

SEASONAL SCHEDULING METHODOLOGY FOR REFRIGERATION SYSTEMS ON DEEP-LEVEL PLATINUM MINES

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ABSTRACT

Title: Seasonal Scheduling Methodology for Refrigeration Systems on Deep-Level Platinum Mines

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Keywords: Deep-level mining, refrigeration system, cooling systems, seasonal control, energy savings, ESG.

Environmental, Social, and Governance (ESG) is a company policy focusing on environmental, social, and governance concerns. In recent years, more emphasis by corporations has been placed on implementing sustainable and environmentally friendly solutions into their operations.

South Africa stands as one of the globe's most energy-intensive economies, surpassing the international average in energy consumption per unit of gross domestic product (GDP). This study focuses on mitigating carbon emissions within South African mines by implementing energy-saving measures. Notably, refrigeration systems on deep-level platinum mines have emerged as major energy consumers, prompting the need for enhanced operational efficiency.

The study identifies an opportunity to refine the seasonal control of refrigeration systems in these mines. A tailored seasonal control strategy is developed to optimise the energy consumption of refrigeration systems amidst seasonal changes. This strategy dictates when to activate or deactivate refrigeration machines based on seasonal shifts. A rigorous methodology is devised, tested using simulation software, and validated through implementation at a deep-level platinum mine with refrigeration systems.

The successful implementation of the seasonal control strategy results in the delayed activation of the refrigeration system post-winter, leading to a notable energy saving of 0.6 GWh compared to the baseline year. The seasonal control strategy achieved energy savings while ensuring underground working temperatures are kept within the legal requirements.

Despite the rise in electrical costs, the overall impact of the seasonal control strategy on the mine's electrical expenditure is marginal. Nevertheless, it curtails the mine's expenses by R1.19 million compared to what would have been paid without the strategy. While the financial

impact is moderate, the strategy unequivocally achieves its primary objectives of reducing energy consumption and carbon emissions in deep-level platinum mines. In conclusion, the implemented strategy effectively meets the overarching goals of the study.

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LIST OF ABBREVIATIONS

ABBREVIATION	DESCRIPTION
BAC	Bulk air coolers
BIC	Bushveld Igneous Complex
CCTs	Condenser cooling towers
COP	Coefficient of performance
DSM	Demand side management
ESG	Environmental, social, and governance
GUI	Graphical user interface
NPSH	Net positive suction head
HVAC	Heating, ventilation, and air conditioning
PCTs	Pre-cooling towers
PGM	Platinum Group Metals
SCADA	Supervisory Control and Data Acquisition
TOU	Time of use
VFD	Variable frequency drive
VRT	Virgin rock temperature
VSD	Variable speed drive
VUMA	Ventilation of Underground Mine Atmospheres
WB	Wet bulb

1. BACKGROUND & LITERATURE STUDY

1.1 ESG Globally

Environmental, Social, and Governance (ESG) standards concentrate on the environmental, social, and governance facets of businesses [1]. ESG has evolved into a pivotal criterion for investor decision-making in recent years [2], [3], [4]. The contemporary business landscape places increased emphasis on integrating sustainable and environmentally friendly practices into business models [5].

Within the ESG framework, the environmental dimension highlights a company's proficiency in incorporating strategies for environmental preservation into its operational fabric. These encompass energy conservation, prudent resource utilisation, and the embrace of renewable energies and technologies [2].

The social facet of ESG underscores the responsibility of businesses to society, emphasising a commitment beyond profit maximisation [2] and [5]. In addition to pursuing financial gains, businesses are urged to adhere to pertinent regulations in each country, ensuring that the interests of all stakeholders are duly considered and not unduly compromised [6].

The corporate governance aspect of ESG addresses internal systems, controls, and procedures businesses adopt to govern themselves [1]. Corporate governance establishes a lasting balance within companies by establishing systems with management to consider stakeholders' interests to ensure performance, economic benefits, and social benefits within businesses [4] and [6].

In recent years, investments with a focus on ESG have witnessed a substantial surge, increasing by 68% since 2014 and experiencing a tenfold rise since 2004 [7]. The global value of ESG investments surpassed \$30 trillion in 2019, and an additional US\$50 billion was added to worldwide ESG funds in 2020 [1], [7]. This surge is attributed to a heightened societal, governmental, and consumer awareness of the impact that businesses can have on the environment and society [8].

Furthermore, executives and investors have recognised that a robust ESG position is integral to ensuring the long-term success of their businesses [9]. Notably, industries remain the most

significant contributors to greenhouse gas emissions, accounting for 30% of global emissions (see Figure 1). The mining sector, specifically, is accountable for 4% to 7% of global greenhouse gas emissions [10]. The substantial emissions from the mining industry have prompted investors, governments, and society to exert pressure on the sector to curtail its environmental impact [10].

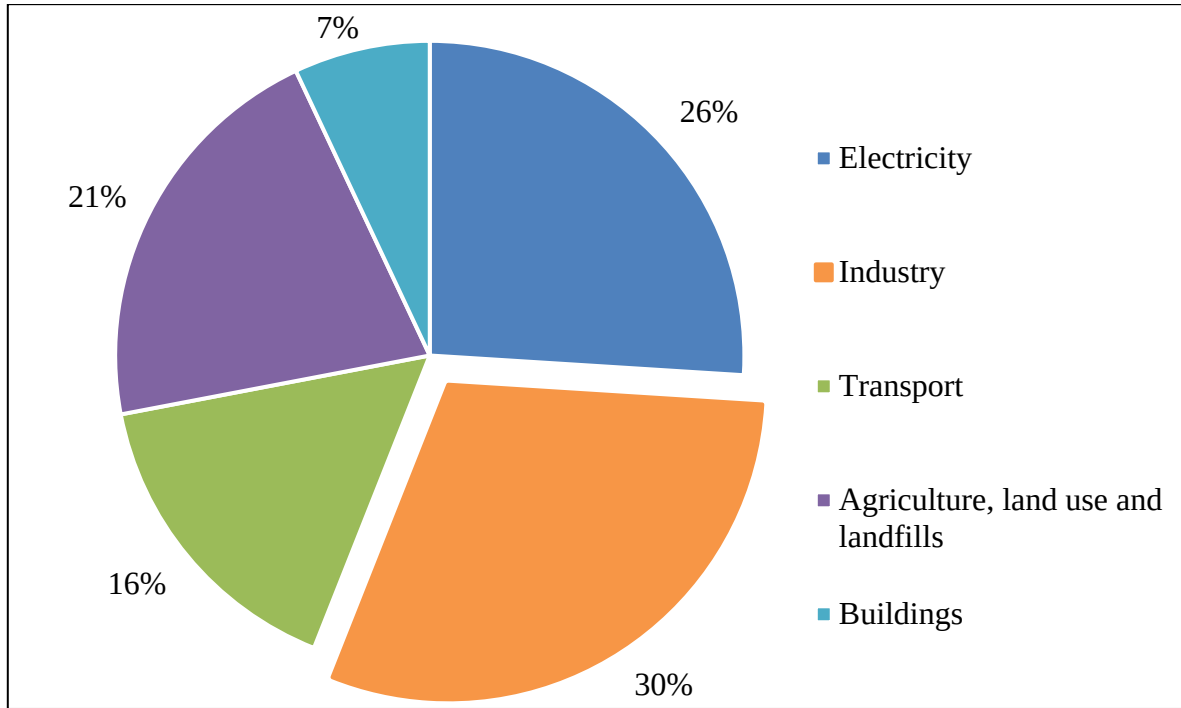


Figure 1: Global Greenhouse Gas Emissions [11]

Theoretically, the mining sector can undergo decarbonisation by enhancing operational efficiency, integrating electric alternative mining equipment, and adopting strategies centred on renewable energy [10]. While these improved approaches and technologies hold the potential to reduce carbon emissions and energy consumption, they necessitate substantial capital investments [10].

The mining sector plays a pivotal role in fostering the economies of developing nations, exemplified by South Africa. Ranking as the world's fifth largest, the mining sector in South Africa contributes a significant 8.4% of the country's gross domestic product (GDP) [12]. Boasting extensive social diversity and abundant natural resources, including sizable deposits of the world's most valuable minerals [13], South Africa heavily relies on mining to sustain and stimulate economic growth [14].

The South African mining sector is, however, energy-intensive and relies heavily on coal-generated electricity for its operation [12]. Because of its reliance on coal-generated power, South Africa has one of the most energy-intensive economies in the world, with energy consumption per unit GDP more than double the worldwide average [15]. For this reason, the study focuses on reducing carbonation emissions in South African mines by utilising energy savings initiatives.

1.2 The Mining Sector in South Africa

Mining in South Africa plays a pivotal role in economic growth [15] and [16], propelling the nation to become the most developed in Africa through the extraction of valuable minerals like gold, Platinum Group Metals (PGM), and coal [15].

South Africa's prominence in PGMs positions it as a global leader, with over 80% of known PGM deposits concentrated in the Bushveld Igneous Complex (BIC) [17], [18], [19], [20]. The PGM mining sector, situated in this complex, stands as the largest employer within South Africa's mining industry, employing nearly double the workforce of gold or coal mines [21], [22].

However, the mining sector faces challenges. Outdated, energy-intensive, and equipped with systems designed in an era when electricity was more abundant and cost-effective, the sector now confronts declining profit margins due to rising operational expenses stemming from the need to access deeper reserves and from escalating electricity rates [23]. Consequently, the mining sector is compelled to enhance operational efficiency for both profitability and sustainability [24].

As one of the largest consumers of electricity in South Africa, the mining sector, along with industrial segments, consumes 37% of the nation's total generated electricity [25]. Specifically, PGM and gold mines are the most energy-intensive, accounting for 33% and 47% of the industry's electricity usage, respectively [25].

Given that South Africa holds most of the world's PGM resources, it is logical that providing this industry with a stable power source is vital to the country's economic success [17], [18], [19], [20]. PGM mines' energy usage and environmental impact must be reduced to improve this sector's carbon emissions.

Figure 2 shows a breakdown of the electrical consumption of a platinum mine's energy systems. The figure shows that generating compressed air consumes the most electrical power in a platinum mine. Previous studies focused on compressed air efficiency initiatives; however, the second largest energy consumer is refrigeration systems, where fewer studies have been conducted.

For this reason, the study focuses on refrigeration systems, which consume 21% of deep-level platinum mines energy consumption [26].

Figure 2 shows a breakdown of the electrical consumption of a platinum mine's energy systems. The figure shows that refrigeration systems consume 21% of deep-level platinum mines' energy consumption [26].

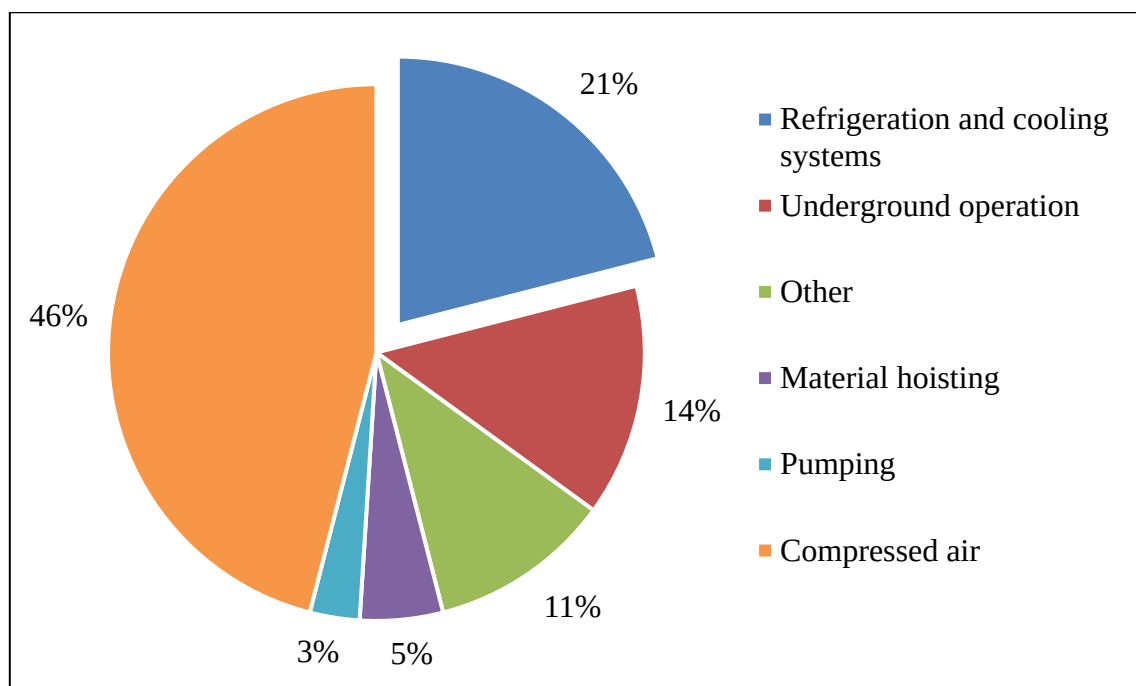


Figure 2: Power consumption in the platinum mining sector [26]

The substantial energy consumption of refrigeration systems is attributed to their expansive scale and intricate design [26]. These systems play a vital role in deep-level mining operations, as most South African mines rely on cooled water to address underground cooling demands, a necessity for ensuring the safety and well-being of underground workers [27].

While refrigeration systems are integral to mining operations, their significant energy consumption poses a challenge. Introducing energy-saving initiatives and incorporating

renewable technologies, such as solar and wind energy, presents an avenue for the mining sector to curtail energy usage and carbon emissions [24]. This reduction not only aligns with environmental goals but also contributes to an enhanced ESG position.

The subsequent chapter delves into a comprehensive examination of refrigeration systems and their auxiliary components. It scrutinises the operational mechanisms of these systems and explores avenues for improving their energy efficiency in the context of a deep-level platinum mine.

1.3 Refrigeration Systems

Refrigeration systems are imperative for deep-level mining operations to maintain temperatures within permissible limits underground [27]. The cooling demand in a mine's subterranean spaces is intricately tied to its depth, with energy consumption escalating as mining operations reach deeper deposits [28].

The South African Mine Health and Safety Act no. 967 of 1996 mandates that underground areas must not exceed a wet-bulb (WB) temperature of 27.5 °C, with a WB temperature below 32.5 °C required in stopping areas [29]. The elevation in underground temperatures is a result of heat radiating from rock surfaces, fissure water, mining equipment, lighting, and auto-compression [30].

The heightened temperatures and humidity in mining environments are notable concerns for the sector [31]. Ensuring safe and acceptable underground conditions is not solely a matter of safety; studies have indicated that the productivity of underground personnel improves as the WB temperature decreases, as depicted in Figure 3 [31].

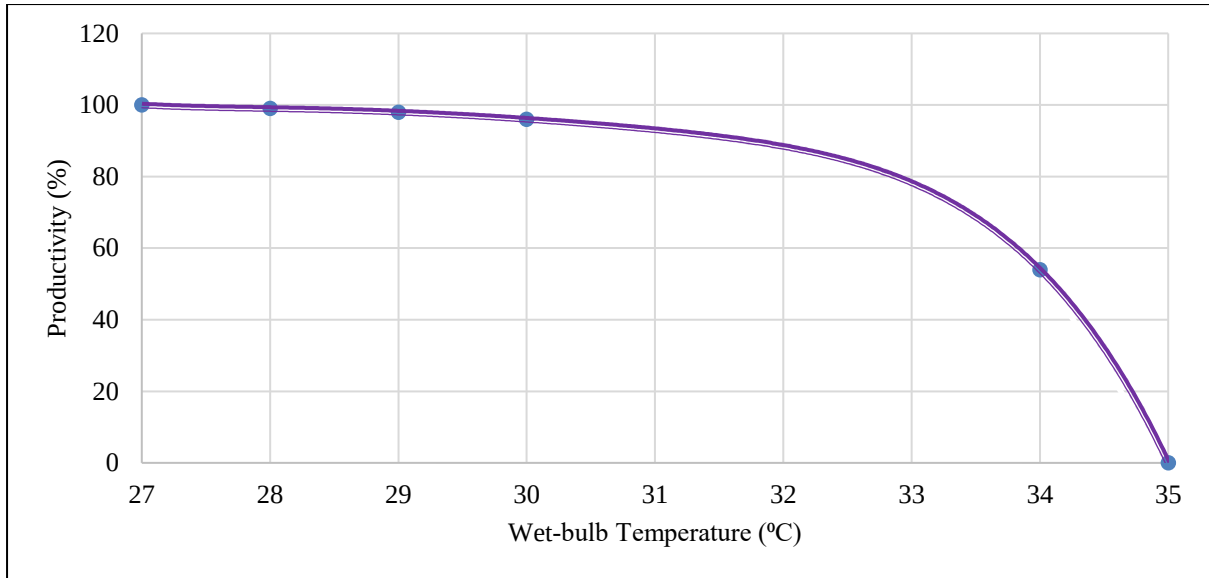


Figure 3: Productivity compared to wet-bulb temperatures [31]

Figure 4 compares the underground VRT (virgin rock temperature) to the mining depth of different South African mining areas [31]. It is clear from Figure 4 that the VRT found in the BIC has a higher temperature gradient compared to other areas in South Africa, such as Carletonville, Welkom and Klerksdorp, see Figure 4 [30].

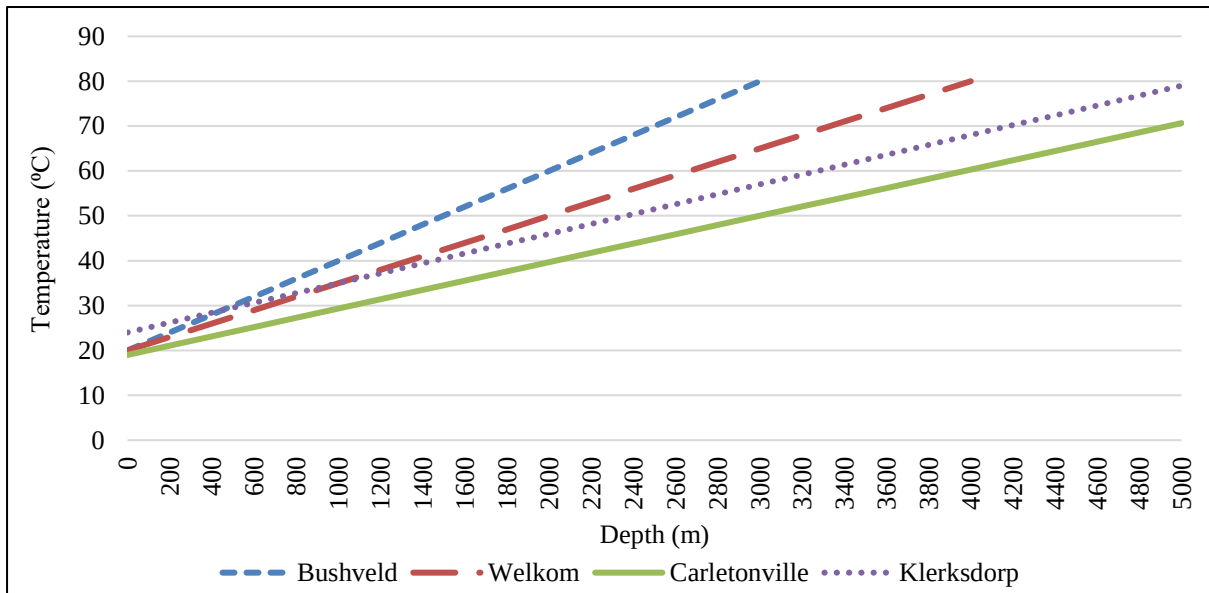


Figure 4: Underground mining temperatures relative to depth in South Africa [30]

The refrigeration system is designed to employ chilled water for cooling heated underground working environments [28] and [29]. Additionally, the chilled water can be stored and utilised

underground to facilitate the cooling of mining areas and equipment [28]. Notably, the original design of the refrigeration systems have not been upgraded since their initial installation [23].

The static nature of these designs fails to account for the heightened heat load as mining operations extend to deeper and more expansive deposits. This outdated configuration presents potential opportunities to optimise the control of the deep-level platinum mine's refrigeration system, offering prospects for energy-saving initiatives.

The introduction of supplementary cooling equipment may inadvertently lead to overcooling if comprehensive studies are not conducted on the existing equipment and control philosophies. This underscores the potential for enhancements, particularly in the realm of energy consumption within the refrigeration systems of deep-level platinum mines in South Africa [32]. The subsequent subsections of this chapter delve into a detailed examination of each auxiliary component of the refrigeration system.

1.3.1 Overview of Refrigeration Systems

The configuration of refrigeration systems varies based on several factors, including mining activity, ambient temperature, geographical location, and mining depth [33]. These systems constitute an integrated network comprising refrigeration machines, bulk air coolers (BACs), condenser cooling towers (CCTs), pre-cooling towers (PCTs), and storage dams [33].

These components can be strategically installed on the surface, underground, or as part of an integrated semi-closed loop system [34]. The system is termed a semi-closed loop system because underground fissure water can be collected within the water reticulation network [34].

The water reticulation network functions by extracting underground mining water, pumping it to the surface, cooling it using refrigeration machines, and subsequently recycling it within the mine. The chilled water serves multiple purposes, either cooling ventilation air or being returned underground to contribute to the cooling of mining operations and equipment.

A commonly employed technique for cooling mining areas involves a combination of surface and underground cooling systems. However, preference is given to surface refrigeration systems due to their greater capacity for heat rejection compared to systems situated

underground [30] and [35]. Figure 5 provides a simplified depiction of a surface refrigeration system alongside an underground water reticulation layout.

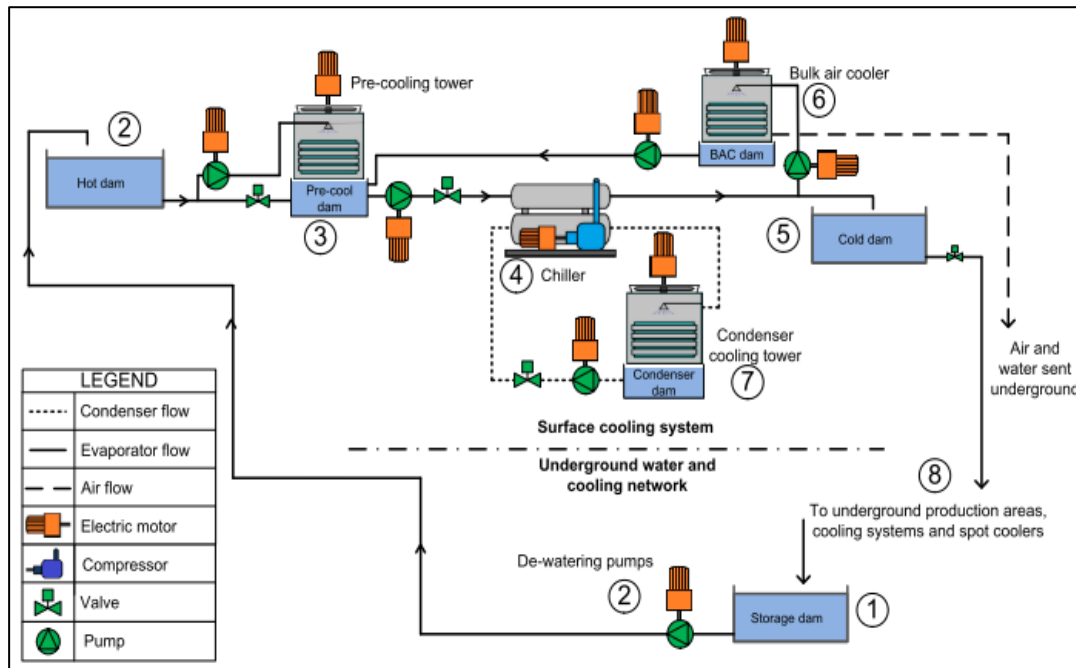


Figure 5: Deep-level mine refrigeration system with water reticulation schematic

The functions of the refrigeration system's auxiliary components are outlined as follows:

1. Hot water storage dams: Water used for underground mining operations is collected in the underground hot water storage dams.
2. Underground dewatering system: Pumps located underground pump hot water to the surface storage dam(s).
3. Pre-cooling tower: The hot water is pumped through the pre-cooling towers. The water is pre-cooled and stored in the pre-cooling dam. The pre-cooled water is pumped to the evaporator heat exchangers of the refrigeration machine.
4. Refrigeration machine: The water is cooled to the desired outlet temperature (3 °C to 6 °C) using ammonia absorption or vapour compression cycles.
5. Chilled water storage dams: The chilled water from the refrigeration machine(s) is pumped from the evaporator side to the surface chilled dams or pumped directly to the BACs.
6. BACs: Chilled water from the evaporator supplies the BAC with water. The water is sprayed inside the BAC chambers, while ambient air is forced through the chamber

using a fan. The cold water and warm ambient air come into contact, causing the ambient air to cool down. The cooled air is then sent underground for ventilating underground working areas.

