



A simulation-based method to optimise ice plant production in deep-level mines

H Meyer

 [orcid.org/ 0000-0003-1195-6705](https://orcid.org/0000-0003-1195-6705)

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

Supervisor: Dr JC Vosloo

Graduation: May 2026

ABSTRACT

Deep-level mines have large heat loads and as the depth and scale of the mine increases, so do the heat loads. Artificial cooling methods are introduced to keep mines below the legal wet-bulb temperature limit of 32.5 °C. One artificial cooling technique involves utilising ice plants to supply a steady flow of ice into the mine. These ice plants are typically employed in mines surpassing depths of 2 000 m.

Ice manufacturing plants on deep-level gold mines lose efficiency over time, and due to their complexity, it is difficult to identify the causes. Ice plants will therefore have lowered production, which reduces their overall cooling capacity. A method to identify and solve these problems is crucial in increasing the cooling capacity of ice plants, which is essential in mitigating the rising heat loads encountered in deep-level mines.

The method was constructed and tested by making use of a case study methodology. Initially, a method based on literature was created and tested on an ice plant network. Thereafter, improvements were made by including a simulation model, facilitating more precise problem identification.

By using this refined method, a bottleneck in the water chilling phase was identified on a case study. Addressing this inefficiency is anticipated to yield an ice production increase of 15.8% on Mine A, which is an annual energy value of R 5.03 million. When extrapolated to Mine B, an annual energy saving of up to R 15.09 million could be expected.

The method serves as an investigative tool for pinpointing inefficiencies within an ice plant network, which enables potential resolutions to increase ice production.

Keywords: Ice plant optimisation, deep-level gold mining, ice plant simulation, refrigeration network, simulation method.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank the Lord for blessing me with the opportunity, strength, and talents to complete this dissertation. Without His guidance and grace, this achievement would not have been possible.

My sincere thanks also go to ETA Operations for granting me the opportunity to pursue this work and for their continuous support throughout this journey.

I would like to express my deepest appreciation to my supervisor, Jan Vosloo, for his invaluable expertise and steady encouragement, which have been instrumental in shaping this research.

I am equally thankful to my co-supervisor, Jean van Laar, for consistently offering thoughtful advice and providing steadfast support throughout every stage of my thesis journey.

I would like to thank iSprout for their support in my final year of study which allowed me to complete this thesis.

Finally, I extend my heartfelt gratitude to my family and friends for their love, understanding, and encouragement, which have been a constant source of strength.

DEDICATION

I dedicate this thesis to my loving wife for her unwavering love, patience, and constant support. Without your encouragement and understanding, I could not have come this far.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	I
ABSTRACT	I
DEDICATION	I
TABLE OF CONTENTS.....	IV
LIST OF FIGURES.....	VII
LIST OF TABLES	X
LIST OF SYMBOLS	XI
LIST OF EQUATIONS	XI
LIST OF ABBREVIATIONS	XI
CHAPTER 1 INTRODUCTION.....	1
1.1 Preamble	1
1.2 Gold mining in South Africa	1
1.3 Deep-level mining and cooling	5
1.4 Ice plants on deep-level mines	6
1.5 Simulations in mining	9
1.6 Problem statement	11
1.7 Aim & Objectives	11
1.8 Research methodology	12

1.9	Outline of the Dissertation	13
CHAPTER 2 LITERATURE.....		15
2.1	Preamble	15
2.2	Deep-level mine cooling systems.....	15
2.3	State-of-the-art matrix	28
2.4	State-of-the-art literature review summary	37
2.5	Summary	39
CHAPTER 3 METHOD CONSTRUCTION		41
3.1	Preamble	41
3.2	Develop method.....	41
3.3	Step 1: Investigation.....	43
3.4	Step 2: Simulation	46
3.5	Step 3: Solution development	48
3.6	Step 4: Solution implementation	51
3.7	Step 5: Evaluation	52
3.8	Summary	53
3.9	Method verification.....	55
3.10	Conclusion.....	55
CHAPTER 4 CASE STUDY AND RESULTS		56
4.1	Preamble	56
4.2	Case study background	56

4.3	Step 1: Investigation.....	58
4.4	Step 2: Simulation	66
4.5	Step 3: Solution development	69
4.6	Step 4: Solution implementation	84
4.7	Step 5: Evaluation	84
4.8	Limitation of the case study	87
4.9	Method Validation.....	87
4.10	Conclusion.....	91
CHAPTER 5: CONSLUSION		92
5.1	Preamble	92
5.2	Conclusions.....	92
5.3	Recommendations.....	94
5.4	Reflection on method and objectives.....	96
REFERENCES.....		98

LIST OF FIGURES

Figure 1-1: The GDP contribution of the mining industry compared with number of people employed [4]	1
Figure 1-2: South African gold production [4].....	2
Figure 1-3: Operating expenses in mining 2023 [8]	2
Figure 1-4: Cooling hierarchy based on depth of mine [23].....	4
Figure 1-5: Schematic diagram of ice forming on a plate ice maker [48]	7
Figure 1-6: Cost comparison of chilled water vs ice systems [23]	8
Figure 1-7: Publications of simulation research from 2001 to 2021 [54].....	9
Figure 1-8: Simulation based studies for deep level mines [55]	10
Figure 1-9: Case study methodology research process [20],[21],[22]	12
Figure 1-10: Case study research methodology process relating to dissertation chapters	13
Figure 2-1: Analyse literature section in research process.....	15
Figure 2-2: Simplified diagram of deep-level mine cooling network [36].....	17
Figure 2-3: Vapour-compression cycle for a refrigeration plant (Adapted from [70])	19
Figure 2-4: Mine water consumption during different shifts [36]	21
Figure 2-5: Cross-section of a settler [37]	22
Figure 2-6: A schematic layout of a typical direct-contact force-draught cooling tower [74].....	23
Figure 2-7: Schematic of an evaporative condenser [75].....	24
Figure 2-8: Diagram of a vertical- and crossflow BAC [15].....	25
Figure 2-9: Simplified diagram of a cooling car [34]	26
Figure 2-10: Average chill dam temperature [39]	29

Figure 2-11: BAC outlet air temperature during summer months [85]	30
Figure 2-12: Increase of condenser outlet temperature due to fouling over time [86].....	32
Figure 3-1: Develop method step in the research process.	41
Figure 3-2: Proposed method to optimise ice production in deep-level mines using simulation.....	42
Figure 3-3: Proposed investigation step	43
Figure 3-4: Proposed simulation step	46
Figure 3-5: Visualisation of the baseline ice plant simulation model in PTB	48
Figure 3-6: Proposed solution development step.....	49
Figure 3-7: Proposed solution implementation step	51
Figure 3-8: Proposed evaluation step	52
Figure 3-9: Full diagram of proposed method	54
Figure 4-1: Case study implementation, evaluation and improvement stage in research process.	56
Figure 4-2: Average daily ice production per month for the KTI ice plant.....	57
Figure 4-3: Diagram of Mine A's KTI ice plant network	58
Figure 4-4: Side view of KTI ice plant on Mine A	60
Figure 4-5: Simplified diagram of ice plant unit's top container and condenser	60
Figure 4-6: Simplified diagram of ice plant unit's bottom two containers	61
Figure 4-7: PTB component calibration simulation.....	67
Figure 4-8: PTB chiller specifications menu.....	67
Figure 4-9: Comparison between average daily ice production and water inlet temperatures for KTIs	69

Figure 4-10: Comparison between average KTI water inlet temperature and daily ice production	70
Figure 4-11: Running status comparison between KTI 1-4 and KTI 5,7-9.	71
Figure 4-12: Comparison between compressor running status and daily ice production	72
Figure 4-13: Chiller 1 and 2 average performances	75
Figure 4-14: Average water inlet flow rates for Chillers 1 and 2	76
Figure 4-15: Diagram illustrating option 1's leak water rerouting.....	77
Figure 4-16: Diagram illustrating option 2's leak water rerouting.....	78
Figure 4-17: KTI network diagram with chiller rerouting	79
Figure 4-18: Effect of various solutions on KTI inlet temperature	83
Figure 4-19: KTI ice plant production after solution implementation.....	85
Figure 4-20: KTI average inlet temperature comparison after leak water rerouting	85
Figure 4-21: Results comparison between present study and previous studies	91

LIST OF TABLES

Table 2-1: State-of-the-art literature search keyword combinations.	28
Table 2-2: State-of-the-art summary.....	38
Table 2-3: Legend for state-of-the-art matrix	38
Table 3-1: Method criteria verification.....	55
Table 4-1: Legend for Figure 4-3.....	59
Table 4-2: Technical data for KTI ice makers and chillers.....	63
Table 4-3: Available data sets from Mine A's SCADA system.....	64
Table 4-4: Manual measurements taken on Mine A.....	64
Table 4-5: KTI water inlet flow comparison between SCADA data and spot check data.	65
Table 4-6: Simulated chiller output verification	68
Table 4-7: Simulated KTI input verification	68
Table 4-8: Statistical summary of inlet temperature vs ice production.....	70
Table 4-9: Statistical summary of running status vs ice production.....	72
Table 4-10: Chiller 1 outlet temperature compared with KTI inlet temperatures.....	73
Table 4-11: KTI compressors running hours.....	74
Table 4-12: Chiller duty on KTI inlet water	83
Table 4-13: Expected ice production for different scenarios	86
Table 4-14: Actual inlet temperatures compared to simulated temperatures after implementation.....	87
Table 4-15: Study objectives validation	88
Table 4-16: Result comparison to previous studies	90

LIST OF SYMBOLS

R^2	Coefficient of determination	-
σ	Standard deviation	-
Q	Dynamic cooling duty	MW
m	Mass flow	kg/s
C_{pw}	Specific heat capacity of water = 4.184	kJ/kg°C
T	Temperature	°C

LIST OF EQUATIONS

$$\text{Ice Production} = -40.82 \cdot T + 1609.8 \quad (4.1)$$

$$\text{Ice Production} = 149.29 + 1321.09 \cdot \text{Running Status} \quad (4.2)$$

$$Q = \frac{(m_1 + m_2) \cdot C_{pw} \cdot \left(\frac{T_1 + T_2}{2} - T_o \right)}{1000} \quad (4.3)$$

LIST OF ABBREVIATIONS

BAC	Bulk Air Cooler
CFPP	Coal-Fired Power Plants
DSM	Demand-Side Management
GDP	Gross Domestic Product
GPSS	General Purpose Simulation System
PCT	Pre-Cooling Towers
KTI	Plersch Kältetechnik (Plersch refrigeration technology)
PRV	Pressure Reducing Valve
PTB	Process Toolbox
SCADA	Supervisory Control and Data Acquisition
SP	Spindle Pump

CHAPTER 1 INTRODUCTION

1.1 Preamble

This chapter opens with the background to give context for the study presented. The problem statement is then discussed, followed by the objectives required to complete the study, and the research methodology used. The chapter concludes with the outline of this document.

1.2 Gold mining in South Africa

Gold was first discovered in South Africa in 1884 in the Witwatersrand Basin [1]. This ore body holds the world's largest gold reserve and has produced an estimated 50% of all gold that is accounted for today [2]. Soon after the discovery, the first large-scale gold mining company was formed in 1886 [3]. Since this discovery, gold mining has contributed significantly to the South African economy.

In 2024, the mining industry contributed 6% of the national Gross Domestic Product (GDP) and had over 470 000 employees [4]. Figure 1-1 gives a graph of the number of people employed by the mining industry and the contribution towards the South African GDP.

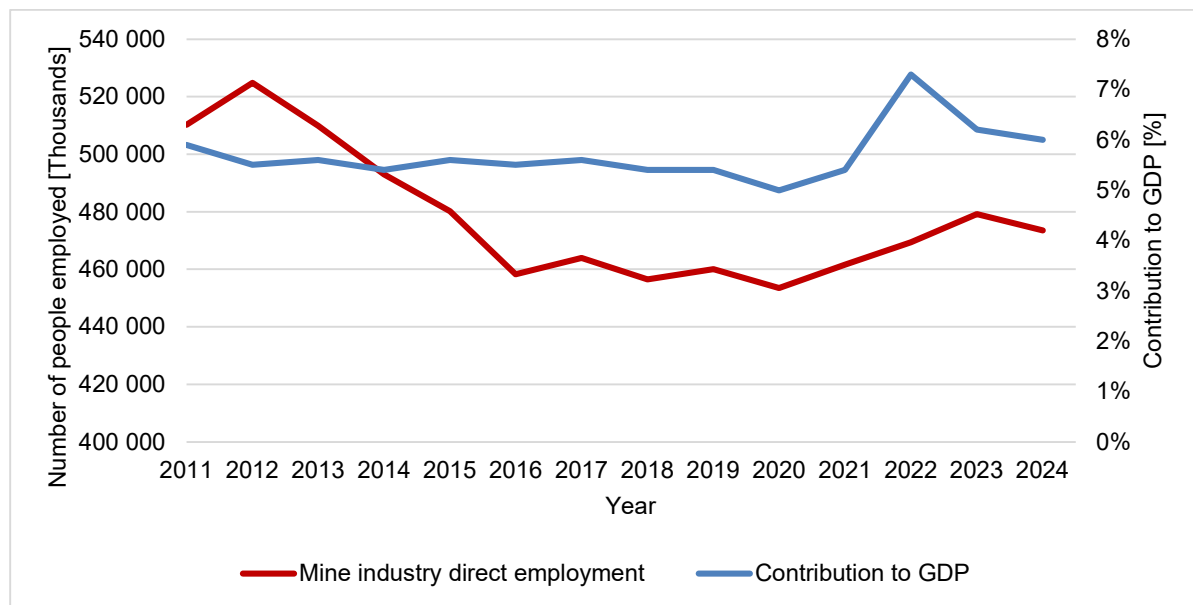


Figure 1-1: The GDP contribution of the mining industry compared with number of people employed [4]

South Africa was a world leader in gold production for several years. Its peak gold production was 1 000 tonnes in 1970 [5]. In 2023, South Africa has dropped down to 11th place among gold-producing countries [6]. Figure 1-2 illustrates South Africa's declining gold production. This is caused by the reduction of easily accessible gold reserves and the increase in cost associated with deeper mining operations [7].

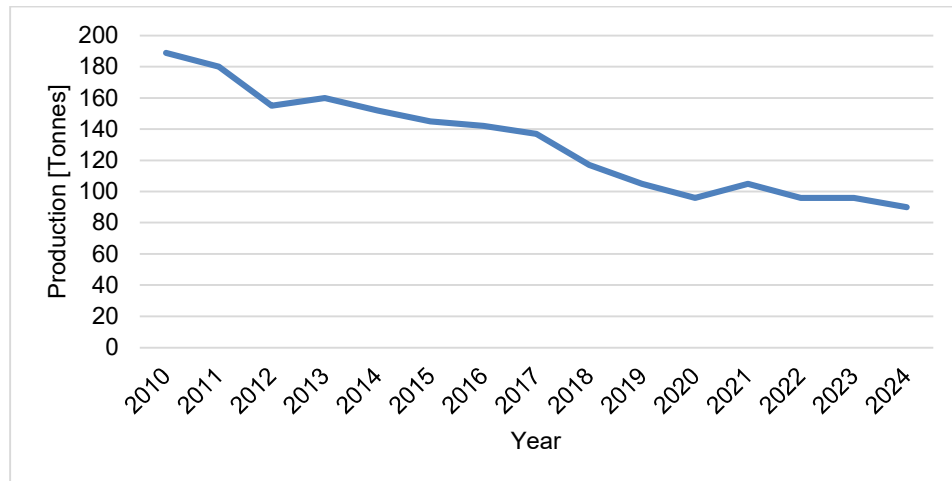


Figure 1-2: South African gold production [4]

Gold mining is a resource intensive endeavour. Figure 1-3 illustrates the operating expenses of mines in 2023. Employee benefits and contractors account for the majority of the operating expenses. This is a decrease from 38% to 33% when compared to 2022 [8], [9]. South African mines are influenced by mining labour unions. Unionised miners demand higher wages, using strikes which forces mines to retrench many workers to compensate for the increased costs [10]

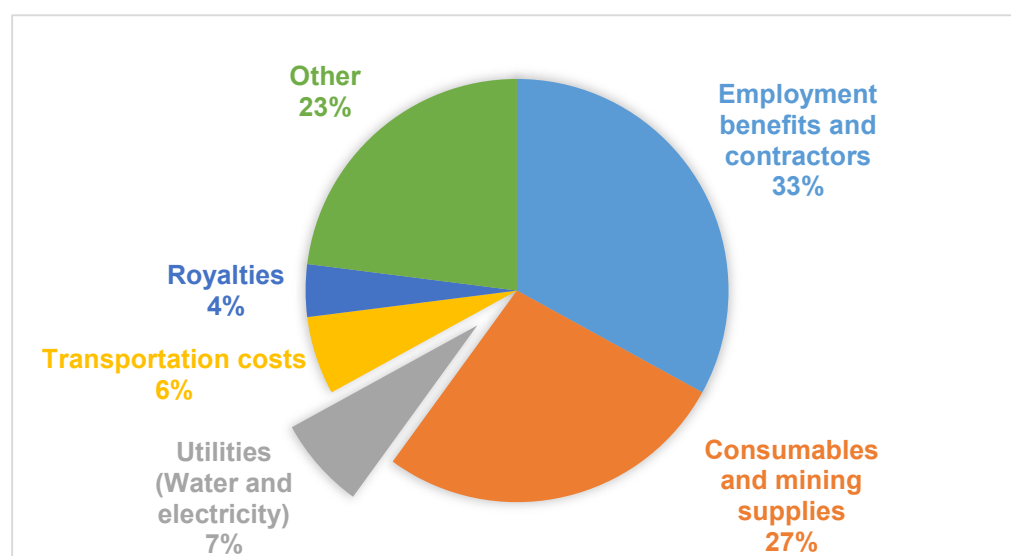


Figure 1-3: Operating expenses in mining in 2023 [8]

The second largest operating expense in mines are consumables and mining supplies, as shown in Figure 1-3. From 2022 to 2023, this percentage has decreased slightly by 1%.

Another significant operating expenditure is utilities, like water and electricity. This expense has seen a 1% decrease compared to the previous year. Eskom has implemented tariff increases throughout the recent years [11]. This increase has incentivised mines to implement electricity saving projects [11], [12]. However, further potential for savings exists.

Mines often attribute more than 20% of their electricity usage to cooling [13], [14]. As mines are expected to expand with time, their cooling needs will also increase. Mines can potentially reap a significant cost-saving benefit by reducing their cooling system energy usage [15].

Despite the high cost associated with cooling, the cooling systems are largely unoptimised. This misuse is commonly due to underdeveloped maintenance plans, incorrect operating conditions, or inefficient infrastructure layouts. Identifying these problems can be challenging due to the scale and complexity of these systems. These problems only worsen as mines get deeper and heat loads increase [16].

As gold mines get deeper, the ambient temperature will also increase. This increase is caused partly by higher virgin rock temperatures, which can reach temperatures as high as 60 °C at the average gold mining depth of 2 000 m [17]. Another contributing factor on the ambient temperature of deep-level mines is auto-compression [18]. Auto-compression causes the ventilated air to increase in temperature due to increasing pressure as it descends the mine [19].

These factors, among others, lead to extreme temperatures in deep-level gold mines. Ventilation and cooling systems are used in mines to keep ambient wet bulb temperatures below the legal limit of 32.5 °C [20], [21]. As mines get deeper and bigger, more powerful and complex cooling methods are employed as shown in Figure 1-4.

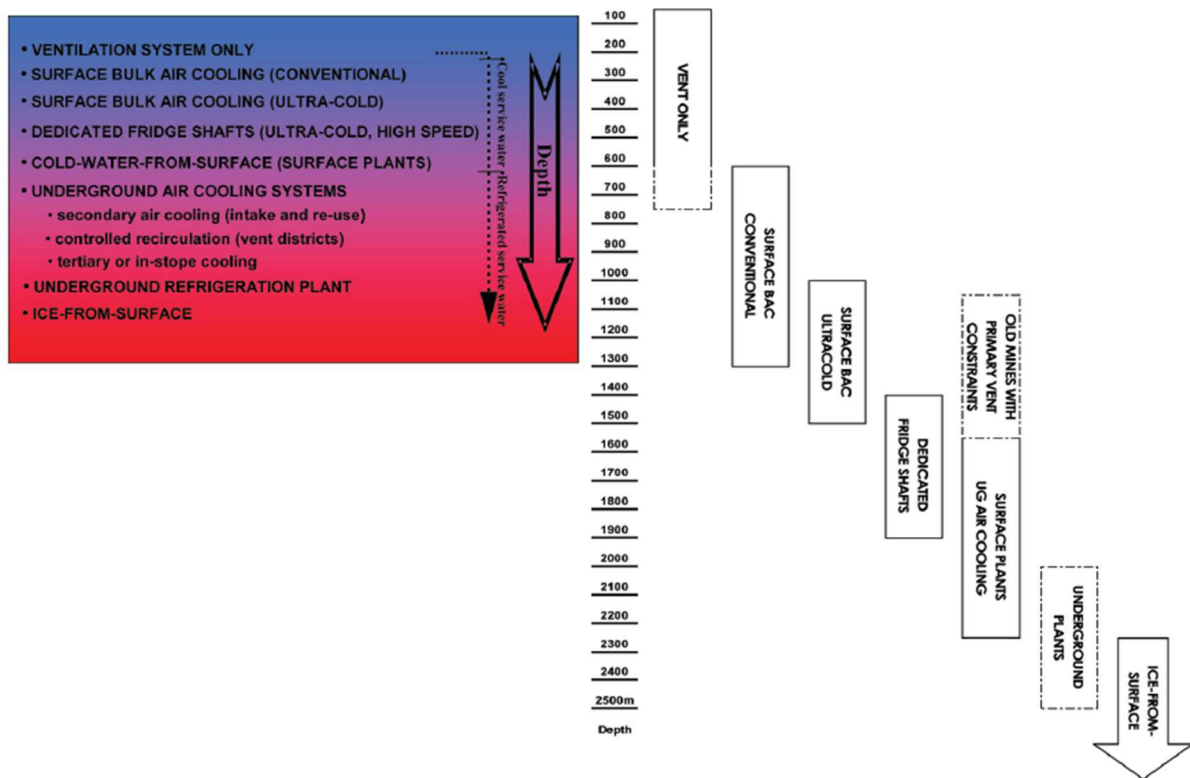


Figure 1-4: Cooling hierarchy based on depth of mine [23]

Figure 1-4 illustrates that an increase in depth leads to an increased need for cooling systems. The complexity and size of these systems will increase with the cooling requirements. The size and complexity of these cooling systems allow oversight in maintenance and incorrect operation of components in the system [22].

