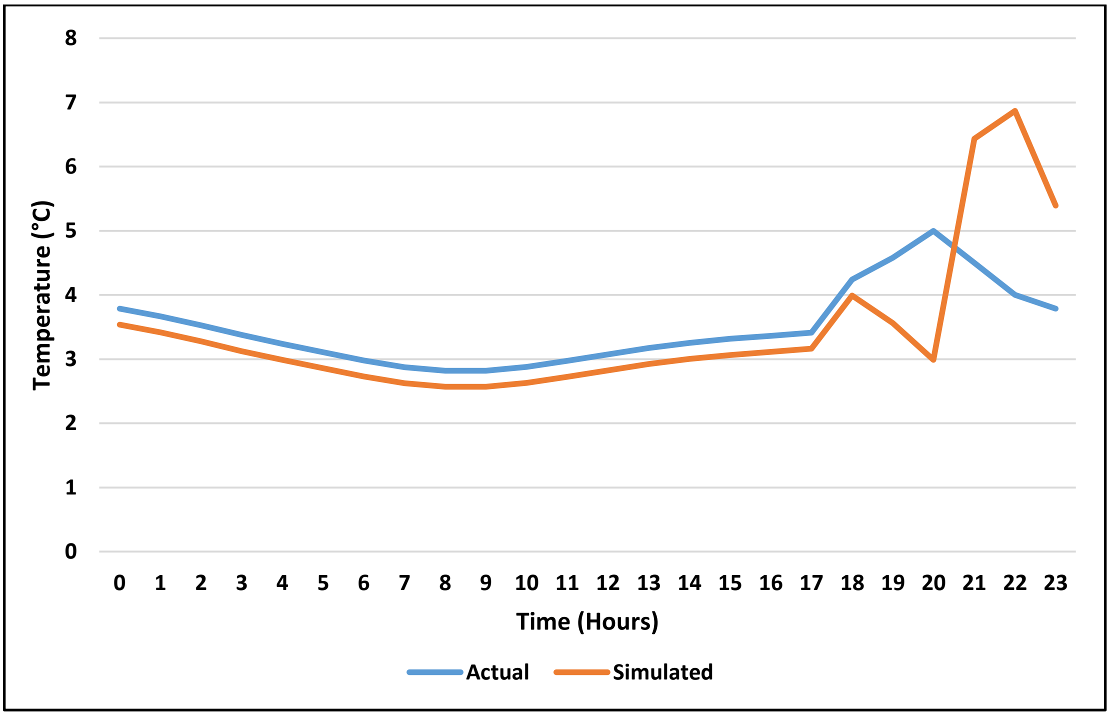


Figure 50: Surface dam temperature for Strategy 6

Figure 50 shows that the simulated temperature drastically rose and exceeded the actual surface dam temperature around 20:00. As previously mentioned, the surface dam temperature should not exceed 9°C between 07:00 and 14:00. No such instances occurred during the period which Strategy 6 was tested. The simulations show that Strategy 6 did not lead to any dangerous situation.

Equation 23, Appendix D, was used to predict the load demand shifting for Strategy 6. The process of developing the load demand prediction model was discussed in Appendix D, although the same process was followed to develop the load demand prediction model for the dewatering water reticulation group (discussed Section 3.3.2). Table 16 presents the average parameters used to calculate the predicted load demand shifting when Strategy 6 was used.

Table 16: Average parameters for Strategy 6

| Parameter | Value |
|---|---|
| *u* | 10 |
| *v* | 82 |
| *w* | 25 |
| *x* | 72 |
| *y* | 0 |
| *z* | 19 |

The predicted load demand shifting achieved for Strategy 6 was calculated to be 4.04 MW. Figure 51 shows the power profiles obtained for Strategy 6. These power profiles include the baseline, actual power profiles and predicted load demand shifting.

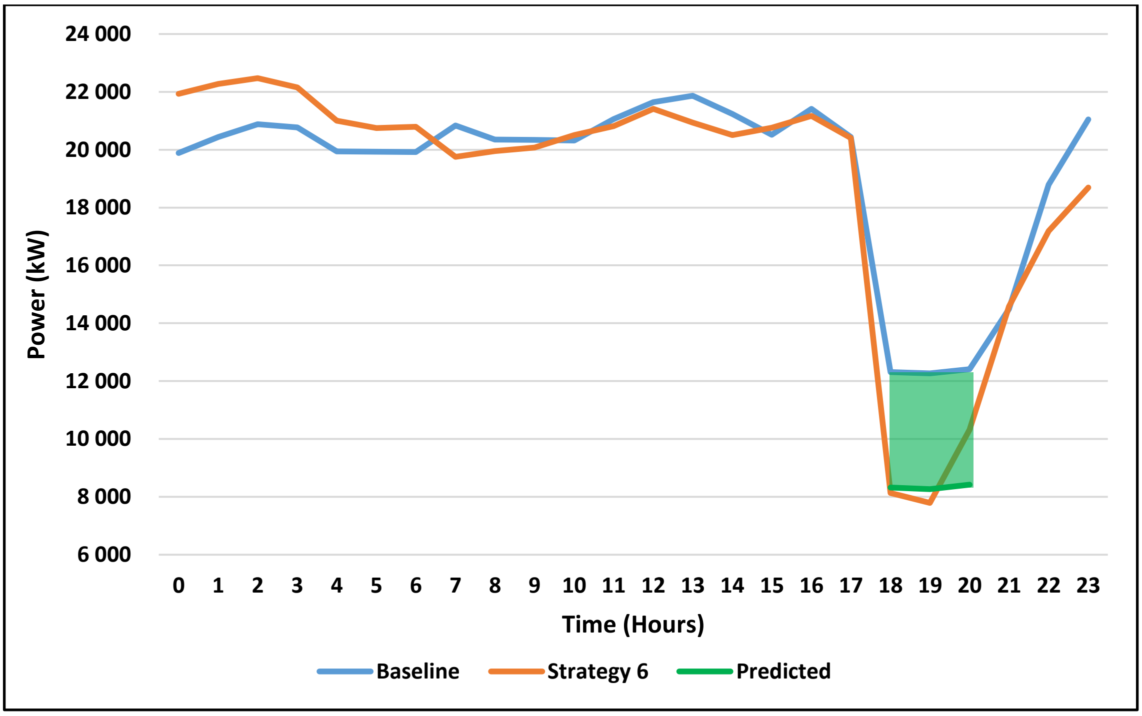


Figure 51: Power profiles for Strategy 6

By evaluating the power profiles for each of the scenarios, an actual load demand shifting of 4.07 MW was achieved in the period during which Strategy 6 was implemented. The percentage error between the actual and predicted load demand shifting was 0.79%. The green block in Figure 51 shows the predicted load demand shifting to be 4.04 MW. Strategy 6 is validated as load demand shifting was achieved in a safe manner.

**Strategy 7: Second fridge plant failure**

Another strategy is required should a second fridge plant fail and Strategy 7 was developed specifically for this purpose. It was deemed necessary to illustrate the section of the refrigeration system where the failures occurred. Figure 52 shows the location of the failures (shown by the red block) where Strategy 7 would be required.

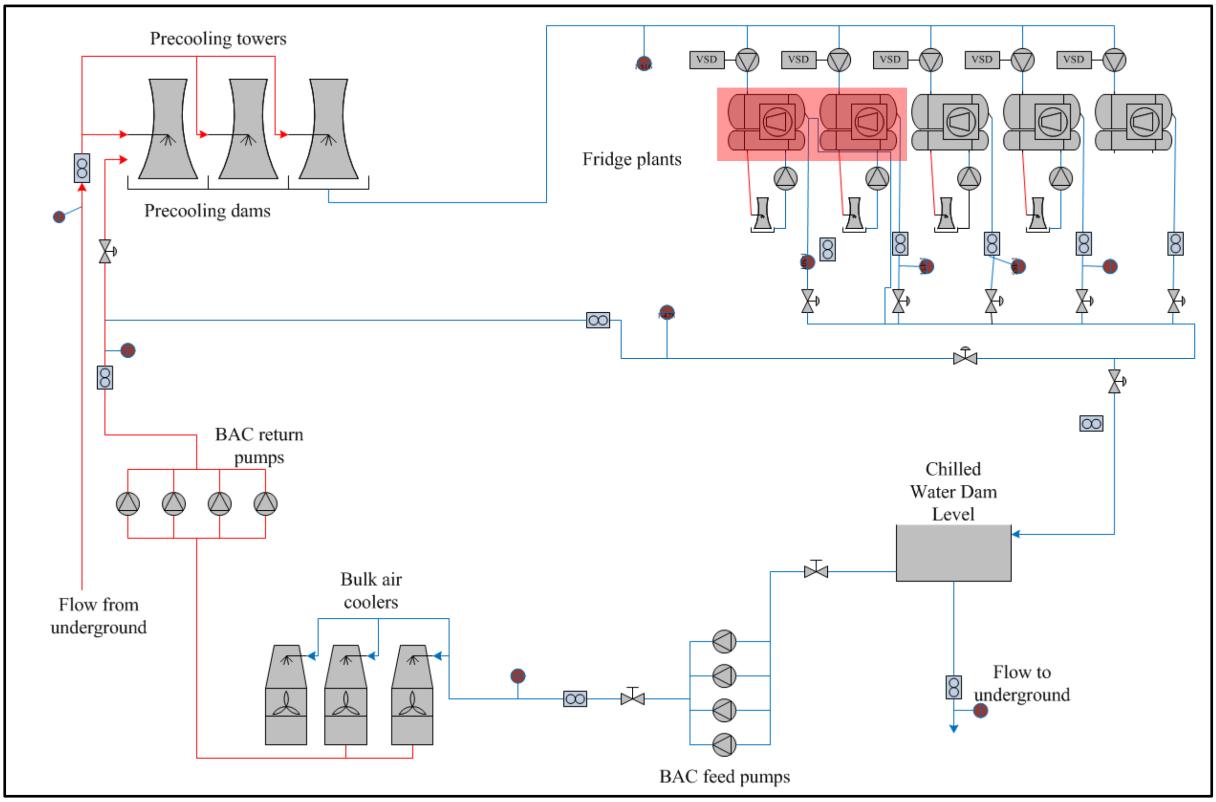


Figure 52: Strategy 7 failures

Safety will be discussed first as it remains a priority. Figure 53 shows the actual, simulated and predicted dam levels associated with Strategy 7. The profiles are similar to those of Strategy 6 although the dam levels were lower. The reason is that less water was cooled and the system stabilised when the control was adjusted. No dangerous scenarios occurred in terms of dam levels when Strategy 7 was implemented. The surface chill dam temperature was the next important parameter that had to be evaluated.

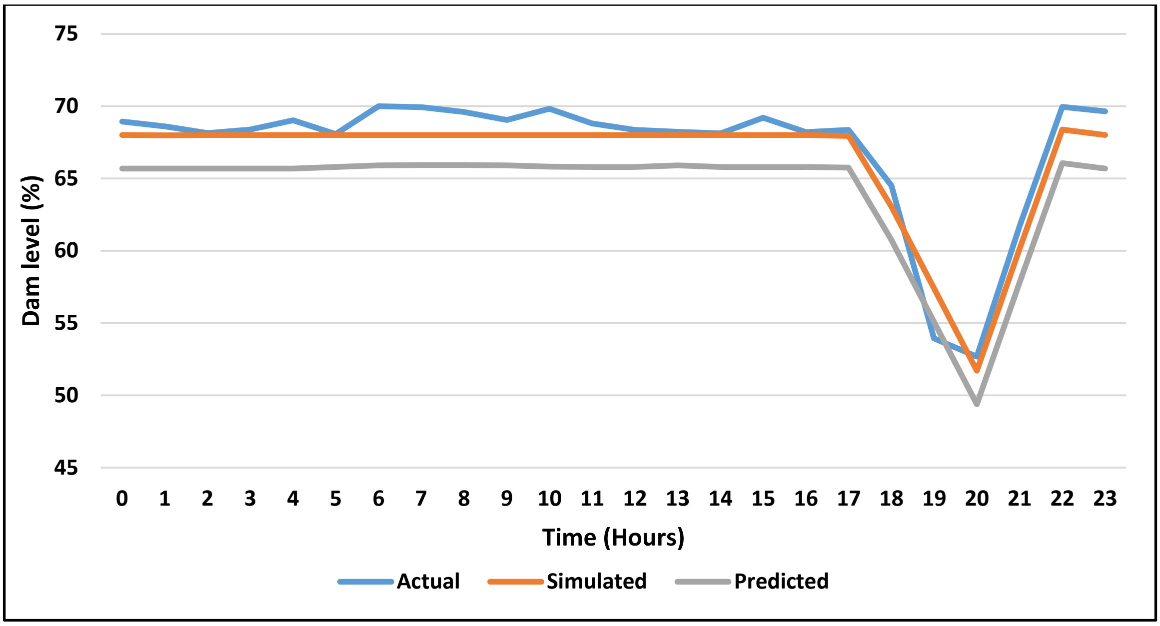


Figure 53: Dam levels for Strategy 7

Figure 54 presents the actual and simulated surface chill dam temperature for the period during which Strategy 7 was implemented.

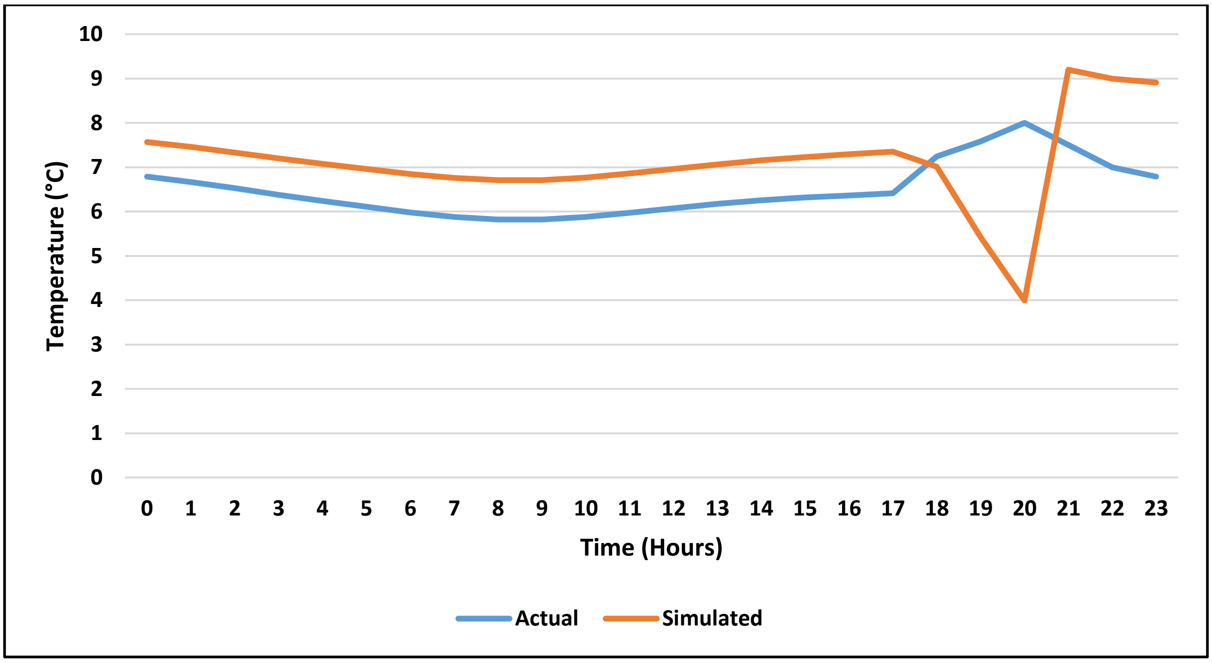


Figure 54: Surface dam temperature for Strategy 7

Figure 54 shows an increase in surface chill dam temperatures compared with Strategy 6's results. The reason is that less water was cooled as a second fridge plant failed. Fortunately, the surface chill dam temperatures were lower than the maximum limit, thus no dangerous situations were caused.

As the strategy did not pose dangerous scenarios when implemented, load demand shifting could possibly be achieved. Equation 23 (in Appendix D) was used to predict the load demand shifting for specific scenarios. Table 17 shows the average parameters used to calculate the predicted load demand shifting when Strategy 7 was implemented.

Table 17: Average parameters for Strategy 7

| Parameter | Value |
|---|---|
| $u$ | 9 |
| $v$ | 77 |
| $w$ | 24 |
| $x$ | 69 |
| $y$ | 1 |
| $z$ | 17 |

The predicted load demand shifting was calculated to be 3.70 MW. Figure 55 shows the power profiles obtained for Strategy 7. This figure includes the baseline, actual and predicted power profiles. The actual load demand shifting achieved when Strategy 7 was implemented was calculated to be 3.64 MW. The percentage error between actual and predicted load demand shifting equated to 1.53%. The green block represents the predicted load demand shifting. In the case where Strategy 7 was implemented, load demand shifting could be achieved safely. This validates the use of Strategy 7.

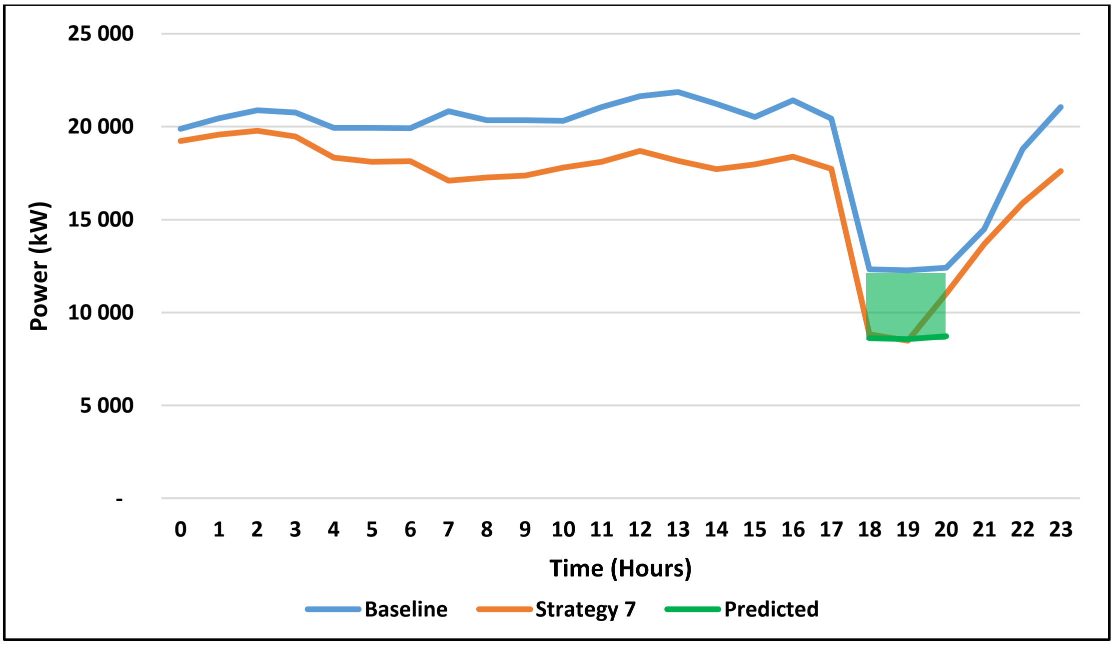


Figure 55: Power profiles for Strategy 7

### Strategy 8: BAC failure

Strategy 8 and Strategy 9 were specifically developed for scenarios where BAC failures occur. These control strategies are developed in Appendix D. Strategy 8 is required when a single BAC fails. It was deemed necessary to illustrate the section of the refrigeration system where the failures occurred. Figure 56 shows the location of the failure (shown by the red block), where Strategy 8 would be required.

