Utilising mine-cooling auxiliaries for optimal performance during seasonal changes

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Abstract

Electricity is a major concern for energy-intensive consumers. The price of electricity in South Africa has increased by 300% over the last ten years, and the future price increase is forecasted to surpass inflation. This is unfavourable for industries such as the mining industry that consume, on average, 15% of all the electricity generated in South Africa. Due to the growing demand of electricity in South Africa, new ways of reducing the demand of energy-intensive industries such as the mining industry should be explored.

The gold mining industry is the largest electricity consumer of all mining industries in South Africa. The industry is under pressure as the increasing electricity tariff, the increasing consumer price index, and the constant need to expand mines to reach deeper deposits contribute to increasing operational costs and decreasing profit margins. The mining industry is thus forced to improve their efficiency and drive any possible energy-saving initiatives by adopting the latest technologies and processes to ensure sustainable operations while maintaining cost-efficiency..

Mine-cooling systems are the largest consumers of energy in the gold mining industry, consuming 22% of a mine's total electricity demand. As mines become deeper, the cooling requirements also increase, increasing the energy consumption required for operation. With the increased tariffs, these cooling systems need to be as efficient as possible, especially in wintertime when electricity is three times more expensive than in summer.

Scope to optimise mine-cooling auxiliaries in terms of cost saving and sufficient cooling during seasonal changes was identified, and a control strategy to utilise mine-cooling auxiliaries for optimal performance during seasonal changes was developed. The strategy consists out of utilising the bulk air coolers (BACs) and low wet bulb (WB) conditions during wintertime. The BAC acts as a precooling tower that cools down the chilled water with the lower WB temperature. The strategy was simulated with simulation software and verified upon implementation, and was developed for combined service delivery and energy efficiency improvement.

The strategy was implemented on Mine A, yielding a 4.3°C reduction in precool dam temperatures and an average load reduction of 0.8 MW on the fridge plants. The strategy did not, however, reduce chill dam temperatures, as the fridge plants were already achieving their setpoints prior to implementation. Though the strategy did not improve service delivery, it maintained service delivery with a lower electricity consumption.

In conclusion, the control strategy can be implemented on all mines with suitable fridge plant BAC configurations and appropriate ambient winter conditions. The strategy achieved savings of R40 000 per day; however, these savings could only be achieved on days where the WB temperature was lower than the chilled water temperature for the entire day. The strategy was, therefore, optimised through simulation to achieve savings on days with a higher wet-bulb temperature to ensure that savings are achieved more often throughout the year. The optimised control strategy resulted in lower daily savings but higher annual savings overall due to its ability to be frequently implemented. It was also found that the optimised control strategy was not correctly implemented by control room operators; therefore, two control strategies were also developed to ensure sufficient savings in the future, namely manual implementation or automatic implementation.

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1. Introduction

1.1 Background

Energy awareness and preservation has become a critical issue in the modern world. Large amounts of readily available electricity are a thing of the past [1] [2], as non-renewable energy sources are becoming depleted on a worldwide scale. The global demand for energy has increased with rising populations, growing economies, and rising living standards [3].

South Africa's main source of electricity is provided by the energy utility Eskom. Eskom is one of the largest suppliers of electricity in the world, providing 95% of South Africa's electricity as well as exporting electricity to neighbouring countries [4]. Eskom's reserve margin is currently under extreme pressure, and the lack of maintenance and unplanned breakdowns have recently caused frequent load shedding. [5]. Energy efficiency is consequently of absolute importance in South Africa, as the economy cannot thrive without electricity [5].

Eskom will increasingly be faced with significant challenges to produce enough electricity to keep up with the rising demand, challenges including the building of new power stations, which can take up to an estimated ten years to build, while existing power plants need to be upgraded in order to continue their operations [6]. An evident solution for providing sufficient, reliable, and affordable electricity for South Africa's economy is to control and manage the demand of electricity [7]. The most effective approach to initiate energy efficiencies in terms of energy conservation is to target the larger energy-intensive consumers [8]. Figure 1-1 shows Eskom electricity distribution for various consumers.

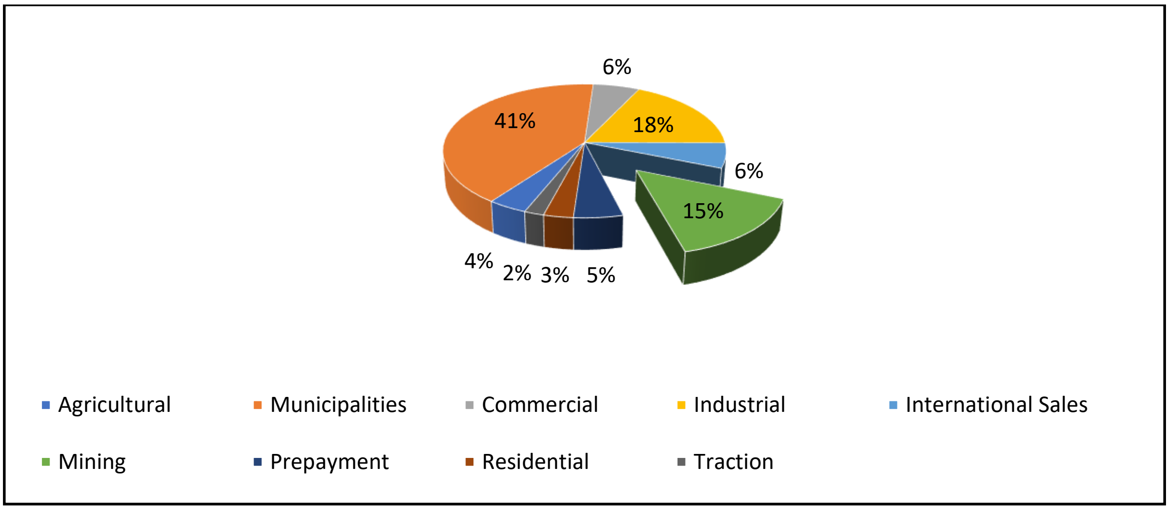


Figure 1-1: Eskom annual electricity sales distribution 2019 [9]

The largest energy consumers after the municipal sector are the mining and industrial sectors. These industries usually do not have the resources and skills to successfully initiate energy management and energy efficiency programmes [10]. The mining and industrial sectors are struggling with outdated and inefficient systems designed when electricity was more readily available. Controlling the demand of a consumer such as a mine and initiating energy efficiency projects on energy-intensive mining systems are crucial for reducing the load on the grid.

Mining as an energy consumer

South Africa has one of the largest reserves of gold, coal, and platinum in the world [11]. The exportation of these resources is one of South Africa's largest commercial industries. As stated in the background, mining is an energy-intensive consumer – in 2019, the industry consumed 15% of Eskom's total generated power. The gold mining sector is the largest industrial electricity client in the industry, consuming roughly 47% of all the electricity supplied to mines [12]. The rest of this section will focus solely on gold mining, given that the amount of energy used by the gold mining industry is approximately as much as all the other mining industries combined.

The gold mining industry's economic viability is currently under pressure. Figure 1-2 illustrates the Eskom electricity tariff increases versus inflation increase from 1987 to 2019 (with future projection). The average tariff increase of electricity has been significantly higher than the increase in inflation, which is not favourable for the gold mining industry.

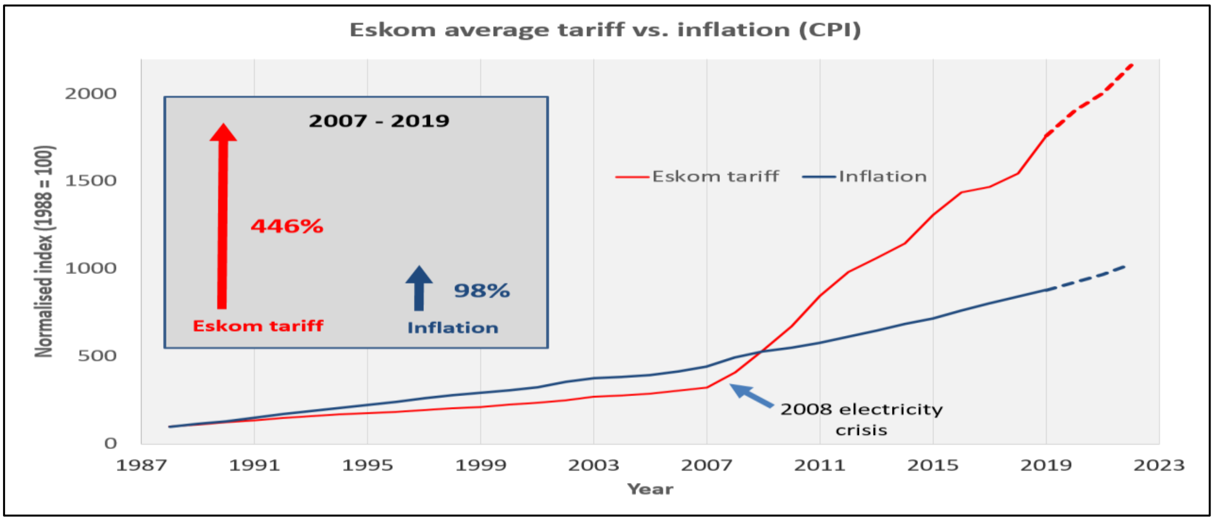


Figure 1-2: Electricity and inflation increase comparison [13]

Due to the growing demand for electricity in South Africa, Eskom introduced the Demand-Side Management (DMS) programme which uses the Time of Use (TOU) pricing structure [12]. This programme entails the reduction of electricity usage by energy-intensive industries such as mining during peak demand periods in an attempt to relieve pressure on the grid [14]. The TOU is a feasible solution for reducing mine electricity consumption; however, TOU and electricity increases prove to be costly for mines, especially in winter when considering the Megaflex TOU tariffs for 2019/2020 that can be seen in Figure 1-3 below. Winter tariffs are on average three times higher than summer tariffs.

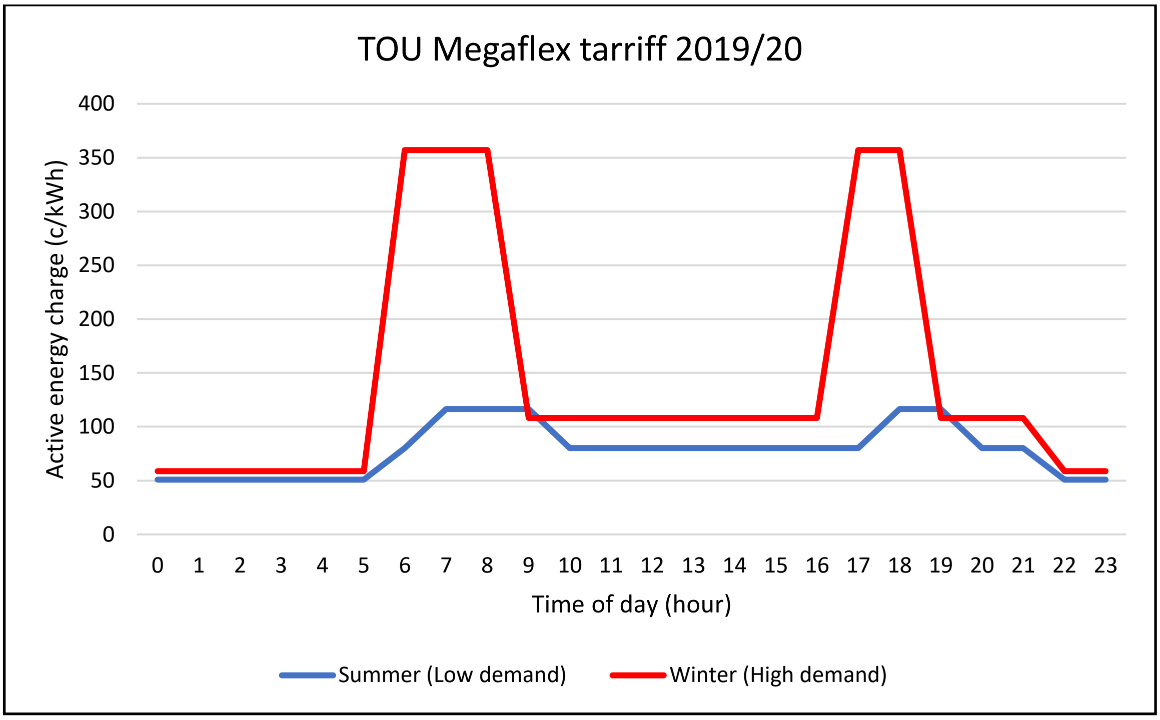


Figure 1-3: Megaflex weekday tariff structure [15]

The increasing electricity tariffs, consumer price index (CPI), and constant need to expand in order to reach deeper deposits all contribute to increasing the operational costs and decreasing the profit margin of the industry. This forces mines to improve their efficiency and drive any possible energy-saving initiatives by adopting the latest technologies and processes to ensure sustainable operations while still being as cost effective as possible [16]. To address the energy conservation of a deep-level gold mine, a breakdown of a typical electrical consumption is needed.

A typical deep-level gold mine can be split into production and services. The main purpose of production is to mine the gold reef, while the purpose of services is to ensure that the auxiliary systems on the mine are in good working order and available for production. All these sub-auxiliary systems are intensive electricity consumers. The following graph shows a typical gold mine’s electricity distribution.

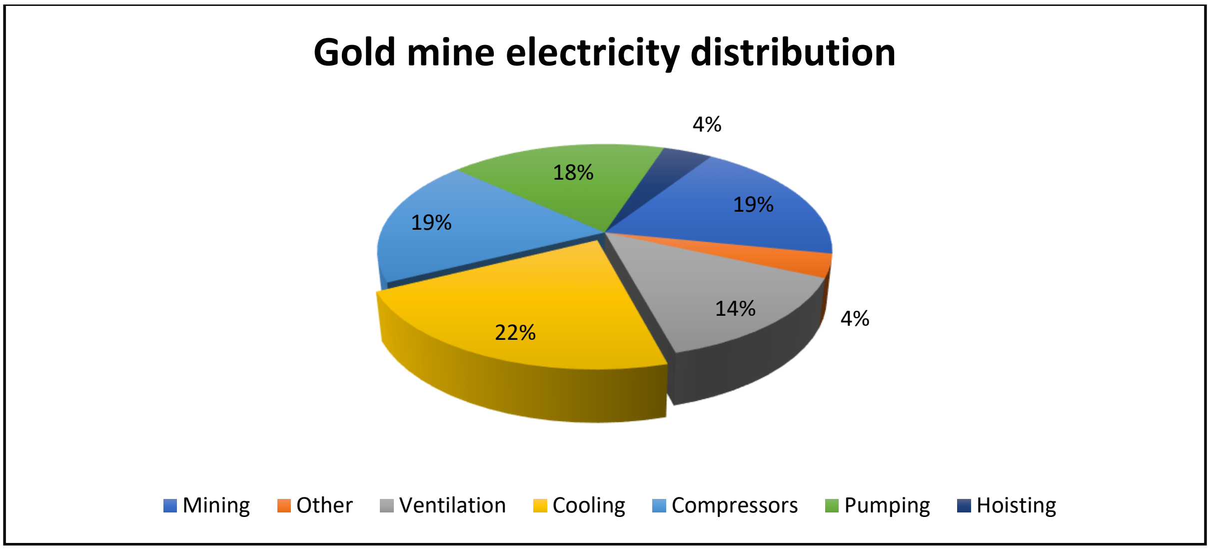


Figure 1-4: Typical gold mine electricity distribution in South Africa

As can be seen in Figure 1-4, cooling is the most electricity-intensive system in a typical gold mine in South Africa. This percentage can also change with the mine's need to get deeper to reach their deposits. Given the inevitably increasing cooling requirements, these cooling systems must be targeted to implement energy-efficient initiatives to keep the rising energy demand as low as possible.

1.2 Mine-cooling systems

1.2.1 Relevance of cooling

Gold mines in South Africa are some of the deepest mines in the world, reaching depths of 3 km with some looking to develop to 5 km [17]. When mining is done at these depths, large amounts of cooling are required, as mines can reach a virgin rock temperature, or VRT, of 60°C [18]. Mine-cooling systems are used to create a safe working environment by maintaining a legally prescribed average wet bulb (WB) temperature of 27.5 °C [17]. This requirement is crucial because it is not only connected to the safety of the mine workers but also directly proportional to the production figures of the mine, as mine-worker productivity decreases when the WB temperature exceeds 28 °C [19].

The electricity intensity of a typical mine-cooling system increases as mines continuously need to get deeper and develop in order to reach their deposits. Given South Africa's extreme geothermal gradient increase of 10-20 °C/km, the typical deep-level gold mine requires 370 kW of refrigeration per kiloton per meter (kt/m) at a depth of 3 km and 570 kW of refrigeration per kt/m at a depth of 3,5 km [20] [17]. When the working areas exceed an average dry bulb (DB) temperature of 32°C, artificial cooling is applied to the mine [17].

When mines reach a depth of more than 1,3 km below the surface, an underground temperature of 38 °C can be expected [21]. Surface ventilation with bulk air coolers (BAC) are then used to ventilate the mine with cool air and ensure adequate underground working conditions [22]. The surface BACs with their dedicated refrigeration plants can be used up to a depth of 1,9 km, where a VRT of 45 °C can be expected [21] [22]. Surface fridge plants (FPs) are used to cool water from underground in order to supply the BACs with chilled water and send cold water underground. The surface BACs use the chilled water to cool the ambient air that is sucked through the mine by the main vent fans. Underground, the chilled water is used to cool mining equipment and bring down the VRT of 35°C. At a depth of 1,57 km, the efficiency of the surface BACs and FPs becomes limited; therefore, underground cooling systems are required at these depths [21] [22]. The pictures below illustrate a typical surface FP and BAC on a deep-level gold mine.

Figure 1-6 : Fridge plant on a deep-level gold mine

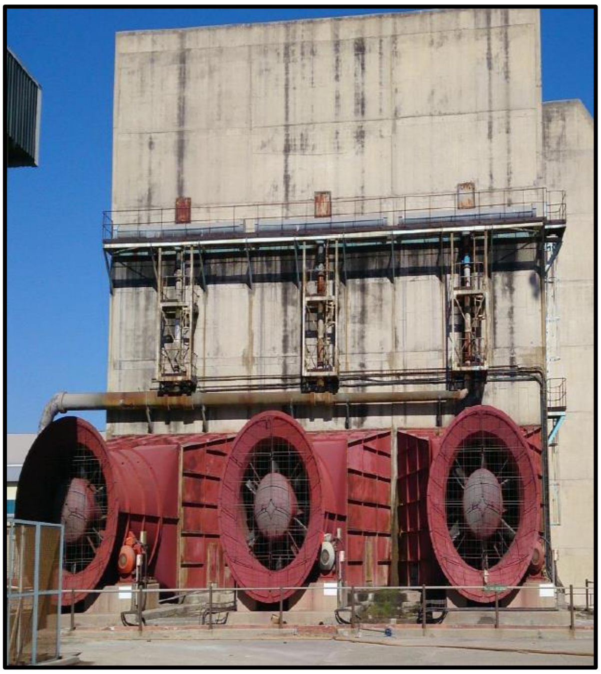


Figure 1-5 : Surface BAC towers with fans

The temperature of the chilled water that is sent down from the surface can increase at a rate of 1 °C per 250 m as it travels vertically down the shaft and horizontally through the haulages to the mining operations. This increase is largely a result of heat absorption from the hot underground environment and auto-compression [23]; therefore, mining activities beyond 2 km require underground FPs with BACs [22]. These underground FPs are less efficient than surface FPs because underground FPs reject their heat into the return airway (RAW) or hot-water spray chambers and not into ambient cooling towers as is the case for surface FPs. The RAW is where all the used hot air is extracted from the mining block The underground FP’s coefficient of performance (COP) values reduce from approximately 5.4 to 3.6. Underground FPs and BACs are sufficient systems for cooling deep-level gold mines, but some mines opt for a different solution, such ice dams, instead.

At a depth of 2,3 km below the surface, the VRT can reach 51 °C. Some of the mines use surface ice plants to cool these hot conditions. The ice plants produce large amounts of ice on the surface which are then sent underground to an ice dam. When the ice melts, it absorbs all the heat from the hot water that is pumped into the dam [24]. A typical ice dam can reach temperatures as low as 1 °C at 2,3 km below the surface [25]. The water from the ice dam is then sent down to be used in the same way as the chilled water that is sent down from the surface. It is common for mines in South Africa that have developed to below 3,9 km with a VRT of 78°C to use surface FPs, surface BACs, underground FPs, underground BACs, and surface ice plants to bring down these extreme temperatures [21] [26].

The cooling systems' main purpose on a deep-level mine is to counteract the heat that is added by auto-compression, virgin rock faces, fissure water, equipment, and machinery [27] [28]. These cooling systems are, therefore, essential, as they are responsible for maintaining a safe working environment that complies with South African laws and operating regulations. However, these cooling system components and concepts have not changed since their inception [29]; therefore, there is a lot of room for improvement, especially when it comes to electricity consumption and operating efficiency. The original mine-cooling design did not compensate for the increasing heat load from the mining, as the mines began to develop their mining techniques for operation at greater depths [30]. The techniques that were introduced resulted in an increased distance between the station and the stopes [31], causing the current cooling systems of mines in South Africa to maintain underground temperatures on the crucial limit.

On account of these issues, mines tend to apply more cooling or to buy new cooling equipment without exploring whether there is scope for improving or utilising their current cooling equipment to improve service delivery and energy efficiency [25]. The cooling systems that are currently being used must be identified in order to determine scope for improvement.

1.2.2 Deep-level mine-cooling systems

Considering the discussion in Section 1.2.1, a mine's cooling system can be regarded as one of the most important systems on the mine. The cooling systems are responsible for ensuring safe underground working environments and optimising the productivity of mine workers. Mine-cooling systems can have a variety of configurations and layouts that depend on the specifics of an individual mine's service delivery requirements and depths [32]. A well-used method is to combine the use of underground cooling systems with surface cooling systems to cool the underground environment [21]

[26]; however, mines prefer surface cooling systems as they have more capability in terms of heat rejections with an increased COP [33].

Figure 1-7 illustrates a schematic layout of a typical deep-levels mine's surface cooling system. Typical surface cooling systems on a deep-level mine consist of storage dams, precooling towers, refrigeration plants (FPs), bulk air coolers (BACs), and condenser cooling towers [34].

Service hot water (A) with a temperature ranging from 29-30 °C is pumped from underground into the hot dams (B). The service hot water is the water that has been used by the mining block underground. The hot water is pumped with precooling pumps (C) to the precooling towers (D). The precooling towers use the ambient temperatures to cool the hot water by spraying the water into the precool filling while ambient air is sucked in through the filling by fans. The precooling towers cool the water by approximately 2° C depending on the ambient WB temperature having a lower WB temperature than the water. The water then collects in the precooling sump (E). Next, the precooling water is pumped through the refrigeration plants (chillers) (G) by the evaporator pumps (F).

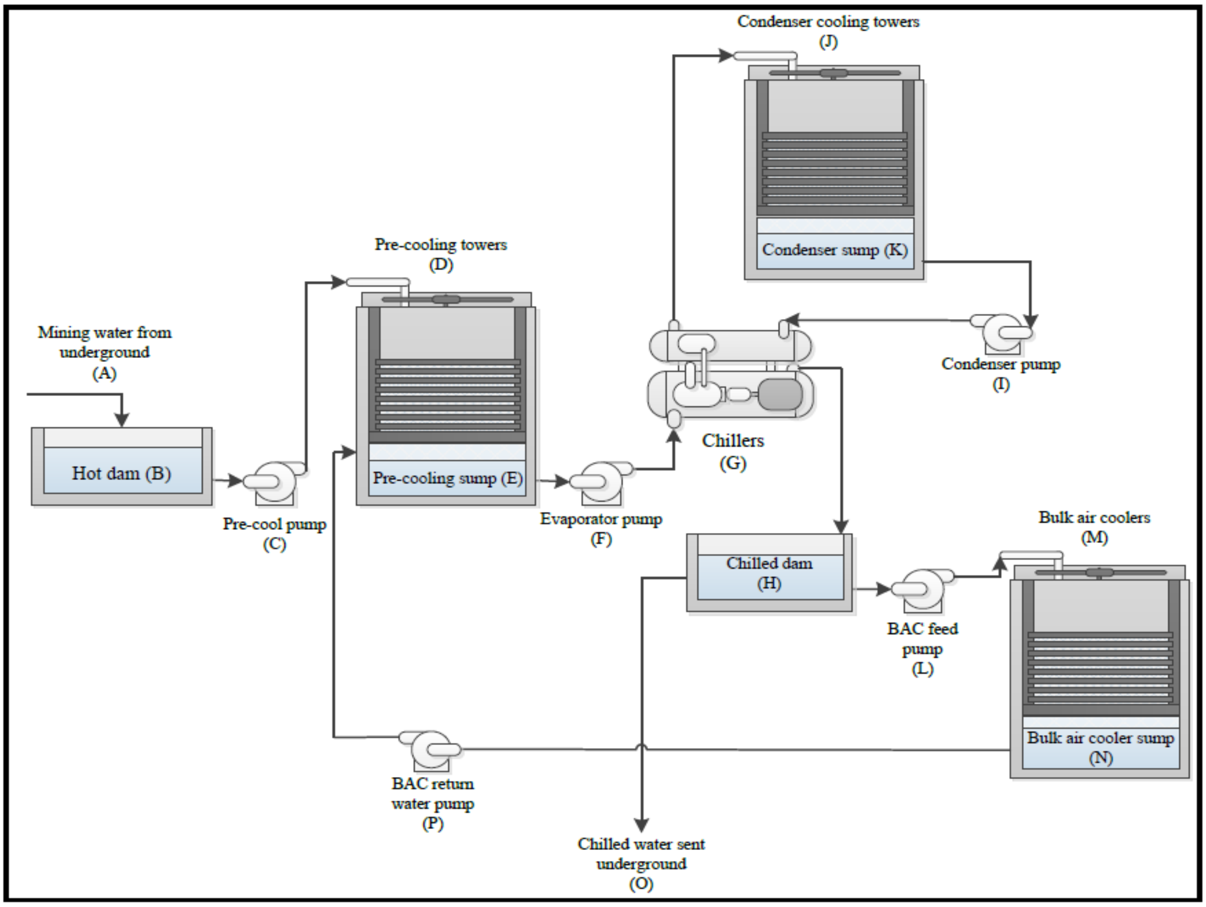


Figure 1-7: Schematic layout of a typical mine-cooling system

After the water has flowed through the chillers, the water is cooled to a temperature between 4 °C and 6 °C and stored in the surface chill dams (H). The chilled water is then gravity-fed underground (O) and pumped to the surface BACs (N). The BACs use the chilled water to dehumidify and cool ambient air. The cold air is then forced into the mine with a series of BAC fans. Once the air is in the shaft, it is sucked through the mine by the main fans. After the water has gone through the BAC, the water is slightly warmer and is collected in the BAC sump (N). The water is then pumped (P) back to the precooling sump (E). The condenser pumps (I) are used to pump condenser water to the condenser cooling towers (J). The condenser cooling towers work in the same way as the precooling towers and are used to reject heat from the chillers into the atmosphere. After the water has gone through the condenser cooling towers, the cooled condenser water is stored in the condenser sump (K) and pumped back to the chillers (G) in a closed loop.

The following sections will provide an in-depth look at each of these components in order to determine which of them can be used or optimised to achieve a combined service delivery and energy efficiency improvement.

1.2.3 Storage dams

Storage dams on deep-level mines are used to store hot or cold water underground and on the surface. On the surface, the dams are used as thermal storage units to create a capacity buffer as the chilled water demand fluctuates throughout the day [23]. The surface chill dams receive water directly from the refrigeration plants and are usually completely closed to prevent any unwanted temperature losses to the atmosphere [35]. To ensure that friction losses are kept at a minimum, the refrigeration plants are placed close to the shaft [36]. Underground storage dams are used to store cold water or hot water that is pumped up or sent down in a cascading format [37].

Surface FPs are used to maintain a set chilled water temperature in the surface chill dams for the purposes of underground cooling and services [17]. Fluctuation in the demand for the stored chilled water can occur, and these fluctuations are primarily attributed to seasonal changes which reduce the ambient temperatures and which affect the number of chillers that must be used [38]. Mines recirculate water from the surface chill dams to the precool sump if the refrigeration supply exceeds the underground water demand and the chill dams reach full capacity [23]. The recirculated water is controlled by throttling a manual valve on a bypass pipeline. This has been proven to be inefficient, and variable flow strategies would be beneficial for these systems [39] [40].

Due to the mine's poor water quality, a continuous sediment build-up occurs in storage dams which severely restricts the capacity and dam-level control [36]. As a result, the dams need to be regularly cleaned to restore dam capacities. The impurities in the water are caused by production water that exceeds the underground settler limits [41].

To ensure optimal dam-level control and maximum storage capacities, thermal storage dams require regular maintenance [42]. If the mine-water quality can be managed and the dam maintained on a regular basis, the refrigeration systems can effectively be controlled on dam levels to save electricity, according to Schutte [23].

1.2.4 Precooling towers.

Precooling towers are used as heat-rejection systems to remove heat from hot service water using ambient conditions. Precooling towers are direct-contact evaporative coolers that are used not only to precool hot service water before it is used by the chillers but also to dissipate heat from the condensers of the refrigeration machines into the atmosphere. Precooling towers use evaporative cooling and convection to extract available cooling from the ambient air, given that the ambient WB temperature is lower than the temperature of the water being cooled [37].

Deep-level mines typically use mechanical draft cooling towers on the surface [33]. These mechanical draft cooling towers have nozzles that are used to spray water into the tower, which causes a series of small droplets to form [44]. While these droplets fall, ambient air is sucked through the tower with a mechanical axial fan, and there is direct contact between the air and the water droplets. The contact time and size of the water droplets together with the pressure drop over the nozzles influence the temperature of the water [44]. These cooling towers can reduce hot water temperatures by 3 to 6 °C [45].

Figure 1-8 illustrates a typical mechanical draft cooling tower that is used on the surface of a deep-level mine. The hot mine water is pumped from the hot dam to the cooling towers. As the water enters the cooling tower, it is sprayed to form droplets in the tower. The droplets fall through a fill that is installed in the tower to increase the contact time between the water and air. Ambient air is sucked in through the filling and droplets with a velocity ranging from between 1.5 and 3.6 m/s forms [36]. The cooled water is then collected in the sump of the cooling towers and pumped to the chillers. The only electricity consumer on the cooling tower systems is the fans used to create the draft and the pumps to reticulate and replace water.

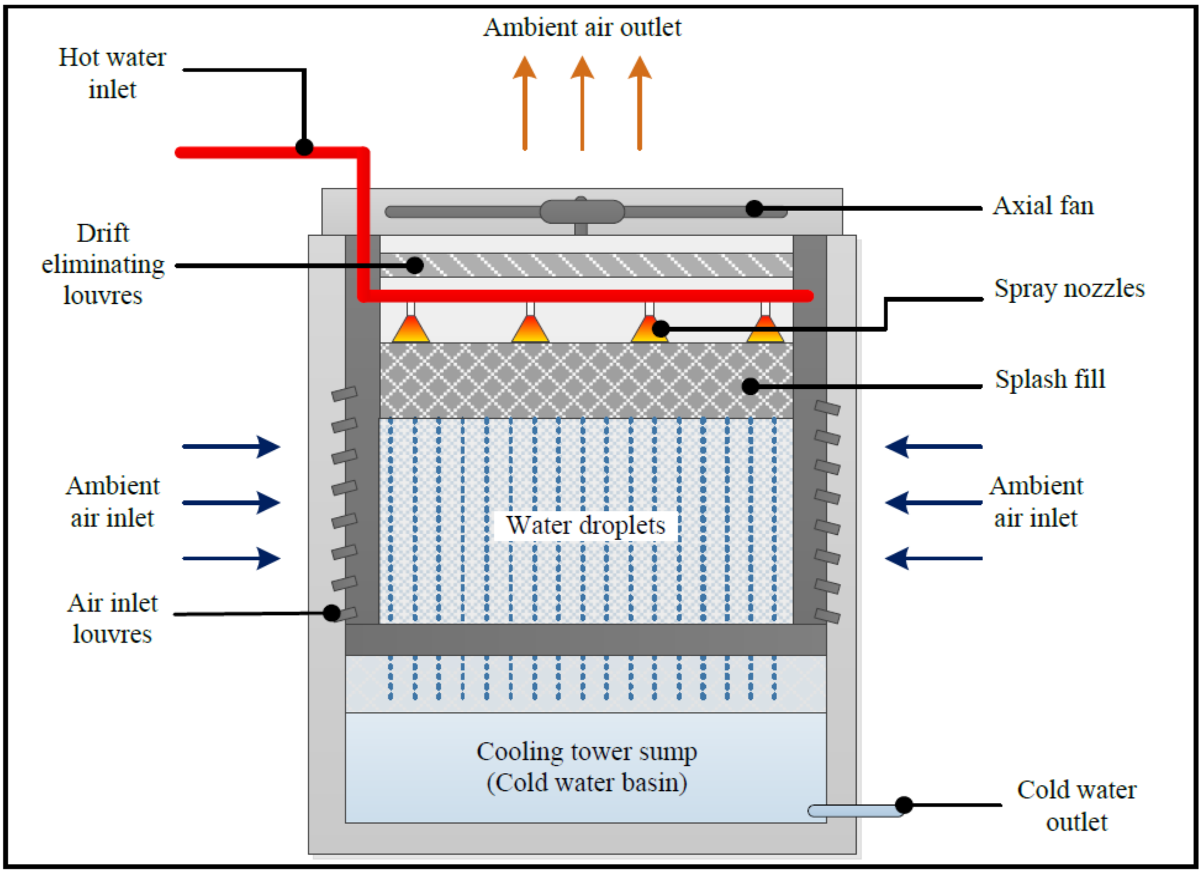


Figure 1-8: Schematic drawing of a cooling tower

Due to the low work input required for cooling towers, the COP tends to be much higher than that of refrigeration systems, and is approximately 30 [36] [46]. The COP of cooling towers can be affected by various operational parameters such as ambient temperatures, water flow rates, and pressures. Inadequate water flow and pressure drop over the nozzles in the cooling tower will cause an uneven distribution of water and affect the amount of water having sufficient contact time with the ambient air [44]. These insufficient flow conditions are also favourable for scaling and fouling which decrease efficiency and cause unnecessary maintenance [10]. The ambient WB temperature can, however, either increase or decrease the performance of the cooling tower; there is, therefore, a direct relationship between the WB temperature and the performance of the cooling tower [14].

Each mine cooling tower is designed for its own operating conditions to produce a desired output temperature. When a lower WB temperature is reached (during seasonal changes) than what the tower was designed for, the water can be over-cooled [14]. The WB conditions, therefore, create an opportunity to utilise the cooling towers to cool the water and thus save electricity on the refrigeration plants that receive the water.

1.2.5 Refrigeration plants

Refrigeration plants are used on deep-level mines to cool hot service water that is pumped from underground. This water is then used by the surface and underground BACs. The mines use surface and underground FPs for cooling. Surface FPs are much more efficient than underground FPs because they do not have heat rejection constraints [36]. Surface refrigeration plants can cool water down to between 3 °C and 6 °C, depending on the design and configuration [37].

FPs are configured to reach a desired outcome. Figure 1-9 shows the different types of configurations that are typically used by mines [37]. The parallel flow configuration (1) is used when the seasonal water-flow demand fluctuates, and the inlet temperature stays relatively constant throughout the year. The series flow configuration (2) is used for variable temperature requirements, where the flow stays constant throughout the year while the inlet temperature fluctuates. The combination of series and parallel flow configurations is used for both variable flow and temperature requirements [47].

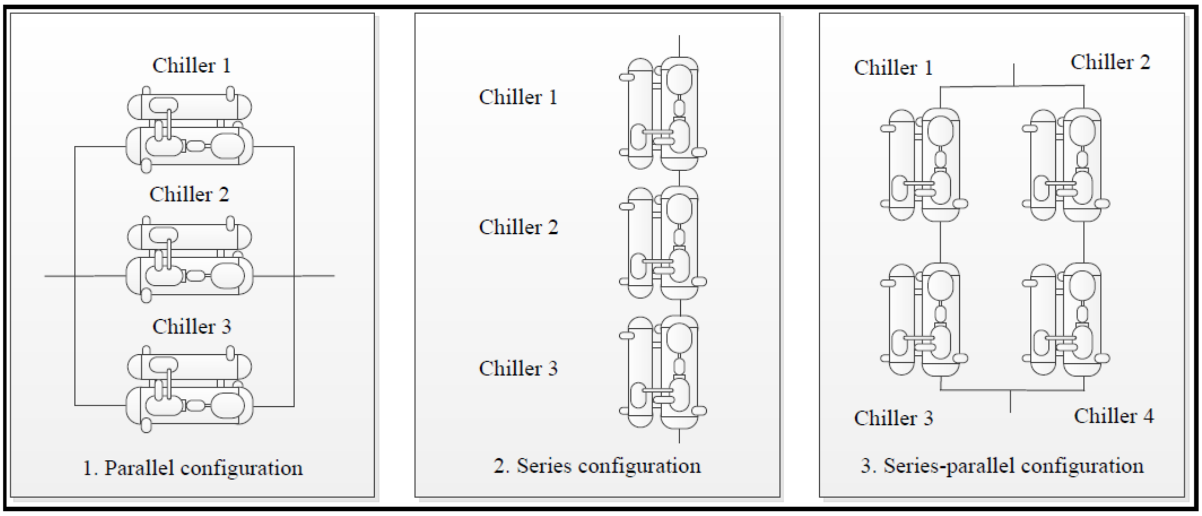


Figure 1-9: Various chiller configurations[10]

The FPs use either a vapour compression or ammonia absorption refrigeration cycle [48]. There are many different types of models and designs of FPs available, but most of the FPs use the same vapour-compression cycle basics. The mining industry uses the vapour-compression cycle because of its simplicity and low operating cost compared with other cycles available on the market [24]. The two working fluids that are suitable for a mine's temperature and pressure ranges are freon (R134a) and ammonia (R717) [49]. Mines prefer to use the freon gas instead of the ammonia because it is less toxic [50].

The vapour-compression cycle used in a mine's FPs is illustrated in Figure 1-10. Superheated freon gas enters the compressor to increase the pressure and temperature of the gas. The heat that is generated by the compressor is rejected by the condenser shell and tube heat exchanger. The gas is cooled by the condenser at a constant pressure, allowing for latent heat transfer. The heat is absorbed by the water in the condenser cycle and rejected into the atmosphere by condenser cooling towers.

The gas flows through an expansion valve to reduce the pressure of the gas. As the gas pressure is lowered by the throttling expansion valve, the phase of the gas changes to a liquid vapour. This low-pressure vapour then enters the evaporator where latent heat transfer takes place between the water that flows in the tubes and the refrigerant in the vessel, thus cooling the service hot water. The gas temperature increases and changes from a subcooled vapour to a superheated gas and flows back to the compressor in a continues cycle [48].