7. Condensing cooling towers: These towers are used as heat rejection systems. Air is pulled through the towers using a fan. Water is sprayed (like the BAC towers) inside the cooling tower, dissipating the heat generated in the refrigeration cycle to the environment.
8. Chilled service water: The chilled water is sent underground via a piping network to the necessary underground working areas. The chilled water is used to cool down mining areas and equipment.

The upcoming section elaborates on each component to discern which can be utilised to enhance energy consumption. It delves into the operations, configurations, technologies, and available control strategies for each component, aiming at improving energy efficiency.

1.3.2 Storage Dams

Refrigeration systems necessitate both cold and hot water storage capacity to accommodate the fluctuating demand for service water throughout the day [36]. These demand fluctuations stem from variations in service water requirements underground, with seasonal conditions playing a significant role in the number of operational refrigeration machines [37].

Given that refrigeration machines are substantial energy consumers designed to supply cold water to storage dams [38], these dams are meticulously insulated to mitigate temperature losses [39]. To further optimise efficiency, refrigeration machines and storage dams are strategically positioned in proximity to the mine to minimise temperature losses [40].

The regular maintenance of storage dams is paramount due to the suboptimal quality of underground service water, which often contains sediment. The sediment deposition can impede storage capacity, resulting in energy wastage as more frequent dam refilling becomes necessary [40]. Thus, the regular maintenance and cleaning of storage dams are essential, not only enhancing energy consumption efficiency but also reducing labour costs by averting breakdowns attributable to sediment build-up [41].

1.3.3 Refrigeration Machine

Refrigeration systems in deep-level mines employ refrigeration machines to provide cold water to the mine [42]. These machines, characterised by their complexity, stand as the most significant energy consumers within a deep-level mine's refrigeration system, contributing to 66% of the system's overall energy consumption [36].

Refrigeration machines in deep-level mines operate through various refrigeration cycles [43], with the choice between the ammonia-absorption or vapour-compression cycle contingent on the specific needs and requirements of a mine [44]. While both cycles adhere to similar principles and find application in most mining operations [36], the vapour-compression cycle is generally preferred due to its simplicity, lower operational costs, and the less toxic nature of its working fluid compared to the ammonia-absorption cycle [27] and [34].

The refrigeration machine for a vapour-compression cycle comprises two heat exchangers (condenser and evaporated heat exchangers), an expansion valve, and a compressor unit, as illustrated in Figure 6.

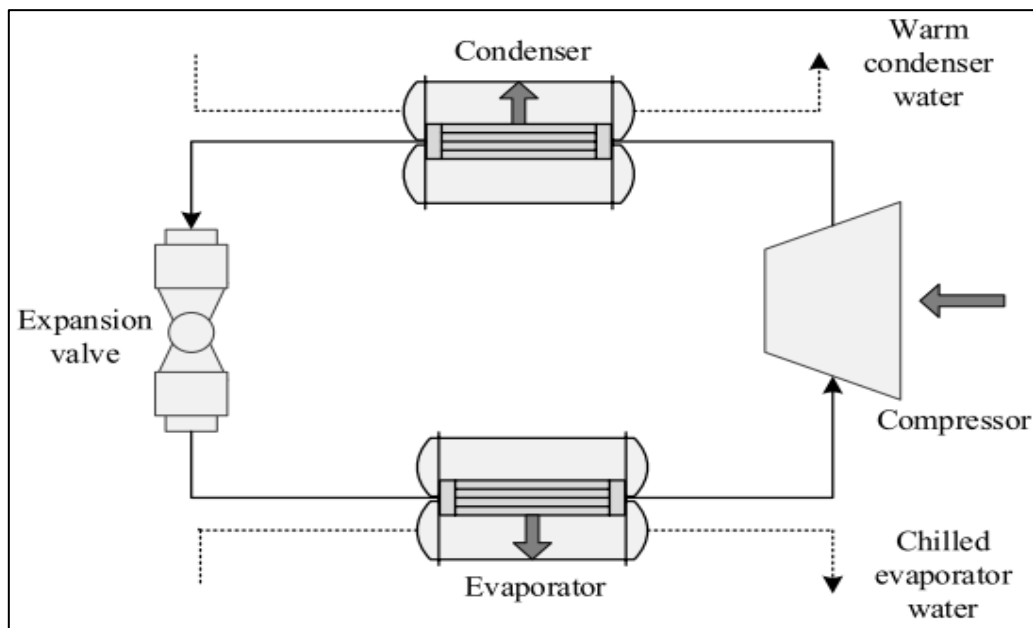


Figure 6: Vapour-compression cycle

The ideal vapour-compression cycle can be explained in the following four steps:

- a) Compressor: The working fluid or refrigerant (in vapour form) is drawn into the inlet of the compressor at a low temperature and pressure [44]. The vapour is compressed adiabatically (irreversible) into superheated vapour at high pressure [44]. The superheated vapour is discharged to the inlet of the condenser heat exchanger [44].
- b) Condenser heat exchanger: The superheated vapour is condensed and cooled as heat is transferred to water in the heat exchanger [44]. The heated water is transferred via pumps to the condenser cooling tower, where heat is rejected to the atmosphere. The working fluid/refrigerant exits the heat exchanger as a high-pressure liquid [44].
- c) Expansion valve: The high pressure of the liquid is reduced by throttling the expansion valve [36]. Most of the liquid flashes into a cold liquid, causing the saturation temperature of the fluid to decrease due to the pressure drop [45].
- d) Evaporator heat exchanger: The liquid flows through the evaporated heat exchanger at constant pressure and low temperature [36]. The evaporator water heats the refrigerant and causes the refrigerant to evaporate, cooling the water. The heated refrigerant exits the heat exchanger as a vapour before re-entering the compressor, completing the cycle [45].

Refrigeration machines consist of multiple units arranged in different configurations depending on the application. Refer to Figure 7 for the different configurations. The refrigeration machines can be arranged in parallel; however, a series configuration is employed when a variable temperature and constant water flow are needed, accommodating fluctuations in ambient temperatures throughout the year. [46]. A combination of series and parallel configurations is used when there is a demand for variable temperature and water flow [46].

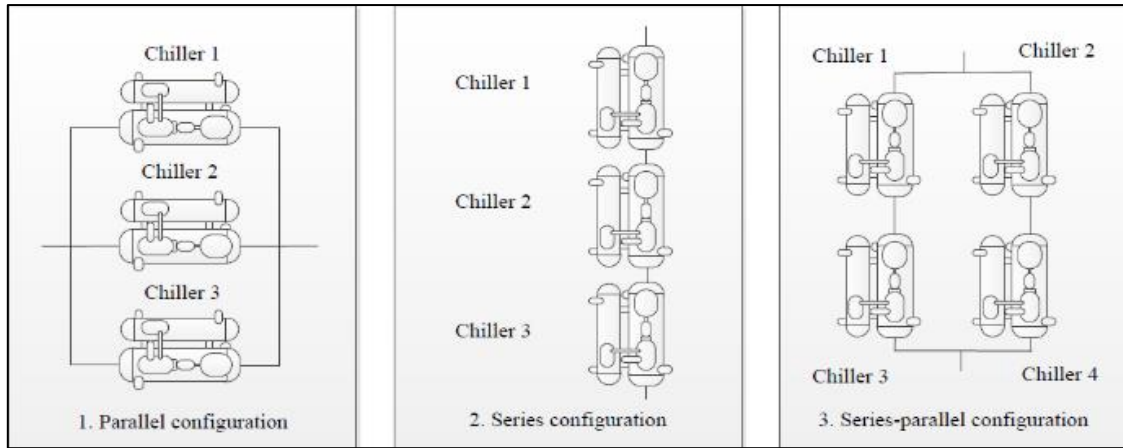


Figure 7: Refrigeration unit configurations [47]

The vapour-compression cycle can be visualised using a pressure (P)–enthalpy (h) diagram, depicted in Figure 8. This diagram illustrates the variations in pressure, enthalpy, and phases as the refrigerant progresses through the cycle.

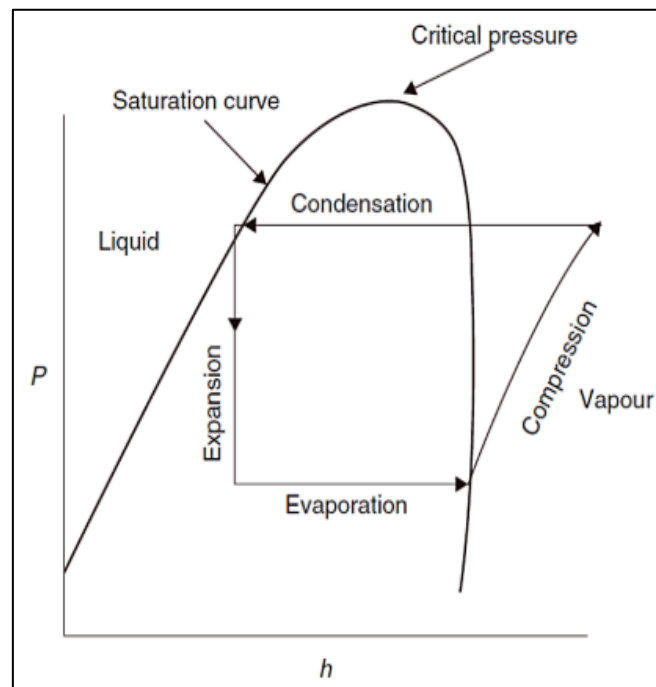


Figure 8: Vapour-compression cycle pressure-enthalpy diagram [44]

The refrigerant in a vapour-compression cycle requires a compressor unit to circulate the working fluid/refrigerant throughout the system. Centrifugal and screw compressors are typically used for this application [48].

Screw compressors are primarily used in the mining environment for their more comprehensive temperature range. Additionally, they are less susceptible to changes, ensuring minimum electrical power wastage [37] and [49]. The compressor unit ensures that the working fluid/refrigerant is delivered at a stable high pressure during the cycle [50].

The system's flow rates are controlled by a sliding valve for screw compressors and guide vanes of the centrifugal compressor [49]. Controlling the flow rate enables the refrigeration unit to adjust the required cooling load, ensuring the desired evaporator outlet temperature is reached [49]. Using Equation 1, the power delivered by the electrical motor can be calculated.

Equation 1: Compressor power calculation

Where:	$W_{comp} = \frac{\dot{m} C_p T_{in} \left[\left(\frac{P_{out}}{P_{in}} \right)^{\left(\frac{k-1}{k} \right)} - 1 \right]}{\eta}$
	$W_{comp} = \text{Motor power}$ [kW]
	$\dot{m} = \text{mass flow rate}$ $\left[\frac{kg}{s} \right]$
	$C_p = \text{Specific heat constant}$ $\left[\frac{kJ}{kg K} \right]$
	$T_{in} = \text{Refrigerant inlet temperature}$ [K]
	$P_{out} = \text{Refrigerant outlet pressure}$ [kPa]
	$P_{in} = \text{Refrigerant inlet pressure}$ [kPa]
	$k = \text{Specific heat ratio}$ [-]
	$\eta = \text{Efficiency}$ [-]

Electricity cost savings on the compressor unit can be achieved by adjusting the delivery flow and the discharge pressure to match the outlet temperature to the desired temperature range. Equation 1 shows that several variables can affect a compressor's power consumption, such as the mass flow rate, inlet temperature, pressure difference and the efficiency of the compressor.

Each variable has been designed to have a predetermined parameter according to the system's cooling demand [49]. The efficiency of a refrigeration machine is essential for reduced energy

consumption. The efficiency of a refrigeration machine can be determined using the coefficient of performance (COP) equation seen in Equation 2. The COP expresses the ratio between the refrigeration unit's thermal output (cooling capacity) and electrical input [49].

Equation 2: Coefficient of performance

<i>Where:</i>	$COP = \frac{Q_{Evap}}{W_{Comp}}$	
	$COP = \text{Coefficient of Performance}$	[-]
	$Q_{Evap} = \text{Thermal energy}$	[kW]
	$W_{comp} = \text{Motor power}$	[kW]

The thermal energy transferred from the refrigerant to the evaporator heat exchanger is expressed in Equation 3 [49].

Equation 3: Thermal energy absorbed by the evaporator

	$Q_{Evap} = \dot{m} C_p \Delta T_w(1)$	<i>Equation 3</i>
	$\Delta T_w = T_{w_{out}} - T_{w_{in}}$	
<i>Where:</i>	$Q_{Evap} = \text{Thermal energy}$	[kW]
	$\dot{m} = \text{Mass flow rate}$	$\left[\frac{kg}{s}\right]$
	$C_p = \text{Specific heat constant}$	$\left[\frac{kJ}{kg}K\right]$
	$T_{w_{out}} = \text{Water outlet temperature}$	[K]
	$T_{w_{in}} = \text{Water inlet temperature}$	[K]

In Equation 2, a higher COP signifies a more efficient system, indicating that the refrigeration process requires less energy or electricity to achieve the desired cooling capacity. Enhancing COP values involves reducing the system's energy consumption, achievable through

adjustments to the sliding valve or guide vanes, thereby reducing the flow rate produced by the compressor.

It is important to recognise that the cooling capacity and energy consumption of a refrigeration unit are directly influenced by ambient conditions, chilled water temperatures, and the required volumes of water [49]. An opportunity exists to optimise the seasonal control of a refrigeration plant based on the changing seasons.

1.3.4 Cooling Tower

Standard practice in deep-level platinum mines involves the use of cooling towers, as depicted in Figure 9, for pre-cooling hot water supplied underground and cooling the condenser circuit water [51]. In both applications, the cooling tower serves as a heat rejection system, utilising direct contact evaporation and convection to extract available cooling from the environment and release heat into the atmosphere [36]. Notably, the cooling process takes place only when the ambient WB temperature is lower than the water temperature [52].



Figure 9: Surface cooling tower [Taken by author]

Figure 10 illustrates a detailed drawing of a cooling tower fitted with an axial fan on top that is used to draw air in from the sides of the tower. Water is simultaneously pumped from a hot

water storage dam through sprayer nozzles, forming tiny water droplets [53]. The water droplets fall onto packing material found inside the tower. The fill ensures even water distribution throughout the tower and increases the contact time between the air and the water, improving the cooling efficiency of the tower.

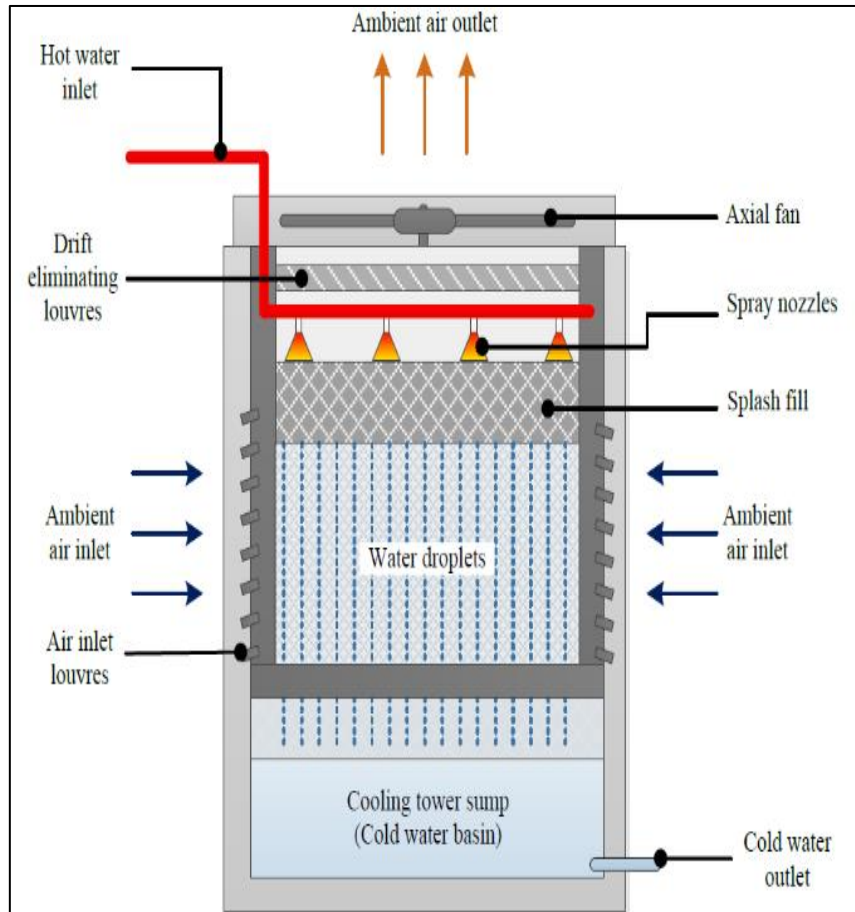


Figure 10: Detailed drawing of a cooling tower [36]

The efficiency of a cooling tower is directly influenced by the ambient WB temperature since cooling towers utilise ambient air to cool water [54]. The direct contact between water droplets and ambient air, coupled with the pressure drop over the sprayer nozzle, results in a temperature reduction of the water ranging from 3°C to 6°C, contingent upon ambient conditions [27] and [53].

Following pre-cooling, the water is stored in the tower's sump before being pumped to the refrigeration machine for further cooling. Cooling towers are tailored to the specific conditions of a given mine to achieve the desired output water temperature. However, over-cooling may occur during periods of low ambient temperatures, leading the tower to waste energy.

1.3.5 Bulk Air Cooler

BACs are integral components of the refrigeration and cooling system, functioning to absorb heat by extracting it from the ambient ventilation air [55]. In deep-level mining, both surface and underground BACs are employed to provide supplementary cooling for underground working areas. Some deep-level mines necessitate additional underground cooling to lower temperatures in the working areas [54].

BACs operate on a principle akin to condensers or pre-cooling towers but in reverse. Ambient air is forced through the BACs by fans. The air undergoes cooling as cold water is sprayed over it, after which fans draw the cooled air underground. This ambient air mixes with cold air from the BAC as it descends the main shaft, with the cooled air then directed to the mining areas before exiting through the exhaust ventilation system. Surface ventilation fans situated at the ventilation shaft create a substantial pressure differential within the mine, pulling air from the surface down into the mine [54].

Deep-level mines employ two configurations of BAC: vertical and horizontal BAC [56]. In both configurations, ambient air is mechanically drawn through the BAC using fans. There are primarily two fan layouts for BAC, namely forced draft and induced draft towers. Forced draft towers use fans to push ambient air through the BAC tower, while induced draft towers utilise an axial fan to pull air through the tower.

Vertical-oriented BACs are usually located on the surface due to its larger area and cooling capacity when compared to horizontal BACs [37]. Conversely, horizontal BACs are favoured to be used underground as they require fewer excavations, leading to a more cost-effective implementation [36].

After cooling, the water collected in the BAC sump is pumped back to the pre-cooling dam, where it is reused in the cooling systems. The sump water contributes additional cooling to the pre-cooling tower sump. Inefficient operation of the tower can cause an increase in the BAC outlet air temperature, resulting in a lower COP. The waterside efficiency of the BAC tower can be calculated using Equation 4.

Equation 4: BAC water side efficiency

Where:	$\eta = \frac{T_{w_{out}} - T_{w_{in}}}{T_{a_{in}(WB)} - T_{w_{in}}} \times 100$
	$\eta = \text{Efficiency (water side)}$ [%]
	$T_{w_{out}} = \text{Water outlet temperature}$ [K]
	$T_{w_{in}} = \text{Water inlet temperature}$ [K]
	$T_{a_{in}(WB)} = \text{Ambient wet bulb temperature}$ [K]

Equation 4 articulates the efficiency of the waterside in terms of a temperature range and approach. The range represents the variance between the water's inlet and outlet temperatures, while the approach signifies the distinction between the inlet ambient WB and water outlet temperatures. It is evident from Equation 4 that the efficiency of the BAC is contingent upon the inlet air temperature and water temperature. During winter, the BAC can be deactivated since the ambient WB temperature is proximate to the inlet water temperatures [23].

1.3.6 Pumps

Refrigeration and cooling systems typically utilize centrifugal or axial pumps for distributing water throughout the evaporator and condenser cycles [57]. These pumps, classified as auxiliary, can be independently controlled [40]. The configuration of the pumping network is contingent on the application, required flows, and pressures.

Pumps can modulate their speed through variable speed or frequency drive (VSD/VFD); however, it is important to consider all variables, as altering the speed may impact the pump's efficiency [58]. It is important to note that adjusting the impeller's speed can lead to changes in the pump curve and efficiency, potentially resulting in undesired breakdowns and repairs. Therefore, energy savings on pumps should be carefully assessed to ensure their operation within a safe vibrational range [54].

1.3.7 Effect of Seasonal Changes

The efficiency and power consumption of a cooling system are influenced by ambient conditions, including temperature and humidity. These conditions vary with daily temperatures and changing seasons, presenting an opportunity to control the entire cooling system based on ambient conditions.

In deep-level platinum mines, refrigeration machines and auxiliary components are often deactivated in winter due to the shifting ambient conditions [40]. The significant changes in relative humidity and ambient dry bulb temperature from summer (December - February) to winter (June to August) impact the cooling system's performance. The lower ambient temperatures can cause the temperature difference in the condenser cooling tower to fall below the design specifications of the refrigeration unit, potentially triggering a trip due to low temperatures [23].

Figure 11 illustrates the changes in the BIC dry-bulb temperature, relative humidity, and WB temperature throughout the year [36]. Relative humidity is defined as the amount of water vapor in dry air [36]. The WB temperature represents the temperature to which air can be cooled through evaporation; a lower WB temperature enhances the cooling capacity of a cooling system [36]. Lower WB temperatures directly impact the efficiency and performance of the refrigeration machine(s) [59].

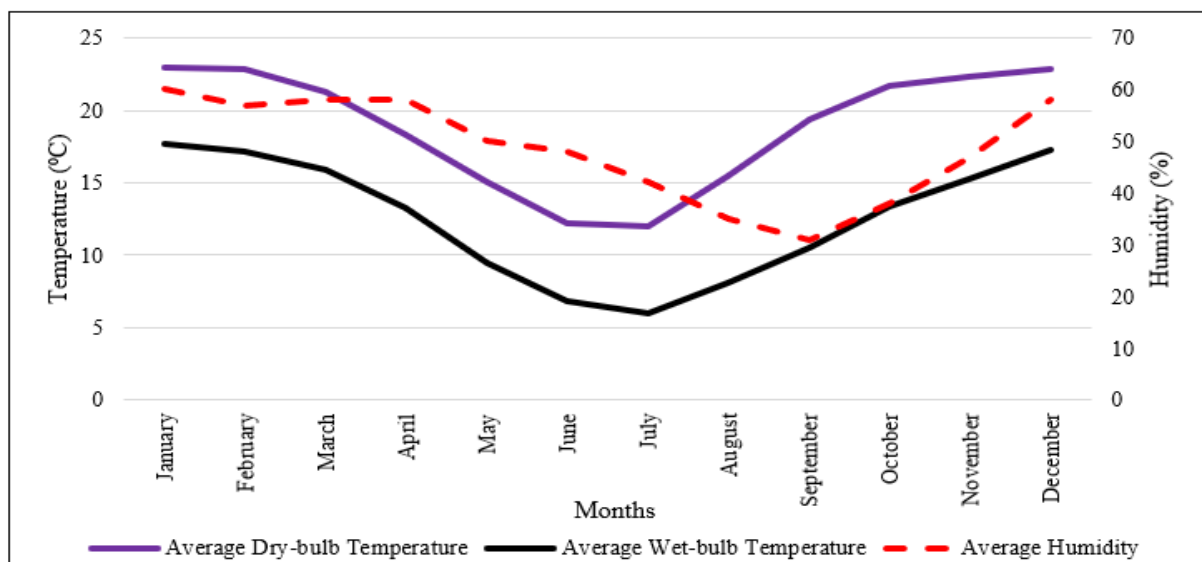


Figure 11: BIC Average ambient conditions

During the winter months, the ambient WB temperatures may fall below both the water outlet temperature of the refrigeration machine(s) and the inlet water temperature of the BAC. This lower ambient WB temperature diminishes the efficiency of the BAC and prompts the refrigeration machine(s) to scale back on the inlet guide vanes or sliding valves [53].