This results in mines operating their cooling systems with inefficiencies that they are not aware of, which can have a significant financial impact on the mine as more energy is used to reach their cooling quotas. Additionally, mines with constrained cooling might not reach their cooling targets.

Mines with extreme depths, starting at 2 000 m, make use of ice supplied from surface ice plants to achieve the required cooling [24], [25]. This is a very expensive method for cooling and is only viable in ultra-deep mines due to their reduced pumping costs [24], [25]. Before going into the benefits and structure of an ice plant network on a mine, the general goals of cooling in a deep-level mine are discussed.

1.3 Deep-level mining and cooling

Deep-level gold mines in South Africa face extreme thermal challenges due to a combination of geothermal heat, auto-compression of air as it descends, and heat generated by mining equipment [23], [26]. Without effective cooling, underground conditions quickly exceed safe working limits, making cooling systems an essential component of modern mining operations [15], [27].

The main objectives of a cooling system are to:

- **absorb heat** underground using chilled water or ice, removing unwanted thermal loads from working areas [23];
- **reject heat** at surface through cooling towers or upcast shafts [28], [29] ;
- **provide chilled supply** via refrigeration or ice plants, ensuring the cooling medium reaches sufficiently low temperatures [30], [31], and
- **store cooling capacity** in chilled water dams to balance fluctuations in daily demand [25], [32], [33].

The type of cooling required is strongly dependent on mine depth. At moderate depths (~600–800 m), ventilation and surface bulk air coolers (BACs) are often sufficient [23], [25]. Deeper mines (1 300–1 800 m) experience greater heat loads, requiring secondary cooling such as underground BACs [23]. Below 1 500 m, tertiary cooling systems like cooling cars and spot coolers provide localised cooling close to active faces [34]. At ultra-deep levels (>2 000 m), ice plants become necessary due to their ability to transport large amounts of cooling efficiently to depth, where the ice melts into chilled water [24], [25].

To achieve these objectives, deep-level mines employ a range of interconnected components, typically including refrigeration plants or ice plants, chilled water dams for storage, settlers for water treatment, pumps for circulation and dewatering, and cooling towers for heat rejection [23], [35], [36], [37]. Together, these systems form complex cooling networks that require careful monitoring and optimisation to operate effectively and cost-efficiently [36], [38].

The complexity of such systems, combined with the high cost of cooling, highlights the importance of optimisation strategies such as those investigated in this study [39], [40].

1.4 Ice plants on deep-level mines

As mentioned in the sections above, ice is used to cool down mines starting at a depth of 2 000 m, but recent studies have shown that ice can be used as a cooling medium in mines starting at 1 760 m [35]. This is mostly due to modern ice makers, which are more cost effective, and the substantial increases in the South African power tariff which makes pumping more expensive [35].

Ice is produced from ice plants on surface and then delivered underground to a chilled dam. The chilled water is used by various consumers to cool down working areas and operate machinery.

Ice plants make use of a vapour-compression cycle to cool down water, similarly to refrigeration plants. The primary components in an ice plant are compressors, condensers, evaporators and expansion valves [41], [42], as explained in Section 2.2.3.1. Ice plants have an additional component which makes them differ from refrigeration plants: an ice making unit [43].

The ice making unit is where chilled water gets frozen by a refrigerant at sub-zero temperatures [43]. There are two categories of ice making units being utilised on deep-level mines: soft ice/vacuum ice and hard ice plants. The two different types of plants produce ice with a differing ice mass fraction. Hard ice has a mass fraction of 0.9 and above, while soft ice has a lower ice mass fraction [44]. A recent case study performed by ice plant manufacturer Howden found that hard ice outperforms soft ice by supplying equal cooling at only 73% of the cost [45]. Hard ice was found to be a more cost-effective option due to lower auto-compression losses and lower fluid mass flow, which reduces pumping costs [35], [45].

1.4.1 Hard ice plants

There are different types of hard ice plants utilised by mines, which are classified by the type of ice they produce. The most common of ice plants are known as block ice plants, plate ice plants and tubed ice plants [42].

Block ice plants form ice in water-filled cans that are submerged in a freezing tank containing chilled brine [43]. The brine circulates in the tank and is cooled by a refrigerant where its temperature is maintained at -10 °C [43]. Solid blocks of ice form inside the cans before they are removed from the freezing tank. The cans are then emptied whereafter it is refilled with water [42], [46]. Block ice's geometry makes it a favourable choice in scenarios where ice needs to be transported over longer distances.

Plate ice plants form ice by spraying chilled water on stainless steel plates that contain tubes of refrigerant at temperatures of $-12\text{ }^{\circ}\text{C}$ to $-26\text{ }^{\circ}\text{C}$ inside, as shown in Figure 1-5. Ice forms on the plates until it reaches a thickness in the range of 6–20 mm [42], [47]. Once a desired thickness is reached, hot gas flows through the stainless-steel plates, which causes the ice layer to break off [48]. Plate ice plants are less sensitive to low quality water and are easy to clean and maintain [47].

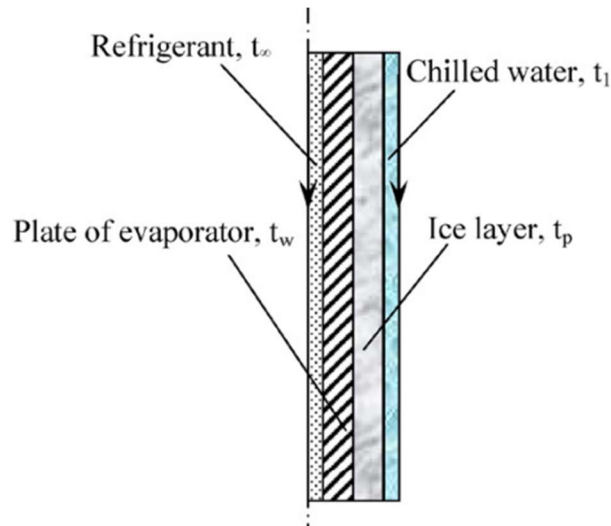


Figure 1-5: Schematic diagram of ice forming on a plate ice maker [48]

Tubed ice plants operate on a similar principle as plate ice plants, except that ice forms on the insides of tubes [42]. Tubed ice plants are more susceptible to low quality water as the tube cleaning process is more difficult and time consuming.

1.4.2 Ice plant network

Deep-level mines making use of ice plants to supply cooling require large quantities of ice. Networks of multiple ice making units are established to supply sufficient ice to the mine. These networks are known to share a water chiller. Chillers are used to pre-cool water to around $3\text{ }^{\circ}\text{C}$ – $7\text{ }^{\circ}\text{C}$. This precooled water can then be turned into ice much faster as less heat needs to be removed from the water.

Ice plants are not commonly seen in the mining environment as it has a high operating cost. This cooling method is only considered in mines exceeding depths of 1 900 m – 2 300 m, where its operating cost starts to compare similarly to other cooling methods, as shown in Figure 1-7 [23]. Ice has a higher energy capacity than water due to its ability to absorb latent heat during phase change [25]. One kilogram of ice has the equivalent cooling capacity of five litres of chilled water

[45]. Less mass needs to be delivered underground for the same amount of cooling. The energy saved from a reduction in pumping is what makes ice a feasible solution at extreme depths [35].

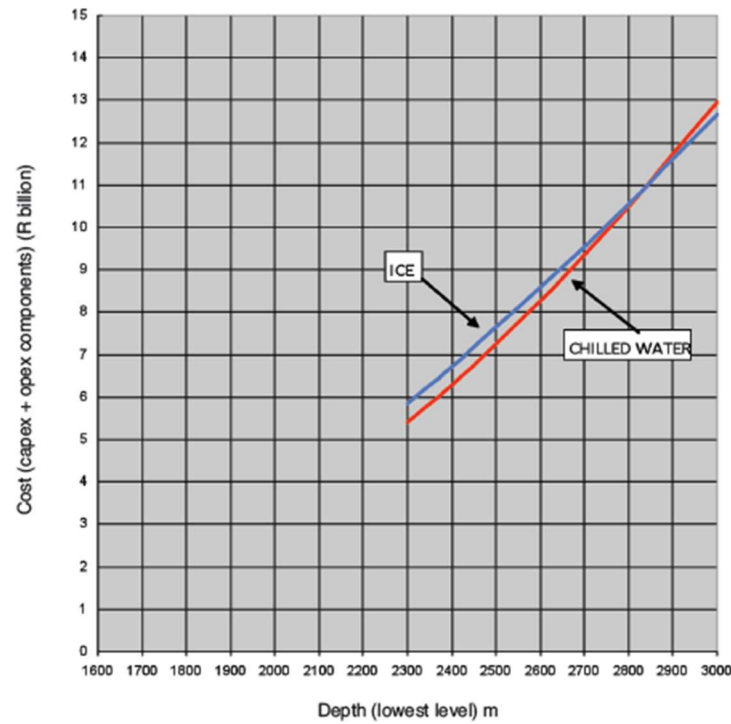


Figure 1-6: Cost comparison of chilled water vs ice systems [23]

Besides the high operating cost of ice plants, they tend to be run under sub-optimal conditions. To minimise the down time of ice plants, critical components are only replaced or repaired when breakdowns occur [49]. It has become an industry standard to make use of predictive or preventative maintenance practices, but it is not always implemented, and mines might fall back on corrective maintenance [50]. Additionally, conditions of mines change over time, and outdated designs are inefficient in the new environment [51]. These problems contribute to a lower operating efficiency, which results in less ice produced overall.

Although ice plants offer a viable cooling solution for deep-level mines, they often operate in suboptimal conditions due to maintenance challenges, evolving mine environments, and outdated system designs [49], [51]. As a result, overall efficiency and ice output can decline over time, reducing the cooling capacity.

The overall efficiency of an ice plant network can be assessed, and improvements can be identified by making use of simulations. Some of these methods are discussed in the following section.

1.5 Simulations in mining

1.5.1 A brief history of simulations in mining

The first general-purpose computer simulation model, named the General Purpose Simulation System (GPSS) was developed in 1961 by Geoffrey Gordon [52]. The potential of simulations in the mining industry was quickly identified, and it was used to optimize a deep-level mine cooling water pipeline in 1982 [53].

The popularity of simulations has increased steadily since its inception, especially in the engineering field [54]. Figure 1-7 shows the trend of simulation-based publications since 2001, where around 33% of all publications are in the engineering field and information and computer science is second place at 9% [54].

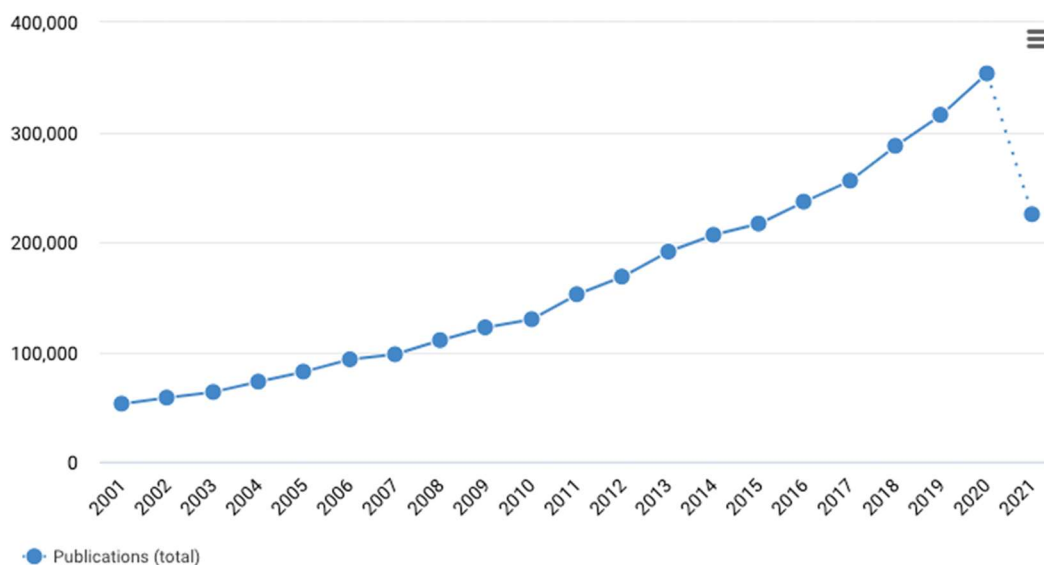


Figure 1-7: Publications of simulation research from 2001 to 2021 [54]

The popularity and usage of simulations in the mining industry followed a similar trend as the graph shown in Figure 1-7. Today, most modern deep-level mines make use of simulation-models to optimise various departments in the mining process. Simulations in deep-level mines have mostly focused on ventilation or surface cooling systems [55]. Figure 1-8 shows the distribution of simulation-based studies for deep-level mines.

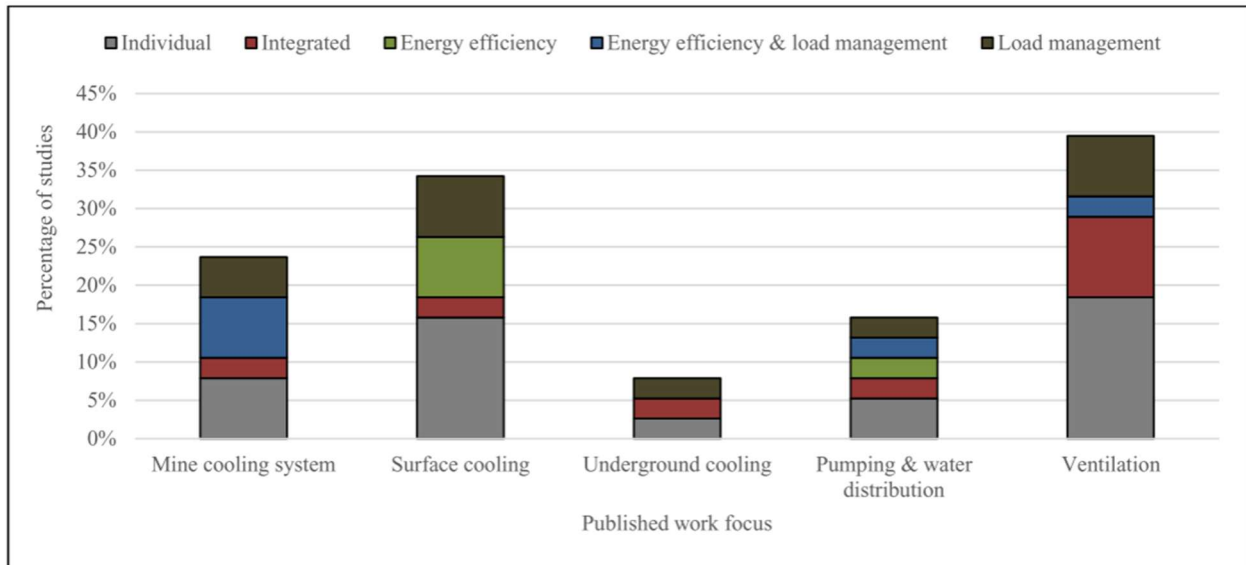


Figure 1-8: Simulation based studies for deep-level mines [55]

1.5.2 The role of simulations in mining

Simulations used in deep-level mines typically come in the form of hybrid and digital twin simulations. Hybrid simulations are typically used on a case-by-case basis, where simulations are combined with optimisation methods. Digital twins are simulation models that represent a physical system, with the capability of being updated with an evolving data set relating to the system [56]. These simulations allow for mapping actual data over the physical system layout, which can be used to identify system limitations [56].

As mines become more and more complex, the need for more accurate and comprehensive solutions grows alongside it. This need is satisfied with the addition of simulation software to the decision-making process in deep-level mining. There are many advantages to utilizing simulation techniques, as mentioned by authors such as C.K Kocsis *et al.* [40]. These advantages include the following:

- **Making correct choices:** Dynamic simulations allow the user to test different scenarios without committing any resources to the development and testing of solutions. The correct solution can be identified from the simulation results [40].
- **Exploring possibilities:** Once a validated model has been developed, the engineering team can explore new and previously untested configurations, designs and operating procedures. This exploration can be done without the risk of interrupting the real system that the model is based on and may reveal possible improvements [40].

- **Diagnosis of problems:** Deep-level mining layouts can be very complex and difficult to evaluate. By making use of simulations, the engineering team can better understand the interactions between components and variables in the mining environment, which can give them the necessary insight when attempting to diagnose a problem [40].
- **Preparing for change:** The dynamic nature of deep-level mines ensures that the mining environment will change over time as new production areas open and old ones close. Simulation allows one to predict the conditions in the mine for different scenarios. Knowing future mining conditions is extremely useful when redesigning the mine [40].

Another overarching benefit of using simulation models as an analysis tool is the reduction in workload and cost required to develop several system variations. This leads to a higher throughput in solving complex analytical problems in deep-level mines, which ultimately reduces the analysis time by ~67% [55].

1.6 Problem statement

Ice manufacturing plants on deep-level gold mines lose efficiency over time, and due to their complexity, it is difficult to identify the causes. Ice plants will therefore have lowered production, which reduces their overall cooling capacity. A method to identify and solve these problems are crucial to increase the cooling capacity of ice plants to combat the increasing heat loads in mines.

1.7 Aim & Objectives

The aim of this study was to develop a simulation-based method which can optimise ice yields in ice plants located on deep-level mines. To complete this goal, the following objectives had to be met:

1. Optimise ice plant production
2. for deep-level gold mining operations
3. by applying a simulation-based approach
4. using a structured method
5. focused on the water pre-cooling (refrigeration) network
6. to improve service delivery.

1.8 Research methodology

This study made use of a case study methodology [57], [58], [59]. A new method was created and then tested on a case study. The research process is shown in Figure 1-9 below.

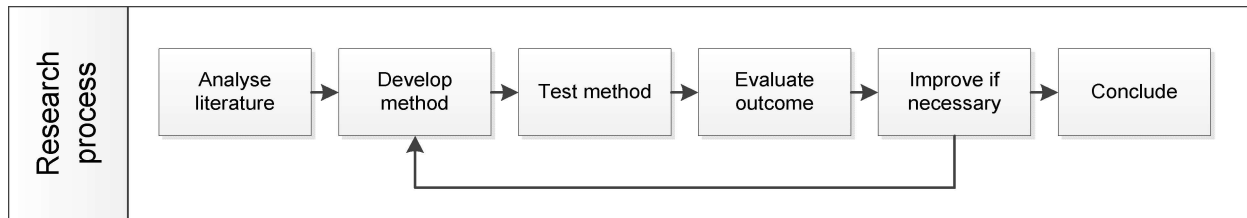


Figure 1-9: Case study methodology research process [20], [21], [22]

Analyse literature

The research methodology started off with a narrative literature review. This narrative review is a qualitative interpretation of prior knowledge [60], [61]. In this study it allowed one to summarise what is known about ice plants in the mining industry [60], [61].

The literature considered was limited to relevant studies relating to the optimisation of ice plants on deep-level mines, the refrigeration and cooling networks of mines, simulation in mining and the development and implementation of methods.

The need for the study, objectives and critical studies are identified in this section. The critical studies, as well as any additional information, lay the foundation for the research process. The process could then continue into the development section.

Develop method

A method, which meets the requirements of the problem statement, was developed based on literature.

Test method

The developed method was tested on a case study. During this phase, data were collected and closely monitored.

Evaluate outcome

The success of the method was determined based on the case study outcome. The outcome of the case study was quantified with new sets of data.

Improve if necessary

In the case where the method was determined to be unsuccessful, the method needed to be improved. Insights gained from the testing and evaluation phase were used to improve the method. The new iteration of the method then went through the testing and evaluation phase again. This process was repeated until a satisfactory outcome was obtained.

Conclude

The last step in the case study methodology research process was to summarise the presented information in a conclusion.

1.9 Outline of the Dissertation

Here follows the dissertation outline which is based on the case study methodology mentioned in Section 1.8. The chapter in the dissertation aligning with each step in the case study research methodology is illustrated in Figure 1-10 below.