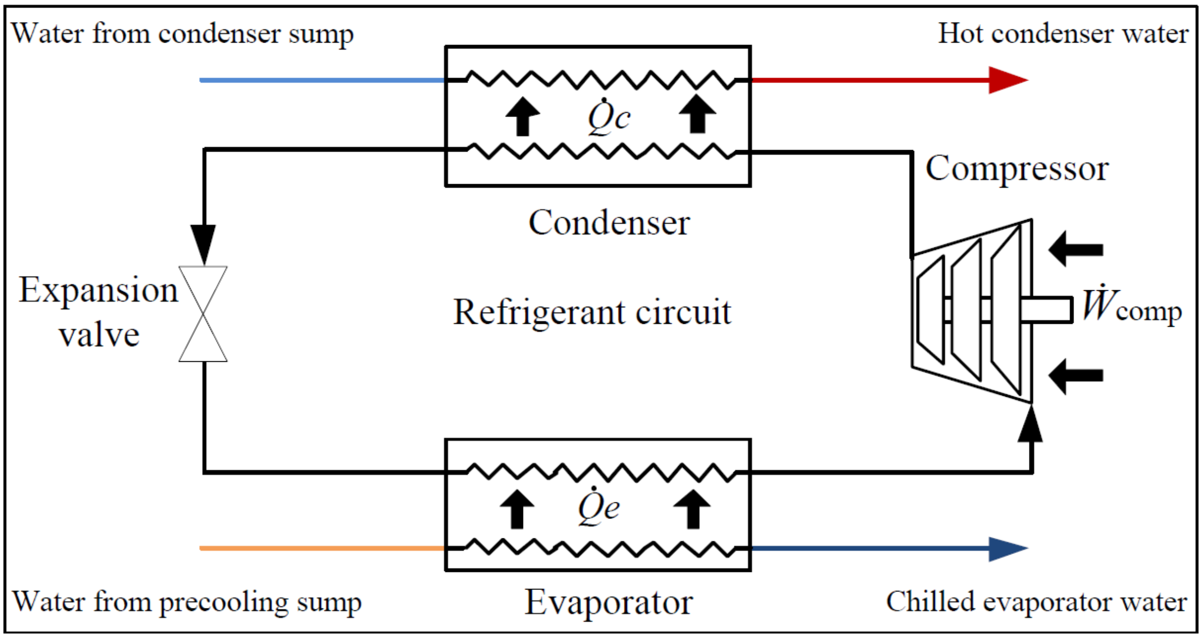


Figure 1-10: Vapour-compression cycle

The compressors are the only components in the compression-vapour cycle that put work into the system as can be seen in Figure 1-10. Based on the system's requirement, the compressor of this cycle can either be a centrifugal or a screw compressor [51]. The desired outlet temperature is controlled by a guide vane on the centrifugal compressor and a sliding valve on the screw compressors [51] [52]. The guide vanes and sliding valve on the compressors control the flow of the refrigerant to reach a desired evaporator outlet temperature [45]. As these guide vanes cut back, the compressor's electricity consumption will also cut back, which is desirable since the compressor is the main contributor of the FP's electricity consumption [37].

The COP of an FP is the amount of cooling that is done compared to the electrical usage of the FP. The COP is largely dependent on the compressor's electricity usage as the compressor is the main power source in the FP. The COP of FPs can be calculated using the following equations [50]:

$$COP = \frac{Q_{evaporator}}{P_{ref}} \qquad \text{(Equation 1.1)}$$

where

COP = coefficient of performance

$Q_{evaporator}$ = energy absorbed by evaporator (kW)

P_{ref} = Compressor motor power (kW)

The heat load is defined as Equation 1.2 [49]:

$$Q_{evaporator} = mC_p(T_{w_{in}} - T_{w_{out}}) \qquad \text{(Equation 1.2)}$$

where

$Q_{evaporator}$ = energy absorption rate by evaporator (kW)

m = water mass flow (kg/s)

C_p = specific heat constant (kJ/kg. K)

$(T_{w_{in}} - T_{w_{out}})$ = Temperature difference between inlet and outlet water of the evaporator

Equation 1.1 shows that refrigeration machines are more efficient with a higher COP and more inefficient with a lower COP value [37]. Refrigeration machines with a large capacity can get a COP of six and smaller capacity machines a COP of three [48]. It is clear from Equations 1.1 and 1.2 that the performance of a refrigeration plant is influenced by the flow rate and inlet temperatures of the evaporator. Parameters such as ambient temperature and scaled-up tubes in the evaporator can also affect the performance of an FP [37]. The opportunity does arise to lower the inlet temperature of the FPs to achieve a combined service delivery and energy efficiency improvement.

1.2.6 Bulk air coolers

BACs are used by deep-level mines to cool ambient air and send the cold, dehumidified air underground. There are two types of BACs, namely horizontal draft and vertical draft BACs. BACs work on the same principal as a cooling tower, but in the reverse direction. BACs use the cold, chilled water temperature from the chillers to cool the ambient air. The cold dehumidified ambient air is then sucked underground.

Extraction fans located on the vent shaft of the mine create negative pressure in the mine, which causes air to be sucked into the main shaft [23]. The air that is sucked in is a mixture of cold BAC air and hot ambient air that is sent underground. Deep-level mines prefer vertical draft BACs to be situated on the surface due to their large cooling capacities [38]. Figure 1-11 illustrates a vertical draft BAC.

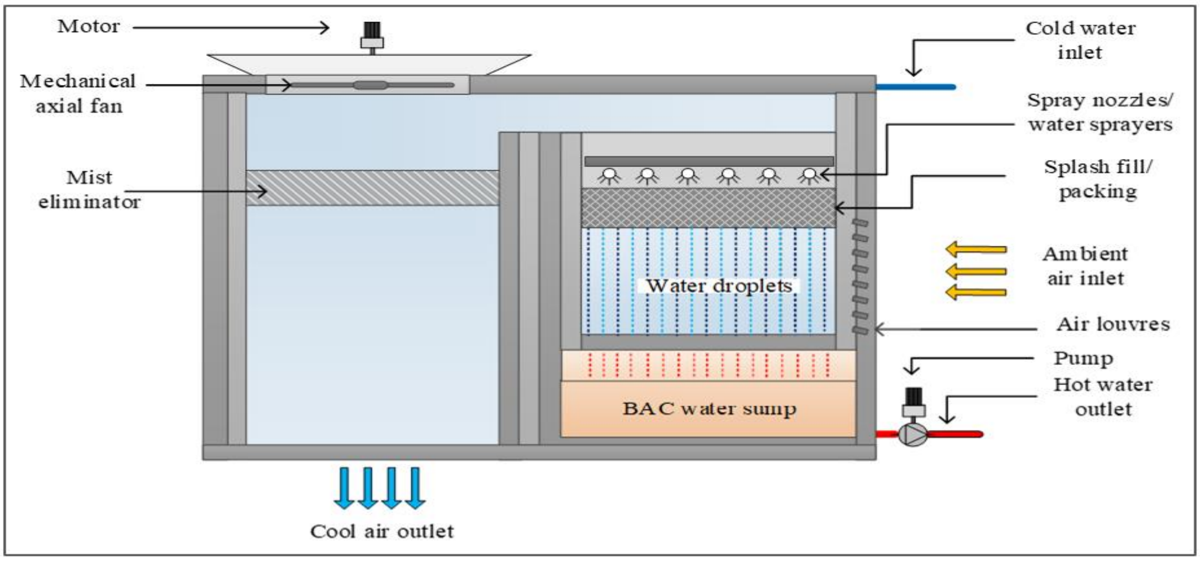


Figure 1-11: Vertical draft BAC [38]

A vertical draft BAC is situated close to the main shaft of a deep-level mine. Ambient air is sucked into the BAC by a mechanical axial fan. While the air is sucked through the BAC, chilled water from the chill dams is sprayed into the BAC by a series of nozzles. The chilled water and ambient air are in direct contact with each other. The chilled water's temperature that is lower than the ambient WB temperature causes heat transfer to take place between the water mist and the ambient air. The ambient air is then cooled and forced into the ducting of the main shaft where it is sucked underground by extraction fans. The cold air goes through a series of mist plates to remove water droplets before it is sent underground. The water mist is collected in the BAC sump where it is pumped back to the precooling dam.

Horizontal draft BACs work on the same principal as vertical draft BACs. The ambient air passes horizontally through the BAC while nozzles spray chilled water into the passing air from above and below. A uniform spray and flow pattern are maintained in the BAC by accurately placing nozzles for optimal BAC performance [38]. The horizontal BACs have a series of cooling stages where the chilled water that accumulates in the BAC sump is recirculated and used in other stages of the BAC. Figure 1-12 illustrates a horizontal forced draft BAC.

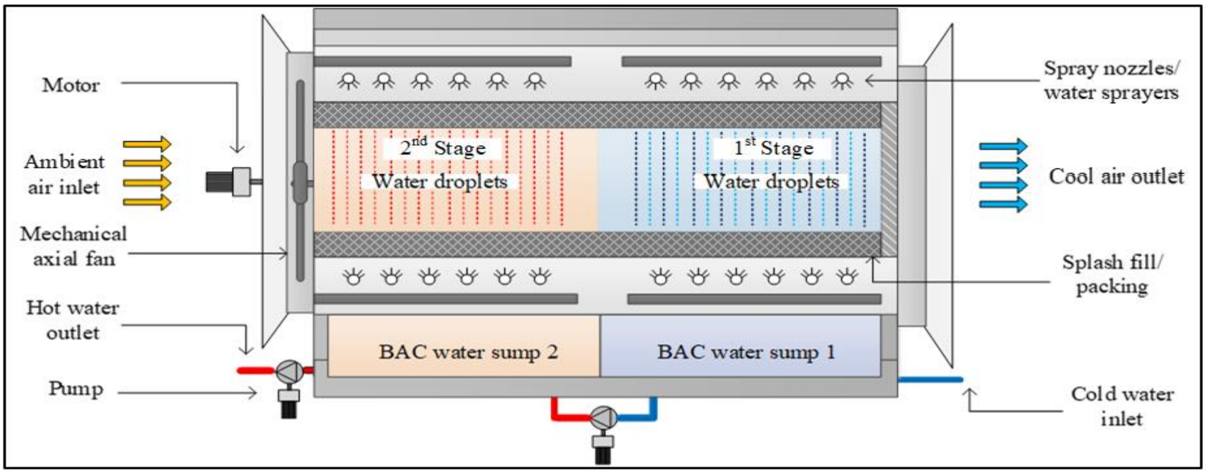


Figure 1-12: Horizontal forced draft BAC [38]

On the surface, the BAC sump water is pumped back to the precooling dam. This helps to cool the precooling dam temperature because the BAC sump temperature is usually lower than the precooling dam temperature. The inefficient and ineffective performance of a BAC can increase the outlet air temperature, which will lower the COP of the cooling system significantly [38]. The COP of the refrigeration plants can be affected by the water side efficiency of the BACs [53]. The water side efficiency of a BAC is calculated by using Equation 1.3.

$$Eff_w = \frac{T_{wo} - T_{wi}}{T_{ai(WB)} - T_{wi}} \qquad \text{(Equation 1.3)}$$

where

EFF_w = water side efficiency

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

T_{wi} = water inlet temperature [°C]

$T_{ai(WB)}$ = WB temperature of ambient air [°C]

On closer inspection, Equation 1.3 shows that the water side efficiency is expressed in terms of a range and an approach [37]. The range is the difference between the water inlet and outlet temperatures and the approach is the difference between the inlet ambient WB temperature and the water outlet temperature [54]. As per Equation 1.3, it is clear that the performance of a BAC is dependent on the inlet temperatures of the water and ambient air. This means that the BAC can typically be switched off during the winter months as the WB of the ambient is too close to the chilled water temperatures [36]. It can also potentially mean that the cold ambient air in winter can be used to cool the chilled water. This needs further research, as it can potentially lower electricity demand in wintertime.

1.2.7 Pumps

Pumps are part of all the surface cooling systems that were explained in the sections above. The pumps' main purpose is to reticulate water between different cooling systems. All these pumps are known as auxiliary pumps, as they can be controlled independently from the cooling system they supply. The condenser and evaporator pumps that reticulate the chiller's water will be explained in this section, since the basic principles for all the other pumps are the same. The pumps that supply the FPs with water can be configured in parallel or in series. Figure 1-13 illustrates the different pump layouts.

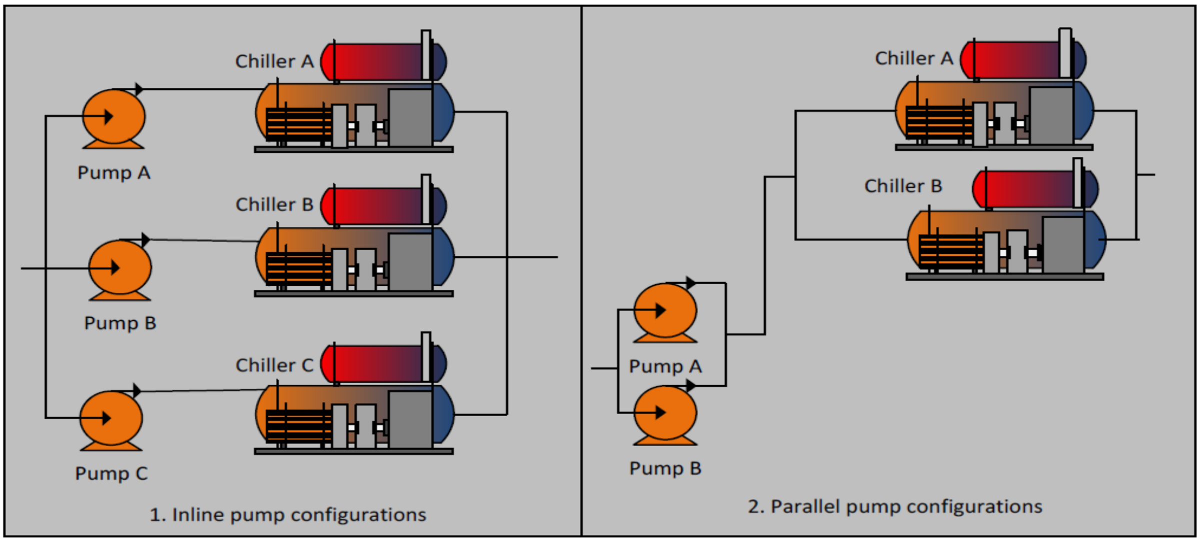


Figure 1-13: Pump configuration

In Figure 1-13, (1) illustrates an inline pump configuration and (2) a parallel pump configuration. The parallel configured pumps pump water into a manifold that supplies either a single FP or multiple FPs. The inline pump configuration pumps to an FP that is configured in line with the pump.

Parallel configured pumps can be found on FPs that are configured in series or parallel-series configurations. This type of pump-plant configuration increases redundancy in the system, as maintenance or replacing a pump can easily be done without affecting the water flows of the plants if the parallel configured pumps have a spare isolated pump. However, identifying whether maintenance is needed for a specific pump in a parallel configuration can be difficult, as mines usually only install a flow meter on the manifold and not after each pump.

Inline connected pumps are commonly found on FPs that are connected in series with the inline FP. In this configuration, areas that need maintenance are easily detected as water flow will drop through the fridge plant. This can, however, be costly for the mine, as the potential FP needs to be stopped in order to conduct the maintenance. These pump-plant configurations are usually configured in parallel with other pumps and plants. With this configuration, the water flow to each FP can easily be controlled, unlike parallel-flow configured pumps where water is fed from a manifold.

Due to the pressure drop caused by the common manifold in parallel configured pumps, a valve is required on the inlet of the FP to control the flow rate [36]. Inline pump configurations have the opportunity to be controlled by VSDs (variable speed drives), as the speed reduction of the pump will only affect the individual FP [35]. Other components like the BAC pumps can also be controlled with VDSs, as stated by Van Jaarsveld [55].

1.2.8 Summary

All these surface cooling systems work together to send chilled water and air down the mine. The mine cannot operate without any one of these components and, as such, they are crucial to the mine's production since all these systems influence the underground water and air temperatures. These systems are all electricity-intensive, but the one cooling system that uses the most electricity is the FP's compressors.

All the other cooling components are essentially connected to the FPs and hence influence the FPs' power consumption. However, all the systems are influenced by ambient temperature and seasonal changes; therefore, the effect of seasonal changes on cooling auxiliaries and system performance will be investigated in the following section in order to determine whether they can be used to the mine's advantage.

1.3 Cooling auxiliaries and seasonal changes

This section will investigate the effect of seasonal changes on cooling auxiliaries. All the cooling systems, such as BACs and cooling towers, can be controlled separately from the refrigeration plants on the surface. These cooling systems are, therefore, known as cooling auxiliaries [36]. These cooling auxiliaries are known to be affected by seasonal changes as stated in the previous section. These seasonal changes refer to when the ambient temperatures begin to change with the seasons. The key seasonal change that will be addressed in this section is summer to winter. During this change, some of the mines switch off their cooling auxiliaries for maintenance due to the ambient air being sufficiently cold and the cooling requirements that, therefore, decrease [36].

During the seasonal change from summer to winter months (June to August in South Africa), the ambient DB temperatures and relative humidity drop significantly as can be seen in Figure 1-14. The relative humidity is the amount of water vapour that dry air contains [48]. The dryer the ambient air, the lower the relative humidity and the lower the WB temperature. The WB temperature is known as the temperature to which air can be cooled by means of evaporation [48] [56]. A lower WB temperature in winter months has a greater influence on the cooling auxiliary's performance, as the auxiliaries largely depend on WB temperature.

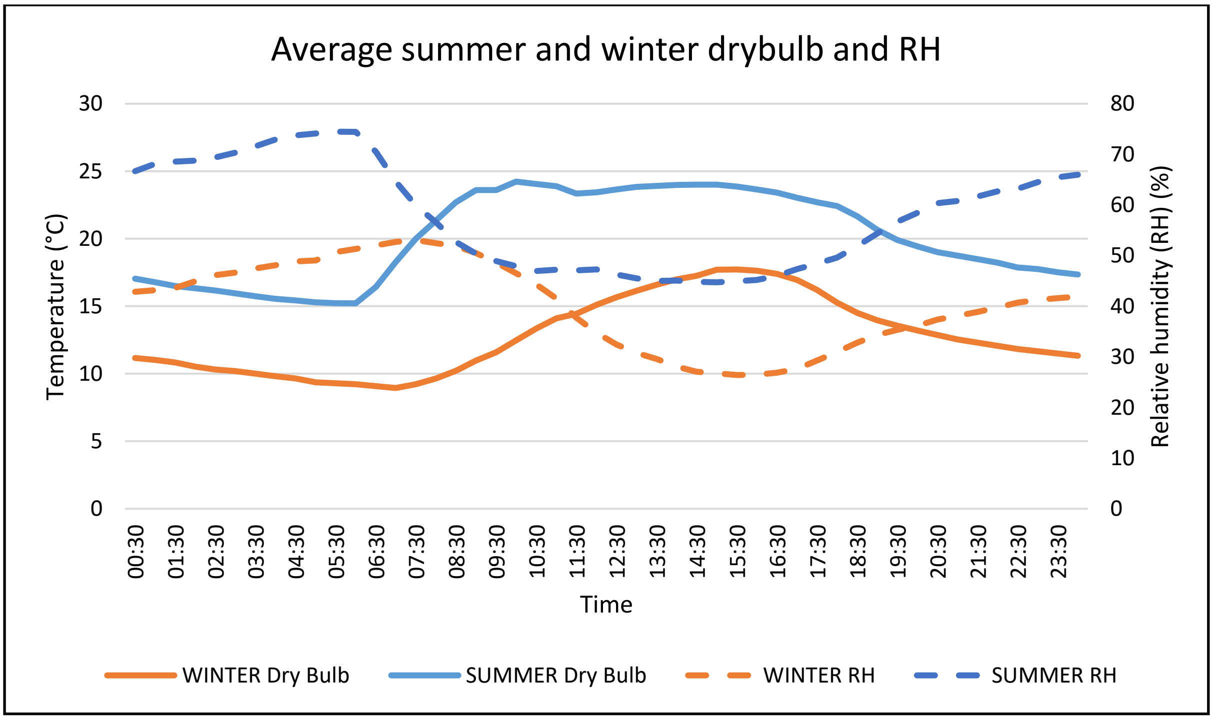


Figure 1-14: Winter and summer daily average ambient psychrometric conditions

The cooling auxiliaries that are largely affected by ambient WB temperatures are surface precooling towers, condenser towers, and BACs. The precooling and condenser towers are used as heat-rejection systems that reject heat from hot underground and FP condenser water. The towers use the ambient WB temperature to cool the service hot water, and the BACs use the chilled water to cool the ambient

WB temperature. Both these systems clearly show the influence a drop in ambient WB temperature will have on them.

The effect of the ambient WB temperature on the cooling towers can be explained by Equation 1.4. This equation is used to calculate the effectiveness of precooling towers, and can be defined in terms of a range and an approach. The range is the difference between the inlet and outlet of the water, and the approach is the difference between the outlet cold water and the inlet ambient WB temperature [44]. The approach is a critical factor in the performance of the cooling tower – the lower the approached value, the better the performance.

$$Eff_w = \frac{T_{wi} - T_{wo}}{T_{wo} - T_{ai(WB)}} \qquad \text{(Equation 1.4)}$$

where:

EFF_w = water side efficiency

T_{wo} = water outlet temperature

T_{wi} = water inlet temperature

$T_{ai(WB)}$ = WB temperature of ambient air

The BAC’s effectiveness equation stated in the previous section is very similar to the precooling tower’s equation for effectiveness (Equation 1.4) and is also defined in terms of a range and an approach with the only difference being that the BAC’s heat transfer is in the opposite direction. Heat is rejected from the hot water into the ambient air in the precooling towers, and in the BACs, the chilled water absorbs the heat from the ambient air, hence the approach of a BAC being the difference between the ambient air WB temperature and the inlet water temperature [44]. The closer the WB temperature gets to the inlet water temperature, the less effective the BAC becomes.

During the winter months, the ambient WB temperature can drop below the BAC inlet water temperature. This is when BACs are deemed most inefficient and are, therefore, switched off for maintenance [44]. However, during this time, the BACs can be utilised as a precooling tower. Table 1-1 shows a theoretical depiction of how a BAC’s effectiveness and cooling duty approach zero as the ambient WB temperature approaches the inlet water temperature. As the WB temperature drops below the inlet water temperature, the water can , be cooled down as in a precooling tower.

Table 1-1: The effect of WB temperature on a BAC

T_{wi} (°C)	T_{wo} (°C)	$T_{ai(WB)}$ (°C)	Range (°C)	Approach (°C)	BAC effectiveness	Water cooling duty (kW)
5	9	12	4	7	57	2966.4
5	8	10	3	5	60	2224.8
5	7	8	2	3	66	1483.2
5	6	7	1	2	50	741.6
5	5	3	0	-2	0	0
5	4	2	-1	-3	33	-741.6
5	3	0	-2	-5	40	-1483.2

The water flow and water inlet temperature are kept constant as the BAC receives water from the FPs, which maintains on a set outlet temperature between 4 °C and 6 °C [44]. According to Table 1-1, as the WB temperature gradually drops, the BAC starts to act as a cooling tower. This can potentially help to cool the chilled water. This cooled chilled water can potentially be sent back to the precooling sump to ultimately reduce the FP inlet temperatures.

The refrigeration plant's COP is largely dependent on the efficiency and effectiveness of the condenser towers, precooling towers, and BACs [53]. During the winter months, the refrigeration plants receive lower inlet temperatures from the precooling and condenser towers, largely because of the lower WB temperatures. This causes FPs to cut back on their guide vanes as the cooling requirement decreases. The COPs of lagging FPs that run in series with leading machines drop significantly. Inefficient FPs are then switched off during wintertime [36]. The same volume of water is then cooled to the desired set point by the remaining FPs.

The condenser cooling towers help the remaining FPs by reducing the average condenser temperature during wintertime. This improves the FP COP by lowering the required condenser refrigerant pressure[45]. However, the condenser temperature reduction is limited, as the condenser delta T needs to stay in the FP design parameters to prevent the FP from tripping out [24]. The precooling towers contribute the most by switching off FPs and helping remaining FPs to achieve the chilled water set point during the winter months. As the WB temperature drops, the outlet water temperature of the precooling towers also drops, reducing the cooling requirement of the FPs. The BACs also affect the FP's inlet temperature by cooling down the precooling sump. This cooling of the sump almost always takes place, as the BAC outlet temperature is never higher than that of the precooling tower outlet water. It is the efficiency of the BAC that determines by how much the sump will be cooled.

We can, therefore, conclude that the cooling auxiliaries are influenced by seasonal changes. The precooling towers benefit from the fact that they can deliver lower outlet temperatures to the FPs.

The effects on the BACs are both negative and positive because while the WB temperature decreases the efficiency of the BAC, it can turn the BAC into a precooling tower and help to cool precooling sump temperatures. However, both these cooling auxiliaries influence the FPs' COPs by helping to cut back on compressor guide vanes, which is beneficial in wintertime when electricity is 300% more expensive. Investigating new ways to utilise surface cooling auxiliaries during seasonal changes to improve energy efficiency will greatly benefit the mining industry.

1.4 Previous research

Mine-cooling systems in the deep-level mining sector are a well-researched topic. Most of the research has focused on demand-side load shifting projects and improving energy efficiency and has been implemented by ESCOs (energy saving companies). This enables the researchers to validate their research.

From the sections discussed in this study thus far, it can be concluded that mine-cooling systems are energy-intensive and, therefore, require new initiatives that will help to reduce the electricity consumption of these systems while improving or maintaining service delivery. Furthermore, ambient conditions can improve the performance of these systems. Therefore, this section will review and evaluate all the research that has been done on mine-cooling systems to establish which control philosophies can be used to improve these systems and which of these control philosophies were based on the use of ambient conditions.

The mine-cooling systems that were researched include BACs, precooling towers or FPs, since they are the main components in a mine's surface cooling system. The control philosophies that were identified in all the studies were pump-flow control, reconfiguration of existing equipment, set-point control, the full automation of this equipment, and seasonal control. All these control philosophies managed to improve energy efficiency or service delivery. A short description of each author's research is listed below, followed by Table 1-2 that summarises each author's findings according to the specific control philosophy that was implemented.

Maré, P [10] – Maré conducted a study on existing implemented energy-efficiency DSM projects and developed strategies to improve and maintain project sustainability. Maré identified all these projects' inefficiencies and developed strategies on how to overcome the problems associated with them. These strategies were implemented on new projects as well as on old projects where energy savings had been neglected. Both these projects realised a payback period of 7 and 17 months, respectively. Maré used Process toolbox (PTB) simulation software to validate his research's accuracy compared to his case studies. His research did not include seasonal control but only mentioned that the BACs and chillers were switched of during winter months.

Buys, JL [10] – Buys conducted a study on implementing DSM projects on platinum mine-cooling systems. He achieved a power saving on cooling auxiliaries by installing variable speed drives on the auxiliaries and the BAC pumps. The installation of VSDs improved the cooling auxiliaries' efficiency by controlling the water flow to match the cooling supply. His research was implemented on a case study and achieved respectable savings. His research did not include the seasonal control of cooling auxiliaries; however, his study did include that flow through the BAC was reduced during winter months due to overcooling.

Moropa, TS [57] **–** Moropa conducted a study on implementing DSM projects on deep-level gold mines. His study focused on load reduction on surface cooling systems during Eskom's peak periods. The studies were implemented on two different mines – one with a closed loop cooling system and one with a semi-closed loop cooling system. A respectable cost saving was achieved while adhering to the operational safety boundary of the mine. His study only included load shifts during the summer and winter months and not seasonal control on the cooling auxiliaries.

Nel, AJH [58] – Nel conducted a study for developing a strategy to optimise the sustainability of existing DSM projects on surface refrigeration systems. Nel identified the factor that had been affecting the two mines' existing DSM refrigeration projects and developed a strategy accordingly for sustainability and optimised performance. The strategy includes maintaining electrical cost-saving and optimising refrigeration systems by detailed monitoring, control, and reporting measures. The study validation did prove a sustainable average daily power saving. Nel used PTB simulation software to validate his research's accuracy when compared to his case studies. Nel's study did not include seasonal control of mine-cooling auxiliaries.

Oberholzer, KJ [24] – Oberholzer researched the feasibility of reconfiguring mine-cooling auxiliaries for optimal performance. Oberholzer used PTB simulation software to prove that improved service delivery is possible by reconfiguring a mine's cooling systems. The implementation on the reconfiguration was done and used to validate the simulation. The simulation proved to be accurate, and other configurations were also considered. Respectable savings were achieved with different chilled water set points. Oberholser's study developed a reconfiguration control philosophy for summer- and wintertime but did not focus on seasonal control in terms of utilising cooling auxiliaries.

Schutte, AJ [23] **–** Schutte conducted a study for developing a strategy for the implementation of load management and energy-saving projects on mine-cooling and ventilation systems. Schutte also developed a peak clip project on the surface BAC that was part of the strategy. The BAC project was implemented and found to have no effect on underground temperatures. The load shift of the BAC achieved an annual saving. Schutte's study did prove that a two-hour load shift is possible on surface BACs and that additional energy saving could be realised if the BAC operated under design water flow specifications. Schutte's study did not include seasonal control but did prove that the air is sufficiently cold for the surface BAC to be switched off during the winter months.

Du Plessis, GE [23] **–** Du Plessis conducted a study that was based on developing a strategy for DSM projects on large cooling systems of deep-level mines. The study focused on the use of VSD to match the cooling system's supply with the demand. The strategy includes the modulation of all surface cooling systems. The strategy feasibility was simulated and verified upon implementation. The strategy was implemented on four large gold mines. Du Plessis's strategy realised a total power saving of 35.4%. The study did not include seasonal control and only focused on variable flow and set point control.

Holman, AM [36] **–**Holman researched the advantages of advanced monitoring on mine-cooling auxiliaries. Holman's study focused on quantifying the effects of maintenance periods on the machine's efficiency and life expectancy. His theory was developed by using PTB simulation software. The study was implemented as a DSM project on a gold mine and proved that the saving potential of mine-cooling systems can be improved by regular maintenance. His study did not include seasonal control, but his research did indicate that cooling auxiliaries can be switched off during the winter months because of the decreased cooling requirements that the low ambient conditions bring in winter.

Crawford, J [59] **–** Crawford conducted a study on developing a fully automated dynamic control strategy. The strategy focused on optimising the control mine-cooling systems by reducing operational costs and improving system sustainability. The strategy was formulated as an integrated dynamic temperature set point algorithm and dry-bulb temperature prediction model. The model was simulated by using PTB and verified upon implementation. The simulation had a 4% correlation error. The model was implemented as a TOU project (DSM) and achieved a 45.7% power reduction. Crawford's study did not include seasonal control, but his simulation did account for a winter and summer baseline.

Van Jaarsveld, A [55] **–** Van Jaarsveld researched the development of a fully integrated BAC control system. The BAC controller was developed and combined various inputs and constraints to determine the outcome. The BAC controller was incorporated in the Real-time Energy Management System

(REMS) and implemented on three mines. Power usage was reduced during the evening peaks via load shifting that was controlled by Van Jaarsveld's developed system. Van Jaarsveld did not include seasonal control of BACs in his calculations and controller because they were switched off during the winter months.

Peach, PFH [60] **–** Peach conducted a study on developing an optimised control strategy for deep-level mine refrigeration systems. The strategy was developed with PTB simulation software and verified by a series of practical tests on respective refrigeration systems. The strategy focus was to load-shift outside Eskom peak periods while still maintaining chilled water set points. The strategy achieved respectable savings for the mine. The study proved that sustainable cost saving is possible on deep-level mines by implementing optimised control strategies. Peach's study only focused on optimised control strategies during summer months; however, load management was implemented during winter months in one of the case studies.

Du Plessis, JJL [61] – Du Plessis conducted his study on reconfiguring the inlet guide vanes on the main surface fans of a mine-cooling system for improved energy efficiency. The study reduced the underground air flow but achieved a substantial energy efficiency saving of 13.03 MW. Du Plessis did not focus on a different control strategy for the winter months.

Greyling, J [26] – Greyling conducted his study on the feasibility of utilising air-cooled units or chilled water coolers in a deep-level mine. His study concluded that air-cooled units are preferred, and that the implementation of these units reduces the total load required from the surface BACs. Greyling's study did not focus on a winter control strategy but it did highlight that surface BACs' cooling requirements decrease during the winter months.

ELS, R [62] – Els conducted his study on implementing load-shifting initiatives on mine surface and underground cooling systems. He focused on developing a strategy for implementing a load reduction on refrigeration plants during the Eskom peak periods. His strategy was validated by simulation software and achieved a total load reduction of 19 MWh. Els did not mention any winter control strategies for load-shifting refrigeration plants.

Faramarz, P [63] – Faramarz conducted a study on the feasibility of using BACs to reduce natural gas costs by helping to pre-heat the Canadian winter ambient air before it enters the bulk air heaters to be sent underground. The strategy focused mainly on using hot water from underground and sending it through surface BACs to heat up the ambient air, which helped to achieve a large natural gas saving. The hot water that was sent through the BACs was also cooled by the -7 °C ambient air and sent back underground to be used by the underground BACs.

GUNDERSEN, R. E [66] **–** Gundersen conducted a case study on the feasibility of controlling mine-cooling systems on demand. The study focused on the automation of ventilation and cooling systems like ventilation fans and fridge plants. The study achieved improvements by live interaction between ventilation networks and live monitoring. The study did not specifically include any winter control philosophy.

Casella, F. [67] – Casella conducted a study in developing a cooling tower control stategy that minimises the combined enegy consumtion of the cooling tower circulation pumps and fans. The developed stategy focused on monitoring the ambient WB tempertature and controlling the circulation pumps with a variable speed drive. The stategy was not implemented, but an estimated saving of 200 000 EUR was calculated if the stategy was implemented over a year.

It is evident from all the research authors that the topic of mine cooling is a well-researched and documented field. Most of the research primarily focused on DSM projects done with varying control philosophies such as flow control, reconfiguration, set-point control, and automation. All of these philosophies were implemented on the particular mines and achieved either an energy efficiency or service delivery improvement. Table 1-2 illustrates all the authors together with their relevant research.

Table 1-2: State of the art table

Authors	**Mine Cooling System**		**Control Philosophy**				**Improvement**		**Combined improvement**
	BACs	**Precooling towers**	**Chillers**	**Flow control**	**• Reconfiguration** **• Set-point control** **• Automation**	**Seasonal control**	**Energy efficiency**	**Service delivery**	
[10]	✓	✓	✓	✓	✓	×	✓	×	×
[14]	✓	×	×	✓	×	×	✓	×	×
[57]	✓	✓	×	✓	×	×	×	✓	×
[58]	✓	✓	✓	✓	×	×	✓	✓	✓
[24]	✓	✓	×	✓	✓	✓	✓	✓	✓
[23]	✓	×	✓	✓	×	×	✓	✓	✓

[23]	✓	✓	×	✓	×	×	✓	×	×
[36]	✓	✓	✓	✓	×	×	✓	×	×
[59]	✓	✓	✓	✓	✓	×	×	✓	×
[64]	✓	×	✓	×	×	×	×	×	×
[55]	✓	✓	✓	✓	×	×	✓	×	✓
[60]	×	×	✓	✓	✓	×	✓	×	×
[61]	×	×	×	✓	✓	×	✓	×	×
[26]	✓	×	×	×	×	×	×	✓	×
[62]	×	×	✓	×	×	×	×	✓	×
[63]	✓	×	×	×	×	✓	✓	✓	✓
[66]	×	×	✓	×	✓	×	✓	×	×
[67]	×	✓	×	✓	✓	×	✓	×	×

Table 1.2 indicates that multiple control philosophies have been implemented on mine-cooling systems over the years. Most of these control philosophies did mention colder ambient conditions in wintertime but did not include it in their strategies to be used to the mines' advantage.

Oberholzer did, however, create at strategy for summer and winter months [24]. The winter strategy achieved better savings, since the reduced cooling requirements on the cooling systems means less power consumption, but it did not focus on utilising the cold winter conditions. Faramarz created a winter control philosopy that focused on utilising the cold ambient conditions with the BAC to the mine's advantage. Casella developed a stategy to control the cooling towers' circulation pumps by using the WB temperature as a control parameter.

Not all the control philosophies achieved a combined service delivery and energy efficiency improvement as can be seen in Table 1.2. Therefore, a seasonal control that uses the cold ambient conditions to the mine's advantage together with a philosophy that gives a combined improvement is a field that potentially offers scope for improvement and thus needs to be researched.

1.5 Need for the study

From the sections discussed in this study thus far, it can be concluded that electricity cost is a major concern for intensive electricity users in South Africa. Electricity costs have increased by 300% over the last ten years and the forecasted increases are set to be higher than inflation [12]. This is not favourable for deep-level mines, as they need to get deeper to reach their deposits. At these deeper levels, higher VRTs are reached, which implies increased cooling requirements that demand higher electricity consumption. Cooling systems were identified as one of the highest electricity consumers on deep-level mines, as the average cooling system consumes 25% of their total electricity.

Research on surface cooling systems shows that cooling is an integral part of deep-level mining. These cooling systems are associated with high electricity costs, especially during the winter months when electricity consumption is on average three times higher. Therefore, new ways are needed to reduce the energy usage of these cooling systems.

All surface cooling systems and the different control philosophies that have previously been implemented on them were researched. Each of these control philosophies yielded either a service delivery improvement or an energy efficiency improvement. From these researched philosophies, seasonal control was identified as a field with the potential to achieve a possible improvement in both service delivery and energy efficiency by utilising the colder winter conditions.

Therefore, the need to optimise the performance of mine cooling systems in terms of cost saving and sufficient cooling over seasonal changes has been identified in the literature.

The objectives of this study are hence to:

- develop a control strategy for mine-cooling systems over seasonal changes,
- identify and quantify the associated energy efficiency and cost savings of the strategy, and
- maintain or improve service delivery in terms of mine-cooling systems.

These objectives will be achieved by analysing surface mine-cooling data during seasonal changes and developing a strategy based on the potential that was found in the data. This strategy will then be simulated and tested on a deep-level gold mine. Thereafter, the strategy will be optimised through simulation and then implemented.

1.6 Overview

Chapter 1: Literature study – This chapter introduced the study and the concern of electricity cost rises for gold mines in South Africa. The electricity-intensive cooling systems on gold mines were discussed, followed by the effect of seasonal changes on cooling systems and the existing saving initiatives, which were identified and analysed. The need for the study that arose from the literature was defined and discussed.

Chapter 2: Methodology – The methodology for developing a seasonal control strategy will be presented in this section. The methodology will follow a step-by-step approach on how to develop a seasonal control strategy on a deep-level gold mine.

Chapter 3: Results – This chapter will discuss the methodology that was implemented on a case study and the seasonal control strategy that was developed for the mine's specific surface cooling system. The strategy was simulated, verified, and validated upon implementation, and was then optimised through simulation.

Chapter 4: Conclusion – This chapter will discuss the outcomes of the dissertation and make recommendations on what can be changed and improved in the study.