Lower ambient temperatures can also manifest during transitional months, such as April to May and September to October, between summer and winter. During these periods, temperature and humidity decrease due to seasonal changes.

The refrigeration machine(s) can be turned off earlier or kept inactive for a more extended period during the transition between summer and winter. Currently, mines often rely on predetermined dates or the tripping of refrigeration machines to activate or deactivate refrigeration systems rather than considering ambient weather forecast conditions.

This approach proves inefficient, as each year's seasonal changes differ, leading to energy wastage by either keeping cooling systems operational for an extended duration or starting them earlier than necessary. Hence, further research is needed to explore solutions employed by other studies to address this issue in deep-level platinum mine refrigeration systems.

1.4 Existing Energy Management Strategies for Cooling Systems

1.4.1 Introduction

The subsequent section presents a review of prior studies conducted in various industries and the mining sector, specifically addressing the enhancement of energy consumption in refrigeration systems with a focus on seasonal changes. The selected studies encompassed optimisation techniques for cooling systems, the optimisation of cooling systems within deep-level mine industries, platinum mining, energy-saving initiatives, and investigations into improving the scheduling of refrigeration systems based on seasonal variations.

This comprehensive literature review aims at identifying gaps in existing methodologies, underscoring the necessity for the current study.

1.4.2 Cost-effective Control of a PGM Mine Cooling System Using Combined DSM Strategies [60]

Overview:

The study introduces a cost-effective method for reducing the cooling system's daily energy consumption through an improved management strategy. The strategy proposes using existing infrastructure combined with installing VSDs to implement an evening peak clip on the cooling system. The peak clip reduced the cooling system energy consumption during the Eskom evening peak periods.

Discussion:

While effective in reducing daily energy consumption, the study was limited in scope as it did not explore the implementation of a seasonal scheduling system for the refrigeration and cooling system.

1.4.3 Optimising Deep-Level Mine Refrigeration Control for Sustainable Cost Savings [61]

Overview:

The study is centred on adapting the current control philosophy to a cooling system, with a refined strategy emphasising the shutdown of refrigeration system components during Eskom's evening peak periods. The analysis delves into the operational aspects of the existing components, and a simulation was developed to assess the potential impact of the proposed control strategy. The study achieved success in reducing daily energy consumption.

Discussion:

The study did not focus on developing a seasonal scheduling methodology for the cooling system. The study can be adapted to account for seasonal ambient conditions, changing from summer to winter.

1.4.4 Dynamic Optimisation of Deep-level Mine Refrigeration Control [62]

Overview:

The authors conducted a reassessment of the control philosophy for a cooling system, identifying three key control measures: guide vane control, evaporate flow control, and condenser flow control. A dynamic control philosophy was formulated by comprehending the specifications of each component in the cooling system and their interrelationships. The study specifically concentrated on the adjustment of the set-point control for evaporated flow. A simulation was then developed to assess the effects of this control by varying the evaporated flow rates.

Discussion:

The study takes seasonal changes into account, although its main emphasis lies in proposing new evaporator outlet temperatures. The primary objective was not the development of a seasonal scheduling methodology, which would involve creating a system to ascertain when refrigeration is necessary during each season.

1.4.5 Optimised Dynamic Control Philosophy for Improved Performance of Mine Cooling Systems [63]

Overview:

The study employed an integrated dynamic temperature set-point algorithm and an ambient dry-bulb prediction model to regulate the cooling system of a gold mine. The implemented strategies successfully enhanced the overall performance of the cooling system.

Discussion:

The study exclusively concentrated on daily enhancements to the cooling system's performance. The control strategy did not encompass the implementation of a seasonal control strategy.

1.4.6 Optimising the Refrigeration and Cooling System of a PGM Mine [54]

Overview:

VSD technology can enhance the controllability of a cooling system. The study implemented a control strategy in which water flow control aligns with the cooling supply to meet the cooling demand.

Discussion:

The study demonstrated effectiveness in its implementation, albeit with a sole focus on improving the daily energy consumption of cooling systems. It did not address the impact of seasonal changes on a cooling system.

1.4.7 Improved Implementation Strategies to Sustain Energy-Saving Measures on Mine Cooling Systems [47]

Overview:

The study aimed at enhancing existing strategies and the sustainability of the implemented approaches. The author conducted an evaluation of current strategies and put forth a new control philosophy to enhance the overall management of the cooling systems. The introduction of a new project, such as VSD on the pumping systems, served to enhance strategies through energy-saving considerations that previous projects had overlooked.

Discussion:

The study concentrated on enhancing the daily operations of a refrigeration and cooling system, with no specific evaluation of the effects of seasonal changes on cooling systems. However, the author did underscore that ambient conditions could impact the performance of BAC and cooling towers.

1.4.8 An Integrated Energy Efficiency Strategy for Deep Mine Ventilation and Refrigeration [64]

Overview:

The study formulated and integrated control strategies for refrigeration systems in deep-level gold mines. These strategies assessed various energy-saving projects and identified the most effective combination. One notable project involved implementing a load shift on BAC towers with the aim of reducing BAC energy consumption during Eskom's peak hours.

Discussion:

The project was successfully implemented without impacting underground temperatures. However, the study did not specifically address the influence of seasonal changes on refrigeration systems. Its primary goal was to enhance the daily operations of refrigeration systems.

1.4.9 Cost-Effective Management Strategies of PGM Mine Cooling Systems [65]

Overview:

The study systematically assessed several successfully implemented control strategies on refrigeration systems in various mining areas. Each control strategy was evaluated to determine its cost-effectiveness, utilizing simulation software to verify the outcomes. The study concluded that a strategy involving control room operators monitoring refrigeration system parameters and switching off the systems during Eskom Peak times would be the most cost-effective approach.

Discussion:

The study exclusively focused on reducing energy consumption during Eskom's peak periods and did not explore avenues for the implementation of a seasonal control strategy as part of the solution.

1.4.10 A Variable Water Flow Energy Efficiency Strategy for Mine Cooling Systems [42]

Overview:

The study concentrated on optimising the control strategy of deep-level mine refrigeration systems and implementing real-time monitoring and reporting of energy consumption. The developed energy management system facilitates straightforward control and optimisation of each controlled subsystem within the refrigeration system, taking into account real-time interactions with other subsystems.

Discussion:

The strategy utilises information to ascertain the optimal operating conditions for each cooling component. While the study acknowledged the effect of ambient conditions on refrigeration systems, it did not incorporate changes in ambient conditions caused by seasonal variations.

1.4.11 Benefits of Improved Performance Monitoring of Mine Cooling Systems [40]

Overview:

The study implements an enhanced maintenance schedule for a refrigeration system. Results showed that cleaning the systems more frequently increased the COP, resulting in additional electrical cost savings.

Discussion:

While the study's improved energy savings are notable, it did not consider the inclusion of a seasonal control strategy in the maintenance schedule, which might have yielded even greater cost savings. However, the study did acknowledge the potential to switch off certain cooling auxiliaries during winter.

1.4.12 Integrated Energy Simulation of a Deep-Level Mine Cooling System Through a Combination of Forward and First-Principal Models Applied to System-Side Parameters [66]

Overview:

The study aimed to create an integrated energy modelling approach for refrigeration systems in deep-level mines. The model is designed to analyse the effects of adjusting a component's control or input variable. The simulation was successfully developed and demonstrated accurate results.

Discussion:

While the modelling method proved accurate, the study exclusively concentrated on its development and did not explore its application in assessing the influence of seasonal fluctuations on refrigeration systems.

1.4.13 Chillers Energy Consumption, Energy Savings and Emission Analysis in an Institutional Building [67]

Overview:

The study focused on evaluating the impact of a VSD on the energy consumption of cooling systems in commercial and industrial buildings and found that a VSD can improve energy consumption by precisely meeting the cooling system's current load requirements.

Discussion:

The study's success granted, the effect of seasonal changes on the cooling system is remiss. The study only focused on matching the load requirements of the system.

1.4.14 HVAC System Optimisation for Energy Management by Evolutionary Programming [68]

Overview:

The study investigates the use of simulation software to optimise the performance of cooling systems inside a train station. By leveraging simulation software and optimisation algorithms, the study sought to predict optimal control strategies for the cooling systems throughout the year.

Discussion:

The study achieved a marginal reduction in energy consumption within the cooling system. Similar to previous studies, it overlooked the impact of seasonal changes on cooling systems, and the devised strategy was not implemented in platinum mines.

1.4.15 Optimisation of Industrial Refrigeration Plants: Including a Case Study at Stonyfield Farm Yogurt [69]

Overview:

The study concentrated on enhancing the energy efficiency of an industrial refrigeration plant by deploying diverse control strategies for individual components. It explored various approaches for controlling or upgrading compressors, condensers, and evaporators to optimise the energy consumption of each component. The research delved into enhanced compressor control and the implementation of VSD control on the condenser fans.

Discussion:

The study implemented its findings in a case study, successfully lowering the system's energy consumption. It primarily concentrated on enhancing the control of individual components. However, the research did not explore the implementation of a seasonal control strategy to optimise the system's energy consumption in response to changing seasonal ambient conditions.

1.4.16 Seasonal Analysis Comparison of Three Air-Cooling Systems in Terms of Thermal Comfort, Air Quality and Energy Consumption for School Buildings in Mediterranean Climates [70]

Overview:

The study focused on reducing energy consumption in Heating, ventilation, and air conditioning (HVAC) systems installed in school buildings in the Mediterranean. Specifically, it compared various HVAC systems and control strategies to identify the most efficient approach.

Discussion:

Unlike the aforementioned studies, this study did consider the impact of seasonal changes. Specifically, the study assessed the effect of seasonal changes on the performance of three HVAC systems respectively. However, the study was not conducted in a deep-level platinum mine.

1.4.17 Cascade-based Short-term Forecasting Method of the Electric Demand of HVAC Systems [71]

Overview:

The research centred on a commercial and industrial HVAC system deployed in Canadian buildings. Given the challenges in aligning the electrical grid with peak demand, the electric supplier encourages customers to curtail electricity consumption during these high-demand periods. To address this, the authors devised a multistep forecasting model capable of predicting system energy and cooling demand at 15-minute intervals. This model facilitates a nuanced understanding of energy and cooling needs throughout the day, enabling a reduction in energy consumption during peak periods while maintaining adequate cooling and ventilation.

Discussion:

The study effectively predicted energy and cooling demands. However, it is important to note that the forecasting model was not implemented in an HVAC system within a deep-level platinum mine.

1.4.18 Environmental Performance and Economic Analysis of All-variable Speed Chiller Systems with Load-based Speed Control [72]

Overview:

The study concentrated on enhancing the control of extensive commercial refrigeration systems by integrating VSDs into key components such as the reeration unit, pumps, and fans. The authors devised a model to integrate VSD systems, aiming at optimising the energy consumption of the overall system.

Discussion:

The study examined the impact of changes in WB ambient temperature on the system's performance. However, it was not applied to the refrigeration and cooling system of a deep-level platinum mine. Furthermore, the author did not incorporate a seasonal scheduling methodology into the operation of its control philosophy.

1.4.19 Utilising Mine Cooling Auxiliaries for Optimal Performance During Seasonal Changes [23]

Overview:

The study centred on optimising the energy consumption of auxiliary systems in a refrigeration system during seasonal changes in deep-level gold mines. Specifically, the study explored the utilization of BAC and leveraged the low ambient air conditions prevalent in winter, employing the BAC as a pre-cooling tower.

Discussion:

The operational modification enabled the systems to consume less energy during winter by allowing the refrigeration machines to be switched off. While the study concentrated on leveraging seasonal conditions to decrease energy consumption, it was solely implemented in a gold mine.

1.5 Summary of Literature

Refrigeration systems constitute a well-explored domain within the engineering field, where a plethora of research studies are dedicated to enhancing control philosophies for improved energy efficiency. The majority of these investigations have centred around deep-level gold and platinum mines, with additional studies focusing on commercial HVAC systems. Simulation software has played an important role in evaluating and refining various control strategies. The specific research areas covered by each paper are succinctly summarised in Table 1.

Table 1: State of the art

Reference	Author	Field of study											
		Deep level mining	Platinum mining	Refrigeration systems	Seasonal changes	Seasonal control strategy	Simulation	Cost-effective solution	Control optimisation	Energy management	Cost-saving	VSD control	Load shift or peak clipping
[60]	J. Engles	×	×	×			×		×	×	×	×	×
[61]	P.F.H. Peach	×		×			×		×	×	×		
[62]	P.F.H. Peach	×		×	×		×		×	×	×		
[63]	J.A. Crawford	×		×	×		×	×	×	×	×		
[54]	J.L. Buys	×		×			×		×	×	×	×	
[47]	P. Mare	×		×	×		×		×	×	×	×	
[64]	A.J. Schutte	×	×	×	×		×	×	×	×	×		×
[65]	J. Vermeulen	×	×	×			×	×	×	×	×		×
[42]	G.E. du Plessis	×		×	×		×	×	×	×	×		
[40]	A.M. Holman	×		×			×		×	×	×		
[66]	W. Borman	×		×			×						
[67]	R. Saidur			×			×		×	×	×	×	
[68]	K.F. Fong			×	×		×		×	×	×		
[69]	M. D'Antonio			×	×		×	×	×	×	×		
[70]	M.J.Romero - Lara			×	×		×	×	×	×	×		
[71]	M. Le Cam			×	×	×	×	×	×	×	×		×
[72]	F.W. Yu			×			×		×	×	×	×	
[23]	J.A. Badenhorst	×		×	×	×	×	×	×	×	×		
The "×" indicates that the study did consider the topic. Also, the purple highlighted areas are the main focus points of the study.													

The literature review underscores the substantial impact of ambient conditions on the functionality of refrigeration systems and their auxiliary components. Le Cam [71] and

Badenhorst's [23] studies revealed that the anticipation of ambient conditions can be instrumental in achieving energy reduction during specific periods. These studies developed models to adjust the system's operating temperature strategically, ensuring the continued provision of necessary cooling for buildings or mines while minimising energy consumption.

The prevailing trend in the literature is a predominant emphasis on implementing control philosophies that dynamically adjust system performance either throughout the day or at specific intervals. Notably, Badenhorst [23] stands out as the sole contributor who implemented a control strategy utilising changes in seasonal ambient conditions to optimise the operation of a deep-level gold mine's refrigeration system. However, a notable gap remains, as none of the studies implemented a cost-effective seasonal control methodology specifically for deep-level platinum mine refrigeration systems. Furthermore, limited efforts have been made to account for seasonal changes within ambient conditions, revealing a pressing need within the platinum mining industry for such methodologies.

1.6 Need for the Study

The literature review highlights that refrigeration systems in deep-level platinum mines pose significant energy consumption challenges. Implementing cost-saving initiatives for these systems can contribute to reducing carbon emissions and enhancing the platinum mining sector's ESG position. Studies indicate that refrigeration systems are notably influenced by shifts in seasonal ambient conditions. Moreover, the research underscores that mines often fall short in optimising system control, particularly during winter when Eskom's electricity costs are three times higher than in summer.

A new control methodology is needed to improve the scheduling of deep-level platinum mines' refrigeration systems.

1.7 Aim and Objectives

The study aimed to optimise the scheduling of deep-level mine refrigeration systems by determining the optimal activation and deactivation times for the refrigeration system based on seasonal changes.

The objectives of the seasonal control methodology were as follows:

1. Achieve a reduction in energy consumption by implementing a seasonal based scheduling method on the refrigeration system
2. Establishing the appropriate time for stopping the refrigeration systems during the transition from summer to winter seasons and also
3. Identifying the optimal time for starting the refrigeration systems during the transition from summer to winter seasons
4. The methodology must not require any investment or capital to be implemented

The methodology was developed by analysing data from the refrigeration systems and ambient conditions during seasonal changes. Subsequently, a seasonal control methodology was crafted using this data to optimise system control. Once formulated, the methodology underwent simulation to assess its effectiveness. Finally, the methodology was implemented in a case study to enhance the control of a deep-level platinum mine refrigeration system.

1.8 Study Research Methodology

The research employed a research methodology that encompasses both qualitative and quantitative methods [73]. The qualitative aspect is dedicated to formulating a method derived from the existing literature, while the quantitative part is oriented towards assessing the developed methodology [74]. Figure 12 illustrates a modified version of the overall research approach utilised in this study [75].

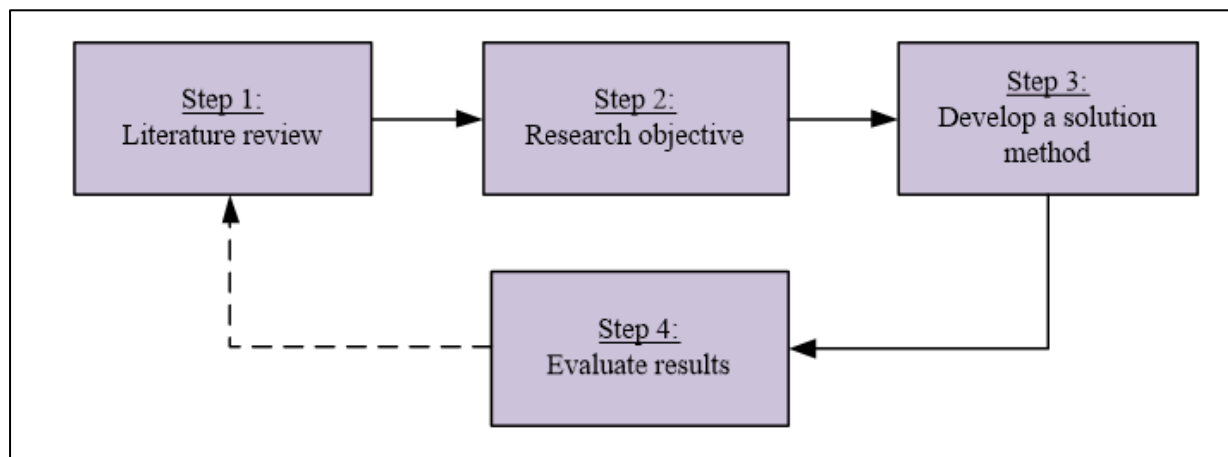


Figure 12: Generic research methodology [75]

A systematic research process must be employed when sifting through vast amounts of online information to ensure the accuracy of the study. This approach aims at streamlining the literature

review, minimizing the time invested while ensuring the presentation of only pertinent and valuable material.

Step 1: Literature review

A literature review delves into previous research on the given topic to identify gaps and set the objectives for a new study. It explores other theories and models to enhance the understanding of potential phenomena and outcomes. Therefore, a comprehensive grasp of existing methodologies is key to designing an innovative approach.

Step 2: Research objective

The pivotal step is articulating clear research questions and objectives, as they give the research purpose and significance. Without them, the study becomes a mere compilation of data lacking direction. The questions identify gaps in existing literature and inherently shape the study's aims. Objectives, in turn, specify the study's scope and sequence. Addressing the questions and meeting the objectives are pivotal for advancing research. It is imperative to sift the literature for material directly relevant to the study's questions, objectives, and challenges.

Step 3: Develop a solution method

An integral aspect of the study involves applying the findings to formulate a solution to the research problem. This is achieved by constructing a framework derived from the literature, serving as both the groundwork and a checklist to verify that the solution addresses the defined problem in a manner distinct from previously explored techniques and solutions.

Step 4: Evaluate results

The conclusive phase of the research involves a quantitative analysis, meticulously measuring the advantages and drawbacks of the proposed solution while underscoring its distinctions from existing alternatives. Employing a case study, the efficacy of the developed method is assessed in comparison to scrutinized approaches and alternative solutions. In instances where the outcomes are inconclusive, additional scrutiny through literature evaluation and research is undertaken to address the study's objectives effectively.

1.9 Overview of Chapters

1.9.1 First Chapter – Background and Literature Study

The initial chapter encompasses the first two stages of the research methodology. The first step delves into the rationale behind selecting the study, emphasising the pivotal role of ESG considerations in contemporary society. Moreover, the chapter underscores the study's specific concentration on the environmental aspect of ESG.

Moving to the second step of the methodology, an exploration of existing research reveals that employing a seasonal-based control strategy in deep-level platinum refrigeration systems holds promise for significant energy savings. The impetus for this study was identified and thoroughly examined through a comprehensive review of relevant literature.

1.9.2 Second Chapter – Development of Seasonal Scheduling Method

The second chapter of the study constitutes the third step in the research methodology. This section is dedicated to elucidating the process of formulating the control strategy designed to secure energy savings. Specifically, the chapter outlines the development of a seasonal control strategy, hinging on forecasted weather data to predict the future operating parameters of the refrigeration systems.

1.9.3 Third Chapter – Implantation of Seasonal Scheduling Methodology

The third chapter represents the conclusive phase of the research methodology. This section delineates the methodology applied in a case study, elucidating the seasonal control strategy tailored for a deep-level platinum mine refrigeration system. Prior to implementation, the approach underwent a comprehensive process involving simulation, thorough checks, validation, and optimisation.

Furthermore, the chapter critically examines and assesses the ultimate results to ascertain the success of the study in its practical implementation.

1.9.4 Fourth Chapter – Conclusion

This chapter examines the dissertation's findings and suggests changes and improvements to the study for future studies.

2. DEVELOPMENT OF SEASONAL SCHEDULING METHOD

2.1 Introduction

The research carried out in Chapter 1 serves as the foundation for crafting a seasonal scheduling methodology aimed at diminishing the energy consumption of a refrigeration system within a deep-level platinum mine. This methodology achieves energy savings by strategically optimising system control in response to variations in ambient conditions. This methodology has been adapted from insights gleaned in previous studies [55] and [76].

2.2 Step 1: Investigation

2.2.1 Introduction

The initial phase of the methodology involves pinpointing a suitable mine equipped with a refrigeration system. Upon identification, the refrigeration system undergoes characterisation through the collection of essential information and data. This characterisation process is instrumental in providing insights into the system's operations, thereby facilitating a comprehensive understanding of potential areas for improvement.

2.2.2 Characterising Refrigeration System

The initial stage of the investigation centres on comprehending the operational characteristics of the system. This involves gathering pertinent information about the refrigeration system, including layouts and operational data. The subsequent subsections delineate the requisite details essential for characterising the methodology:

Data and component specifications:

Gaining a thorough understanding of the operating conditions and specifications of the refrigeration system is pivotal for pinpointing areas where improvements or optimisations can be implemented. This information can be sourced from the engineering team or found on the equipment build plate. Operational data of the refrigeration system should be gathered from the mine's SCADA (Supervisory Control and Data Acquisition) systems. Table 2 enumerates

the key components of the system, along with essential information and data that should be acquired from both the mine and the engineering team.

Table 2: Component specification list

System components	Component specification	Units
Environmental conditions	Dry bulb temperature	°C
	Wet-bulb temperature	°C
	Barometric pressure	kPa
	Relative humidity	%
Dams	Temperature	°C
	Level	%
	Level limits	%
Valves	Position	%
	Status	0/1
Pumps	Flow rate	L/s
	Power	kW
	Water inlet temperature	°C
	Water outlet temperature	°C
Condenser cooling Tower and Bulk Air cooler	Air inlet temperature	°C
	Air outlet temperature	°C
	Water flow rate	L/s
	Air flow rate	kg/s
	Fan power	kW
Refrigeration unit	Power	kW
	Evaporator inlet temperature	°C
	Evaporator outlet temperature	°C
	Condenser inlet temperature	°C
	Condenser outlet temperature	°C

The data obtained from the SCADA system should be analysed to understand the system's operating parameters. The obtained data is later used to build and calibrate the simulation model.