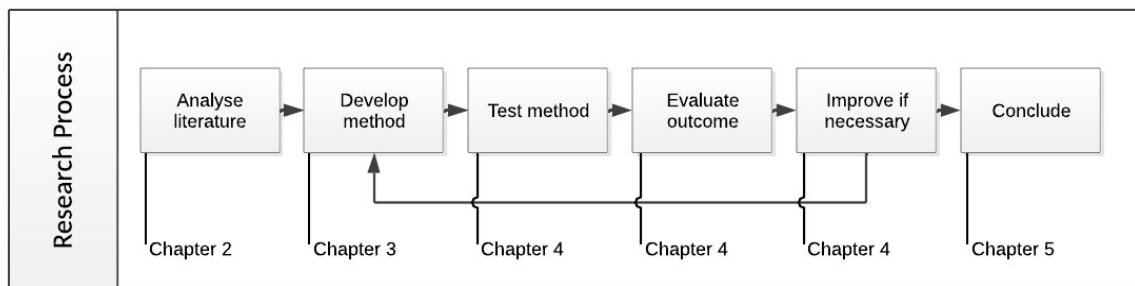


Figure 1-10: Case study research methodology process relating to dissertation chapters

Chapter 1: Introduction

This chapter gives the background required for the study. From there, the need for the study is defined and the objective of the study are discussed. The research methodology used in the study is given and the chapter finishes with an outline of the document.

Chapter 2: Literature study

This chapter discusses the literature used in the research process. Critical studies are discussed, and the chapter concludes with a state-of-the-art matrix.

Chapter 3: Method

This chapter describes step by step how the method was constructed, supported by the literature study from Chapter 2.

Chapter 4: Case study and results

Chapter 4 describes how the method developed in Chapter 3 was applied to the case study mine's ice plant network. The results from the case study were evaluated and it was found that there was an improvement on the ice plant network. The chapter finishes with a validation which determines that the method was a success.

Chapter 5: Conclusion

This chapter concludes the study with a study overview and discusses shortcomings as well as recommendations for future work.

CHAPTER 2 LITERATURE

2.1 Preamble

In Chapter 1, it was stated that ice plant cooling systems are complex in nature, and they are run with many inefficiencies in deep-level mines. A need was identified for a method to optimise ice plants on deep-level gold mines.

Possible solutions to the problem given in Chapter 1 were investigated in Chapter 2 by analysing available literature, as stated in the research process and illustrated in Figure 2-1 below. This chapter starts by explaining the role of cooling systems in mining, the relevant components in the cooling cycle, how ice plants operate and how simulations can be used in mining. Afterwards, previous studies where possible optimisation methods on various cooling systems are investigated and discussed.

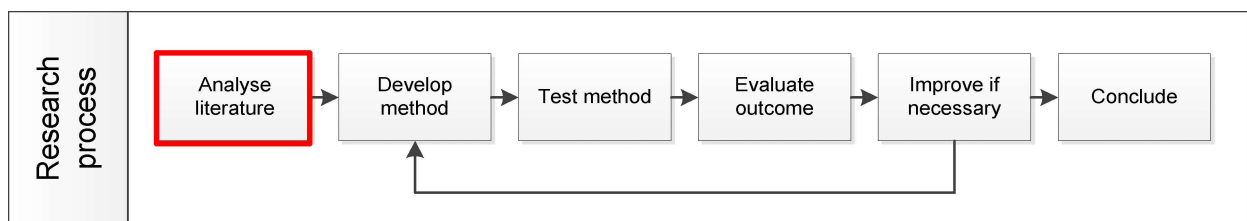


Figure 2-1: Analyse literature section in research process

The chapter continues with a state-of-the-art matrix, which categorises the critical studies reviewed for this paper, and then concludes with a summary on methods used to optimise ice plants.

2.2 Deep-level mine cooling systems

Section 1.3 introduced the overall objectives and layout of cooling systems. This section provides a more detailed discussion of their technical components and operation.

2.2.1 Cooling system objectives

Deep-level mine cooling systems all have a similar goal: to remove heat from the underground environment. Cooling systems consist of numerous complex components all working together [15]. The main functions performed by cooling systems are as follows [27]:

- **Heat absorption:** The first function that a cooling system tries to achieve is to remove unwanted heat from underground working areas by absorbing the heat in a medium like chilled water [23]. The heat can be removed from strategic locations or large bulk coolers can be used.
- **Heat rejection:** The next step is to remove unwanted heat from the cooling system by rejecting it into the atmosphere. This is done by using extraction fans to direct hot air to the surface or cooling tower [28], [29].
- **Chillers:** The heat absorption of the cooling medium is directly influenced by its temperature [23]. Chillers are used to cool the cooling medium, which is transported underground where it is used to cool the mine [30], [31].
- **Heat storage:** Heat storage units are used as a buffer in a cooling system [32], [33]. they allow the cooling system to react to a fluctuating cooling demand. They most commonly occur in the form of chilled water dams [25].

2.2.2 Deep-level mine cooling hierarchy

Mine cooling systems can be split up into a hierarchy as shown in Figure 1-4. The depth and heat load of the mine determines the cooling systems used. Mines make use of a combination of different cooling methods which suits their needs.

Ventilation with the assistance of refrigeration starts becoming a requirement from 600–800 m below collar [23]. The downcast air entering the mine is typically cooled with bulk air coolers (BACs) [25]. This type of ventilation becomes insufficient on their own in mines deeper than 1 300–1 800 m, partly due to auto-compression and excessive heat loads underground [23].

Secondary cooling methods, like underground BACs in the downcast, are then introduced at depths of 1 500 m and deeper to keep working places sufficiently cooled [23]. These secondary cooling methods are commonly used in conjunction with tertiary cooling methods. Tertiary cooling methods include cooling cars and spot coolers, which specialise in localised cooling [34].

Mines with extreme depths, starting at 2 000 m, make use of ice supplied from surface ice plants to achieve the required cooling [24], [25]. This is a very expensive method for cooling and is only viable in ultra-deep mines due to their reduced pumping costs [24], [25].

2.2.3 Cooling system components

As mentioned above, various components make up of a deep-level mine cooling system. Figure 2-2 illustrates a simplified version of a deep-level mine water reticulation system, which includes cooling components. The components present in the figure are listed below:

1. Refrigeration plant
2. Chilled dam
3. Settlers
4. Pumps
5. Cooling towers
6. Chilled water users

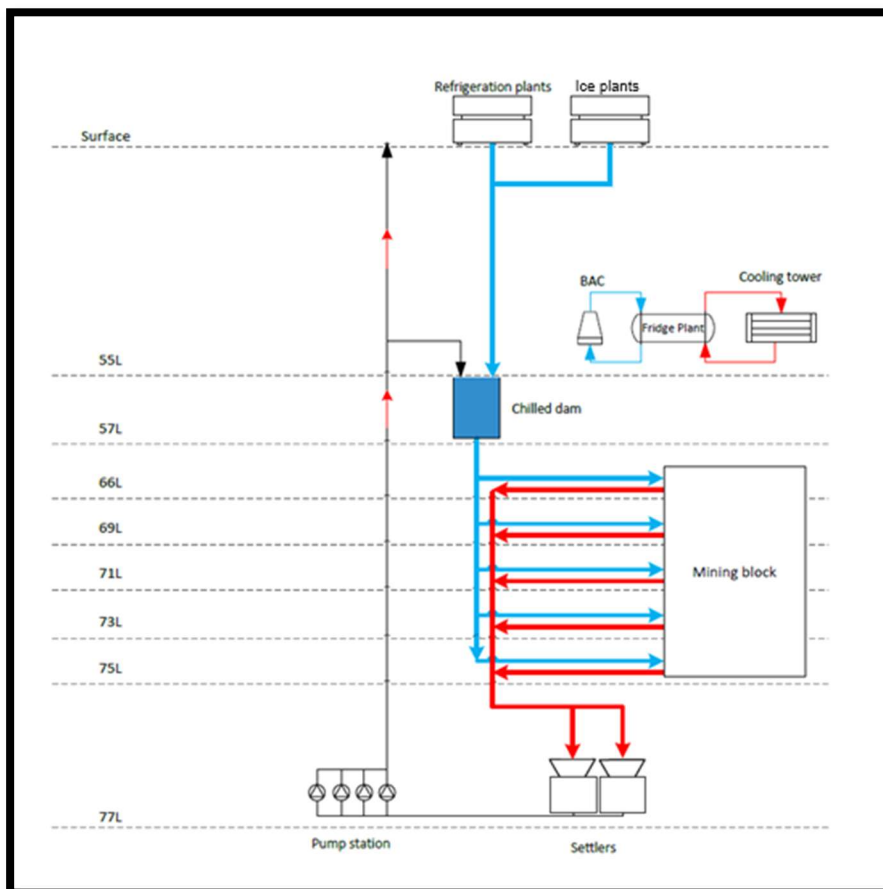


Figure 2-2: Simplified diagram of deep-level mine cooling network [36]

Starting from the surface, mines employ a refrigeration system to produce chilled water to counter-act the large heat loads in the mining block [23], [35]. Chilled water is required for effective heat transfer between ambient air and water. In this example, an ice plant is used to produce ice which melts into chilled water, but using refrigeration plants to cool down water is also a common method[36].

From the surface, the ice or chilled water descends down the shaft column into a chilled dam by gravity feed [35]. Any ice present in the chilled dam will melt before moving on. The chilled water continues down the shaft column and splits off to each mining level where it is used by several consumers, as explained in Section 2.2.4. Extreme pressures are expected in the shaft column due to the head difference of the chilled water travelling in the pipes [62], [63]. To prevent tremendous pressures which could damage the pipes, pressure reducing valves (PRVs) are installed on each level inlet [62], [63].

After the consumers have utilised the chilled water, it is pumped back to the shaft column by small pumps [36]. At this stage, the chilled water has picked up considerable heat and has mixed with hot fissure water [36], [38]. It is no longer suitable for use as a cooling medium. The return water collects at the lowest point of the mine in settlers where it is treated to remove unwanted mud and grit [37], [64].

Large multi-stage pumps are used to send the warm water back to the surface to be re-cooled for further use [35]. However, in this example, the water is pumped back into the chilled dam where it is reintroduced to the refrigeration circuit. The refrigeration circuit supplying chilled water to the chilled dam is crucial in keeping the dam temperature appropriately cold [65]. Additional water introduced to the system, whether by fissure water or from the refrigeration plant on surface, is pumped to the surface to be removed from the cycle [36], [38].

Besides the surface cooling system described above, secondary cooling systems are also commonly used in deep-level mines [34], [65]. In this example, there is a refrigeration plant underground which is used to supply chilled water to a BAC.

The BAC is placed close to the main shaft column where it facilitates air to water heat exchange to cool down the incoming air [65], [66]. The descending air temperature increases, primarily due to auto-compression [26]. The deeper BAC allows more effective heat transfer between the chilled water and warmer air when compared to a surface BAC [34], [65].

The underground refrigeration plant is used to remove heat from the water line. Excess heat is ejected into the upcast through a cooling tower. This is a closed loop system which only requires small amounts of additional water in the cooling tower to replace evaporating water [67].

2.2.3.1 Refrigeration Plants

One of the main methods of supplying chilled water is by making use of a water-cooled vapor compression chiller, which is also known as a refrigeration plant [15]. This cycle works on the principle that a liquid's saturation temperature changes with its pressure [68], [69]. The refrigeration plant absorbs heat from return water to reduce its temperature to around 2 °C [70]. A vapour compression cycle for a typical refrigeration plant is shown in Figure 2-3.

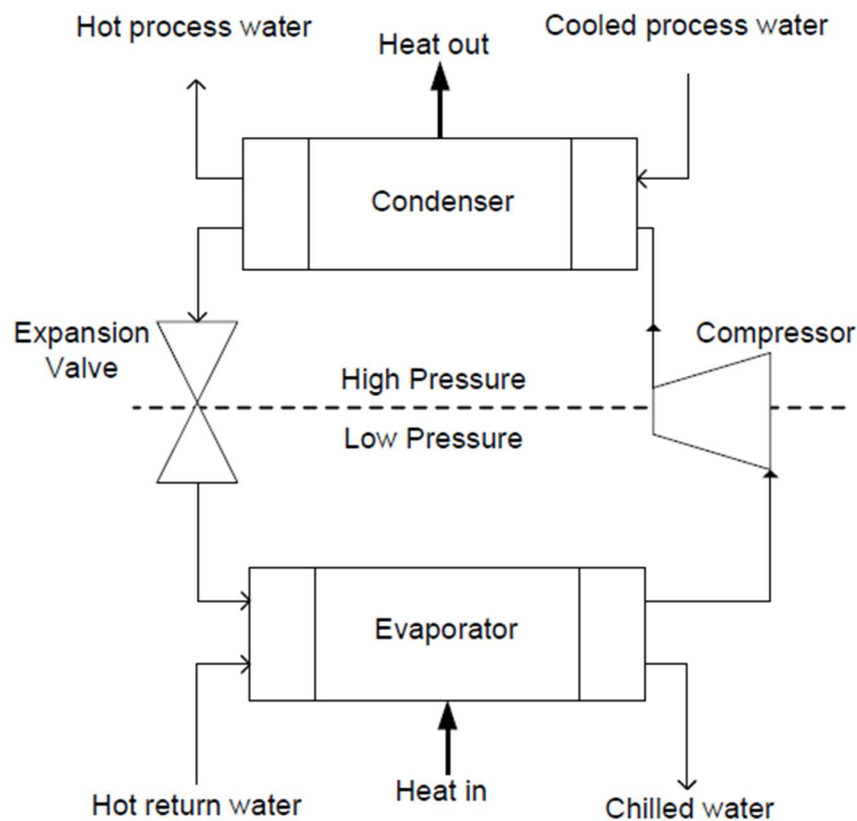


Figure 2-3: Vapour-compression cycle for a refrigeration plant (Adapted from [70])

As shown in Figure 2-3, a refrigeration plant is separated into two sections, a high- and low-pressure side. The return water from the mine enters the evaporator on the low-pressure side of the refrigeration plant where excess heat from the water is absorbed by the cool, low pressure liquid refrigerant [70]. As the refrigerant absorbs heat from the water, it begins to boil and changes to a low-pressure vapour [71]. A low-pressure vapour refrigerant exits the evaporator and

continues to the compressor, while the chilled water flows to a cold-water storage or directly to the shaft column.

At the next stage of the vapour compression cycle, the refrigerant enters the compressor as a low-pressure vapour. The compressor compresses the refrigerant into a high-pressure vapour, causing it to become super-heated in the process, before it continues to the high-pressure side of the refrigeration plant [71].

After leaving the compressor, the super-heated vapour enters a condenser where it exchanges heat with the cooler ambient air. The super-heated refrigerant cools down until it reaches its saturation temperature and changes phases into a high-pressure liquid [71]. The heat absorbed from the return water in the evaporator is ultimately expelled into the ambient air at the compressor.

The high-pressure liquid refrigerant leaves the condenser and flows to the expansion valve. Here, the high-pressure liquid moves to the low-pressure side of the refrigeration plant. During expansion, the refrigerant experiences a pressure drop which reduces the temperature of the refrigerant to sub-zero temperatures [71].

The low-pressure liquid refrigerant flows back into the evaporator, ready to absorb heat from the mine's return water. The vapour compressor cycle starts again from this point.

2.2.3.2 Chilled dams

Chilled dams are a type of thermal heat storage. They are used as a buffer to account for the fluctuating demand of chilled water in the mine's cooling system [72]. This buffer allows the mine to provide cooling during working hours and withhold cooling at off-peak times [72].

In order to understand the fluctuating chilled water demands within a mine, one must be familiar with the working schedule for mines over the course of a normal day. Figure 2-4 illustrates a typical working day in a mine.

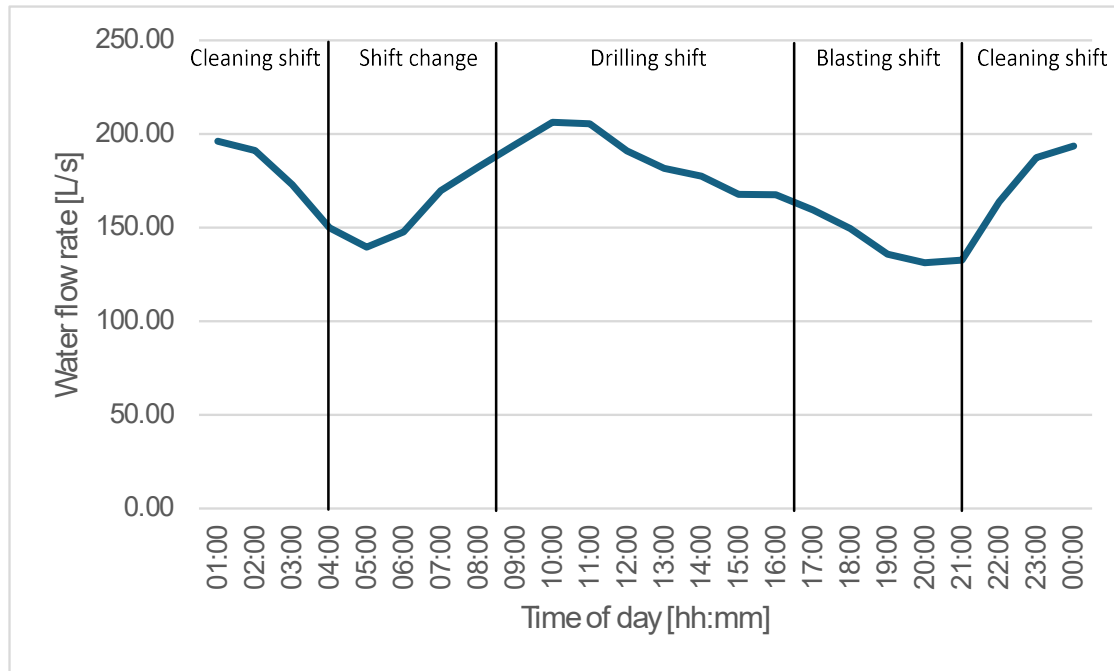


Figure 2-4: Mine water consumption during different shifts [36]

Chilled water demand peaks in drilling shifts when the most crews are active and the number of chilled water consumers are at its peak [36]. Later in the day, a sweeping shift will be active where chilled water is once again required by the crews to perform their respective jobs [36]. A drop in water usage can be seen during off-peak times as chilled water is only used by refrigeration consumers [36].

Control systems are usually installed in valves and pumps going to and from chilled dams [38], [39]. This is used to control the rate of water flowing through the dams to prevent flooding or water shortages [38]. Control systems can also be used to prioritise chilled supply water flow during peak hours in the day by restricting warm return water flow into the chilled dam. By restricting warm return water flow, the water inside the chilled dam remains at lower temperatures. The warm water is allowed to flow into the chilled dam at off-peak times when the average chilled dam water temperature increases for this period [38].

2.2.3.3 Settlers

Underground settlers, as shown in Figure 2-5, act as water treatment plants that separate service water from unwanted mud and grit that was picked up along its dewatering route [37]. Service water is typically used to water down blasted faces and to move loose rocks around (See section 2.2.4.4).

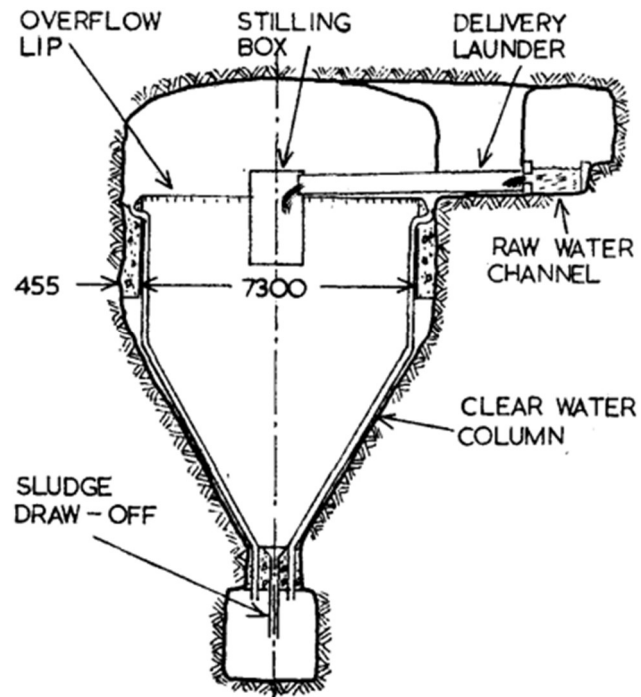


Figure 2-5: Cross-section of a settler [37]

These actions result in a considerable number of solids being swept up in the service water. An accumulation of these unwanted particles can damage pumps, or it can settle in the chilled water dam, effectively reducing its holding capacity.

Dirty water enters the settler and is immediately neutralised with soda ash to increase its pH to approximately 8. This is done to reduce corrosion of the water and to increase flocculation [37], [64]. The solids in the water settle to the bottom while the clear water overflows into a clear water holding dam where it will be eventually pumped to the surface or the chilled water dam [64].

Small amounts of solids make their way into the clear water dam where secondary settlement occurs. The sludge is removed weekly from the dam to prevent buildup [64].

2.2.3.4 Pumps

Pumps are used in mines to transport water throughout a system [15], [36]. Chilled water from a refrigeration plant or chilled dam can be gravity fed to consumers on lower elevations, which eliminates the need of pumps on the supply side. On the other hand, once the water collects at the bottom of the mine, pumps are needed for dewatering.

Dewatering is the process of removing excess water from the mine. Typically, excess water needs to be sent back to surface, so sets of large centrifugal pumps are required [15]. These pumps are commonly oversized to accommodate fluctuating dewatering needs throughout the day and can consume more than 4 MW due to extreme depths of some mines [71]. Smaller pumps ranging from 15 kW to 250 kW are used to circulate water inside refrigeration components like condensers, evaporators, cooling towers, heat exchangers and other auxiliary equipment [73].