2. Methodology to utilise cooling auxiliaries for seasonal changes

2.1 Introduction

The research that was conducted in Chapter 1 will be used to develop a methodology and control strategy for utilising cooling auxiliaries for improved energy efficiency and maintained or improved service delivery during seasonal changes. Figure 2-1 presents an overview of the methodology that will be discussed in this chapter. The research method used in this section for developing the methodology was adapted from Peach [60] and Oberholzer's [24] studies, as they have proven to have developed sufficient and successful control strategies.

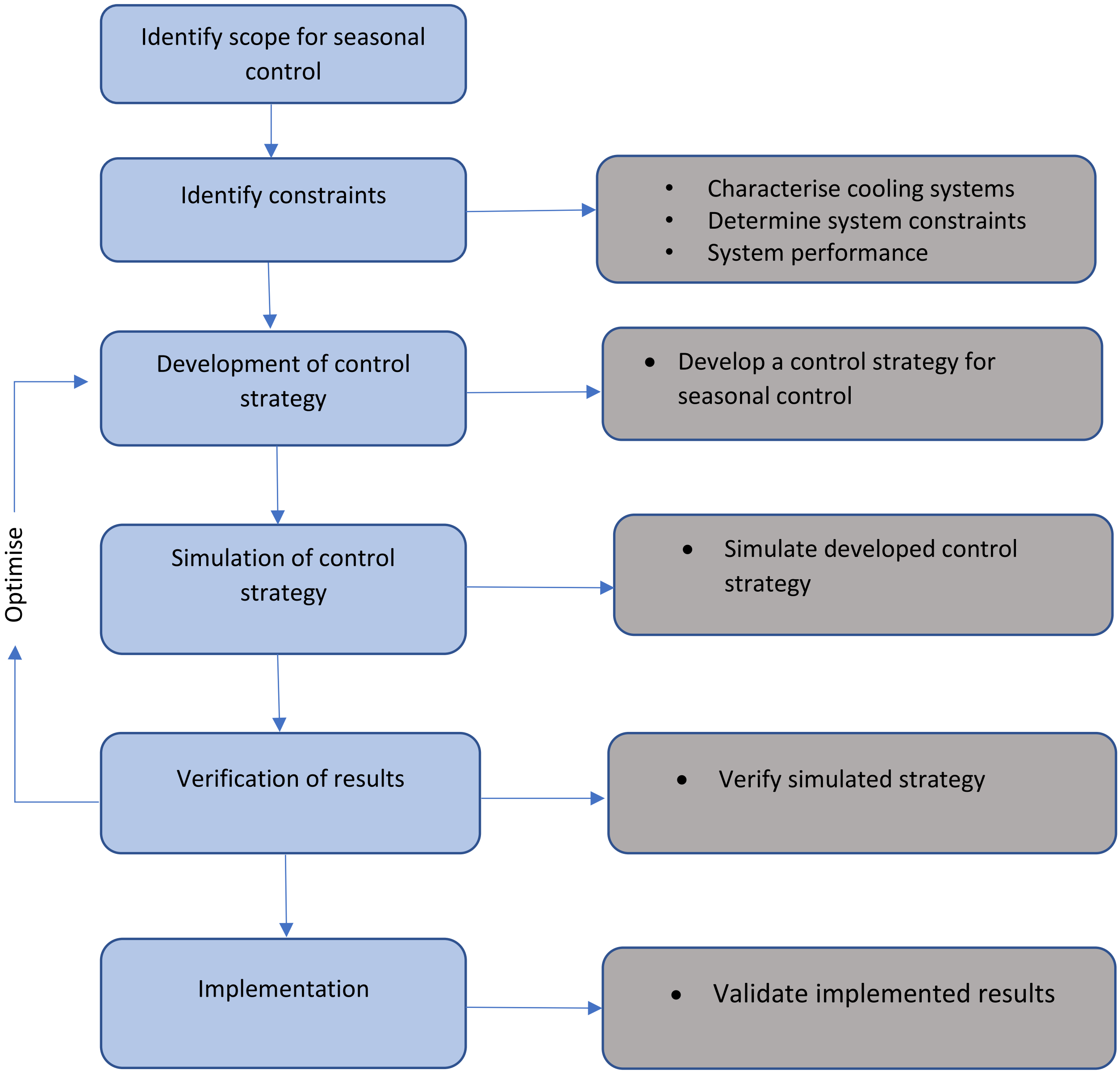


Figure 2-1: Methodology

The first step in developing a seasonal control strategy will be to identify cooling systems for seasonal control. All these system constraints must be evaluated in order to understand the extent of the effect that seasonal control will have on the cooling systems. After the constraints have been evaluated, a seasonal control strategy will be developed, simulated, verified, and validated.

The strategy will then be optimised by repeating the development and simulation phases until the strategy produces the best possible service delivery and energy efficiency outcomes. The optimised control strategy will then be implemented, and the results validated.

2.2 Identifying scope for seasonal control

Due to the increasing demand for electricity in South Africa and Eskom's shortcomings in providing sufficient electricity, the electricity price has risen by 300% over the last ten years. These price increases put the mines under excessive financial pressure, and they are thus forced to save where they can, especially during the winter months when electricity tariffs are three times higher than in the summer months as stated in Chapter 1.

Gold mines in South Africa reduce the usage of intensive electricity users such as cooling systems during wintertime due to the decreased cooling requirements that the lower ambient conditions bring. Potential scope, therefore, will be determined by estimating the potential to utilise the lower ambient condition with the cooling auxiliaries to improve service delivery and energy efficiency on the already scaled-down machines.

The first step will be to consult with mine personnel to determine the scope for seasonal control on their specific system. Temperature data must be collected to verify the potential. The scope will be identified from the data as illustrated by the following example:

Mines are already using the lower ambient conditions to their advantage by switching off BACs and refrigeration plants during the winter months, although a further scope must be identified for utilising the lower ambient conditions (WB temperature) with the cooling auxiliaries to reduce water temperature.

Figure 2-2 is an example that indicates the inlet, outlet, ambient and WB temperature profiles where further scope is present. As the ambient conditions lower, the WB temperature drops below the inlet water temperature of the BACs and begins to cool the outlet water temperature.

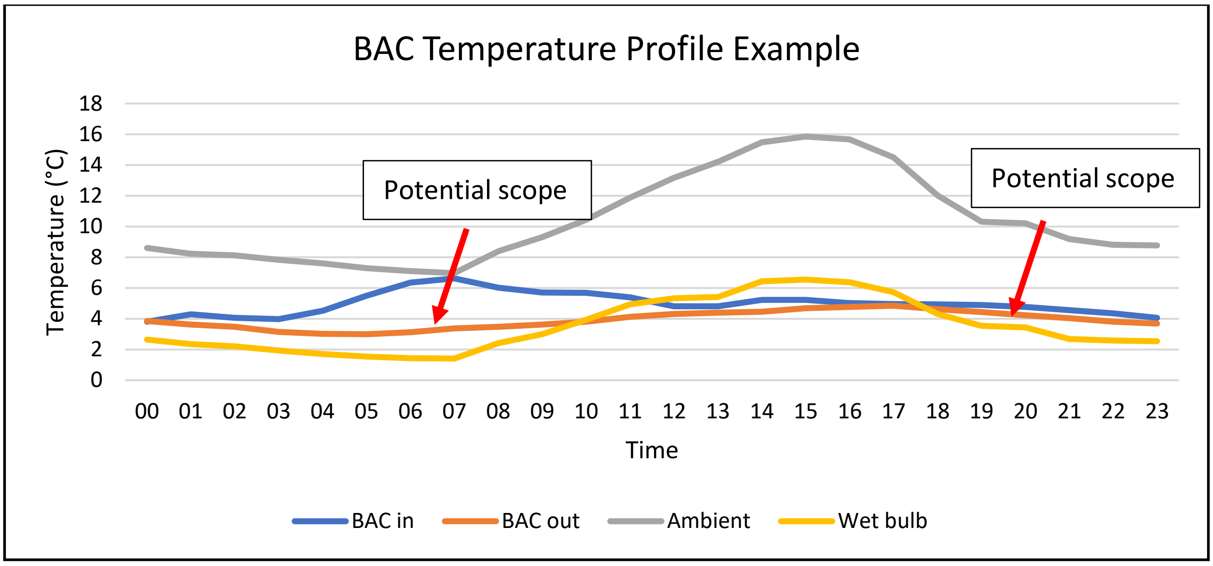


Figure 2-2: Potential scope for seasonal control

The seasonal control scope which can be used to the mine's advantage is visible in the example above, for instance, using the outlet temperatures of the BAC to cool dams such as the precooling dams. The scope for using the cold WB temperatures to cool water or other mediums that will be an advantage to the mine, as in the example, must, therefore, be identified. However, factors such as the psychrometric conditions and the system constraints of each mine will need to be addressed in order to fully support this scope. The psychrometric conditions of each individual mine's average winter temperatures will have to be analysed to determine whether the area's WB temperature is suitable for a seasonal-control scope.

The potential scope will only be possible if the mine's WB temperature is colder than the specific water source or dam that must be cooled down. The scope of each mine must, therefore, be determined by calculating the percentage of time of the day that the WB temperature drops below the water temperature that must be cooled down over the winter months. This can be calculated by using Equation 1.5:

$$Scope\ (\%) = \left(\frac{t_{WB<water\ source/dam}}{t_{day}}\right) x\ 100 \qquad \text{(Equation 1.5)}$$

where

$t_{WB<water\ source/dam}$ = The number of hours that the WB temperature drops below the water source that must be cooled down,

t_{day} = The number of hours in a day, and

$Scope\ (\%)$ = The percentage of time of the day that the WB temperature drops to below the water source or dam temperatures.

This scope will be different for each day, since it depends on the ambient WB temperature that varies each day. A good indication will be given as to whether the scope is visible on the mine if the percentage scope for each day is calculated over the winter period.

The improvements in service delivery and energy efficiency will be determined based on how the cooled down water source or dam can be used to improve cooling or reduce FP load. After the potential improvement through seasonal control has been determined, the system constraints must be identified in order to quantify the feasibility of the scope.

2.3 Identifying constraints

The constraints of a mine cooling system are very important, as they can alter the potential seasonal control strategy. Before the constraints can be identified, the cooling system first needs to be characterised by listing major components and their relevant data that must be collected. After this is done, the listed components will be identified in a simplified layout of a mine-cooling system. After these two steps have been completed, the constraints of each component will be analysed to determine what impact they are going to have on the mine-cooling system when a potential seasonal control strategy is implemented.

2.3.1 Characterising simple mine-cooling systems

Listing major components and data collection

A site visit will be needed to identify all the components and their installed capacities. The mine's Supervisory Control and Data Acquisition (SCADA) system can be used to help with the data that needs to be collected for each system. The mine personnel and SCADA layouts can help in characterising the components. Table 2-1 lists the major components that are used in a general surface mine-cooling system.

Table 2-1: Major components in a simple surface mine-cooling system

Components	**Data collection required**
Fridge plants	• FP power consumption [kW] • Evaporator inlet and outlet water temperatures [°C] • Condenser inlet and outlet water temperatures [°C]

	• Evaporator flow rate [l/s]
BACs	• Water inlet and outlet temperatures [°C] • Air inlet and outlet temperatures [°C] • Water flow rate [°C] • Air flow [kg/s] • Fan power [kW]
Cooling towers	• Water inlet and outlet temperatures [°C] • Air inlet and outlet temperatures [°C] • Water flow rate [l/s] • Air flow [kg/s] • Fan power [kW]
Pumps	• Pump flow rate [l/s] • Pump power [l/s]
Valves	• Valve positions [%] • Capability to be automatically controlled
Dams	• Temperatures [°C] • Dam level [%] • Operating limits [%]
General	• Ambient dry bulb [°C] • Ambient wet bulb [°C] • Ambient pressure [kPa] • Relative humidity [%]

All the components and relevant data listed in Table 2-1 will be used to construct and accurately calibrate a simulation of the mine-cooling systems' operation. The collected data will also be used to verify the potential impact of the simulated seasonal control strategy. After all the mentioned information has been collected, the next step will be to identify and understand the components' operations in a simplified layout.

Cooling system layout and operations

The following layout is an example of a simplified surface mine-cooling system layout. These systems are much more complex in real life, but the sole purpose of the layout for this study is to identify the main components and to understand their operations. Once all the components and their operations have been identified, the potential scope for seasonal control can be verified by evaluating the current operations of the specific system. Figure 2-3 illustrates a simplified surface mine-cooling system on a typical deep-level gold mine in South Africa.

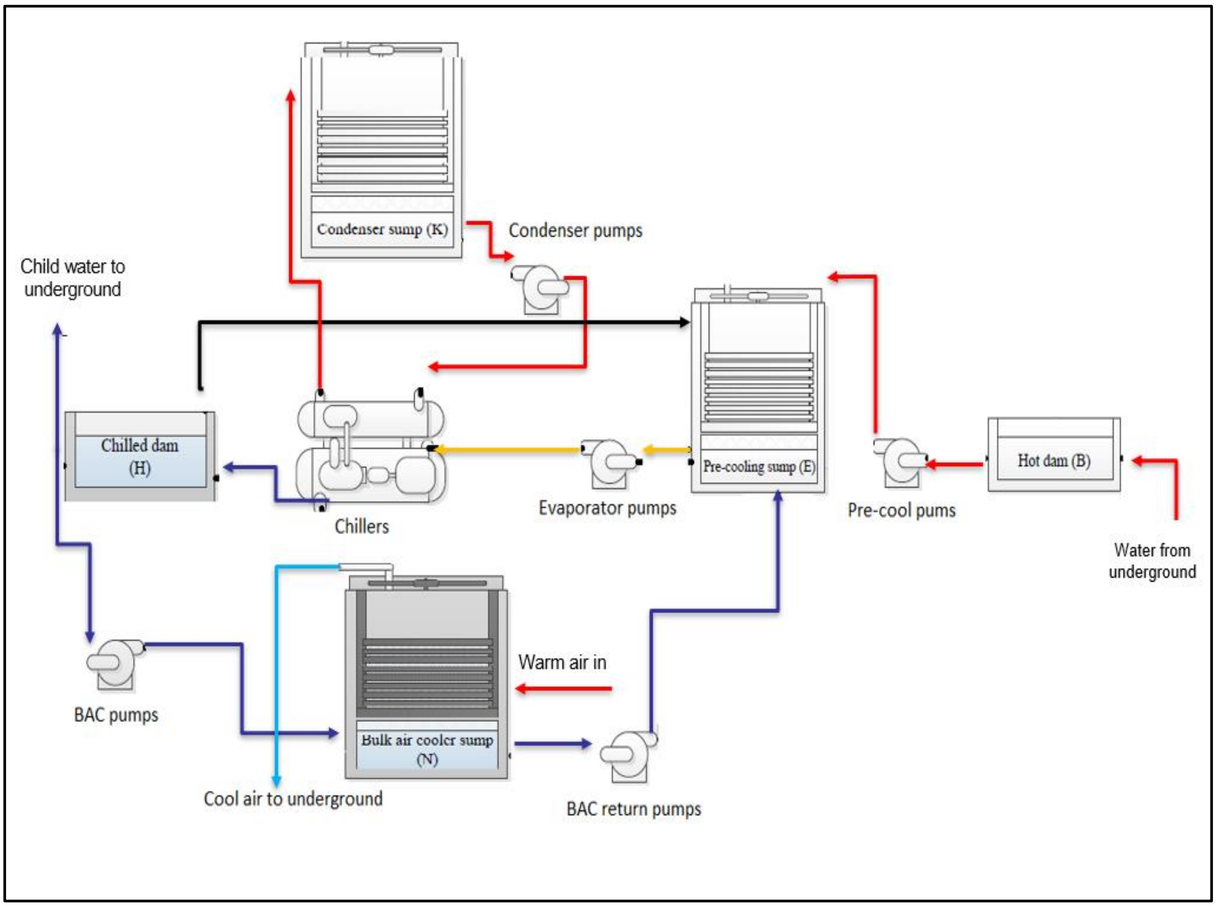


Figure 2-3: Simplified surface mine-cooling system

It is important to note that not all mine-cooling systems are configured as in Figure 2-3. Each mine's cooling system differs from the next, but their basic operations remain the same, which are depicted in Figure 2-3. The correct layout of the mine's cooling system will be crucial in determining whether the system can be adapted to the potential seasonal control strategy. The next step will be to determine the system's constraints that could potentially alter or prohibit the implementation of seasonal control.

2.3.2 Identifying constraints of listed components

Utilising cooling auxiliaries for a different purpose than what they were originally designed can affect the system's operational conditions. Understanding the constraints and operational set points of each component is important, as these can influence the implementation of a potential winter control strategy. Table 2-2 gives a summary of all the major constraints and their associated risks that can influence the operation of the cooling system when a potential seasonal control strategy is implemented. A detailed explanation of each component's risk will be explained after the table.

Table 2-2: Cooling system constraints

Cooling system constraints	Risk
Chilled water storage capacity	High
Ventilation air temperature	High
Precool dam temperatures	Low
Precooling dam levels	Low
Maximum operating flow	Moderate
Machine mechanical capability	Moderate
Mine personnel	High
System performance	Moderate

Chilled water storage capacity

During the winter months, the mines scale down on the number of FPs on the surface. This makes it harder for the FPs to match the chilled water demand and can cause the chilled water capacity to be unstable at times. It is important that the volume of chilled water is always kept above a certain limit to ensure enough capacity for a spike in chilled-water demand.

Ventilation air temperature

The ventilation air temperature during the winter months is enough to be sent down without the use of BACs. Potentially using the BAC to cool water may increase the air temperature. It is of utmost importance that the air is not heated above the mine's specified air temperature set point. The potential scope that was identified would be useless if the ventilation air is heated above the set point. This is seen as a high risk since the BAC outlet air temperatures can influence underground temperatures.

Precooling dam temperature

The precooling dam temperature is the inlet evaporator temperature. The FPs have a low inlet water temperature trip limit. The precooling dam temperature must not fluctuate around this temperature, as it would mean that the FPs must constantly be started up after they have tripped out. This can result in higher maintenance costs for the FPs in the long term. The precooling dam temperature is, however, a low risk because as the FPs trip out, they must be kept off until the precooling dam temperatures have increased and must not be started up directly after tripping out.

Precooling dam levels

The precooling dam levels are a low risk, as on most mines, the precooling dam is fed by the surface hot dams. This means that the precooling dam level can easily be controlled and will only run low if no water is pumped from underground, which, under normal operations, rarely happens.

Maximum operating flow

Where a different control strategy is implemented, the flows of components in the system can be increased to improve efficiency. It is important to understand the maximum flow that each component and the maximum flow that the total system can handle in order to stay within the system's boundaries. If the maximum flow capacity is not sufficient for a winter control strategy, the optimal performance of the strategy will be negatively affected.

Machine mechanical capability

Most of the machines in a cooling system on a South African gold mine are still the same ones that were installed when the mine was commissioned. This means that some components in the system are old and will not have the mechanical capability or efficiency to be operational in a strategy that is different from normal operations.

Mine personnel

As stated before, in wintertime, mines can switch off BACs and FPs to do maintenance. Mine personnel are reluctant to accept a different winter control strategy, as it may interfere with their winter maintenance schedules. It is important that winter maintenance plans be kept in mind when developing a winter control strategy. The strategy will not be feasible if it uses equipment that is scheduled for needed maintenance. Neglecting maintenance may cause these components to break down during summertime when they are needed to maintain a safe underground working environment.

System performance

Mine-cooling system performance is important when developing an energy efficiency or service delivery improvement strategy. The performance of large cooling equipment must be considered when developing a control strategy for using mine-cooling systems during seasonal changes. By ensuring that the performance is not influenced, the achieved energy efficiency or service delivery improvements will not be cancelled out by increased maintenance and replacement costs in the long term. The parameters and constraints that influence all system COPs, therefore, also need to be considered and evaluated before and after implementation of any strategy to quantify the improved energy efficiency or service delivery with the performance of all the mine-cooling systems.

After all the constraints have been identified and mitigated, the next step will be to develop a control strategy for cooling auxiliaries during seasonal changes.

2.4 Developing a control strategy

All the information that has been researched in Chapters 1 and 2 will be used to develop a seasonal control strategy for mine-cooling auxiliaries. The basic methodology for developing the strategy will be discussed in this section, with the methodology for the simulation and verification following in the next section. The development of the control strategy will mainly focus on utilising cooling auxiliaries to improve the performance of the cooling system.

The first step in developing a seasonal control strategy is to know that mines already follow a winter control philosophy. The typical winter control philosophy can be explained in the simple schematic layout of a mine-cooling system in Figure 2-4. The mine uses all the components in the cooling system as in normal operations, as explained in Chapter 2, except that they reduce the amount of FPs and completely shut down the BACs. Figure 2-4 illustrates the typical winter control philosophy.

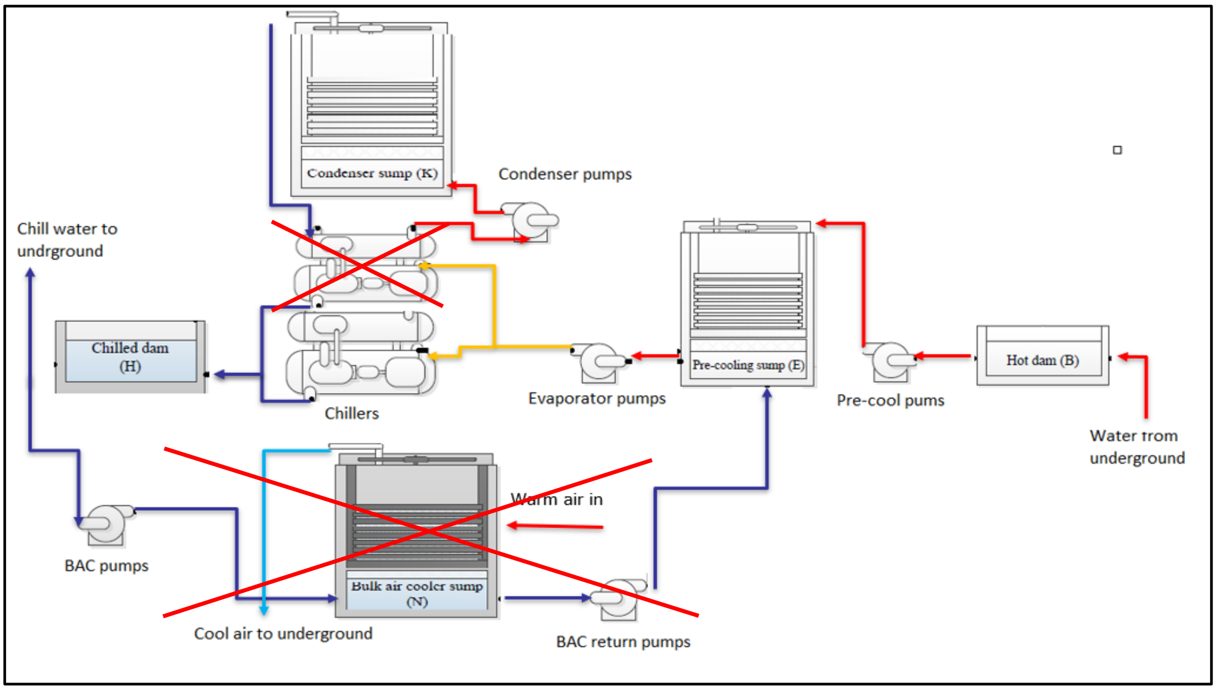


Figure 2-4: Normal winter operations

The second step will be to identify all the cooling auxiliaries that are influenced by lower WB conditions and to see which can be utilised to use the lower WB conditions to the mine's advantage. These identified auxiliaries must then be used to develop a seasonal control strategy. These auxiliaries would typically be BACs, cooling towers, and condenser towers, as stipulated in Chapter 1. From these auxiliaries in the typical winter control example above, it can be noted that the precooling towers and condenser towers are operational. The BACs are the only auxiliaries that are non-operational and can, therefore, be utilised as precooling towers for lower outlet water temperatures as can be seen in Figure 2-5.

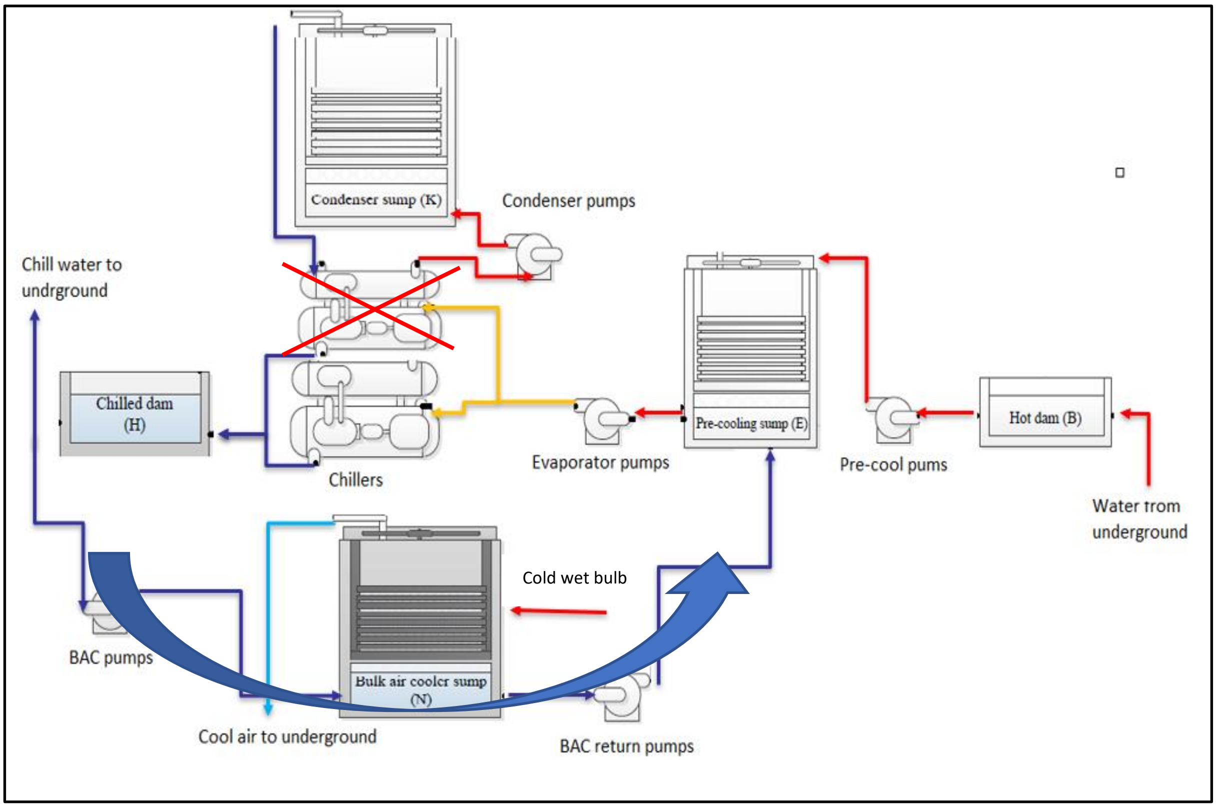


Figure 2-5: Winter control strategy example

This strategy will only be implemented when the ambient WB temperatures are suitable to be used to the mine's advantage; for example, when the WB temperature drops below the inlet water temperature, the BAC should be switched on, otherwise it should be kept off.

The mine-cooling systems on deep-level mines are very large and much more complex than what is shown in the simplified layouts in Figure 2-4 and Figure 2-5. The proposed control strategy must be simulated in order to verify that the system constraints are not negatively affected and to quantify the feasibility of the strategy on the practical system.

2.5 Simulation of the control strategy

The control strategy must be simulated to determine the feasibility of the project and the impact that the implementation of the strategy will have on the cooling system. The strategy will be simulated with the PTB simulation package.

PTB is a dynamic simulation model specifically designed for mine systems. The software can simulate any energy and mass flow over a certain period. PTB has the capability to simulate mine-cooling systems such as dewatering, ventilation, and compressed air networks. The simulation package was used in a number of studies and has been proven to be a suitable package with which to determine optimal operations and predict power savings in the mining environment [59] [24] [60] [55]. Other suitable simulation packages can also be used to simulate the strategy. However, PTB will be used in this study as an example to explain how to build a typical surface mine-cooling system.

The mine-cooling systems that must be simulated are very large and complex systems and thus need to be simulated with precise accuracy, which is a time-consuming factor. The potential system that will be simulated for the proposed control strategy must be on a mine where all the data is available, and the mine personnel must be willing to implement the control strategy at a later stage.

The simulation will use all the data that was mentioned in Section 2.3.1 to simulate and calibrate each component. All the mentioned data will be collected over a period of three months and then averaged in order to get a good representation of how the component operates on a usual business day. Some component parameters like BACs and precooling tower air flows are usually not measured and logged by the mines. The simulation needs all the parameters to be solved; therefore, assumptions will be made on what these parameters are and then iterated until the component is an accurate representation of how it operates in the practical system. An example of a typical surface mine-cooling system simulation will be explained in order to give clarity on how the simulation must be built and calibrated to ensure acceptable accuracy.

PTB uses a graphical user interface (GUI) that enables the drag and drop of system components [65]. Each component is connected with a series of pipes and nodes that enable the user to calculate the flow and hydraulic properties of each component. Each component has its own series of inputs in order to calibrate the component and give a good representation of the component in the practical system.

Figure 2-6 illustrates a typical and basic surface mine-cooling system's graphical interface in PTB. All the components are connected by a series of pipes and nodes and must be connected in the exact same manner as in the practical system that is being simulated. The surface mine-cooling system can be isolated from the rest of the mine as it will be a smaller and less complex simulation to build. This means that the simulation will need three key inputs in order to run, namely the average 24-hour water-flow profile that is pumped from underground, the average 24-hour water-flow profile that is sent underground, and the average 24-hour profile of the ambient conditions of the specific day that is being simulated. The inputs must be in a 24-data-point format, as the simulation must represent a 24-hour profile to depict the influence of the implemented strategy on a full day.

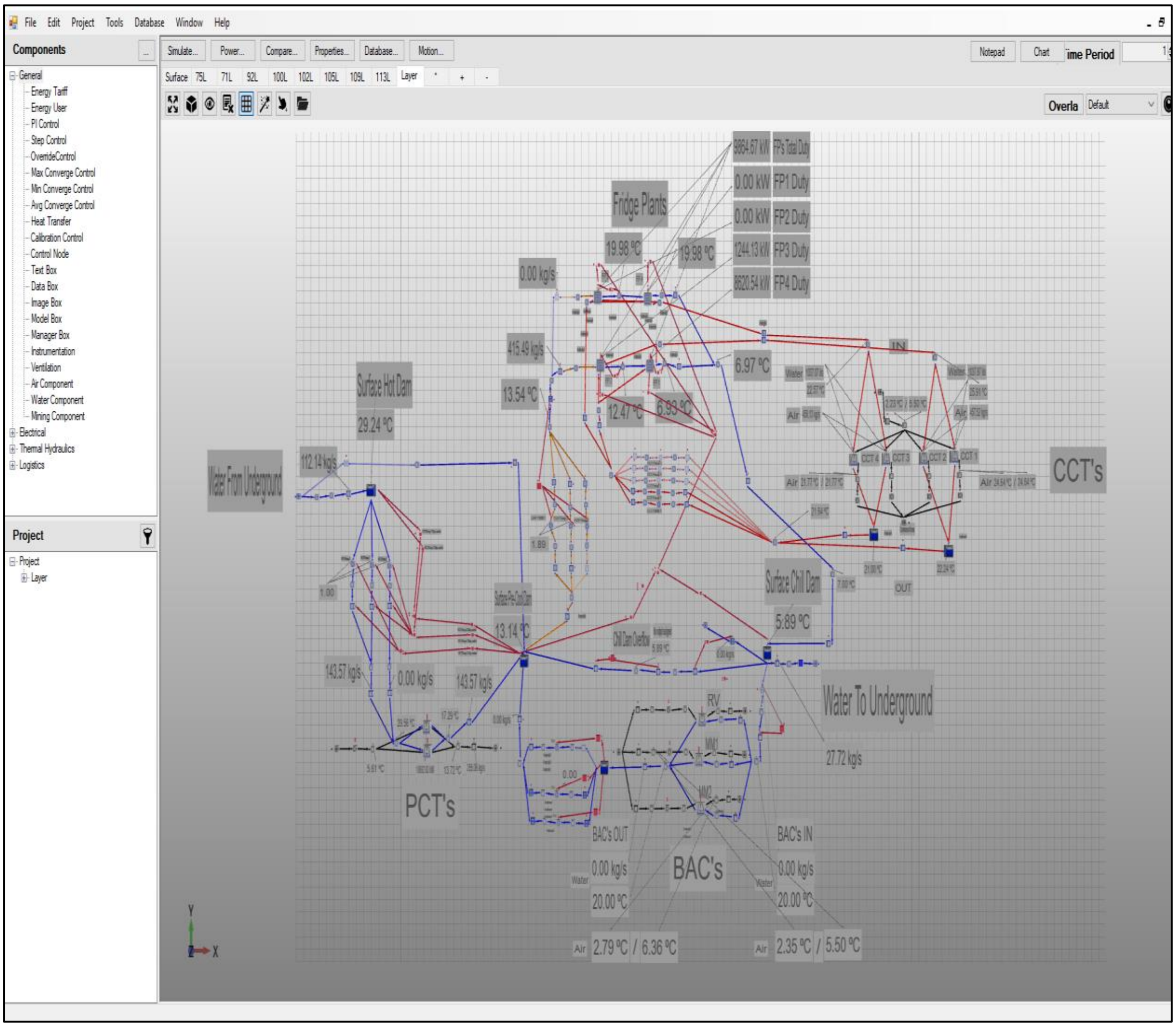


Figure 2-6 Typical graphical interface of a surface mine-cooling system in PTB

The main components to be calibrated in a mine’s surface cooling system are FPs, BACs, cooling or condenser towers, air fans, pumps, dams, pipes, mass flows, and PI controllers. The only components that do not need to be calibrated are the nodes and boundary points because the nodes are only used to connect the pipes with other pipes and other components, and the boundary points are the points that must be connected to the rest of the simulation but also the points where the simulation stops or are isolated from the rest of the mine's components. Each component has its own set of inputs that must be given to the component to be calibrated and to depict the actual component accurately in the practical system. Table 2-3 below explains what components are used to act as the components in the practical system and what inputs are needed to calibrate the specific component in PTB.

Table 2-3: Basic component description with required inputs for accurate calibration

Component	Description	Inputs
Water chiller	A water chiller is used in PTB as an FP. The water that must be cooled is connected to the evaporator ports and the water that rejects the heat from the compressors is connected to the condenser ports.	Evaporator inlet temperature [°C]
		Evaporator outlet temperature [°C]
		Evaporator flow [l/s]
		Condenser inlet temperature [°C]
		Condenser outlet temperature [°C]
		Compressor motor power [kW]
Water air-cooling tower	A water air-cooling tower is used as a BAC, precooling and condenser cooling tower in PTB. The water circuit that is connected to the water ports is used to cool the air that is connected to the air ports via an air fan in a BAC, and for a condenser cooling tower in the reverse direction.	Barometric pressure [kPa]
		Water inlet temperature [°C]
		Water outlet temperature [°C]
		Water flow rate [l/s]
		Air flow rate [kg/s]
		Air inlet temperature [°C]
		Inlet air relative humidity [%]
Air fan	Air fans are used as main ventilation fans and small ventilation fans to create a draft in the BACs or precooling towers.	Fan motor power [kW]
		Fan flow rate [kg/s]
		Fan motor efficiency [%]

	The fan can be calibrated by using either the fan curves obtained on-site or with various input that is mentioned in this table.	Fan efficiency [%]
		Fan inlet pressure [kPa]
		Fan inlet temperature [°C]
Water pump	Water pumps are used to create water flow between the components. The pump can be calibrated by using either the pump curves or a series of inputs mentioned in this table.	Pump motor power [kW]
		Pump flow [l/s]
		Pump motor efficiency [%]
		Pump efficiency [%]
		Pump head [m]
Water dam	Water dams are used as storage for chilled water that is going underground or for hot water that is pumped from underground. It is important to obtain the correct sizes of the dams, as these can affect the accuracy of the simulation significantly.	Pressure [kPa]
		Temperature of water [°C]
		Volume [l]
		Level [%]
		Heat transfer coefficient [W/m^2 °c]
		Heat transfer area [m^2]
		Ambient temperature [°C]
Pipes	Pipes are used to transfer the water between different components. Pipes can also be changed into valves if their valve fraction functions are activated. The inlet and outlet pressures are important, as these will	Flow [l/s]
		Inlet pressure [kPa]
		Outlet pressure [kPa]
		Valve fraction [%]

	represent the friction inside the pipe	
Water mass flow	Mass flow components are used to give the simulation the correct amount of flow where it is supposed to receive the water from another part of the mine that is not included in the simulation, for example, the water that is pumped to surface from underground.	Flow [l/s]
PI controller	The PI control component is an integral and proportional controller. The controller takes two control input signals and subtracts them from each other to calculate the error. This controller is used where a flow or pressure must be controlled on a specific set point. This component helps to calibrate the correct flow and pressures at certain points.	Inlet control limit 1
		Inlet control limit 2
		Integral gain
		Minimum output
		Setpoint
		Schedule
Step controllers	The step controller component allows for multiple stops and starts. This component is commonly used where a dam must be controlled between specific levels.	Number of steps
		Slope
		Start limit
		Stop limit

		Maximum/minimum start
		Maximum/minimum stop

All the mentioned input data required for each component must be a three months' average to ensure that the component is calibrated as accurately as possible. After all the components are calibrated and connected in the same way as in the practical system, the simulation can be simulated to obtain all the mentioned components' output data to be compared to the components' actual data to test calibration accuracy.

The simulation accuracy will be verified by comparing the simulation result to actual historical data. To be deemed verified, the simulation results will be required to match the actual electric power data and all other key performance indicators like outlet air and water temperatures. After the simulation has been verified, the proposed control strategy can be simulated.

Simulating the system and ensuring that the system constraints and key performance indicators (KPIs) are within the prescribed limits will confirm the feasibility of the control strategy. The following section will discuss the validation of the developed control strategy on the actual cooling system.

2.6 Validation of the control strategy

Before the control strategy is simulated, the simulation first needs to be verified by simulating a business-as-usual day and comparing the results to the actual data. This will ensure an accurate simulation to start simulating the control strategy. After the control strategy has been simulated and is feasible from a theoretical standpoint, the next step will be to physically test the strategy on a chosen suitable mine-cooling system. This will ensure the feasibility of the developed control strategy and validate the results that were obtained by the simulation. During the test, the following parameters will have to be monitored to ensure that no KPIs and system constraints are exceeded and that relevant data is collected. The following KPIs were chosen, as they were classified as high risk in Section 2.3.2:

- Precooling temperatures
- Chill dam temperatures
- Chill dam level
- FP power consumption

- Ventilation air temperature to underground

When the control strategy tests have been done, the relevant data can be collected. The data will be compared to the results from the simulation. The comparison between the different data will give an indication of the simulation accuracy and the feasibility of the developed seasonal control strategy for a combined service delivery and energy efficiency saving. When the validation phase is complete, the strategy can be improved for optimal performance.