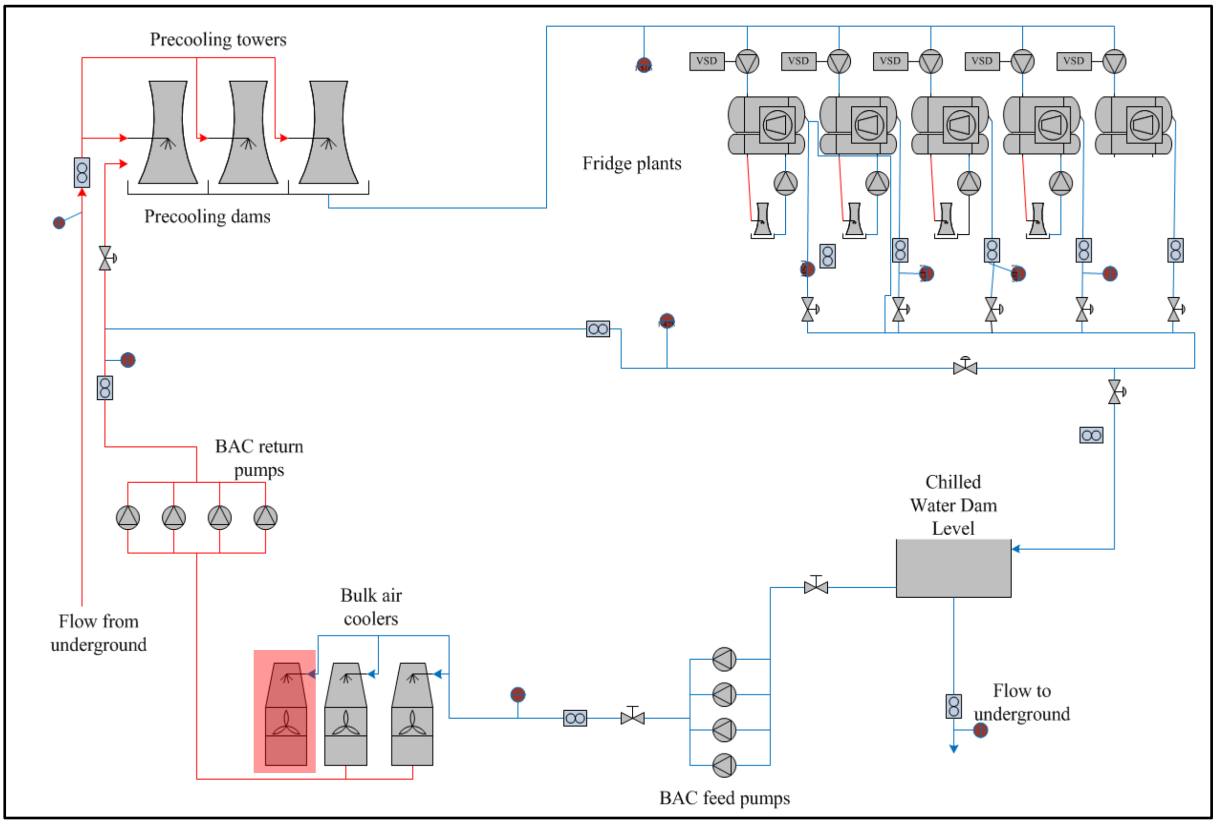


Figure 56: Strategy 8 failures

Less cold air would be available to send underground, which could mean that underground temperatures would rise. This will would in the underground working environment becoming dangerous for mining personnel. In the scenario where the BAC dam level emptied, less water would be available for cooling. The BAC dam was also used to store water, which could be pumped to a surface hot dam, from where the fridge plants received water. In the case where less water was available for cooling, it could also lead to dangerous situations caused by higher outlet temperatures on the fridge plants. In the next paragraphs, BAC dam levels will be discussed first.

Figure 57 shows the actual, simulated and predicted dam levels. The dam levels decreased significantly over a period of time as less water was supplied to this dam, which could cause problems if the dam emptied. A method of avoiding this problem was to bypass the malfunctioning BAC. The dam level would thus be controlled and empty dams avoided.

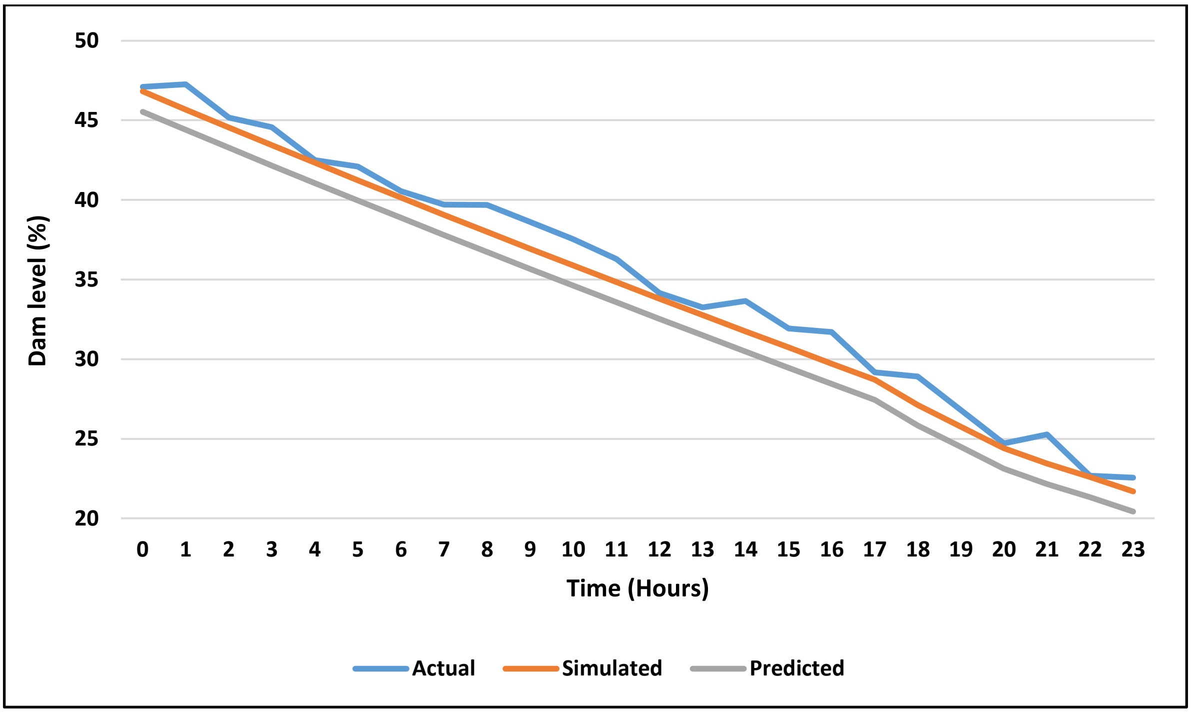


Figure 57: BAC sump level for Strategy 8

The second problem when a BAC fails is that less cold air is available to be sent underground, which could lead to higher underground temperatures. For this reason, the average outlet air temperatures of the remaining operational BAC will be discussed.

Figure 58 shows the actual and simulated BAC outlet air temperatures in the scenario where Strategy 8 was required. These profiles were similar with an average percentage error of 8.27%. The maximum outlet temperature prescribed for this mine was 10°C, which was set by mining personnel. This maximum limit was not reached within the period that mining personnel were underground (07:00 to 14:00). This implies that Strategy 8 could be implemented safely.

The next step was to evaluate whether it would be financially beneficial to implement Strategy 8. The evaluation was done by comparing the actual power consumption against the simulated power for Strategy 8.

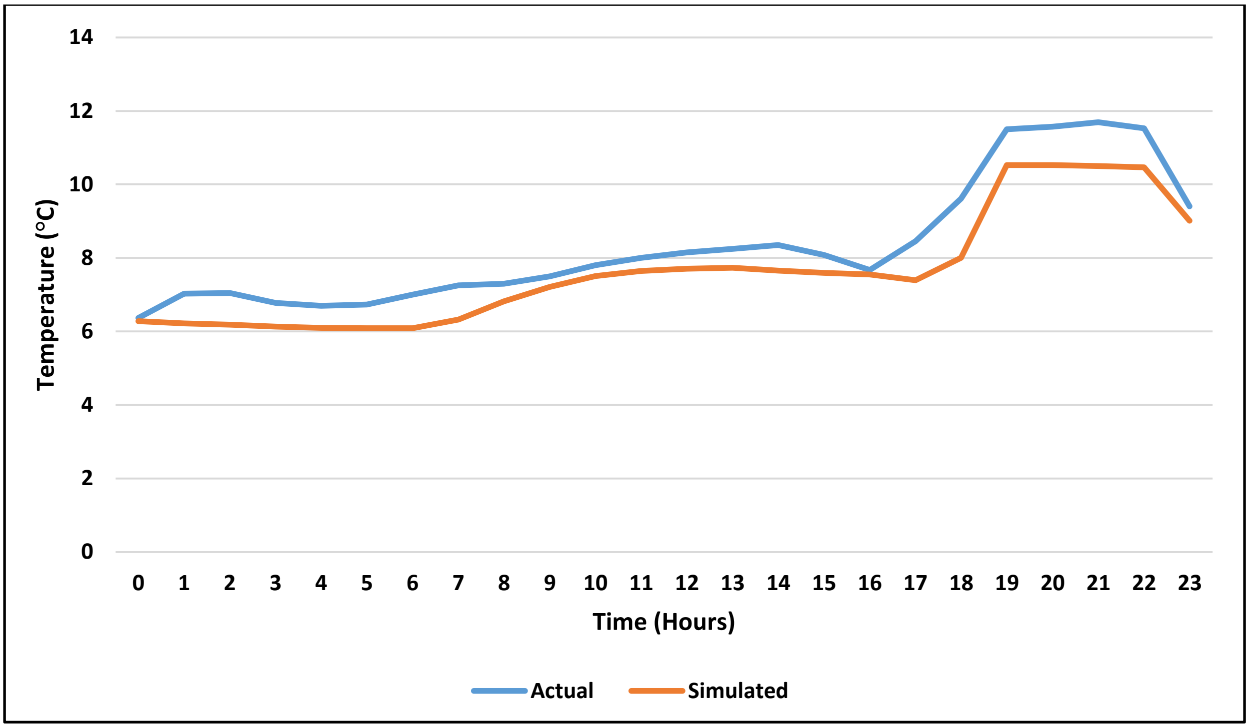


Figure 58: BAC outlet air temperature for Strategy 8

Figure 59 shows the baseline and actual power profiles for the period during which Strategy 8 was implemented. Strategy 8 consumed less power than the baseline. Strategy 8 achieved load demand shifting of 3.16 MW in the Eskom evening peak period. This validates that Strategy 8 could be used to safely achieve load demand shifting in the Eskom evening peak period.

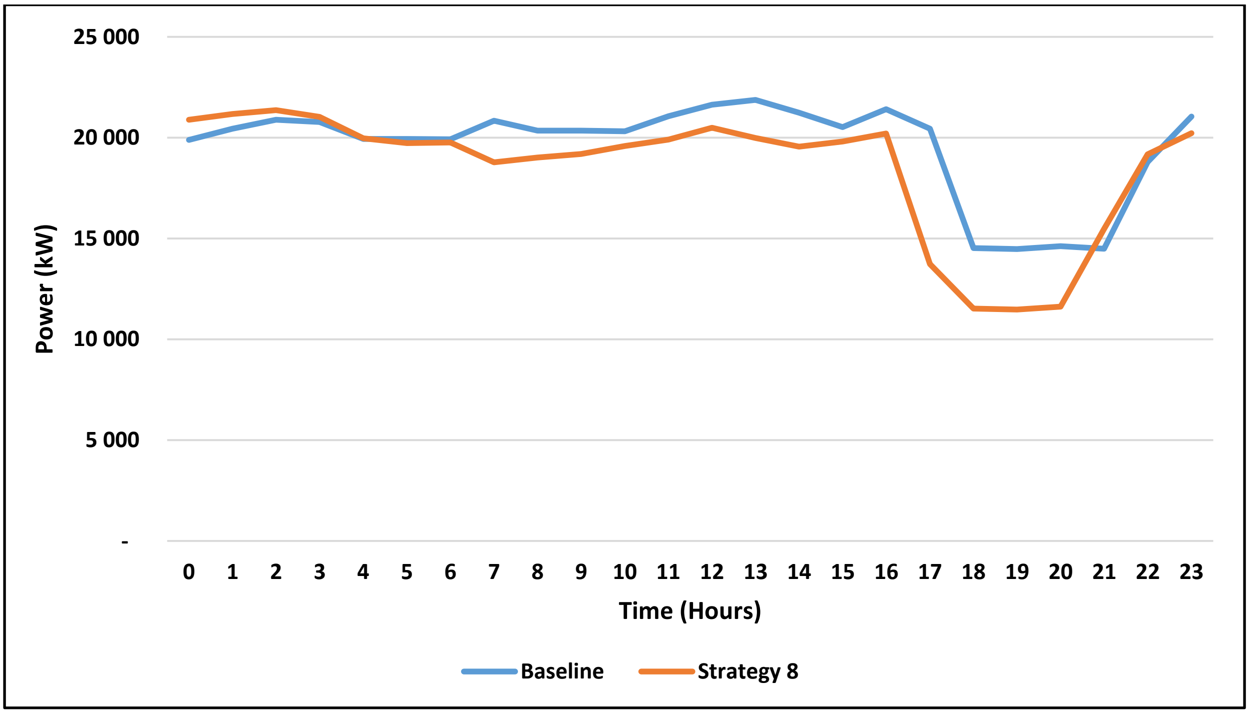


Figure 59: Power profiles for Strategy 8

**Strategy 9: Second BAC failure**

Strategy 9 was developed as an additional control strategy should a second BAC fail. It was deemed necessary to illustrate the section of the refrigeration system where the failures occurred. Figure 60 shows the location of the failures (shown by the red block) where Strategy 9 would be required.

The same dangerous scenarios should be avoided as for Strategy 8. BAC dam levels will be discussed first as part of analysing the safety of Strategy 9.

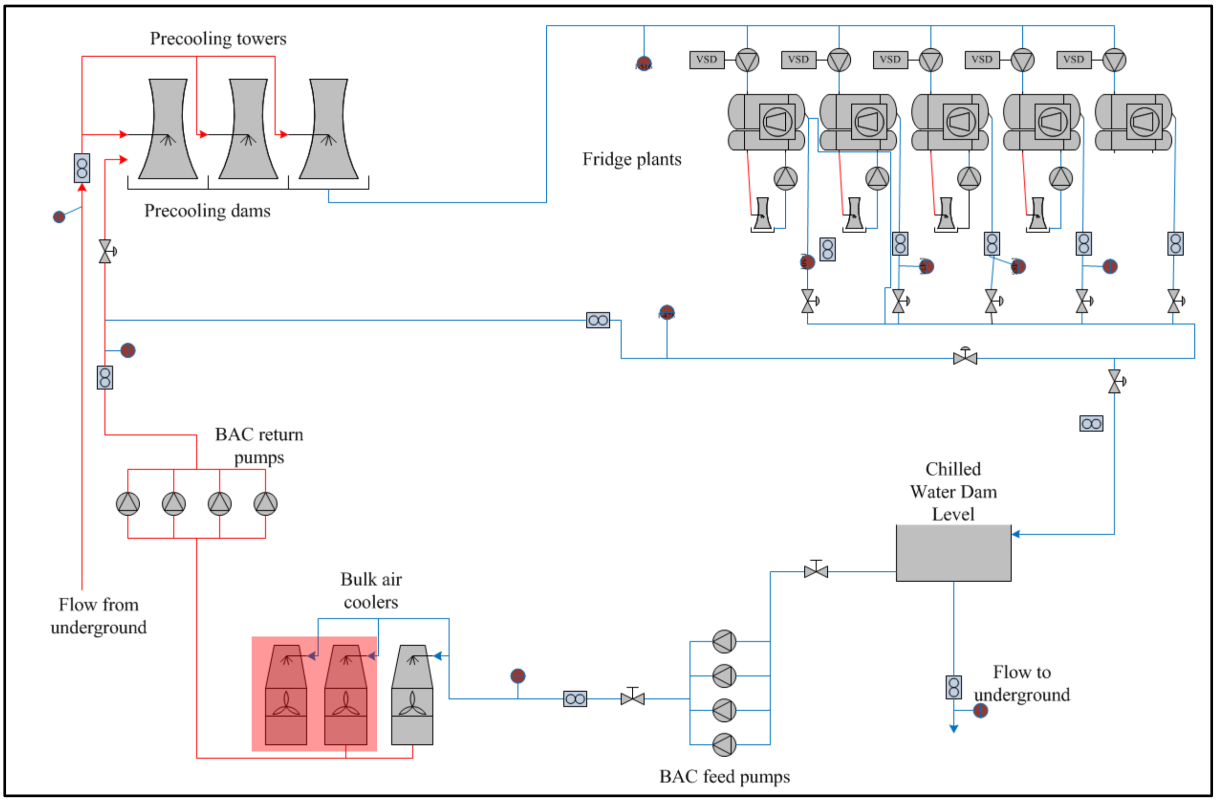


Figure 60: Strategy 9 failures

Figure 61 illustrates the actual, simulated and predicted dam levels for the period during which Strategy 9 was implemented. The average simulated and predicted dam levels were considered accurate and compared with the actual dam levels since the average percentage error was calculated to be less than 5%. Figure 61 clearly shows that the actual dam level percentages compared well with the predicted dam levels. These two profiles also compared well with the simulated levels with an average error of 4.03% between the simulated and the actual dam levels. The percentage error calculated between the predicted dam levels and actual dam levels was 1.14%. This confirmed that the dam levels were accurate. No dangerous scenarios occurred as dam levels were within normal operational limits (between 25% and 90%).

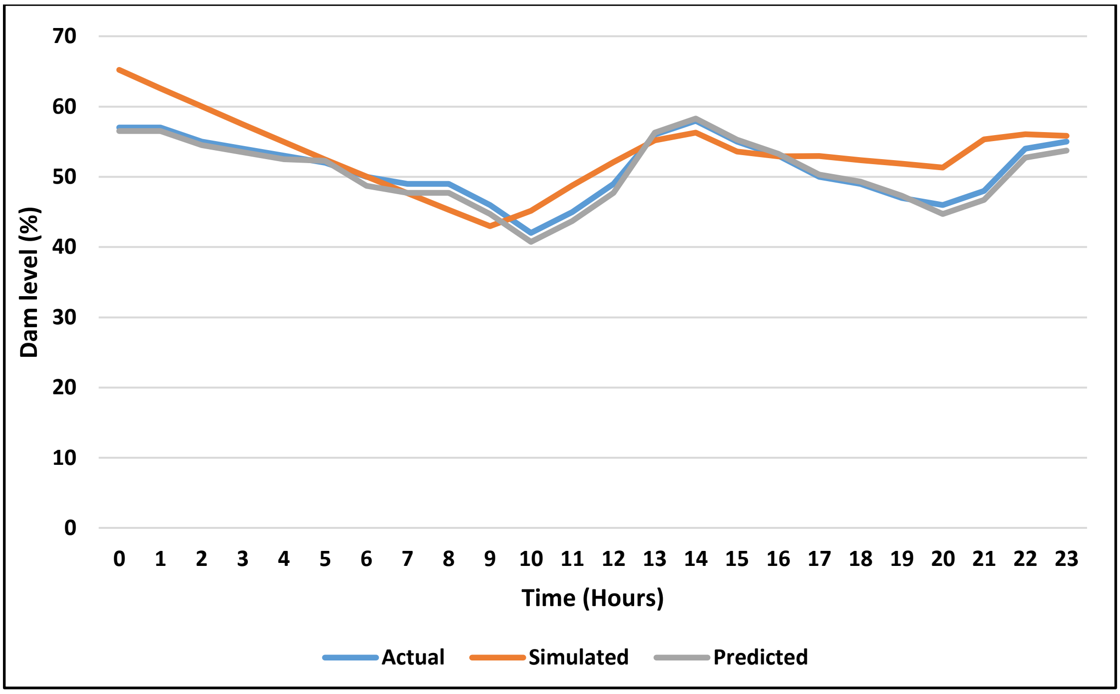


Figure 61: BAC sump level for Strategy 9

Figure 62 shows the actual and simulated BAC outlet temperatures for the period during which Strategy 9 was implemented.