Pumps are selected based on the water volume and pressure head required. A suitable power source in the form of an electric motor with an appropriate size and power rating is then selected to operate alongside the pump [15], [73].

2.2.3.5 Cooling towers

Cooling towers are commonly used to cool down condenser cooling water by rejecting excess heat into ambient air. Warm process water is sprayed into the cooling tower by means of nozzles [28]. The surface area of the water is increased with the use of splash bars or fills which increase heat transfer inside of the tower [28], [67]. Ambient air flows over the water droplets, absorbs excess heat, and then exits the cooling tower. Cooled process water gathers in the cooling tower sump before being pumped to a condenser to absorb heat from a refrigerant [28], [67].

Depending on the location of the cooling tower, air is drawn into it by one of two methods. If the tower is on the surface, then air will flow through the tower with the help of fans, as shown in Figure 2-6 [74]. Localised fans are not used in the case of underground towers. These cooling towers make use of the upcast air leaving the mining block [67].

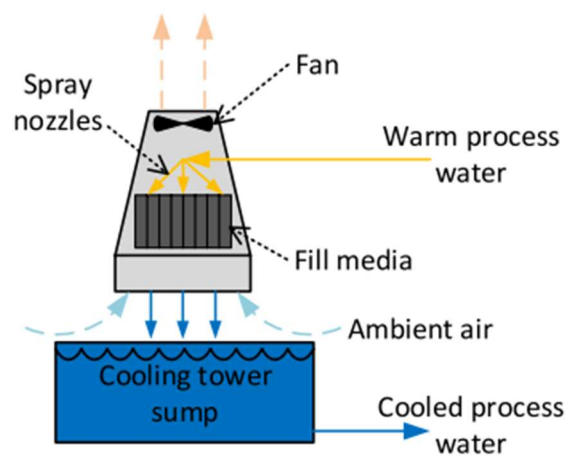


Figure 2-6: A schematic layout of a typical direct-contact force-draught cooling tower [74]

Ice plants may make use of a different type of cooling tower known as an evaporative condenser to cool down its refrigerant. The function of a heat exchanger, to cool down a refrigerant, and the function of a cooling tower, to cool down water, are combined. The evaporative condenser, as shown in Figure 2-7, makes use of evaporating water to directly cool and condense a refrigerant [75], [76].

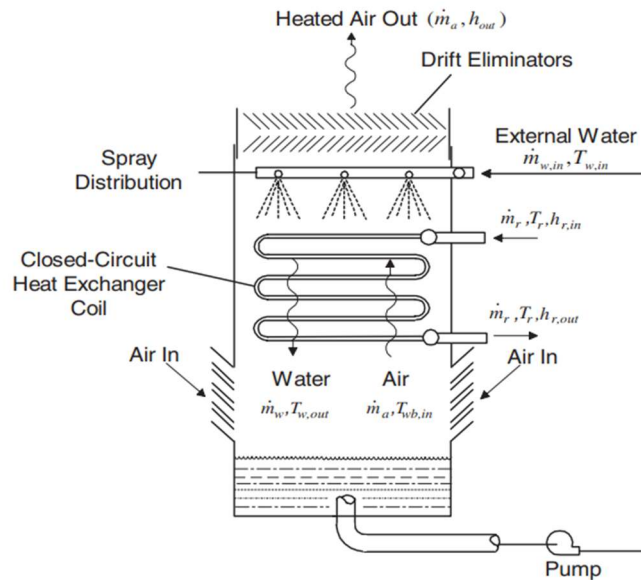


Figure 2-7: Schematic of an evaporative condenser [75]

2.2.4 Cooling system consumers

2.2.4.1 Bulk Air Coolers

BACs are large cooling units utilized to cool significant volumes of air entering the mine [77]. They are commonly located near a chilled water source like a chilled dam or a refrigeration plant [78]. Their function involves spraying chilled water into the air, facilitating direct heat exchange within a cooling chamber [77]. These BACs typically have a potential cooling duty of 0.5–20 MW [65].

There are two types of BACs, vertical flow and crossflow BACs, which are depicted in Figure 2-8. The chilled water can be gravity fed to the BAC unit or it can be pumped [79]. If the chilled water temperature remains constant, then the flow rate of chilled water will determine the outlet temperature of air, with higher flow rates resulting in lower air temperatures [15].

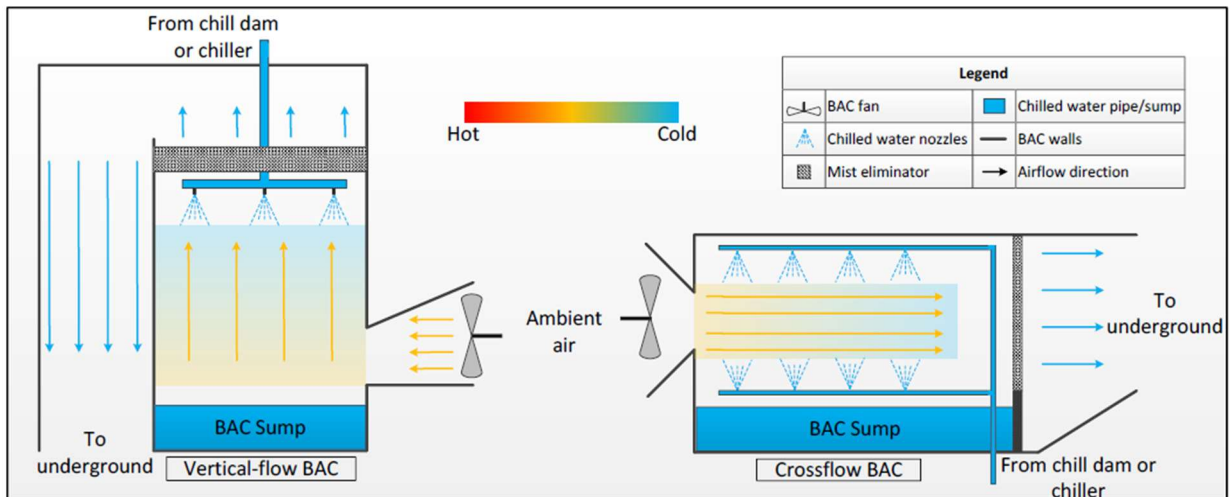


Figure 2-8: Diagram of a vertical- and crossflow BAC [15]

BACs operate with an open- or closed loop system [79]. For underground BACs, a closed-loop system working with a dedicated refrigeration plant is more energy efficient, as an open-loop system needs to pump outlet water up to the surface for cooling [36], [79].

BACs operate on the same principle as cooling towers [67]. They both make use of direct heat transfer between water and air. The difference is that cooling towers make use of ambient air to cool down water, while BACs make use of chilled water to cool down the ambient air entering a mine [23], [65], [77].

2.2.4.2 Cooling cars

Cooling cars, as shown in Figure 2-9, are smaller, fan operated, indirect heat exchangers commonly boasting a cooling capacity of 1.5 MW and lower [34], [65]. A fan forces underground air over coils that contain flowing chilled water. Heat exchange occurs between the hotter air and the chilled water. Hot water is dumped back into the dewatering system while cooler air flows out of the cooling car [78].

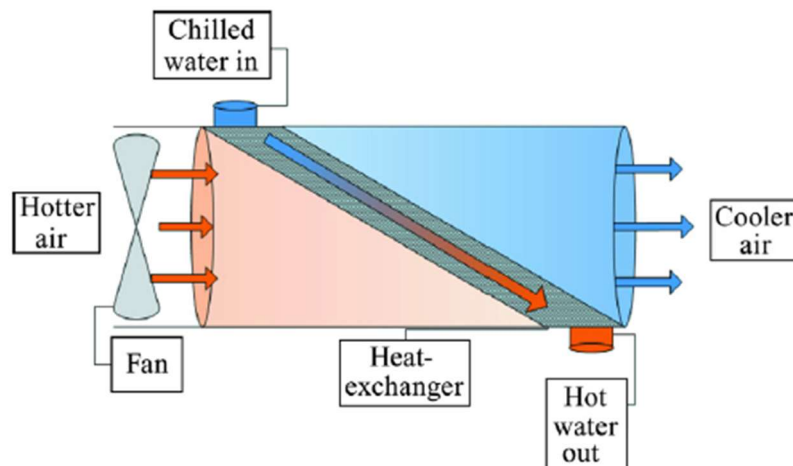


Figure 2-9: Simplified diagram of a cooling car [34]

The mobility of cooling cars is advantageous, as it enables them to be strategically placed in hot underground areas [34], [65]. Additionally, the mobility of cooling cars makes it possible to adapt to cooling needs in the mine, which can delay expensive refrigeration installations [65]. Water is less susceptible to temperature increases due to ambient conditions and auto compression, so it can effectively be used with cooling cars for localised cooling [34], [65].

Like in BACs, the outlet temperature of air is heavily determined by the flow rate of the chilled water. Cooling cars have a much lower maximum flowrate than BACs, which limits their cooling duty [34].

2.2.4.3 Drilling and blasting

The primary goal of a mine is to extract ore from underground rocks. To get loose rocks that can be transported underground and out of the mine, drills are used. Numerous holes are drilled into a rock face and explosives are placed inside the cavities. The explosives are detonated, which breaks up rocks into manageable pieces [80], [81].

Pneumatic drills are typically used in underground mines and chilled water is required to cool the drill bit and suppress dust. Alternatively, hydro powered drills can be used, which utilise chilled water as its driving force [81].

2.2.4.4 Cleaning equipment

After blasting a rock face, the rock shatters into loose smaller sized pieces. These pieces can be moved by using scraper winches. An alternative method is to use water cannons or water jets to move the rock with high pressured chilled water, which has the added benefit of cooling down the virgin rock face [82].

2.2.4.5 Water sprayers

Mine activities like blasting, tipping, scraping and drilling can all produce excessive amounts of dust. Dust can be dangerous when inhaled and can cause pneumoconiosis and silicosis. Chilled water is sprayed into the air and onto rock faces to reduce hazardous airborne particles [83].

2.2.4.6 Unintended uses

The mine can lose cooling through unintended uses of chilled water. This can come in the form of water wastage or illegal chilled water usage. The additional water being used needs to be pumped out, which increases energy usage as well.

Water wastage comes in two forms, leaks and negligent water wastage. Leaks can occur on chilled water and warm water lines due to faulty installation or degradation of pipes through corrosion. Leaks need to be constantly reported and patched to lower the mine's water usage [36].

Negligent water wastage occurs when mine employees use chilled water for unintended purposes or when personnel fail to close water valves when required to. Strong anti-wastage culture as well as strong discipline is required to prevent water wastage [36].

Illegal miners will make use of chilled water for their own mining needs. The chilled water is used for mining and cooling, similar to the mines' operations. This illegal usage of chilled water can disrupt the water network for an otherwise smoothly operating mine [84].

As one can see, cooling networks in deep-level mines can be extensive and highly complex, often involving numerous interconnected systems that require precise monitoring and control. Given this complexity, simulations play a crucial role in identifying inefficiencies and predicting changes on the system without impacting operation [40]. Consequently, the use of simulation models is strongly recommended in modern mine design and optimisation to enhance cost-effectiveness [39], [40].

2.3 State-of-the-art matrix

This section presents several studies used to guide the construction of a method, as described in Chapter 3. These studies include investigations into refrigeration plants, ice plants, and other refrigeration systems and how to improve their performance. The following section will summarise the criteria outcomes of each study.

Search Strategy

The state-of-the-art matrix search strategy involves inputting various combinations of keywords into an academic resource database and collecting relevant studies for further review. The primary database used to find literature in this study was Google Scholar.

Table 2-1 shows the search terms used to identify desired literature in the academic database. Different searches were constructed by assembling combinations of keywords and modifiers.

Table 2-1: State-of-the-art literature search keyword combinations

Pre-modifier	Core Keyword	Post-modifier 1	Post-modifier 2
Deep-level mine	Refrigeration	Reconfiguration	Improvements
	Ice plant	Control	Optimisation
		Production	

Studies relating to the research topic were selected from the database for further review, with preference given to studies published within the last 10 years. The total studies included in the state-of-the-art was limited to 11. This was done to keep the reviewed studies focused on the research topic.

2.3.1 Optimising load management on a deep-level mine's refrigeration systems through maintenance and operational improvements [39]

Overview

Year 2017

Authors F.G. Janse van Rensburg, J.I.G Bredenkamp, J.F. van Rensburg

This study aimed to optimise the surface refrigeration system of a deep-level mine by conducting low-cost maintenance and using a new control philosophy to accommodate these changes. The focus of the study was to improve service delivery.

Key Outcomes

The study identified key challenges and inefficiencies in the refrigeration network caused by inadequate maintenance and control philosophy. Solutions were identified and then simulated to determine their theoretical impact on the system. The simulations tested different scenarios, which included the repair of broken equipment, chill dam empty and recovery times, and the maximum load shift time.

After confirming the feasibility of the solutions through simulations, they were implemented. The improvements resulted in an average temperature decrease of 10.9 °C in the chill dam over the Eskom evening peak periods from January 2017 and March 2017, as shown in Figure 2-10. This improvement had an additional cost savings of R 375 000 due to the load shift performance increase.

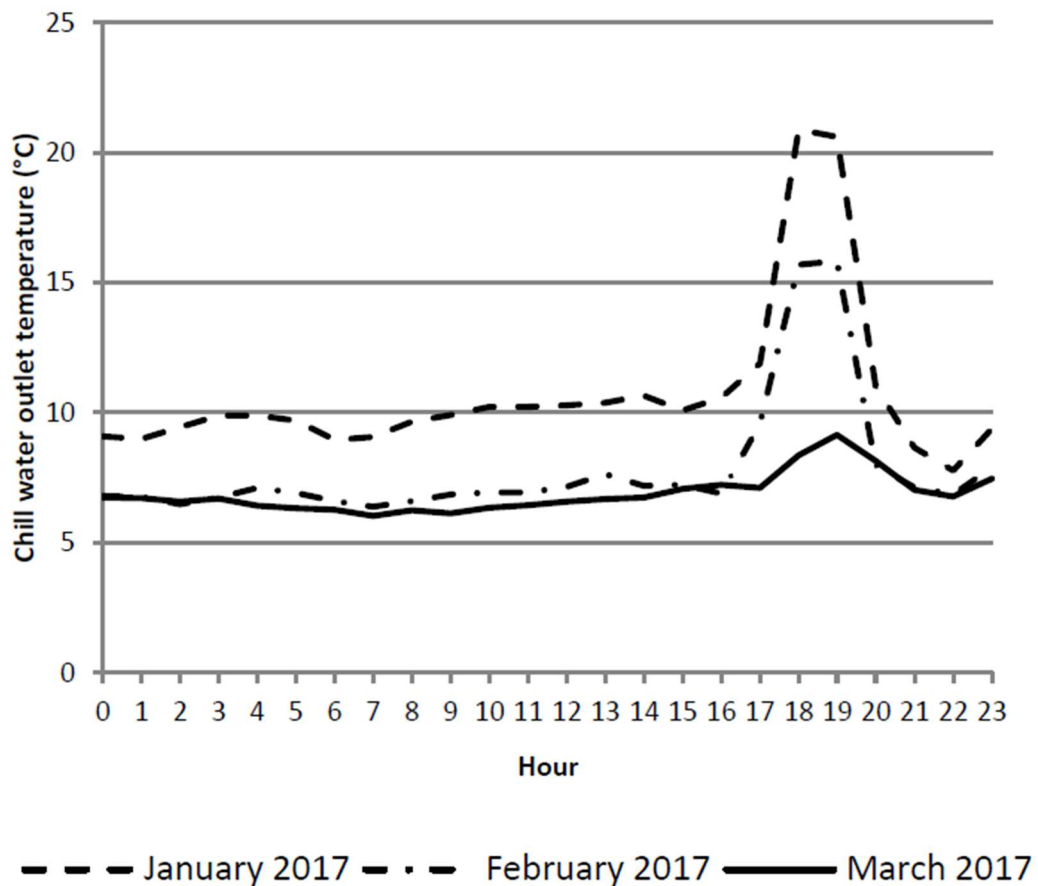


Figure 2-10: Average chill dam temperature [39]

Janse van Rensburg showed that it is possible to achieve service delivery improvements through the combination of optimised control strategies, maintenance, and reconfiguration.

2.3.2 Dynamic optimisation of deep-level mine refrigeration control [85]

Overview

Year 2018

Authors P.F.H Peach, J.I.G. Bredenkamp, J.F. van Rensburg

This study focused on the development and implementation of a dynamic control optimisation method, which was used to improve the operational performance of deep-level mine refrigeration systems.

Key Outcomes

The study implemented a dynamic control strategy which allowed the evaporator water flow to be automatically adjusted to adapt to changes within the system. This dynamic control system improved the operational performance of the refrigeration system in both the summer and winter months by increasing the COP of the system by 5% and 4%, respectively. During summer months, the average air temperature being sent down to the mine was reduced by 2.6 °C or 18%, as shown in Figure 2-11.

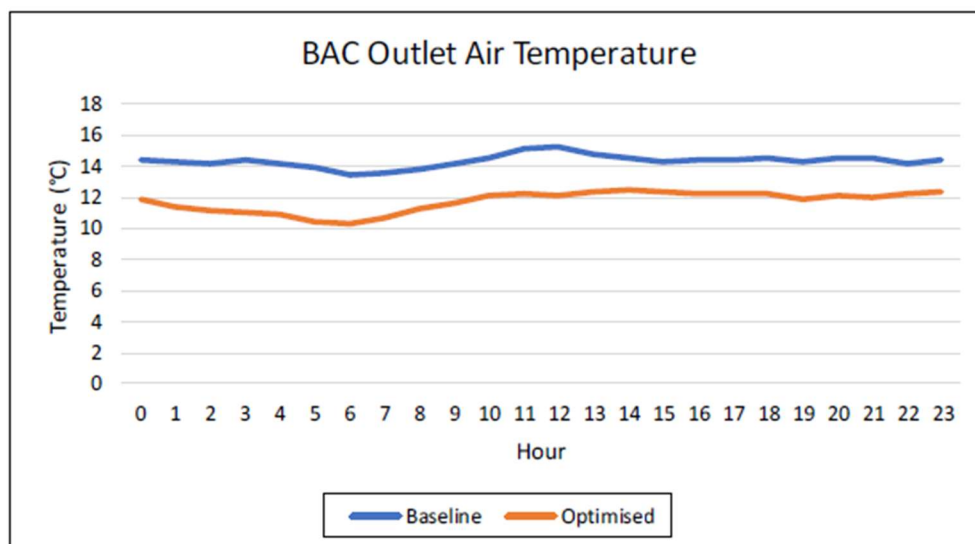


Figure 2-11: BAC outlet air temperature during summer months [85]

2.3.3 Dynamic simulation and analysis of a water chiller refrigeration system [30]

Overview

Year 2005

Authors Z. Lei, M. Zaheeruddin

This study aimed to dynamically model a water chiller refrigeration system based on mass and energy balance principles. A control-oriented approach was taken during development and the effects of control inputs on the output performance were investigated.

Key Outcomes

This study presented a method of modelling the superheated section of an evaporator in a refrigeration system. The model investigated the transient response of a system when changing the valve position and operational frequency. The results showed that the refrigerant mass flow rate and pressure in the system reached steady state faster than the outlet water temperature.

The steady-state performance of the refrigeration system was analysed while operating under different valve positions and operating frequencies. From this analysis, it was discovered that, for a given operating frequency, there exists a minimal feasible valve position. Valve positions below the minimum percentage should be avoided to prevent freeze ups.

2.3.4 A simulation-based prediction model for coal-fired power plant condenser maintenance [86]

Overview

Year 2020

Authors I. Mathews, E.H. Mathews, J.H. van Laar, W. Hamer, M. Kleingeld

This study aimed to determine the most cost-effective condenser maintenance schedule for old Coal-Fired Power Plants (CFPP). A simulation-based model was developed, which integrated the thermohydraulic effects of all the components of a CFPP. This model was then used to find an optimal schedule.

Key Outcomes

Two old South African CFPPs were modelled, calibrated, and verified in order to predict the performance of CFPPs when changes were made to the condenser. With this model, the effect

of fouling on the plant performance was determined and displayed as a function of condenser output temperature over time in Figure 2-12.

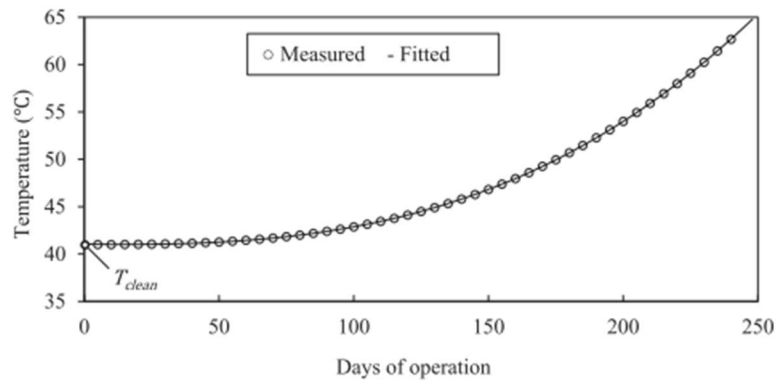


Figure 2-12: Increase of condenser outlet temperature due to fouling over time [86]

An economic model was integrated into the thermohydraulic simulation and the graph of condenser outlet temperature in Figure 2-12. A loss in daily profit was then calculated for the scenario and an optimal condenser maintenance schedule was determined for the scenario. The results were extrapolated to the entirety of the South African CFPP fleet and a potential saving of R 900 million per year was found.