2.7 Optimisation of the control strategy

The strategy must be optimised in terms of optimal performance for mine-cooling auxiliaries during seasonal changes. Optimal performance entails performance in terms of optimal cost-saving while improving or at least maintaining service delivery. The strategy must, therefore, be optimised to achieve the best saving for the longest time possible while maintaining or improving service delivery.

The procedure that will be followed when optimising the strategy is illustrated in Figure 2.7. Before the strategy can be optimised, the ambient conditions must be evaluated, as the strategy will depend on the ambient WB temperature. The strategy must be optimised to achieve as much saving throughout the month as possible and not just on cold days where the WB temperature is suitable throughout the day. The strategy must be optimised to utilise the WB temperature on a day with a variety of scopes.

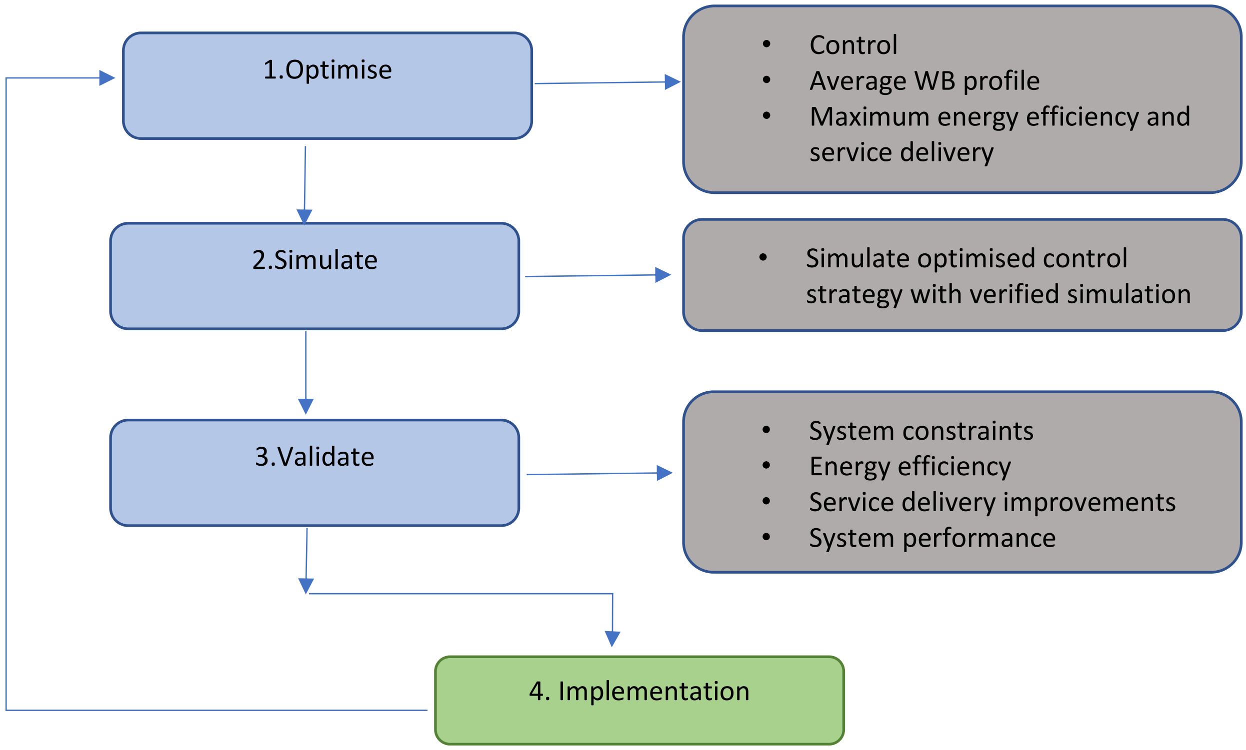


Figure 2-7: Optimisation procedure for seasonal control strategy

First, how much scope there is to utilise the WB temperature and how many times a month does different percentage scopes occur must be calculated. An average WB profile with the potential to achieve savings more frequently throughout the month must be obtained. Once this profile has been obtained, it can be used to develop an optimised control strategy that can be implemented on more days throughout the month.

The strategy's optimisation, therefore, entails the different times that the WB temperature would be optimally used on a daily basis to achieve a saving throughout the month. This would typically mean changing the existing control strategy by switching on different components at specific times according to the WB profile obtained above. The optimised control strategy will then be simulated and validated upon implementation. These four steps in Figure 2.7 will be repeated until the strategy has been optimised for optimal performance. The next step will be to implement the optimised control strategy.

2.8 Implementation

The optimised control strategy can be implemented after it has been simulated and verified. All sites that have suitable mine-cooling system configurations and ambient conditions can be identified and approached for implementation of the strategy. The strategy's implementation should typically not change any configuration or have any increased cost implication for the mine, as this may affect the maximum energy saving.

The strategy can be implemented from the control room by mine personnel, as all mine-cooling systems can be controlled from the SCADA in the control room. A SCADA is the mine's centralised monitor and control system that enables personnel to remotely control the entire mine. The SCADA connects with optic fibre cables to a remote terminal unit (RTU) or PLCs, which receive signals to switch equipment on or off or to control them.

Control room mine personnel control all the systems in the control room. It is important that the control room operators receive the correct training and understand the control philosophy of the strategy. The operators must also understand all system constraints and KPIs that are affected by the strategy. Although these system constraints and KPIs have been verified by the simulation, understanding them is still of utmost importance, as they can affect the strategy's feasibility and, therefore, constantly need to be monitored before and after implementation. It would be ideal to uses the mine's SCADA systems to automatically monitor KPIs whenever possible.

2.9 Conclusion

In this section, a methodology for an optimised seasonal control strategy was developed on deep-level gold mines in South Africa. The strategy mainly focused on utilising mine-cooling auxiliaries to achieve optimal performance during seasonal changes. The methodology comprises identifying potential scope for seasonal control, identifying constraints regarding the identified scope, development of an optimised control strategy, and finally, the validation and implementation of the strategy.

The methodology in this section adheres to the study objectives that were identified in Chapter 1, which involve developing a control strategy for mine-cooling systems over seasonal changes for maximum energy efficiency with an improved or maintained service delivery. Implementation of the strategy will ensure maximum cost-saving for gold mines during seasonal changes.

The next section, Section 3, will focus on the implementation and results of the methodology for a case study.

3. Implementation of utilised cooling auxiliaries during seasonal changes

3.1 Introduction

The methodology that was developed in Chapter 2 will be used in this section to develop an optimised seasonal control strategy on a gold mine in South Africa. The mine will be referred to as Mine A, as the mine prefers to remain anonymous. Mine A was chosen because the mine personnel were willing to help with the data generation and implementation of the strategy.

The seasonal control strategy focuses specifically on winter months; hence the case study will only focus on winter operations of the mine-cooling systems. In this section, all the steps of the methodology will specifically be implemented on Mine A.

In this section, a scope for seasonal control will be identified on Mine A. A seasonal control strategy will then be developed, simulated, verified, and validated by comparing the simulation results to the results on an actual system in order to determine the possible improvements on energy consumption and service delivery associated with the strategy.

3.2 Case study on Mine A

3.2.1 Identifying scope for seasonal control on Mine A

The mine was approached, and all the cooling auxiliaries and ambient temperature data for a two-month period were collected. The data was extracted from the mine's data servers where all the cooling system's data has been logged. The two coldest months were chosen because this was the time that the highest scope was available. The scope for seasonal control was determined by calculating the percentage of the day that the WB temperature dropped below the chill dam temperature. The chill dam temperatures were chosen because this was the only water that had scope to be cooled, as the precool and condenser towers are already operational throughout winter. Figure 3-1 illustrates each day's percentage over a period of two months.

It is clear from the graph in Figure 3-1 that a lot of days in June have been identified for a seasonal control scope. The percentage scope for each day differs as the scope is dependent on the ambient WB conditions. Most of the scope is visible in the early hours of the morning and in the evening periods, which was expected; however, there are days where the scope is visible for 100% of the day.

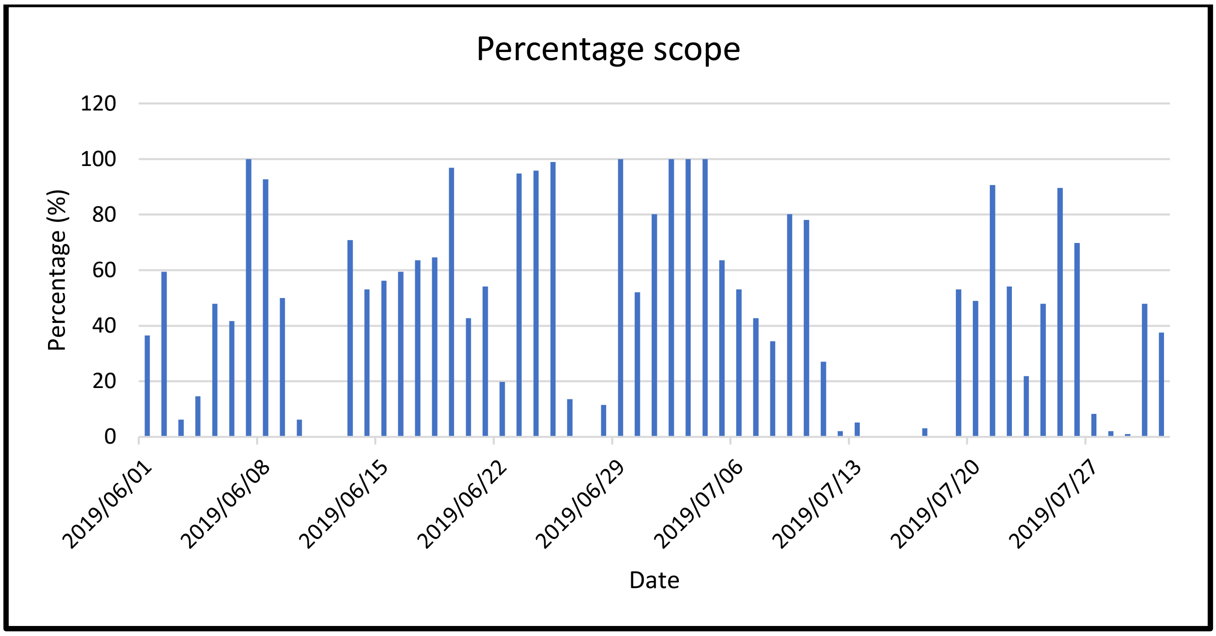


Figure 3-1: Percentage scope for seasonal control on Mine A

Figure 3-2 illustrates one of the days where the percentage scope was high – this caused the BAC outlet temperatures to be lower than the BAC inlet temperatures for a large portion of the day. Thus, the BAC was identified as a system for which a control strategy that utilises the cold ambient conditions can be developed. The BACs can essentially be used to reduce the chilled water temperature that is sent through them and then use this water to cool precooling dam temperatures.

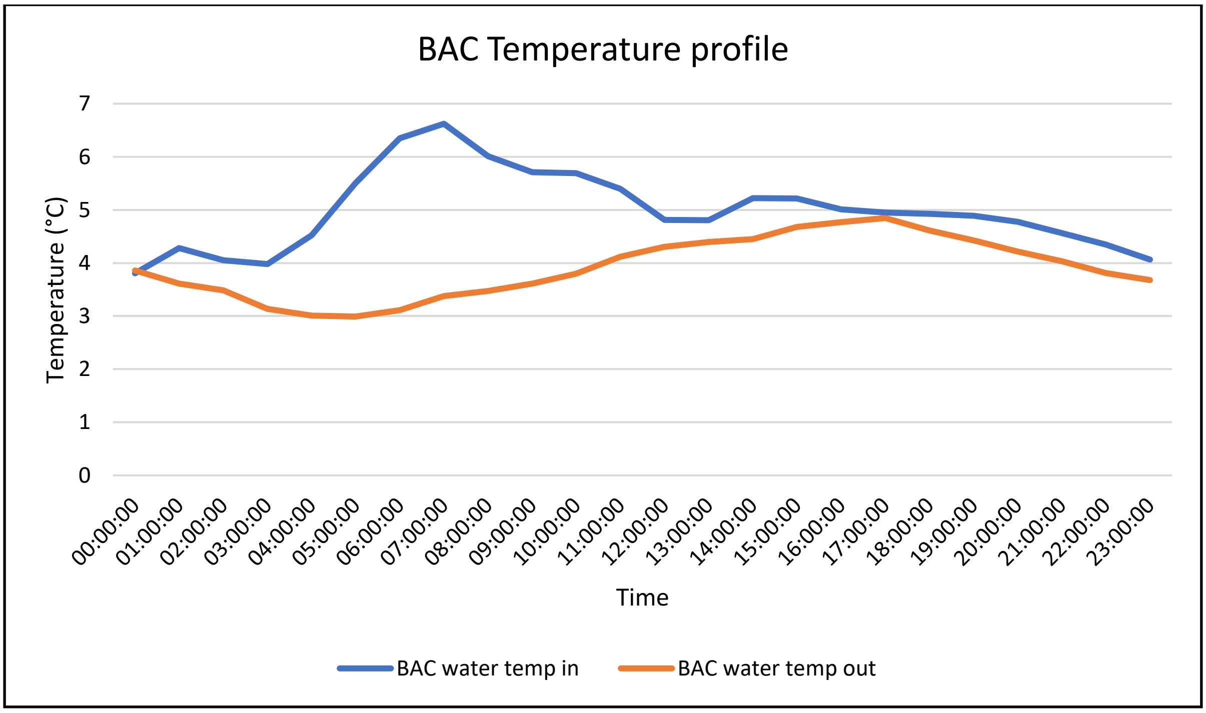


Figure 3-2: Scope for seasonal control

3.2.2 Identifying constraints

The constraints were identified by first characterising Mine A's cooling system and understanding how the system works. After the system had been characterised and studied, the constraints were identified.

3.2.2.1 Characterising Mine A's cooling system

The system was characterised by first listing all the major components in the cooling system to understand which components were included. After all the major components had been identified, the system layout was explained on a detailed drawing.

Listing of major components and data collection:

A site visit was conducted to identify all the components and installed capacities of Mine A's cooling system. The SCADA system and mine personnel assisted in collecting the data and characterising the system. All the components' data and specifications that were collected from Mine A are visible in Appendix A. Table 3-1 lists all the major components in Mine A's cooling system:

Table 3-1: Components in Mina A's cooling system

Components	Quantity
Fridge plants	4
BACs	3
Cooling towers	2
Condenser towers	3
Dams	4
Evaporator pumps	4
BAC return pumps	2
Precooling pumps	3
BAC fans	3

Precooling fans	16
Condenser tower fans	3
Isolation valves	3

Cooling system layout and operations:

Figure 3-3 shows Mine A's surface cooling system. The layout shows the normal running configuration during the winter months, which is only two FPs and no BACs. All condenser cooling towers, precooling tower pumps, and fans run as they do during normal summer operations.

An investigation of the normal winter operational strategy of Mine A revealed that the mine conducts load shifts on their FPs during the Eskom evening peak times. The load-shift control strategy is to pump the chill dams to their high limits and the precooling and hot dams to their low limits so that when the FP and evaporator pumps are switched off, enough capacity is left over for chilled water to be sent underground and warm water to be pumped from underground. During the rest of the day, the system runs as illustrated in Figure 3-3.

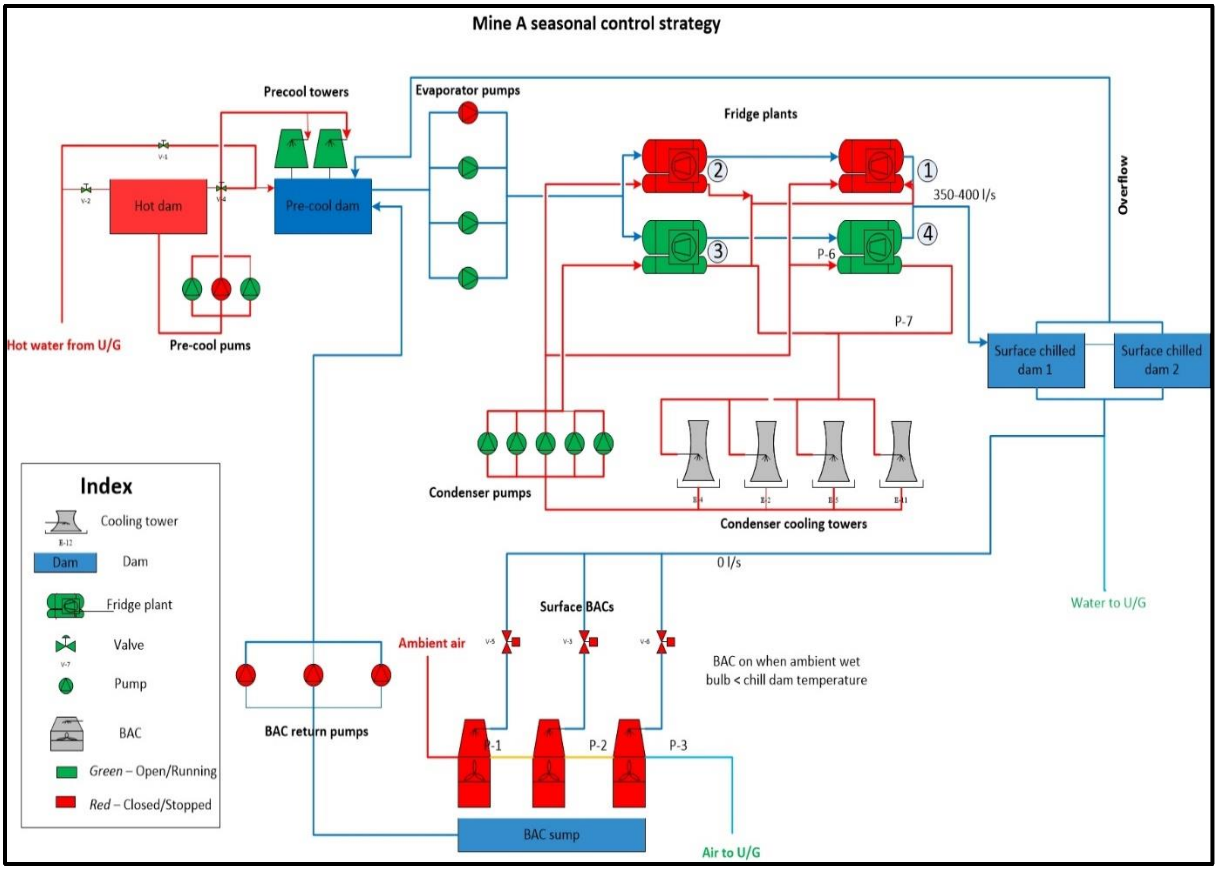


Figure 3-3: Mine A surface cooling system

3.2.2.2 Identifying constraints of listed components

The following constraints were identified after investigating the system layout. These constraints must be monitored, as they can be altered by the scope that is identified and can thus influence the feasibility and operations of the seasonal control strategy.

- Chill dam level
- BAC sump capacity
- BAC nozzle upgrade
- FP trip limits
- Ventilation temperature to underground

Table 3-2 provides the risk and mitigation of each identified constraint.

Table 3-2: Identified constraints that can affect a seasonal control strategy

Identified constraint	Risk	Mitigation
Chill dam level	As the number of FPs are reduced, the evaporator flow is also reduced. This creates the risk of running the chill dams at a low level when BAC is also running, thus having an insufficient amount of chilled water.	Match the BAC flow with the demand. When there is a large demand for underground, lower BAC flow, and when there is a low demand, increase BAC flow.
BAC sump capacity	BAC sump can overflow when flow is too high.	Start second BAC return pump to match incoming water with outgoing water.
FP trip limit	When the inlet evaporator temperatures drop, the compressor guide vanes cut back. The FPs' trip limits are too low, as the guide vanes reduced to 1% open before the FPs trip.	Operators must be informed that the FPs must be switched off before the guide vanes reach low positions. This will ensure a better FP COP.
BAC nozzle refurbishment	The BAC was receiving an inadequate amount of water because the nozzles were blocked and damaged.	One of the BAC's nozzles has already been changed and the other two BACs are in the process of being refurbished.

Ventilation temperature	BAC outlet air temperature can increase.	If the BACs are going to be utilised as precooling towers, the outlet air temperate will increase. The temperature will, however, not increase above the prescribed limits.

3.2.3 Developing a control strategy

The strategy is to run all other equipment in the cooling system as normal during the winter months except for the BACs. The BACs can be operated in the lower ambient conditions as precooling towers, then the chilled water temperature that is pumped through the BACs will reduce. The water will then be pumped back to the precooling dam where it will mix with hot service water in the precooling dam, reducing precooling dam temperatures. The remaining FPs will receive a lower inlet temperature which will cause their compressor guide vanes to cut back and reduce the electrical load of the FP.

This strategy is not the only strategy that can be implemented on the BACs. The BACs can also be connected to the precool dam and then used to cycle hot precool dam water through the dormant BACs as an additional precooling tower. The strategy will reduce the complexity of implementation, as the BACs do not have to be controlled because the water only needs to be cycled throughout the day.

This strategy does, however, require a large amount of capital to connect the BAC with the precool dam and to divert the hot ventilation air that will be generated by the hot precool water away from the shaft intake. Therefore, this strategy was not investigated, as mine A is not willing to spend capital and prefers to implement a strategy on existing infrastructure.

The BAC fridge plant loop was chosen as the seasonal control strategy because all the infrastructure was already available, and no capital was required to implement the strategy. Figure 3-4 illustrates how the control strategy will work. The BACs will be switched on when the ambient WB temperature drops below the chill dam average temperature. The BAC will receive 200 l/s of chilled water and the evaporator pumps will pump between 350 l/s and 400 l/s of water.

The exact flow and times that the BAC needs for optimal performance will be investigated in the optimisation section of the report. The strategy will also be optimised to accommodate the FP load-shift philosophy that is already implemented on the mine.

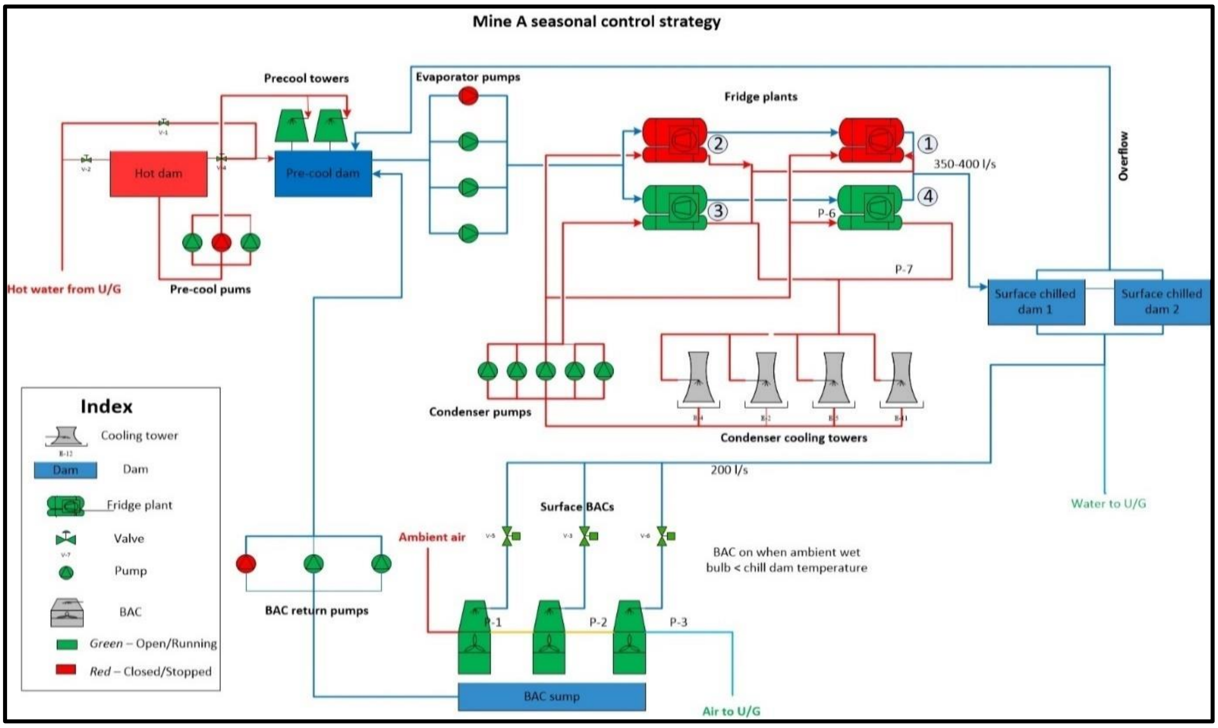


Figure 3-4: Mine A's seasonal control strategy

3.2.4 Simulating of control strategy

Before the control strategy could be simulated, a normal operating day was simulated and compared to the actual results to verify the simulation. Details of the simulation verification can be seen in Appendix B. The KPIs that were chosen to be verified are the precooling dam temperatures, chill dam temperatures, chill dam levels, and refrigeration power consumption, since the focus of the strategy is to reduce precooling dam temperatures that will influence FP power and chill dam temperatures and levels. The percentage errors between the simulated and actual KPIs of a normal operating day can be seen in Table 3-3.

Table 3-3: Normal operating day simulation verification

KPI	Simulated	Actual	Error
Precool dam temperature (°C)	13.49	13.42	0.5 %
Chill dam temperature (°C)	5.18	5.44	5 %
FP power consumption (kW)	2536.3	2474.56	2.4 %
Chill dam level (%)	99.3	91.3	7.1 %

The normal operating day's simulation can be deemed accurate, as the average error between the simulated and actual KPIs was 3.75 %. The developed control strategy was simulated next. The simulations results were compared against a baseline to determine the impact of the strategy.

The baseline that was used to compare the simulation results of the control strategy was calculated from all the days that had more than 80% scope to utilise the BAC but were not used. This means that the baseline consisted out of all the days where the BAC was kept off while it was cold enough to use the BAC to cool the precooling dam. The simulation results and baselines of the precooling dam temperatures, chill dam temperature, and FP power consumption are provided in the figures below.

The ambient conditions that were used for the simulation were the ambient conditions where 100% scope was realised. This means that an average of all the coldest days was used as the ambient conditions in the simulation. This would give a good indication of the strategy's possible impact on days where 100% scope is visible.

Figure 3-5 illustrates Mine A's simulated precooling dam temperatures. An average temperature reduction of 4.6 °C was achieved through the simulation.

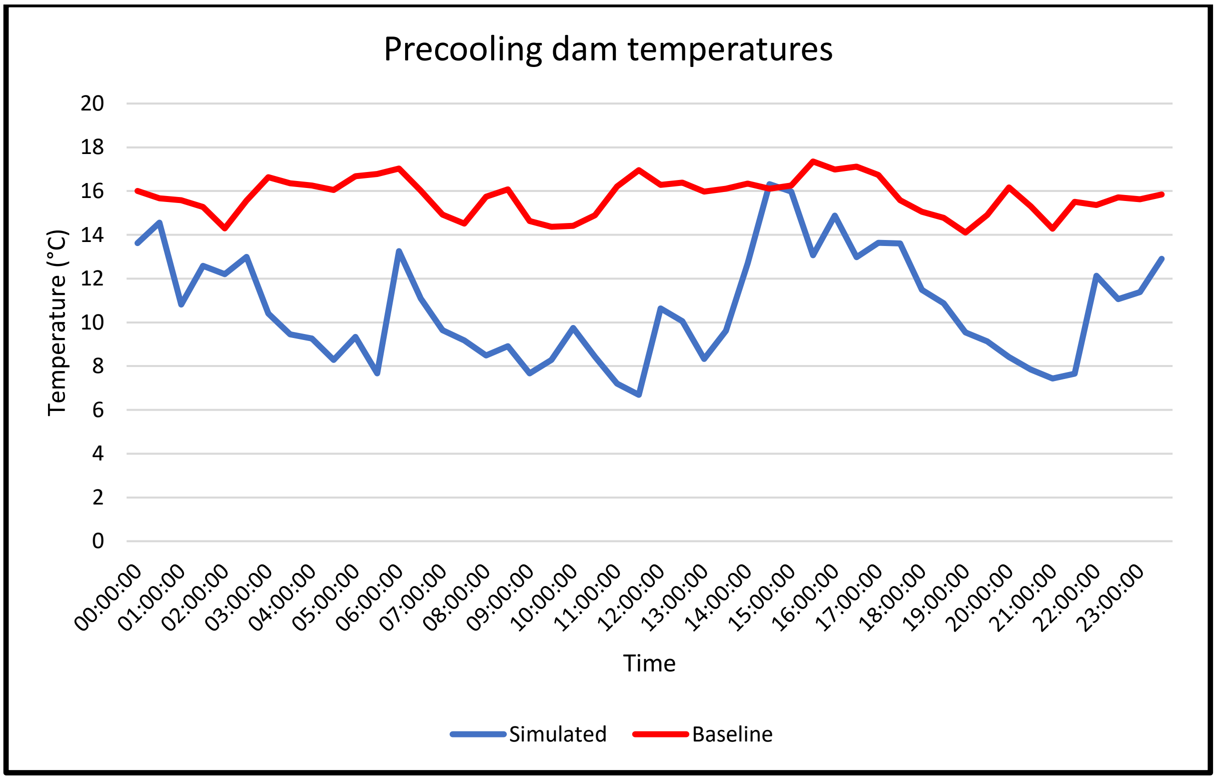


Figure 3-5: Simulated precooling dam temperatures compared to baseline temperatures

The precooling dam showed a significant drop in temperatures. The greatest drop in temperatures was realised between the early hours of the morning, as this is the coldest time of the day. The peak that can be seen at 14:00 is a result of the ambient temperatures being higher at that time than can be expected after the hottest time during the day.

Figure 3-6 illustrates the simulated FP's power consumption. An average load reduction of 1.1 MW was achieved through the simulation.

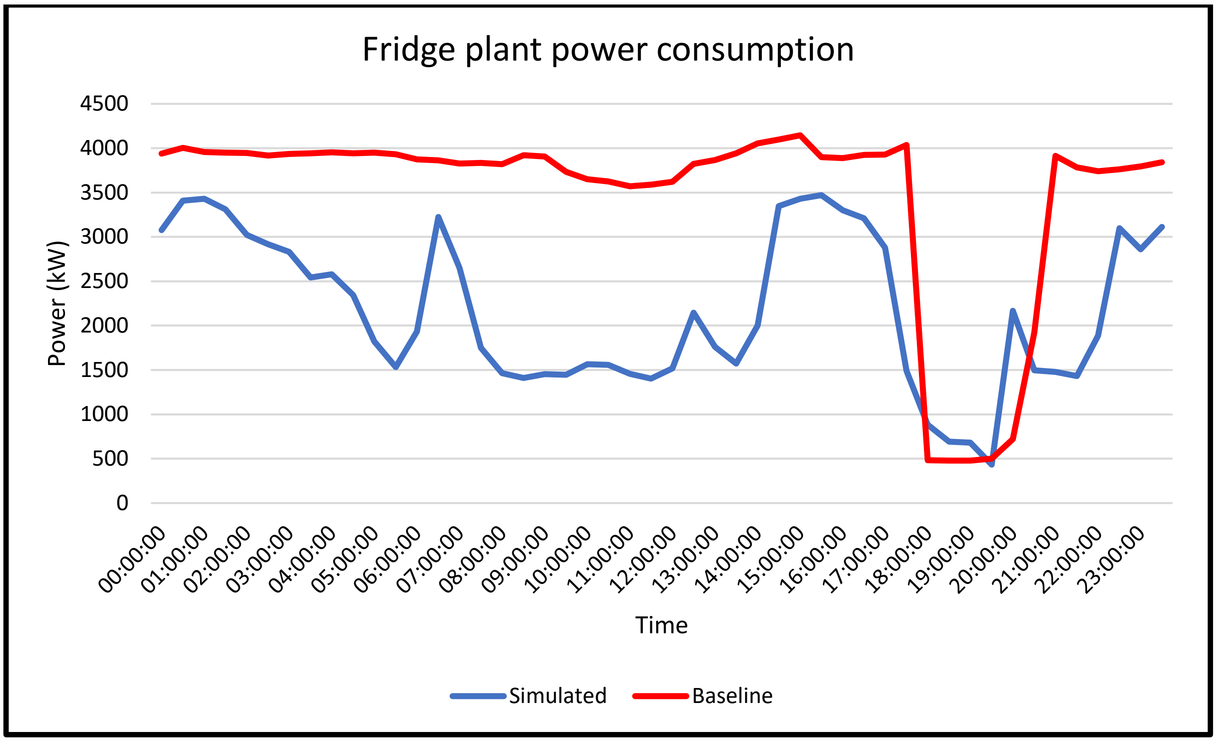


Figure 3-6: Simulated fridge plant power consumption compared to baseline consumption

The simulated strategy showed a significant drop in FP power consumption as expected. This is mainly due to the decreased inlet evaporator temperature which caused the FP to cut back on compressor guide vanes and reduce power consumption. The time that the FP reduced their power consumption corresponds with the time that the precooling dam temperatures were reduced. The spike that can be seen at 07:00 is because the simulation switched one FP on and caused it to ramp up and down as it tried to reach the temperature set point. The drop in consumption between 18:00 and 20:00 is because the mine implemented an evening load-shift on the FPs.

Figure 3-7 illustrates the simulated chill dam temperatures. No reduction in temperatures were achieved through the simulation.

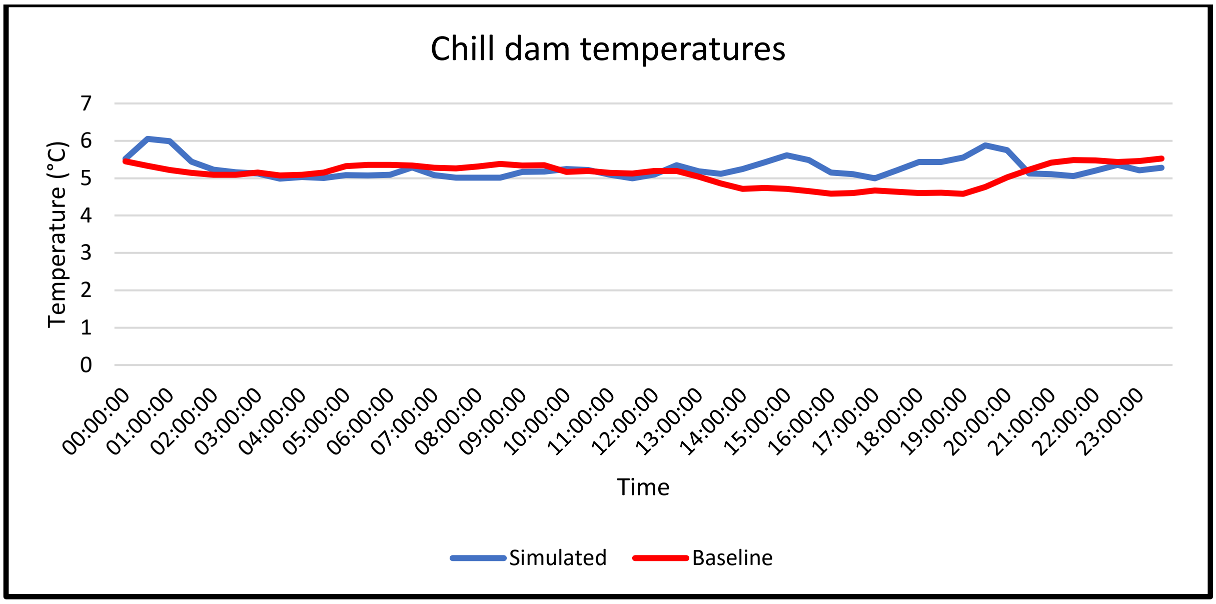


Figure 3-7: Simulated chill dam temperatures compared to baseline temperature

The simulated chill dam temperatures showed no reduction in temperature and stayed constant. This is mainly because the FPs are set to control on a desired outlet temperature of 5.1 °C. The FPs were, however, already reaching their set points as can be seen in the baseline, and would, therefore, reach their set points with a lower electricity consumption as seen in the power consumption graph in Figure 3-6. The objective of lowering the chill dam temperatures was not achieved through the simulation but was at least maintained.

Figure 3-8 illustrates the simulated BAC outlet air temperature sent underground. The temperature was kept below the prescribed baseline.

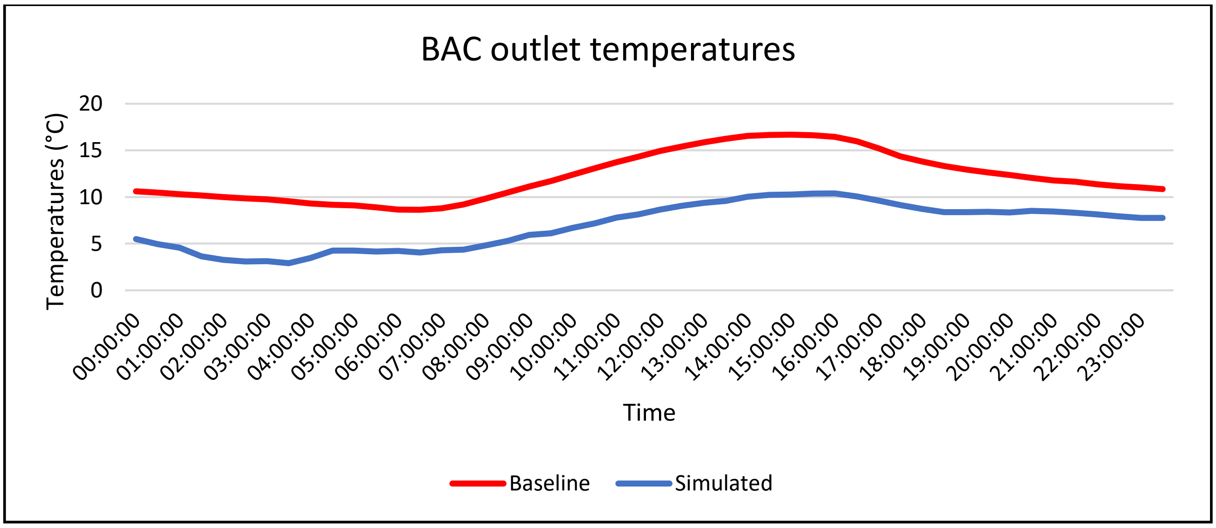


Figure 3-8: Simulated BAC outlet temperature compared to prescribed temperature limit

The air that is sent underground will be slightly warmer that the ambient temperature because BACs are utilised as a precool tower. The outlet temperature will, however, still be lower than the baseline temperature. In the early morning, the air will be heated up close to the inlet water temperature, as the cooling effectiveness will be high. As the WB temperature heats up throughout the day, it will approach the inlet water temperature that will reduce the cooling effect. As the cooling effect is reduced, almost no cooling will take place. This means that the outlet air temperature will approach ambient inlet air temperature, which is why the outlet air temperature increases throughout the day. However, the outlet air temperature of the BAC is still below the baseline, which means there will be a minimal effect underground, as the baseline is the temperature that is sent underground during winter. This temperature, however, needs to be monitored when the strategy is going to be implemented on a day with lower scope.