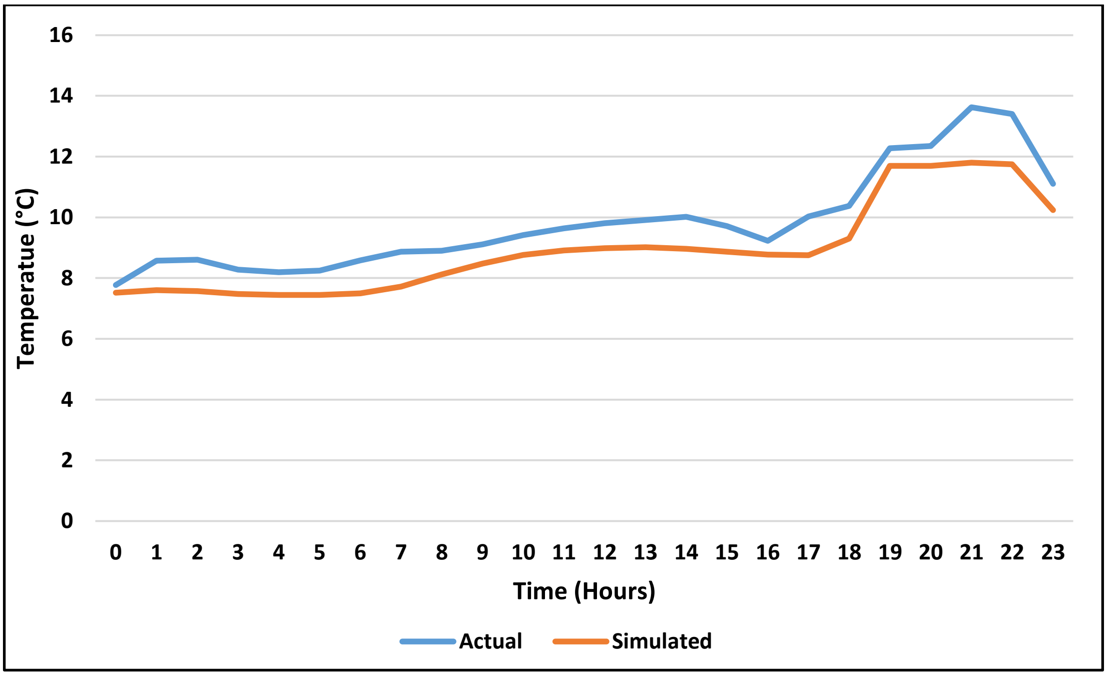


Figure 62: BAC outlet air temperature for Strategy 9

When evaluating the actual and simulated temperature profiles for Strategy 9, it can be seen that the two profiles follow the same path and compare well with one another with an average percentage error of 9.17%. The maximum BAC outlet temperature in the period that mining personnel were underground was 10°C. This limit was reached at 14:00 when there was an attempt to lower the BAC outlet temperature by starting one additional BAC return pump and one additional BAC feed pump. An increase in cold water was used in the BAC, which reduced the outlet air temperature. This can be seen in Figure 62 as the BAC outlet temperature at 15:00 is lower than the temperature at 14:00.

When a limit is reached, actions are put in place to ensure dangerous situations are managed and reduced immediately. No dangerous scenarios were experienced underground in the drilling period (from 07:00 to 14:00). Although the BAC outlet temperature increased from 18:00, this was not a concern as it occurred during the no-entry period when no mining personnel were allowed in underground working areas.

Figure 61 and Figure 62 show the accuracy of the simulation results. The potential electricity cost savings could therefore be simulated. Figure 63 shows the baseline and average actual power profiles for the period during which Strategy 9 was implemented.

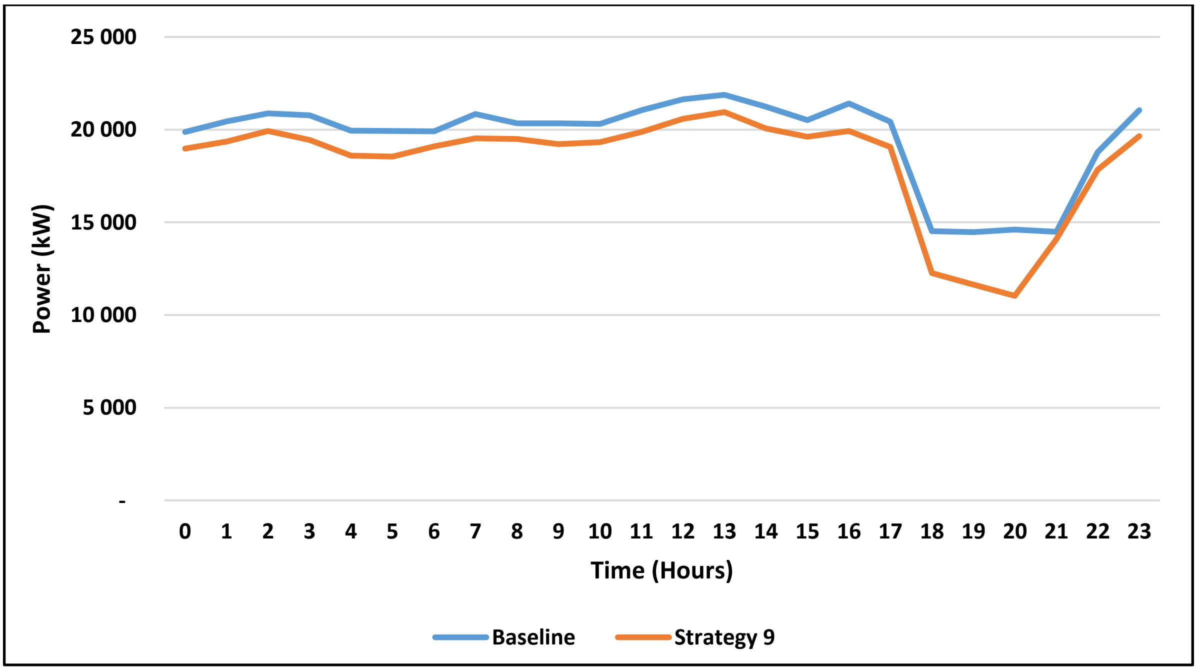


Figure 63: Power profiles for Strategy 9

Figure 63 shows that in spite of the failures, load demand shifting was achieved through the control strategy. As more BACs failed, a reduction in load demand shifting was achieved within the Eskom evening peak. The load demand shifting achieved for the period during which Strategy 9 was implemented equated to 2.54 MW. This validates the use of Strategy 9 in case of two BAC failures as load demand shifting was safely achieved. In the scenario where all BACs fail, little can be done to ensure underground temperatures will remain within temperature limits to ensure safe underground working conditions.

**Strategy 10: PCT failure**

The final strategy was developed for the scenario where a PCT fails. This failure is very unlikely as there are three PCTs, but only one is required constantly. Therefore, two PCTs have to fail before this strategy will be needed for cases where a second PCT is required. It was deemed necessary to illustrate the section of the refrigeration system where the failures occurred. Figure 64 shows the location of the failures (shown by the red block), where Strategy 10 would be required.

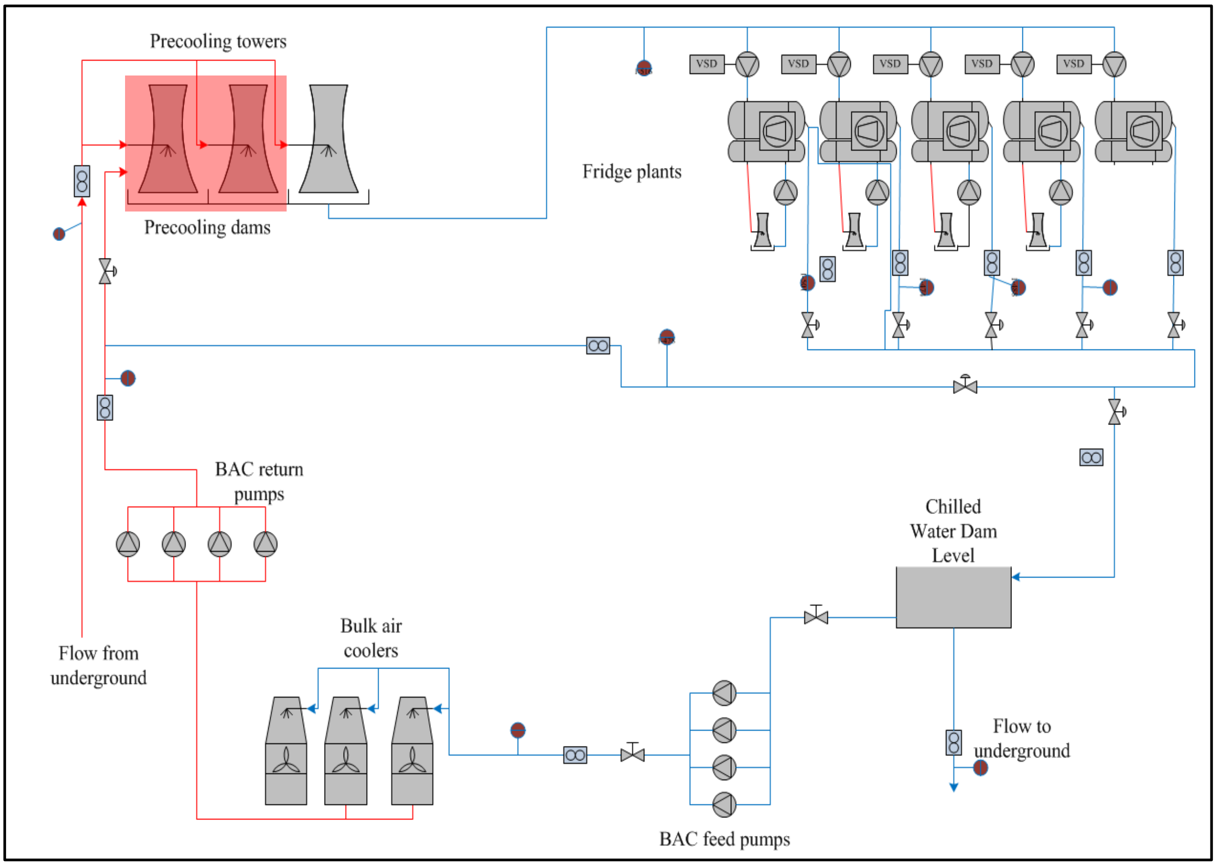


Figure 64: Strategy 10 failures

Safety will be discussed first. For this failure, dam levels and temperatures will be discussed. The PCD levels will be discussed and an average value will be used as these dams are linked.

The location of these dams were between the PCTs and fridge plants. If the PCDs were empty, less water would be available for fridge plants to cool. Figure 65 shows the dam level profiles for Strategy 10. These profiles include the actual, simulated and predicted dam levels for the period during which Strategy 10 was implemented.

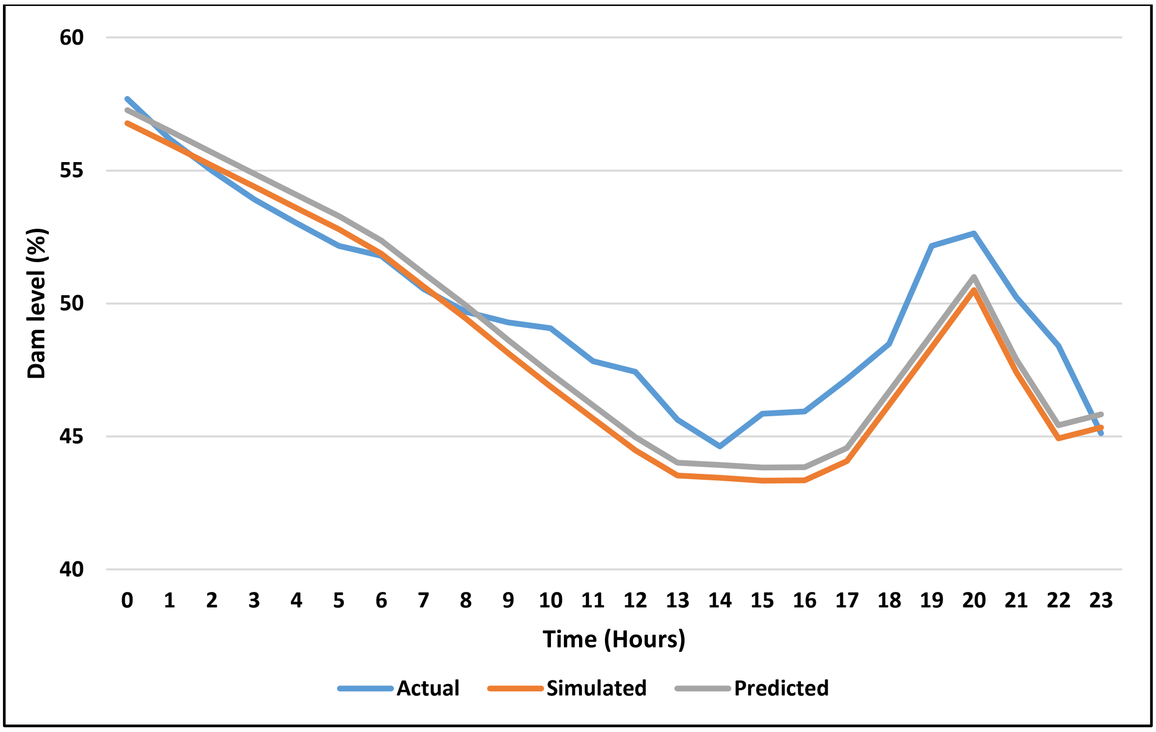


Figure 65: PCD profiles for Strategy 10

Figure 65 shows that the dam level decreased significantly in the drilling period (07:00 to 14:00) although it recovered in the evening (from 17:00). This recovery corresponds with the period when fridge plants were stopped in the Eskom evening peak. Fortunately, this failure did not occur for more than a day. If PCTs fail for more than a day, there is a possibility that the PCD might empty. In this scenario, water from underground would be pumped directly into the PCD.

Figure 66 shows the temperature profiles for the period during which Strategy 10 was implemented. The guideline value used on this case study for PCT outlet temperature was 20°C, which was set by mining personnel. The actual maximum temperature reached 17°C. The temperature profile was therefore within acceptable limits and no dangerous situation regarding the temperature was observed.

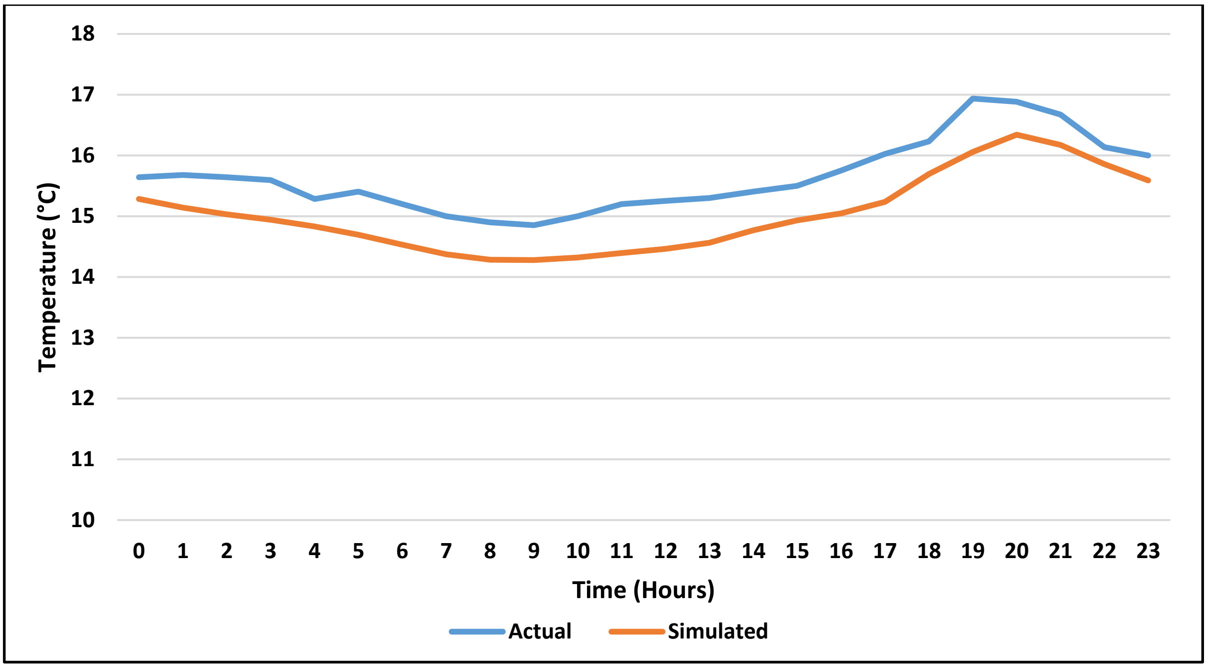


Figure 66: PCD temperature profiles for Strategy 10

Figure 67 shows the baseline and actual power profiles for the period during which Strategy 10 was implemented. Load demand shifting of 4.14 MW was achieved after implementation. This was achieved on the entire water reticulation system, which is the combined load demand shifting achieved from all water reticulation systems (dewatering, fridge plant, BAC and PCT systems).

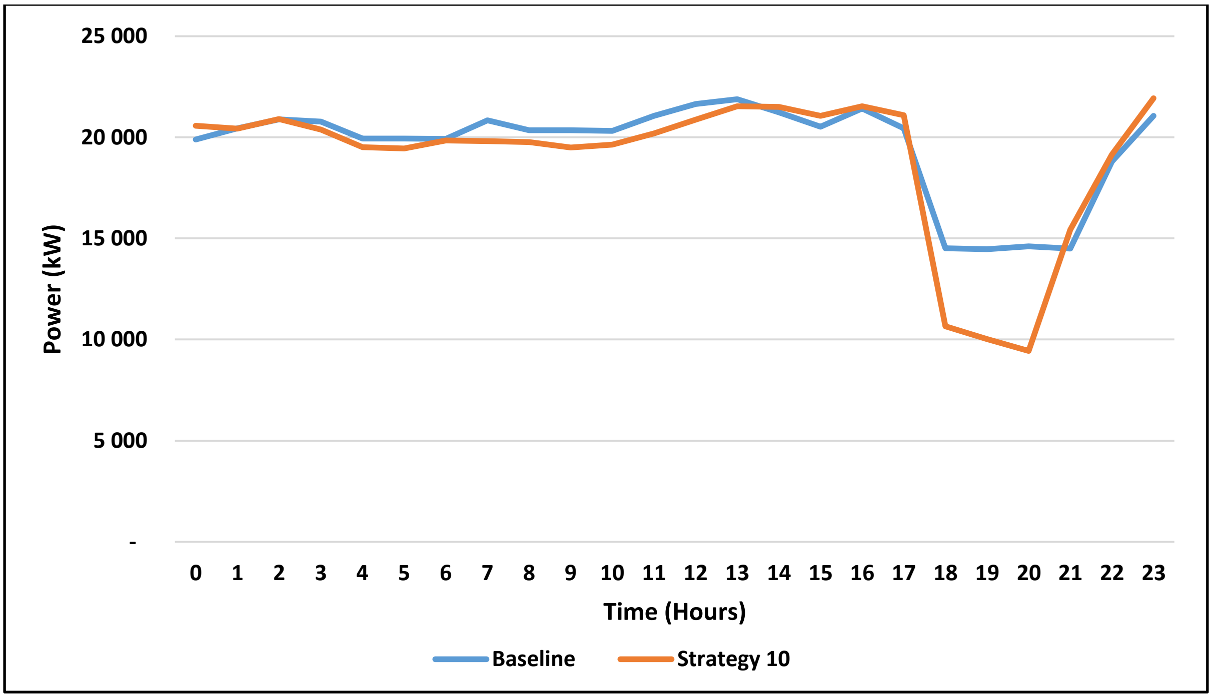


Figure 67: Power profiles for Strategy 10

From the comprehensive discussion in the previous paragraphs, it was observed that significant load demand shifting was achieved for all tested control strategies. Safety was also discussed for all control strategies. It can be concluded that load demand shifting was achieved safely using the implemented control strategies; therefore, all tested strategies were validated successfully. The untested control strategies were not needed for the one-year testing period. The likelihood of these types of failure are very low, although control strategies are required, which were simulated.