Layouts:

Refrigeration systems are inherently intricate and substantial, underscoring the significance of comprehending their operational dynamics. Obtaining layouts of the refrigeration system from the mine's engineering department simplifies the process of understanding its operations. In

cases where layouts are not available, it becomes imperative to create them. Figure 13 serves as an illustrative example, depicting the surface refrigeration system of a deep-level platinum mine.

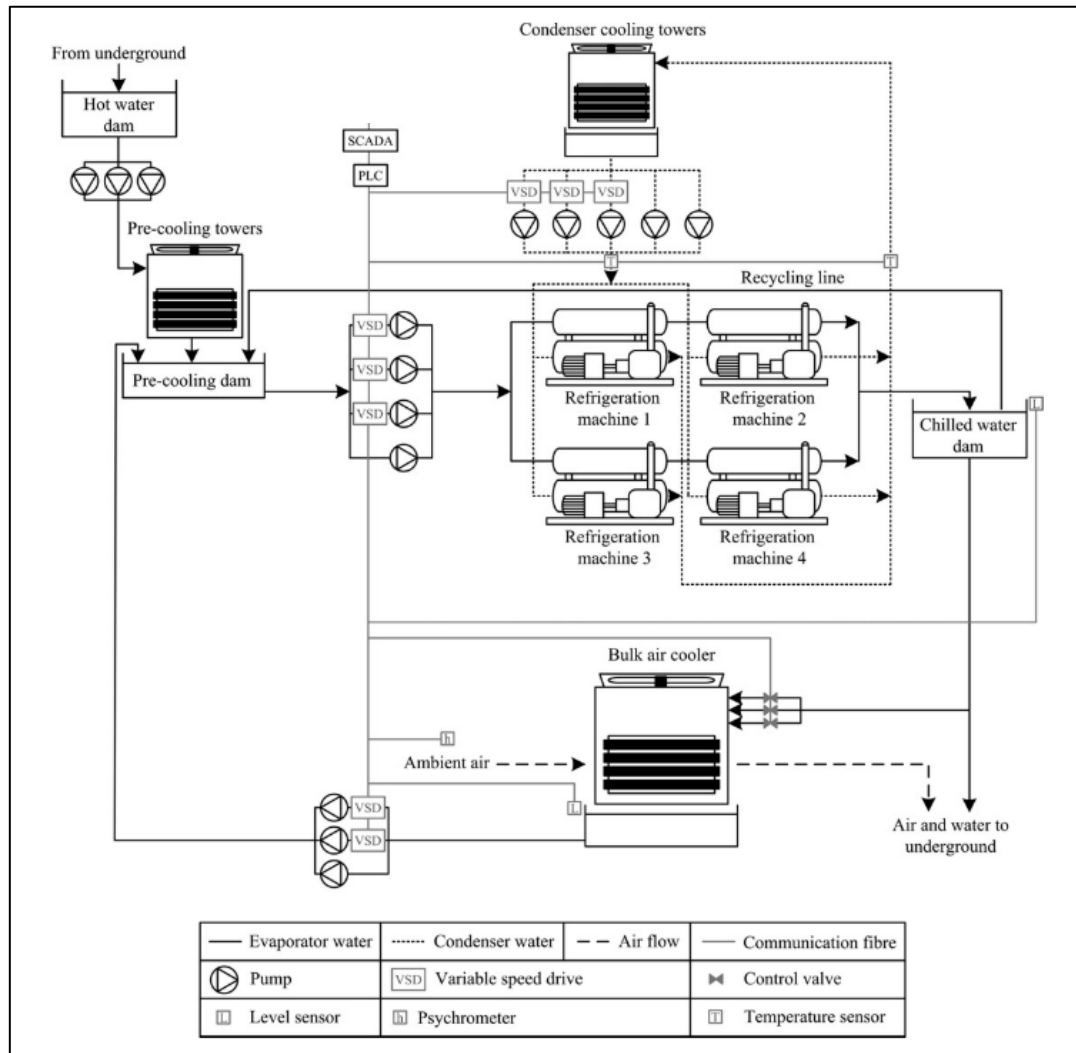


Figure 13: Illustration of a mine refrigeration layout [33]

The layout(s) play a pivotal role in rendering the comprehension of the refrigeration system's functionality accessible. These layouts vividly describe and illustrate the pumping system, elucidating the pathways of water and airflow within. Proceeding to the next stage of the investigation in this section involves acquiring component specifications and operational data. This step is key for gaining an in-depth understanding of the current control philosophy in place.

Operating conditions:

The mine refrigeration systems' control philosophy or operating conditions must be understood. Below is a list of operating parameters that need to be understood:

- System availability
- Operating limit
- Mines cooling requirements
- Maintenance scheduling of the system
- When the system is switched off due to changes in seasons and if it is switched off
- How the system is controlled
- Set-points of the system

The information collected in this section is used to set the limits and constraints of the simulation model. For example, what BAC outlet temperature the mine requires and the necessary evaporate flow rates, to name a couple.

The information collected from the mine's refrigeration system ensures that the control strategy is adhering to the mine requirements, ensuring a safe underground working environment for the miners throughout the year. The following section uses the information collected to develop a simulation model.

2.3 Step 2: Simulation Model

2.3.1 Introduction

A simulation model is required to estimate the impact of implementing the seasonal scheduling methodology on a mine's refrigeration system. Once the simulation model is defined, the user can simulate the methodology on a refrigeration system. The simulation assists the user in assessing the impact of implementing changes on the system and making necessary adjustments to the system to increase its performance and sustainability.

2.3.2 Building the Simulation Model

Within the framework of the seasonal scheduling methodology, a simulation is indispensable to model the consequences of the seasonal control, assessing its effects and impact on the refrigeration system. Among the considered simulation software tools—ENVIRON, Process Toolbox, and Ventilation of Underground Mine Atmospheres (VUMA)—it was concluded that Process Toolbox (PTB) is the optimal choice. This decision stems from PTB's specialised development tailored for simulating mining systems, including water, ventilation, compressed air, and refrigeration. Moreover, PTB's established track record in numerous studies further supports its suitability for the current research [55], [61], [63], [76].

The selected software serves as a potent tool for forecasting energy consumption and identifying optimal operational strategies within mining systems, aligning seamlessly with the focus of this study on refrigeration systems. The simulation model excels in realistically replicating system responses, disruptions, and the effects of parameter adjustments.

PTB exemplifies a component-based simulation software program, as illustrated in Figure 14. Its capability to integrate multiple variables across various components enables the determination of dynamic system responses. Consequently, the simulation model faithfully adheres to the boundary conditions inherent in a dynamic system. Moreover, this simulation software package provides intricate insights that can be scrutinised at the component level.

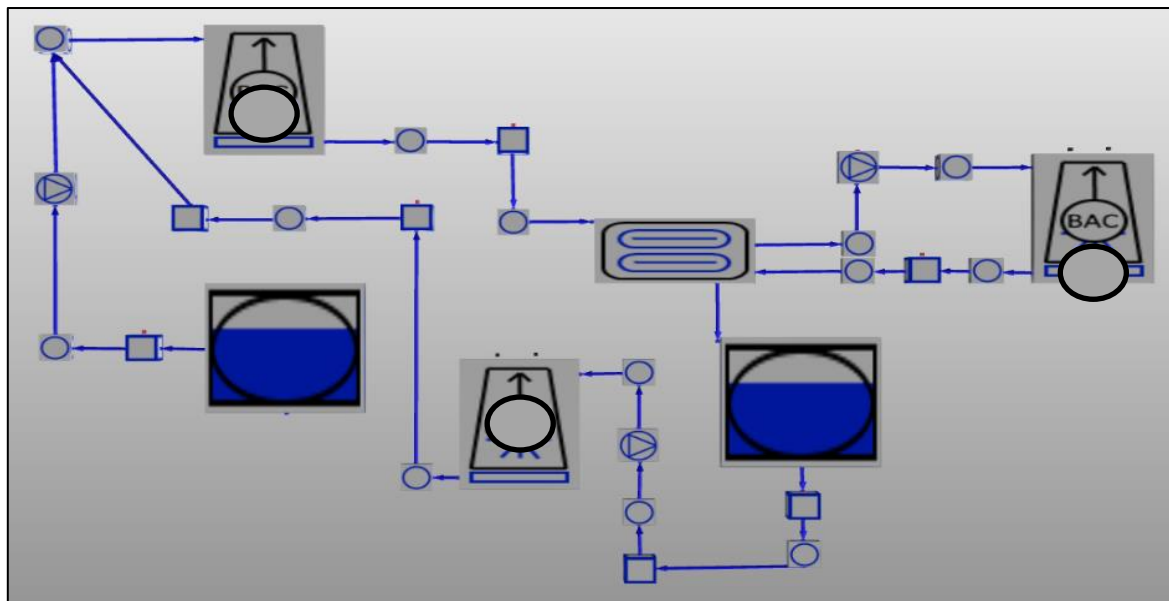


Figure 14: PTB simulation example

Each refrigeration system's auxiliary components are simulated and calibrated using data collected in Table 2. All the data must be gathered over three months and averaged to show how the component functions on an average business day. The data should be obtained during summer to calibrate the simulation when the refrigeration system operates at its maximum capacity.

Mines often do not measure and record all the component data, such as BACs, condenser cooling towers, and pre-cooling tower air flows. If data is not available, on-site measurements need to be taken. All parameters must be gathered for the simulation model to be calibrated accurately. To correctly reflect how the component behaves in the system, assumptions are made regarding these parameters and then iterated.

The PTB software uses a GUI (graphical user interface) to drag and drop system components. Each component has its own set of inputs used to calibrate and accurately represent the component in the practical system. The components' input and description are shown in Figure 15 to Figure 22 for the refrigeration system.

Each component is linked by a network of pipes and nodes, allowing the user to compute each component's parameters. Blue blocks indicate water pipes and black blocks are used for air components. The dam is a thermal-hydraulic system with changeable thermal storage in which the intake and outflow flows are independent (see Figure 15).

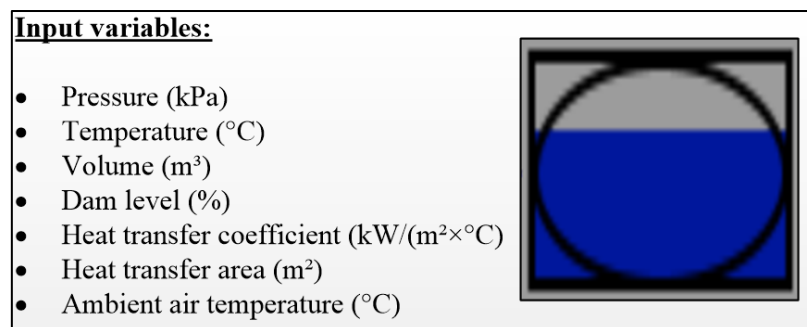


Figure 15: Water dam PTB component

The water chiller in PTB is used to simulate the refrigeration machine in the system. The water chiller component removes heat from the water circuit linked to the evaporator ports (cooling). The heat from the compressor is then transported to the water circuit (heating) linked to the condenser ports; see Figure 16.

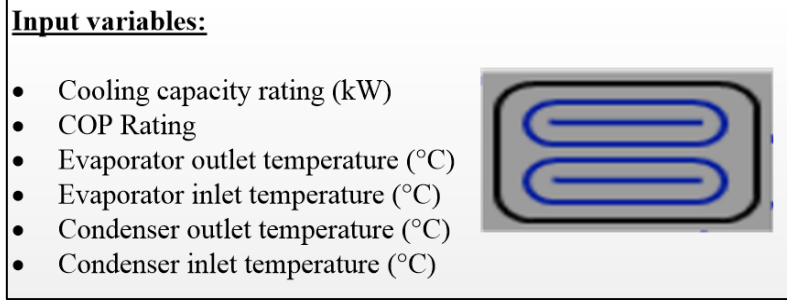


Figure 16: Refrigeration machine PTB component

The water air cooling tower component is a counterflow direct contact heat exchanger that transfers heat and mass between air and water at the same time. The air can be chilled, humidified, dehumidified, or heated and humidified by directly contacting water. The simulation uses the component as a BAC, pre-cooling, or condenser cooling tower, see Figure 17.

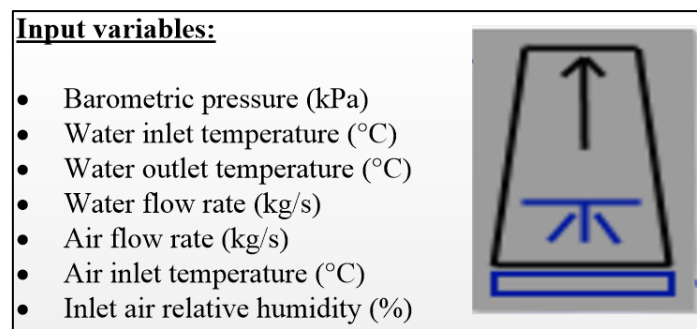


Figure 17: Pre-cooling, BAC, and cooling tower PTB component

The pump component causes pressure differences in the flow network, causing water to flow through it. Due to inefficiencies, the pump component creates heat in the fluid, see Figure 18

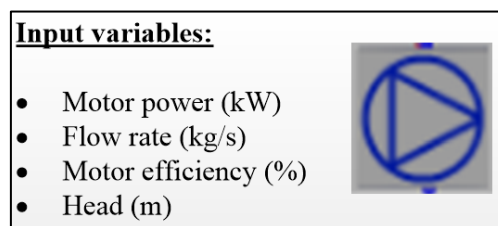


Figure 18: Water pump PTB component

The fan component plays a pivotal role in inducing airflow across the network by generating pressure differences. However, it is essential to note that inefficiencies and adiabatic

compression within the fan component led to the generation of heat in the fluid, as depicted in Figure 19.

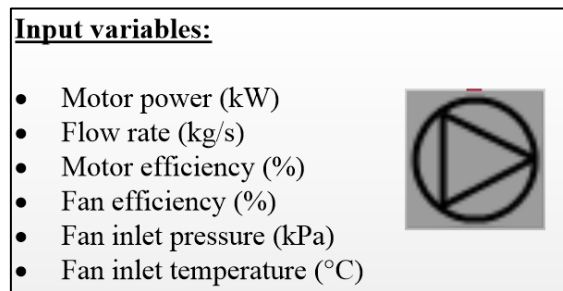


Figure 19: Air fan PTB component

The pipe component calculates the flow network pressure losses. A variable valve fraction for flow or pressure control is included in the pipe component. The pipe component calculates auto-compression heat as well, see Figure 20.

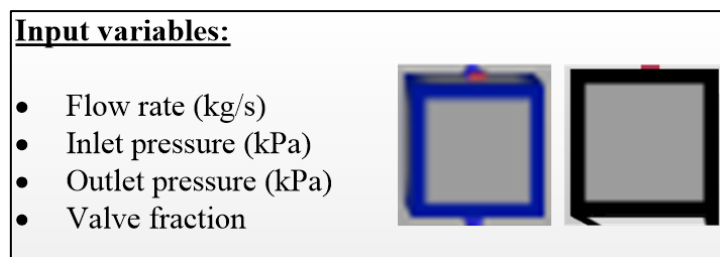


Figure 20: Pipe PTB component

The nodes component specifies the medium's height (change in network elevation) and volume, see Figure 21. The nodes calculate all network parameters, such as pressure, temperature, and density.

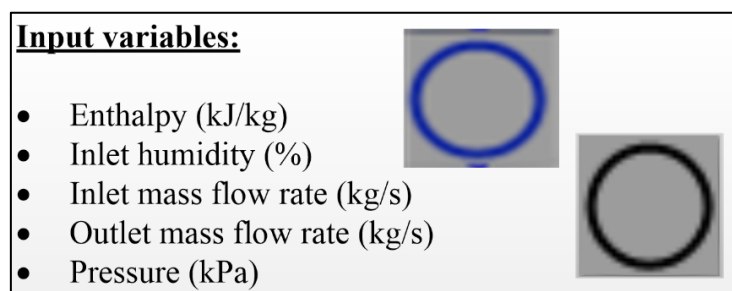


Figure 21: Node PTB component

The air pressure boundary has constant user-specified pressures, temperatures, and humidity each time (see Figure 22). This component is used to link the network to other systems or sources. The primary components of a mine refrigeration system that must be calibrated are refrigeration machines, BACs, condenser cooling towers, pre-cooling towers, air fans, water pumps, water dams, and pipes.

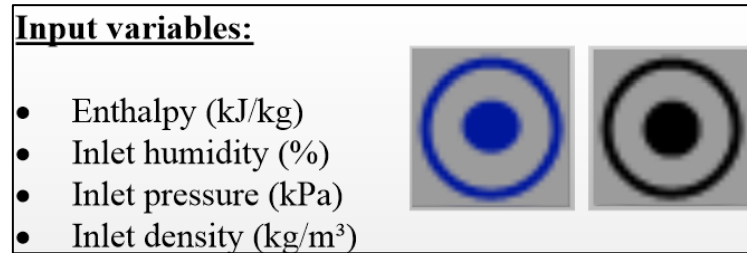


Figure 22: Pressure boundary PTB component

The only components that need not be calibrated are the nodes and boundary points since the nodes link the pipes to other pipes and other components. The pressure boundary is the point at which the simulation is separated from other components. The effectiveness of the simulation model is verified by comparing the findings to original historical data to the simulated results.

2.4 Step 3: Verification of Simulation Model

2.4.1 Introduction

In Chapter 2.3, the method of building a simulation model was delineated, utilising an existing refrigeration system from a deep-level platinum mine as a basis. A pivotal step involves calibration to ensure the reliability of the simulation model. During this phase, the accuracy of the simulation model is meticulously validated against historical data obtained from the mine's SCADA systems.

2.4.2 Accuracy of Simulation Model

Baselines from historical data are required to compare simulation model output results to actual data. The baseline is an hourly average daily profile of the operating parameters of the refrigeration system, such as:

- BAC air outlet temperature
- Evaporator water flows in and out, and
- Condenser water flows in and out

The parameters of the refrigeration that require a baseline are determined in the refrigeration characterisation section in Chapter 2.2. The baseline values are compared against the simulated values to determine the accuracy of the simulation model.

It is essential to compare the refrigeration actual data against the simulation simulated values to assess the accuracy of the simulation model. Therefore, to determine the accuracy of the simulation compared with the actual performance.

The mean absolute percentage error determines the simulation model's accuracy, see Equation 5. A mean absolute error of less than 5% is necessary for the simulation to be considered accurate [77], [78].

Equation 5: Mean absolute percentage error [78]

<i>Where:</i>	$\% \text{ Error} = \frac{1}{N} \times \sum_{n=1}^N \left \frac{A_n - S_n}{A_n} \right \times 100\%$
	$\% \text{ Error} = \text{Percentage Error}$ [%]
	$N = \text{Total number of data points}$ [–]
	$n = \text{Number of data point}$ [–]
	$A = \text{Actual value (data point)}$ [–]
	$S = \text{Simulated value (data point)}$ [–]

The comparison between baseline and simulated values allows the user to verify the simulation model's accuracy before implementing any system changes. The following section describes the seasonal control strategy implemented on the selected refrigeration system.

2.5 Step 4: Seasonal Control Strategy

2.5.1 Introduction

In the previous steps of the seasonal scheduling methodology, all the information on the refrigeration system is collected. A simulation model is built from the available information and data. In step three of the simulation model, accuracy is verified before implementing the seasonal control strategy. In this section, the seasonal control strategy is verified on a mine's refrigeration systems before it is implemented to validate the methodology (Chapter 3).

2.5.2 Control Strategy

The seasonal control strategy aims at determining when components are switched on and off based on changes in the ambient conditions due to seasonal changes. The section describes the control strategy to determine when the systems can be switched on or off.

Figure 23 illustrates the seasonal control strategy. The strategy shows the process followed in deactivating the refrigeration system post-summer and reactivating it following the winter season. This depiction offers a clear representation of the strategic process guiding the system's operational adjustments based on seasonal changes.

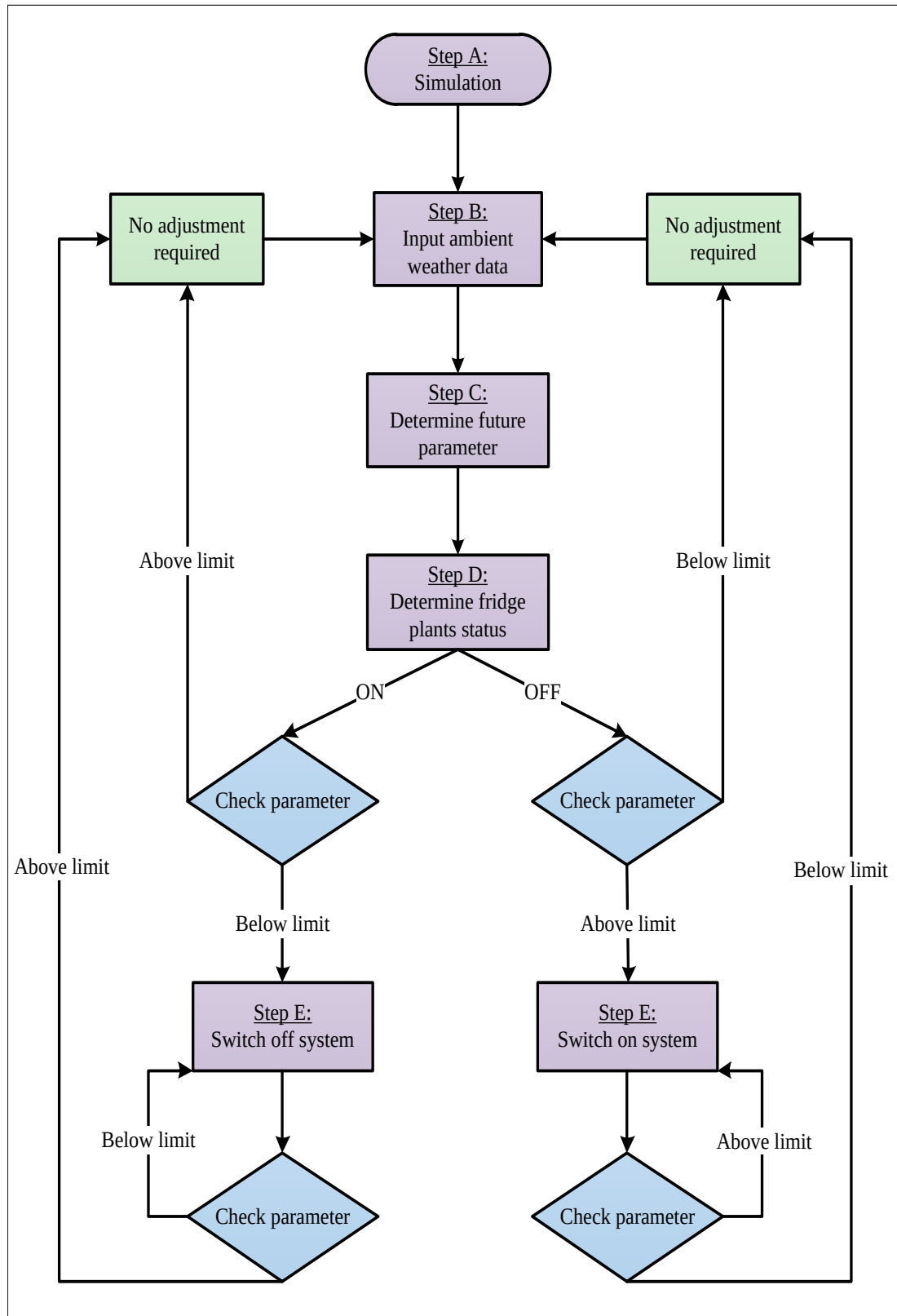


Figure 23: Proposed seasonal control strategy

Each of the control strategy's steps is discussed in more detail below:

Step A: Simulation

The first step in Figure 23 is to build a simulation using the PTB software. The accuracy of the simulation must be verified (the accuracy of the simulation model is verified in Chapter 2.4). The simulation determines/calculates the effect changes in ambient conditions have on refrigeration systems.