Figure 3-9 illustrates the simulated chill dam level. The chill dam levels did reduce when the mining demand was high, but remained above acceptable levels.

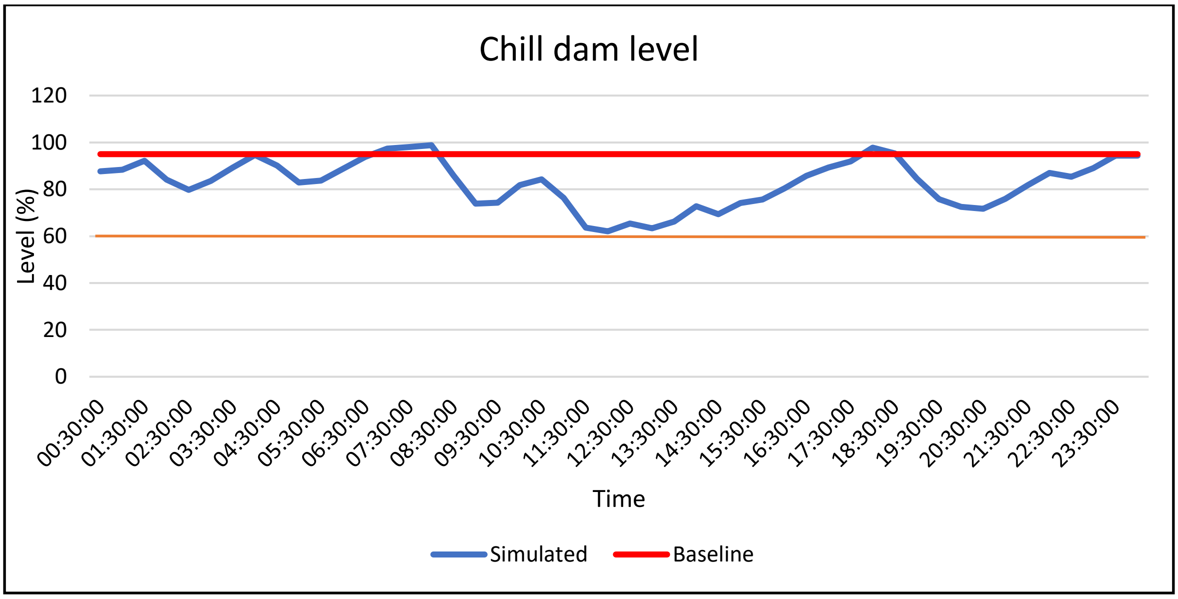


Figure 3-9: Simulated chill dam levels compared to average chill dam level

The chill dam levels will drop, as only two FPs are running, which means that the reduced evaporator flow must supply the BACs and underground with water. This causes the chill dam levels to drop slightly at times as the mining demand increases; however, the chill dams are still above acceptable levels since they do not decrease below 60%.

No KPIs or system constraints were over their prescribed boundaries as can be seen in the graphs in this section. The next step was to implement the simulated strategy and compare the actual data with the simulated data.

3.2.5 Validation of control strategy

The simulated control strategy was implemented on Mine A's refrigeration system. The strategy was implemented on a day with similar ambient conditions as in the simulation. This means that the BACs were kept on throughout the day as the scope to utilise the BACs, as the precooling towers were 100%. The actual data was obtained by manually implementing the control strategy through the control room operators and logging the actual data on the mines' SCADA. The actual data was analysed and compared to the simulated results. Table 3-4 below indicates the average error between actual and simulated results.

Table 3-4: Average error between actual and simulated KPIs

KPI	Actual	Simulated	Percentage error (%)
Precool dam temperature (°C)	11.17	10.65	4.80
Chill dam temperature (°C)	5.13	5.26	2.43
FP power (kW)	2383.96	2176.60	9.53
BAC outlet temperatures (°C)	6.01	6.91	13.10
Chill dam level (%)	85.5	82.9	3.2

The simulated control strategy can be deemed accurate since the average percentage error between the simulated and actual results is 6.61 %. The following series of graphs compare all the simulated and actual KPIs' 24-hour profiles.

Figure 3-10 illustrates Mine A's simulated precooling dam temperatures versus the actual precooling dam temperatures. The percentage error between the simulated and actual precooling temperatures is 4.8%. This error can be attributed to the time that the BACs did not return and the precooling pumps were switched on by the simulation. The pumps cannot be simulated to be switched on as in real life because the control room operators do not always switch them on at the same time or level.

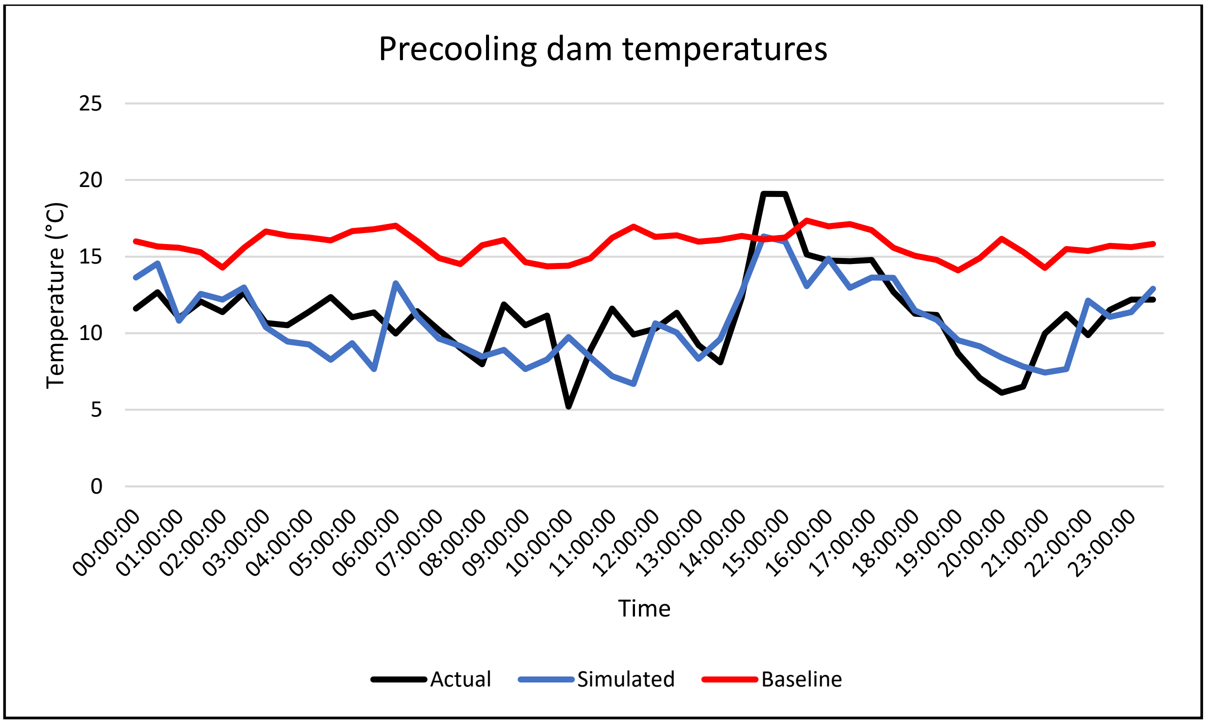


Figure 3-10: Precooling dam actual temperatures compared to the simulation results

Figure 3-11 illustrates the simulated FP power consumption versus the actual FP power consumption.

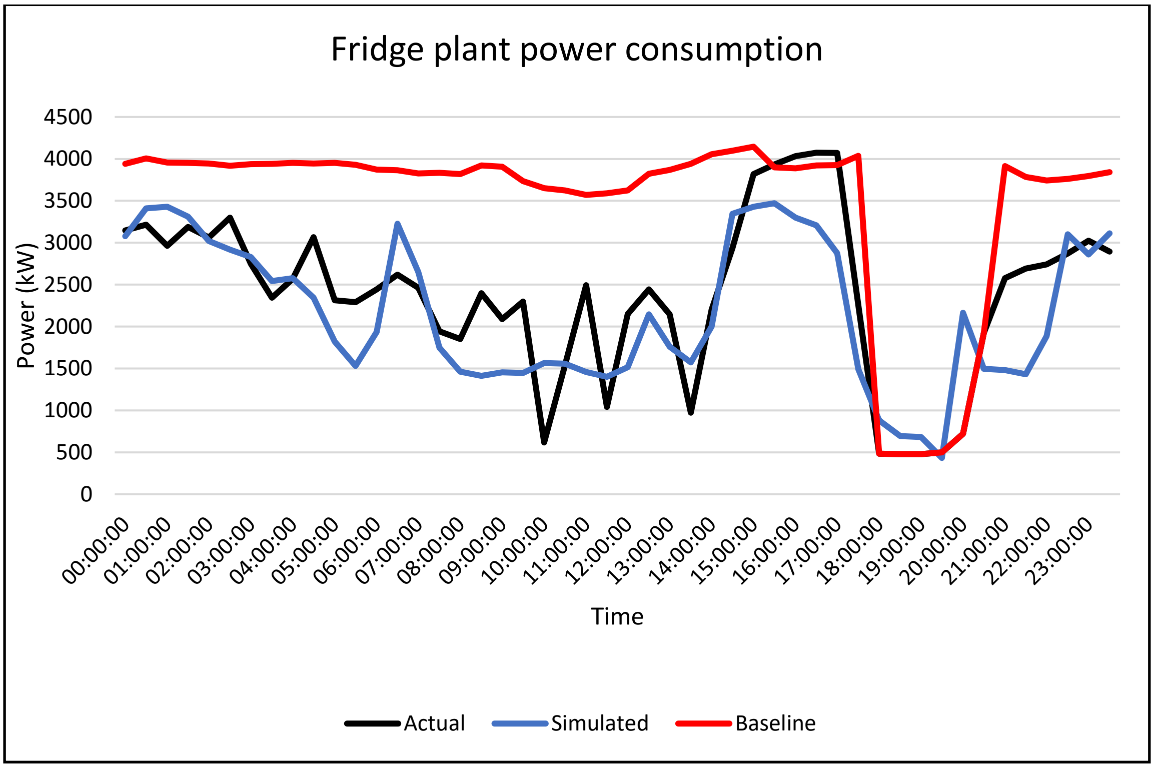


Figure 3-11: Fridge plant actual power compared to the simulation results

The percentage error between the simulated and actual FP power consumption is 9.5%. This error is due to the simulation not fluctuating as much in an attempt to reach the set outlet temperatures the FPs did in the actual results.

Figure 3-12 illustrates the simulated chill dam temperatures compared with the actual chill dam temperatures after implementation.

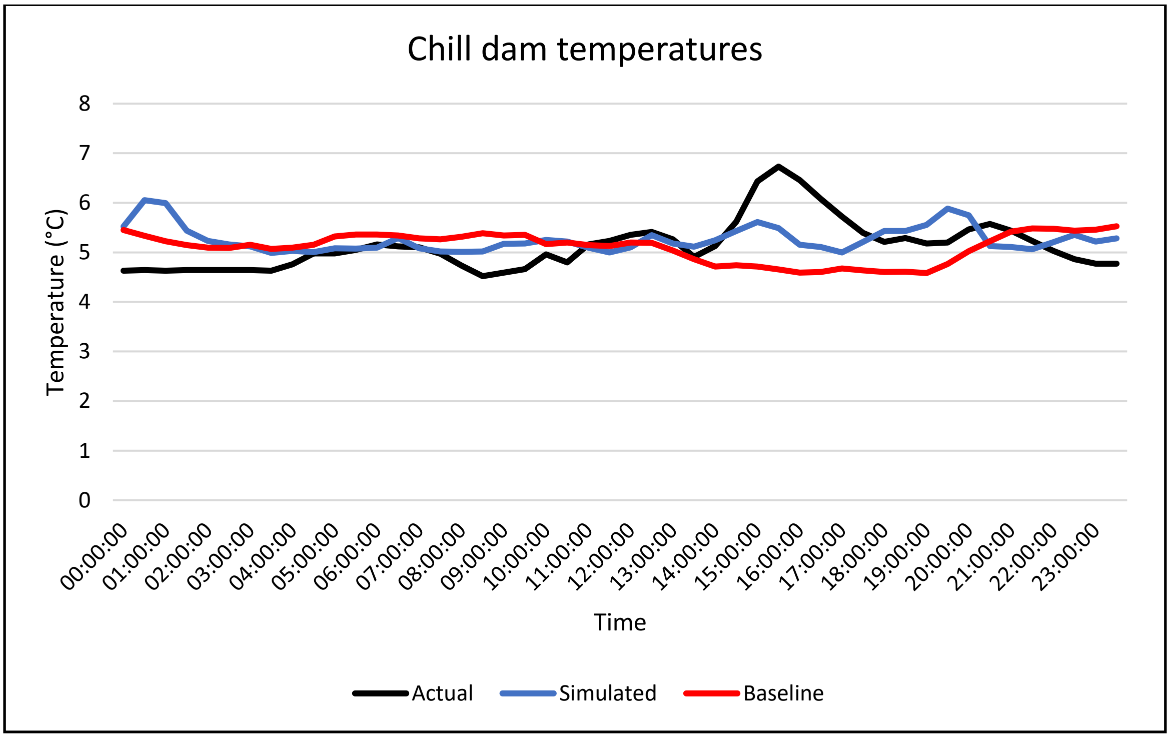


Figure 3-12: Chill dam actual temperatures compared to the simulation results

The percentage error between the simulated and actual chill dam temperatures is 2.4%. This small error can be attributed to the fact that the actual chill dam temperatures had increased between 15:00 and 16:00. The increase was caused by precooling dam water that was pumped directly into the chill dams during this period.

Figure 3-13 illustrates the simulated BAC outlet air temperatures compared to the actual BAC outlet air temperatures.

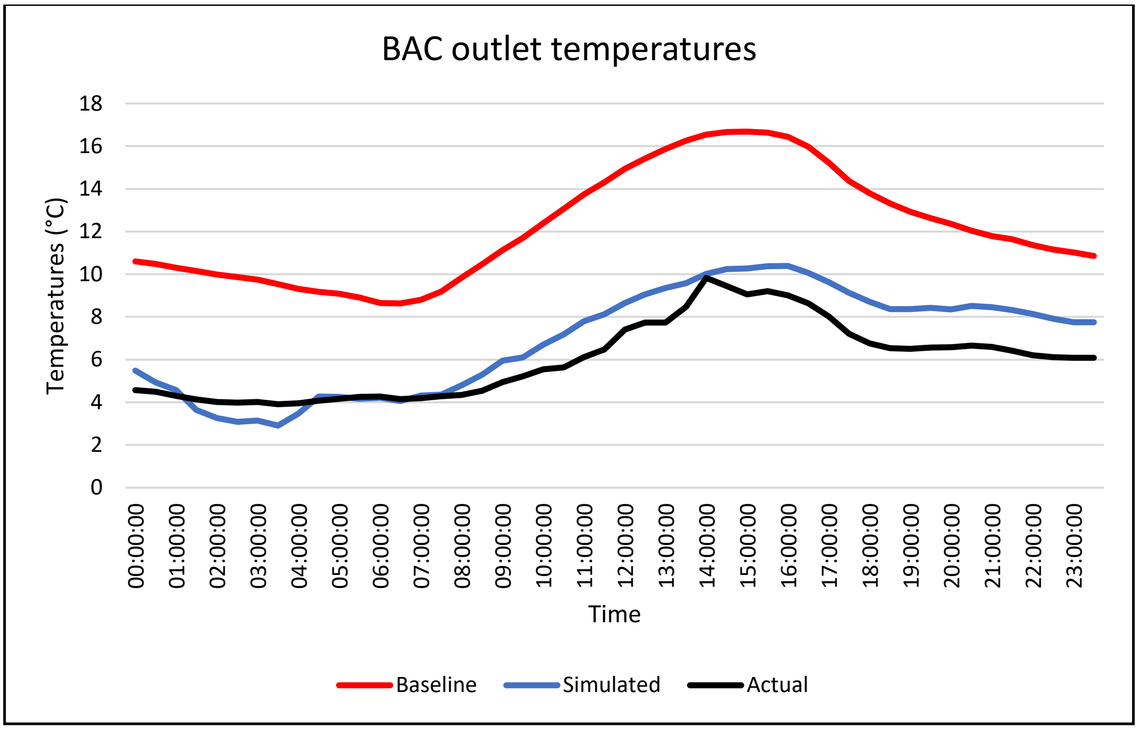


Figure 3-13: Actual BAC outlet air temperatures compared to the simulation results

The actual and simulated values have a 10% error and can be deemed accurate. The difference may be due to the fact that the BAC air flow was calculated and could not be measured. The BAC outlet air temperature will be heated up because the inlet BAC water is warmer than the inlet ambient air temperature. In the early mornings, the outlet temperature is heated but stays below 6°C, which is far below the baseline, and then heats up as the day's ambient temperature rises. This means that in the early morning, the reverse cooling will be much more effective as the WB is low, and as the WB temperature approaches the inlet BAC water temperature, the reverse cooling effect will be low. When the reverse cooling effect is low and almost zero, the outlet air temperature will then start to approach the ambient inlet temperature. Therefore, the outlet air temperature does increase throughout the day but remains below the baseline.

Figure 3-14 shows the underground temperatures at 73 level while the strategy was implemented. The graph only shows the underground baseline compared to the actual temperature and does not have a simulated line, as only surface operations are simulated. The graph illustrates how the underground temperatures are affected. The underground temperatures are measured by the mine's existing temperature probe on 73 level, and it currently being logged on the SCADA. The temperature can also be used to set up an alarm on the mine's SCADA system that will warn the control room operators that it has increased while the strategy is being implemented.

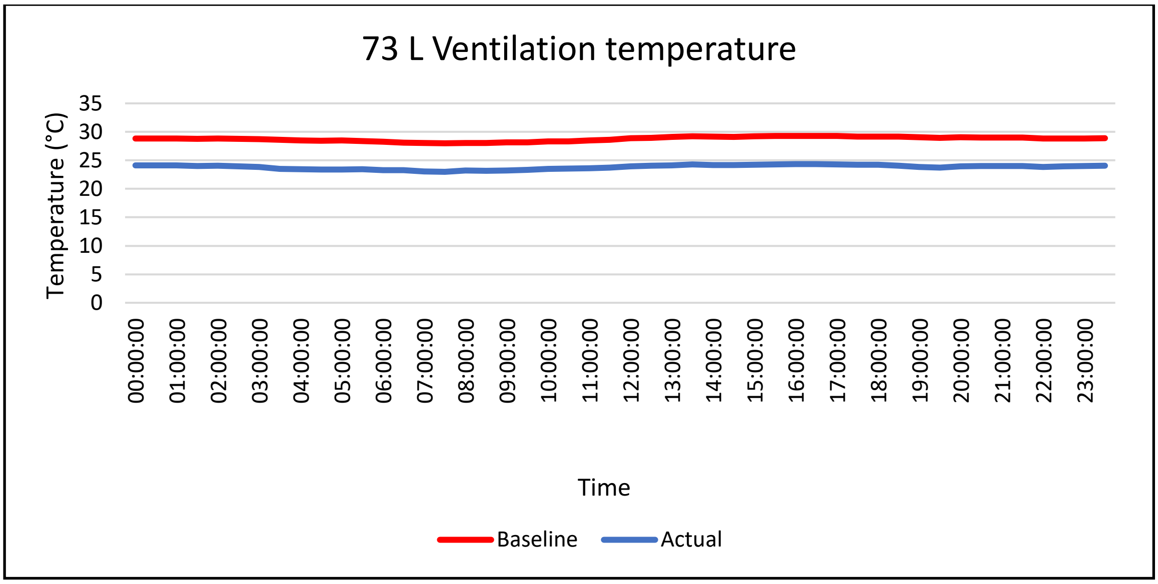


Figure 3-14 Actual underground ventilation temperatures while strategy was implemented

The underground temperatures remain below the baseline as depicted in the surface BAC graph. Therefore, the conclusion can be made that if the BAC outlet temperature remains below the baseline on surface, the underground temperature will also remain below the baseline. This means that no underground temperatures will be affected if the surface BAC temperatures remain below baseline while the strategy is implemented.

Figure 3-15 illustrates the simulated chill dam levels compared to the actual chill dam levels.

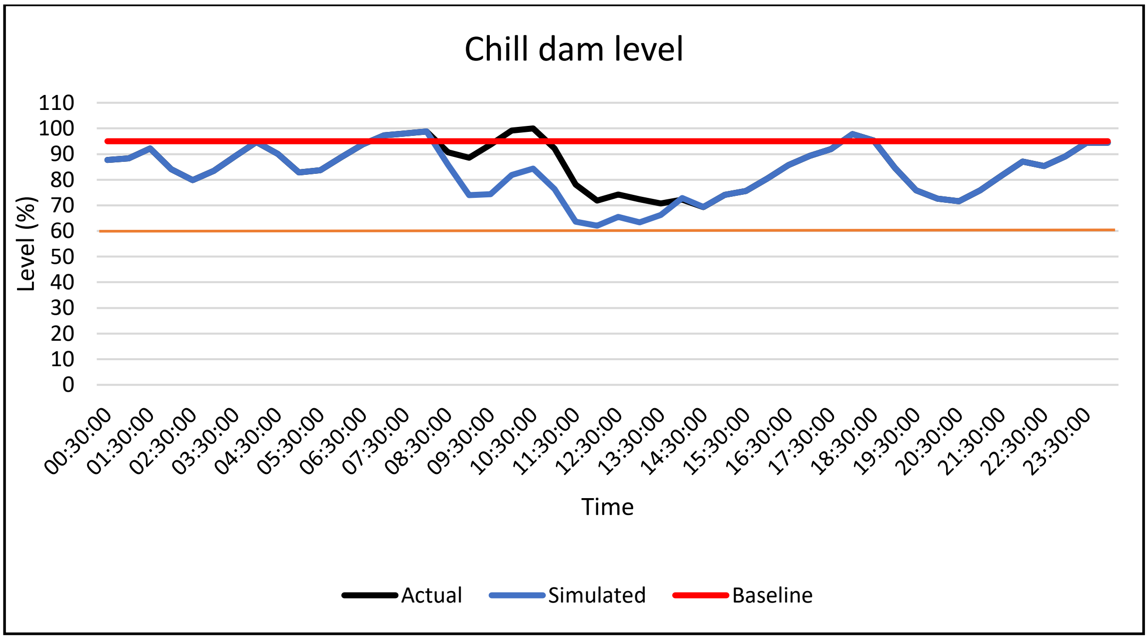


Figure 3-15: Actual chill dam level compared to the simulated results

The chill dam levels did fluctuate throughout the day. The levels showed a drop from 7:30 as the mining consumption increased. Although the levels did stay above acceptable levels, it is a concern, as the mine prefers to keep the chill dams above their low limit to ensure that there is enough water for emergency use.

The simulated strategy can be deemed accurate, as the average percentage error between the KPIs is 6.61%. The KPIs did not exceed their limits; however, the chill dam levels did get close to their limits. As a result, the ventilation temperature will need to be monitored when the strategy is optimised and implemented on warmer days with higher WB temperatures. The next step will be to optimise the developed control strategy for optimal performance.

3.2.6 Optimisation of the control strategy

The developed control strategy must be optimised for optimal performance. A typical dictionary definition of optimal describes something that operates at its best performance possible. Optimal performance in terms of mining entails a strategy that achieves maximum savings while improving or maintaining service delivery while keeping additional costs at a minimum.

The developed strategy in the previous section did achieve a cost saving while maintaining service delivery with no additional costs; however, the strategy did reduce chill dam levels, which must be taken into consideration as discussed in the previous sections. The strategy is also very dependent on ambient conditions, which means that the cost-saving potential will differ from day to day. The strategy was implemented on a day where 100% scope was available, which will achieve a large saving. However, this saving cannot be achieved throughout the month, as 100% scope is not always available, and the fluctuating mining water demand can cause the levels to drop below acceptable levels.

This means that the strategy needs to be optimised to achieve savings on days throughout the month where 100% scope is not available and for a range of mining water demands. The average WB temperatures in 2019 were analysed to indicate which months have enough scope to implement an optimised control strategy and to identify the lowest amount of scope from where to start the optimisation process. The average mining water demand over a period of June to August was taken as the average mining consumption to represent the wide range of mining water demands during the winter months.

Figure 3-16 illustrates the average WB temperature of each month plotted against the BAC inlet water temperature.

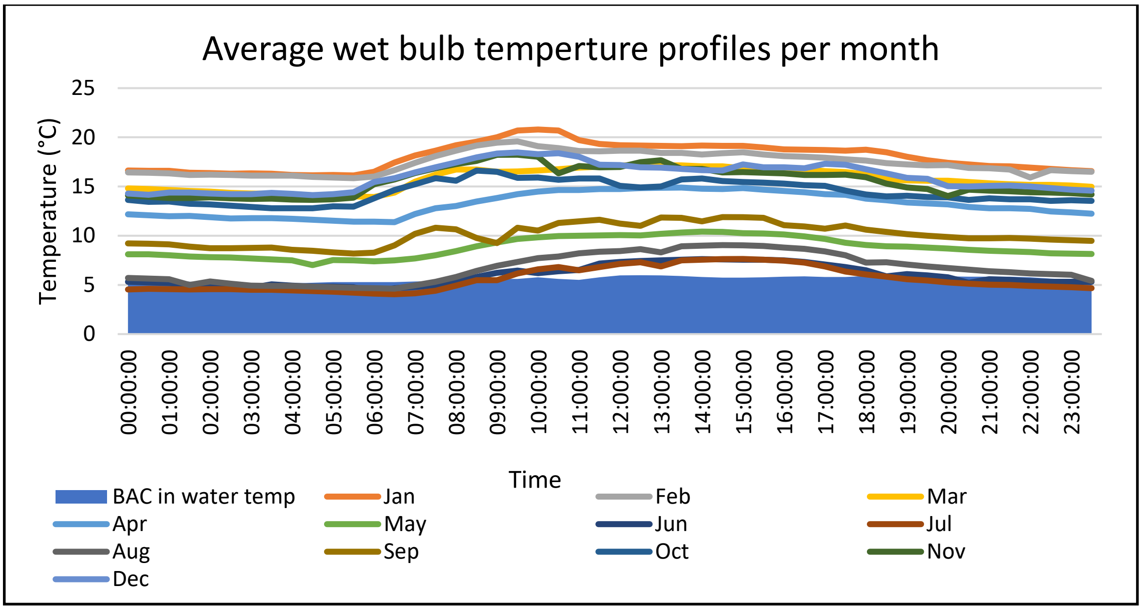


Figure 3-16: Average monthly WB temperatures during 2019

It is clear from Figure 3-16 that only June to August has scope for an optimised control strategy, as these are the only months where the average WB temperature drops below the water inlet temperatures of the BACs. The average WB temperatures during these three months were analysed in order to see which time of the day would be the best time to apply the strategy and obtain an average worst-case WB temperature profile from which to start the optimisation process.

Figure 3-17 illustrates the average WB temperatures where the scope to implement the strategy was above 30%, 50%, 100%, and below 30%, respectively.

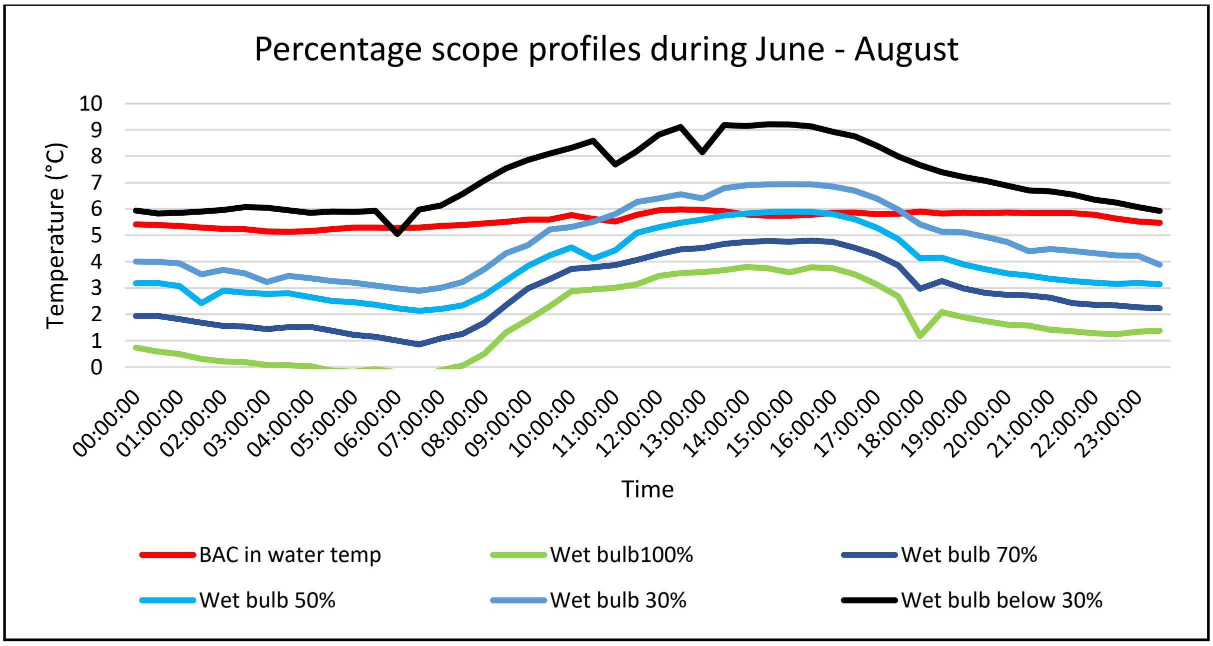


Figure 3-17: Average percentage scope WB profiles from June - August

It is clear to see from Figure 3-17 that the WB temperatures are lowest in the early morning and midnight hours, as expected. The strategy must be optimised to use these hours of the day to ensure that savings will be achieved more frequently throughout the month. It can also be seen that the 30% scope profile must be used to start the optimisation process from, as the WB profile with scope below 30% will not supply an adequate amount of time to cool water since the average is above the BAC inlet water temperature. By using this profile, an optimisation strategy can be developed from a worst-case scenario perspective that will ensure that all scope profiles can achieve optimal savings if this strategy is implemented on all the other scope days.

Figure 3-18 shows the amount of time in percentage that these different average WB temperature profiles can be expected throughout the months with adequate scope. The graph shows the total percentage of scope that consist out of 25% of 30% scope days, 18% of 50% scope days, 11% of 70% scope days, and 8% of 100% scope days, which adds up to 62% percentage of total scope to be utilised. This graph also shows the parentage of time the original strategy would have achieved an optimal saving against the total amount of scope that is available.

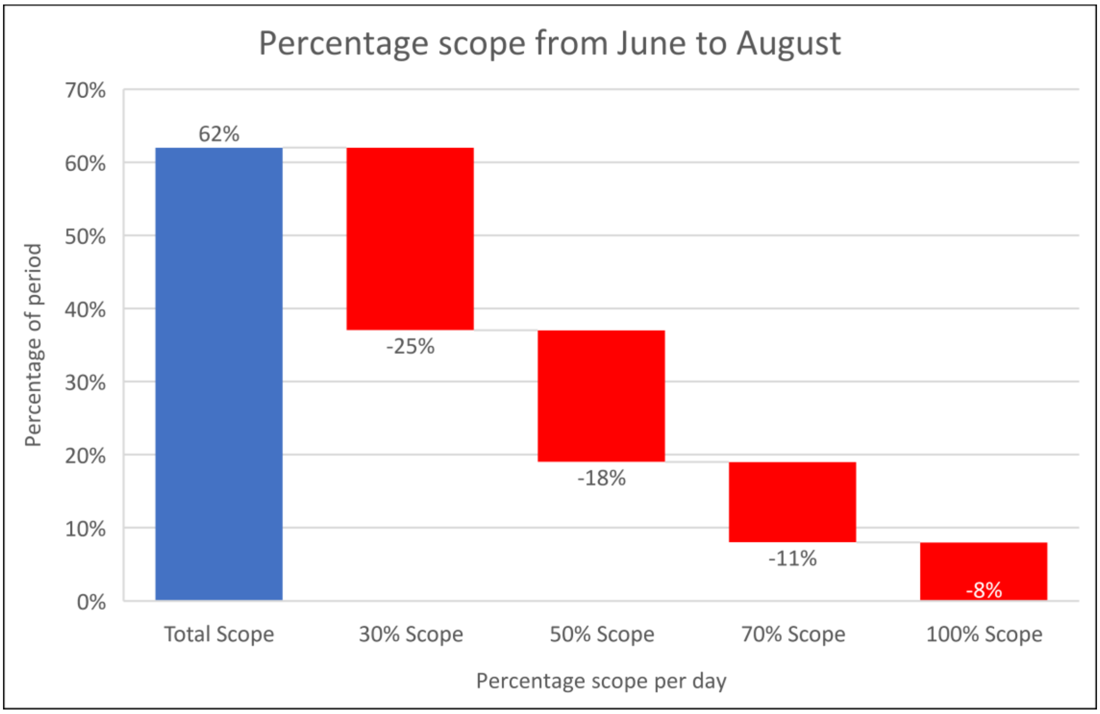


Figure 3-18: Percentage of time that different scopes are available over June- August

Figure 3-18 indicates that the original strategy that was implemented on a 100% scope day would only have achieved an optimal saving on 7 days of the three-month period (8% of the three-month period). The rest of the days with lower percentage scope would not have achieved an optimum saving during the three-month period, as the water that was opened throughout the day would not have been cooled for the entire day. Therefore, the optimised control strategy needs to be developed to achieve an optimum saving from a 30%-scope day. The strategy can then be adapted from the 30%-scope strategy to achieve optimum saving from 30% up to 100%. This means that the optimisation process is started from the worst-case scenario and implemented on all the other scope days. This will ensure that an optimum saving is achieved on 62% of the three-month period.

The optimised control strategy entails the time and flow that the BAC needs to be switched on and off to achieve the maximum saving throughout the month without reducing chill dam levels below acceptable limits. Therefore, the different times that the BAC can be switched on with the different flow profiles were simulated. The different times were chosen from the 30% scope WB temperature profiles, as this was the worst-case scenario, and the flows were chosen according to how low the chill dam levels dropped. Each period that the BACs were on together with different flows and average daily power savings can be seen in Table 3-5.

Table 3-5 shows all the simulated periods with the corresponding BAC flows that were used. These different flow profiles were chosen to see how the chill dam levels would react. The acceptable chill dam level was taken to be 60%, as this is the mine’s acceptable level for ensuring adequate chilled water capacity if an emergency arises. The different flows were also chosen to be fixed values, as the BACs do not have valves that can control a specific flow, which means that the valves would need to be fixed in a certain position to give the desired flow, and remain in that position. The average daily power saved was calculated by adding the BAC fan power to the FP power consumption and subtracting that from the baseline.

Table 3-5: Simulated time periods with corresponding flows and average power saving

Time period	BAC Flow (l/s)	Average daily power saved (kw)	Acceptable chill dam level
18:00-10:00	200	794	No
	150	616	No
	100	541	No
19:00-09:00	200	693	No
	150	608	No
	100	646	No
21:00-09:00	200	534	No
	150	473	Yes
	100	370	Yes

23:00-09:00	200	567	No
	150	513	Yes
	100	426	Yes
00:00-09:00	200	567	No
	150	513	Yes
	100	426	Yes
01:00-09:00	200	572	No
	150	516	Yes
	100	435	Yes
02:00-09:00	200	579	No
	150	525	Yes
	100	445	Yes
03:00-09:00	200	583	No
	150	540	Yes
	100	441	Yes
04:00-09:00	200	597	No
	150	548	Yes
	100	447	Yes
05:00-09:00	200	602	No
	150	529	Yes
	100	455	Yes

Table 3-5 shows that all the periods with a flow of 200 l/s dropped below the acceptable limit. The chill dam levels remained above acceptable limits when a flow of 150 l/s and 100 l/s were used for all the periods. When looking at the average daily power saved for all the periods with a flow of 150 l/s or 100 l/s, the savings for 150 l/s can be seen to be higher than the savings for 100 l/s. Thus, all the periods with a flow of 150 l/s were compared, and the period of 04:00 to 09:00 achieved the highest average daily power saving.

After an analysis of the period’s savings, it was found that there was room for more optimisation, as this period identified a point where the BACs together with their fans can be switched on for optimal savings. There is still a small amount of scope before this point, however, where the WB temperature is still suitable, but the BAC fan power reduces the small amount of power that is saved by the FPs before this point.

Therefore, this period's savings was increase by utilising the small amount of scope before 04:00 by only running water through the BACs with no fans from 00:00 to 04:00 and then to start up the fans from 04:00 to 09:00. This increases the average daily power saving from 548 kW to 624 kW. The optimisation of this period and scope profile provided the data from where it is feasible to start BAC fans and to open and close the water. This data was, therefore, used to optimise the 50%-, 70%-, and 100%-scope profiles to obtain their respective savings.

From the data that was obtained, the optimised control strategy would be:

- Open BAC water from 00:00 if the WB temperature is below the BAC inlet water temperature.
- Start BAC fans if the WB temperature is 0.7 °C lower that the inlet BAC water temperature.
- Stop BACs and water by 09:00.

The 0.7 °C difference is the temperature that corresponds with the point where it is feasible to start BAC fans without negatively affecting saving. The optimised control strategy's simulated results of the 30%-scope profile can be seen in the graphs below.

Figure 3-19 illustrates the simulated precooling dam temperatures of the optimised control strategy.

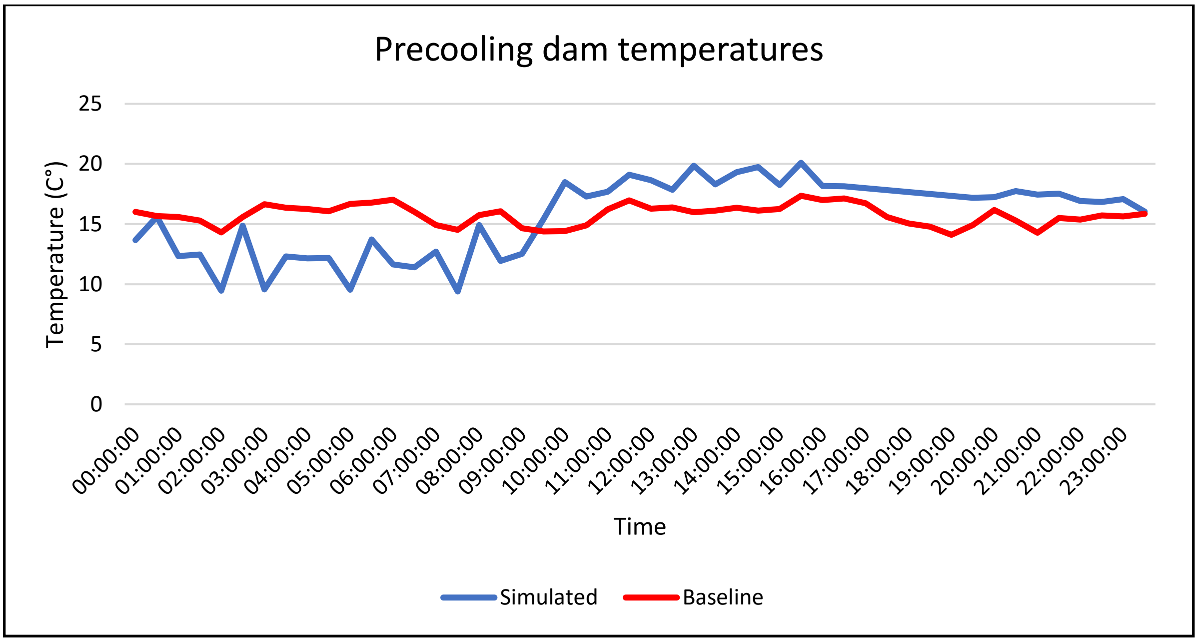


Figure 3-19: Precool dam temperatures compared to the baseline temperature

The graph indicates that the temperatures reduced during the period that the strategy was implemented. The fluctuations that can be seen in the simulated graph is the precool dam temperatures that steeply increase as hot water is pumped from the hot dams to the precool dams for that period. The slight fluctuations can also be seen in the baseline graph.