Various control strategies were developed for this case study, which completes the once-off section of the failure process. The next step, as discussed in the methodology (Section 2.5), is the continuous section of the failure process that should be implemented.

### 3.4.3 Failure process – continuous section

Figure 68 shows the continuous section of the failure process, which was discussed in Section 2.5, Figure 18. The purpose of this process is to select a control strategy for a failure. This selection should take the possible real-time variables that might exist into account.

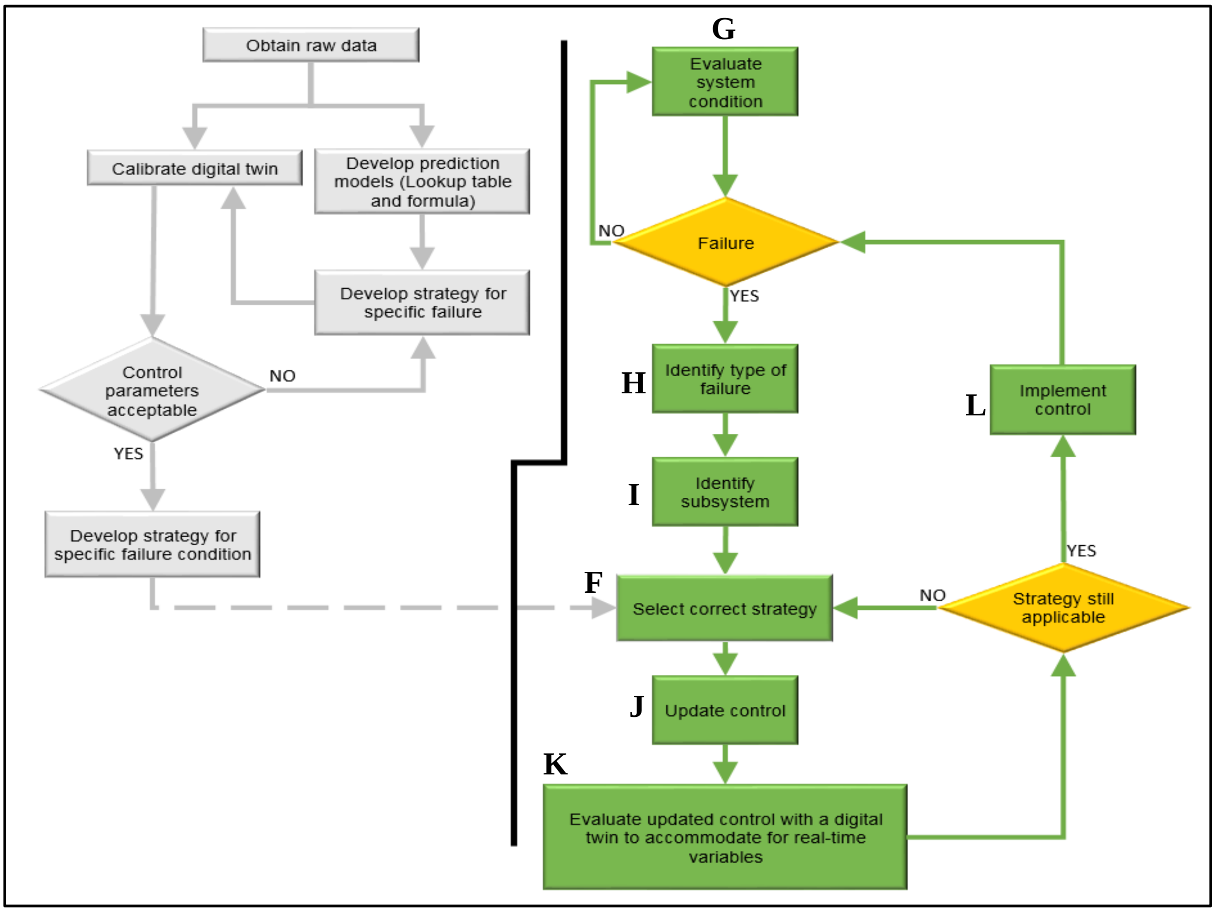


Figure 68: Failure process – continuous section recap

The purpose of the recap is to show the methodology of the process required to be implemented on a mine water reticulation system. The methodology consists of the continuous section of the failure process. When all control strategies have been developed, they will be available in Step F. Step G is used to evaluate the water reticulation system's condition, which identifies a failure as soon as it occurs. Step H determines the type of failure, which also identifies the subsystem (Step I).

In Step J, an improved control strategy for a given scenario is selected. The adjustments corresponding to the control strategy and failure will be implemented into the digital twin to evaluate if this strategy is still applicable in Step K. There is a scenario where the control strategy will not by a viable option as real-time variables will be taken into account. When the selected control strategy is acceptable for a given scenario, it can be implemented as illustrated by Step L. This implementation refers to the actual implementation on a water reticulation system.

When the continuous process was implemented on the case study, it was seen that the frequency of some failures was higher than other failures. It was deemed necessary to provide more information regarding the occurrence of all control strategies (as per Section 3.4.4).

### 3.4.4 Occurrence of failures

The previous section (Section 3.4.3) discussed the selection of control strategies. It was deemed necessary to calculate the probability of each failure as the frequencies of failures differ. The probability was also used to calculate the approximate electricity cost savings in the event that failures did occur. Table 18 shows the percentage occurrence of each failure for the testing period of one year (the year 2017).

Table 18: Percentage occurrence per strategy

| Strategy | Occurrence (%) |
|---|---|
| **1** | 2.19 |
| **2** | 10.14 |
| **3** | 0.27 |
| **4** | 10.68 |
| **5** | 0.27 |
| **6** | 16.74 |

| Strategy | Occurrence (%) |
|---|---|
| **7** | 2.24 |
| **8** | 16.16 |
| **9** | 39.72 |
| **10** | 3.87 |

It was estimated that the probability of each untested strategy being used was 0.27%, which equated to once a year. The total percentage occurrence was higher than 100%. It should be noted that different water reticulation group failures could occur simultaneously. This does not affect the system's control as each water reticulation group control strategy was developed to have limited to no effect on the other water reticulation groups.

Table 19 indicates the load demand shifting achieved per control strategy in the Eskom evening peak period. Most of the strategies have been tested and actual load demand shifting will be used in further calculations. Simulated load demand shifting will be used for the remaining untested strategies.

Table 19: Load demand shifting achieved

| Strategy | Load Demand Shifting (MW) | Date of Failure | Actual/Simulated |
|---|---|---|---|
| **1** | 3.26 | 2018-06-12 | Actual |
| **2** | 2.99 | 2018-01-22 | Actual |
| **3** | 1.98 | N/A | Simulated |
| **4** | 2.05 | 2018-03-15 | Actual |
| **5** | 3.34 | N/A | Simulated |
| **6** | 4.07 | 2018-04-23 | Actual |
| **7** | 3.64 | 2018-09-25 | Actual |
| **8** | 3.16 | 2018-10-03 | Actual |
| **9** | 2.54 | 2018-01-10 | Actual |
| **10** | 4.14 | 2018-03-28 | Actual |

The Load Demand Shifting column (Column 2) of Table 19 shows the actual or simulated load demand shifting achieved in the Eskom evening peak period. The actual load demand achieved was for a specific day the applicable failure took place. The third column shows the date each of these strategies were tested.

The Actual/Simulated column shows whether the load demand shifting was simulated or actual. It can be seen that Strategy 3 and Strategy 5 were the only control strategies that were not implemented as these failures did not occur in the testing period of one year. Table 20 shows the estimated daily and annual electricity cost savings calculated per control strategy. The daily electricity cost savings was calculated using Equation 9.

$$\text{Cost savings} = \text{Tariff} \times \text{power profile} \times \text{occurrence}$$

Equation 9: Daily cost savings

An estimated 260 working weekdays were used to calculate the annual electricity cost savings. The calculations used the 2018/19 Eskom tariffs [75]. Power profiles were used to calculate the electricity cost savings for a period of 24 hours. The daily electricity cost savings along with the annual electricity savings are depicted in Table 20.

Table 20: Cost savings

| Strategy | Daily cost savings (R) | Annual cost savings (R) |
|---|---|---|
| **1** | 342.30 | 88 998 |
| **2** | 1 453.63 | 377 943 |
| **3** | 26.01 | 6 762 |
| **4** | 1 049.71 | 272 924 |
| **5** | 41.38 | 10 758 |
| **6** | 3 266.58 | 849 311 |
| **7** | 390.92 | 101 640 |
| **8** | 2 448.34 | 636 568 |
| **9** | 4 837.11 | 1 257 650 |
| **10** | 768.17 | 199 723 |
| **Total** | **14 624.14** | **3 802 276** |

An estimated annual electricity cost saving of R3.8 million was realised after implementing these failure processes on this case study. It should be noted that this cost saving was achieved specifically when failures occurred, thus the total electricity cost savings included current initiatives as well. It was noted that most of the electricity cost savings were realised using Strategy 9.

This was not expected as fridge plants and dewatering pumps have higher power consumption than BACs. BAC control strategies had high electricity cost savings due to the high percentage occurrence of these failures. Strategy 8 and Strategy 9 were developed specifically for BAC failures.

The savings achieved when a failure occurs are not limited to the subsection. The savings achieved are calculated on the entire water reticulation system. The percentage occurrences of BAC failures were higher than expected; thus, the total electricity cost savings on the entire water reticulation system when a BAC failure occurred were higher than expected.

These processes can be implemented without requiring funds for implementation; therefore, no initial capital expenses were required. Each control strategy was validated, which showed that load demand shifting could be achieved safely. The processes developed in this study could possibly be implemented in other industries to mitigate similar problems.

## 3.5 Conclusion

Chapter 3 discussed the validation of the models developed in Chapter 2. A digital twin for the mine water reticulation system was verified using power consumption and BAC outlet air temperatures.

The method for developing a control strategy was discussed using a relevant case study. The integration between a digital twin and the actual load demand shifting achieved combined with safety were also discussed for each control strategy. Section 3.4.2 discussed each strategy, which included actual and simulated (critical component failure and selected strategy implemented within the digital twin) results. Therefore, each uniquely developed strategy's results were discussed, which showed that the first half of contribution one and contribution two were achieved.

Section 3.4.3 was used to discuss the continuance section of the process developed in Chapter 2 (Section 2.4 and Section 2.5). This section discussed the method of selecting a control strategy. Section 3.4.4 was used to discuss the occurrence of failures and the effect of each selected and implemented strategy. These sections (Section 3.4.2 and Section 3.4.4) were deemed necessary as the goal of this study was to safely achieve load demand shifting should a critical component fail. All tested control strategies were validated with actual data.

The result of each simulated strategy was discussed along with the possible effect of the failure should no strategy be implemented. The probability of each control strategy was combined with possible annual electricity cost savings. It was calculated that an approximate R3.8 million annual electrical cost savings could be achieved by implementing these control strategies. It was found that most of the electricity costs savings were realised with the implementation of the control strategies developed for BACs. The reason is the high number of failures compared with other water reticulation systems.

Load management control strategies were developed, which achieved load demand shifting safely in spite of critical component failures. A process was developed to identify an ideal load management control strategy for when known failures occur.

A digital twin was also used to identify and verify possible load demand shifting with acceptable risks associated when critical component failures occur. This proves the use of the novel contributions mentioned in Chapter 1. This study could possibly be implemented in other industries as well where there are similar problems regarding critical component failures.

# Chapter 4: Conclusion and recommendations

*"Scientists study the world as it is, engineers create the world that never has been."*

**Theodore von Karmen**

## 4.1 Preamble

This study was conducted to develop processes that can be implemented to achieve load demand shifting in spite of critical component failures. The reason for the study was stated in Chapter 1 along with the aims, objectives and novel contributions. A literature study was also conducted in Chapter 1, which gave a broad overview of previous studies on mine water reticulation systems. Chapter 2 provided the methodology where after the developed processes were validated in Chapter 3 with a relevant case study.

Chapter 4 is the concluding chapter of the document. This chapter will therefore provide the various findings of the study. Conclusions regarding each chapter will be provided first followed by a discussion of the novel contributions as well as recommendations for further studies. The document is then essentially closed with a final conclusion.

## 4.2 Conclusions

Chapter 1 mentioned that the mining industry in South Africa is a harsh environment for mining personnel and equipment. This environment leads to critical component failures. These failures leads to neglect in load management control, which reduces safety and achievable load demand shifting on mines. An extensive literature review was conducted to prove the need of this study. The literature study led to the problem statement, which led to the objectives of this study:

- Sustain achievable electricity cost savings despite component failures.
- Implement control strategies without incurring additional risk.
- Develop a simulation model to determine the effect that critical component failures have on safety and electricity cost savings.

These objectives were followed by two novel contributions to address the objectives. Novel contributions were mentioned in Chapter 1, which were keys to solving the problem stated in Section 1.5. The following section will be used to evaluate whether each novel contribution was implemented successfully in this study. Each novel contribution is stated in a block, similar to the discussion in Section 1.6.

**1. Develop a process to create and select unique water reticulation control strategies to sustain electricity cost savings when a failure occurs**

Section 2.4 discussed a process for developing unique water reticulation control strategies. Control strategies were developed per water reticulation group (dewatering, fridge plant, BAC and PCT). One control strategy was discussed in Section 3.3, with the remaining control strategies discussed in Appendix D. Each control strategy was validated in Section 3.4.2.

Section 3.4.2 provided results of all implemented strategies. This section included validating each strategy, which included dam levels, water temperatures and savings obtained. This section showed that each implemented strategy obtained savings while maintaining safe operating conditions for mining personnel and equipment.

Section 2.5 discussed the process to determine the ideal control strategy. A process was developed per water reticulation group to identify the ideal control strategy for a given scenario. The water reticulation selection process to identify the ideal control strategy for a given scenario was also discussed in Section 2.5. The remaining selection processes were discussed in Appendix B. It should be noted that these processes are similar with the main difference being the selection of different control strategies.

Section 3.4.4 provided information on the percentage occurrence each strategy would be required the previous year. This was followed by actual load demand shift savings achieved for all tested control strategies and the actual date each of these strategies was tested.

**2. Application of digital twin methodology to implement improved control processes when failures occur**

Section 2.2 discussed a digital twin, which included the modification of this simulation. This modification included the implementation of unique control strategies on the digital twin. This was tested on each control strategy and was discussed in Section 3.4.2.

The preceding discussion of each novel contribution provided proof that each contribution stated in Section 1.6 was successfully implemented in this study. The methodology of this study can be duplicated in other industries where the failure of critical components can lead to hazardous scenarios and a decrease in load demand shifting. In the case where critical component failures lead to production loss, similar principles can be used to mitigate the effect of failures.

This was followed by the methodology of this study, which was to develop processes for identifying and developing control strategies for a water reticulation system – specifically when critical component failures occur. In the development of the methodology, two prediction models (dam level prediction model and load demand prediction model) were discussed. A simplified example was also included in Chapter 2 for the load demand prediction model, which was done to convey the method of developing this model.

Chapter 3 discussed the results of this study. Most control strategies were validated using actual data. Safety and load demand shifting were discussed per control strategy. The remaining control strategies were simulated with a digital twin. It was seen that load demand shifting was possible in the case of water reticulation component failures.

A significant increase in load demand was shifted after implementing these processes and control strategies. When translating the load demand shifting into financial savings, an annual electricity cost saving of R3.8 million was estimated for this case study. This electricity cost saving is only applicable in cases where there are critical component failures. It was found that BAC failures occurred significantly more than other water reticulation system failures, which led to the most electricity cost savings being achieved by implementing all developed processes and control strategies.

The results of this study included an example of developing a control strategy, which covered both the dam level and load demand prediction models. After this example, the digital twin used in the study was verified, which was seen as an important step as the effects of all control strategies were simulated.

The next step of this study was to validate all control strategies. Most control strategies were validated by using actual results. The remaining strategies could not be validated with actual results as these specific failures did not occur during the testing period of one year. These control strategies were, however, validated using the digital twin. The selection process was the final implemented process, which was used to select an ideal control strategy for failure conditions for the one-year period.

During this study, opportunities were identified to improve the control in the mining industry. These opportunities were not investigated further as they did not form part of this study. These opportunities are discussed in Section 4.3, which can be used for future work.

## 4.3 Recommendations for future work

During this study, various possible improvements were identified. These improvements were not investigated as they did not form part of the study's focus. However, these improvements can be investigated in future studies.

An addition to this study would be to **investigate the effect that water reticulation component failures has on production**. This investigation should focus on achieving the production target in the event of failures. Safety should also be considered when investigating this study further.

Another study could focus on **condition monitoring of each water reticulation system**. It could be valuable to reduce the number of failures in water reticulation systems. When the number of failures is reduced, electricity cost savings could increase and also maintain the safety of underground mining personnel. This study can also focus on improving service delivery if fewer failures occur.

Lastly, investigations can be done on **other types of failure in water reticulation systems**. These failures can include water pipe bursts, water column breaks, pressure reduction valves etc. Similar processes should be developed as discussed in this study.

## 4.4 Closure

This study introduced new control strategies and processes that could be followed to obtain achievable demand load shifting in the event of critical component failures in deep level gold mines. This study showed that failures are a common occurrence in the mining industry. These failures reduce possible demand load shifting, which has a direct influence on the amount of electricity cost savings. Processes and control strategies were developed to mitigate electricity cost saving losses. The results revealed that by implementing the developed processes and control strategies, an additional electricity cost saving of R3.8 million can be achieved.

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# Appendix A: Prediction models

Table 21 shows an example of a daily pump matrix. This represents the total running hours for a dewatering system. The average hourly values were rounded up to the nearest number. This example only shows a seven-day period as limited space is required to explain this step. The three different time periods are shown using different colours. The green block represents the total pump running hours from 00:00 to 17:59. The blue block represents the total pump running hours from 18:00 to 19:59. The pink block represents the total pump running hours from 20:00 to 23:59.