Step B: Input ambient weather data

The second step in the control strategy is gathering forecasted weather data from the refrigeration system's area. The forecasted weather data is used as input values in the simulation model. The simulation model determines the output values of the refrigeration system. The forecasted weather data used in the study is collected from the South African Weather Service.

Step C: Determine future parameter

Chapter 2.2.3 characterised the refrigeration system, and all the relevant data was collected. From this characterisation, the main parameters of the refrigeration system are determined, and the evaluated parameters are unique to each system. The parameter could be a BAC outlet temperature, flow rate, or dam level.

The simulation model uses the weather data as input values to simulate the output values of the parameters. The output values are converted to a daily running average value that is evaluated against the limit of the refrigeration system.

Step D: Determine fridge plant status

The next step in the control strategy is to determine the fridge plant's status (on or off).

Check parameters:

The future parameters are simulated, and the results are evaluated according to the following criteria:

- The control should remain the same if the parameter does not exceed the mine's requirements. The simulation is redone again with the following week's forecasted weather data.
- If the parameter is below the limit of the requirements, the refrigeration system can be switched off.
- The control should remain the same if the parameter does exceed the mine's requirements. The simulation is redone again with the following week's forecasted weather data.
- The refrigeration system should be switched on if the parameters exceed the higher limit for two to three consecutive days.

Step E: Switch the system on or off

The refrigeration systems can be switched on or off based on the results of the previous steps. The check parameter section is redone to determine whether the system operation should remain or change.

The seasonal control strategy evaluates the effect of the changing conditions on the system and determines the future operating parameters of the refrigeration system. The system can be switched on or off based on whether the operating parameters are above or below the limits. The following section describes the validation process needed before implementing the strategy on an actual system.

In Chapter 1.7, the objectives of this study were discussed. Objective 2 and Objective 3 are to determine when the refrigeration system can be stopped for winter and started for summer. This section is used to achieve these objectives.

2.6 Step 5: Validation of Seasonal Control Strategy

After the seasonal control strategy has been modelled and shown to be theoretically possible, the method can be tested on a suitable mine cooling system. The test confirms the practicality of the suggested control technique and evaluates it.

The appropriate data may be obtained once the control strategy testing has been completed. The data is compared to the simulation findings. The comparison of the various data indicates the correctness of the simulation and the practicality of the planned seasonal control strategy for integrated service delivery and energy efficiency savings. The strategy may be optimised for maximum performance during the validation process. The first objective of this study is achieved in this section, as discussed in Chapter 1.7.

2.7 Conclusion

Chapter 2 describes the seasonal scheduling methodology that can be implemented in deep-level platinum mines. The methodology focuses on using existing infrastructure to optimise the seasonal control of the refrigeration system by determining the optimal time the refrigeration system can be switched on or off based on changes in seasonal conditions. Figure 24 summarises Chapter 2 in a flow diagram.

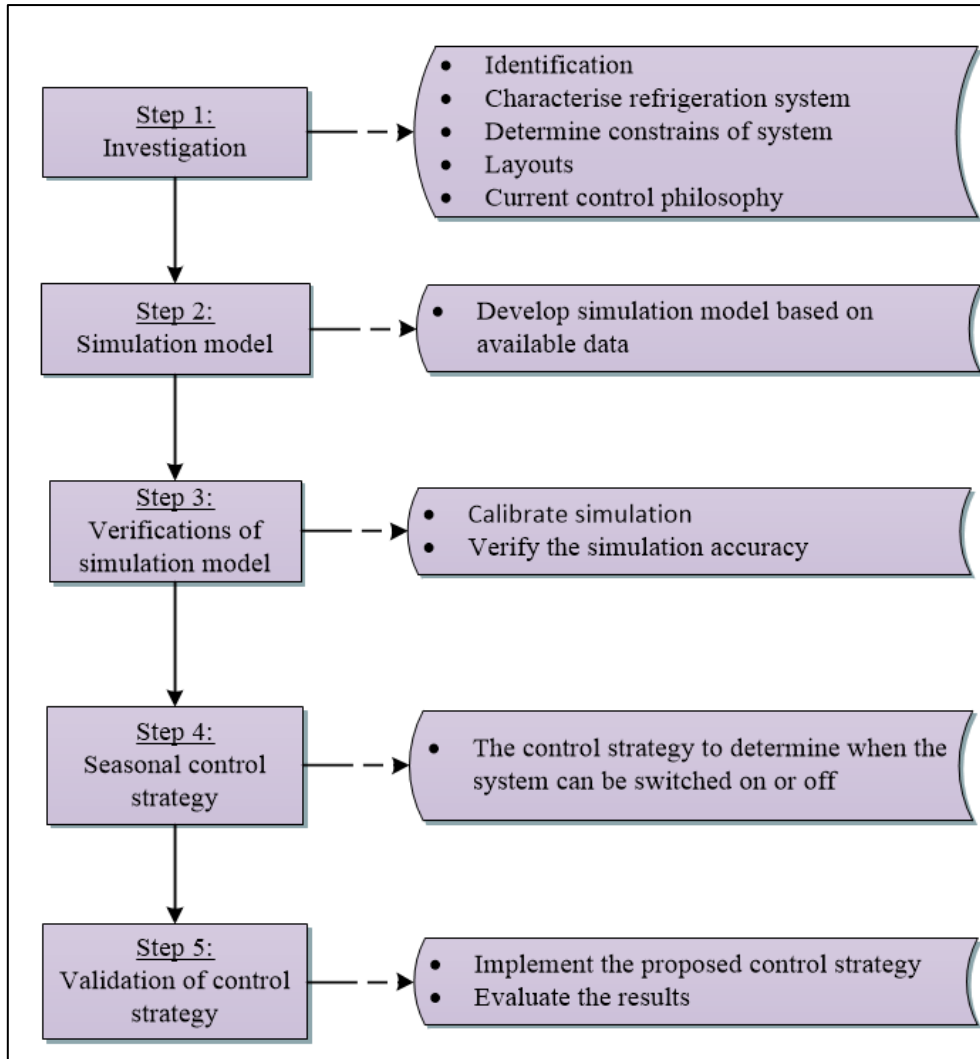


Figure 24: Seasonal scheduling methodology for deep-level platinum refrigeration system

The first step in the methodology is conducting an investigation to identify a mine with a suitable refrigeration system. Once identified, all the refrigeration system's information must be collected in the investigation step to build a simulation model. Once built and calibrated in step two, the accuracy of the simulation model is verified in the third step.

The verification and simulation model steps are repeated to improve the model's accuracy. Once the simulation accuracy is verified, a simulation model can test the seasonal control strategy. The simulation model is used to evaluate the effects of the seasonal control strategy on the refrigeration system. Lastly, the control strategy is validated by implementing it in a case study, which is done in Chapter 3.

The methodology in this part corresponds to the study goals mentioned in Chapter 1, which include establishing a control plan for mine cooling systems to maximise energy efficiency over seasonal changes. The following chapter goes over implementing the control strategy and the results obtained from implementing the strategy in a case study.

This chapter achieved Objectives 1, 2 and 3 with the proposed season control strategy to improve the scheduling for stopping and starting the refrigeration system. The chapter also implemented the strategy cost-effectively, only utilising additional infrastructure.

3. IMPLEMENTATION OF SEASONAL CONTROL STRATEGY

3.1 Introduction

In the previous section (Chapter 2), a seasonal scheduling methodology and seasonal control strategy were developed to be implemented in a deep-level platinum mine's refrigeration system. In this chapter, a suitable mine is identified, a simulation model is developed, and the control strategy is implemented in the refrigeration system.

The simulation model is verified against actual data to ensure the model's accuracy. After verification, the methodology is validated by comparing the simulation results against the actual results from implementing the control strategy of the methodology.

3.2 Step 1: Investigation of Case Study

3.2.1 Identification

The investigation section is the methodology's first step, as seen in Figure 24. This part identifies a mine with a suitable refrigeration system. The selected mine's refrigeration system is investigated to collect necessary data and operational parameters to characterise the system. The information collected from the investigation step is used to develop and calibrate a simulation model.

As described in Chapter 1, the study focuses on optimising the control of deep-level platinum mines' refrigeration systems. This paper primarily investigates deep-level platinum mines found in Rustenburg in the North-West province of South Africa. The names and locations of the mines are kept anonymous throughout the study due to confidentiality clauses with these mines.

Figure 25 shows the monthly energy consumption of three mines (A, B and C). The figure shows that during summer months, Mine C consumes the most energy compared to the other two. However, Mine C uses less energy in the winter compared to the other mines. The lower energy usage in the winter is due to the reduced number of operational refrigeration systems.

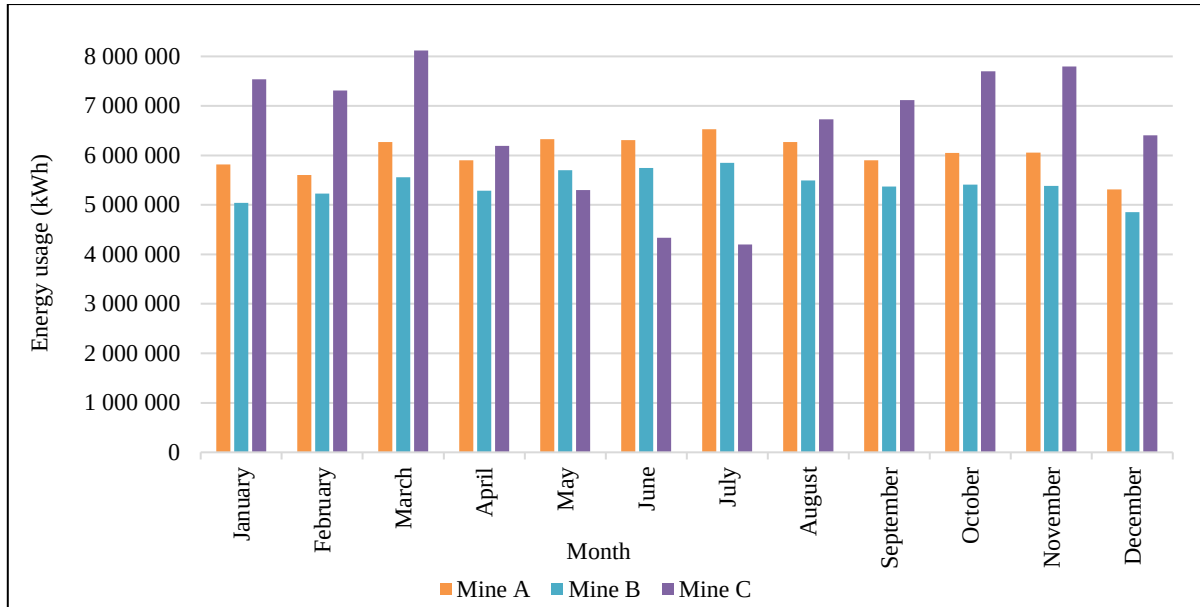


Figure 25: Three platinum mines' monthly energy usage for a year

Mine C is chosen as the ideal candidate as it is the only mine with a refrigeration system. The primary objective is to optimise the timing of when a mine deactivates and activates its refrigeration systems, transitioning between summer and winter and vice versa. The subsequent phase involves characterising the system to gain a comprehensive understanding of the operational conditions specific to Mine C's refrigeration system.

3.2.2 Characterising Refrigeration System

Mine C was identified as suitable for implementing the methodology in the previous step. The next part of the investigation is to characterise the refrigeration system. All the information and operational data are collected and used to understand the refrigeration system's operational parameters and control philosophy.

The analysis of Mine C's refrigeration system drew information from diverse sources such as machine plates, commissioning papers, orders/invoices, discussions with mine staff, and historical operating data. It was determined that the system comprises two distinct refrigeration systems.

At the current stage of this study, only one of the systems is operational. Consequently, the study predominantly concentrates on optimising the functioning of this operational system. The primary purpose of the refrigeration system is to cool intake air for ventilating working areas.

Nevertheless, it is noteworthy that the system was also engineered to convey cold water down the mine for supplementary cooling.

3.2.3 Data and Component Specifications

In this part of the investigation section, all the necessary components, specifications, and operational data are collected. Table 3 covers all the design specifications for Mine C's refrigeration system components. These parameters are needed to build the simulation model and are later used to calibrate the model.

Table 3: Refrigeration system design conditions

Refrigeration machine	Value	Unit
Compressor motor rating	1740	kW
Cooling capacity	9600	kW
Evaporator temperature water in	6.12	°C
Evaporator temperature water out	1	°C
Evaporator water flow rate	240	l/s
Condenser temperature water in	24	°C
Condenser temperature water out	29.5	°C
Condenser water flow rate	492	l/s
Condenser tower	Value	Unit
Barometric pressure	89	kPa
Temperature air in	20	°C
Temperature air out	Ambient	°C
Air flow rate	Unavailable	kg/s
Temperature water in	29.5	°C
Temperature water out	24	°C
Flow rate	492	l/s
Dame capacity	0.5	MI
Bulk air cooler	Value	Unit
Barometric pressure	89	kPa
Temperature air in	20	°C
Temperature air out	9	°C
Air flow rate	300	kg/s
Temperature water in	1	°C
Temperature water out	10.6	°C
Flow rate	240	l/s
Dam capacity	0.5	MI

The information shown in Table 3 is the original design specifications and the installed capacities of each of the system's components. Additional operational data of the system were collected from the mine's SCADA system. The information specifications and data collected from the mine are used to build the comprehensive layout shown in Figure 26.

3.2.4 Layout

The layouts for Mine C's refrigeration system were collected, and a Microsoft Visio drawing of the system was made, which is illustrated in Figure 26. The drawing shows the location of the two refrigeration systems and how they are connected, as well as the location of each of the system's auxiliary components.

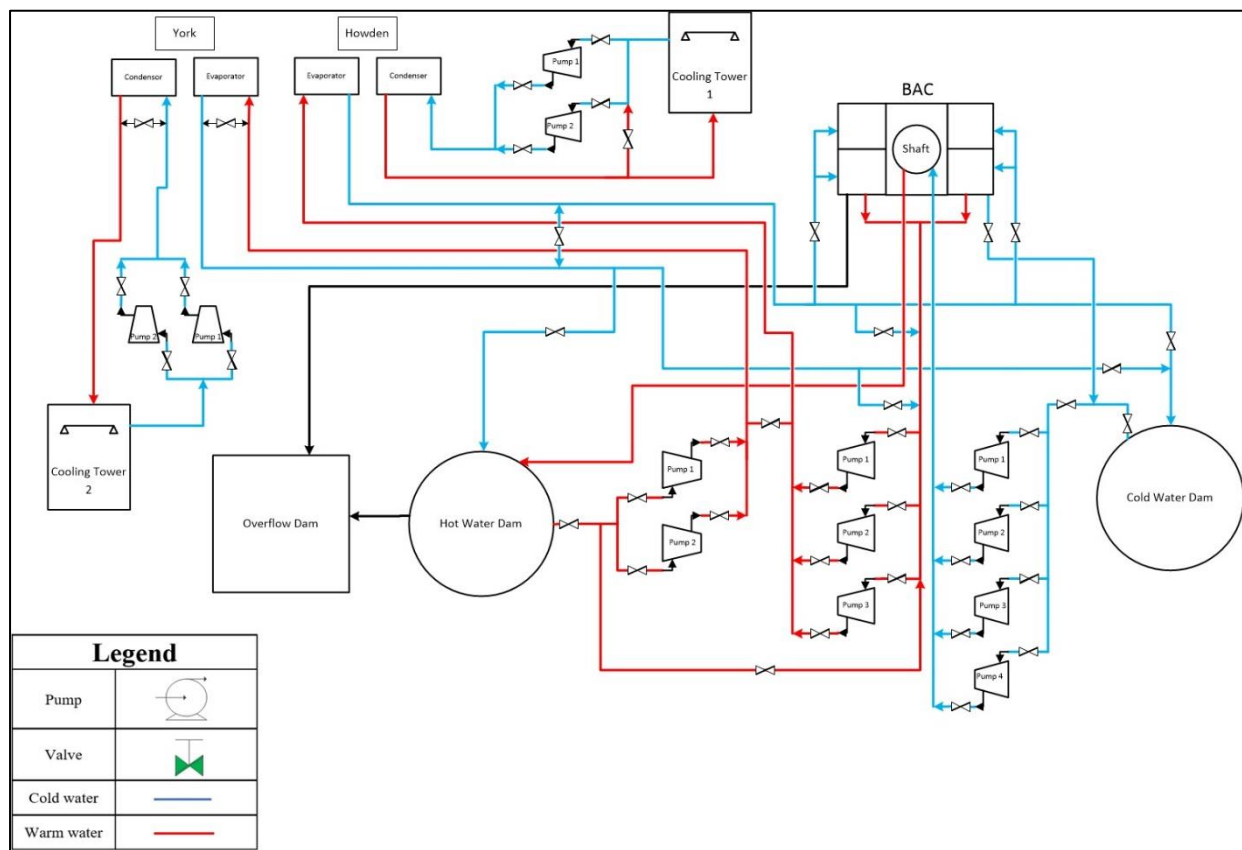


Figure 26: Mine C refrigeration system layout

Ensuring the precise placement of all components and connections is vital, requiring meticulous attention to detail. All relevant information and layouts of the system have been compiled, with the layout serving as a foundation for constructing the simulation model in the subsequent section.

The next step involves delving into the control philosophy of the refrigeration system, seeking a comprehensive understanding of how it is governed and regulated.

3.2.5 Current Control Philosophy

All the information and data from the refrigeration system were collected in the previous parts of the identification step. This part of the identification step is used to gain a full understanding of the current control philosophy of the mine's refrigeration systems.

Gaining insight into how the system is controlled is pivotal for identifying potential areas for improvement. The control philosophy of the refrigeration systems was comprehended through discussions with mine personnel and a thorough analysis of the system's data. The investigation revealed the following control mechanisms:

- The refrigeration machine is controlled with a sliding valve.
- The water and air flow rates on the cooling towers and BAC do not change.
- The dam that is connected to the system is not in use.
- The refrigeration machine, cooling tower, and evaporator pumps are switched off in winter.
- The mine does not determine when the refrigeration is switched off in winter and on again in summer. They have set dates for winter and summer.
- All four BAC fans are used for ventilation during the winter months.

The mine's refrigeration system's seasonal control can be improved by the investigation. The next step in the methodology is to use the gathered information to build a simulation model that accurately represents the refrigeration system of Mine C.

3.3 Step 2: Simulation Model

3.3.1 Introduction

Chapter 2.3 describes how the simulation is built and how each component works. All the information collected in the investigation step (Chapter 3.2) is used to build the simulation model.

3.3.2 Simulation

The information collected in the previous section is used to set up the simulation model using the **PTB** simulation software, as discussed in Chapter 2.3. Only the primary refrigeration system was built and used for this study, as the other system was not in working condition at the time of the study. Figure 27 shows a detailed simulation model with all the auxiliary systems.

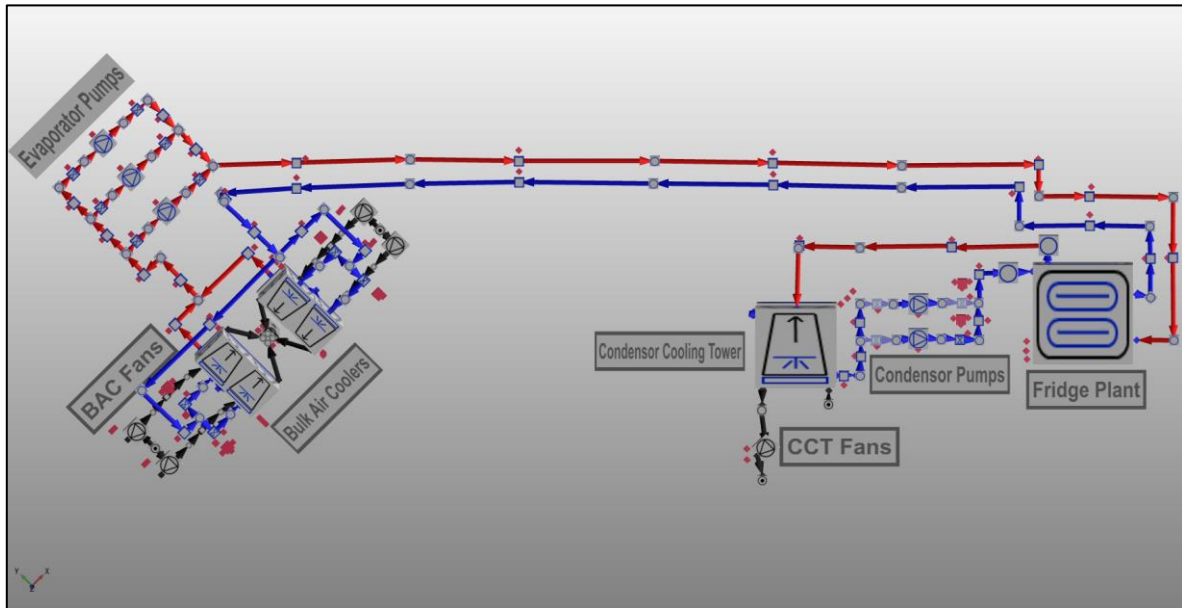


Figure 27: PTB simulation model

The simulation is built using the information and layouts collected from the mine. The next step in the methodology is to use the available data and simulation to calibrate the simulation model as close as possible to the actual systems' conditions.

3.4 Step 3: Verification of Simulation Model

3.4.1 Introduction

In the previous sections (Chapter 3.3), the refrigeration was identified, and a simulation model was built using the information collected in the investigation section. This section shows the simulation model's accuracy before the simulated control strategy.

3.4.2 Simulation Verification

The accuracy of the simulation needs to be verified before the control strategy can be tested in the simulation model. The verification was done by simulating a working summer day in the simulation and comparing the results to actual site data.

The simulation data of the following components are compared to the assault site measurements:

- Bulk air cooler air outlet temperature
- Condenser cooling tower water inlet temperature
- Evaporator water inlet temperature
- Condenser cooling tower water outlet temperature
- Bulk air cooler water inlet temperature

Figure 28 compares the bulk air cooler's simulated outlet air temperature (the air sent to the underground working areas) to the actual operational data. The simulation shows an average percentage error of 4.2% compared to the actual data.

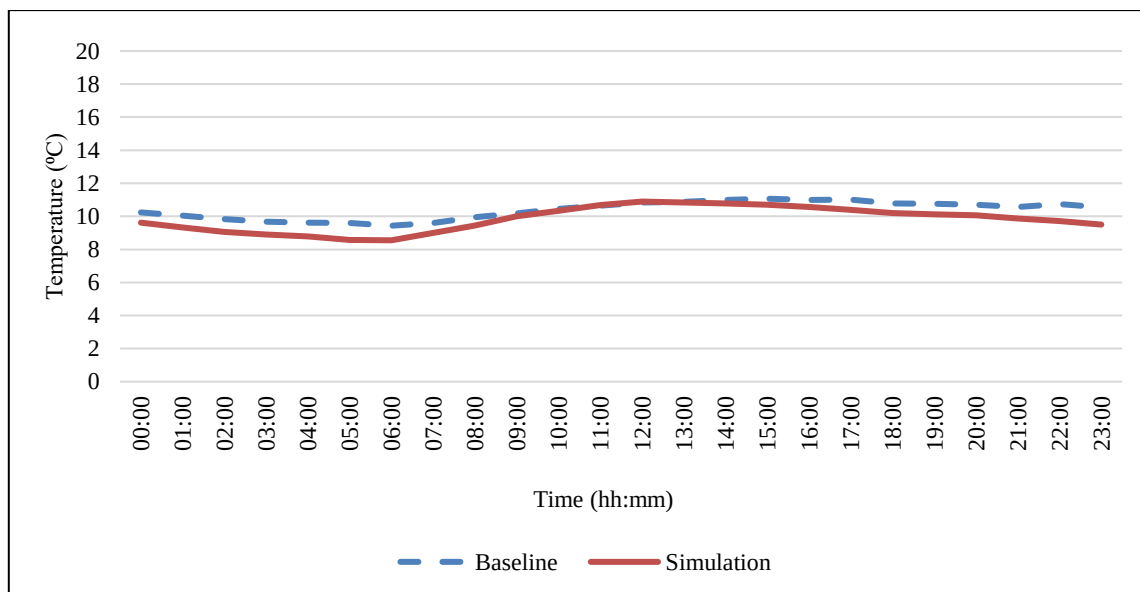


Figure 28: Bulk air cooler air outlet temperature

Figure 29 compares the simulated outlet water temperature of the condenser cooling tower to the actual operational data. The spikes in the data are due to the simulation not being able to be calibrated to 100% accuracy. The simulation shows an average percentage error of 5% compared to the actual data.