The FP power decreased during the same period that the precooling dam temperatures decreased. Due to the lower inlet temperature, the leading FP cut back to minimum guide vanes and switches off from 04:00 to 09:00. The same fluctuation can be seen on the simulated graph. These fluctuations are due to the different inlet water temperatures that the fridge plant is receiving. Figure 3-20 illustrates the simulated FP power consumption of the optimised control strategy.

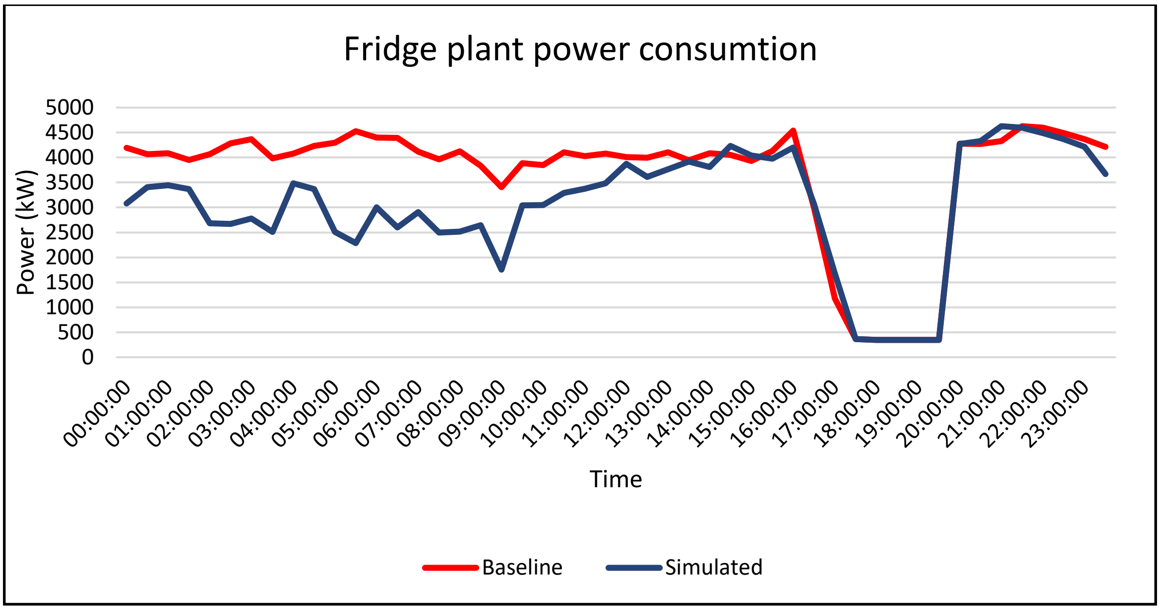


Figure 3-20: Simulated chill dam temperature compared to the baseline temperature

Figure 3-21 illustrates the simulated chill dam temperatures of the optimised control strategy.

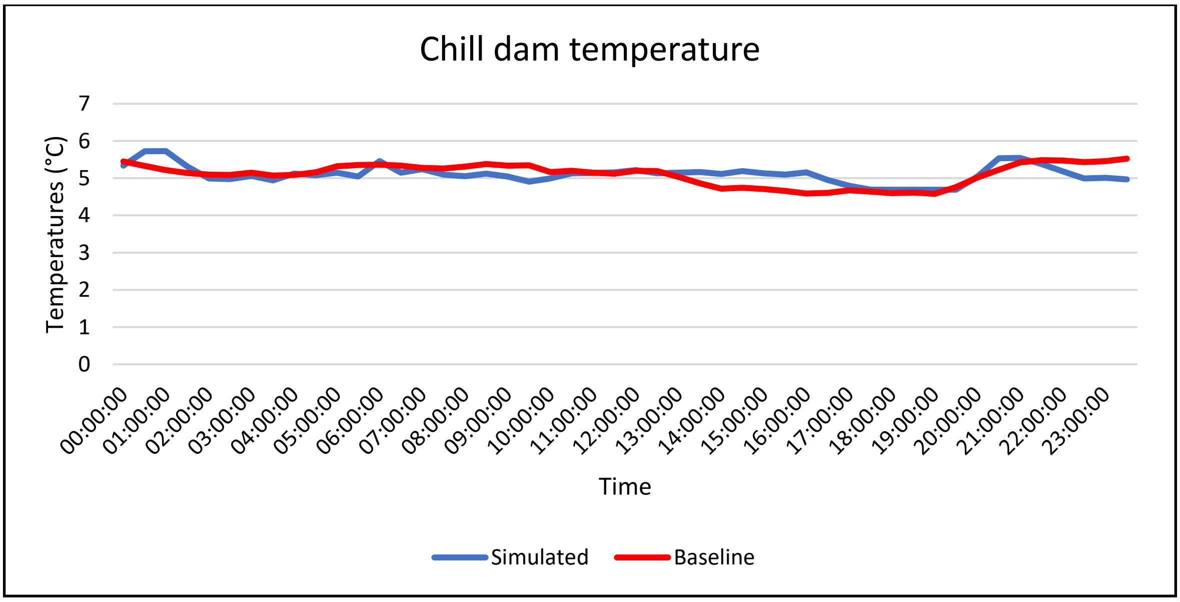


Figure 3-21: Simulated chill dam temperatures compared to the baseline temperature

The chill dam temperatures remained constant during the time that the optimised control strategy was implemented.

Figure 3-22 illustrates the simulated chill dam levels compared to the acceptable limit.

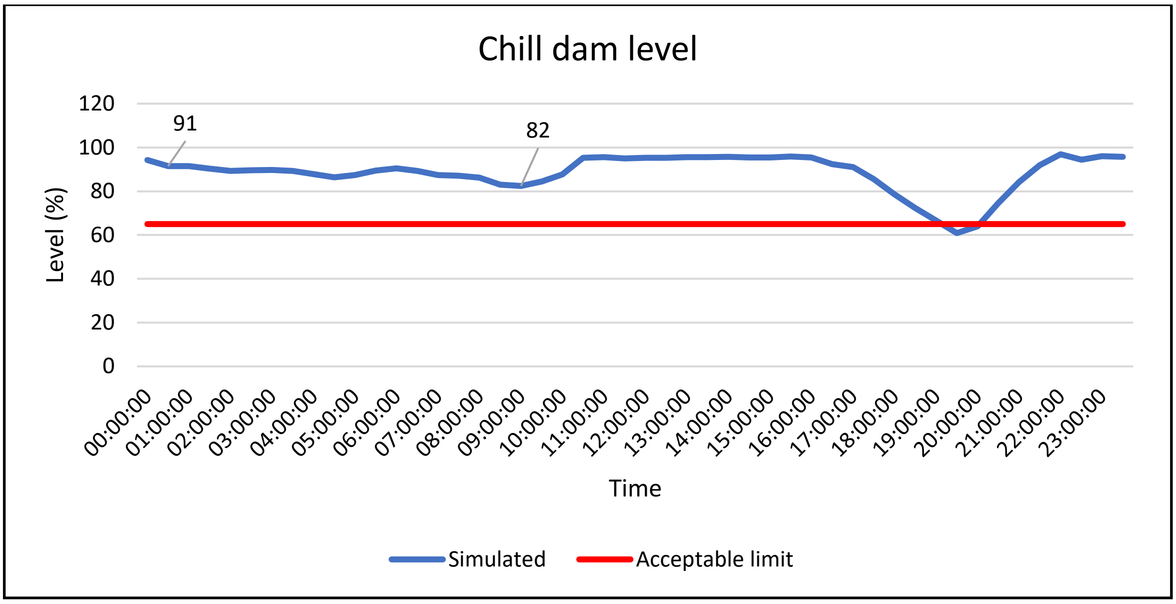


Figure 3-22: Simulated chill dam levels compared to the acceptable limit

Figure 3-22 illustrates that the chill dam began on 91% and dropped to 82% after the strategy was implemented. The level increased back to 95% by 10:30, which is a sufficient amount of water for drill shift. The drop seen at 19:00 is because the mine implemented a load-shift that caused the evaporator water flow to be switched off during that time, causing the chill dam levels to drop.

Figure 3-23 illustrates the simulated inlet and outlet air temperatures compared to the mine baseline ventilation temperatures that are sent underground.

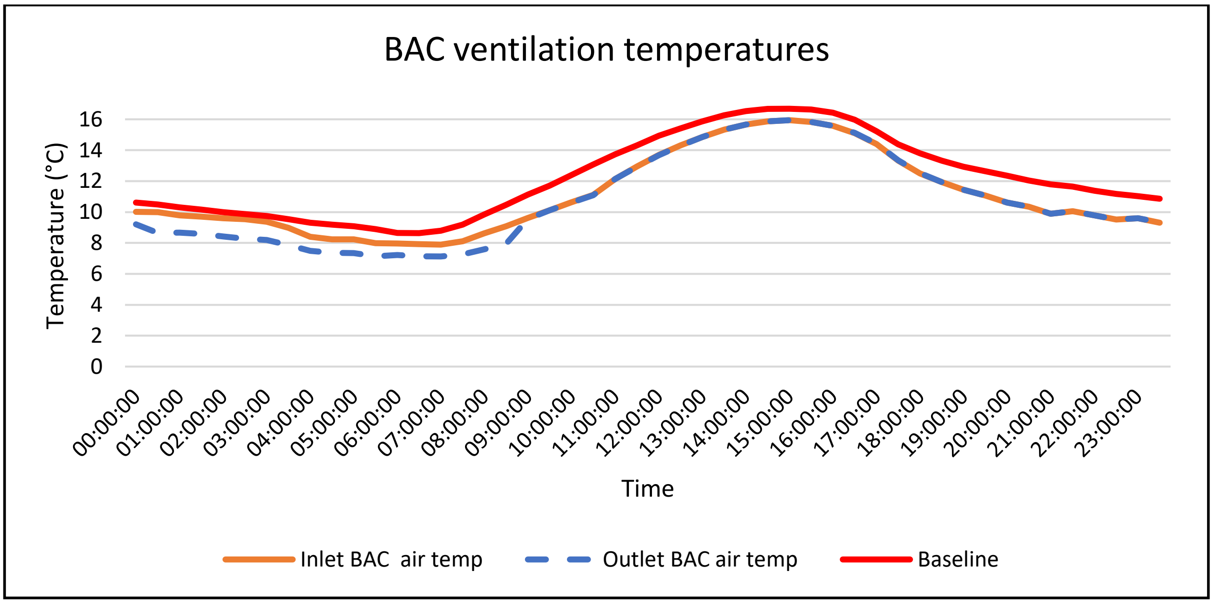


Figure 3-23: Simulated BAC outlet and inlet air temperatures compared to the baseline temperature

It can be seen from Figure 3-23 that the outlet BAC air temperature is lower than the inlet air temperature. This is due to a lower scope-day such as a 30%-scope day that has a higher DB temperature with low relative humidity. The graph shows that the outlet air temperature is cooled and not heated during a 30%-scope day, and that the outlet air temperature is below the average baseline temperature that is sent underground during winter. Therefore, while the strategy is implemented from the worst-case scenario, the outlet air temperature was cooled and remained below the baseline temperature. This means that the temperature will also remain below the baseline temperature when the optimised control strategy is implemented on higher scope days.

The strategy that was obtained by optimising the 30%-scope profile, and was also implemented on 50%-,70%- and 100%-scope days. On all these scope days, the temperature difference between the WB temperature and inlet BAC water temperature was found to be more than 0.7°C from 00:00 to 09:00. The BAC fans were, therefore, switched on from 00:00. The average daily power saving calculation of the 30%-scope day is explained below. Only the 30%-scope saving calculations are explained, as all the other scope days were calculated in the same manner.

The power saving of the 30%-scope simulation was 624 kW. This power saving is an average daily power saving which is derived from subtracting the average power profile and baseline profile over a 24-hour period. The daily average is used because this will be a more accurate representation of what savings can be expected, especially when the Megaflex tariff system is used to calculate the saving. Figure 3-20 illustrates the power profile of the simulated 30%-scope day compared to the baseline power, and Table 3-6 shows the data of the two power profiles from which the average daily power saving is derived.

Table 3-6: Simulated power profile data table

Time	Baseline (kW)	Simulated (kW)
00:00:00	4197.0	3080.3
00:30:00	4064.4	3406.8
01:00:00	4085.7	3442.5
01:30:00	3952.8	3366.8
02:00:00	4068.0	2682.9
02:30:00	4286.6	2668.8
03:00:00	4366.7	2778.3
03:30:00	3981.4	2508.2
04:00:00	4080.6	3481.5
04:30:00	4230.7	3369.0
05:00:00	4298.7	2509.0
05:30:00	4528.3	2287.9

06:00:00	4402.1	3001.1
06:30:00	4395.6	2598.3
07:00:00	4120.1	2908.1
07:30:00	3964.1	2495.9
08:00:00	4122.6	2515.5
08:30:00	3835.6	2647.4
09:00:00	3407.6	1753.1
09:30:00	3885.3	3043.4
10:00:00	3846.4	3046.8
10:30:00	4104.6	3290.9
11:00:00	4026.8	3372.0
11:30:00	4077.1	3485.2
12:00:00	4007.5	3876.7
12:30:00	3998.1	3608.9
13:00:00	4103.9	3762.2
13:30:00	3946.9	3918.7
14:00:00	4088.5	3808.7
14:30:00	4052.1	4232.1
15:00:00	3931.5	4039.2
15:30:00	4130.3	3977.3
16:00:00	4537.5	4200.9
16:30:00	2989.9	3066.0
17:00:00	1176.5	1676.3
17:30:00	0.7	365.0
18:00:00	0.8	347.0
18:30:00	0.8	347.0
19:00:00	0.8	347.0
19:30:00	0.8	347.0
20:00:00	4275.5	4274.2
20:30:00	4274.2	4325.9
21:00:00	4325.9	4627.7
21:30:00	4627.7	4598.8
22:00:00	4598.8	4485.9
22:30:00	4485.9	4369.0
23:00:00	4369.0	4213.3
23:30:00	4213.3	3671.1
Average	3671.14	3046.368
Average daily power saved		624.8

The average daily power saved can be calculated by using the equation below:

$$Average\ daily\ power\ saved = avg(baseline) - avg(simulated\ profile)$$

The average daily power saved was used to calculate the daily cost saving. The cost saving was derived by multiplying the average daily power saved by 24 hours to give kWh per day. The kWh's were then multiplied with an average daily winter tariff for weekdays, Saturdays, and Sundays to get the average weekday, Saturday, and Sunday daily saving. An average was then derived from all these daily savings over a week to get an average daily winter saving that takes all the different days and tariffs that the strategy can be implemented on into account. The following formulas illustrate how the savings are' derived.

$$\begin{aligned}&Average\ weekday\ saving\ R\\&\qquad = Average\ daily\ power\ saved\ kW * 24\ h * Average\ weekday\ tarrif\ R/kWh\end{aligned}$$

$$\begin{aligned}&Average\ Saturday\ saving\ R\\&\qquad = Average\ daily\ power\ saved\ kW * 24\ h * Average\ Saterday\ tarrif\ R/kWh\end{aligned}$$

$$\begin{aligned}&Average\ Sunday\ saving\ R\\&\qquad = Average\ daily\ power\ saved\ kW * 24\ h * Average\ Sunday\ tarrif\ R/kWh\end{aligned}$$

$$\begin{aligned}&Average\ daily\ cost\ saving\\&= \frac{Average\ weekday\ saving\ R * 5 + Average\ Saterday\ saving\ R + Average\ Sunday\ saving\ R}{7}\end{aligned}$$

The average weekday, Saturday and Sunday tariff is received from the Megaflex tariff that is provided by Eskom [13]. The tariffs are categorised by the supply voltage and the distance of the transmission line that Mine A operated under. Mine A falls into the 500 V to 66 kV range, with a transmission distance of below 300 km. Table 3-7 shows the daily average tariff for a weekday, a Saturday, and a Sunday.

Table 3-7: Eskom Megaflex tariff for Mine A 2020

Winter Tariff (R/kWh)			
Time	Weekday	Saturday	Sunday
0	0.5874	0.5874	0.5874
1	0.5874	0.5874	0.5874
2	0.5874	0.5874	0.5874
3	0.5874	0.5874	0.5874
4	0.5874	0.5874	0.5874
5	0.5874	0.5874	0.5874
6	3.5704	0.5874	0.5874
7	3.5704	1.0816	0.5874
8	3.5704	1.0816	0.5874
9	1.0816	1.0816	0.5874

10	1.0816	1.0816	0.5874
11	1.0816	1.0816	0.5874
12	1.0816	0.5874	0.5874
13	1.0816	0.5874	0.5874
14	1.0816	0.5874	0.5874
15	1.0816	0.5874	0.5874
16	1.0816	0.5874	0.5874
17	3.5704	0.5874	0.5874
18	3.5704	1.0816	0.5874
19	1.0816	1.0816	0.5874
20	1.0816	0.5874	0.5874
21	1.0816	0.5874	0.5874
22	0.5874	0.5874	0.5874
23	0.5874	0.5874	0.5874
Average daily tariff	1.435367	0.731542	0.5874

All the average daily tariffs can now, therefore, be used in the average daily power saved equations. The following calculations illustrate how the average daily power saving of the 30%-scope day was calculated:

$$Average\ daily\ power\ saved = 3671.14\ kW - 3046.37\ kW$$

$$Average\ daily\ power\ saved = 624.77\ kW$$

$$Average\ weekday\ saving = 624.77\ kW * 24\ h * 1.435367\ R/kWh$$

$$Average\ weekday\ saving = R21\ 522$$

$$Average\ Saturday\ saving = 624.77\ kW * 24\ h * 0.731542\ R/kWh$$

$$Average\ Saturday\ saving = R10\ 969$$

$$Average\ Sunday\ saving = 624.77\ kW * 24\ h * 0.5874\ R/kWh$$

$$Average\ Sunday\ saving = R8\ 807$$

$$Average\ daily\ cost\ saving = \frac{R21\ 522 * 5 + R10\ 969 + R8\ 807}{7}$$

$$Average\ daily\ cost\ saving\ 30\%\ scope = R18\ 176$$

The calculations that were used to calculate the 30%-scope average saving were also used to calculate an average daily power saving of each different scope simulation by using the different average power saved. Each different scope's average daily saving can be seen in Table 3-8.

Table 3-8: Different percentage scope simulated savings

Percentage scope	Average daily cost saving per percentage scope
30%	R18 100
50%	R19 200
70%	R22 500
100%	R23 400

Table 3-8 indicates that the daily cost savings increase as the percentage scope increases. This is due to the lower ambient WB temperature that causes more cooling to take place, which means lower precool dam temperatures. The average daily cost saving that each scope achieved can be used to estimate an annual saving by multiplying the daily cost saving with the number of days that the specific scope occurred throughout the year. Table 3-8 shows the annual saving that each percentage scope can achieve. The number of days that each scope occurred can be calculated off Figure 3-18 that shows the percentage time that each scope occurred during June to August which was the only months with suitable scope.

Table 3-9: Total annual saving per percentage scope

Percentage scope	Average daily cost saving per percentage scope	Percentage of month that scope occurred	Number of days	Total saving over period
30%	R18 000	25%	23	R414 000.00
50%	R19 200	18%	17	R326 400.00
70%	R22 500	11%	10	R225 000.00
100%	R23 400	8%	7	R163 800.00

In conclusion, the control strategy in the previous section achieved a saving of R41 400 per day but could only achieve an optimal saving 8% of the year and caused the chill dam levels to drop to a level too close to the low limits. Alternatively, the optimised control strategy can achieve an average saving of R20 775 per day for 62% of wintertime while keeping the chill dam levels above acceptable limits. The optimised control strategy can, therefore, achieve a total annual saving of R1 129 200.

3.2.7 Implementing the optimised control strategy

The optimised control strategy could not be implemented on Mine A during 2020 as originally planned. Due unforeseen circumstances caused the BAC maintenance to be moved. The BACs on Mine A were scheduled to be refurbished in May 2020. The COVID-19 pandemic caused the mine to go into a reduced production phase where only 50% of mine personnel were allowed to work. This meant that no contractors were allowed on-site until such time that the mines received permission to increase their production. No BAC refurbishment could take place and was postponed until further notice.

The mines got the go ahead for an increased production phase by mid-June 2020. Contractors were allowed on site with the correct documentation. The refurbishment of the BAC was finished by the end of July 2020, which meant that, at the time of this study, the optimised control strategy could not be implemented because the BAC was non-operational from mid-June 2020 to the end of July 2020, which is the time when the tests were scheduled to take place. This meant that the tests were postponed to August 2020, which did not have suitable atmospheric conditions, as August is when the temperatures start to increase.

The amount of scope to implement the strategy in 2021 was also analysed and it was found that ample scope was available as can be seen in Figure 3-24.

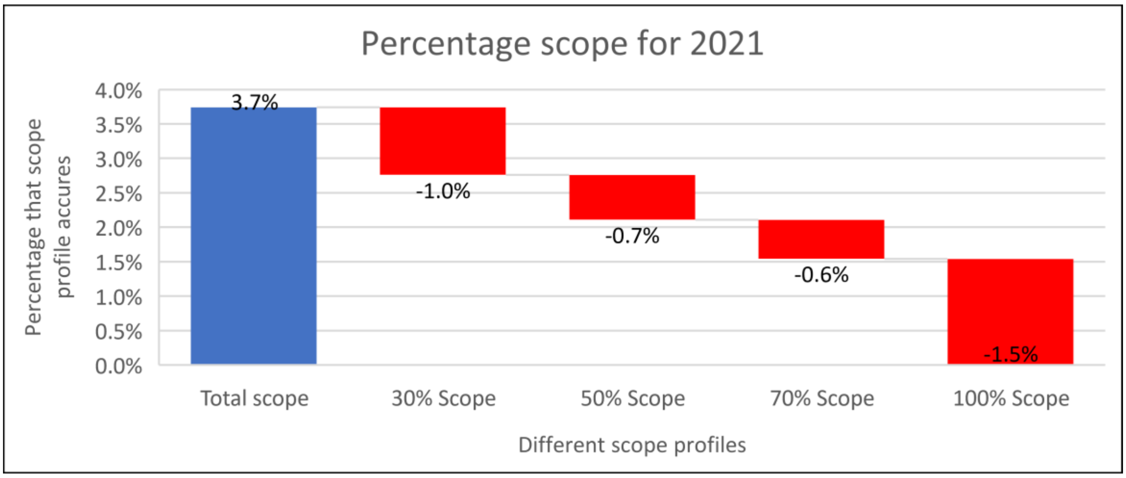


Figure 3-24: Percentage scope to implement the optimised control strategy during 2021

The strategy was, however, also not implemented due to fridge plant breakdowns and control room operators not implementing the strategy correctly. In order to implement the strategy sufficiently in the future, the strategy will either need to be implemented by training and constantly monitoring the control room operators or by automating the strategy on the mines' SCADA or with a dedicated control system. The automation of the strategy is recommended, as this will completely reduce the risk of control-room error. The steps to implement the strategy through the control room or by automation will be illustrated in the rest of this section.

Control room operator:

The control room operators will need to be trained and monitored to implement the strategy. This can be achieved by giving them a simplified control philosophy to follow and then monitoring if they are following the philosophy by analysing each day's data. The following process can be followed:

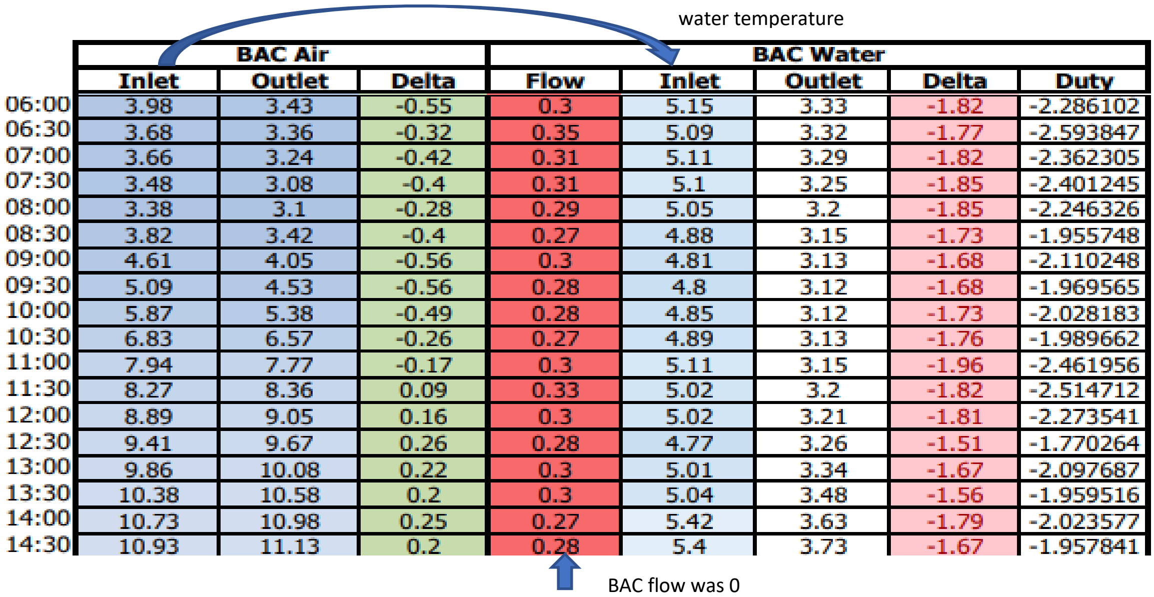
- A control philosophy of the strategy will need to be given to the operators.
    - Control philosophies need to be signed and approved by site management.
- The strategy will be to:
    - Open BAC water from 00:00 if the WB temperature is below the BAC inlet water temperature.
    - Start BAC fans if the WB temperature is 0.7 °C lower that the inlet BAC water temperature.
    - Stop BACs and water by 09:00.
- Operators must be trained to ensure that the control philosophy is understood and correctly implemented.
    - Operators need to understand where to get all the parameters in the philosophy.
    - Operators needs to understand all the parameters.
    - First implementation of the philosophy by operators needs to be supervised by mine personnel to ensure the operators understand the philosophy.

The control room operators and the performance of the strategy will then need to be monitored by a daily report. The daily report was an already existing report that was created on Mine A and was modified in order to monitor the strategy. The daily report automatically generates each day and will contain all the necessary surface BAC data to track whether the strategy was implemented or not. The report will be sent out to all relevant mining engineers. The report has the following data:

- BAC water inlet and outlet temperature
- BAC water delta T
- BAC air inlet and outlet temperature
- BAC water flow

- BAC cooling duty
- BAC ambient temperature

The daily report's surface BAC data can be seen in Figure 3-25. The data clearly indicates that this specified day was a day where the strategy could have been implemented, as the ambient temperature (inlet air) was lower than the BAC inlet water temperature, but BAC water flow was zero, which means that the strategy was not implemented. This is an example of data that can typically be used to follow up with the control room operators on why the strategy was not implemented. The pages of the report that show all the surface BAC data can be seen in Appendix C.



Inlet air was lower than inlet water temperature

	BAC Air			BAC Water				
	Inlet	Outlet	Delta	Flow	Inlet	Outlet	Delta	Duty
06:00	3.98	3.43	-0.55	0.3	5.15	3.33	-1.82	-2.286102
06:30	3.68	3.36	-0.32	0.35	5.09	3.32	-1.77	-2.593847
07:00	3.66	3.24	-0.42	0.31	5.11	3.29	-1.82	-2.362305
07:30	3.48	3.08	-0.4	0.31	5.1	3.25	-1.85	-2.401245
08:00	3.38	3.1	-0.28	0.29	5.05	3.2	-1.85	-2.246326
08:30	3.82	3.42	-0.4	0.27	4.88	3.15	-1.73	-1.955748
09:00	4.61	4.05	-0.56	0.3	4.81	3.13	-1.68	-2.110248
09:30	5.09	4.53	-0.56	0.28	4.8	3.12	-1.68	-1.969565
10:00	5.87	5.38	-0.49	0.28	4.85	3.12	-1.73	-2.028183
10:30	6.83	6.57	-0.26	0.27	4.89	3.13	-1.76	-1.989662
11:00	7.94	7.77	-0.17	0.3	5.11	3.15	-1.96	-2.461956
11:30	8.27	8.36	0.09	0.33	5.02	3.2	-1.82	-2.514712
12:00	8.89	9.05	0.16	0.3	5.02	3.21	-1.81	-2.273541
12:30	9.41	9.67	0.26	0.28	4.77	3.26	-1.51	-1.770264
13:00	9.86	10.08	0.22	0.3	5.01	3.34	-1.67	-2.097687
13:30	10.38	10.58	0.2	0.3	5.04	3.48	-1.56	-1.959516
14:00	10.73	10.98	0.25	0.27	5.42	3.63	-1.79	-2.023577
14:30	10.93	11.13	0.2	0.28	5.4	3.73	-1.67	-1.957841

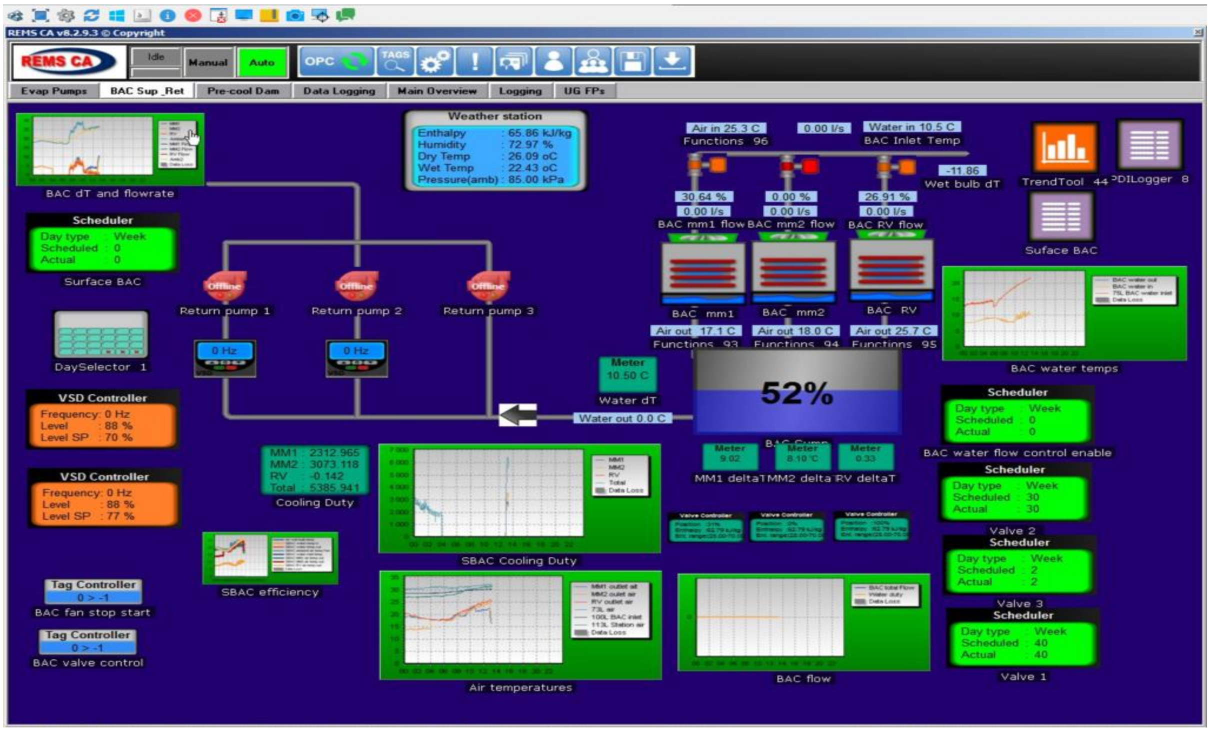
BAC flow was 0

Figure 3-25: BAC daily report monitoring data

As mentioned previously in this section, manual control will always give limited results since optimised energy saving is not the main responsibility of the control room operators. It is, therefore, suggested that automation of the strategy should be considered.

<u>Automation:</u>

The automation of the strategy can be done using Mine A's Remote Energy Management System (REMS). The mine's SCADA also has the ability to implement the automated strategy; however, REMS will be used due to its simple graphical user interface which makes programming the automation without any PLC training easier. REMS is a management system that is developed to communicate with the mine's SCADA system. Van Jaarsveld [55] has proven that REMS can be used to control mine equipment. REMS comprises a GUI platform with a series of components where mine-cooling models and systems can be built and controlled. All these components on REMS are connected to the mine's SCADA via a tag. REMS can use a series of SCADA and internal tags to control site equipment. A SCADA tag is assigned to a specific component on the mine that gives or receives either an analog or digital value to or from the PLC that is used to control specific mine systems or equipment. A REMS internal tag is used internally in REMS to do calculations and to assign new values to SCADA tags. Figure 3-26 illustrates Mine A's existing surface BAC REMS platform.



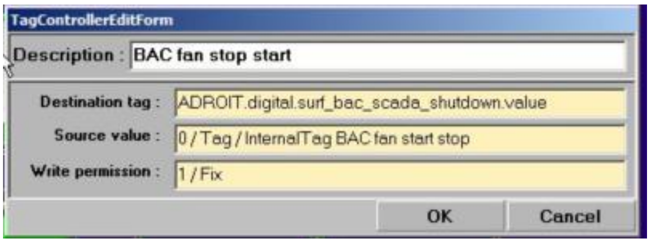
Enthalpy : 65.86 kJ/kg
Humidity : 72.97 %
Dry Temp : 26.09 oC
Wet Temp : 22.43 oC
Pressure(amb) : 85.00 kPa

Figure 3-26: Mine A's surface BAC REMS platform

The existing REMS platform has been used for wide range of different controls. Some of these controls, such as VSD control on BAC return pumps, were disabled by Mine A. All the values that are displayed in the REMS' platforms are linked to as specific SCADA tag to give a representation of the actual surface BAC system. The tag controller components that can be seen in the bottom left corner are the components that are going to be used to automate the control strategy and can be seen in Figure 3-27.

The components' settings and setup are also displayed in Figure 3-28. The setup of the control is straightforward and only consists of two tags. The tag controller is used to writes out a specific value to a SCADA tag which is used to control the mine equipment. The SCADA tag in the tag controller is the destination tag, and the tag that gives a value to the destination tag is the source tag. In the tag controller edit form, the destination tag is a BAC-shutdown tag and the source tag is a BAC start-stop tag. This means that BAC start and stop tag writes out a 1 or a 0 to the BAC shut-down tag which then starts and stops the BAC fans. The BAC's start and stop tag is an internal programmable tag that gives a 1 or a 0 if certain conditions are true. A step-by-step explanation will follow to illustrate how to use these tag controllers to automate the strategy.