Table 21: Daily pump matrices

| | Days | | | | | | |
|---|---|---|---|---|---|---|---|
| **Hours** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| **0** | 5 | 3 | 3 | 3 | 4 | 3 | 4 |
| **1** | 5 | 2 | 3 | 3 | 5 | 4 | 2 |
| **2** | 3 | 3 | 2 | 3 | 5 | 3 | 2 |
| **3** | 3 | 2 | 2 | 2 | 4 | 1 | 3 |
| **4** | 2 | 2 | 1 | 2 | 2 | 1 | 2 |
| **5** | 2 | 3 | 1 | 2 | 3 | 4 | 2 |
| **6** | 2 | 3 | 2 | 2 | 3 | 5 | 2 |
| **7** | 1 | 1 | 0 | 0 | 1 | 3 | 0 |
| **8** | 0 | 1 | 0 | 0 | 2 | 2 | 0 |
| **9** | 0 | 1 | 0 | 0 | 2 | 4 | 3 |
| **10** | 3 | 2 | 2 | 3 | 3 | 2 | 3 |
| **11** | 3 | 3 | 3 | 3 | 3 | 2 | 3 |
| **12** | 3 | 3 | 3 | 3 | 3 | 3 | 2 |
| **13** | 4 | 3 | 4 | 4 | 2 | 2 | 3 |
| **14** | 3 | 1 | 4 | 4 | 1 | 3 | 4 |
| **15** | 2 | 1 | 3 | 3 | 3 | 2 | 3 |
| **16** | 2 | 2 | 3 | 2 | 2 | 2 | 3 |
| **17** | 2 | 3 | 0 | 2 | 0 | 3 | 2 |
| **18** | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| **19** | 0 | 0 | 0 | 0 | 1 | 2 | 0 |
| **20** | 0 | 1 | 1 | 0 | 2 | 2 | 2 |
| **21** | 0 | 4 | 2 | 3 | 4 | 3 | 3 |
| **22** | 3 | 4 | 2 | 3 | 4 | 2 | 2 |
| **23** | 3 | 5 | 2 | 4 | 3 | 2 | 2 |

Table 22 shows the parameters calculated using Table 21. Parameter *x* in Table 22 is the total running hours of the green block taken from Table 21. Parameter *y* in Table 22 is the total running hours of the blue block taken from Table 21. Parameter *z* in Table 22 is the total running hours of the pink block taken from Table 21.

Table 22: Parameter matrices

| | **Days** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Parameters** | **1** | **2** | **3** | **4** | **5** | **6** | **7** |
| **x** | 45 | 39 | 36 | 41 | 48 | 49 | 43 |
| **y** | 0 | 0 | 0 | 0 | 1 | 3 | 0 |
| **z** | 6 | 14 | 7 | 10 | 13 | 9 | 9 |

Table 22 shows the average values for three time periods. This table was used to create three formulas including the three constants, shown in Equation 1. Table 23 shows the calculated values for the three parameters. The load demand shifting values were calculated with actual data for each time period. This is the actual load demand shifting achieved using historical data.

Table 23: Formula creation

| | **Load demand shifting** | ***x*** | ***y*** | ***z*** |
|---|---|---|---|---|
| **Time period 1** | 1.44 | 49.92 | 1.62 | 10.77 |
| **Time period 2** | 1.83 | 60.15 | 3.62 | 14.15 |
| **Time period 3** | 1.65 | 50.56 | 1.78 | 12.33 |

Equation 10, Equation 11 and Equation 12 are the preliminary equations derived from Table 23. Each time period was used to develop a preliminary formula.

$$1.44 = 49.92x + 1.62y + 10.77z$$

Equation 10: Preliminary Equation 1

$$1.83 = 60.15x + 3.62y + 14.15z$$

Equation 11: Preliminary Equation 2

$$1.65 = 50.56x + 1.78y + 12.33z$$

Equation 12: Preliminary Equation 3

# Appendix B: Selection processes

## Fridge plant

Figure 69 shows the selection process when a fridge plant fails.

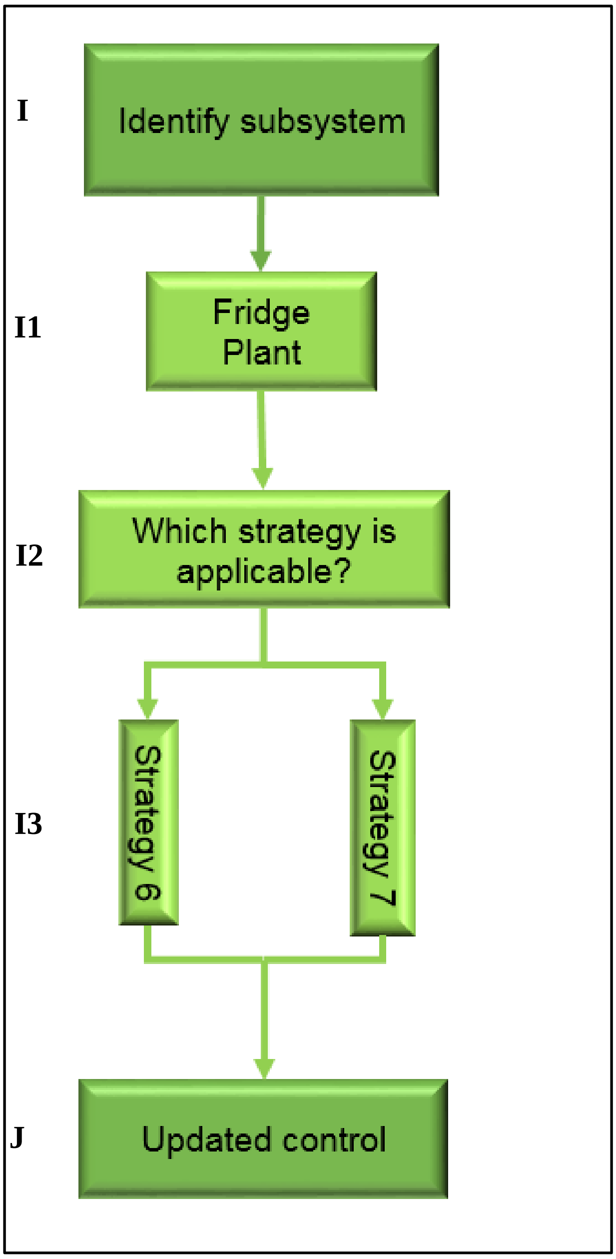


Figure 69: Fridge plant selection process

**Bulk air cooler**

Figure 70 shows the selection process when a BAC fails.

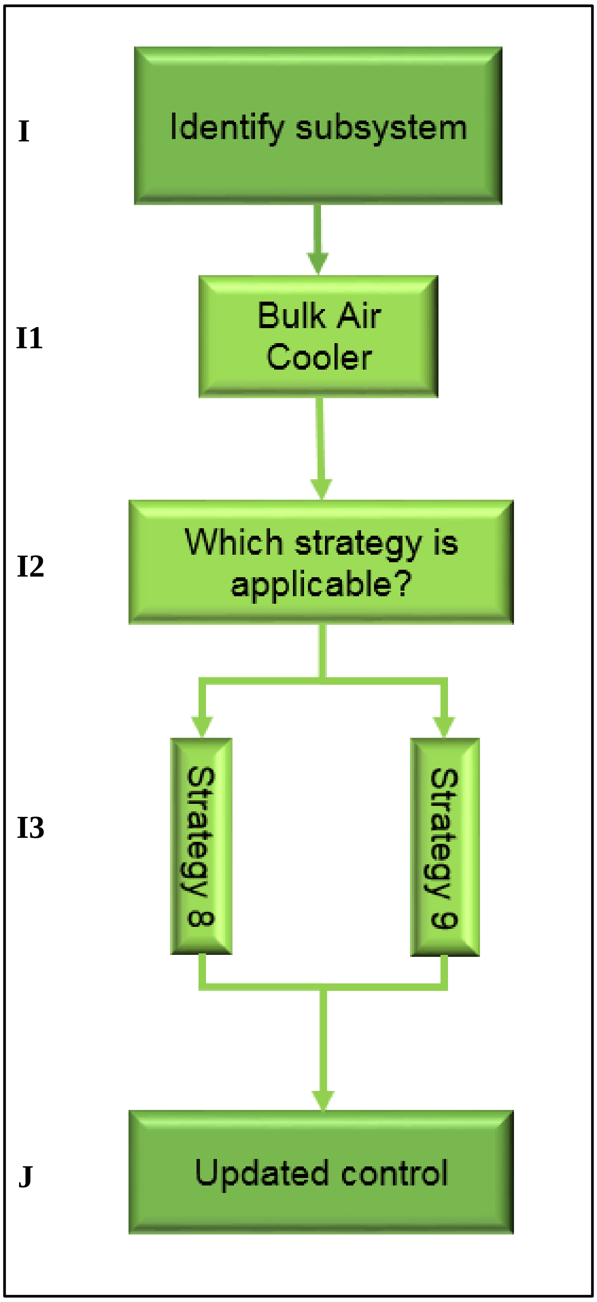


Figure 70: BAC selection process

**Precooling tower**

Figure 71 shows the selection process when a PCT fails.

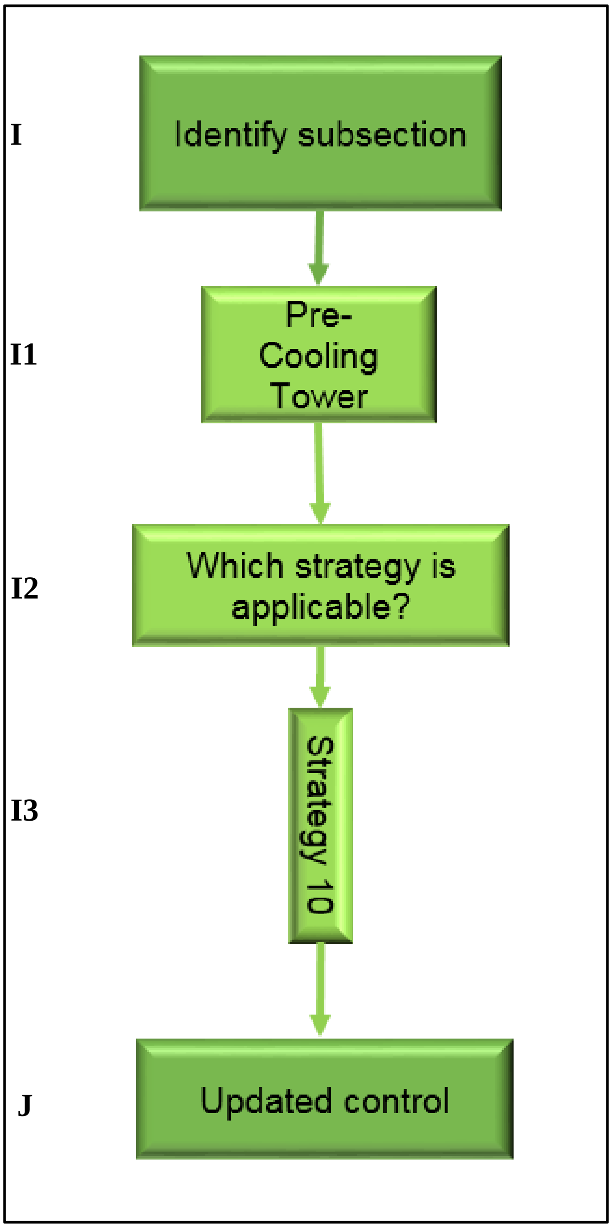


Figure 71: PCT selection process

The use of each selection process (Figure 69, Figure 70 and Figure 71) was discussed in Section 2.5. The same process should be followed as discussed for Figure 19 in Section 2.5.

# Appendix C: Prediction calculations

Equation 13, Equation 14, Equation 15 and Equation 16 represent the remaining preliminary equations developed for the load demand prediction formula required for the dewatering group. This was discussed in Section 3.3.2.

$$1.40 = 54.18x + 3.32y + 13.23z + 20.68w + 67.41v$$

Equation 13: Preliminary Formula 2 for Strategy 1

$$-0.45 = 49.40x + 3.85y + 10.90z + 20.15w + 60.30v$$

Equation 14: Preliminary Formula 3 for Strategy 1

$$0.74 = 51.44x + 3.11y + 11.80z + 20.89w + 63.40v$$

Equation 15: Preliminary Formula 4 for Strategy 1

$$0.92 = 53.07x + 3.11y + 11.93z + 20.90w + 65.17v$$

Equation 16: Preliminary Formula 5 for Strategy 1

Table 24 shows the matrix developed using Equation 13–Equation 16. This matrix should be solved to determine the constants for each parameter. The formula created by doing so is shown in Chapter 4, Equation 8.

Table 24: Formula creation for the dewatering savings formula

| | **Savings** | ***x*** | ***y*** | ***z*** | ***w*** | ***v*** |
|---|---|---|---|---|---|---|
| **Time period 1** | 1.44 | 49.92 | 1.62 | 10.77 | 22.38 | 60.67 |
| **Time period 2** | 1.40 | 58.18 | 3.32 | 13.23 | 20.68 | 67.41 |
| **Time period 3** | −0.45 | 49.4 | 3.85 | 10.9 | 20.15 | 60.3 |
| **Time period 4** | 0.74 | 51.44 | 3.11 | 11.8 | 20.89 | 63.4 |
| **Time period 5** | 0.92 | 53.07 | 3.11 | 11.93 | 20.9 | 65.17 |

# Appendix D: Control strategies

Table 25 shows the strategy number for each possible failed water reticulation component (dewatering, fridge plant, BAC and PCT). The pumps on Pumping Level 1 only have one possible failure because a second pump was not used for a period of one year. This is possible due to the 3CPFS on Pumping Level 1 and because few operations are done above this pumping level.

Table 25: Strategy numbering

| **Strategies** | **Dewatering** | | | **Fridge Plant** | **BAC** | **PCT** |
|---|---|---|---|---|---|---|
| | **Pumping Level 1 Pump** | **Pumping Level 2 Pump** | **Pumping Level 3 Pump** | | | |
| **1** | 1 | | | | | |
| **2** | | 1 | | | | |
| **3** | | 2 | | | | |
| **4** | | | 1 | | | |
| **5** | | | 2 | | | |
| **6** | | | | 1 | | |
| **7** | | | | 2 | | |
| **8** | | | | | 1 | |
| **9** | | | | | 2 | |
| **10** | | | | | | 1 |

**Dewatering system**

The prediction models developed for the dewatering system were used for all dewatering related strategies. These models were developed per water reticulation group. The percentage occurrence of dewatering strategies in a year was 25.2%. Strategy 1 was discussed in Section 3.3. The remaining control strategies for the dewatering system (Strategy 2–Strategy 5) will be discussed in the subsections that follow.

## Strategy 2: Dewatering pump failure on Pumping Level 2

Figure 72 shows the actual dam level and the predicted dam level for the Pumping Level 2 hot dam for a five-day period. This prediction model was considered accurate as the average percentage error over the five-day period was 0.16%. The load demand prediction model developed in Section 2.3.2 was used for the dewatering system. Only one load demand prediction model was required per water reticulation group.

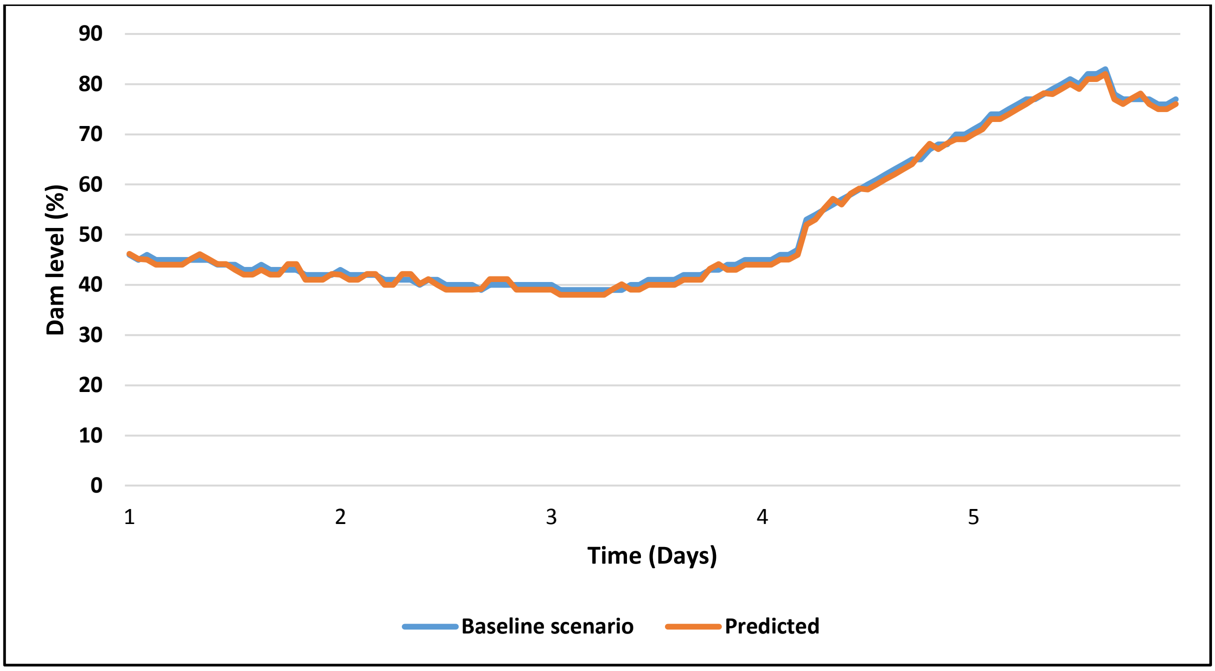


Figure 72: Dam level prediction model comparison for Pumping Level 2 hot dam

Figure 73 compares the actual dam levels with the predicted dam levels in the case of one Pumping Level 2 dewatering pump failing. The predicted dam level in case of a failure was based on no attempt to avoid flooding the Pumping Level 2 hot dam. In this prediction, it is clear that a strategy would be required if one Pumping Level 2 dewatering pump has failed as it could lead to flooding of the Pumping Level 2 hot dam.

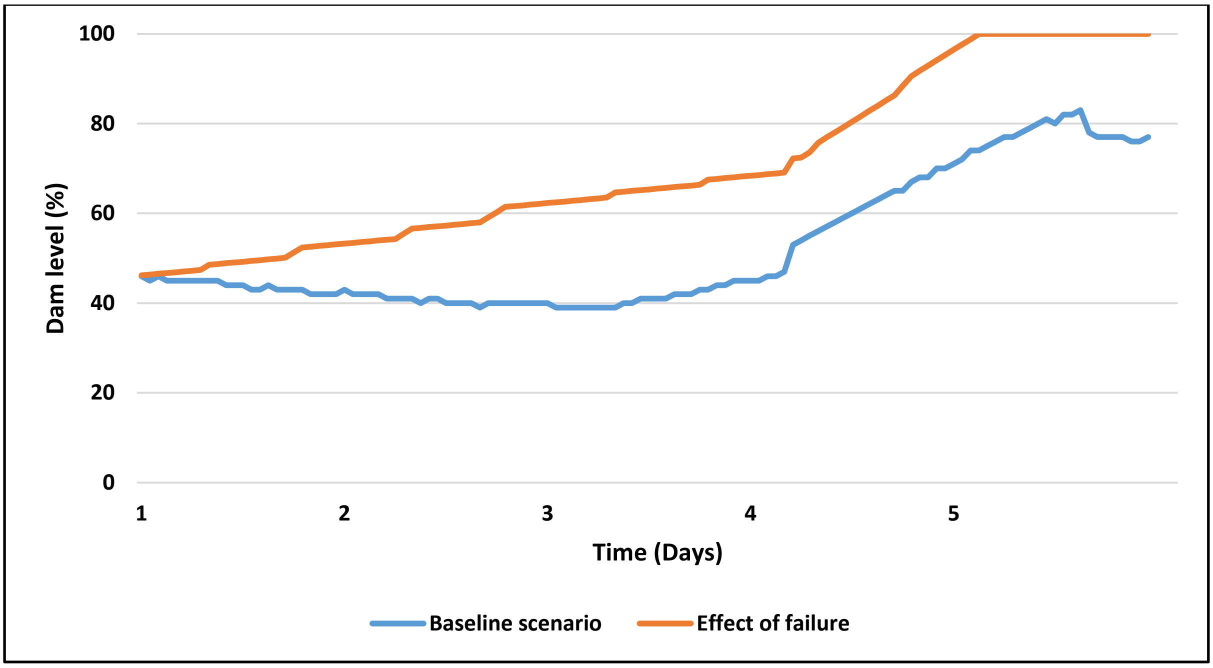


Figure 73: Effect of failure Strategy 2

Table 26 shows the control adjustments for Strategy 2. These adjustments will be discussed in the following points:

Table 26: Control adjustment for Strategy 2

| Number | Control adjustment |
|---|---|
| I | Increase 3CPFS set points on Pumping Level 2 to high. |
| II | Change 3CPFS set points on Pumping Level 1 to low or medium depending on the level of Pumping Level 1's hot dam. |
| III | Stop dewatering pumps on Pumping Level 3 depending on the level of Pumping Level 2's hot dam. |

Number I:

- Maximise both 3CPFS set points on Pumping Level 2. The level of Pumping Level 2's hot dam will decrease due to this adjustment.
- If Pumping Level 2's hot dam level is lower than 40%, change both set points to medium.
- If Pumping Level 2's hot dam level is lower than 30%, change both 3CPFS set points to low.