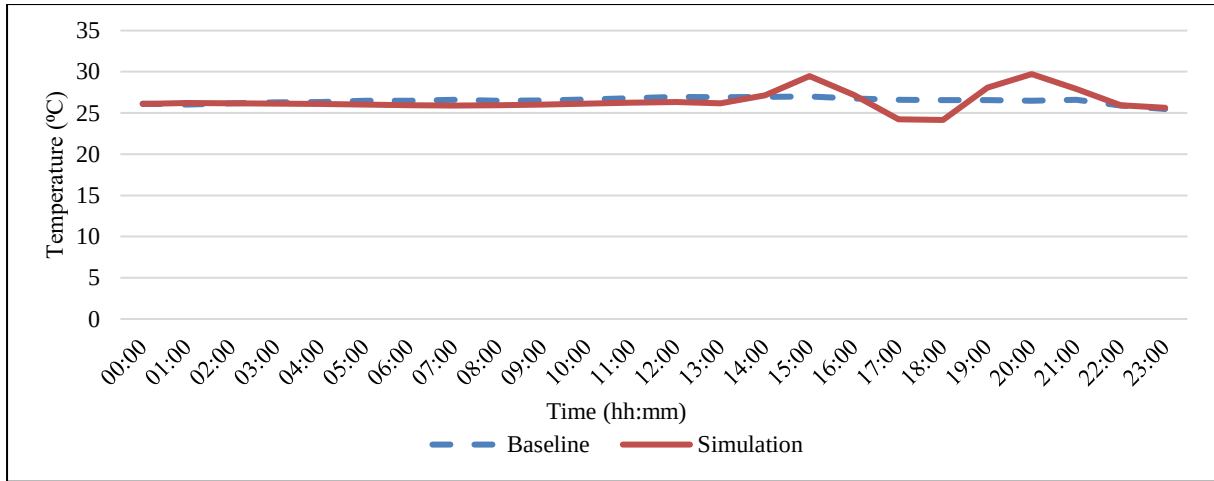


Figure 29: Condenser cooling tower water inlet temperature

Figure 30 compares the simulated inlet water temperature of the evaporator to the actual operational data. The simulation shows an average percentage error of 2.3% compared to the actual data.

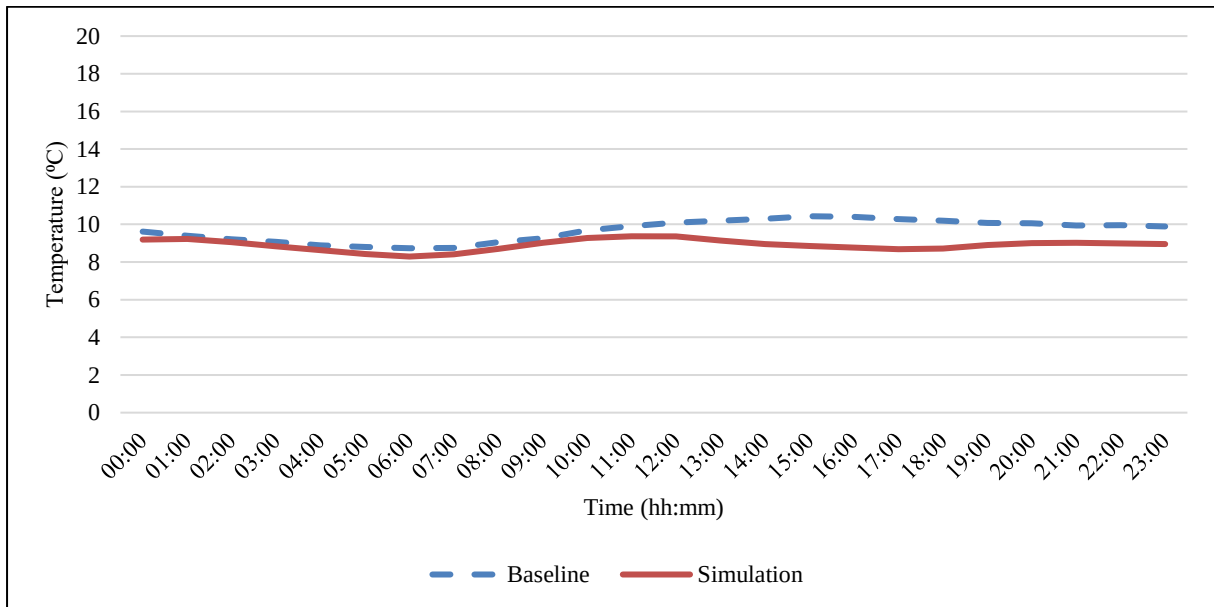


Figure 30: Evaporator water inlet temperature

Figure 31 compares the condenser cooling tower simulated outlet water temperature to operational data. The simulation shows an average percentage error of 5% compared to the actual data.

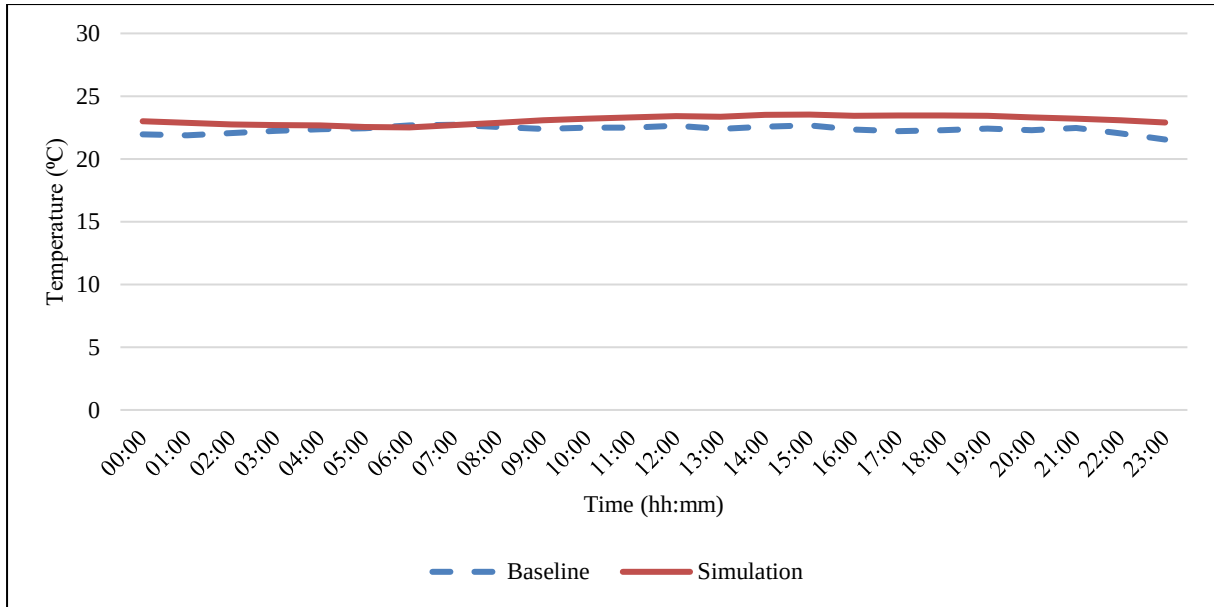


Figure 31: Condenser cooling tower water outlet temperature

Figure 32 compares the BAC's simulated inlet water temperature to operational data. The simulation shows an average percentage error of 2.5% compared to the actual data.

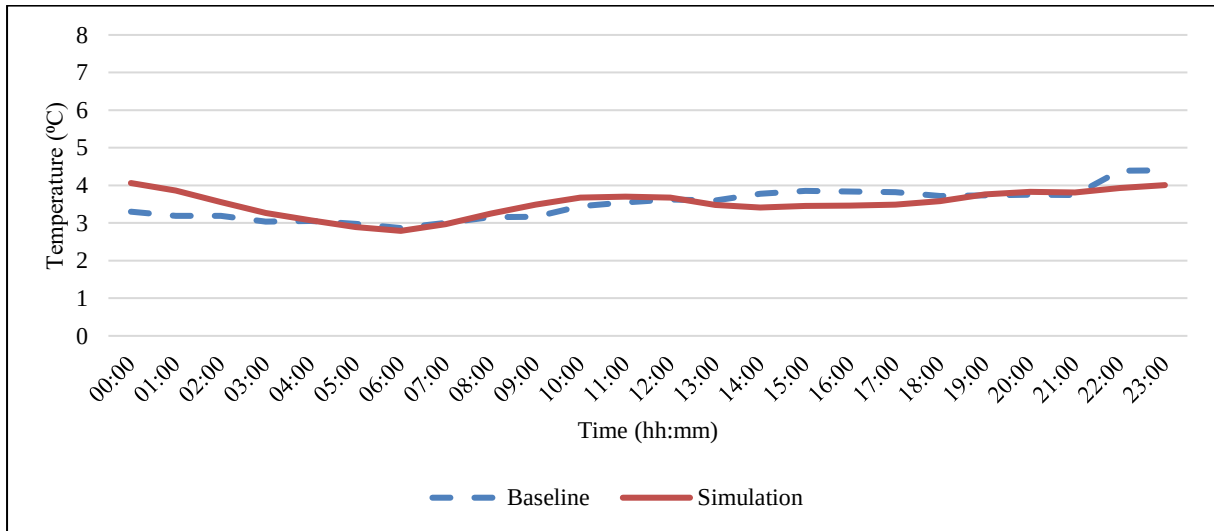


Figure 32: Bulk air cooler water inlet temperature

Table 4 compares the average simulated values to the actual average site data. Each of the components is within 5% of the actual values. The simulation has a total percentage error of 3.7%.

Table 4: Simulation model percentage error

Description	% Error
Bulk air cooler air outlet temperature	3.2
Condenser cooling tower water inlet temperature	5
Evaporator water inlet temperature	2.3
Condenser cooling tower water outlet temperature	5.0
Bulk air cooler water inlet temperature	2.5
Average percentage error	3.7

The information above proves that the simulation model has been calibrated as close to the actual operation as possible. The accuracy of the simulation model is proof that the control strategy can be tested before it is implemented. The following section shows the results of implementing the control strategy in the simulation model before it is implemented in the refrigeration system.

3.5 Step 4: Seasonal Control Strategy

3.5.1 Introduction

In the previous sections of the chapter (Chapter 3.4), all the necessary information was collected from the mine and used to build a simulation model. The simulation model was calibrated and verified with site data to ensure the system's accuracy.

In this section, the next step of the methodology (as seen in Figure 12) was implemented. The seasonal scheduling methodology is implemented in the simulation model to determine when the refrigeration system can be switched on or off based on changes in seasonal conditions.

3.5.2 Simulation Results

In Chapter 3.3, the simulation model was built using the PTB software and the specifications and operational parameters of the refrigeration system. In Chapter 3.4, the simulation model was calibrated and verified against actual operational data and was found to be accurate.

Chapter 2.5 details the seasonal control strategy, and within this section, the implementation of seasonal control strategies in the simulation model is undertaken. This involves determining

the optimal times for activating or deactivating the refrigeration system based on variations in seasonal conditions.

The seasonal control strategy is exclusively employed for activating or deactivating the system in response to seasonal ambient weather changes. Consequently, particular emphasis is placed on the months of April, May, June, July, and August.

In April, a close monitoring of weather data and simulated values of the refrigeration systems was conducted to assess the feasibility of deactivating the systems. The outcomes for April, depicted in Figure 33, reveal that the running average simulated BAC outlet air temperature values surpass the temperature limit. Consequently, the refrigeration systems could not be deactivated during April.

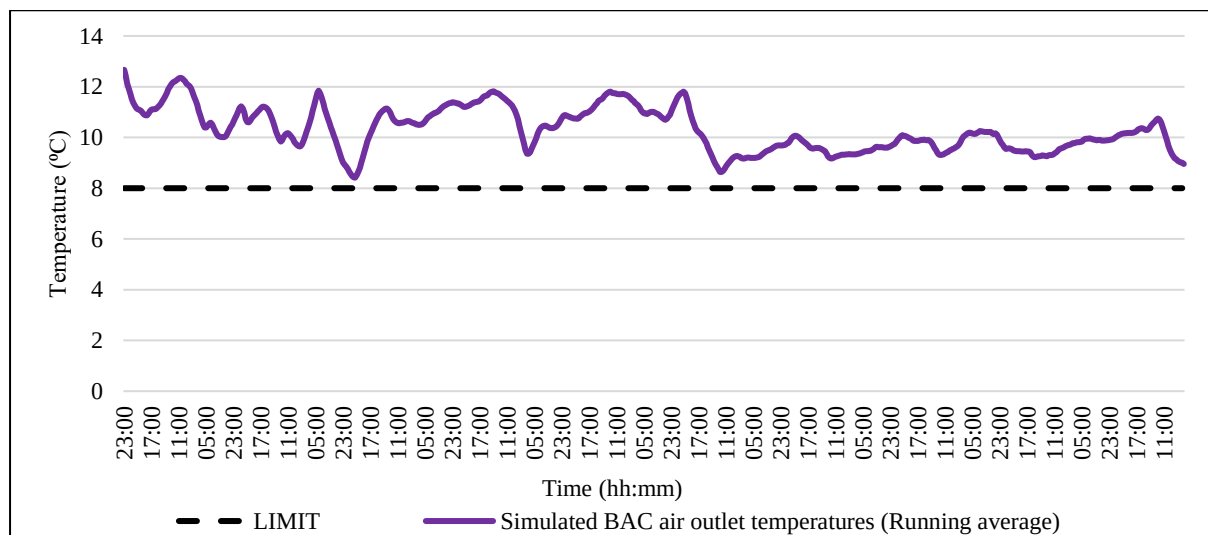


Figure 33: Simulated results for April

Following April, the ambient temperatures started to decrease. Consequently, a more meticulous monitoring of weather data and its impact on the refrigeration systems was undertaken. Forecasted weather data for the initial week of May was compiled and simulated to assess the possibility of deactivating the refrigeration system, with detailed results available in Appendix A.

The outcomes for the last week of May, as depicted in Figure 34, clearly indicate a decline in ambient temperatures. The colder conditions lead to a lower running average BAC outlet

temperature. Notably, for eight consecutive days, the BAC outlet temperature remains below the specified limit.

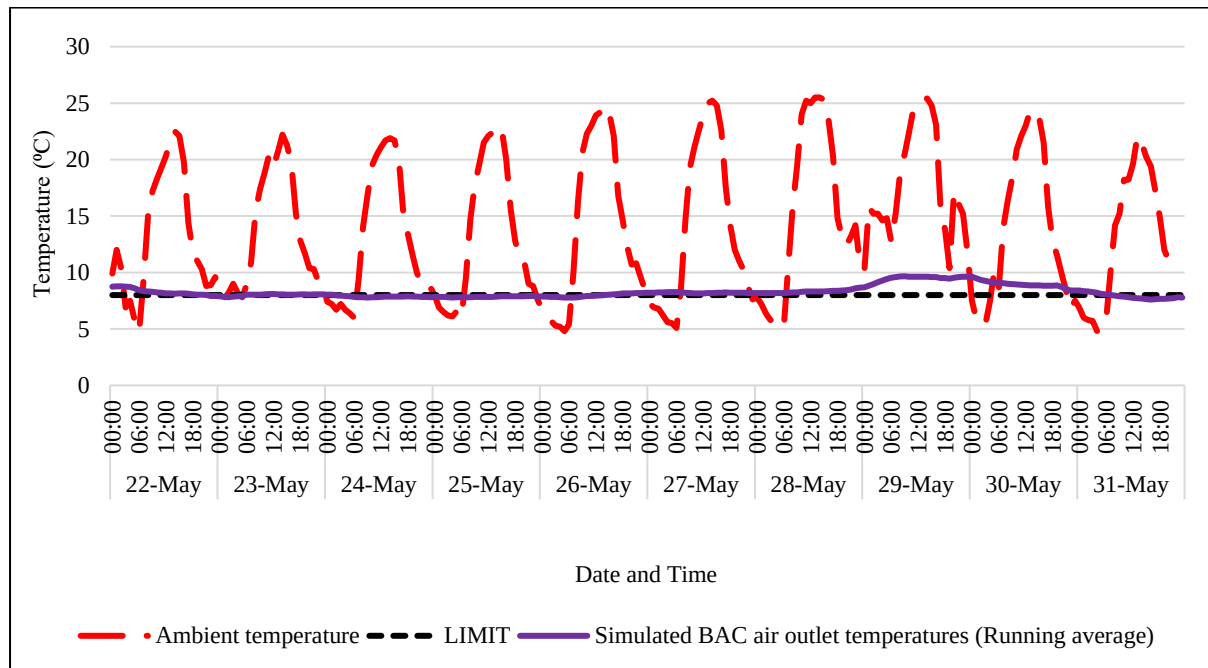


Figure 34: Simulation result 05/22 - 05/31

It is recommended that the refrigeration system be deactivated in the last week, specifically on the 24th of May, to prevent unnecessary energy consumption beyond what is required. The BAC outlet temperature during this period is sufficiently low. Importantly, switching off the refrigeration system on this date has no adverse impact on underground temperatures.

For the winter months, the mine's refrigeration system is deliberately turned off to conserve energy. Now, the seasonal scheduling methodology is tested to ascertain the optimal time for reactivating the refrigeration system. This is determined by assessing BAC outlet air temperatures using the simulation model alongside forecasted weather data.

In the case of July, monitoring and simulating the weather forecast revealed that the BAC outlet temperatures remained within the desired range, indicating that the refrigeration system did not need to be started. Figure 35 illustrates the ambient weather temperature for the mine alongside the running average value of the predicted BAC outlet temperature. The figure highlights that the daily running average of the mine's BAC outlet temperature consistently falls below the specified temperature limit, signifying that the refrigeration system can remain inactive.

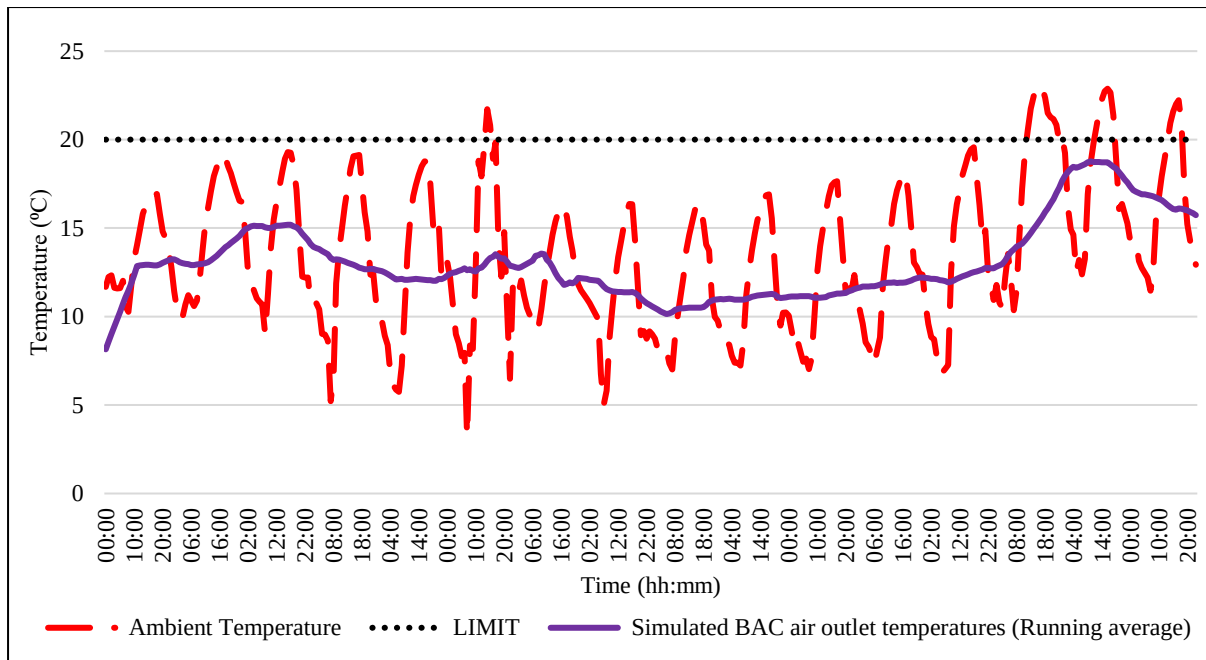


Figure 35: Simulation results for July

Upon scrutinising the data from July, it became evident that ambient temperatures were on the rise, accompanied by a steady increase in daily running average temperatures. Moving to August, a weekly simulation was conducted to determine the optimal time to initiate the refrigeration system.

Given the potential changes in August, a more thorough monitoring of weather and mine temperatures was conducted. Figure 36 depicts the weather conditions and weekly predicted mine BAC outlet air temperature.

The simulation results presented in Figure 36, specifically from the last week of August, indicate a need to activate the refrigeration systems. The daily average running BAC outlet temperature consistently surpasses the specified limit. It is recommended that the refrigeration systems be started on 22 August to ensure the safety of underground working conditions.

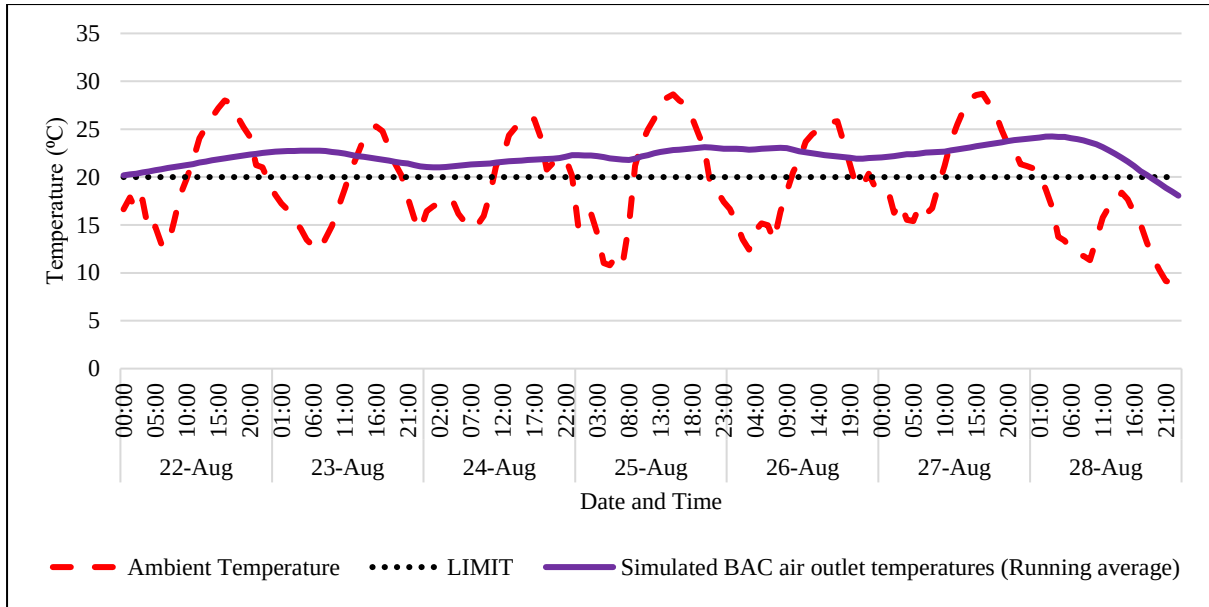


Figure 36: Simulation result 08/22 - 08/28

Figure 37 shows the simulated results from 29 August until 4 September. A cold front is observed from 27 August until 1 September. A recommendation is made for the mine to keep the refrigeration system off during a prevailing cold front, suggesting that it be activated only on 3 September. This approach aims at conserving additional energy by strategically aligning the system's operation with the prevailing weather conditions.