Figure 3-27: Tag controller component



Description : BAC fan stop start

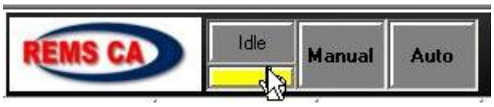
Destination tag : ADROIT.digital.surf_bac_scada_shutdown.value

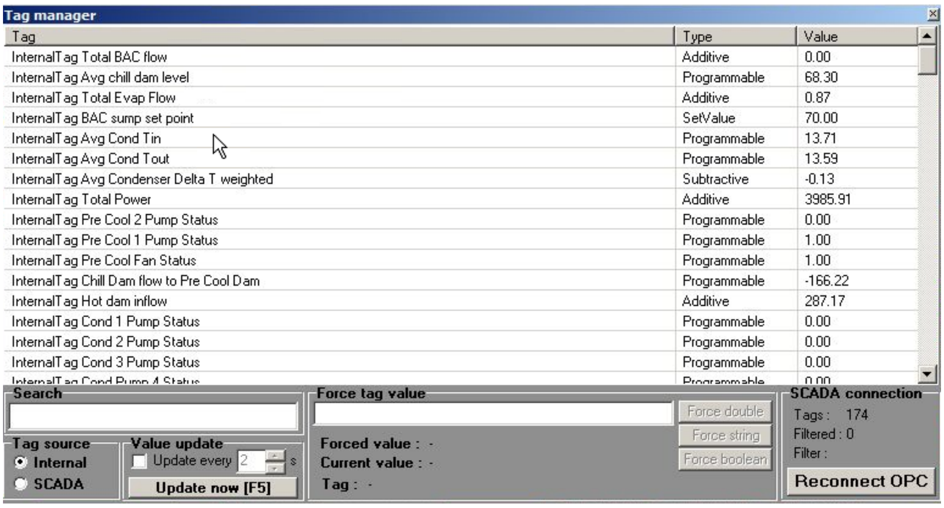
Source value : 0 / Tag / InternalTag BAC fan start stop

Write permission : 1 / Fix

Figure 3-28: Tag controller settings

The following steps will show how REMS was used to automate the strategy:

- The first step is to activate the idle capability of the REMS platform to ensure that the platform is in edit mode.
    - Idle form is where changes can be made on a REMS platform (edit mode).
    - The platform can be switched into idle mode by clicking on the idle button in the top-left corner of the main menu bar.
    - 

- All the tags that are going to be used in the strategy first need to be created or added onto the REMS system.
    - These tags are the WB temperature and the BAC inlet water temperature.
    - If these tags do not exist, the mine's instrumentation technician personnel should be able to help.
    - The tags should be visible under the tag manager and can be identified by using the search function in the tag manager at the bottom-left corner.
    - 

Tag manager

Tag	Type	Value
InternalTag Total BAC flow	Additive	0.00
InternalTag Avg chill dam level	Programmable	68.30
InternalTag Total Evap Flow	Additive	0.87
InternalTag BAC sump set point	SetValue	70.00
InternalTag Avg Cond Tin	Programmable	13.71
InternalTag Avg Cond Tout	Programmable	13.59
InternalTag Avg Condenser Delta T weighted	Subtractive	-0.13
InternalTag Total Power	Additive	3985.91
InternalTag Pre Cool 2 Pump Status	Programmable	0.00
InternalTag Pre Cool 1 Pump Status	Programmable	1.00
InternalTag Pre Cool Fan Status	Programmable	1.00
InternalTag Chill Dam flow to Pre Cool Dam	Programmable	-166.22
InternalTag Hot dam inflow	Additive	287.17
InternalTag Cond 1 Pump Status	Programmable	0.00
InternalTag Cond 2 Pump Status	Programmable	0.00
InternalTag Cond 3 Pump Status	Programmable	0.00
InternalTag Cond Pump 4 Status	Programmable	0.00

Search

Tag source: ● Internal ○ SCADA

Value update: ☐ Update every 2 s

Update now [F5]

Force tag value

Forced value : -

Current value : -

Tag : -

Force double

Force string

Force boolean

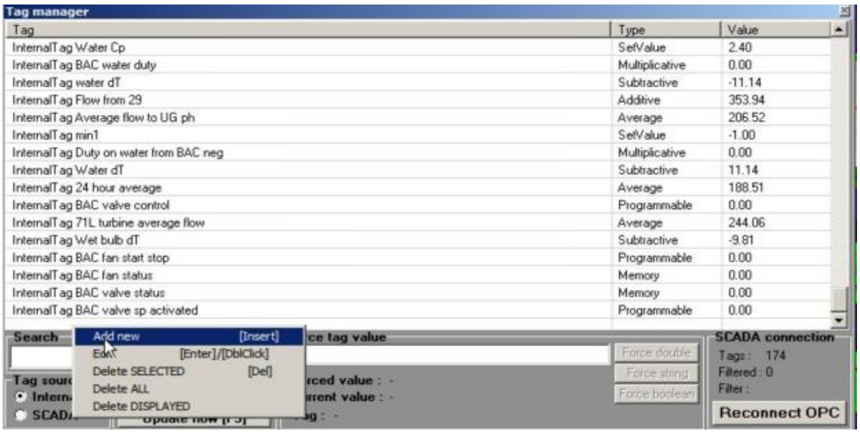
SCADA connection

Tags : 174

Filtered : 0

Filter :

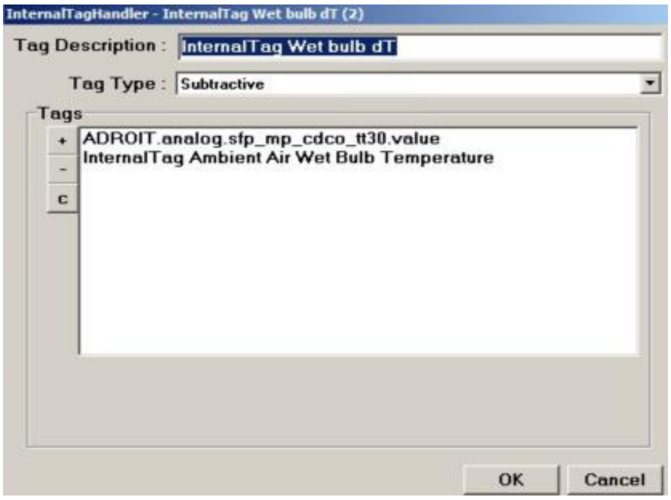
Reconnect OPC

  - The tag manager can be found by using the tag button in the main menu bar at the top of the screen
  - TAGS
- An internal tag needs to be created that calculates the temperature difference between the BAC inlet water temperature and the ambient WB temperature that will be used to write out a 1 or a 0 when this tag satisfies a specific value.
  - This tag can be created using the tag button in the main menu bar.
  - TAGS
  - When the tag manager is open, a tag can be created by *selecting internal* at tag source, right click and selecting *Add new tag*.
  - 

Tag manager

Tag	Type	Value
InternalTag Water Cp	SetValue	2.40
InternalTag BAC water duty	Multiplicative	0.00
InternalTag water dT	Subtractive	-11.14
InternalTag Flow from 29	Additive	353.94
InternalTag Average flow to UG ph	Average	206.52
InternalTag min1	SetValue	-1.00
InternalTag Duty on water from BAC neg	Multiplicative	0.00
InternalTag Water dT	Subtractive	11.14
InternalTag 24 hour average	Average	188.51
InternalTag BAC valve control	Programmable	0.00
InternalTag 71L turbine average flow	Average	244.06
InternalTag Wet bulb dT	Subtractive	-9.81
InternalTag BAC fan start stop	Programmable	0.00
InternalTag BAC fan status	Memory	0.00
InternalTag BAC valve status	Memory	0.00
InternalTag BAC valve sp activated	Programmable	0.00

SCADA connection
Tags: 174
Filtered: 0
Filter:

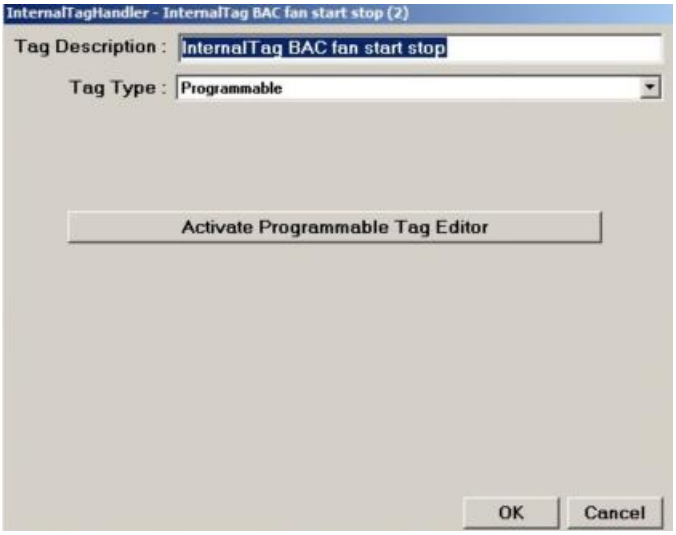
  - The internal tag handler will open as can be seen in the internal tag handler figure below.
  - In the tag description, type the tag name you wish to create. Under *Tag Type*, select *Subtractive*. Under tags, all the tags are added that need to be subtracted from each other. The second tag is subtracted from the first tag.
  - Click *Ok* and the tag will be created.
  - 

InternalTagHandler - InternalTag Wet bulb dT (2)

Tag Description : InternalTag Wet bulb dT

Tag Type : Subtractive

Tags
ADROIT.analog.sfp_mp_cdco_tt30.value
InternalTag Ambient Air Wet Bulb Temperature

  - In the internal tag handler, an internal tag is created that subtracts the BAC inlet temperature from the ambient WB temperature.
- Next, an internal programable tag needs to be created that gives a start-stop (1 or a 0) command when the temperature difference between the WB temperature and BAC inlet water temperature is suitable.
  - The tag can be created by selecting a programmable tag under tag type in the internal tag handler.
  - 

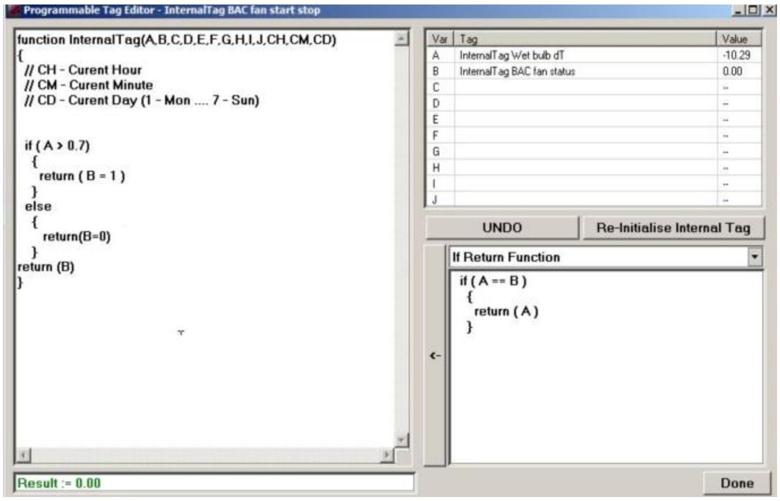
    InternalTagHandler - InternalTag BAC fan start stop (2)

    Tag Description : InternalTag BAC fan start stop

    Tag Type : Programmable

  - Click *Activate Programmable Tag Editor* to open the tag editor where programming can be done.
  - The program needs to write out a 1 when the WB temperature is above 0.7 and a 0 when it is not.
  - The internal WB dT tag that is already created and can be used in a simple if-else statement to achieve the desired outcome as can be seen in the programmable tag editor below.
  - In the lower-right corner of the tag editor, the statement you wish to program with can be selected to be used in the program.
  - In the upper-right corner of the tag editor, the variables of the program are specified.
    - A is the WB dT tag that was created.
    - B is a memory tag that saves and returns the result of the if-else statement.
    - The memory tag's result is equal to the BAC fan start-stop programmable tag value.

        - The if-else statement in the tag editor is to return a 1 (start) if the WB dT tag is greater than 0.7 and to return a 0 (stop) if the value is below 0.7.



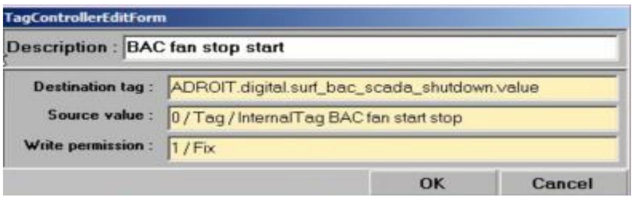
```
function InternalTag(A,B,C,D,E,F,G,H,I,J,CH,CM,CD)
{
 // CH - Curent Hour
 // CM - Curent Minute
 // CD - Curent Day (1 - Mon .... 7 - Sun)


 if ( A > 0.7)
  {
   return ( B = 1 )
  }
 else
  {
   return(B=0)
  }
return (B)
}
```

Var	Tag	Value
A	InternalTag Wet bulb dT	-10.29
B	InternalTag BAC fan status	0.00
C		--
D		--
E		--
F		--
G		--
H		--
I		--
J		--

```
if ( A == B )
 {
  return ( A )
 }
```

Result := 0.00

    - The BAC fan start-stop tag can now be used in a tag controller to write out a 0 (stop) or a 1 (start) value to a SCADA tag that is assigned to start or stop the BAC fans.
    - A SCADA BAC start-stop tag needs to be provided by mine instrumentation technicians.



Description : BAC fan stop start

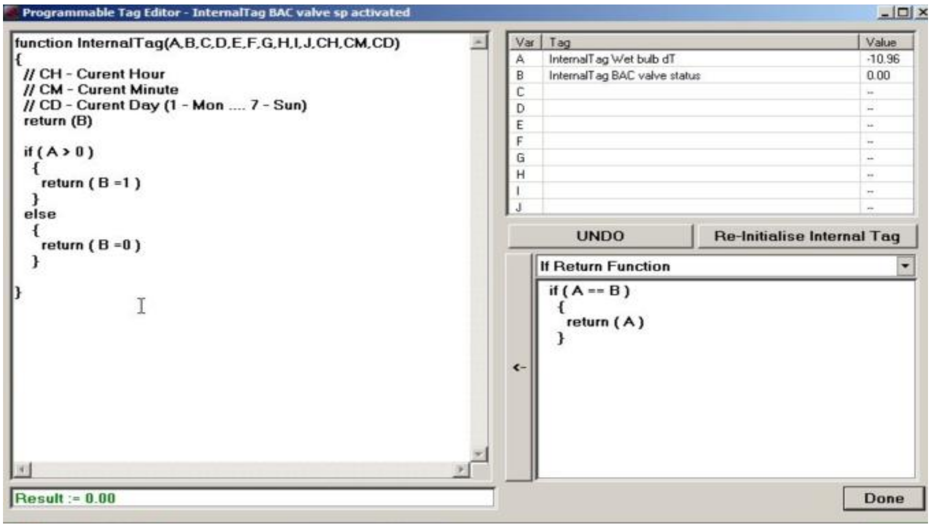
Destination tag : ADROIT.digital.surf_bac_scada_shutdown.value

Source value : 0 / Tag / InternalTag BAC fan start stop

Write permission : 1 / Fix

- The next step is to create an internal programmable tag to open and close the BAC water valves when the WB temperature drops below the inlet water BAC temperature.
    - The tag will be created in the same manner as the BAC start-stop programable tag.
    - The tag will need its own programming that will write out an open signal when the WB temperature is lower than the inlet water temperate and a close signal when it's not.
    - In the upper right corner of the tag editor, the program's variables are specified.
        - A is the WB dT tag that was created.
        - B is a memory tag that saves and returns the result of the if-else statement.
        - The memory tag's result is equal to the BAC valve set point activated programmable tag's value.

        - The if-else statement in the tag editor is to return a 1 (start) if the WB dT tag is greater than 0 and to return a 0 (stop) if the value is below 0.



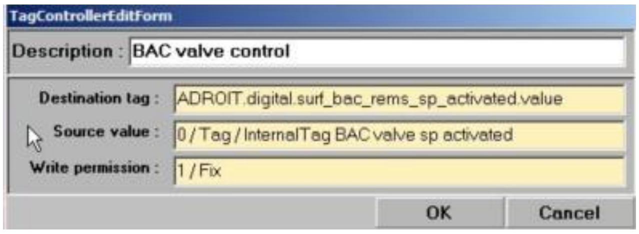
```
function InternalTag(A,B,C,D,E,F,G,H,I,J,CH,CM,CD)
{
  // CH - Curent Hour
  // CM - Curent Minute
  // CD - Curent Day (1 - Mon .... 7 - Sun)
  return (B)

  if ( A > 0 )
   {
    return ( B =1 )
   }
  else
   {
    return ( B =0 )
   }

}
```

Var	Tag	Value
A	InternalTag Wet bulb dT	-10.96
B	InternalTag BAC valve status	0.00
C		--
D		--
E		--
F		--
G		--
H		--
I		--
J		--

```
if ( A == B )
 {
  return ( A )
 }
```

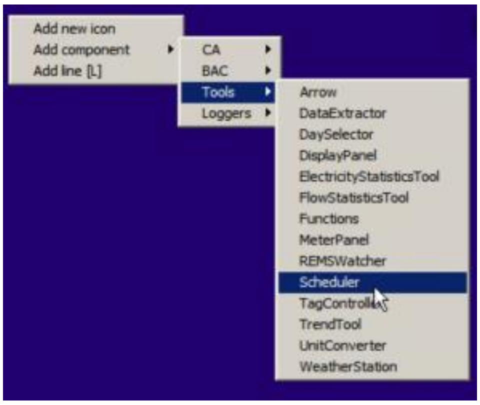
```
Result := 0.00
```

    - The BAC set point activate tag can now be used to give an open and close signal to a SCADA tag that is connected to BAC valves in a tag controller component.

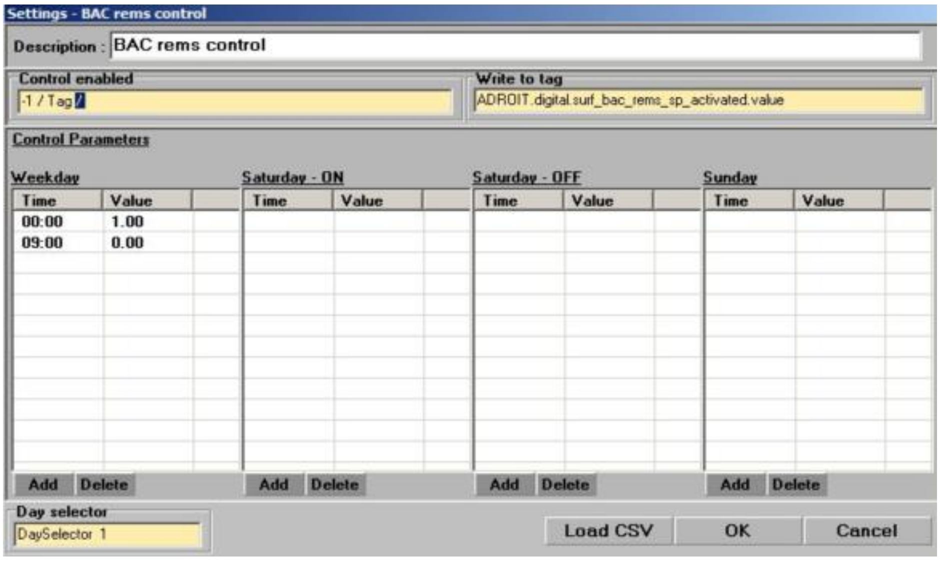


Description : BAC valve control
Destination tag : ADROIT.digital.surf_bac_rems_sp_activated.value
Source value : 0 / Tag / InternalTag BAC valve sp activated
Write permission : 1 / Fix

    - The BAC valves will receive an open signal and open all the valves to a set valve position.
    - The valves are manually set to a valve position that will ensure a flow of 150 l/s, as the valves do not have the capability to control on a specific flow.
- The next step will be to add a Scheduler that will only enable the REMS BAC control between 00:00 and 09:00 to ensure that the control in not active before 00:00.
    - The Scheduler component is already an existing component on the layout but can be added if one is not visible by right clicking on a blank space on the layout and going to *Add component, Tools* and then selecting *Scheduler*.

  - 

  - 

  - The Scheduler settings can be accessed by double clicking on the Scheduler.
  - In the Scheduler's settings, a SCADA permission tag needs to be inserted in the *Write To Tag* field that will enable REMS control on the BAC during specific times that are stated in the Scheduler.
  - The permission tag needs to receive a 1 (activated) value between 00:00 and 09:00.
  - 

Settings - BAC rems control

Description : BAC rems control

Control enabled: -1 / Tag

Write to tag: ADROIT.digital.surf_bac_rems_sp_activated.value

Control Parameters

Weekday

Time	Value
00:00	1.00
09:00	0.00

Saturday - ON

Time	Value

Saturday - OFF

Time	Value

Sunday

Time	Value

Day selector: DaySelector 1

  - The Scheduler writes out a 1 from 00:00 to 09:00 and a 0 for the rest of the day, ensuring no control will be enabled outside the stipulated time frame.
- The last step is to activate the auto-control capability of the REMS platform.
  - The platform can be switched into automatic mode by clicking on the *Auto* button in the top-left corner of the main menu bar.
  - 

All the steps that were provided will ensure that the strategy can be implemented by the control room operators or by the mine's SCADA and REMs systems; however, the strategy first needs to be implemented and tested before the strategy can be controlled automatically. The automated control of the BACs that was stipulated is to control the BACs on Mine A by using all the available tools on this specific mine. The automation that was stipulated on REMS can also be achieved in more ways, but this specific manner was chosen due to the specific SCADA tags that were available.

3.3 Interpretation of results

This section will discuss the results before and after optimisation. The results before optimisation were simulated, tested, and validated, and the results after optimisation could only be proven through verified simulation. The optimised simulation was developed from the simulation that was validated upon implementation on the mine and was deemed an accurate simulation. The simulated results of the optimised control strategy can, therefore, be deemed accurate.

The results before optimisation were obtained by first identifying scope for seasonal control to be implemented. A strategy was then developed off the scope that was identified to utilise the identified scope to the mine's advantage. The strategy was then simulated with a verified simulation to ensure all constraints were stratified. The simulated strategy was then implemented on Mine A and compared to actual data for validation.

The outlet water temperature that was lower than the inlet water temperature during times when the WB temperature was lower than the inlet water temperature of the BACs was identified as the seasonal control scope. A strategy was then developed to run the BAC during these times, which causes the BAC to be utilised as a precooling tower to help cool precool dam temperatures and reduce FP power while maintaining service delivery.

Table 3-10 depicts the average daily FP power consumption and cost savings of the simulated and implemented results of the developed strategy before optimisation. The error between the simulation and actual results was 9.5 % for the FP power consumption and 14 % for cost saving.

Table 3-10: Implemented validation before optimisation

Average predicted FP power consumption	Achieved FP power consumption
2176 kW	2383 KW
Average predicted cost saving	Achieved cost saving

R41 400	R35 500

The strategy before optimisation achieved a greater saving, but was implemented on a day with 100% scope, which means that the BAC could be utilised for 100% of the day to cool precooling dam temperatures because the ambient WB temperature was low. The strategy also lowered chill dam levels, which could cause problems if a sudden spike in consumption would arise. Thus, the strategy before optimisation had two problems – it would only achieve a large saving during 100%-scope days, which only occurred 8% of the three-month winter period, and chill dam levels decreased to lower levels, which mines do not prefer.

The optimised control strategy was, therefore, developed off a 30%-scope day which was chosen as the worst-case scenario to achieve a saving from. By using the strategy that was developed of the worst-case scenario, an optimal saving could be achieved for 62% of the three-month winter period. The optimised control strategy was also developed to achieve this frequent saving without lowering chill dam levels below 80%. The optimised control strategy would, therefore, achieve a greater annual saving than the strategy before optimisation.

Table 3-11 shows the optimised control strategy’s average daily fridge plant power consumption and the cost savings of each day. Note that the power consumption is higher and the cost savings less for the optimised control strategy. This is because the strategy is optimised to achieve this lower cost-saving more frequently throughout the month than the strategy before optimisation.

Table 3-11: Simulation results for the optimised control strategy

Average predicted fridge plant power consumption
2949 kW
Average predicted cost saving
R20 775

Table 3-12 shows the annual saving before and after optimisation. The annual saving after optimisation is more than the saving before optimisation, as the strategy could achieve savings more frequently throughout the year.

Table 3-12: Average monthly savings before and after simulation

Yearly saving before optimisation	Yearly saving after optimisation
R289 800	R1 129 200

The optimised control strategy's annual saving was only calculated through simulation and by analysing the amount of scope that was available during 2020. The strategy could unfortunately not be implemented during 2020 because of the COVID-19 pandemic. During 2021, ample scope to implement the strategy was also missed as can be seen in Figure 3-24. The ample scope added up to a R 971 700 annual saving that was missed. The missed scope can largely be attributed to a series of fridge plant breakdowns which were out of the mine's control. While the few days that were available with operational fridge plants and scope were not utilised due to the control room operators not implementing the strategy correctly. Therefore, a step-by-step automation program was developed on Mine A's REMS system to ensure that sufficient implementation of the optimised control strategy will be achieved in the future.

In conclusion, the results before and after optimisation were discussed in this section. The results before optimisation were simulated and verified on Mine A. The strategy did achieve a power saving while maintaining service delivery. The strategy before optimisation did, however, reduced chill dam levels to unacceptable levels and needed to be optimised. The strategy was optimised through simulation and achieved a larger calculated annual saving without reducing chill dam levels. The strategy was, however, not implemented due to a number of controllable and uncontrollable factors. The controllable factors like control room operator error were rectified by developing an automation program on Mine A's REMS system.

3.4 Conclusion

In this section, a seasonal control strategy was developed and implemented on Mine A. The strategy was developed by first identifying a scope for a seasonal control strategy and identifying all the system constraints associated with the identified scope. After all the system constraints were investigated and mitigated, a control strategy was developed, simulated, and tested on Mine A's cooling system.

The strategy that was developed was to utilise the BACs as precooling towers when the WB temperature drops below the BAC inlet temperature. By implementing this strategy, the BACs can be used to help cool precooling dam temperatures and reduce the FP load. The strategy was simulated and implemented on Mine A. The simulated and actual results had an average error of 6.6%, which can be deemed accurate.

The implemented strategy achieved a daily cost saving of R41 100 while maintaining service delivery. However, the strategy was implemented on a day with 100% scope, which only occurred 8% of the three-month winter period with suitable scope. During implementation of this strategy, the chill dam levels decreased to just above the prescribed low limit, which can be seen as a concern as it is custom for this specific mine to try to remain far above their low limits because of unpredictable chill-water demands.

The existing strategy was optimised to achieve a saving on 62% of the three-month period while keeping the chill dam levels stable above 80% and maintaining service delivery. The optimised control strategy achieved an average daily saving of R20 775. This daily saving is less than the original saving but adds up to an R1 129 200 annual saving where the original annual saving before optimisation would only have added up to R289 800.

The optimised control strategy could only be proven through simulation, as it could not be implemented due to the 2020 COVID-19 pandemic restrictions that caused the BAC refurbishment to be moved. Therefore, the implementation of the optimised control strategy was postponed and could not be implemented during suitable WB conditions during that year. In 2021, the strategy was also not implemented, regardless of ample scope. The strategy could not be implemented due to fridge plant breakdowns and control room operators incorrectly implementing the optimised control strategy. The control room operator error was rectified by developing a daily monitoring system or using the developed atomisation program on Mine A’s REMS system that implements the strategy automatically.

In conclusion, a strategy was developed in this section to utilise mine-cooling auxiliaries for optimal performance during seasonal changes, and the associated energy efficiency and cost savings of the strategy were identified and quantified while still maintaining service delivery. Thus, all the mentioned study objectives identified in Section 1 were achieved.

4. Conclusion and recommendations

4.1 Executive summary

Electricity cost is a major concern for intensive electricity users in South Africa. Electricity costs have increased by 300% over the last 10 years, and the forecasted increase is set to be higher than inflation [12]. This is not favourable for deep-levels mines, since the increasing electricity tariff, CPI, and constant need to expand in order to reach their deposits all contribute to increasing operational costs and decreasing profit margins. This forces mines to improve their efficiency and drive any possible existing and new energy-saving initiatives and processes to ensure sustainable operations while still remaining as cost effective as possible[16].

Mine-cooling systems were identified as one of the most electricity-intensive consumers on a deep-level gold mine in South Africa. These mine-cooling systems were researched, and the research found that a great deal of energy-saving studies have been conducted on mine-cooling systems. These studies focused on increasing energy efficiency and improving service delivery through the implementation of a series of control philosophies. Most of the control philosophies focused on reducing electricity through load management.

The studies found that historically implemented energy-saving initiatives, however, did not focus on a winter control philosophy in terms of utilising the cold ambient WB temperatures to the mine's advantage aside from one study in Canada that used a BAC to heat up cold ambient air with hot water from underground. Therefore, the potential to reduce mine-cooling systems' energy efficiency and improve service delivery by utilising the cold ambient conditions during seasonal changes was identified.

This study focused on developing and simulating an optimised seasonal control strategy for deep-level mine-cooling systems. The development focused primarily on optimising the performance of mine-cooling systems in terms of cost saving and sufficient cooling over seasonal changes. The study objectives were, therefore, to develop a control strategy for mine-cooling systems during seasonal changes and to identify and quantify the associated energy efficiency and cost savings of the strategy while still maintaining or improving service delivery in terms of mine-cooling systems.

A seasonal control strategy was developed for one gold mine in South Africa. The strategy entailed utilising the BACs as precooling towers when the WB conditions were suitable. This cooled water that was sent to the precooling dam resulted in a precooling dam temperature reduction. The strategy was simulated to determine the practical impact on the specific mine's surface cooling system. The simulation was first verified with actual data to ensure an accurately calibrated simulation. After verification, the strategy was simulated and compared with actual test data that was obtained after implementation. Table 4-1 gives a summary of the validation results.

Table 4-1: Seasonal control strategy validation results

KPIs	Actual	Simulated	Percentage error (%)
Precooling dam temperature (°C)	11.17	10.65	4.80
Chill dam temperature (°C)	5.13	5.26	2.43
FP power (kW)	2383.96	2176.60	9.53
FP power reduction	1287.18	1494.56	13.87

The tests concluded that a precooling dam temperature reduction was achieved, which caused the FPs to have a lower inlet water temperature. The strategy achieved a reduction in FP power but only managed to maintain service delivery, as the fridge plant was already achieving their outlet water set point before the implementation of the strategy. The strategy did achieve a R41 400 daily saving; however, it was found that this saving could only be achieved on days where the WB conditions were suitable for a large part of the day, which did not occur much throughout the month. Additionally, the strategy reduced chill dam levels to just above acceptable limits. The strategy, therefore, had to be optimised in order to achieve a saving on more days throughout the month while keeping the chill dam stable at acceptable limits and achieving the best possible performance with the cooling system.

The strategy was optimised to achieve a saving on a day where the WB temperature was only suitable for a small part of the day while keeping the chill dam levels stable. However, the strategy could not be implemented due to the COVID-19 pandemic that forced mines to operate at lower production with no site visits. The optimised control strategy was simulated with the same simulation that was validated with the strategy before optimisation. Table 4-2 shows the results that were achieved through the simulation.

Table 4-2: Optimised results achieved through the simulation

Average predicted daily FP power reduction
722 kW
Average daily predicted cost saving
R20 775

The optimised control strategy did achieve a smaller daily saving than the strategy before optimisation, but this smaller saving could be achieved more frequently throughout all the months that had suitable scope during the year. The optimised control strategy could be implemented during 62% of the winter months, which added up to an annual winter saving of R1 129 200, while the strategy before implementation would only have achieved a R289 800 saving for the same period. This means that the optimised control strategy achieved optimal saving over all the winter months while still maintaining service delivery.

The optimised control strategy's savings were calculated by analysing the amount of scope that was available during 2020 and simulating the optimised control strategy with the corresponding amount of scope to calculate an annual saving. The optimised control strategy could unfortunately not be implemented during 2020 or 2021. In 2020, the implementation of the optimised control strategy was postponed due to the COVID-19 Pandemic, and during 2021, it could also not be implemented due to fridge plant breakdowns and control room operators incorrectly implementing the strategy

Steps to automate and manually operate the strategy were, therefore, developed. For manual operation, a detail control philosophy was developed to manually operate the strategy with an automated report to track whether the control room operators were following the control philosophy. For automatic control, a full automation program was developed on Mine A's REMS system to ensure that the strategy can be implemented automatically and reduce control-room error. These two steps will ensure that the strategy is implemented correctly in the future.

The optimised control strategy that was developed in this study was developed for a specific gold mine in South Africa, as this was the only mine willing to test and implement the study. The strategy can, however, also be implemented on other gold mines in South Africa with suitable mine-cooling systems and ambient conditions. The mine-cooling system should have the correct BAC, precool dam, and FP configuration to utilise the cold ambient WB temperature during the winter months in order to cool precool dam water and reduce fridge plant load.

Figure 4-1 below illustrates a mine in Welkom with suitable ambient conditions to implement the strategy on. This gives an indication that a seasonal control strategy can also be implemented on other mines, as suitable ambient conditions are available.

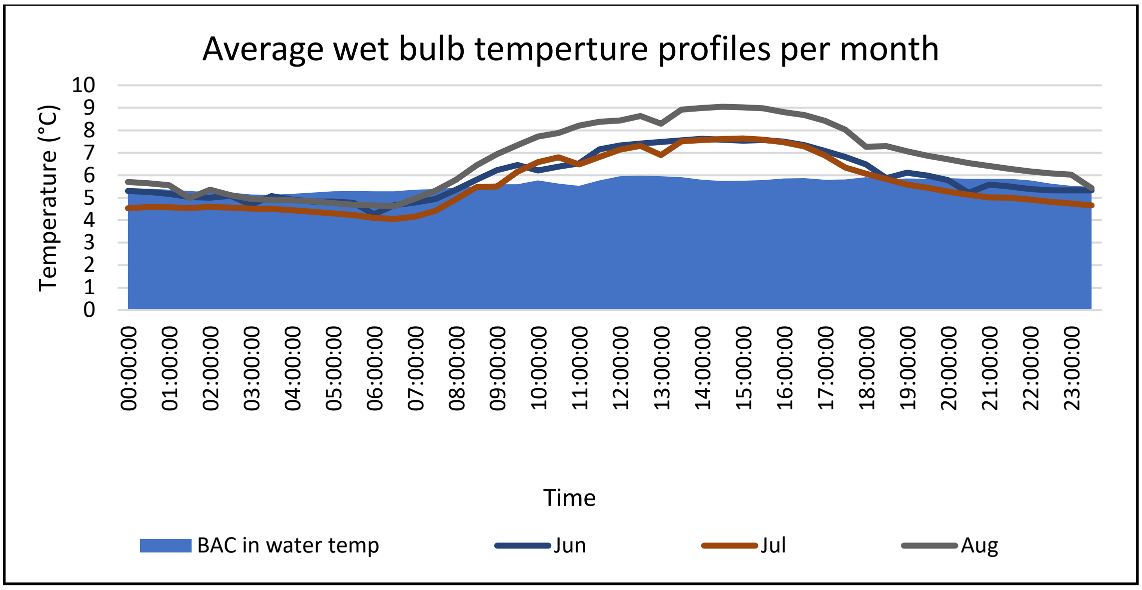


Figure 4-1: Suitable ambient WB conditions on a mine in Welkom

The strategy can also be expanded to not only be used on mines but in any industries using evaporative cooling in conjunction with fridge plants to cool air. Dormant evaporative coolers or BACs can also be used with hot water to heat freezing ventilation or HVAC air to save power on electronic or gas heaters in countries where the WB temperature drops below zero.

The study objectives that were stated in section 1.5 previously were to develop a control strategy for mine-cooling systems during seasonal changes and to identify and quantify the associated energy efficiency and cost savings of the strategy while maintaining or improving service delivery in terms of mine-cooling systems. The study has proven that all these identified study objectives were achieved, as a strategy for seasonal control was developed and the associated energy efficiencies of the strategy were quantified while service delivery was maintained.

The study concludes that a strategy can be developed to utilise mine-cooling auxiliaries for optimal performance during seasonal changes by implementing an optimised seasonal control strategy. The gold mines can benefit from this strategy, as their cooling systems will be more energy efficient during wintertime, which means increasing profit margins.

4.2 Recommendations

The seasonal control strategy has proven to be successful but is still very dependent on the control room operator to switch equipment on and off when the ambient WB temperatures are suitable. The feasibility can be investigated for developing a method for an automatic seasonal control strategy. The automation entails automatically switching systems like BAC and precooling towers on and off when the WB temperature is suitable.

The automation can also be integrated with control philosophies such as flow control and reconfiguration. The flow control can be integrated with the automation to switch equipment on and off while controlling the flow for optimum outlet temperatures. The feasibility of reconfiguring all systems that can utilise the cold ambient conditions to work together with flow control to supply a large amount of cold water must also be tested.

The strategy to connect the dormant BACs with precool towers and continuously cycle hot precool water through the BACs can also be motivated by using the existing strategies' savings to acquire all the necessary infrastructure to implement the BAC precool loop strategy. This strategy will reduce the implementation complexity of the current strategy.

The scope for improving the seasonal control strategy can be investigated on all deep-level mines, as most of them have BACs, precooling towers, and condenser towers. The strategy also has the potential to be implemented in the HVAC industries, as systems like BACs are also used in most large HVAC systems.

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Appendix A: Cooling system component specifications

The following table contains all the design inputs of all the components in Mine A's surface cooling system. These inputs are required for simulation calibration.

System	Component	Data
Fridge plants 1 & 4	Compressor motor installed power	2000 [KW]
	Evaporator in temperature	11 [°C]
	Evaporator out temperature	5 [°C]
	Condenser in temperature	18 [°C]
	Condenser out temperature	22 [°C]
	Evaporator flow	350 [l/s]
	Condenser flow	700 [l/s]
Pumps	Evaporator pump motor	90 [kW]
	Evaporator pump flow	200 [l/s]
	Evaporator pump head	2 [m]
	Condenser pump motor	185 [kW]
	Condenser pump flow	600 [l/s]
	Condenser pump head	5 [m]
	BAC pump motor	80 [kW]
	BAC pump flow	200 [l/s]
	BAC pump head	10 [m]

	Precooling pump motor	90 [kw]
	Precooling pump flow	150 [l/s]
	Precooling pump head	5 [m]
Dam	Chill dam 1 volume	4170 [m^3]
	Chill dam 1 temperature	5 [°C]
	Chill dam 1 operating level	90 [%]
	Chill dam 1 low limit	60 [%]
	Chill dam 2 volume	4170 [m^3]
	Chill dam 2 temperature	5 [°C]
	Chill dam 2 operating level	90 [%]
	Chill dam 1 low limit	60 [%]
	Precool dam volume	3000 [m^3]
	Precool dam temperature	17 [°C]
	Precool dam operating level	70 [%]
	Precool dam low limit	40 [%]
	BAC sump volume	2000 [m^3]
	BAC sum temp	8 [°C]
	BAC sump operating level	50 [%]
	BAC sump low limit	30 [%]
	Condenser sump 1 volume	5000 [m^3]
	Condenser sump 1 temp	18 [°C]

	Condenser sump 1 operating level	90 [%]
	Condenser sump 1 low limit	50 [%]
	Condenser sump 2 volume	5000 [m^3]
	Condenser sump 2 temp	18 [°C]
	Condenser sump 2 operating level	90 [%]
	Condenser sump 2 low limit	50 [%]
	Hot dam volume	3000 [m^3]
	Hot dam temperature	26 [°C]
	Hot dam operating level	70 [%]
	Hot dam low limit	30 [%]
Precooling tower	PCT water inlet temp	26 [°C]
	PCT water outlet temp	18 [°C]
	PCT water flow	350 [l/s]
	PCT Air flow	Need to be calculated
	PCT air inlet temp	Ambient
Condenser cooling tower	CCT water inlet temp	30 [°C]
	CCT water outlet temp	18 [°C]
	CCT water flow	1000 [l/s]
	CCT Air flow	1000 [kg/s]
	CCT air inlet temp	Ambient

BAC	BAC water inlet temperature	5 [°C]
	BAC water outlet temperature	12 [°C]
	BAC water flow	200 [l/s]
	BAC air flow	300 [kg/s]
	BAC inlet air temperature	Ambient
Fans	BAC fan motor	220 [kW]
	BAC fan air flow	250 [kg/s]
	CCT fan motor	45 [kW]
	CCT fan air flow	230 [kg/s]
	PCT fan power	45 [kW]
	PCT fan air flow	230 [kg/s]

Appendix B: Simulation verification and overview

The simulation was calibrated by using the average operating conditions and data listed in Appendix A. Once the components were calibrated, a normal operating day was simulated and compared to an actual operating day's data. The following table shows the percentage error between the simulated and actual KPI results.

KPI	Simulated	Actual	Error
Precool dam temperature (°C)	13.49	13.42	0.5 %
Chill dam temperature (°C)	5.18	5.44	5 %
Fridge plant power consumption (kW)	2536.3	2474.56	2.4 %
Chill dam level (%)	99.3	91.3	7.1 %

The simulation can be deemed accurate, as the average percentage error between the actual and simulated results is 3.75%. The following series of graphs illustrates the 24-hour profiles of the simulated and actual results.