Number II:

- Change both 3CPFS set points on Pumping Level 1 to medium or high. This setting is dependent on Pumping Level 1's hot dam level.
- If the dam level is above 85%, change the set point to high.
- If the dam level is below 85%, change the set point to medium. Pumping Level 1's hot dam level should be as low as possible to ensure that the 3CPFS set points on Pumping Level 2 remain on high until the dam level is low.

Number III:

- Adjust the Pumping Level 3 dewatering pump control according to the level of Pumping Level 2's hot dam.
- If the level of Pumping Level 2's hot dam is above 75%, stop one of Pumping Level 3's dewatering pumps.
- When the level of Pumping Level 2's hot dam is above 85%, stop the other dewatering pump on Pumping Level 3.

### Strategy 3: Second dewatering pump failure on Pumping Level 2

Strategy 3 was developed should two dewatering pumps failing on Pumping Level 2. Figure 74 simulates the effect that this scenario would have and compares it with the actual dam level. It should be noted that the effect on the dam level was predicted with no attempt being made to mitigate the problem.

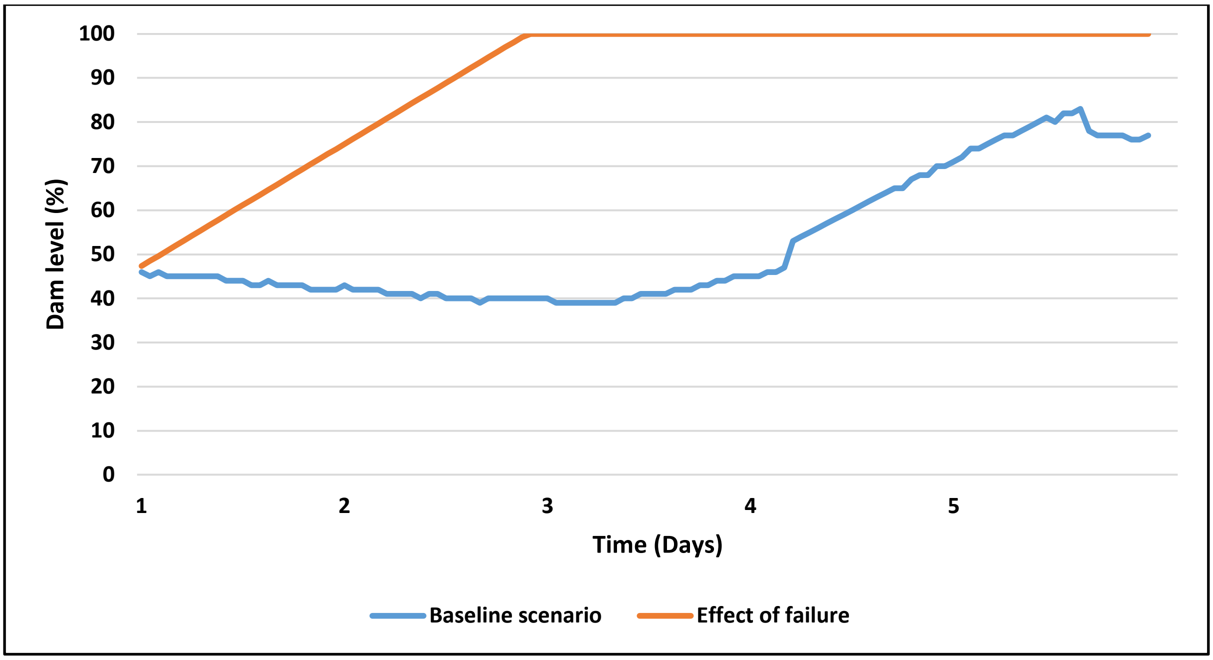


Figure 74: Effect of failure Strategy 3

Table 27 shows the control adjustments for Strategy 3. These adjustments will be discussed in the following points:

Table 27: Control adjustment for Strategy 3

| Number | Control adjustment |
|---|---|
| I | Increase 3CPFS set points on Pumping Level 2 to high until the level of Pumping Level 1's hot dam reaches 85%, then change set points to medium or low. |
| II | Decrease 3CPFS set points on Pumping Level 1 to low until the level of Pumping Level 1's hot dam reaches 80%, then change set points to medium. When the dam level reaches 90%, change set points to high. |
| III | Stop dewatering pumps on Pumping Level 3 when the level of Pumping Level 2's hot dam reaches 75%. |

Number I:

- Change the 3CPFS set points to high on Pumping Level 2. This control should continue until the level of Pumping Level 1's hot dam reaches 85%.
- When the level of Pumping Level 1's hot dam reaches 85%, change the set point to medium.
- Change the set point to low once the dam level reaches 90%.

Number II:

- Change the 3CPFS set points on Pumping Level 1 to low.
- When the level of Pumping Level 1’s hot dam reaches 80%, change the set points to medium.
- When the level of Pumping Level 1’s hot dam reaches 90%, change the set point to high.

Number III:

- If the level of Pumping Level 2 hot dam reaches 75%, stop a dewatering pump on Pumping Level 3.
- If the level of Pumping Level 3’s hot dam reaches 70%, start a dewatering pump on Pumping Level 3 and change the 3CPFS set points on Pumping Level 2 to high.

### Strategy 4: Dewatering pump failure on Pumping Level 3

Strategy 4 was developed for the scenario where one of Pumping Level 3’s dewatering pump fails. This dewatering level does not have a 3CPFS, thus dewatering pumps are the only method for dewatering this level.

Figure 75 compares the dam level predictions with the actual dam levels for a five-day period. The average percentage error for this period was 0.1%. The predicted dam level changed more drastically than expected. Although the model per hour was not as accurate as previous models, this was not seen as a problem as this model was used to develop the control strategy.

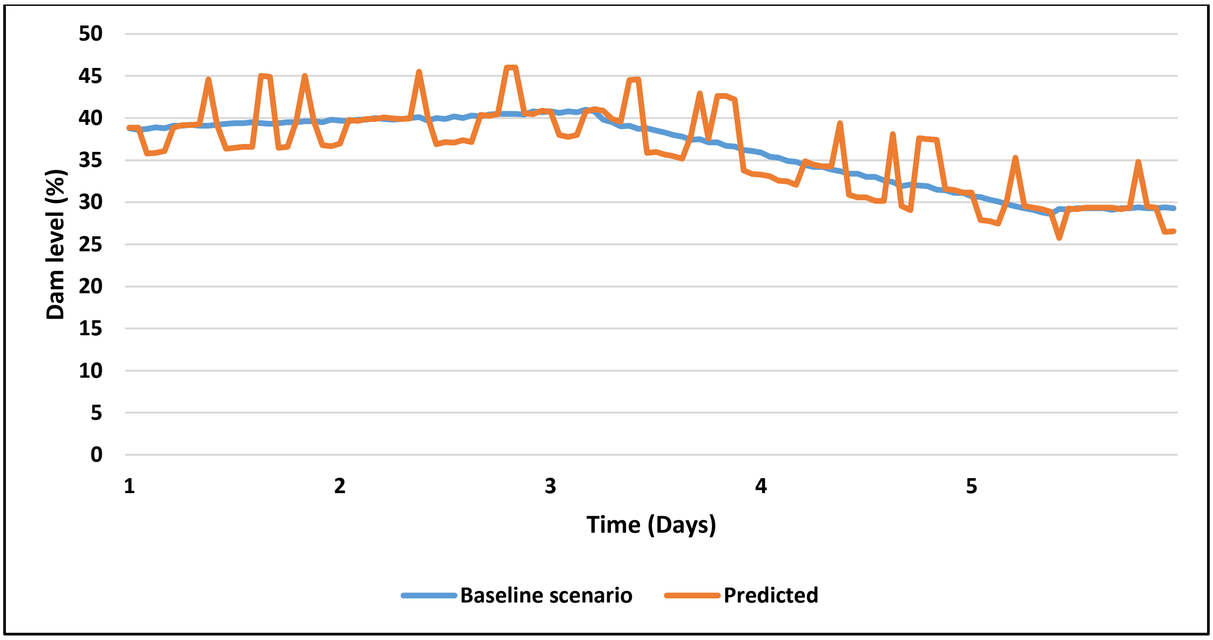


Figure 75: Dam level prediction model comparison for Pumping Level 3 hot dam

Figure 76 shows the effect that a single dewatering pump failure has on the dam level of Pumping Level 3. Strategy 4 was developed to mitigate the problems regarding this failure, which included flooding the hot dam on Pumping Level 3.

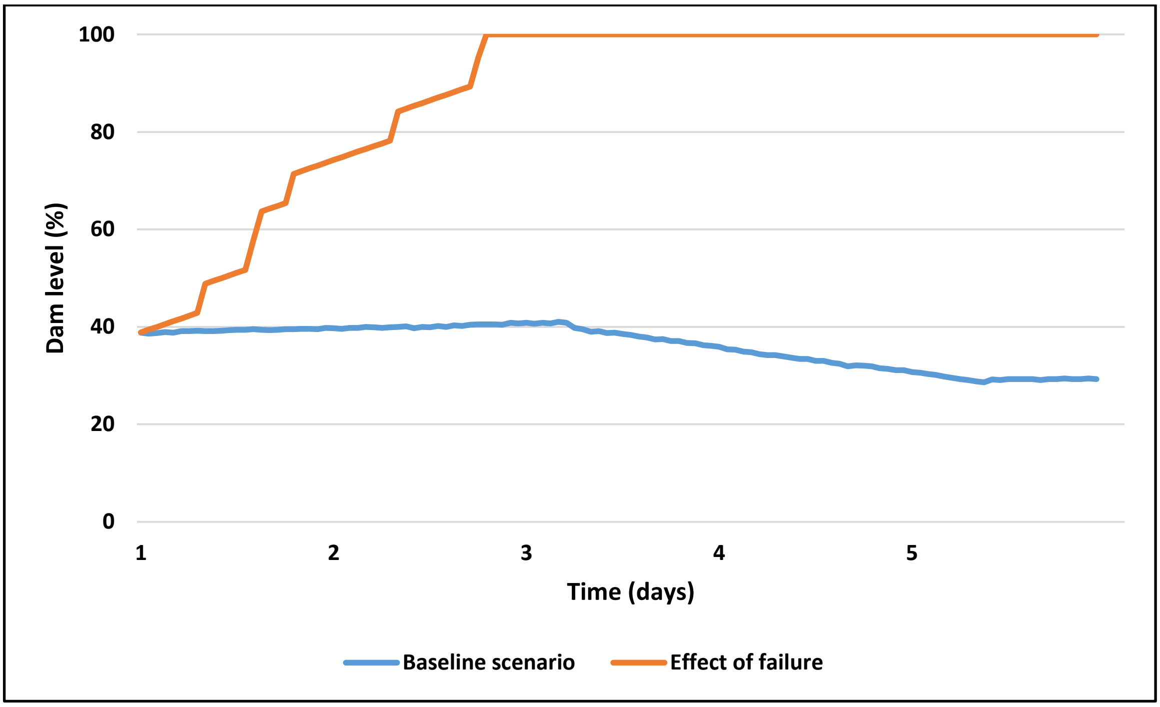


Figure 76: Effect of failure Strategy 4

Table 28 shows the control adjustments for Strategy 4. These adjustments will be discussed in the following points:

Table 28: Control adjustment for Strategy 4

| Number | Control adjustment |
|---|---|
| **I** | Increase 3CPFS set points on Pumping Level 2 to high until the level of Pumping Level 1's hot dam reaches 70%, then change the set points to medium or low. |
| **II** | Increase 3CPFS set points on Pumping Level 1 to medium until the level of Pumping Level 1's hot dam reaches 75%, then increase set points to high. |
| **III** | Stop dewatering pumps on Pumping Level 2 when the level of Pumping Level 1's hot dam reaches 85%. |

Number I:

- Change the 3CPFS set points on Pumping Level 2 to high. This set point should remain on high until the level of Pumping Level 1's hot dam reaches 70%.
- When the level of Pumping Level 1's hot dam reaches 70%, reduce the set point to medium.
- If the set point increases to 80%, reduce the set point value to low.

Number II:

- Change the 3CPFS set points on Pumping Level 1 to medium. This set point should remain on medium until the level of Pumping Level 1's hot dam reaches 75%.
- When the level of Pumping Level 1's hot dam reaches 70%, change the set point to high.

Number III:

- Stop Pumping Level 2's dewatering pumps once the level of Pumping Level 1's hot dam reaches 85%.
- Operate the remaining Pumping Level 3's dewatering pump as long as possible. Therefore, Pumping Level 2's hot dam should have sufficient available storage capacity.

## Strategy 5: All dewatering pumps failing on Pumping Level 2

A strategy had to be developed in the event of all dewatering pump failing on Pumping Level 3. As stated in the explanation of Strategy 4, there are only dewatering pumps and no 3CPFS on Pumping Level 3. In case all dewatering pumps are unavailable on this level, little can be done to mitigate the problem.

Figure 77 shows the effect of all three dewatering pumps failing on Pumping Level 3's dam level. The dam will flood soon after the failures occur. The adjustment with the largest effect that can be made to mitigate these failures would be to reduce the amount of water flowing into Pumping Level 3's hot dam. Unfortunately, this is not a viable option as this would mean that less water would have to be made available to active mining levels.

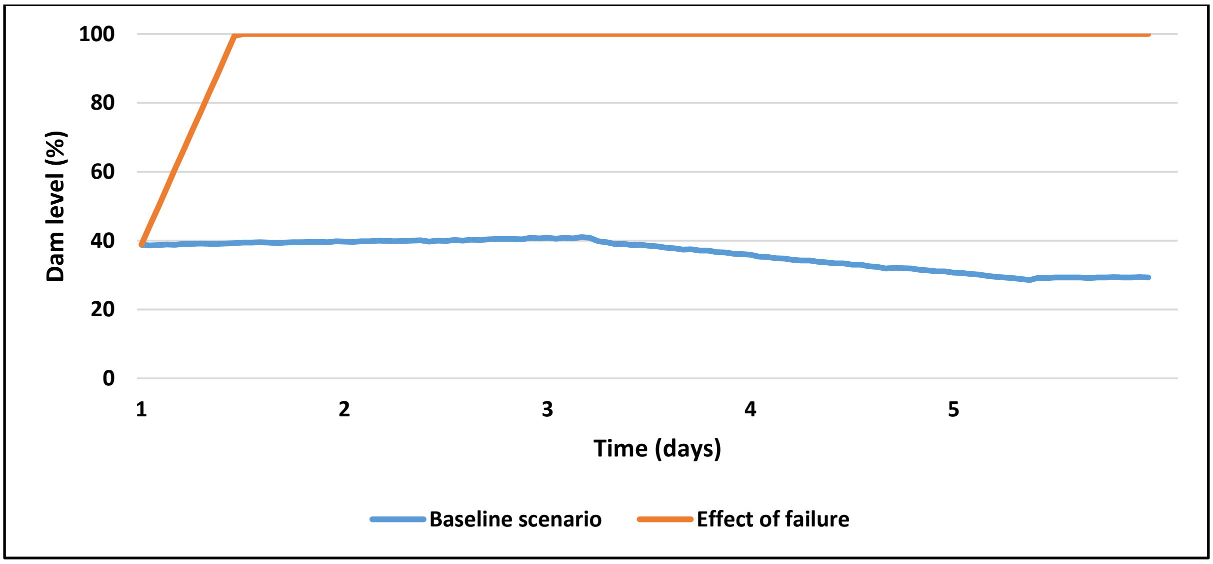


Figure 77: Effect of failure Strategy 5

Table 29 shows the control adjustments for Strategy 5. These adjustments will be discussed in the following points:

Table 29: Control adjustment for Strategy 5

| Number | Control adjustment |
|---|---|
| I | Decrease 3CPFS set points on Pumping Level 2 to low or medium. |
| II | Decrease 3CPFS set points on Pumping Level 1 to low or medium. |
| III | Operate Pumping Level 2's dewatering pumps until the level of Pumping Level 2's hot dam is lower than 40%. |
| IV | Operate Pumping Level 1 dewatering pumps until the level of Pumping Level 1's hot dam is lower than 50%. |

Number I:

- Change the 3CPFS set points on Pumping Level 2 to medium.
- When the level of Pumping Level 2's hot dam decreases to 40%, change the 3CPFS set points on Pumping Level 2 to low.

Number II:

- Change the 3CPFS set points on Pumping Level 1 to medium.
- When the level of Pumping Level 1's hot dam decreases to 35%, change the 3CPFS set points on Pumping Level 1 to low.

Number III:

- Operate two dewatering pumps on Pumping Level 2 until the level of the Pumping Level 2's hot dam decreases to 50%.
- When the level of the Pumping Level 2's hot dam decreases to 50%, operate one Pumping Level 2 dewatering pump.
- If the level of Pumping Level 2's hot dam level decreases to 40%, stop all dewatering pumps on Pumping Level 2.

Number IV:

- Operate one dewatering pump on Pumping Level 1 until the level of Pumping Level 1's hot dam decreases to 50%.
- When the level of Pumping Level 1's hot dam decreases to 50%, stop this dewatering pump.

**Fridge plant system**

The prediction models developed for the fridge plant system were used for all fridge plant related control strategies. The percentage occurrence of fridge plant control strategies in a period of one year was 18.98%.

## Dam level prediction model for fridge plants

Table 30 compares the dam level differences with the number of fridge plants that were operational. The level of the surface cold dam changes according to the number of operational fridge plants.

Table 30: Dam level prediction model for fridge plants

| Number of fridge plants (–) | Dam level percentage difference (%) |
|---|---|
| 0 | −0.51 |
| 1 | −7.79 |
| 2 | −2.31 |
| 3 | −1.87 |
| 4 | 0.66 |

Figure 78 compares the actual dam level and the predicted dam level for a period of five days. The percentage error calculated over the five-day period was 0.15%. Thus, the model was accurate and could be used in the development of fridge plant control strategies.