2.3.5 Optimising Deep-level Mine Refrigeration Control for Sustainable Cost Savings [87]

Overview

Year 2017

Authors P.F.H. Peach, M. Kleingeld, J.I.G. Bredenkamp

This study examined load management initiatives on refrigeration systems with the help of simulation models. It investigated the challenges of implementation constraints as well as the sustainability of cost savings of demand side management controls.

Key Outcomes

This study developed and simulated optimised control strategies for refrigeration systems on deep-level mines. The strategy focused on low-cost and easy to implement solutions, while still complying with the mine's regulations. The developed model identified a load shifting opportunity on mine D, which was then optimised with the model to ensure that the chill dam stayed within required temperatures.

These control strategies were implemented on two mines, Mine D and Mine R, which led to cost savings of R 1.76 million and R 215 000, respectively.

2.3.6 Reconfiguring mine cooling auxiliaries for optimal operation [84]

Overview

Year 2016
Authors K.J. Oberholzer

This study developed a universal methodology to optimise and reconfigure the mine's cooling auxiliaries for optimal operation. The reconfigurations were theoretically tested with a simulation model before implementing the changes.

Key Outcomes

The universal methodology and simulation model developed by this study was used to correctly identify inefficient cooling sub-systems. The study found that by implementing the recommended reconfiguration and by conduction maintenance, an electrical cost savings of 10.4% could be achieved, while also improving the service delivery performance of the mine's cooling system.

2.3.7 Simulation model of an automatic commercial ice machine [88]

Overview

Year 2016
Authors H. Murgham, D Myszka, V. Bahel, R. Rajendran, K. Knapke, S Shivashankar, K. Wynn

This paper focused on developing a simulation model for cube ice making machines. This model was based on fundamental principles and generalised correlations, which were used to simulate the transient operation of a cube ice maker.

Key Outcomes

This paper created a simulation model of a commercial ice making machine which can simulate the vapour compression cycle as well as the heat transfer between the refrigerant and the water flowing over the evaporation grid where ice forms.

The simulation model was compared to the experimental data of a fully instrumented cubed ice maker with a capacity of 225 kg over various ambient air and inlet water conditions. When measuring the cycle times, energy usage per 45 kg and total energy usage over 24 hours, the model's accuracy was within 5%.

2.3.8 Improving deep-level mining refrigeration through increasing pre-cooling efficiency [89]

Overview

Year 2019

Authors B.G.G Terblanche, J.F van Rensburg, W. Bierman

This study aimed to optimise pre-cooling towers (PCT) by identifying inefficiencies and developing solutions with simulation models. The solutions focused on addressing design inefficiencies and maintenance improvements.

Key Outcomes

The study followed a method to optimise PCTs. This method identified inefficiencies, which were then addressed by developing various solutions. These solutions were then simulated to test the feasibility of the proposed solutions.

After verifying the feasibility of the proposed solutions, they were implemented on the case study mine. The implementation resulted in an increased PCT efficiency of 24.4%, which was shown by the increased cooling capacity and temperature drop of water over the PCT. The temperature drop over the PCT resulted in reduced chill dam temperatures, which allowed for larger load shifts. The load shift ensured an annual cost saving of R 0.5 million.

2.3.9 Integrated energy simulation of a deep-level mine cooling system through a combination of forward and first-principal models applied to system-side parameters [90]

Overview

Year 2017

Authors W. Bornman, J. Dirker, D.C. Arndt, J.P. Meyer

This study focused on constructing an integrated simulation model to predict the thermohydraulic behaviour and energy usage of a mine's cooling system.

Key Outcomes

An integrated simulation model that contained major cooling sub-systems modelled as components was developed. The simulation was made to mimic the thermohydraulic behaviour of the cooling system to predict the energy consumption of the entire system.

The simulation model predicted the energy consumption of the integrated cooling system of the mine and received an average error of 3.5%. An average error of 2.5% was found on another data set a month later. The successful predictions proved that the simulation model could be used to plan system changes on the cooling network.

2.3.10 Improving existing DSM initiatives on mine refrigeration systems for sustainable performance [51]

Overview

Year 2017

Authors A.J.H. Nel, J.F. van Rensburg, C. Cilliers

This study investigated existing Demand-Side Management (DSM) initiatives on mine refrigeration systems and attempted to improve upon the design by developing and implementing a performance strategy. The performance strategy was designed to address challenges in existing DSM initiatives in a sustainable manner.

Key Outcomes

A performance strategy was developed and validated by implementing it on Mine A and Mine B, where previous DSM initiatives have deteriorated. Post-implementation electrical cost savings were determined for both mines. Mine A had a cost saving of R 11.9 million over the course of 15 months, while Mine B had a cost saving of R 12.1 million over 17 months.

This study concluded that it was possible to implement a performance strategy on a mine's refrigeration systems with existing DSM initiatives. These strategies will result in significant cost savings.

2.3.11 Analysing the impact of refurbishing precooling towers on a deep-level mine [91]

Overview

Year	2019
Authors	S Jerling

This study focused on measuring the impact of PCT refurbishment on deep-level mines. This was done by creating a refurbishment strategy for PCTs where the solutions were verified with the help of simulations. The impact of these solutions on the refrigeration network was analysed.

Key Outcomes

The study created a five-step methodology to evaluate the impact of PCT refurbishment. The methodology started off with identifying a feasible location, which was followed by Step 2, which evaluated the identified PCTs and found recommended solutions to problems. Implementation of the solutions happened in Step 3, and the PCT performance was re-evaluated in Step 4. The impact of the refurbishments was evaluated in the final step by analysing the changes to the refrigeration network.

The implemented refurbishment strategy enhanced the PCT performance by 29.5%. This led to a reduction in inlet temperature to the refrigeration plants, thereby increasing their effectiveness by 2.6% and subsequently improving the efficiency of the refrigeration network by 12.3%, which resulted in an annual cost saving of R6.86 million.

2.4 State-of-the-art literature review summary

Section 2.3 investigated the current state of methods used to optimise ice plant production. Eleven studies were considered. This section aims to determine the appropriate methods to be used in the construction of the method in Section 3.

The state-of-the-art matrix for the optimisation of ice plants is given by Table 2-2. The legend for the matrix is given by Table 2-3. The matrix highlights which of the evaluation criteria each study met or failed to meet. The evaluation criteria were compiled from the problem statement, as well as from common themes emerging from the narrative review above and is given as follows:

1. **Refrigeration plant optimisation:** Did the study focus on improving a refrigeration plant's performance? This is needed as the goal of this study was to improve the performance of ice plants. Previous methods or tests could be considered when creating a new method.
2. **Ice plants:** Did the study look at ice plants? This is needed as the focus of the study was ice plants, and insights into their operation is critical when doing an investigation on them.
3. **Deep-level mining:** Did the study include the effects of being stationed on a deep-level mine? This is important as deep-level mines have unique operating conditions which can influence ice plant production.
4. **Method:** Did the study create or make use of a method? This is important as the method development of previous studies needs to be studied to assist with the construction of a new method.
5. **Simulation based:** Did the study make use of simulations to gather data and results? This is needed as the study relied on simulations to make accurate predictions on a complex system.
6. **Service Delivery:** Did the changes in the study focus on service delivery? Improvements on the system is considered rather than energy savings.

Table 2-2: State-of-the-art matrix

Source	Refrigeration Plant Optimisation	Ice Plants	Deep-level Mining	Method	Simulation	Service Delivery
[39]	✓	X	✓	✓	✓	✓
[85]	✓	X	✓	✓	✓	✓
[30]	✓	X	✓	✓	✓	X
[86]	X	X	X	✓	✓	✓
[87]	✓	X	✓	✓	✓	X
[84]	✓	X	✓	✓	✓	✓
[88]	X	✓	X	X	✓	X
[89]	✓	X	✓	✓	✓	✓
[90]	X	X	✓	✓	✓	X
[51]	✓	X	✓	✓	✓	✓
[91]	✓	X	✓	✓	✓	✓

Table 2-3: Legend for state-of-the-art matrix

LEGEND	
	Study considered the criteria
	Study did not consider the criteria

From Table 2-2, no studies have accounted for all the evaluating criteria. Furthermore, there are few studies focusing on ice plants. From the studies considered, the most common methods used in optimising refrigeration systems were:

- Control philosophy changes
- Demand side management
- Pre-chiller improvements
- Maintenance philosophy changes

Most methods made use of simulations to test and evaluate the proposed solutions before the implementation phase. Making use of simulations is critical in determining the most appropriate solution. Due to the similarities between refrigeration plants and ice plants, the optimisation strategies used on refrigeration plants can also be used on ice plants to achieve improvements in service delivery.

2.5 Summary

The main objectives of a deep-level mine's cooling system are to absorb heat through a chilled medium stored close to the heat source and to remove the absorbed heat from the underground environment. These objectives are met by using various refrigeration components on surface as well as underground. The components used in the systems varies greatly from mine to mine, but it is mostly determined by the heat loads and depth present in the mine.

A critical component in a cooling network is the refrigeration plant or ice plant, which supplies the chilled water used to absorb heat underground. This chilled water is stored in a chilled dam before being gravity-fed to users. After use, the water accumulates in settlers, where it is cleaned of solids before being pumped back to the surface or into a chilled water dam to be cooled again.

Ice plants are used on ultra deep mines starting at a depth of 2 000 m, where it starts to become more cost effective than traditional refrigeration plants. The increasing power tariff makes ice plants a continuously more attractive cooling method in shallower mines as well.

Ice plants operate on the same principal vapour compression cycle used in refrigeration plants. Optimisation methods on refrigeration plants can thus be applied to ice plants. These plants can suffer from various inefficiencies such as incorrect maintenance practices and outdated designs. These inefficiencies are mostly corrected by optimisation methods based on changes in control- and maintenance philosophies, improvements on the pre-chiller network and by implementing demand side management strategies.

Simulations can be used to evaluate ice plants and identify inefficiencies in the network. Potential solutions can be tested within simulations to ensure the correct choices are made with the lowest amount of risk and down-time.

CHAPTER 3 METHOD CONSTRUCTION

3.1 Preamble

In Chapter 2, the current literature on refrigeration plant improvements was examined. Commonly used methods focus on adjustments in control and maintenance philosophies, improvements to the pre-chiller network, and implementing demand-side management strategies. Although no specific method for optimising ice plants in deep-level mines was identified, strategies used for conventional refrigeration plants can be applied to ice plants.

Building on these findings, we proceeded to develop the method in accordance with the research process illustrated in Figure 3.1.

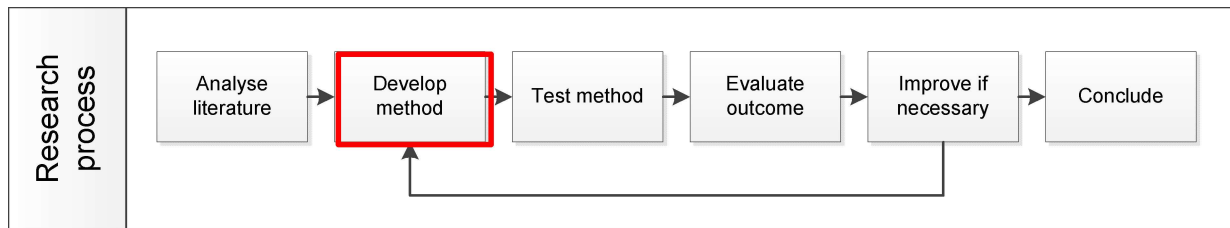


Figure 3-1: Develop method step in the research process

This chapter details the construction of a method to improve ice plants in deep-level mines, guided by the objectives from Chapter 1 and the findings from Chapter 2. Sections 3.2 through 3.7 discuss each major step of the method. Finally, Section 3.9 verifies that the constructed method satisfied the criteria and objectives established in the literature and in Chapter 1.

3.2 Develop method

The primary objective of the method was to optimise ice production in ice plants on deep-level mines. The method was created while adhering to the study criteria shown in the state-of-the-art matrix in Table 2-2. The importance of simulation-based optimisation methods in enhancing the efficiency of refrigeration systems in deep-level mines was demonstrated in Section 1.5. This underscores the need to incorporate simulations in the method. Additionally, the state-of-the-art matrix in Section 2.3 - 2.4 showed that there are multiple strategies which can improve the performance of refrigeration systems.

The proposed method shown in Figure 3-2 was constructed by considering previous studies and the objectives given in Sections 1.7. The method shown in Figure 3-2 was divided into five main steps, each outlining a specific focus. Each main step is further detailed in Sections 3.3 - 3.7. with sub-steps required to achieve the primary objective of the step.

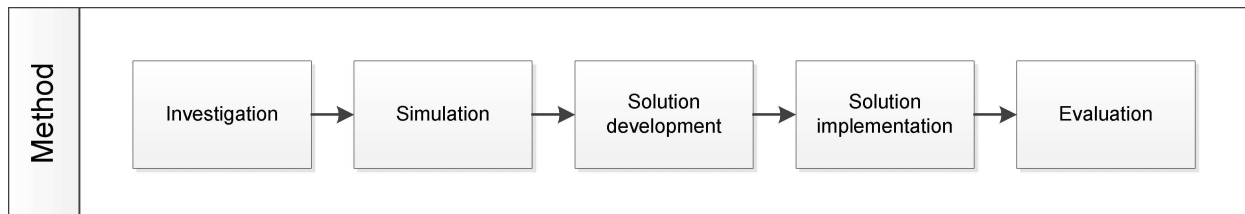


Figure 3-2: Proposed method to optimise ice production in deep-level mines using simulation

Step 1: Investigation focuses on investigating the mine's ice plant system. This includes familiarising oneself with the ice plant network, visual inspections and acquiring and analysing available data on the system.

Step 2: Simulation focuses on creating and simulating a model based on the system layout and the data found in Step 1. The simulation focuses on creating a baseline model which reflects the ice plant network as it is currently running.

Step 3: Solution development focuses on problem identification. The simulation from Step 2 and the data from Step 1 are compared to designed operating conditions of the ice plant. Discrepancies between the designed and actual operating conditions outline problems on the network. The most appropriate solution is selected to be implemented in Step 4.

Step 4: Implementation focuses on the implementation of the accepted solutions. The implementation process relies on the mine to be completed.

Step 5: Evaluation finally evaluates the implemented changes on the system. The benefits of the changes are quantified, and the success of the project can be determined.

In the following sections, we will examine each step involved in constructing the proposed method. This discussion is then followed by a summary, which presents the completed method.

3.3 Step 1: Investigation

The method attempts to identify inefficiencies in the ice plant network and cooling sub-systems in order to improve the production of the ice plants. Previous studies have shown that the investigation phase of a method is a crucial step in creating a foundation for the improvement process [15], [33], [84]. Figure 3-3 depicts the procedure to investigate the ice plant network with the goal to collect and analyse relevant data.

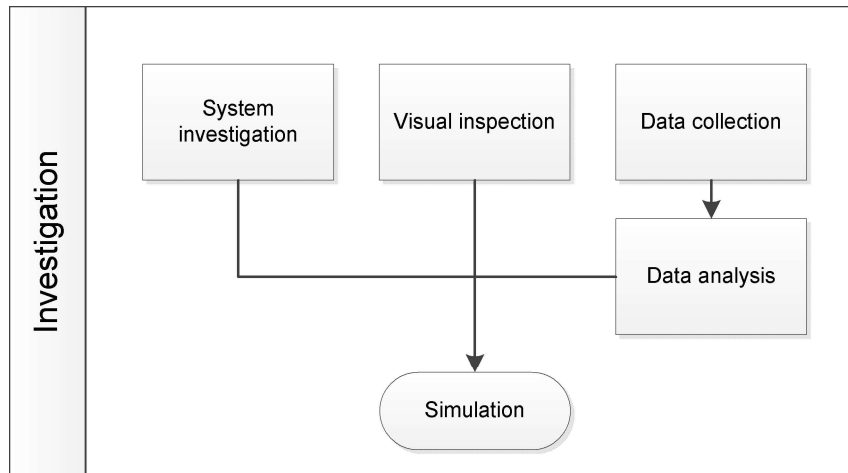


Figure 3-3: Proposed investigation step

From Figure 3-3, there are four steps in the procedure to investigate the ice plant network and identify inefficiencies. Each step is discussed below.

3.3.1 System investigation

The first step in investigating the mine's ice plant system is to do a system investigation. This is done by conducting site visits, speaking with experienced on-site personnel and studying available schematics and drawings of the system's layout [39].

Each mine and its challenges are unique, therefore the ice plant network differs from mine to mine. When familiarising oneself with the site environment, it is required that the locations and specifications of all major components in the ice plant network are known. The components typically found are as follows [36]:

- Ice making unit
- Pre-chiller
- Compressors
- Pumps
- Pipelines
- Valves
- Cooling towers

Where applicable, the following specifications must be gathered for the components listed above:

- In- and outlet flows of a component
- Temperature of water entering and exiting components
- Size and material of piping
- Efficiencies
- External flow rates and temperatures entering the system
- Maintenance schedules and practices

Discussions with experienced on-site personnel give insight regarding the day-to-day operation of the ice plant network and its maintenance schedule. Personnel can help identify inefficiencies that they have experienced, as well as their potential causes [86].

It is important to identify the measurement practices taken by site and how it is logged. This determines where and how much manual measurements must be taken. If a mine does not have an adequate data logging system, part of the solution can be to implement data logging improvements, which allow for a much more accurate investigation of the system [36].

3.3.2 Visual inspection

A visual inspection must be done during a site visit where the ice plant network and all its auxiliary components are inspected. Old and poorly maintained components as well as leaks can be identified [89].

3.3.3 Data collection

Having a reliable data set of the mine's ice plant network is an essential part of the optimisation process. Effective analysis on the ice plant network can only be made when one is aware of critical parameters, as mentioned in Section 3.3.1.

Collecting data on the ice plant's production rate is essential, as the primary goal of this method is to enhance ice production across the network. The actual production rate serves as a baseline to gauge the scope of potential improvements and is also used in Step 5 to quantify the effectiveness of the implemented changes.

Building a baseline simulation in Step 2 requires accurate data on water temperatures and flow rates throughout the ice plant network, including the flow rate through each system component [91]. Manual measurements at various points in the system may be necessary to track diverging and converging water flows, along with their corresponding temperatures [38], [84].

Another essential data set is the operational status of each component. This information helps to identify the running schedules, as well as any unplanned downtimes or unexpected start-ups.

A mine's cooling system's information is usually logged and stored [36]. This practice often includes the ice plant network. Modernised mines with state-of-the-art logging equipment will be able to provide high resolution data in 2-minute intervals. Outdated mines might log data in lower frequencies or have data sets missing [36].

In the case of missing data, manual measurements must be taken. If temperature data is missing, temporary temperature probes can be installed. If water flow data is missing, an ultrasonic flow meter can be temporarily installed at critical locations. Manual measurements are also used in the data analysis step to ensure that the logged data is of sufficient quality.

3.3.4 Data analysis

The collected data are used to analyse the ice plant network. Subsystems with underperforming outputs are identified and causes for the inefficiencies are determined [51], [69].

The data analysis step also includes an inspection of the data quality. Low-quality data compromise the ability to identify inefficiencies on the network. This step is thus vital in optimising ice plant performance. Low-quality data need to be removed from the analysed data set or replaced with calibrated data loggers and/or manual measurements [36], [91].

Using the collected and analysed data, a baseline simulation is constructed to identify problem areas within the ice plant water network. This simulation then serves as a foundation for developing and accessing potential improvements.

3.4 Step 2: Simulation

This step comprises the construction and simulation of ice plant inputs from the data and diagrams gathered in Step 1. Strategies employed in studies identified in the state-of-the-art literature matrix in Sections 2.3 and 2.4 have been consulted to construct this step [33], [36], [39]. The simulation allows quick reconfiguration and analysis of the ice plant network with high accuracy, as discussed in Section 1.5. The simulation is thus vital in the solution generation and selection phase of the method.

From Figure 3-4, there are two steps in the procedure to construct a simulation of the ice plant network. They consist of choosing an appropriate simulation software and then the construction of a baseline simulation [30], [36]. Each step is discussed below.

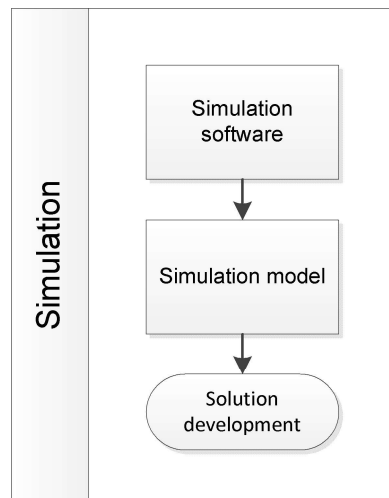


Figure 3-4: Proposed simulation step

3.4.1 Simulation software

The simulation software selected for the method must fully meet all specified requirements to ensure accurate, reliable, and meaningful results. These requirements are essential to effectively model the water network, enabling precise optimisation and facilitating the development of a robust solution [36], [39], [87]. The specific requirements for this study were that the software needed

- the ability to model complex refrigeration and water systems
- and their thermo-hydraulic properties
- while maintaining high accuracy standards,
- had to be able to model the water network to scale, and
- had to have a user-friendly interface.