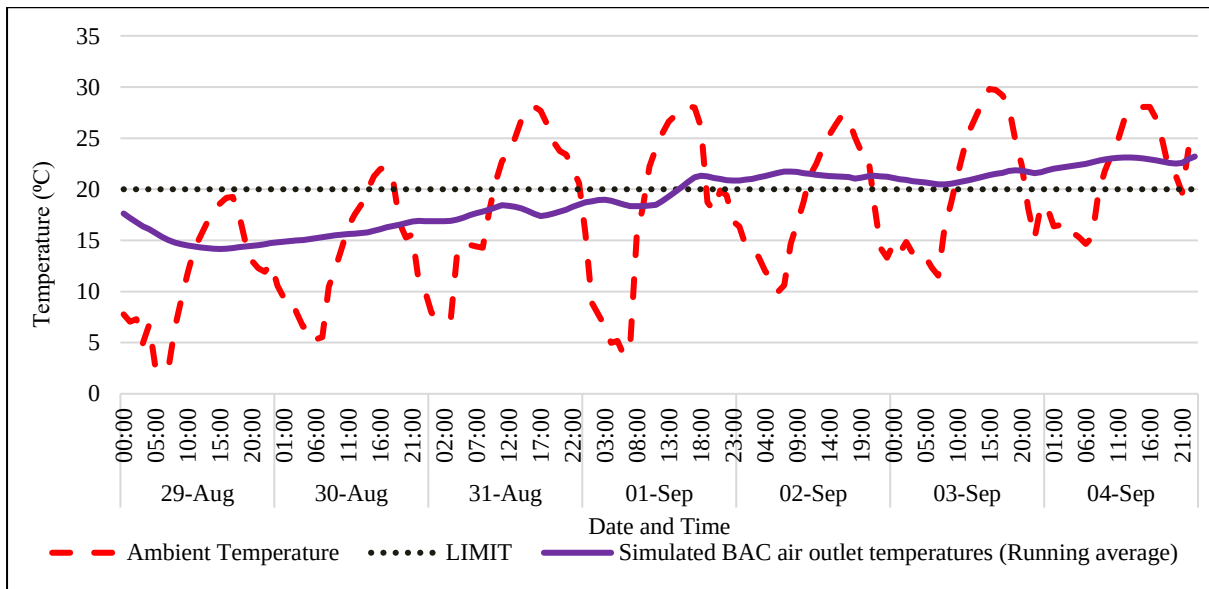


Figure 37: Simulation result 08/29 - 09/04

The results in Figure 37 show that the simulation model was utilised to test the seasonal control strategy to predict when the refrigeration system can be switched on. The simulation model also reveals the possibility of keeping the refrigeration system off for an additional week. Implementing the above simulation suggestions would lead to energy usage and costs, as shown in Table 5. The months of June and July are not included as the control strategy does not include those months.

Table 5: Simulation energy usage compared to baseline year

Month	Baseline year	Simulation results
	Energy usage (kWh)	Energy usage (kWh)
April	1 955 685	1 670 794
May	1 277 245	1 425 996
August	781 096	432 844
September	1 394 638	1 452 115
Total	5 408 663	4 981 749

This section utilised the simulation model to determine optimal times for activating or deactivating the refrigeration system based on seasonal conditions. Through the integration of forecasted weather data, the simulation indicated that the refrigeration systems could be switched off on 24 May. Additionally, the seasonal control strategy, in conjunction with the simulation model, forecasted a cold front in late August, suggesting that the refrigeration systems should only be switched on 3 September.

The implementation of the seasonal control strategy was anticipated to result in an energy usage of 4.98 GWh. A reduction of 0.43 GWh could be achieved by comparing the simulated values with the energy usage from the previous year (referred to as the baseline year in this study).

The implementation of the seasonal control strategy in the simulation indicated a reduction of R 0.8 million in electrical costs compared to what the mine would have paid if the strategy had not been implemented. The subsequent section implements the seasonal control strategy at the mine, and the ensuing results are discussed, drawing comparisons with the simulated results and the baseline year's energy usage and cost.

3.6 Step 5: Validation of Seasonal Control Strategy

3.6.1 Introduction

In Chapter 3.5, the seasonal control strategy was implemented in the simulation model to determine when the system can be switched on or off. The next step in the methodology is to validate or implement the season control strategy in a case study.

3.6.2 Implementing the Control Strategy in the Case Study

The preceding sections utilised the simulation model in tandem with the seasonal control strategy to establish optimal times for switching the system on or off. The simulation model results indicated that the refrigeration system could be switched off in the last week of May and switched on, on 3 September. The subsequent phase in the methodology involves validating the results obtained from the simulation and control strategy.

The seasonal control strategy was simulated using available forecast weather data, successfully determining the optimal time to switch off the refrigeration system in May. As depicted in Figure 24, the next step in the methodology is to implement these simulated results in the case study of the refrigeration system.

Although the control strategy was implemented to convey the optimal time for deactivating the refrigeration system to the engineering team, a lack of operational data at the mine prevented a direct comparison of simulated versus actual results. Despite this challenge, the mine acknowledged and considered the simulation results, ultimately deciding to switch off the refrigeration system on 28 May. The available data for analysis is limited to the power consumption of the refrigeration system, and the energy usage results for the strategy are presented in Chapter 3.6.

Using the simulation model and inputting weekly forecasted weather data, the simulation model determines the outlet BAC temperatures for the system. The weather forecast is systematically input into the simulation model and monitored day by day. A running average of the system-simulated BAC outlet temperature is tracked, triggering the activation of the refrigeration system if the outlet temperatures surpass the specified limit for two consecutive days.

Figure 38 below shows the predicted running average temperature of the BAC outlet temperatures, the upper limit, and the actual BAC outlet temperatures (running average) for July. The figures indicate a close alignment between the simulated values and the actual values. Moreover, the running average temperatures in July did not surpass the specified limit, affirming that the system could remain deactivated during this period.

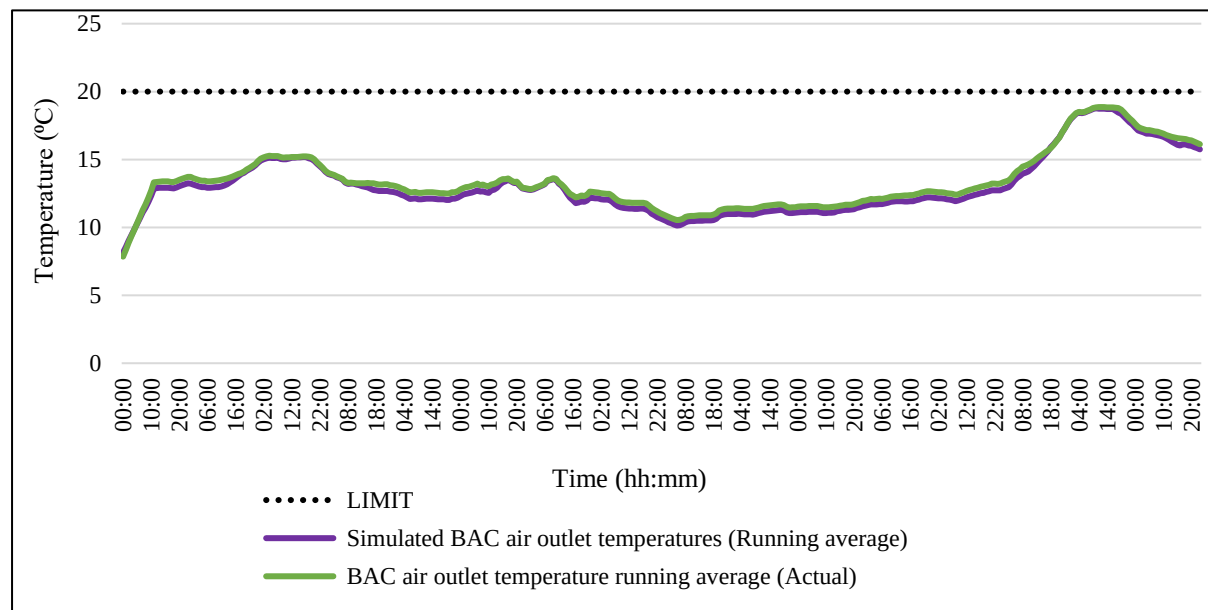


Figure 38: July simulation vs. actual results

Close monitoring of the weather forecast revealed an impending heatwave in the upcoming week. The simulation and implementation results are detailed in Appendix B, with Figure 39 illustrating the outcomes from 22 to 28 August. The simulation prediction indicates that temperatures would surpass the specified limit during that week. Consequently, the refrigeration system should be initiated on 22 August to maintain safe working temperatures underground.

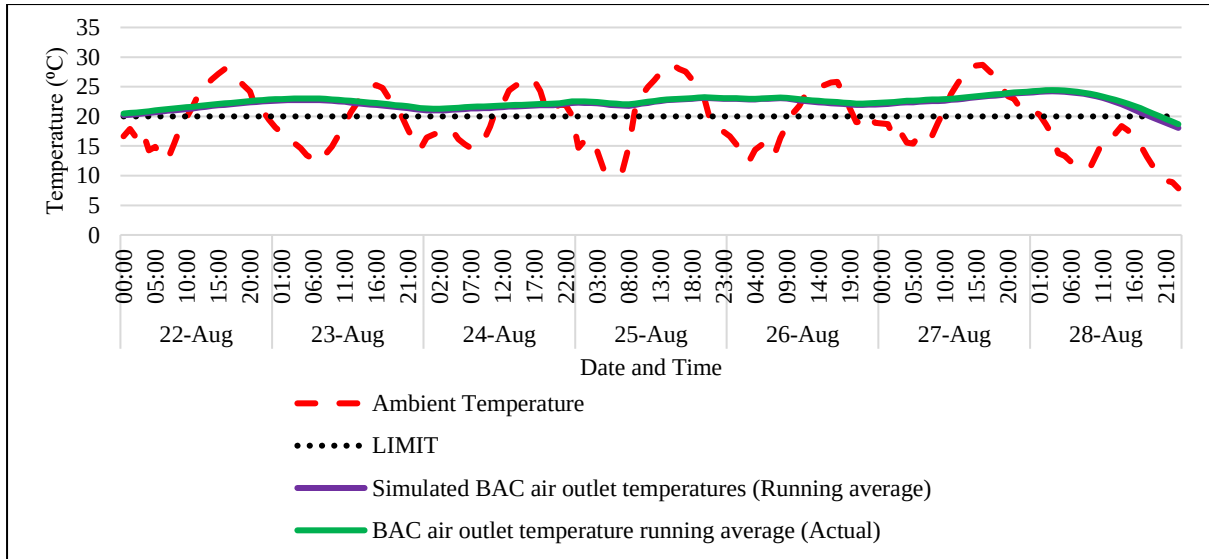


Figure 39: Simulation result 08/22 - 08/28

A recommendation was made to the mine to initiate the refrigeration system; however, it encountered multiple issues and could not be started. During the period when the system remained inactive, the weather forecast and BAC outlet temperatures were continuously monitored. The weather forecast indicated a cold front from 28 August to 1 September. Following the necessary repairs, the refrigeration system was eventually started on 3 September. Figure 40 illustrates the results for the week spanning from 29 August to 4 September.

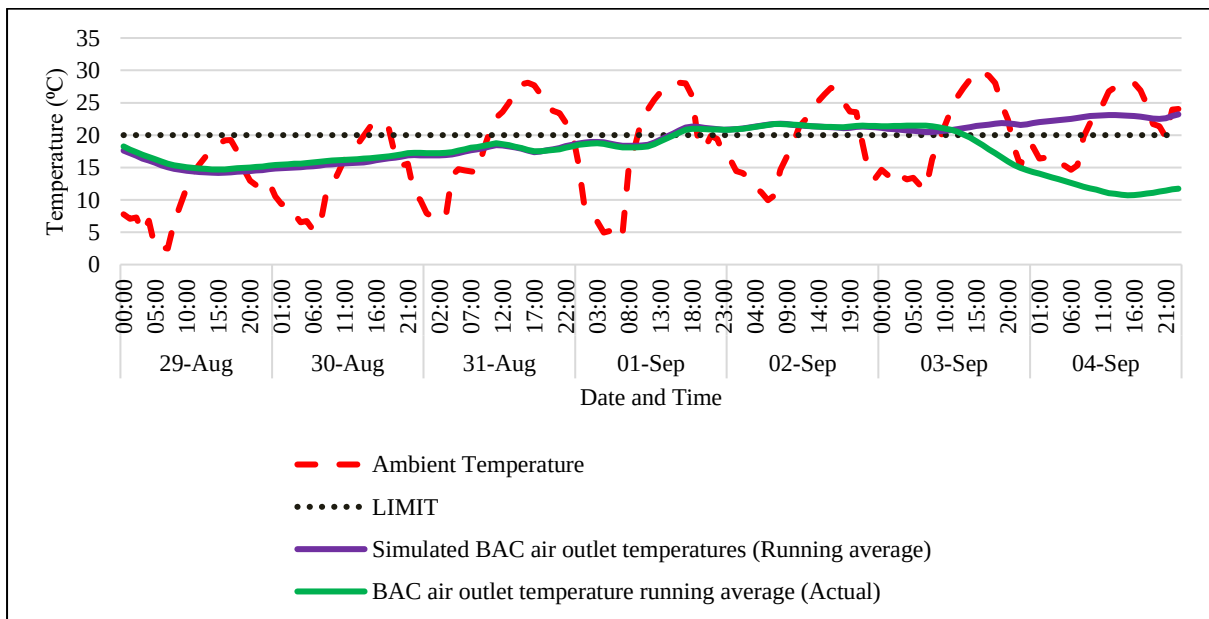


Figure 40: Simulation result 08/24 - 09/04

In this section, the simulated results of the seasonal control strategy were used to predict optimal times for switching the refrigeration system on or off, contingent on changes in ambient conditions. The results of the control strategy indicated that the system could be deactivated in the last week of May, and indeed, the mine switched off the system on 28 May.

The simulation also forecasted when the system would need to be started for the summer months. The predicted optimal time for switching on the refrigeration system was 22 August, but the mine initiated the system on 3 September. The subsequent portion of Chapter 3.6 delves into the energy savings achieved through the implementation of the seasonal control strategy.

3.6.3 Results Discussion

The study concentrates on enhancing the energy efficiency of a deep-level mine refrigeration system through the implementation of a seasonal scheduling methodology. The ensuing discussion in this section is geared towards assessing the savings derived from the application of this methodology. A comparative analysis is conducted between the energy consumption during the baseline period and the energy consumption subsequent to the project's implementation.

In the preceding sections, the seasonal control strategy delineated optimal times for switching the mine's refrigeration systems on or off. The results stemming from the implementation of the control strategy indicated that the mine deactivated the refrigeration system on 28 May and reactivated it after winter on 3 September.

As previously elucidated, the seasonal scheduling model determines when the refrigeration system(s) can be activated or deactivated based on seasonal variations. Consequently, the methodology can only yield savings during the transitional months, namely April, May, August, and September.

Table 6 juxtaposes the simulation results for energy usage and implementation results. It is discernible from the table that the simulated results closely align with the actual implementation results.

Table 6: Simulation vs Actual energy usage

Month	Simulation results	Actual results
	Energy usage (kWh)	Energy usage (kWh)
April	1 670 794	1 611 180
May	1 425 996	1 375 117
August	432 844	417 400
September	1 452 115	1 400 303
Total	4 981 749	4 804 001

The disparity in usage stems from the fact that the mine delayed switching off the refrigeration system in May, which was beyond the timeframe recommended by the control strategy. Additionally, the mine initiated the refrigeration system in September, later than advised by the strategy. The deviations in strategy and start dates were attributed to complications in the refrigeration systems.

Table 7 provides a comparison between the baseline energy usage and electricity cost years and the actual implementation results. Notably, the implemented year exhibited lower energy consumption in April compared to the baseline. This reduction in energy usage during April can be attributed to the lower ambient conditions, resulting in decreased energy requirements from the refrigeration systems.

Table 7: Baseline year vs actual implementation year's electricity usage

Month	Baseline year	Actual results
	Energy usage (kWh)	Energy usage (kWh)
April	1 955 685	1 611 180
May	1 277 245	1 375 117
August	781 096	417 400
September	1 394 638	1 400 303
Total	5 408 663	4 804 001

In May, it is evident that the baseline year exhibited lower energy usage compared to the implemented year. This reduction in energy consumption was attributed to the mine commencing maintenance earlier in the baseline year, enabling the refrigeration system to be switched off early in May.

A comparison of energy usage in August reveals that the refrigeration systems consumed less energy than the baseline year. The diminished energy consumption can be attributed to the

implementation of the seasonal control strategy, which led to a later start of the refrigeration system compared to the baseline year.

Table 8 shows the results of implementing the seasonal control strategy on the mine's refrigeration systems. The negative values in the table show that the implemented year used or cost more than the baseline year. The table shows the total energy saved by implementing the control strategy. The energy consumption was reduced from the baseline period to the actual by 0.6 GWh.

Table 8: Difference in energy usage and cost

Month	Energy usage (kWh)
April	344 504
May	-97 872
August	363 695
September	-5 665
Total	604 662

Upon scrutinising the electricity usage, it becomes evident that there was a reduction in overall energy usage. Table 9 shows the electrical tariff from Eskom for the Baseline year and the Implemented year. From the table, it can be seen that the tariff has increased significantly compared to the baseline year.

Table 9: Eskom electricity tariff comparison

Month	Baseline year (Rand)	Implementation year (Rand)	Percentage increase
April	0.96	1.42	48%
May	0.96	1.53	60%
August	1.44	3.24	125%
September	0.98	1.65	68%
Average increase			75%

The implementation of the seasonal control strategy resulted in a reduction in energy usage. However, the strategy did achieve a notable reduction in electrical costs, saving the mine of R1.19 million compared to what would have been paid without the strategy. These results substantiate that the study has the potential to bring about a reduction in energy usage and generate savings in electrical costs.

3.7 Conclusion

In Chapter 3, a case study mine was identified as a suitable candidate for implementing the seasonal control strategy. Information about the selected mine was collected, and a simulation model was developed. The model was carefully calibrated, achieving accuracy within a 5% error margin and validated against actual operational data.

The seasonal control strategy utilises the simulation model and forecasted weather data to predict the future BAC outlet temperature of the system. These temperatures are then compared to the mine's specified limits, determining whether the system should be switched on or off based on whether these limits are exceeded.

Initially, the seasonal control strategy was simulated before its implementation in the case study mine. The simulation indicated a potential reduction in energy usage of 0.4 GWh. Subsequent implementation of the seasonal control strategy in the case study resulted in an actual energy reduction of 0.6 GWh. Figure 41 provides a comparative analysis of energy usage, showcasing the baseline year, simulation results, and actual implementation outcomes.

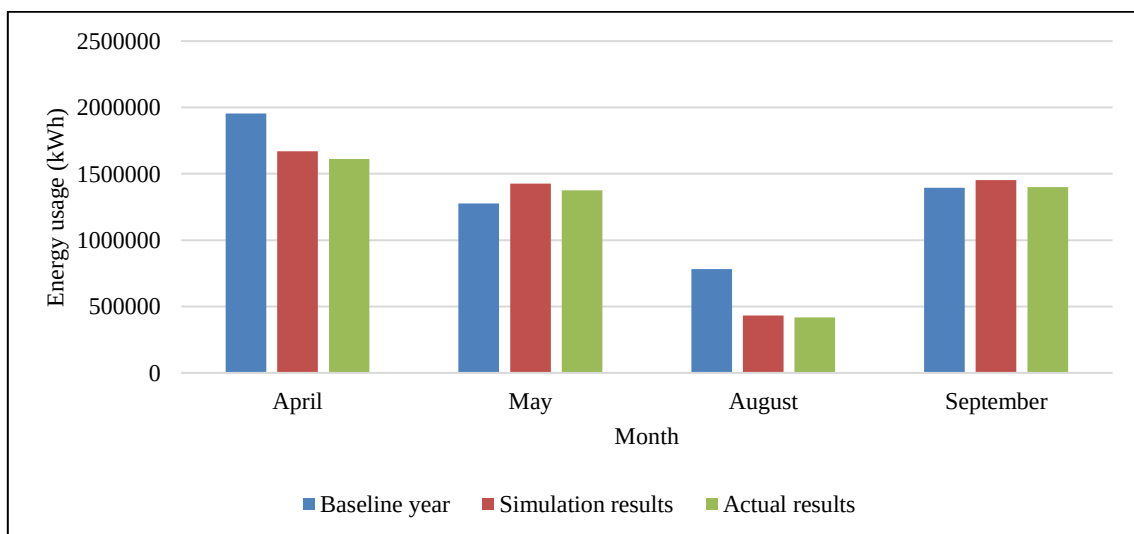


Figure 41: Energy usage results comparison

It is important to note that the mine would have spent an extra expense of R1.19 million in electrical costs if the seasonal control strategy had not been implemented. The implementation of the seasonal control strategy in deep-level platinum mines has demonstrated the potential to reduce energy consumption and increase savings in electrical costs. This strategy, as validated by the study, has successfully contributed to a reduction in energy usage and achieved financial

benefits for the mine. In this chapter, it has been confirmed that seasonal control measures can effectively lead to a reduction in energy consumption, thus enhancing both the environmental and financial aspects of the mine.

4. CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

ESG, a corporate guideline addressing environmental, social, and governance issues [1], has gained increased significance in recent years, urging companies to integrate sustainable and environmentally friendly practices into their operations [5]. Within ESG, the environmental component centres on a company's capacity to incorporate environmental protection initiatives, including strategies such as energy conservation, efficient resource utilisation, and the adoption of renewable energies and technologies [2].

The global mining sector contributes to 4% to 7% of total greenhouse gas emissions [10], prompting heightened scrutiny from investors, governments, and society, urging the sector to curtail its emissions [10]. However, the South African mining industry, characterised by its energy-intensive nature, heavily relies on coal-generated electricity [12]. South Africa possesses one of the world's most energy-intensive economies, with energy consumption per unit GDP surpassing the global average by more than double [15]. Consequently, this study directs its focus on mitigating carbon emissions in South African mines by leveraging energy-saving initiatives.

Among the heaviest power users in one of South Africa's deep-level platinum mines were the mine cooling systems. An investigation into these systems revealed numerous studies addressing energy-saving measures. However, it was observed that historical energy-saving initiatives did not emphasise a winter control philosophy to capitalise on cold ambient WB temperatures during seasonal changes. Consequently, leveraging cold ambient conditions during seasonal transitions was identified as an effective means to reduce the energy usage of mine cooling systems and lower overall energy consumption.

This research aimed at developing and simulating an optimised seasonal control method for deep-level platinum mine refrigeration systems, with a primary focus on enhancing the performance of mine cooling systems in terms of cost savings and efficient cooling across seasonal variations.

The seasonal control strategy, tested on a platinum mine's refrigeration system, operates solely based on switching the system on or off in response to seasonal ambient weather conditions, particularly targeting the months of April, May, July, and August. Utilising PTB software, the strategy employs a simulation model that is both built and calibrated to real operational conditions. Initial input of forecasted weather data into the simulation predicts the future output parameters of the refrigeration system.

Investigations on the refrigeration system delineated key limits, with the BAC outlet air temperature being the vital parameter for the systems under consideration. Implementation of the seasonal control strategy allowed the mine to delay switching on the refrigeration system after winter, resulting in a 0.6 GWh energy saving compared to the baseline year. The control strategy reduced the overall electricity cost the shaft would have paid by R1.19 million.

The strategy empowers deep-level platinum mines to exercise more control over when refrigeration systems are activated, not only leading to energy savings but also enhancing safety by ensuring consistent working conditions throughout the year. However, the strategy did not yield a reduction in the mine's overall operational cost due to increased electricity tariffs, although it did mitigate the impact of the tariff increase.

This cost-effective strategy achieved its objective without requiring any capital for implementation. It successfully determined the optimal times for switching off refrigeration systems based on changes in seasonal conditions, reducing energy usage for deep-level platinum mines. The strategy successfully achieved the study objectives by implementing a cost-effective way to improve the seasonal scheduling of the deep-level platinum mine's refrigeration system, determining when the system can be switched on or off based on seasonal changes.