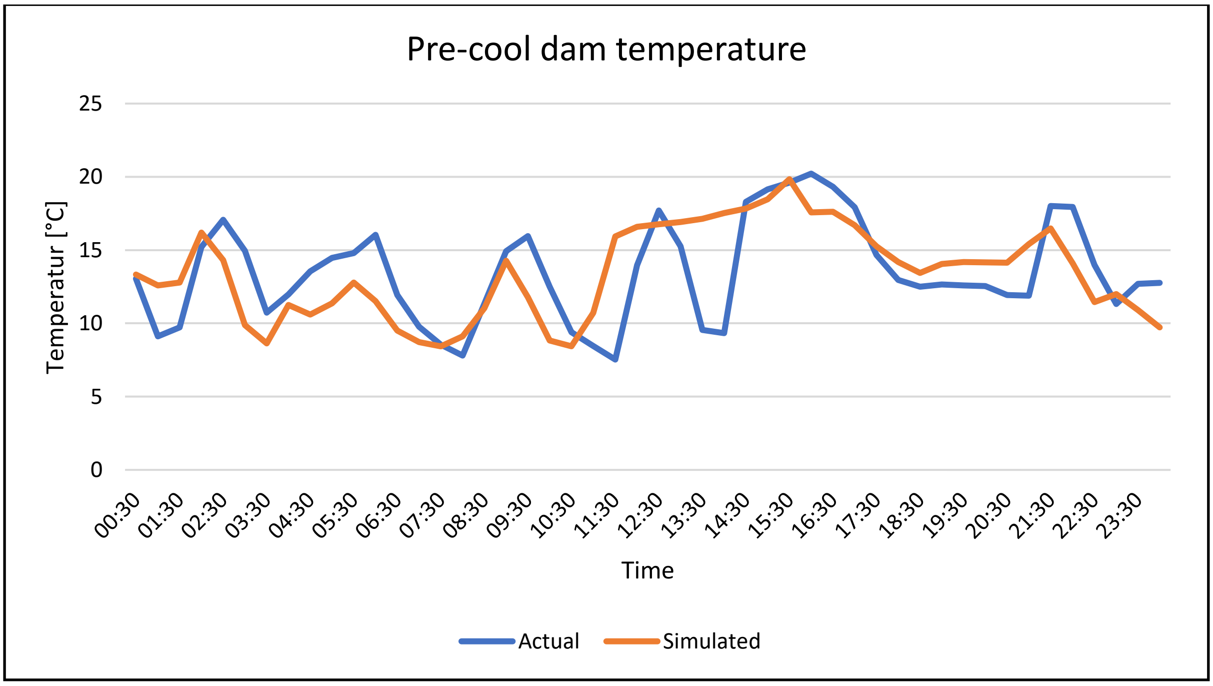


Figure B-1: Precool dam verification

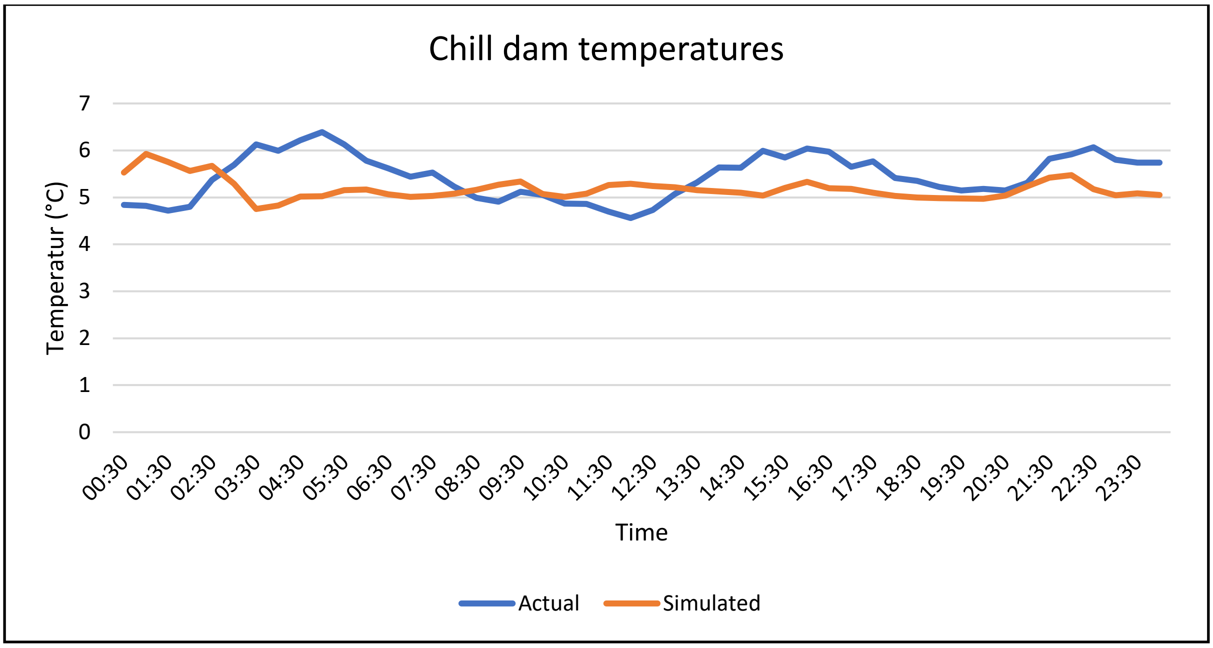


Figure B-2: Chill dam temperature verification

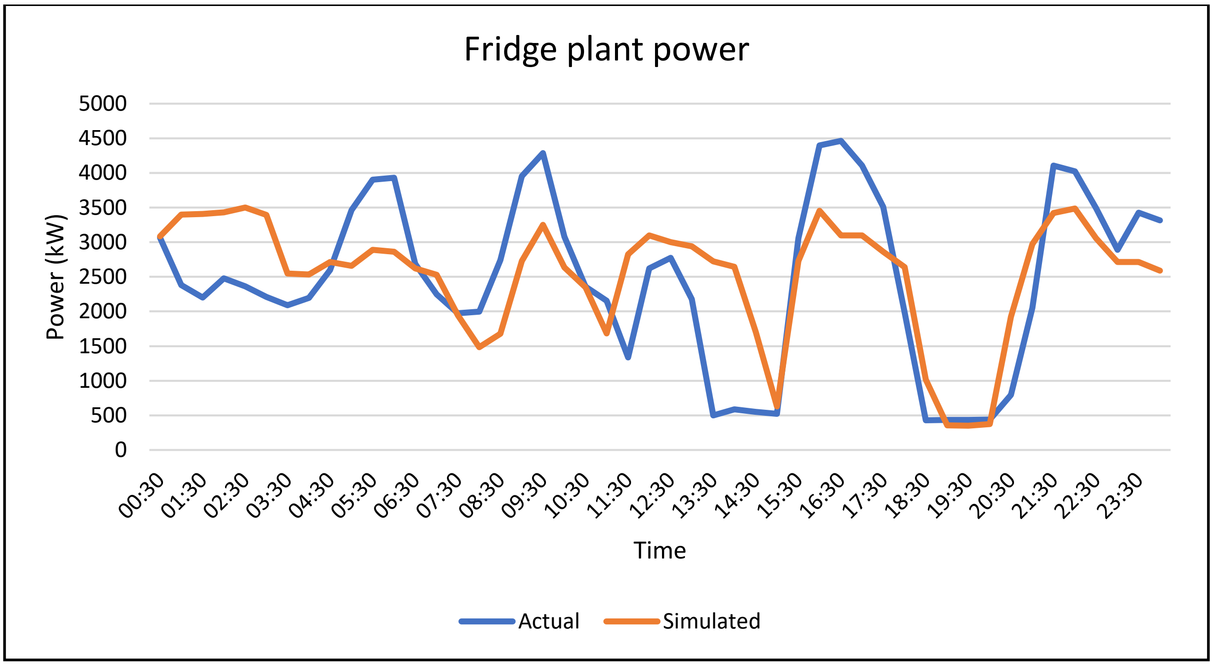


Figure B-3: Fridge plant power verification

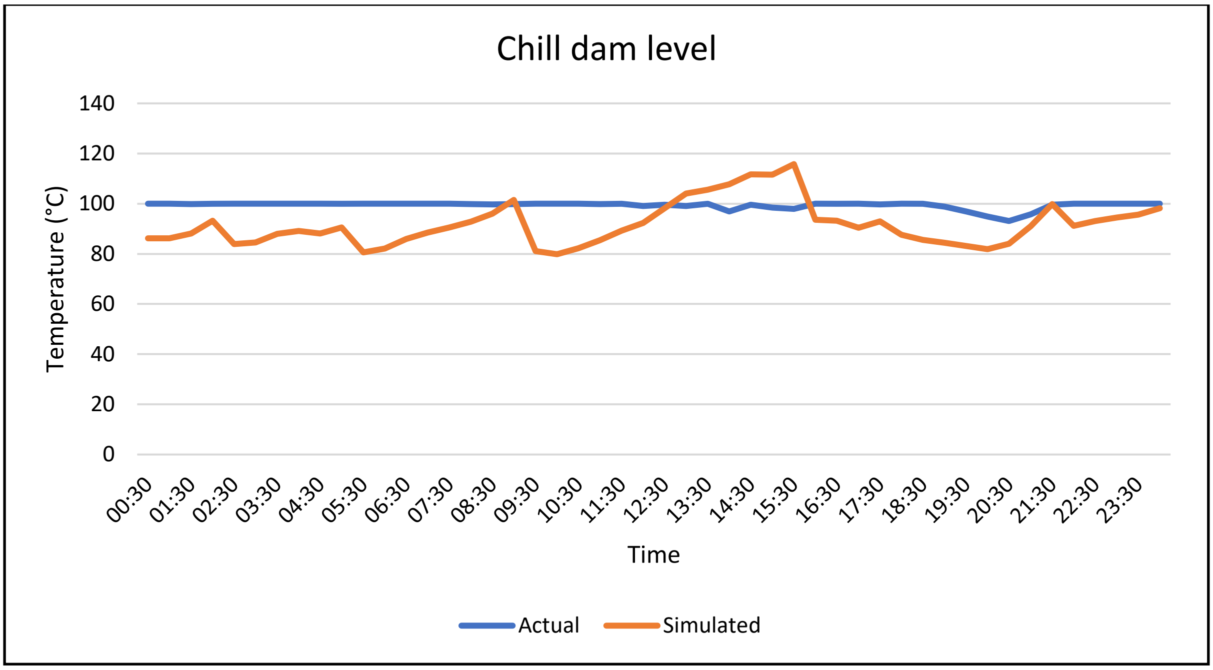
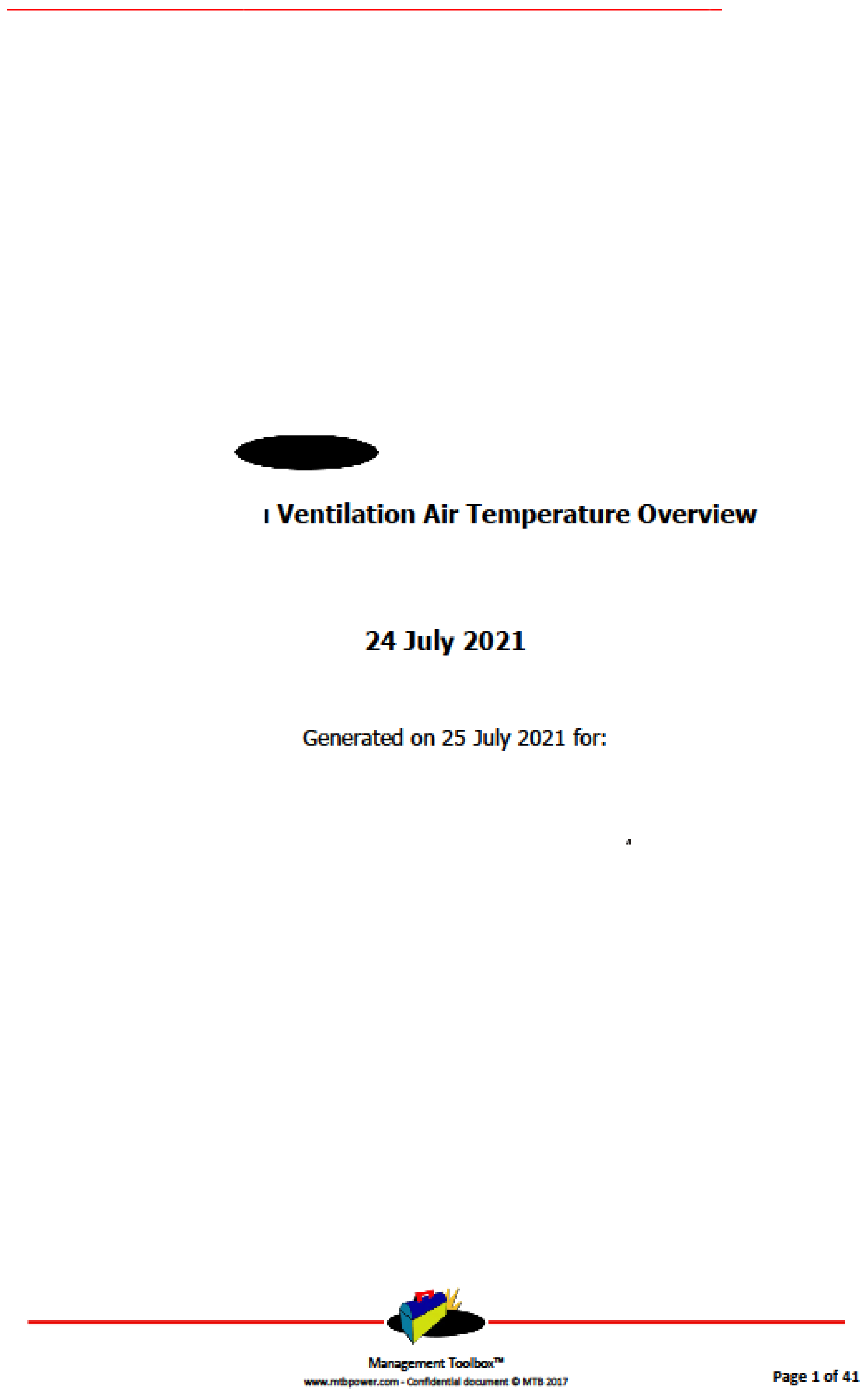


Figure B-4: Chill dam level verification

Appendix C: BAC daily report



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Ventilation Air Temperature Overview

24 July 2021

Generated on 25 July 2021 for:

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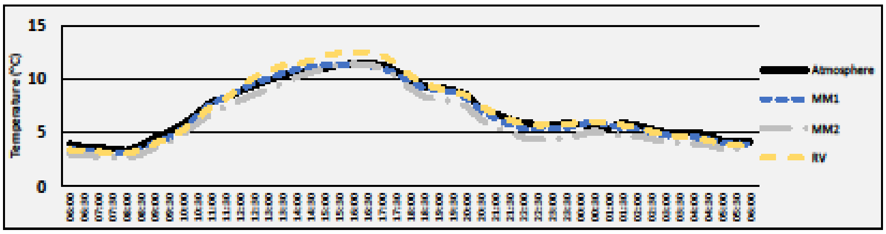
2. Daily Overview

2.1 Surface BAC ventilation air overview

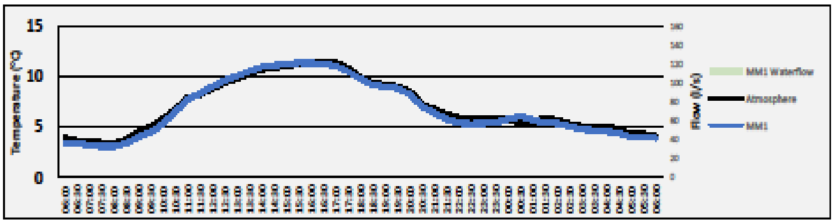


	Inlet	Outlet			Delta		
	Ambient	MM1	MM2	RV	MM1	MM2	RV
06:00	3.98	3.43	2.99	3.4	-0.55	-0.99	-0.58
06:30	3.68	3.36	2.96	3.37	-0.32	-0.72	-0.31
07:00	3.66	3.24	2.82	3.25	-0.42	-0.84	-0.41
07:30	3.48	3.08	2.68	3.08	-0.4	-0.8	-0.4
08:00	3.38	3.1	2.67	3.06	-0.28	-0.71	-0.32
08:30	3.82	3.42	2.98	3.36	-0.4	-0.84	-0.46
09:00	4.61	4.05	3.59	4.02	-0.56	-1.02	-0.59
09:30	5.09	4.53	4.07	4.58	-0.56	-1.02	-0.51
10:00	5.87	5.38	4.91	5.28	-0.49	-0.96	-0.59
10:30	6.83	6.57	5.89	6.32	-0.26	-0.94	-0.51
11:00	7.94	7.77	6.89	7.52	-0.17	-1.05	-0.42
11:30	8.27	8.36	7.41	8.22	0.09	-0.86	-0.05
12:00	8.89	9.05	8.02	9.2	0.16	-0.87	0.31
12:30	9.41	9.67	8.6	10.19	0.26	-0.81	0.78
13:00	9.86	10.08	9.03	10.8	0.22	-0.83	0.94
13:30	10.38	10.58	9.65	11.28	0.2	-0.73	0.9
14:00	10.73	10.98	10.21	11.44	0.25	-0.52	0.71
14:30	10.93	11.13	10.62	11.77	0.2	-0.31	0.84
15:00	11.03	11.3	11.05	12.19	0.27	0.02	1.16
15:30	11.34	11.39	11.36	12.48	0.05	0.02	1.14
16:00	11.47	11.37	11.45	12.58	-0.1	-0.02	1.11
16:30	11.53	11.31	11.38	12.52	-0.22	-0.15	0.99
17:00	11.39	11.08	11.08	12.25	-0.31	-0.31	0.86
17:30	10.84	10.52	10.3	11.49	-0.32	-0.54	0.65
18:00	9.95	9.79	9.19	10.39	-0.16	-0.76	0.44
18:30	9.36	9.2	8.38	9.5	-0.16	-0.98	0.14
19:00	9.23	9.02	8.09	9.17	-0.21	-1.14	-0.06
19:30	9.05	8.86	7.94	8.96	-0.19	-1.11	-0.09
20:00	8.57	8.26	7.43	8.51	-0.31	-1.14	-0.06
20:30	7.28	7.05	6.21	7.44	-0.23	-1.07	0.16
21:00	6.81	6.42	5.53	6.83	-0.39	-1.28	0.02
21:30	6.31	5.8	4.97	6.23	-0.51	-1.34	-0.08
22:00	5.93	5.4	4.56	5.82	-0.53	-1.37	-0.11
22:30	5.85	5.35	4.41	5.72	-0.5	-1.44	-0.13
23:00	5.81	5.37	4.39	5.74	-0.44	-1.42	-0.07
23:30	5.93	5.47	4.49	5.83	-0.46	-1.44	-0.1
00:00	5.84	5.81	4.81	5.96	-0.03	-1.03	0.12
00:30	5.41	6.1	5.16	6.06	0.69	-0.25	0.65
01:00	5.46	5.72	4.96	5.86	0.26	-0.5	0.4
01:30	5.95	5.45	4.67	5.71	-0.5	-1.28	-0.24
02:00	5.71	5.38	4.68	5.51	-0.33	-1.03	-0.2
02:30	5.35	5.08	4.45	5.13	-0.27	-0.9	-0.22
03:00	5.09	4.78	4.15	4.8	-0.31	-0.94	-0.29
03:30	5.02	4.7	4.07	4.64	-0.32	-0.95	-0.38
04:00	5.11	4.6	3.99	4.51	-0.51	-1.12	-0.6
04:30	4.77	4.41	3.84	4.33	-0.36	-0.93	-0.44
05:00	4.32	4	3.49	3.95	-0.32	-0.83	-0.37
05:30	4.34	3.99	3.48	3.91	-0.35	-0.86	-0.43
06:00	4.16	3.92	3.4	3.79	-0.24	-0.76	-0.37
Average	7.04	6.83	6.19	7.10	-0.21	-0.85	0.06

Delta legend	
20	🟧
15	🟧
10	🟫
5	🟨
0	🟩
-5	🟩
-10	🟩
-15	🟩
-20	🟩

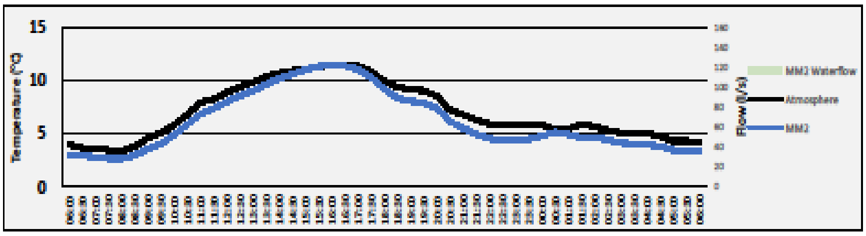
Outlet legend	
30	🟥
25	🟥
20	⬜
15	⬜
10	🟦
5	🟦
0	🟦
-5	🟦
-10	🟦
-15	🟦

2.1.1 Surface BAC MM1



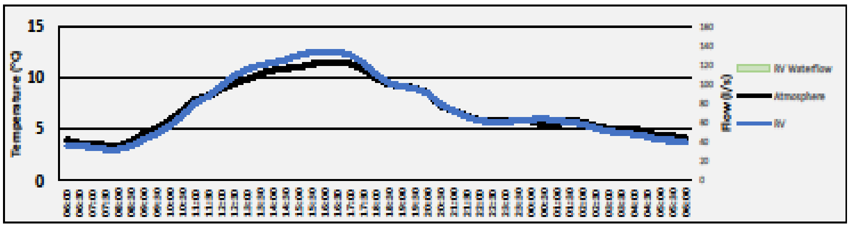
	BAC Air			BAC Water					BAC FAN	
	Inlet	Outlet	Delta	Flow	Inlet	Outlet	Delta	Duty	Status	Power
06:00	3.98	3.43	-0.55	0.3	5.15	3.33	-1.82	-2.286102		
06:30	3.68	3.36	-0.32	0.35	5.09	3.32	-1.77	-2.593847		
07:00	3.66	3.24	-0.42	0.31	5.11	3.29	-1.82	-2.362305		
07:30	3.48	3.08	-0.4	0.31	5.1	3.25	-1.85	-2.401245		
08:00	3.38	3.1	-0.28	0.29	5.05	3.2	-1.85	-2.246326		
08:30	3.82	3.42	-0.4	0.27	4.88	3.15	-1.73	-1.955748		
09:00	4.61	4.05	-0.56	0.3	4.81	3.13	-1.68	-2.110248		
09:30	5.09	4.53	-0.56	0.28	4.8	3.12	-1.68	-1.969565		
10:00	5.87	5.38	-0.49	0.28	4.85	3.12	-1.73	-2.028183		
10:30	6.83	6.57	-0.26	0.27	4.89	3.13	-1.76	-1.989662		
11:00	7.94	7.77	-0.17	0.3	5.11	3.15	-1.96	-2.461956		
11:30	8.27	8.36	0.09	0.33	5.02	3.2	-1.82	-2.514712		
12:00	8.89	9.05	0.16	0.3	5.02	3.21	-1.81	-2.273541		
12:30	9.41	9.67	0.26	0.28	4.77	3.26	-1.51	-1.770264		
13:00	9.86	10.08	0.22	0.3	5.01	3.34	-1.67	-2.097687		
13:30	10.38	10.58	0.2	0.3	5.04	3.48	-1.56	-1.959516		
14:00	10.73	10.98	0.25	0.27	5.42	3.63	-1.79	-2.023577		
14:30	10.93	11.13	0.2	0.28	5.4	3.73	-1.67	-1.957841		
15:00	11.03	11.3	0.27	0.22	5.22	3.76	-1.46	-1.344864		
15:30	11.34	11.39	0.05	0.28	4.95	3.84	-1.11	-1.30132		
16:00	11.47	11.37	-0.1	0.29	4.81	3.94	-0.87	-1.05638		
16:30	11.53	11.31	-0.22	0.25	4.98	4.02	-0.96	-1.00488		
17:00	11.39	11.08	-0.31	0.25	4.9	4.1	-0.8	-0.8374		
17:30	10.84	10.52	-0.32	0.3	4.93	4.18	-0.75	-0.942075		
18:00	9.95	9.79	-0.16	0.29	4.74	4.22	-0.52	-0.6314		
18:30	9.36	9.2	-0.16	0.27	4.65	4.26	-0.39	-0.440891		
19:00	9.23	9.02	-0.21	0.25	4.61	3.39	-1.22	-1.277035		
19:30	9.05	8.86	-0.19	0.24	4.66	3.52	-1.14	-1.145563		
20:00	8.57	8.26	-0.31	0.25	4.65	3.83	-0.82	-0.858335		
20:30	7.28	7.05	-0.23	0.27	4.7	3.67	-1.03	-1.164405		
21:00	6.81	6.42	-0.39	0.29	4.75	3.63	-1.12	-1.359938		
21:30	6.31	5.8	-0.51	0.28	4.73	3.61	-1.12	-1.313043		
22:00	5.93	5.4	-0.53	0.25	4.71	3.58	-1.13	-1.182828		
22:30	5.85	5.35	-0.5	0.29	4.71	3.54	-1.17	-1.420649		
23:00	5.81	5.37	-0.44	0.23	4.74	3.5	-1.24	-1.194132		
23:30	5.93	5.47	-0.46	0.3	4.78	3.48	-1.3	-1.63293		
00:00	5.84	5.81	-0.03	0.31	4.8	3.44	-1.36	-1.765239		
00:30	5.41	6.1	0.69	0.3	5.15	3.33	-1.82	-2.286102		
01:00	5.46	5.72	0.26	0.35	5.09	3.32	-1.77	-2.593847		
01:30	5.95	5.45	-0.5	0.31	5.11	3.29	-1.82	-2.362305		
02:00	5.71	5.38	-0.33	0.31	5.1	3.25	-1.85	-2.401245		
02:30	5.35	5.08	-0.27	0.29	5.05	3.2	-1.85	-2.246326		
03:00	5.09	4.78	-0.31	0.27	4.88	3.15	-1.73	-1.955748		
03:30	5.02	4.7	-0.32	0.3	4.81	3.13	-1.68	-2.110248		
04:00	5.11	4.6	-0.51	0.28	4.8	3.12	-1.68	-1.969565		
04:30	4.77	4.41	-0.36	0.28	4.85	3.12	-1.73	-2.028183		
05:00	4.32	4	-0.32	0.27	4.89	3.13	-1.76	-1.989662		
05:30	4.34	3.99	-0.35	0.3	5.11	3.15	-1.96	-2.461956		
06:00	4.16	3.92	-0.24	0.33	5.02	3.2	-1.82	-2.514712		
Average	7.04	6.83	-0.21	0.29	4.93	3.45	-1.48	-1.79	#DIV/0!	

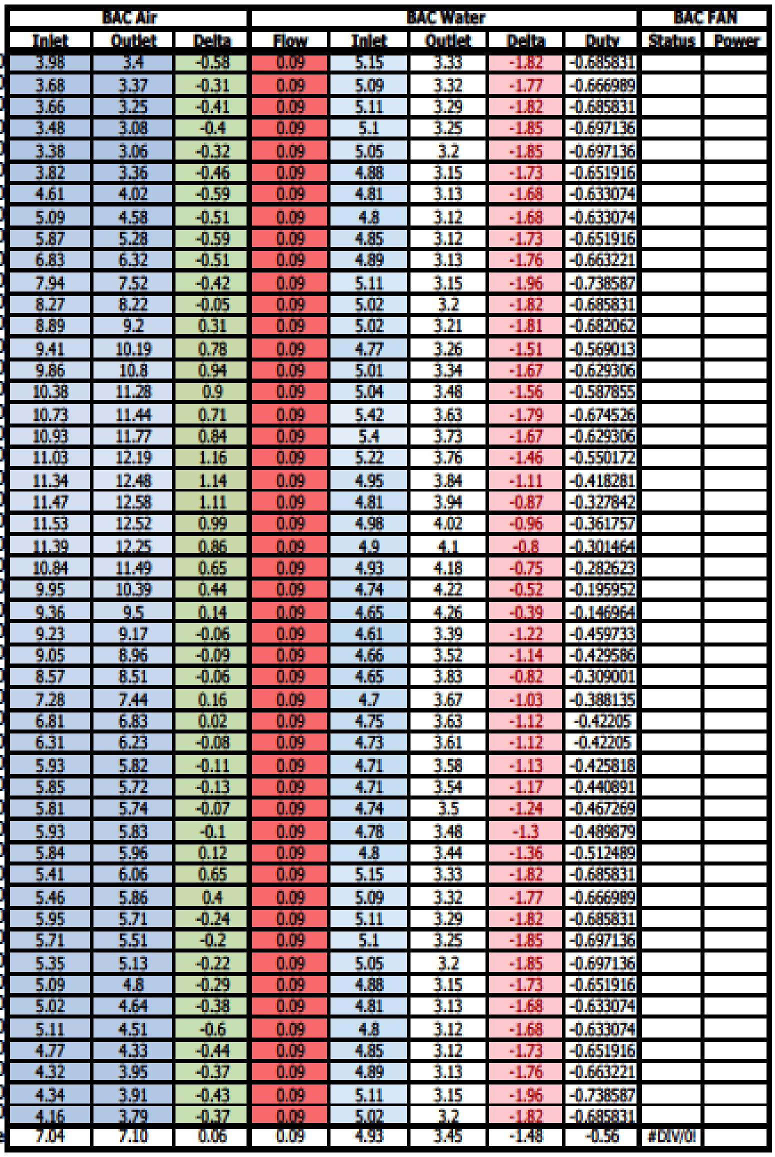
2.1.2 Surface BAC MM2



	BAC Air			BAC Water					BAC FAN	
	Inlet	Outlet	Delta	Flow	Inlet	Outlet	Delta	Duty	Status	Power
06:00	3.98	2.99	-0.99	0.09	5.15	3.33	-1.82	-0.685831		
06:30	3.68	2.96	-0.72	0.09	5.09	3.32	-1.77	-0.666989		
07:00	3.66	2.82	-0.84	0.09	5.11	3.29	-1.82	-0.685831		
07:30	3.48	2.68	-0.8	0.09	5.1	3.25	-1.85	-0.697136		
08:00	3.38	2.67	-0.71	0.09	5.05	3.2	-1.85	-0.697136		
08:30	3.82	2.98	-0.84	0.09	4.88	3.15	-1.73	-0.651916		
09:00	4.61	3.59	-1.02	0.09	4.81	3.13	-1.68	-0.633074		
09:30	5.09	4.07	-1.02	0.09	4.8	3.12	-1.68	-0.633074		
10:00	5.87	4.91	-0.96	0.09	4.85	3.12	-1.73	-0.651916		
10:30	6.83	5.89	-0.94	0.09	4.89	3.13	-1.76	-0.663221		
11:00	7.94	6.89	-1.05	0.09	5.11	3.15	-1.96	-0.738587		
11:30	8.27	7.41	-0.86	0.09	5.02	3.2	-1.82	-0.685831		
12:00	8.89	8.02	-0.87	0.09	5.02	3.21	-1.81	-0.682062		
12:30	9.41	8.6	-0.81	0.09	4.77	3.26	-1.51	-0.569013		
13:00	9.86	9.03	-0.83	0.09	5.01	3.34	-1.67	-0.629306		
13:30	10.38	9.65	-0.73	0.09	5.04	3.48	-1.56	-0.587855		
14:00	10.73	10.21	-0.52	0.09	5.42	3.63	-1.79	-0.674526		
14:30	10.93	10.62	-0.31	0.09	5.4	3.73	-1.67	-0.629306		
15:00	11.03	11.05	0.02	0.09	5.22	3.76	-1.46	-0.550172		
15:30	11.34	11.36	0.02	0.09	4.95	3.84	-1.11	-0.418281		
16:00	11.47	11.45	-0.02	0.09	4.81	3.94	-0.87	-0.327842		
16:30	11.53	11.38	-0.15	0.09	4.98	4.02	-0.96	-0.361757		
17:00	11.39	11.08	-0.31	0.09	4.9	4.1	-0.8	-0.301464		
17:30	10.84	10.3	-0.54	0.09	4.93	4.18	-0.75	-0.282623		
18:00	9.95	9.19	-0.76	0.09	4.74	4.22	-0.52	-0.195952		
18:30	9.36	8.38	-0.98	0.09	4.65	4.26	-0.39	-0.146964		
19:00	9.23	8.09	-1.14	0.09	4.61	3.39	-1.22	-0.459733		
19:30	9.05	7.94	-1.11	0.09	4.66	3.52	-1.14	-0.429586		
20:00	8.57	7.43	-1.14	0.09	4.65	3.83	-0.82	-0.309001		
20:30	7.28	6.21	-1.07	0.09	4.7	3.67	-1.03	-0.388135		
21:00	6.81	5.53	-1.28	0.09	4.75	3.63	-1.12	-0.42205		
21:30	6.31	4.97	-1.34	0.09	4.73	3.61	-1.12	-0.42205		
22:00	5.93	4.56	-1.37	0.09	4.71	3.58	-1.13	-0.425818		
22:30	5.85	4.41	-1.44	0.09	4.71	3.54	-1.17	-0.440891		
23:00	5.81	4.39	-1.42	0.09	4.74	3.5	-1.24	-0.467269		
23:30	5.93	4.49	-1.44	0.09	4.78	3.48	-1.3	-0.489879		
00:00	5.84	4.81	-1.03	0.09	4.8	3.44	-1.36	-0.512489		
00:30	5.41	5.16	-0.25	0.09	5.15	3.33	-1.82	-0.685831		
01:00	5.46	4.96	-0.5	0.09	5.09	3.32	-1.77	-0.666989		
01:30	5.95	4.67	-1.28	0.09	5.11	3.29	-1.82	-0.685831		
02:00	5.71	4.68	-1.03	0.09	5.1	3.25	-1.85	-0.697136		
02:30	5.35	4.45	-0.9	0.09	5.05	3.2	-1.85	-0.697136		
03:00	5.09	4.15	-0.94	0.09	4.88	3.15	-1.73	-0.651916		
03:30	5.02	4.07	-0.95	0.09	4.81	3.13	-1.68	-0.633074		
04:00	5.11	3.99	-1.12	0.09	4.8	3.12	-1.68	-0.633074		
04:30	4.77	3.84	-0.93	0.09	4.85	3.12	-1.73	-0.651916		
05:00	4.32	3.49	-0.83	0.09	4.89	3.13	-1.76	-0.663221		
05:30	4.34	3.48	-0.86	0.09	5.11	3.15	-1.96	-0.738587		
06:00	4.16	3.4	-0.76	0.09	5.02	3.2	-1.82	-0.685831		
Average	7.04	6.19	-0.85	0.09	4.93	3.45	-1.48	-0.56	#DIV/0!	

2.1.3 Surface BAC RV





	BAC Air			BAC Water					BAC FAN	
	Inlet	Outlet	Delta	Flow	Inlet	Outlet	Delta	Duty	Status	Power
06:00	3.98	3.4	-0.58	0.09	5.15	3.33	-1.82	-0.685831		
06:30	3.68	3.37	-0.31	0.09	5.09	3.32	-1.77	-0.666989		
07:00	3.66	3.25	-0.41	0.09	5.11	3.29	-1.82	-0.685831		
07:30	3.48	3.08	-0.4	0.09	5.1	3.25	-1.85	-0.697136		
08:00	3.38	3.06	-0.32	0.09	5.05	3.2	-1.85	-0.697136		
08:30	3.82	3.36	-0.46	0.09	4.88	3.15	-1.73	-0.651916		
09:00	4.61	4.02	-0.59	0.09	4.81	3.13	-1.68	-0.633074		
09:30	5.09	4.58	-0.51	0.09	4.8	3.12	-1.68	-0.633074		
10:00	5.87	5.28	-0.59	0.09	4.85	3.12	-1.73	-0.651916		
10:30	6.83	6.32	-0.51	0.09	4.89	3.13	-1.76	-0.663221		
11:00	7.94	7.52	-0.42	0.09	5.11	3.15	-1.96	-0.738587		
11:30	8.27	8.22	-0.05	0.09	5.02	3.2	-1.82	-0.685831		
12:00	8.89	9.2	0.31	0.09	5.02	3.21	-1.81	-0.682062		
12:30	9.41	10.19	0.78	0.09	4.77	3.26	-1.51	-0.569013		
13:00	9.86	10.8	0.94	0.09	5.01	3.34	-1.67	-0.629306		
13:30	10.38	11.28	0.9	0.09	5.04	3.48	-1.56	-0.587855		
14:00	10.73	11.44	0.71	0.09	5.42	3.63	-1.79	-0.674526		
14:30	10.93	11.77	0.84	0.09	5.4	3.73	-1.67	-0.629306		
15:00	11.03	12.19	1.16	0.09	5.22	3.76	-1.46	-0.550172		
15:30	11.34	12.48	1.14	0.09	4.95	3.84	-1.11	-0.418281		
16:00	11.47	12.58	1.11	0.09	4.81	3.94	-0.87	-0.327842		
16:30	11.53	12.52	0.99	0.09	4.98	4.02	-0.96	-0.361757		
17:00	11.39	12.25	0.86	0.09	4.9	4.1	-0.8	-0.301464		
17:30	10.84	11.49	0.65	0.09	4.93	4.18	-0.75	-0.282623		
18:00	9.95	10.39	0.44	0.09	4.74	4.22	-0.52	-0.195952		
18:30	9.36	9.5	0.14	0.09	4.65	4.26	-0.39	-0.146964		
19:00	9.23	9.17	-0.06	0.09	4.61	3.39	-1.22	-0.459733		
19:30	9.05	8.96	-0.09	0.09	4.66	3.52	-1.14	-0.429586		
20:00	8.57	8.51	-0.06	0.09	4.65	3.83	-0.82	-0.309001		
20:30	7.28	7.44	0.16	0.09	4.7	3.67	-1.03	-0.388135		
21:00	6.81	6.83	0.02	0.09	4.75	3.63	-1.12	-0.42205		
21:30	6.31	6.23	-0.08	0.09	4.73	3.61	-1.12	-0.42205		
22:00	5.93	5.82	-0.11	0.09	4.71	3.58	-1.13	-0.425818		
22:30	5.85	5.72	-0.13	0.09	4.71	3.54	-1.17	-0.440891		
23:00	5.81	5.74	-0.07	0.09	4.74	3.5	-1.24	-0.467269		
23:30	5.93	5.83	-0.1	0.09	4.78	3.48	-1.3	-0.489879		
00:00	5.84	5.96	0.12	0.09	4.8	3.44	-1.36	-0.512489		
00:30	5.41	6.06	0.65	0.09	5.15	3.33	-1.82	-0.685831		
01:00	5.46	5.86	0.4	0.09	5.09	3.32	-1.77	-0.666989		
01:30	5.95	5.71	-0.24	0.09	5.11	3.29	-1.82	-0.685831		
02:00	5.71	5.51	-0.2	0.09	5.1	3.25	-1.85	-0.697136		
02:30	5.35	5.13	-0.22	0.09	5.05	3.2	-1.85	-0.697136		
03:00	5.09	4.8	-0.29	0.09	4.88	3.15	-1.73	-0.651916		
03:30	5.02	4.64	-0.38	0.09	4.81	3.13	-1.68	-0.633074		
04:00	5.11	4.51	-0.6	0.09	4.8	3.12	-1.68	-0.633074		
04:30	4.77	4.33	-0.44	0.09	4.85	3.12	-1.73	-0.651916		
05:00	4.32	3.95	-0.37	0.09	4.89	3.13	-1.76	-0.663221		
05:30	4.34	3.91	-0.43	0.09	5.11	3.15	-1.96	-0.738587		
06:00	4.16	3.79	-0.37	0.09	5.02	3.2	-1.82	-0.685831		
Average	7.04	7.10	0.06	0.09	4.93	3.45	-1.48	-0.56	#DIV/0!	