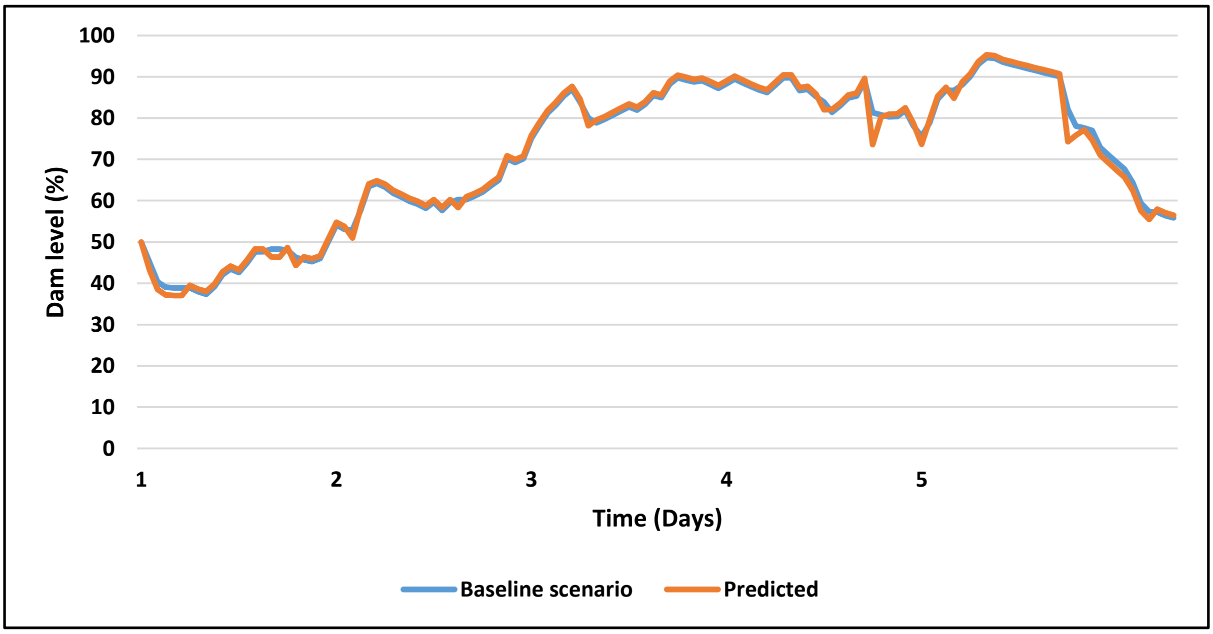


Figure 78: Dam level prediction model for fridge plants

## Load demand prediction model for fridge plants

The first step according to the methodology was obtaining historical data (Step 1 in Section 2.3.2). The next step (Step 2) was creating a standard load demand shifting formula, which was the same formula as used in the development of the dewatering load demand shifting formula. The next step (Step 3) was developing applicable parameters. The development of the load demand shifting formula used similar component parameters than the dewatering load demand shifting formula development (discussed in Section 3.3.2). The fridge plant load demand shifting formula was more complex, which led to more parameters being developed. These parameters were:

- *x*: Total running hours from 00:00 to 17:59
- *y*: Total running hours from 18:00 to 19:59
- *z*: Total running hours from 20:00 to 23:59
- *u*: Total running hours from 06:00 to 14:59
- *v*: x + z
- *w*: 24 − y

It was seen that more parameters could lead to lower percentage errors. Large percentage errors were seen in the initial development with five parameters. For this reason, an additional parameter was used. The six preliminary equations are shown (Step 4):

$$2319.89 = 68.20x + 1.10y + 14.70z + 23.12w + 82.01v + 4.25u$$

Equation 17: Preliminary Formula 1 for fridge plant failures

$$2117.73 = 62.22x + 1.12y + 12.72z + 23.52w + 74401v + 3.01u$$

Equation 18: Preliminary Formula 2 for fridge plant failures

$$1774.09 = 64.31x + 1.01y + 9.71z + 22.90w + 77.42v + 3.28u$$

Equation 19: Preliminary Formula 3 for fridge plant failures

$$1733.01 = 64.31x + 1.02y + 8.64z + 22.99w + 72.95v + 3.08u$$

Equation 20: Preliminary Formula 4 for fridge plant failures

$$1651.94 = 56.20x + 1.03y + 11.70z + 23.22w + 67.21v + 2.78u$$

Equation 21: Preliminary Formula 5 for fridge plant failures

$$1546.60 = 69.58x + 1.52y + 11.06z + 23.48w + 80.64v + 3.43u$$

Equation 22: Preliminary Formula 6 for fridge plant failures

Step 5 is used to solve all the constants. Equation 23 shows the developed load shifting savings model (Step 6). This formula was developed by solving the preliminary equations (Equation 17–Equation 22).

$$\text{Savings} = 0.5x + 0.0258y - 2z + 50w - 5v + 320u$$

Equation 23: Fridge plant load demand shifting formula

Figure 79 shows the actual load demand shifting achieved as well as the predicted load demand shifting for a 14-day period. The load demand shifting prediction model was not accurate with an absolute percentage error of 20.29%. Therefore, the results of the load demand shifting prediction model could not be used to replace other proved methods. It should be noted again that this model was used as a tool in the development of control strategies.

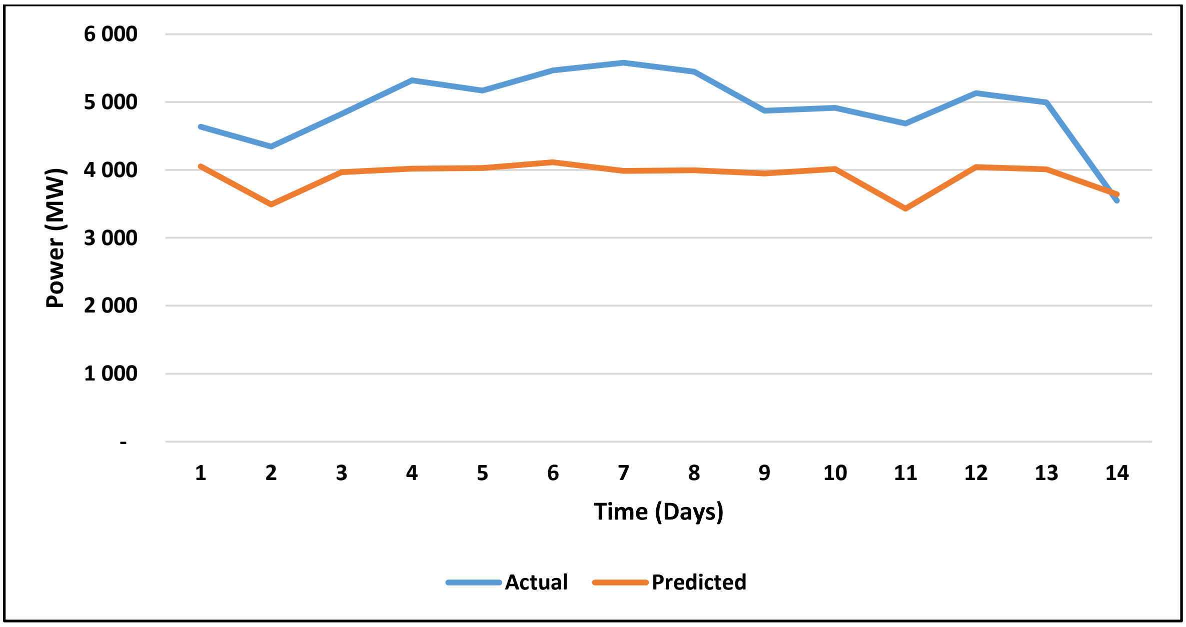


Figure 79: Fridge plant power prediction model

## Strategy 6: Single fridge plant failure

Strategy 6 was developed in the event of a single fridge plant failing. All fridge plants in the case study were located on the surface. However, the same process should be followed if fridge plants are situated underground. Figure 80 shows the effect of a single fridge plant failure, which caused the dam to empty as the fridge plant should pump cold water into this dam. This cold dam should not empty as this water is used for BACs and underground operations.

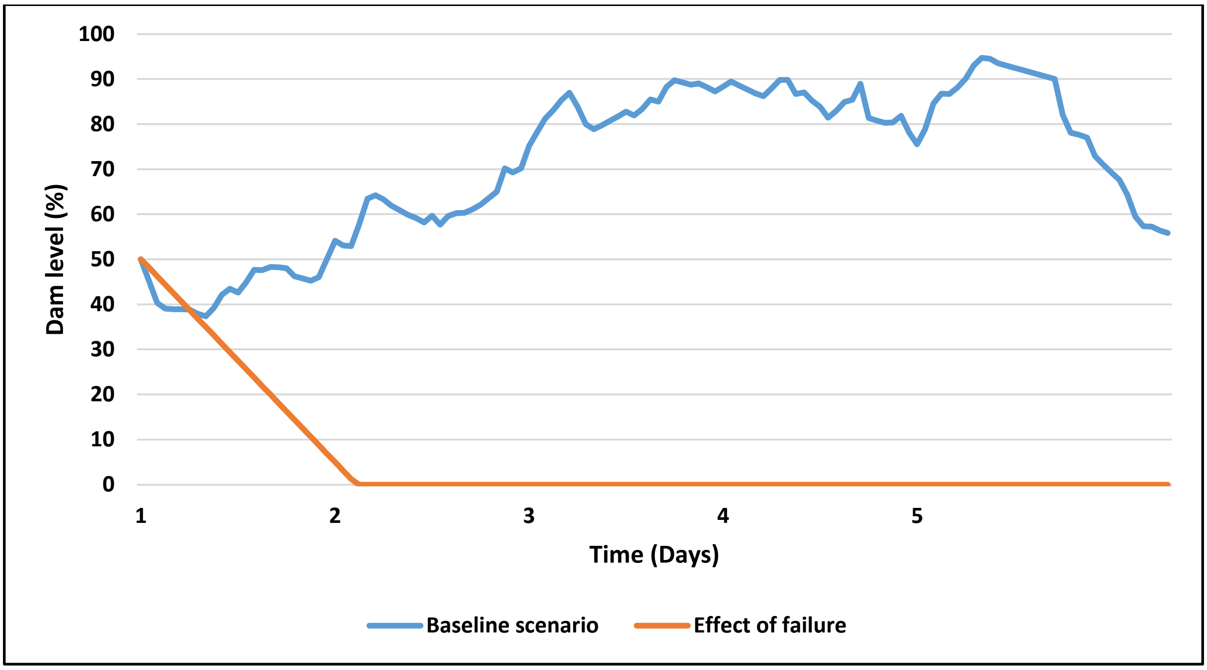


Figure 80: Effect of failure Strategy 6

Table 31 shows the control adjustments for Strategy 6. These adjustments will be discussed in the following points:

Table 31: Control adjustment for Strategy 6

| Number | Control adjustment |
|---|---|
| I | Increase 3CPFS set point on Pumping Level 1 to medium. When this dam level increases to 75%, then change set point to high. |
| II | Increase 3CPFS set point on Pumping Level 2 to medium. When this dam level increases to 75%, then change set point to high. |
| III | Stop Pumping Level 2's pumps until the level of Pumping Level 2's hot dam is above 75%. |
| IV | Stop Pumping Level 1's pumps until the level of Pumping Level 1's hot dam is above 75%. |
| V | Start Pumping Level 3's pump. |

Number I:

- Change the 3CPFS set points on Pumping Level 1 to medium until the level of Pumping Level 1's hot dam reaches 75%.
- When the level reaches 75%, change the set points to high.
- If Pumping Level 1's hot dam decreases lower than 35%, change the set points to low.

Number II:

- Change the 3CPFS set points on Pumping Level 2 to medium until the level of Pumping Level 2's hot dam reaches 75%.
- When the level reaches 75%, change the set points to high.
- If Pumping Level 2's hot dam decreases lower than 35%, change the set points to low.

Number III:

- Stop all dewatering pumps on Pumping Level 2 until the level of Pumping Level 2's hot dam reaches 65%.
- When Pumping Level 2's hot dam reaches 65%, operate one dewatering pump.
- If Pumping Level 2's hot dam reaches 75%, start a second dewatering pump.

Number IV:

- Stop all dewatering pumps on Pumping Level 1 until the level of Pumping Level 1's hot dam reaches 65%.
- When Pumping Level 1's hot dam reaches 65%, operate one dewatering pump.
- If Pumping Level 1's hot dam reaches 75%, start a second dewatering pump.

Number V:

- Start two dewatering pumps on Pumping Level 3 to keep the level of Pumping Level 3's hot dam low.
- If Pumping Level 3's hot dam decreases to 40%, operate one dewatering pump.
- When the dam level decreases to 35%, stop all dewatering pumps on Pumping Level 3.

These control adjustments were implemented to ensure that all dam do not empty or flood. As discussed in Section 3.3.2, the dam levels did not pose any hazardous scenarios when fridge plants could be stopped in the Eskom evening peak period. Normal operations continued with the remaining fridge plants. It was deemed unnecessary to implement further adjustments.

### Strategy 7: Second fridge plant failure

Strategy 7 was developed in case of a second fridge plant failing, which would lead to less cold water being available until another fridge plant is operational. This scenario becomes a problem as cold water is used for cooling and underground operations. Figure 81 shows the effect two fridge plant failures will have on the surface cold dam level. It should be noted that the effect of these failures on dam levels are predicted with no mitigation strategy in place.

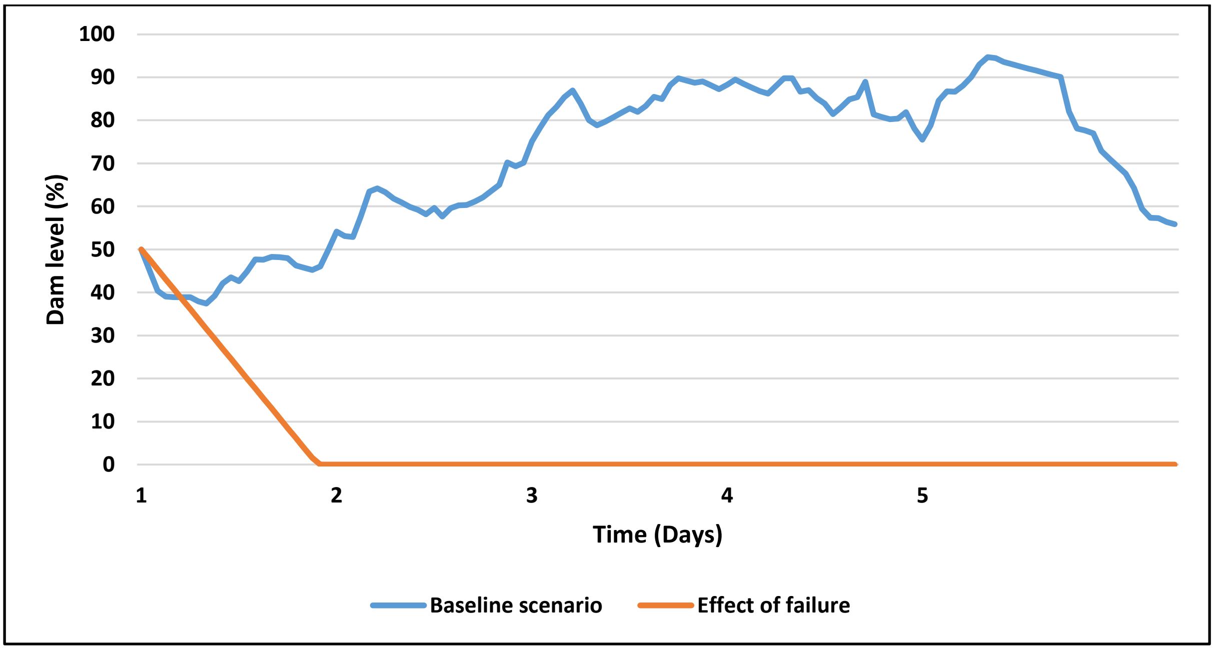


Figure 81: Effect of failure Strategy 7

Table 32 shows the control adjustments for Strategy 7. These adjustments will be discussed in the following points:

Table 32: Control adjustment for Strategy 7

| Number | Control adjustment |
|---|---|
| I | Increase 3CPFS set points on Pumping Level 1 to medium until dam level is above 60%. Thereafter, change the set points to high. |
| II | Increase 3CPFS set points on Pumping Level 2 to medium until dam level is above 60%. Thereafter, change the set points to high. |

| Number | Control adjustment |
|---|---|
| **III** | Stop pump on Pumping Level 2 until Pumping Level 2's hot dam is above 60%. |
| **IV** | Stop pumps on Pumping Level 1 until Pumping Level 1's hot dam is above 80%. |
| **V** | Start pumps on Pumping Level 3 to keep Pumping Level 3's hot dam low. |

Number I:

- Change the 3CPFS set point on Pumping Level 1 to medium until Pumping Level 1's dam level decreases to 35%.
- When the level decreases to 35%, change the set points to low.
- If Pumping Level 1 hot's dam increases above 60%, change the set point to high.

Number II:

- Change the 3CPFS set points on Pumping Level 2 to medium until Pumping Level 2's dam level decreases to 35%.
- If Pumping Level 2's dam level decreases to 35%, change the set points to low.
- If Pumping Level 2's hot dam level increases above 60%, change the set point to high.

Number III:

- Stop all dewatering pumps on Pumping Level 2 until Pumping Level 2's hot dam reaches 60%.
- When Pumping Level 2's hot dam reaches 60%, operate one dewatering pump.
- If Pumping Level 2's hot dam reaches 70%, start a second dewatering pump.

Number IV:

- Stop all dewatering pumps on Pumping Level 1 until Pumping Level 1's hot dam reaches 80%.
- When Pumping Level 1's hot dam reaches 80%, operate one dewatering pump.
- If Pumping Level 1's hot dam reaches 90%, start a second dewatering pump.

Number V:

- Start two dewatering pumps on Pumping Level 3 to keep Pumping Level 3's hot dam level low.
- If Pumping Level 3's hot dam decreases to 40%, operate one dewatering pump.
- When the dam level decreases to 35%, stop all dewatering pumps on Pumping Level 3.

These control adjustments were implemented to ensure that all dam levels do not empty or flood. As mentioned in Chapter 4, the dam levels did not pose any hazardous scenarios and fridge plants could be stopped in the Eskom evening peak period. Normal operations continued with the remaining fridge plants. It was deemed unnecessary to implement further adjustments.

**BAC system**

Only a dam level prediction model was developed for BACs as most of the electricity cost savings were achieved through the dewatering and fridge plant water reticulation groups. The purpose of each BAC strategy was to ensure safe underground temperatures by sending sufficiently low air temperatures underground. The percentage occurrence of these strategies in a year was 55.89%. Table 33 compares the dam level differences with the number of operational BACs. The BAC cold dam level would change according to the number of operational BACs.

Table 33: Dam level prediction model for BACs

| **Number of BACs (–)** | **Dam level percentage difference (%)** |
|---:|---:|
| 0 | 0.299 |
| 1 | 0.035 |
| 2 | −0.481 |
| 3 | −1.274 |

Figure 82 compares the actual BAC dam level with the predicted BAC dam level for a period of five days. The average percentage error was calculated as 0.63%. The dam level prediction model can be used in developing control strategies for BAC failures.

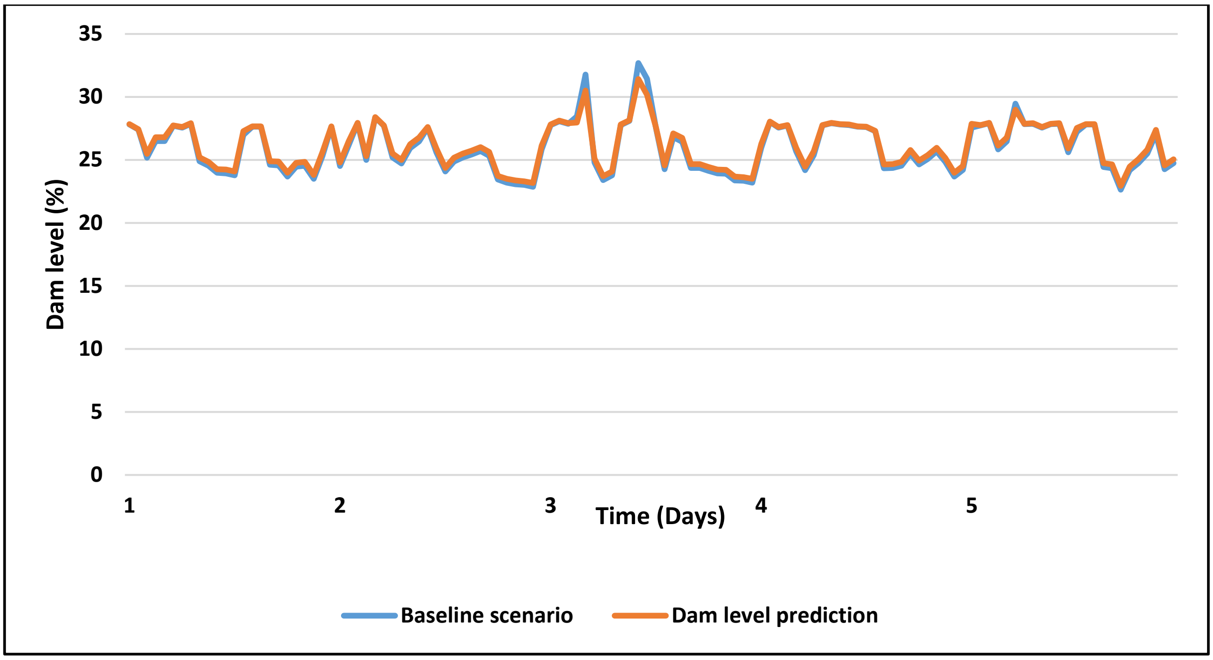


Figure 82: Dam level prediction model for BACs

## Strategy 8: BAC failure

Strategy 9 was developed for the scenario where a single BAC fails, which causes less cold air being available to send underground. This becomes a problem as it could influence the safety of underground mining personnel.