There are multiple simulation packages available that can model a water network in refrigeration plants, such as Process Toolbox (PTB), VUMA, KYPipe and Flownex. PTB was chosen for this study due to the author's familiarity with it as well as available technical support from their study leaders.

PTB meets all the above listed requirements and was therefore suitable for use in this study. PTB has been used in numerous studies to simulate and optimise water networks in surface refrigeration systems, while consistently achieving high accuracies of over 95% [39], [55], [86].

PTB operates on a 3D interface that uses simplified components to represent various elements of a water network, enhancing its user-friendliness. This intuitive setup accelerates the construction and analysis of the model, making it easy to use and reduces setup time. Additionally, PTB incurred no extra costs for this study, further supporting its suitability as the chosen simulation software [36].

3.4.2 Simulation model

The ice plant network simulation model, shown in Figure 3-5, is constructed based on the data acquired from Step 1. Visual inspections and audits ensure that all elements of the simulation are accurate, and that all sub-systems and piping are included.

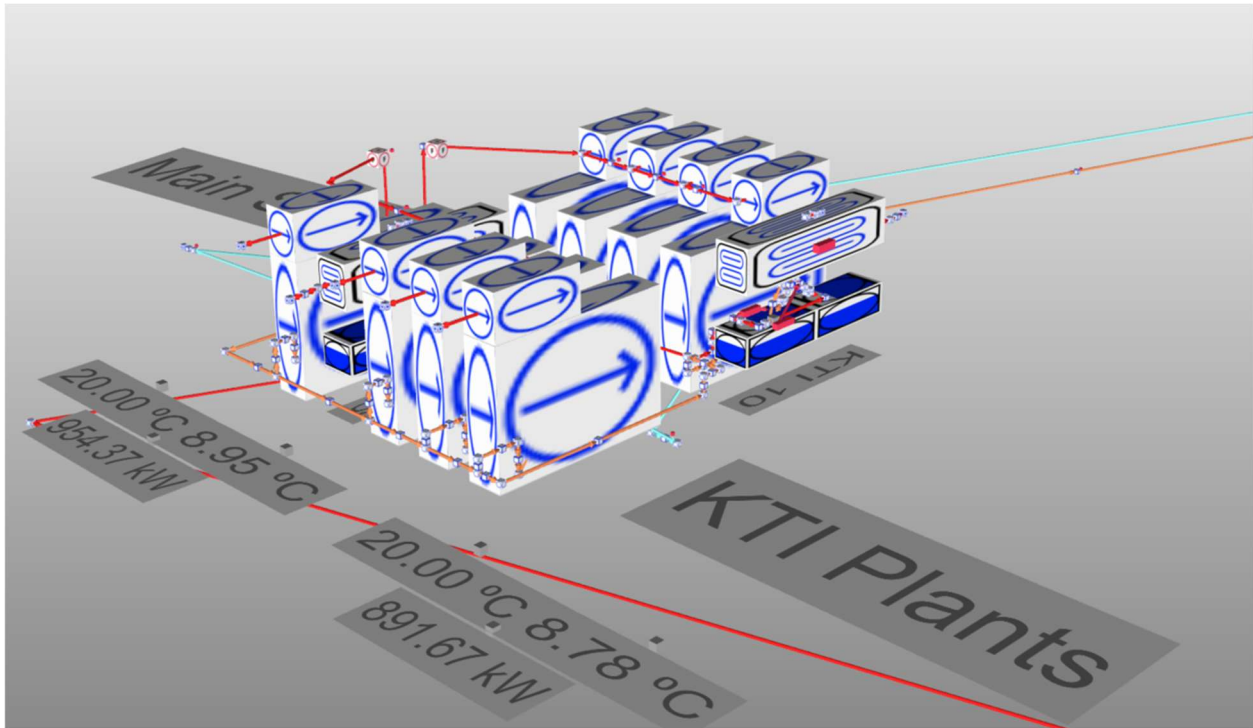


Figure 3-5: Visualisation of the baseline ice plant simulation model in PTB

After adding the components to the simulation model, calibration is required to ensure accurate results. Data from Step 1 are used to verify that each component's inputs and outputs align with actual conditions. This calibration technique, established in previous studies [36], is shown in Section 4.4. The accuracy of the simulation model can be determined by comparing the water flow and temperature in the simulation to the actual values recorded in Step 1.

The simulation model is used as part of the solution development step. As stated in Section 1.5, different scenarios can be tested quickly and without any additional costs. This is done by adjusting the baseline model to reflect potential solutions, which is done in Step 3.

3.5 Step 3: Solution development

With the ice plant network and its components known, the next step is to identify problems, develop solutions and to analyse each proposed solution [51], [89], as shown in Figure 3-6. With multiple solutions available, it is important to ensure the feasibility of each solution and that the correct solution is chosen [91]. The impact of the solution on the mine should be considered to prevent interruptions in the mine's production.

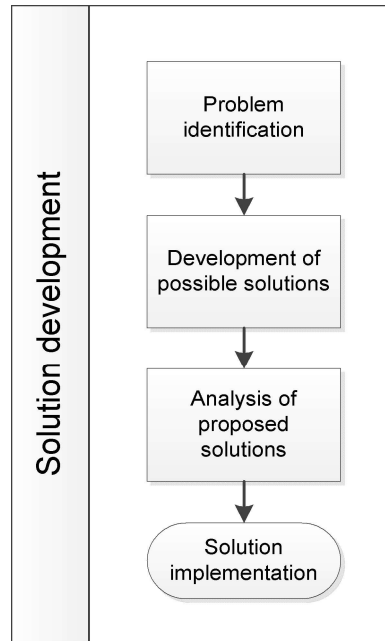


Figure 3-6: Proposed solution development step

3.5.1 Problem identification

Once the ice plant network and its components are known, problems can be identified with available data. When the ice plant network is producing a low amount of ice, it could be the consequence of any combination of the following:

- **Incorrect component inputs:** Components may operate in sub-optimal conditions if they receive incorrect inputs. By comparing the data gathered in Step 1 with the design specifications for each component, discrepancies can be identified. The incorrect input values are then traced to their source to pinpoint the underlying cause [14], [36], [91].
- **Insufficient heat transfer:** Components with inefficient heat transfer can be identified through energy balance calculations. The calculated heat transfer rates are compared with design specifications, and any discrepancies highlight potential inefficiencies [14], [69].
- **External sources of heat:** External heat sources can be challenging to detect. High water temperatures in the chilled water lines, for example, may indicate chiller inefficiencies or heat gains from external sources. Investigating the chilled water pipeline for heat transfer issues, such as inadequate insulation, can help address these problems [33], [36], [87].

3.5.2 Development of possible solutions

The type of solutions developed depend on the specific problems identified in Section 3.5.1. Possible solutions may include reconfiguring the piping layout or eliminating problematic elements within the network [51], [86], [89].

The development of a solution which includes the reconfiguration of the ice plant network can be a complex process. There are many factors that need to be considered. Correct flow rates, temperatures and pressures for different components are some of the factors to consider [90]. There will be multiple reconfiguration solutions available for the network. To test different piping layouts with an accuracy and relatively low turnaround time, one must make use of the baseline simulation built in Step 2 (Section 3.4). The most feasible solution is selected and analysed. If the reconfiguration is deemed impractical or have negative effects on any part of the network, it is revised until a viable solution is developed [91].

For problematic elements within the network, simpler solutions may be implemented without significant risk of negative consequences. These include addressing leaks, removing sources of unwanted heat, or repairing faulty equipment.

To address the three potential issues listed in Section 3.5.1, a systematic approach is followed:

1. Identify incorrect operating conditions using specification sheets.
2. Trace the source of the incorrect inputs.
3. Determine the cause of the issue.
4. Propose the necessary changes to the system.

For example, if high water-inlet temperatures are observed at the ice making units, the investigation may reveal that the water originates from a pre-chiller that is not producing sufficiently cold water [91]. Further analysis may determine that the pre-chiller's condenser has reduced heat-rejection efficiency due to scaling on the coils [39], [49]. Cleaning the condenser coils would then restore the pre-chiller's performance, ensuring the ice making units receive water at the correct temperature.

When developing solutions, it is essential to consider the entire ice plant network to ensure that local changes in one component do not propagate negatively throughout the system. Proposed solutions are evaluated using simulation models to determine their feasibility and potential impact on the overall network [55].

3.5.3 Analysis of proposed solutions

The feasibility of the proposed solution has to be proven by analysing the effects of the solution on the ice production of the ice plant network. This is primarily done by making use of the simulation model which was developed in Step 2 [36], [91]. Communicating with experienced site personnel is recommended to identify any unseen errors in the solution [91].

The proposed changes to the network are made on the baseline model and simulated. In this step, one can test the outcome of the implementations and identify any unforeseen complications. If the solution is deemed to be unfeasible, the solution development step is repeated until a feasible solution is created.

The results of the simulations can be used to determine the theoretical increase in ice production that one can expect. These results are compiled into a report, whereafter this report must be handed over to the mine to motivate the implementation phase of the method [39], [91].

3.6 Step 4: Solution implementation

The implementation phase of the optimisation process can be the most time-consuming step in the entire method [91]. All the recommended changes, improvements and repairs need to be implemented by the mine. The time it takes to implement solutions relies heavily on the mine's available workforce and the available downtime where machinery can be shut off to implement repairs and changes [89].

Figure 3-7 shows the 2 sub-steps necessary to complete this solution implementation step.

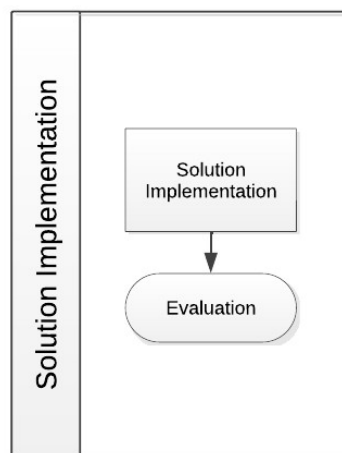


Figure 3-7: Proposed solution implementation step

Once the solutions have been implemented an audit can be performed on the new system. This will allow quantification of the change in performance on the system [38], [84]. The new system can be evaluated to determine the degree of success of the project in Step 5.

3.7 Step 5: Evaluation

The final step of the method is started after the implementation step. This step involves extensive audits on the new system to gather all the relevant data needed for an evaluation of the changes [38], [84]. Similar methods as in Step 1 can be used to gather data. Figure 3-8 shows the two actions in this step.

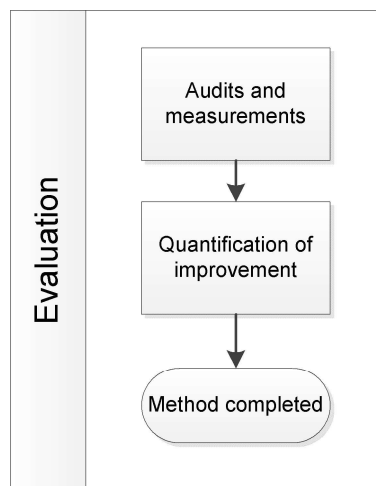


Figure 3-8: Proposed evaluation step

The most important results focuses on the improvement of ice production. The production of ice is monitored daily. The new production quantities are compared with recorded data where the ice plants were running in similar ambient conditions. This is done to get an accurate representation of change in ice production. The system must be monitored for at least a month after implementation to get a data set of sufficient size [84], [89].

Secondary data sets like water flow, temperatures and running times are also compared with historic data to track changes on the system and determine the accuracy of the simulation model's predictions [89].

3.8 Summary

A completed diagram of the proposed steps and sub-steps is shown in Figure 3-9. This method is used to optimise ice plant networks on deep-level mines, and it was constructed based on the objectives and findings from Sections 1 and 2. Studies from the state-of-the-art investigation was used to determine correct strategies and steps.

As shown in the figure, the method is divided into five distinct steps, beginning with Step 1: Investigation. This initial step involves a thorough inspection of the ice plant, along with comprehensive data collection and analysis to establish a foundation for the process.

Step 2: Simulation focuses on constructing and calibrating a baseline model, which serves as a reference point for evaluating potential improvements. This calibrated model is then used in the subsequent step to identify the most effective enhancements for the ice plant network.

Step 3: Solution development is dedicated to pinpointing specific issues within the system, generating potential solutions, and analysing these options to assess their feasibility. This step ensures that only the most practical and effective solutions are carried forward.

Step 4: Solution implementation refers to the phase of the method where the mine implements the recommended solutions developed in Step 3.

Step 5: Evaluation centres on quantifying the improvements made to the ice plant network. In this step, the updated ice production rates are compared with historical data to assess the effectiveness of the implemented solutions.

This structured, five-step method provides a comprehensive approach to optimising ice plant networks, addressing each phase from investigation through to evaluation. The next steps involve verifying the method to ensure that the study criteria are satisfied. Thereafter, the next step is applying this method to a case study mine to validate its effectiveness and measure its impact on ice production efficiency.

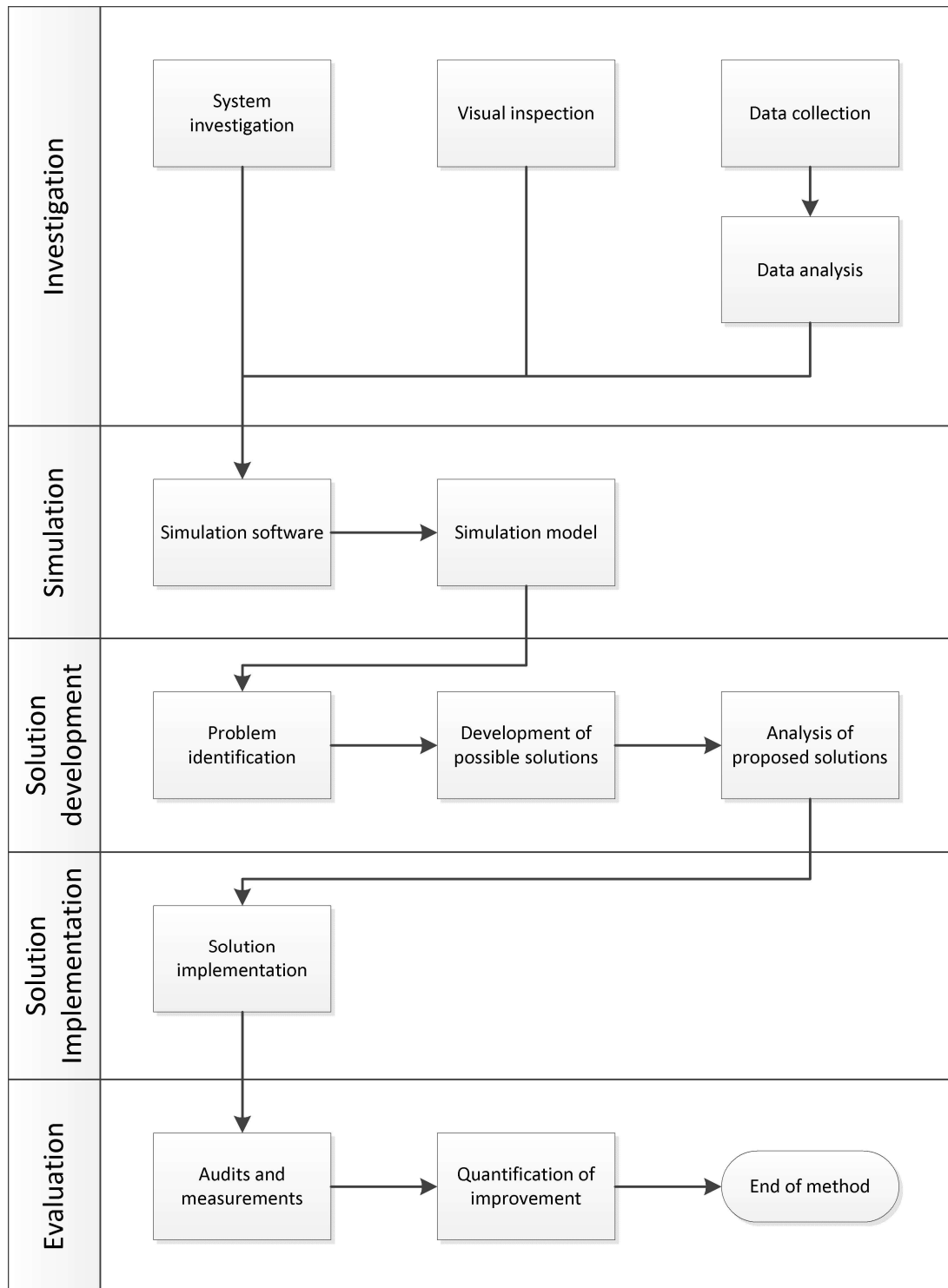


Figure 3-9: Full diagram of proposed method

3.9 Method verification

This section verifies that all the criteria from the state-of-the-art matrix in Table 2-2 have been satisfied. Table 3-1 shows that the study satisfies the criteria laid out as well as in which step it has been satisfied.

Table 3-1: Method criteria verification

Criterion	Criterion satisfied in
State-of-the-art criteria (Section 2.4)	
Improvement of refrigeration plant	Step 1-5
Focus on ice plants	Step 1
Implement on a deep-level mine	Step 1, 4
Create or use a method	Step 1-5
Simulation based	Step 2, 3
Improvements on service delivery	Step 4-5

3.10 Conclusion

A method to increase ice production on an ice plant network, which comprises 5 steps, was developed, discussed and verified. The five steps in the method are as follows: investigation, simulation, solution development, solution implementation and evaluation. The constructed method is a generic method which can be applied to most ice plants on deep-level mines.

The next step was to apply the completed method to a case study mine, allowing for validation against the objectives outlined in Sections 1.7.

CHAPTER 4 CASE STUDY AND RESULTS

4.1 Preamble

A method to optimise ice plants on deep-level mines was constructed. Chapter 3 guides the reader through the necessary steps to optimise ice plant production on a deep-level mine by utilising simulations.

Chapter 4 covers the implementation of the constructed method on the case study Mine A, whereafter the outcome is evaluated and improved. This is shown in the case study research process diagram in Figure 4-1 below.

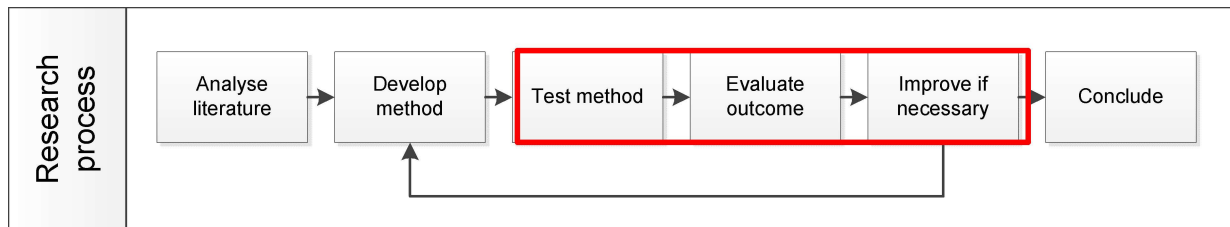


Figure 4-1: Case study implementation, evaluation and improvement stage in research process

The reader is guided through the method for the testing and evaluation process on a step-by-step basis. These steps include:

1. Investigation
2. Simulation
3. Solution development
4. Solution implementation
5. Evaluation

4.2 Case study background

The selected case study mine, Mine A, is a conventional deep-level gold mine in South Africa that mines to a depth of around 2.3 km. Further details of the mine's location have been purposefully removed to maintain its confidentiality.

Figure 2-2 shows a simplified diagram of Mine A's water network. The levels of the mine are numbered from 55L to 77L. The levels are named based on the depth of the level below the shaft collar. The depth is measured in feet and the name is found by dividing the depth by 100, so 77L refers to 7 700 ft or 2 347 m below the collar.

Mine A uses two sets of ice manufacturing plants to produce ice which is used to cool down the mine. Ice is the main form of cooling supplied to Mine A, so it is critical that these ice plants operate continually and efficiently. The case study focused on one set of ice plants. This set of ice plants, manufactured and supplied to Mine A by the German company Plersch Kältetechnik (Plersch cooling technology), is referred to as 'KTIs', in line with the terminology used by on-site personnel.

The KTIs are designed to produce 200 tonnes per ice making unit per day. This results in a designed production of 1 600 tonnes per day for all units combined. For the ice dam on 55L to maintain sufficiently cold temperatures, a target of at least 1 400 tonnes per day was set. The ice plant was unable to reach these targets as shown in Figure 4-2.