4.2 Recommendations for Future Studies

The implemented seasonal control strategy has proven successful in reducing energy consumption and carbon emissions. However, there is room for further improvement and exploration of potential enhancements.

The following recommendations are proposed for consideration:

- Implement the seasonal control strategy to determine when individual auxiliaries of the refrigeration system can be switched on or off based on seasonal changes.
- Investigate a way to simulate live data on the SCADA systems so that the operators and the engineers monitor future parameters.
- Investigate how accurate forecasted weather data is.
- To enhance the scope of this study, I propose the installation of temperature and humidity meters in strategic underground locations within the mine. This addition aims at providing a more accurate and comprehensive representation of the conditions underground when there are temperature fluctuations on the surface. The data collected from these underground meters would offer valuable insights into the localised effects of temperature changes, allowing for a more nuanced understanding of the environmental dynamics within the mine.

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6. APPENDIX

1. Appendix A: Simulation Results

Figure 42 shows the simulated results. It is clear that the refrigeration system is still operating above the temperature limit of the system. No change was required.

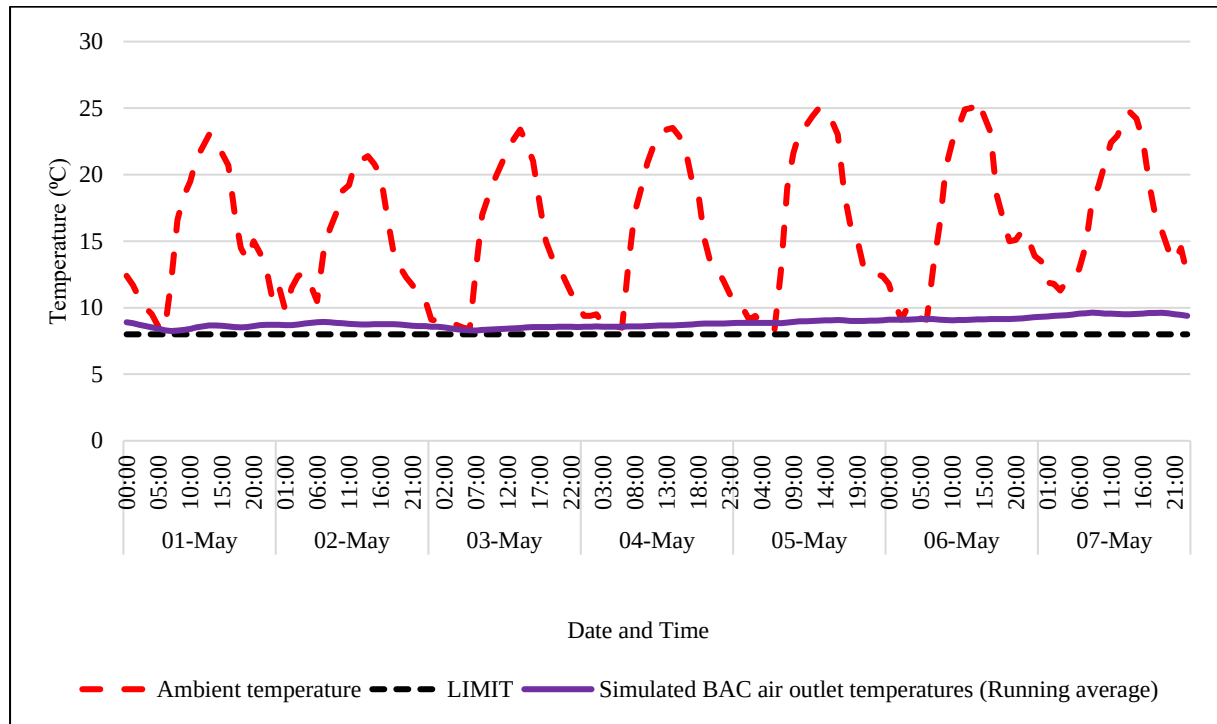


Figure 42: Simulation result 05/01 - 05/07

Following the initial week of May, the forecasted weather data for the period from 8 to 14 May was acquired and applied to the simulation model. The simulation of these forecasted values yielded the results depicted in Figure 43. Once again, the running average BAC outlet temperature is observed to be within the acceptable limit. Therefore, no adjustments to the system are deemed necessary based on these results.

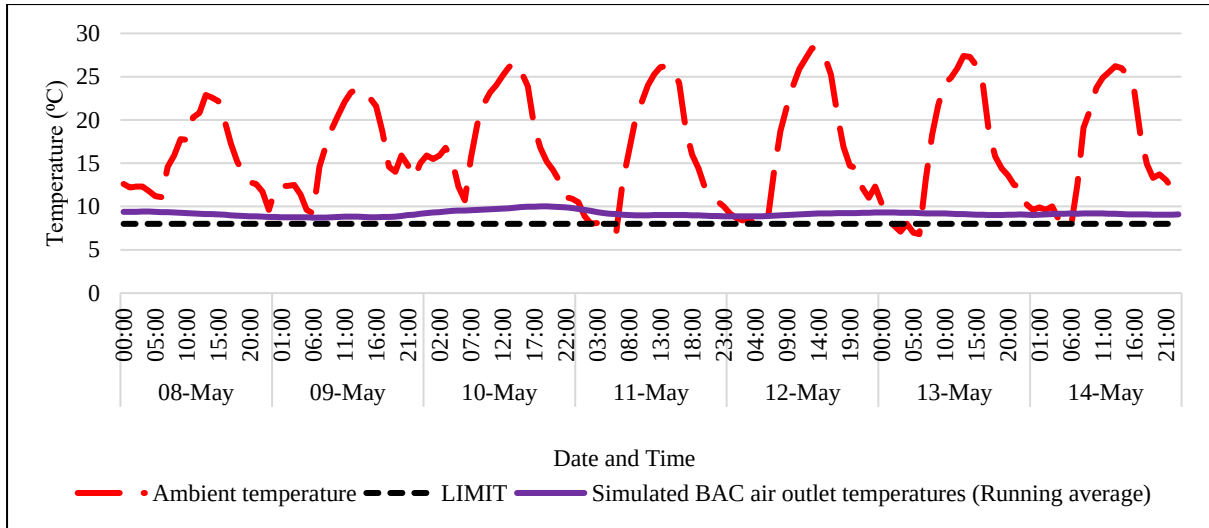


Figure 43: Simulation result 05/08 - 05/14

During the week from 15 to 21 May, the simulation model utilised forecasted weather data to predict BAC outlet temperatures, as illustrated in Figure 44. The results indicate that the running average BAC outlet temperature is approaching the specified limit. The system is nearing the threshold where it can be considered for activation.

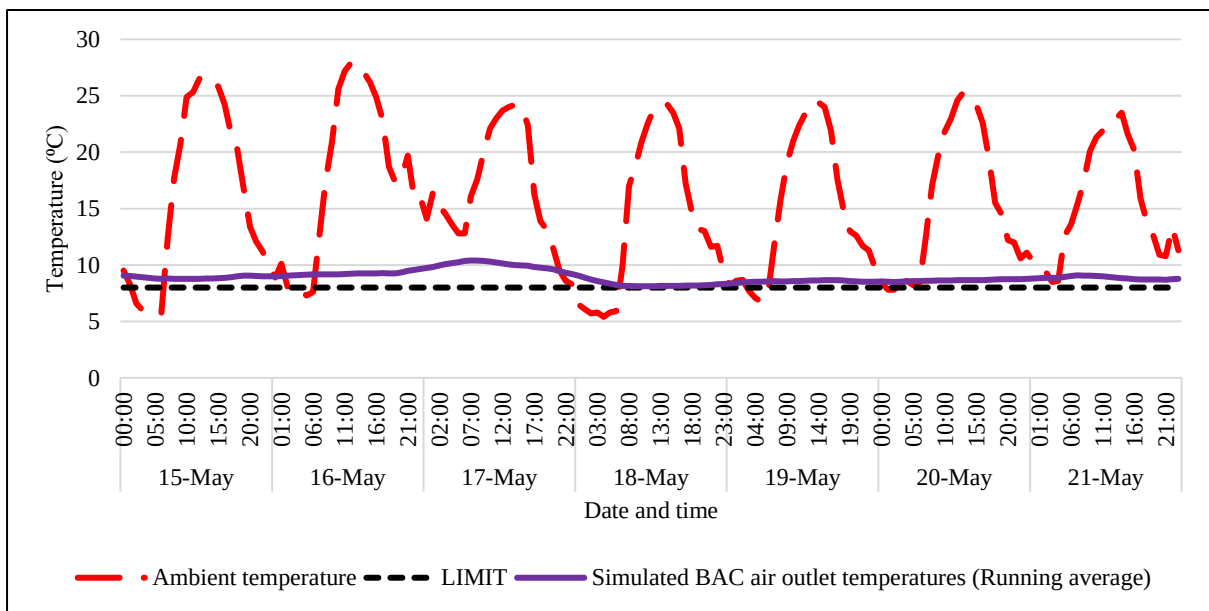


Figure 44: Simulation result 05/15 - 05/21

Figure 45 shows the weather and simulation results for the first week of August. The figure shows that the daily running average temperature is still below the limit.

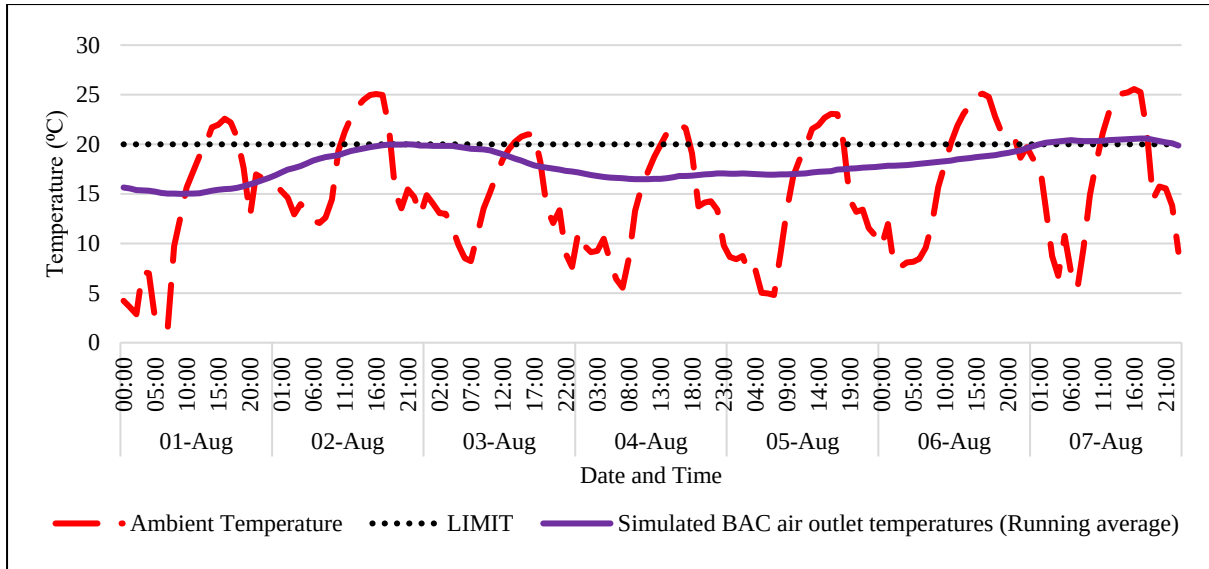


Figure 45: Simulation result 08/01 - 08/07

Figure 46 illustrates the weather conditions and simulation results for the second week of August. The daily running average temperature remains below the specified limit. Although two days exceeded the temperature limit, it was not deemed necessary to initiate the refrigeration system since the limit was not surpassed for two or more consecutive days.

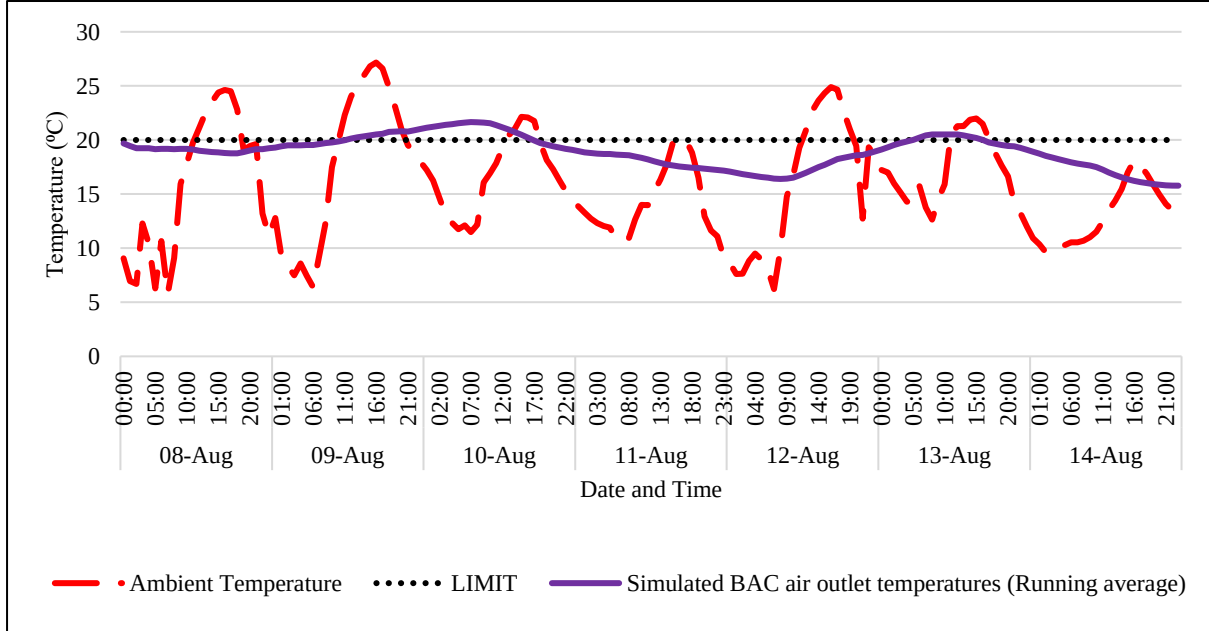


Figure 46: Simulation result 08/08 - 08/14

Figure 47 shows the weather and simulation results for the third week of August. It can be seen from the results that the temperatures are on the temperature limit.

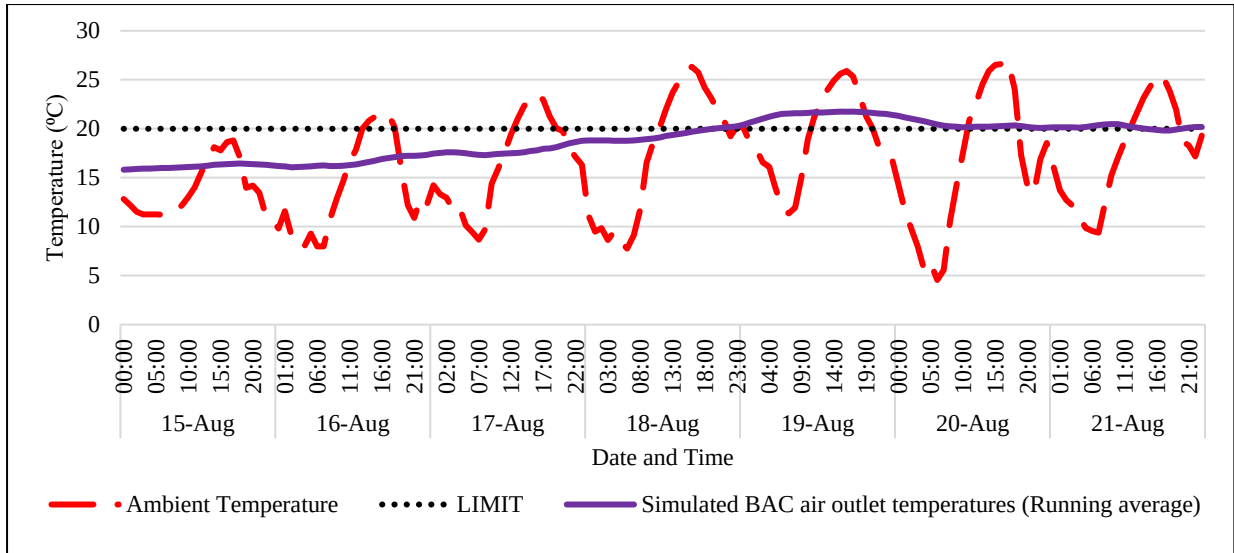


Figure 47: Simulation result 08/15 - 08/21

2. Appendix B: Implementation of Seasonal Control Strategy Results

Figure 48 shows the results of the first week of August (08/01 until 08/07). Monitoring the temperatures showed that the running average temperatures neared the limit line. Therefore, the temperature was monitored closely to ensure the system was switched on to keep mining conditions safe. It was found that the temperature was still under the limit, and the system could remain off.

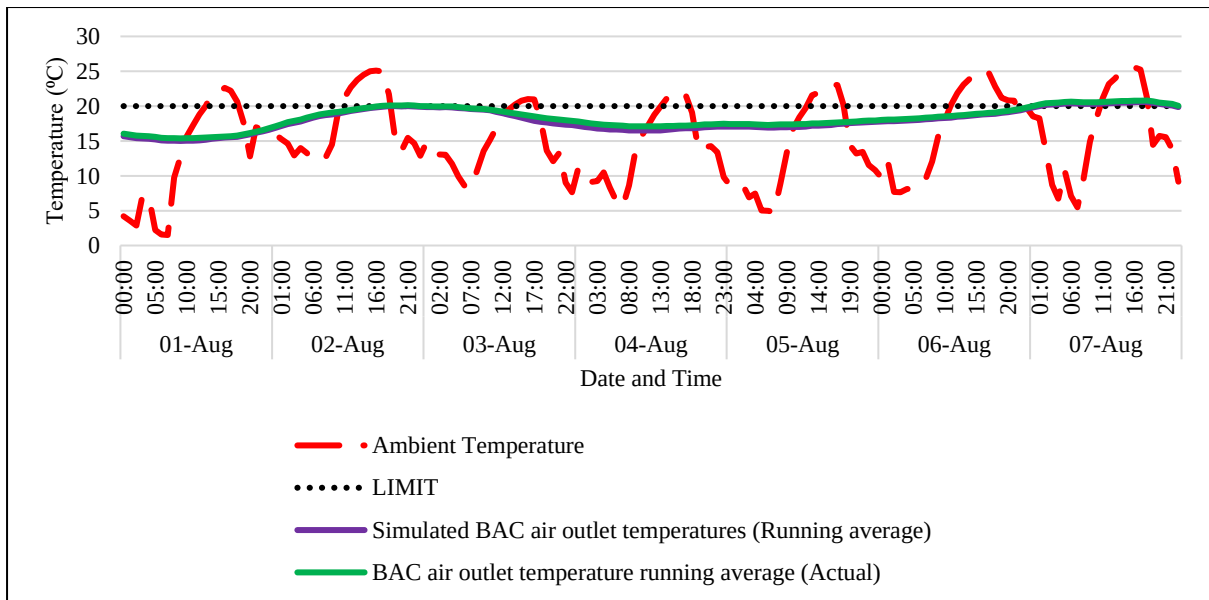


Figure 48: Simulation result 08/01 - 08/07

Figure 49 presents the results for the week spanning from 8 to 14 August. Upon examination, it is evident that the running average remained below the limit for two consecutive days. Consequently, there is no requirement to initiate the system at this point.

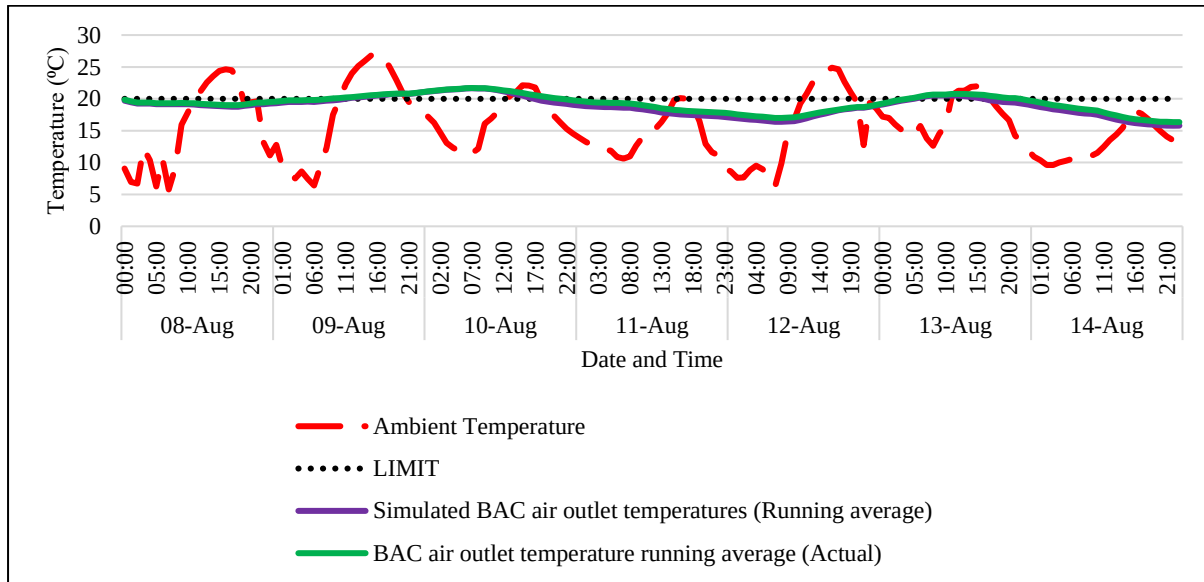


Figure 49: Simulation result 08/08 - 08/14

Figure 50 shows the results from 15 to 21 August. It can be seen that the limit is extended for more than one day.

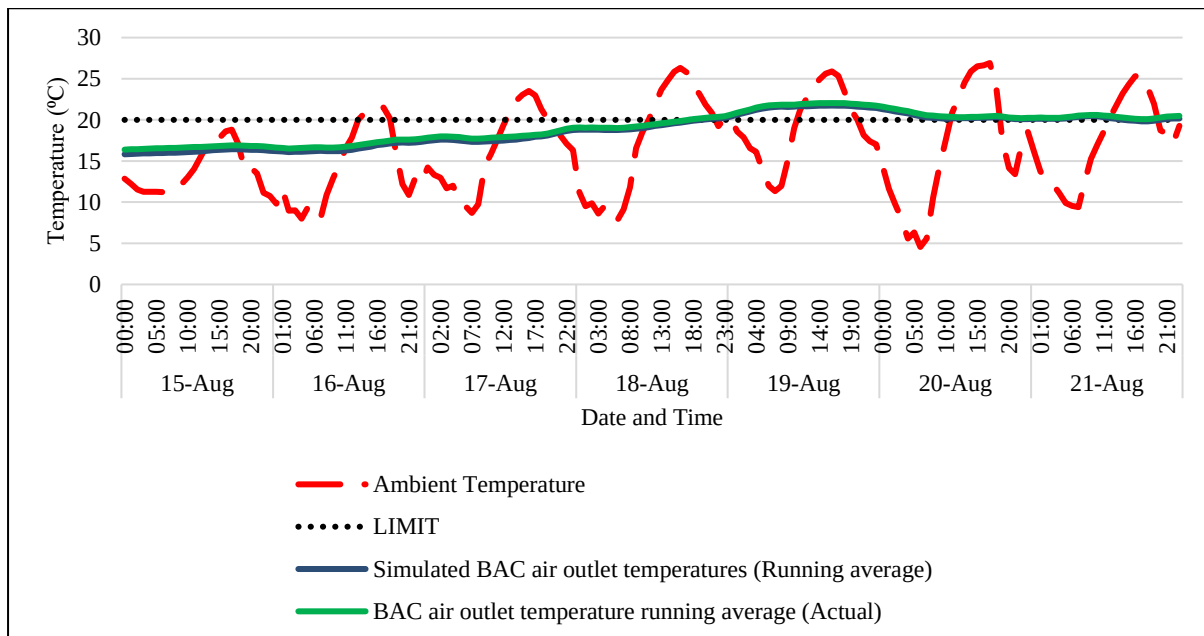


Figure 50: Simulation result 08/15 - 08/21