Figure 83 shows the effect of one BAC failing on the BAC cold dam level.

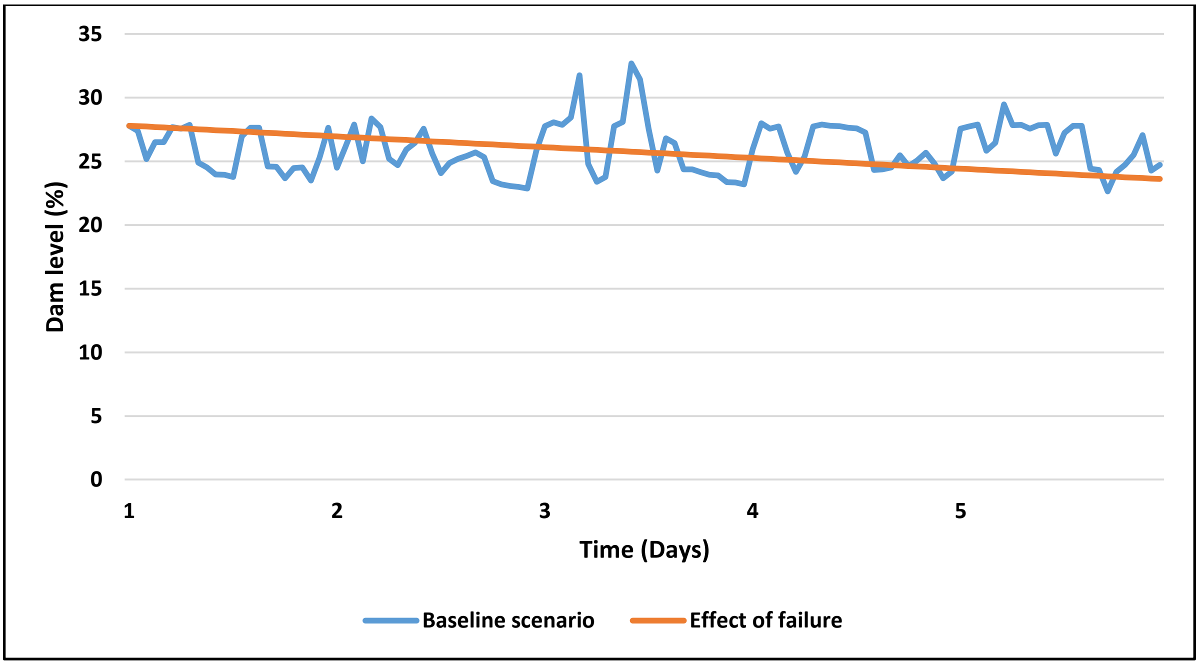


Figure 83: Effect of failure Strategy 8

It should be noted that no attempt to mitigate the problem was taken into account when the effect of the failure was predicted. The effect on the BAC dam levels was minimum. The effect on the amount of cold air sent underground is a larger concern for this failure type. For each BAC that malfunctions, 150 kg/s less air is available underground. This could have an effect on the underground air temperatures.

Table 34 shows the control adjustments for Strategy 8. These adjustments will be discussed in the following points:

Table 34: Control adjustment for Strategy 8

| Number | Control adjustment |
|---|---|
| **I** | Stop an extra BAC feed pump and BAC return pump. |
| **II** | Bypass the water flow for stopped BAC. |

Number I:

- Stop an additional BAC feed pump and BAC return pump. This will ensure that less water is sent to the BACs.
- An increased amount of cold water will remain in the surface cold dam or more water will be sent underground for mining operations.

Number II:

- The other option would be to bypass the malfunctioning BAC, which means that colder water will be available towards the PCT.
- The problem is that less cold air will be available underground, which poses large health and safety risks.

After evaluating the underground temperatures in Section 3.4.2, it was seen that no dangerous scenarios occurred when implementing this control strategy.

## Strategy 9: Second BAC failure

Strategy 9 was developed for the scenario where two BACs failed. Figure 84 shows the effect two BAC failures had on the BAC cold dam level. It should be noted that no attempt to mitigate the problem was taken into account when the failure was predicted.

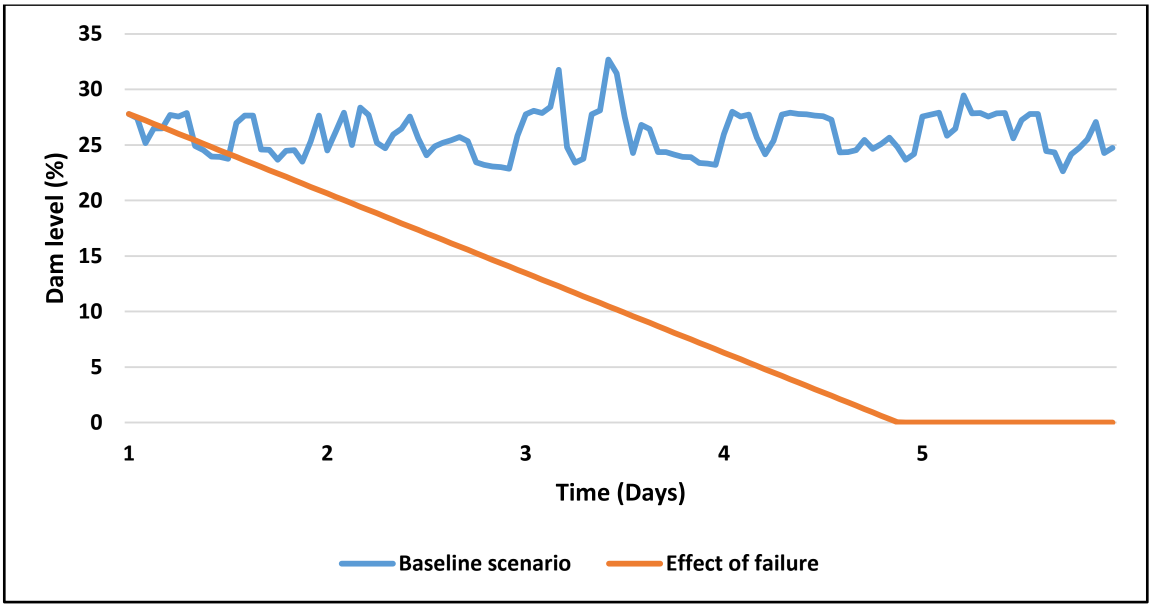


Figure 84: Effect of failure Strategy 9

Table 35 shows the control adjustments for Strategy 9. These adjustments will be discussed in the following points:

Table 35: Control adjustment for Strategy 9

| Number | Control adjustment |
|---|---|
| I | Stop an extra BAC feed pump and BAC return pump. |
| II | Bypass the water flow for stopped BACs. |

Number I:

- Stop an additional BAC feed pump and BAC return pump.
- This will ensure that less water is sent to the BACs, which means that more cold water will remain in the surface cold dam or more water will be sent underground for mining operations.

Number II:

- The other option is to bypass the malfunctioning BACs, which means that colder water will be available towards the PCTs.
- The problem is that less cold air will be available underground, which poses large health and safety risks.

After evaluating the underground temperatures in Chapter 4, it was seen that no dangerous scenarios occurred when implementing this control strategy.

**PCT system**

A dam level prediction model was developed for a PCT failure. A load demand shifting prediction model was not developed for PCT failures, because most of the electricity cost savings were achieved through the dewatering and fridge plant water reticulation systems. The purpose of the PCT control strategy was to ensure that water was cooled before it reached the fridge plants. When cooler water enters the fridge plants, it results in lower fridge plant outlet water temperatures. The percentage occurrence of this strategy in a year was 3.87%

Figure 85 compares the actual PCD level with the predicted PCD level for PCD 1. The percentage error between the actual and predicted dam levels for a five-day period was 0.027%.

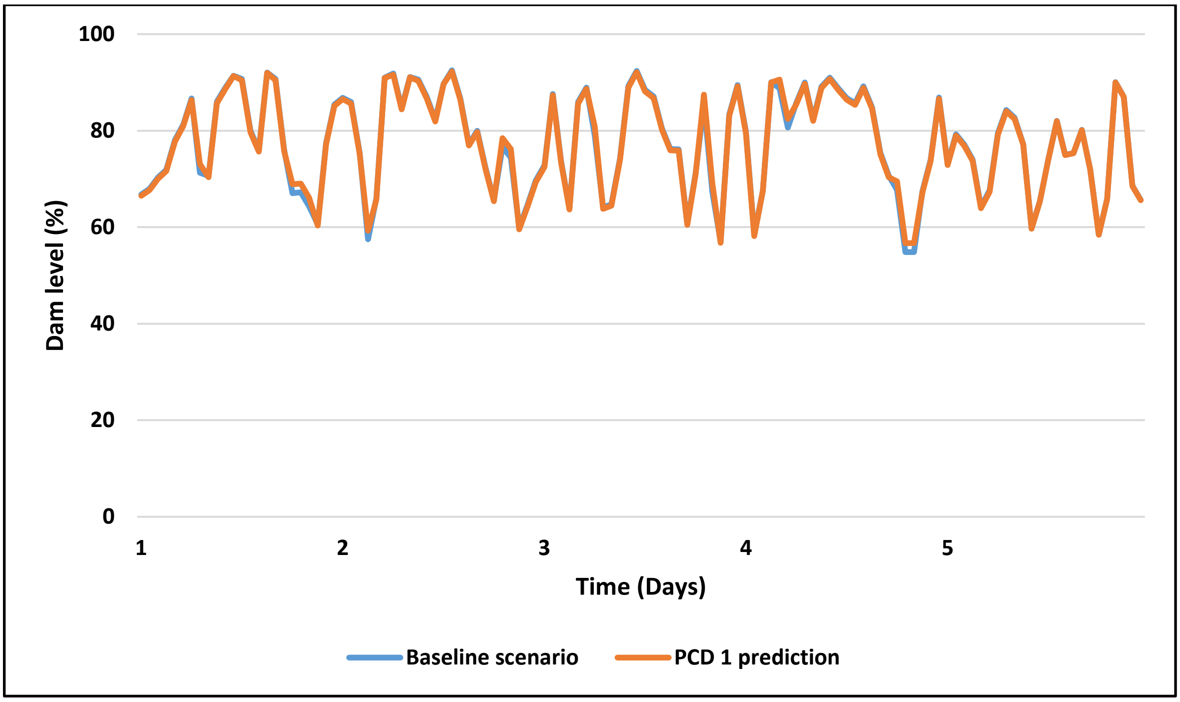


Figure 85: Dam level prediction model for PCD 1

Figure 86 compares the actual PCD dam level with the predicted PCD level for PCD 2. The percentage error between the actual and predicted dam levels for a five-day period was 0.122%. PCD 1 and PCD 2 were linked although it was found that two prediction models would be beneficial for this scenario. The reason is that each PCD has dam level measurements, which simplifies the process if they are considered as individual dams.

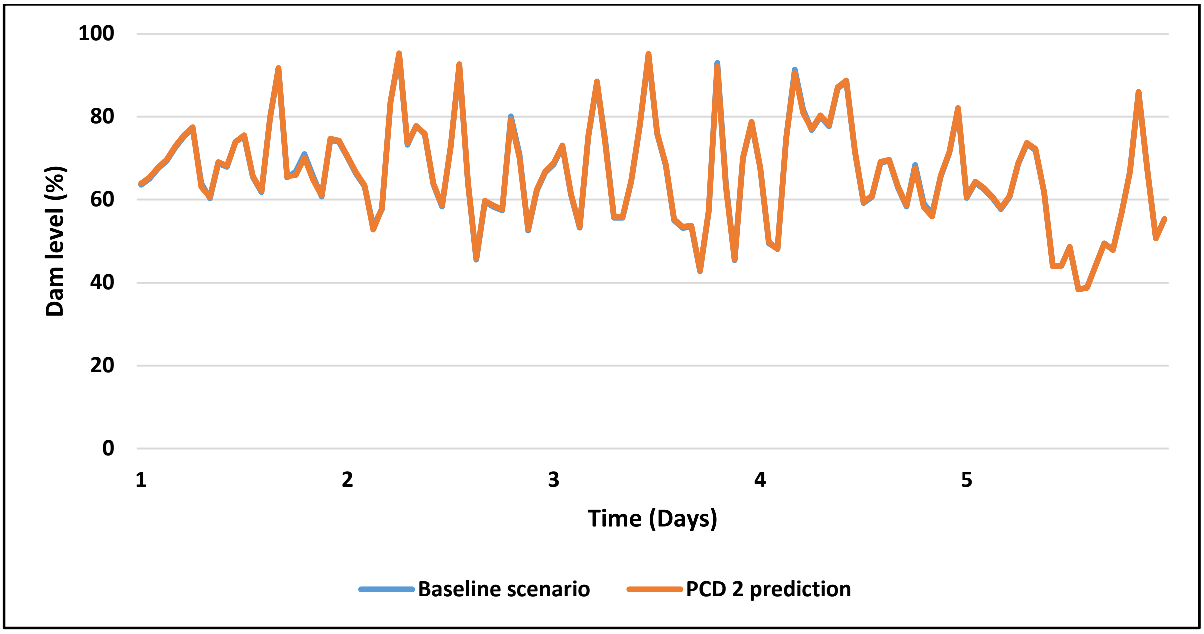


Figure 86: Dam level prediction model for PCD 2

## Strategy 10: PCT failure

If a PCT fails, little can be done besides fixing the component. The effect of the failure means that water will bypass this component. The water temperature in the PCDs will be higher than normal, forcing fridge plants to circulate more water to reach the desired outlet water temperature.

Figure 87 shows the effect of a PCT failure on PCD 1. It can be seen that it has a significant negative effect on the dam levels, which can be avoided by bypassing the PCT. The problem is that the PCD water temperature will increase.

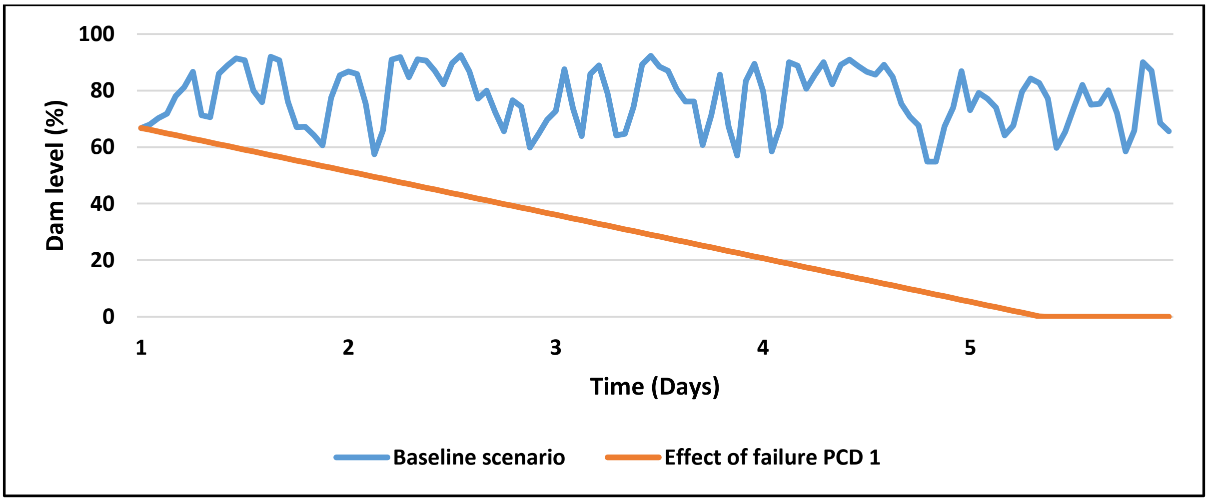


Figure 87: Effect of failure Strategy 10 (PCD 1)

Figure 88 shows the effect of a PCT failure on PCD 2. It can be seen that it has a significant effect on the dam levels.

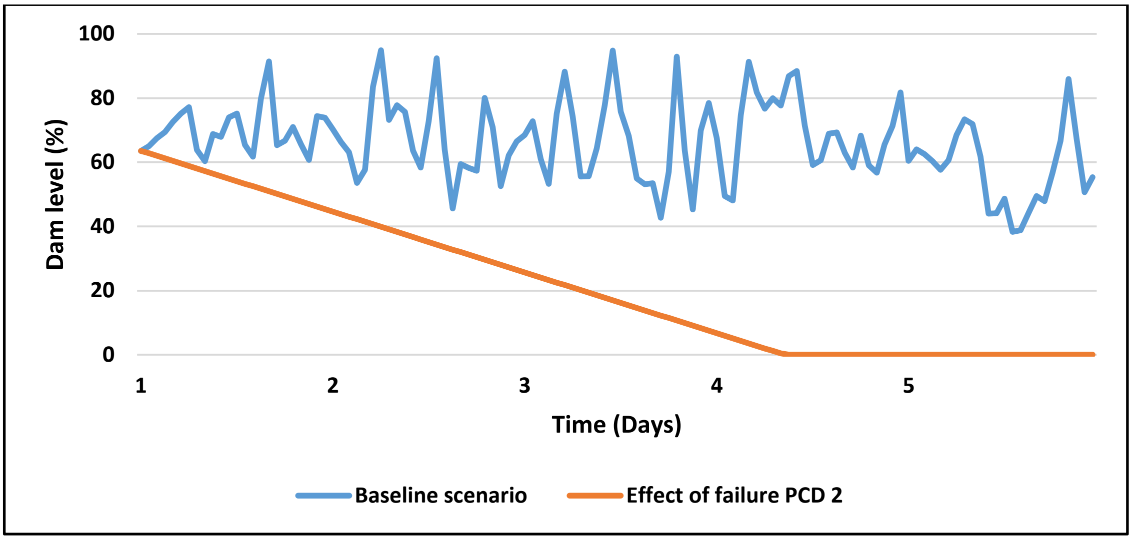


Figure 88: Effect of failure Strategy 10 (PCD 2)

Table 36 shows the control adjustments for Strategy 10. These adjustments will be discussed in the following points:

Table 36: Control adjustment for Strategy 10

| Number | Control adjustment |
|---|---|
| I | Bypass the malfunctioning PCT. |
| II | Recirculate fridge plant outlet water to PCDs. |

Number I:

- The first step is to bypass the malfunctioning PCT.
- The PCD water temperatures will increase.

Number II:

- If the fridge plant water output temperature exceeds the limit, water should be recirculated to the PCDs.
- This will ensure that the PCD water temperatures decrease. This will also ensure that the fridge plant water output temperature is lower.