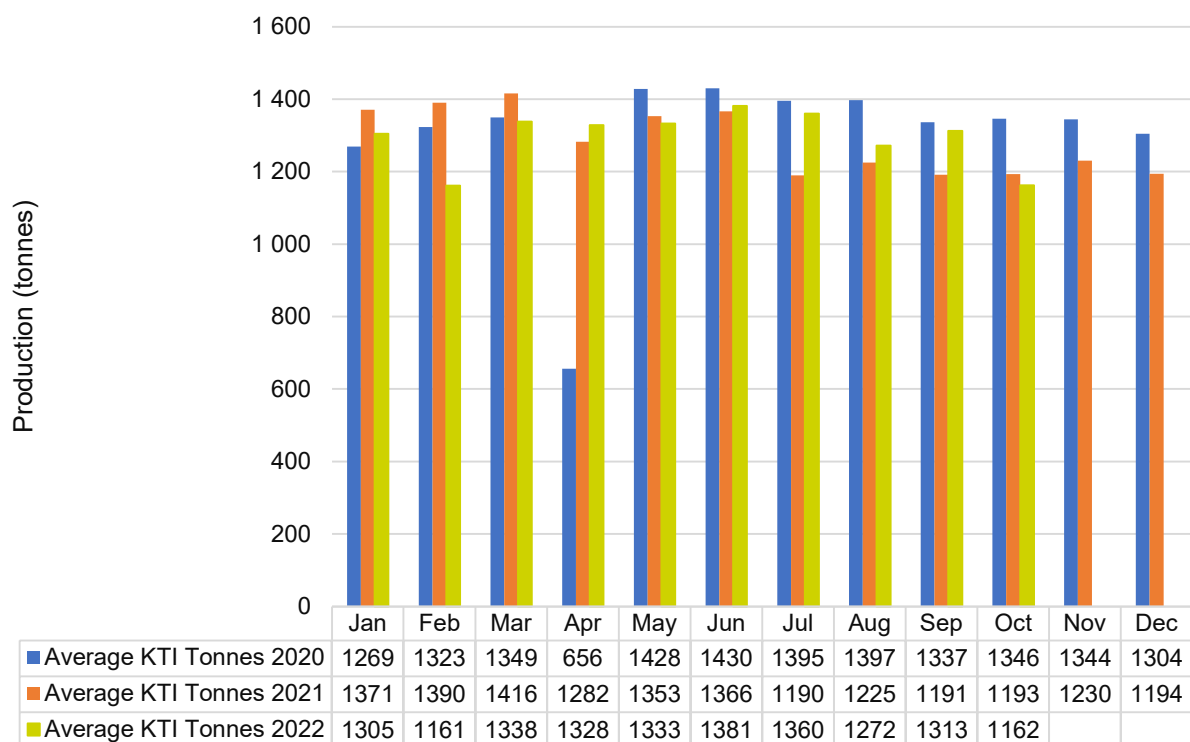


Figure 4-2: Average daily ice production per month for the KTI ice plant

April 2020 will be treated as an outlier. During this month the KTI ice plants were shut down for long periods of time due to water unavailability and other breakdowns.

The low ice production suggested that there was scope for improvements on Mine A's ice plant network.

4.3 Step 1: Investigation

A comprehensive investigation of Mine A's ice plant network was conducted in accordance with Step 1 of the method outlined in Section 3.3. The primary objective of this step was to collect the necessary data to facilitate the development of accurate simulations and effective solutions.

4.3.1 System investigation

The case study was conducted on the KTI ice plants located on Mine A. A diagram of these ice plants is shown in Figure 4-3 which is accompanied by the legend in Table 4-1 . KTI 1-5 and KTI 7-9 are ice making plants, while KTI 6 and 10 are chillers used to cool down water before it reaches the ice making KTIs. KTI 10 supplies chilled water to another group of ice plants, referred to as Icelings, which were excluded from the study.

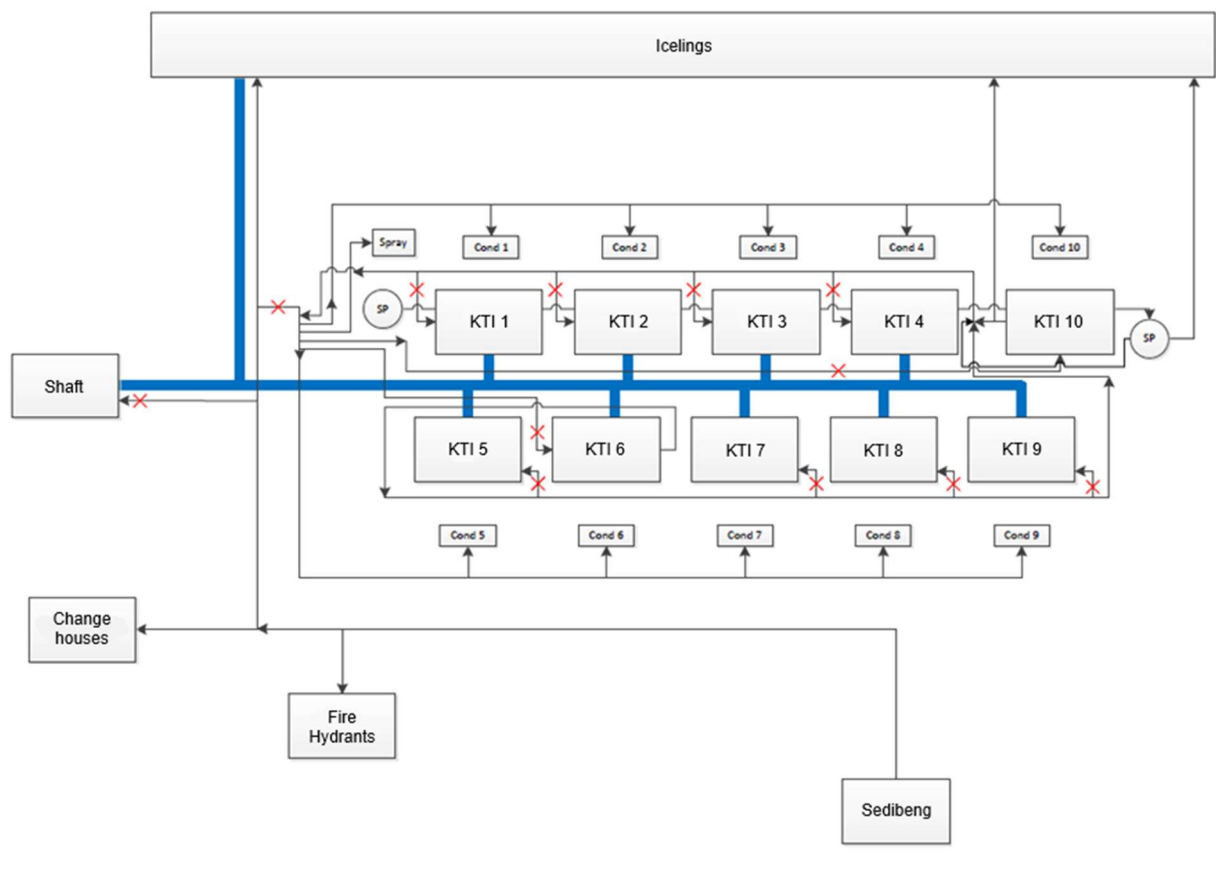


Figure 4-3: Diagram of Mine A's KTI ice plant network

Table 4-1: Legend for Figure 4-3

Legend	
	Valve
SP	Spindle pump
Cond	Evaporative condenser
	Water pipe
	Ice conveyor

Figure 4-3 includes the water pipelines as well as the ice conveyors, shown in black and blue lines, respectively. Potable water is supplied from the municipality run water pumping station Sedibeng and feeds into both the KTI and Iceling ice plant networks. The potable water pipeline flowing to the KTIs reaches a manifold where it splits off towards the two chillers, KTI 6 and KTI 10, as well as to all the condensers coupled with each KTI. Chilled water produced by KTI 6 is distributed to each ice making plant. The chilled water is distributed, starting from KTI 5 to 9, whereafter it continues to KTI 4 to 1.

Any water leaking from pipes or ice making units is collected in a small holding dam and pumped back into the system by two Spindle Pumps (SP). The leak water is reintroduced to the system between KTI 9 and 4. Thus, only KTIs 1–4 receives potable water mixed with leak water.

Further inspection was done on the internal workings of an ice plant unit. A modular and compact approach was taken during the design of the KTIs. As a result, the inner components of the KTIs are housed in three shipping containers stacked on top of one another with an evaporative condenser on the top, as shown in Figure 4-4. KTI 6 and 10 only consist of two containers, where the lower container is used for chilled water storage and the upper container houses components necessary for cooling water.



Figure 4-4: Side view of KTI ice plant on Mine A

Figure 4-5 and Figure 4-6 show simplified cross-sectional views of the components and piping inside an ice plant unit. The ice making process is described below, starting from the upper container.

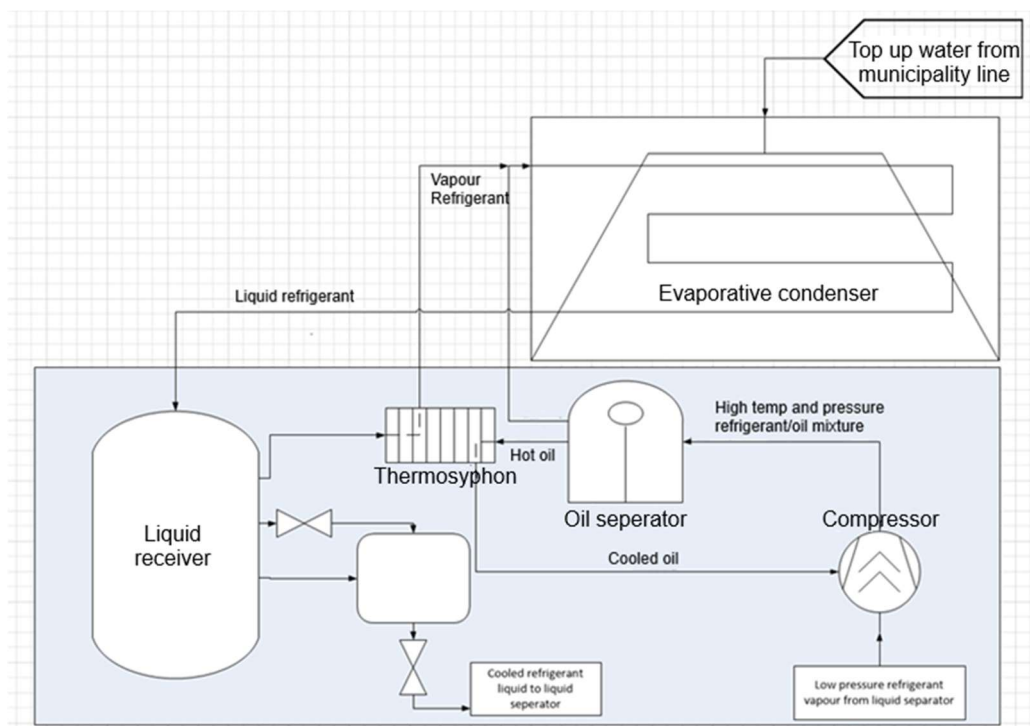


Figure 4-5: Simplified diagram of ice plant unit's top container and condenser

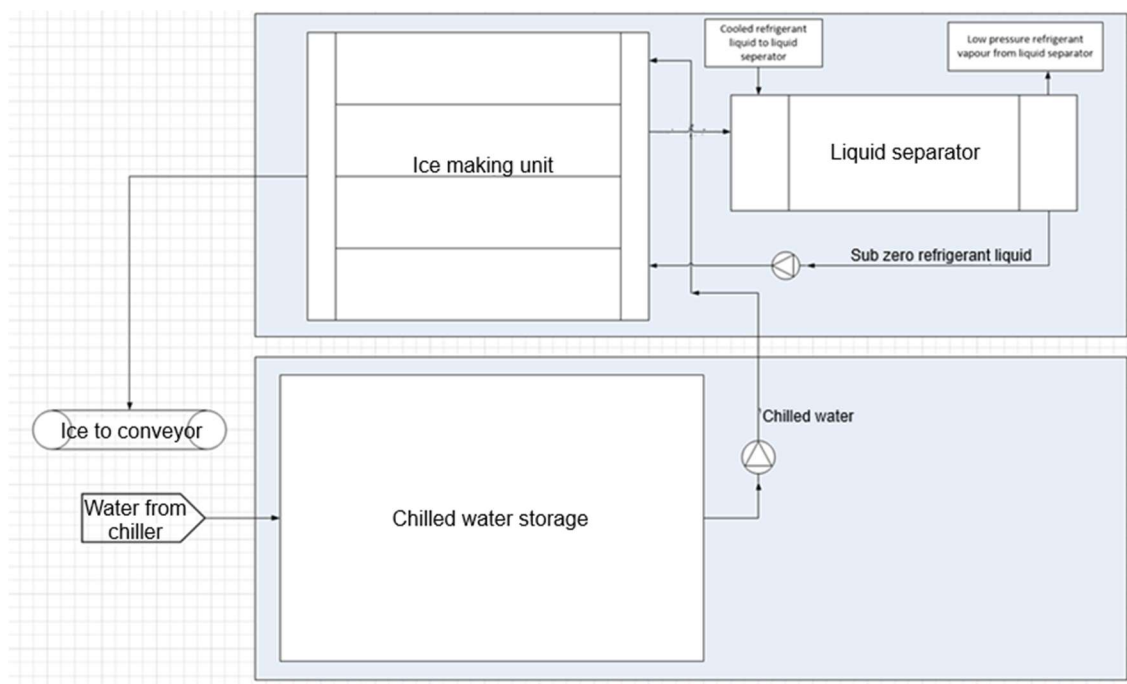


Figure 4-6: Simplified diagram of ice plant unit's bottom two containers

The low-pressure, low-temperature refrigerant vapour leaving the liquid separator enters one of four compressors. As the compressors raise the pressure, the vapour temperature increases as well. The high-pressure vapour, now mixed with compressor oil, flows to the oil separator, where the oil is removed and routed through a thermosyphon to reject excess heat before returning to the compressors.

The refrigerant vapour continues to the evaporative condenser, releases its excess heat to the atmosphere, and condenses into a liquid collected in the liquid receiver. A portion of this liquid circulates through the thermosyphon to absorb heat from the hot oil, evaporates again, and returns to the condenser.

From the liquid receiver, the remaining liquid refrigerant flows to the economizer. One stream expands through a valve before mixing again in the economizer. The refrigerant then passes through a final expansion valve, dropping to sub-zero temperatures. The sub-zero liquid enters the liquid separator in the lower container.

The sub-zero liquid refrigerant collects in the liquid separator shown in Figure 4-6. The liquid refrigerant is pumped to the ice making unit where it moves through thin plates. These plates are covered with a steady stream of pre-cooled water, which allows ice plates to form as described in Section 1.4.1. The ice is allowed to build up for 13 minutes during the ice forming phase,

whereafter the unit proceeds to the ice harvesting phase for 2 minutes before returning to the previous phase.

Hot gas is pumped through the plates during the ice harvesting phase, which causes the ice plates to disconnect and drop into a crusher. The crushed ice then falls onto a conveyor where to be transported to the mine shaft. Most of the liquid refrigerant evaporates in the ice making unit before travelling back to the liquid separator. Any liquid refrigerant still present in the mixture is separated from the vapour to be used again in the ice making unit until it evaporates. The refrigerant vapour travels back to the compressors to restart the refrigerant cycle.

The precooled water used in the ice making unit comes from the chiller (KTI 6). The chilled water is stored in the lower container where it is continuously pumped up to the ice making unit. Water moving over the plates without freezing drops down into the chilled water storage to be reused.

Technical data sheets and specifications were collected for the chiller and KTI, as well as for smaller components, including compressors, evaporative condensers, and pumps. Once the familiarisation of the ice plant system step was completed, the visual inspection stage began.

Technical data

The technical data sheets supplied the expected performance of the ice making units and the chillers. These design conditions are shown in Table 4-2.

Table 4-2: Technical data for KTI ice makers and chillers

Description	Value	Unit
Ice making unit		
Ice production	200	t/day
Fresh water inlet temperature	5	°C
Fresh water supply	2.315	l/s
Refrigeration capacity	1 224	kW
Chiller unit		
Fresh water inlet temperature	27	°C
Fresh water supply	15.750	l/s
Fresh water outlet temperature	5	°C
Refrigeration capacity	1 500	kW
Refrigerant	R717	-

The data presented in Table 4-2 serve as an input for simulating a best-case performance scenario for the chiller and ice making units. By utilising this data, the simulation could model optimal operating conditions, providing insights into the maximum achievable performance under ideal circumstances. Additionally, the information was valuable for assessing the operational effectiveness of the equipment.

4.3.2 Visual inspection

A visual inspection was conducted on the ice plant network to identify poorly maintained components and leaks.

It was found that a considerable amount of water was spilling/leaking out of the lower holding dams onto the floor. The leak water picked up heat and contaminants as it flowed towards the spindle pumps. This water was then pumped, without being cooled again, back into the chilled water line where it was used by KTI 1–4.

It was also noted that the chilled water pipes did not have any form of insulation or cladding. Unwanted heat was added to the chilled water from the ambient air or direct sunlight.

4.3.3 Data collection

Mine A was equipped with a Supervisory Control and Data Acquisition (SCADA) system which logs various data points on a two-minute interval. The mine's installed flow meters and temperature probes' data were sent back to the SCADA system where the data was collected for investigation. Table 4-3 shows the relevant data points being tracked on the SCADA system while

Table 4-4 shows the manual measurements made:

Table 4-3: Available data sets from Mine A's SCADA system

Data	Unit
General	
Daily ice production	Tonnes/day
KTI ice making unit	
Water inlet flow	l/s
Water inlet temperature	°C
Compressor status	Status
Evaporative condenser status	Status
Internal water pump status	Status
Cold water tank temp	°C
Chiller unit	
Compressor status	Status
Evaporator inlet temperature	°C
Evaporator outlet temperature	°C
Evaporative condenser status	Status
Pump status	Status
Cold water tank temperature	°C
Cold water tank pump status	Status

Table 4-4: Manual measurements taken on Mine A

Data	Unit	Collection method
------	------	-------------------

KTI water inlet flow	L/s	Ultrasonic flow meter
KTI water inlet temperature	°C	Infrared thermometer
Chiller water flow	L/s	Ultrasonic flow meter
Chiller water inlet temperature	°C	Infrared thermometer
Chiller water outlet temperature	°C	Infrared thermometer
Chiller water tank temperature	°C	Temperature probe
Leak water return flow	L/s	Ultrasonic flow meter

Water flow and temperature data were gathered manually to compare with the SCADA data set. Additionally, the flow rate of the leak water return line had to be measured manually as there were no SCADA data available. An ultrasonic flow meter, temperature probes and infrared thermometers were used to gather flow and temperature data.

Some irrelevant data sets were available, but there were numerous missing data points or incorrect readings. As these raised concerns about the quality of the usable data, a deeper analysis of the data was required to ensure its reliability and suitability for use.

4.3.4 Data analysis

Low-quality data could compromise the solution development process and had to be eliminated where possible. Calibrated flow meters and temperature probes were placed on various parts of the chilled water pipeline to conduct spot checks. This high-quality, but low-quantity data sets could be compared to Mine A's installed measurement devices to determine their accuracy.

Table 4-5 shows the comparison between the average flow for the spot checks and the built-in flow meters for each ice making KTI.

Table 4-5: KTI water inlet flow comparison between SCADA data and spot check data

KTI	SCADA [L/s]	Spot Check [L/s]	Error percentage
-----	-------------	------------------	------------------

1	10.4	10	4%
2	9.6	9.4	2%
3	8.5	11.2	24%
4	5.3	6.1	13%
5	10.4	17	12%
7	9.9	9	10%
8	9.1	10.9	17%
9	7	8.8	20%

In order to use the data supplied by the built-in meters, a correction factor aligning with the error percentage was applied to each data set. A similar approach was taken for the inlet/outlet temperatures of the KTIs and chillers.

The collected and analysed data could now be used in the construction of the baseline simulation.

4.4 Step 2: Simulation

The data collected in Step 1 could now be used in a simulation model as described in Step 2 of the method. The interfaces and models shown in this section were built in PTB. Other software packages might look different but should function in a similar way.

The components representing the chillers and ice making units required calibration. This was done by running a test simulation that mimicked the input values for the chiller, as shown in Figure 4-7. If the simulated output values matched the recorded outputs to within 5%, the component was deemed accurate.

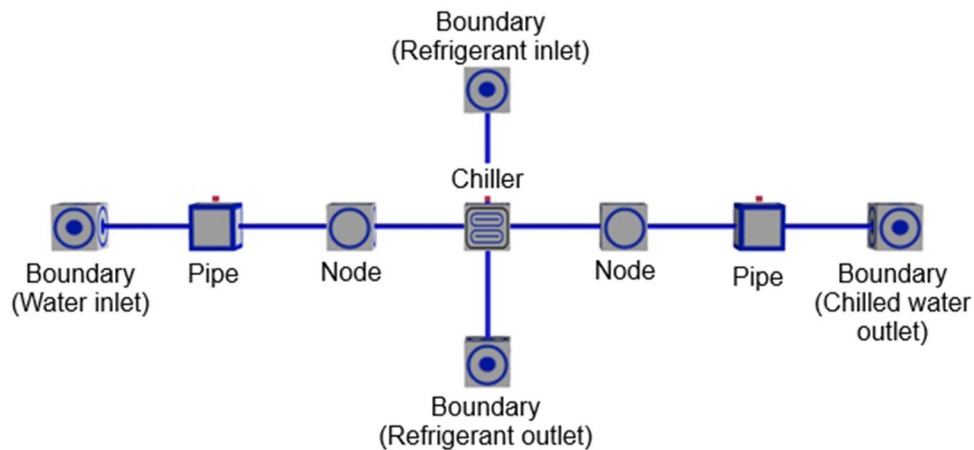


Figure 4-7: PTB component calibration simulation

The water boundaries induced a flow through the chiller where the pipes were used to measure the flow through the component, and the nodes were used to measure the inlet and outlet temperatures of the chiller. The secondary refrigerant boundaries were used to induce a refrigerant flow through the chiller component at a recorded temperature.

The chiller component was calibrated by adjusting its properties within the specification menu, as shown in Figure 4-8. These specifications were modified until the component's outputs aligned with the recorded values.

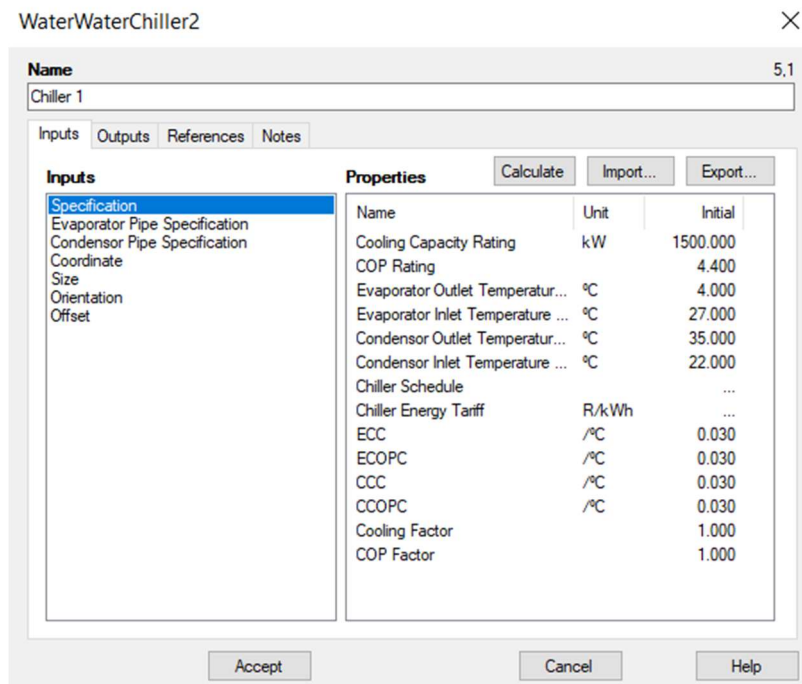


Figure 4-8: PTB chiller specifications menu

The accuracy of the ice plant water network simulation was verified by incorporating the calibrated components into the model. The simulation layout was designed to accurately reflect the real-world ice plant, as illustrated in Figure 3-5. The output values of each component were compared to the recorded values from Step 1. Verification results are presented in Table 4-6 and Table 4-7, where the largest percentage error is 4.29%.

Table 4-6: Simulated chiller output verification

	Actual outlet temperature [°C]	Simulated outlet temperature [°C]	Percentage error [%]
Chiller 1	5.65	5.65	0.06
Chiller 2	3.03	2.99	1.34

Table 4-7: Simulated KTI input verification

	Actual inlet temperature [°C]	Simulated inlet temperature [°C]	Percentage error [%]
KTI 1	8.30	8.09	2.53
KTI 2	8.20	8.06	1.71
KTI 3	8.30	8.05	3.01
KTI 4	8.20	8.04	1.95
KTI 5	5.98	5.73	4.18
KTI 7	5.76	5.75	0.17
KTI 8	5.87	5.78	1.56
KTI 9	5.62	5.81	3.38

The simulation model was used to reflect the water network in the ice plant on Mine A. The pipelines flowing from the chiller into each ice making unit as well as any additional water being introduced from the leak water pipeline was included in the simulation. This information allowed the determination of the potential effects of eliminating inefficiencies before making any changes to the real-world system.

4.5 Step 3: Solution development

4.5.1 Problem identification

By making use of visual inspections and data gathered in Step 1, various inefficiencies on the system were identified. The most prominent issues discovered were untreated leak water pumped into the system, chiller flow capacities, component wear and uncladded pipes.

Leak water

A clear water inlet temperature difference between KTIs 1–4 and KTIs 5,7–9 was identified in Figure 4-9. This temperature difference was attributed to leak water being pumped into the system between KTIs 4 and 9. The average inlet temperature for KTIs 1–4 was 11.54 °C, compared with an overall mean of 8.25 °C with a standard deviation (σ) of 2.73. This was due to the mixing of warmer leak water with the chilled supply.

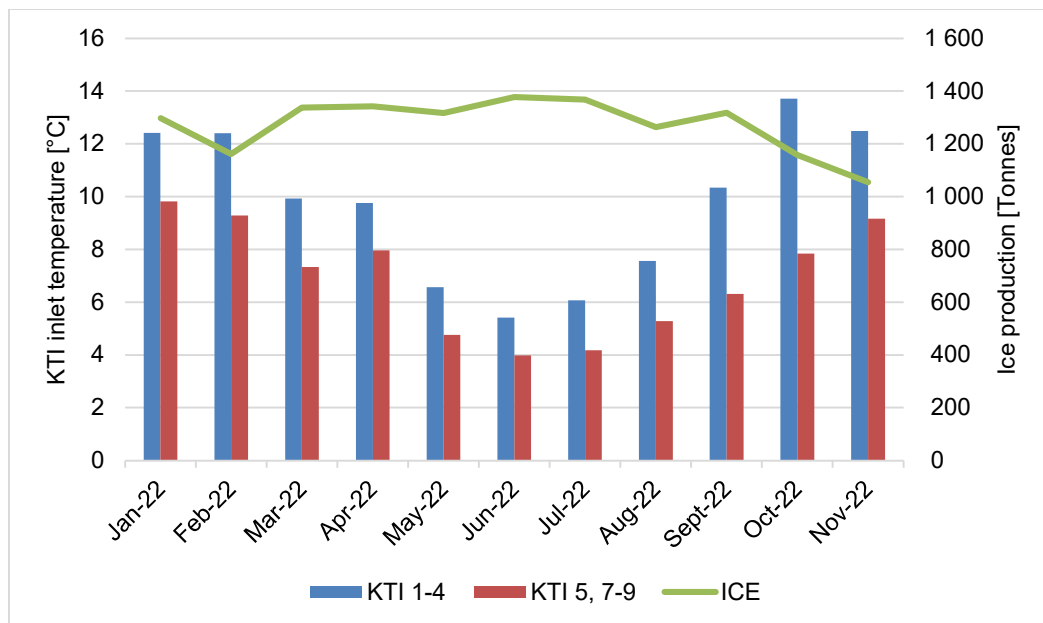


Figure 4-9: Comparison between average daily ice production and water inlet temperatures for KTIs

The relationship between inlet water temperature and daily ice production is shown in Figure 4-10. The mean daily ice production over the dataset was 1 292 tonnes ($\sigma = 189$). The high variance compared to the relatively small variance in inlet temperature suggested that other variables, such as compressor availability and operational interruptions, strongly influenced production. This was

consistent with field observations and was further examined in the analysis of running status. A linear regression gave equation 4.1:

$$\text{Ice Production} = -40.82 \cdot T + 1609.8 \quad (4.1)$$

with a coefficient of determination of $R^2=0.34$. This means that approximately 34% of the variation in ice production could be explained by inlet water temperature. The negative slope indicated that, on average, each 1 °C increase in inlet temperature reduced ice production by about 41 tonnes/day. The regression coefficient was found to be statistically significant with a p-value of 2.39×10^{-17} , confirming that the observed trend was not due to random chance. However, the lower R^2 value suggested that other factors, such as compressor running status, also strongly influenced production. These statistical values are summarised in Table 4-8. If the water inlet temperatures for KTIs 1–4 were lowered to match those of KTIs 5,7–9, it was expected that average ice production would increase substantially.

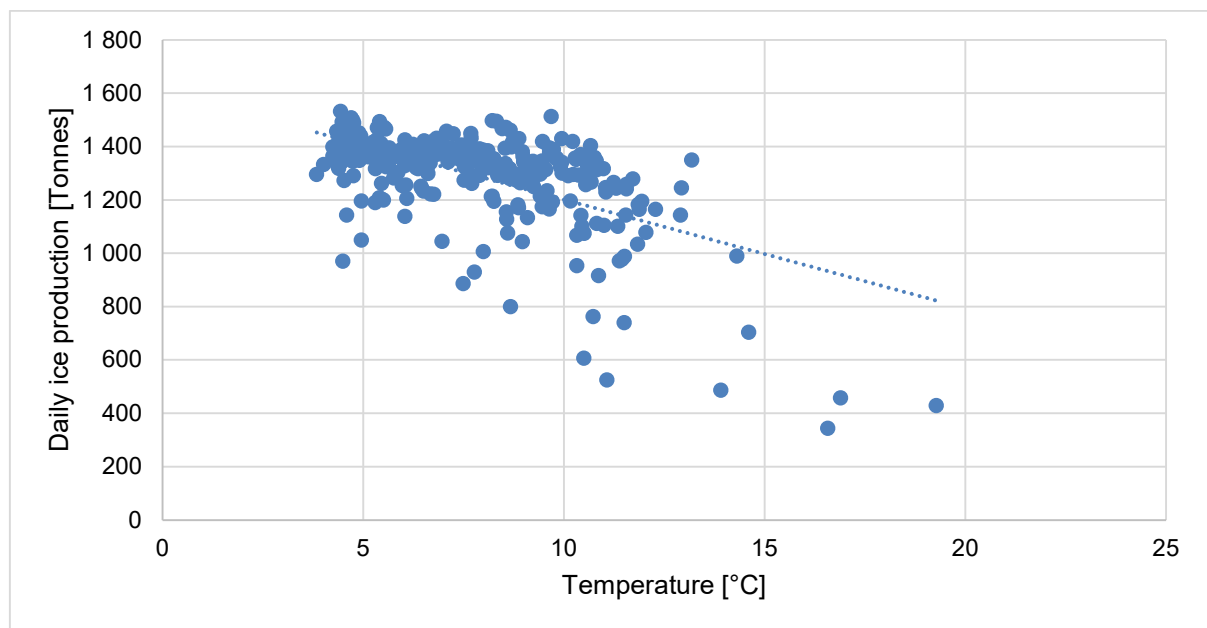


Figure 4-10: Comparison between average KTI water inlet temperature and daily ice production

Table 4-8: Statistical summary of inlet temperature vs ice production

Regression model	Equation	R^2	Slope interpretation	p-value
Linear fit	$y = -40.82T + 1609.8$	0.34	-41 tonnes/°C	<0.0001

Another issue caused by the leak water was the increased maintenance demand for the affected KTIs. Leak water flowing over the ground accumulated contaminants, which promoted faster scale buildup and blockages in the ice making units. As a result, KTIs 1–4 required more frequent shutdowns for cleaning.

Figure 4-11 illustrates that KTIs 1–4 operated on average 6% less than KTIs 5,7–9. Figure 4-12 compares compressor running status with daily ice production, showing a strong positive relationship. A linear regression gave:

$$\text{Ice Production} = 149.29 + 1321.09 \cdot \text{Running Status} \quad (4.2)$$

with $R^2=0.745$, indicating that 74.5% of the variation in ice production could be explained by compressor running status. The slope was highly significant ($p < 0.001$), showing that increased availability directly translated to higher production. The mean running status was 0.866, with a standard deviation (σ) of 0.126, showing that compressors were typically near full utilisation, but with noticeable downtime events. The corresponding mean daily ice production was 1293 tonnes, with $\sigma=189$. This confirmed that small reductions in compressor availability corresponded to disproportionately large reductions in ice production.

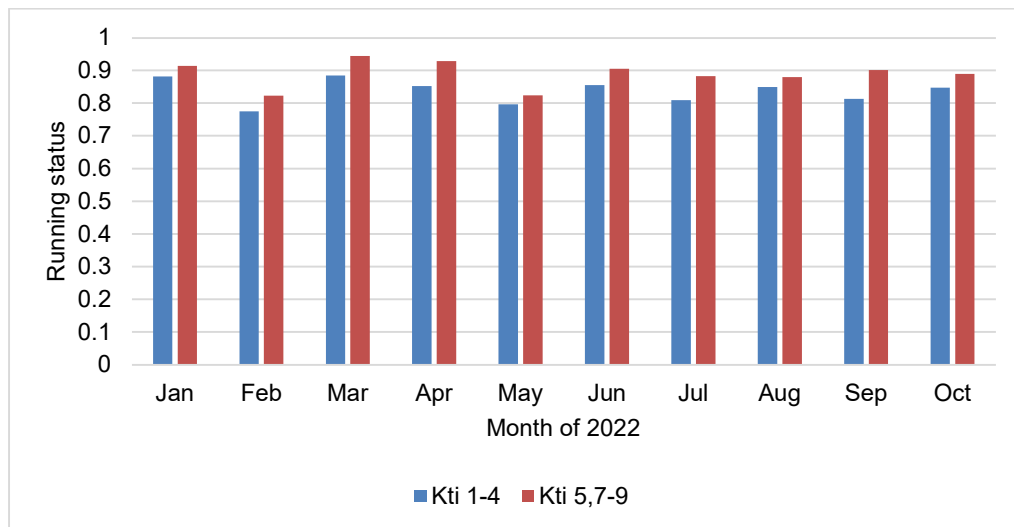


Figure 4-11: Running status comparison between KTI 1-4 and KTI 5,7-9

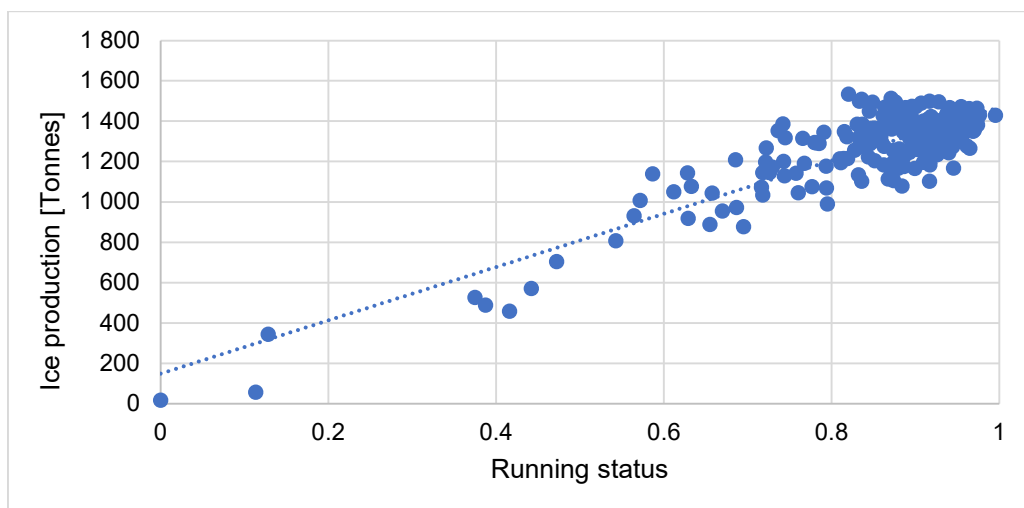


Figure 4-12: Comparison between compressor running status and daily ice production

These statistical values are summarised in Table 4-9. Raising the average operating status of KTIs 1–4 to the levels observed in KTIs 5,7–9 would therefore be expected to significantly increase daily ice output.

Table 4-9: Statistical summary of running status vs ice production

Regression model	Equation	R ²	Slope interpretation	p-value
Linear fit	$y = 149.29 + 1321.09 \cdot Status$	0.745	+1321 tonnes/day/unit status	<0.0001

Cladding on chilled water pipes

The final problem identified was the absence of insulating cladding on chilled water pipes. This allowed heat to be introduced to the system as the cold-water travelled from the chillers to the KTIs. As shown in Figure 4-10, lower inlet water temperatures correlated with higher ice production.

Visual inspections conducted in Step 1 revealed that none of the chilled water pipes were fitted with cladding. These pipes, which can span distances of up to 70 m, were exposed to direct sunlight throughout their journey to their destinations. Manual temperature measurements were taken daily between 10:00 and 11:00 from April 19, 2023, to April 26, 2023, and are summarised in Table 4-10. Note, changes have been made to the system as discussed in the implementation stage in Section 4.6.

Table 4-10: Chiller 1 outlet temperature compared with KTI inlet temperatures

Component	Average Temperature [°C]	Temperature Gain [°C]
Chiller 1 Outlet	7.6	-
KTI 1	7.84	0.24
KTI 2	7.75	0.15
KTI 3	7.87	0.27
KTI 4	7.9	0.3
KTI 5	7.89	0.29
KTI 7	7.6	0
KTI 8	7.82	0.22
KTI 9	7.78	0.18

The measurements indicated an average heat gain of 0.21 °C between Chiller 1's water outlet and the water inlets at each KTI unit.

Chiller Flow Capacity

It was identified that KTI 6, the chiller, was underspecified to sufficiently cool the water flow rate required for the targeted ice production. Specifications gathered from the manufacturer showed that the chiller could cool down a max water flow rate of 15.75 l/s or 1 360 tonnes per day. Measurements from Step 1 showed that Chiller 1 received water flow rates of up to 21 l/s. This higher flow rate was caused by water leaking from the KTIs, which increased the water demand.

Even when all leaks on the pipes were eliminated and all water were used, the water flow rate was still above chiller design limits. The 8 KTIs were designed to produce 1 600 tonnes of ice per day (18.52 l/s), while the target production was 1 400 tonnes per day (16.2 l/s); both required more chilled water than what the chiller could effectively produce.

Component wear

Many compressors inside the KTIs and chillers were operating well past their recommended lifetime of 30 000 hours. It is anticipated that the performance of compressors will decline with age. Data collected in Step 1, presented in Table 4-11 below, indicates that all compressors have exceeded their recommended lifespan, except for Chiller 2.

Table 4-11: KTI compressors running hours

Component	Rated life [hrs]	Current running time [hrs]
KTI 1	30 000	76 000
KTI 2	30 000	76 000
KTI 3	30 000	62 000
KTI 4	30 000	62 000
KTI 5	30 000	62 000
KTI 6 (Chiller 1)	30 000	40 000
KTI 7	30 000	62 000
KTI 8	30 000	39 000
KTI 9	30 000	39 000
KTI 10 (Chiller 2)	30 000	11 000

A performance increase is expected when the over-used compressors are replaced. When queried on why these compressors were allowed to run so far past their recommended lifetime, the on-site personnel stated that new compressors were too expensive and did not fit into the budget. The compressors were only replaced when they break down beyond repair.

The performance of both chillers was investigated to determine their cooling capacities. Figure 4-13 shows the average performance of both chillers as well as their average running hours. As the cooling requirements change from summer to winter, a dynamic duty target was added to the graph to show the required duty to achieve a water output temperature of 5 °C. The equation for determining the dynamic duty is shown in Equation 4.3.

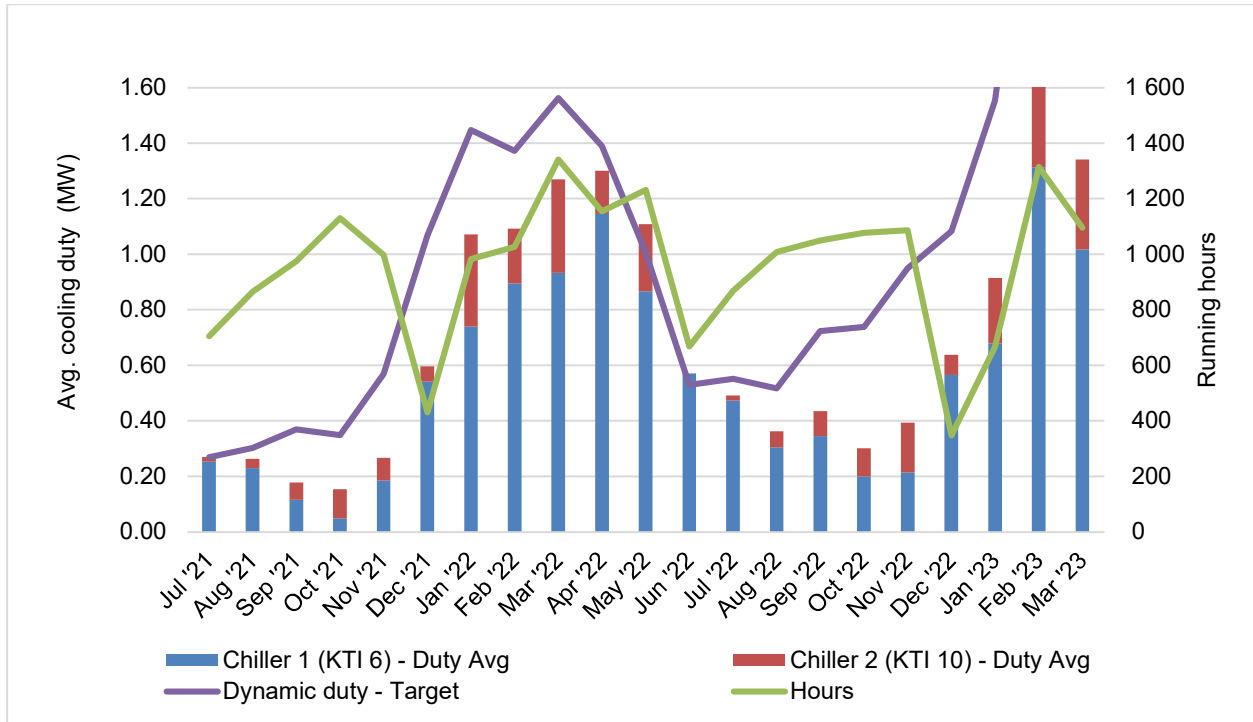


Figure 4-13: Chiller 1 and 2 average performances

$$Q = \frac{(m1 + m2) * Cp_w * (\frac{T_1 + T_2}{2} - T_o)}{1000} \quad (4.3)$$

Q	Dynamic cooling duty	MW
m	Mass flow	kg/s
Cp _w	Specific heat capacity of water = 4.184	kJ/kg°C
T	Chiller inlet temperature	°C
T _o	Target outlet temperature = 5	°C

Figure 4-13 illustrates that both chillers were underperforming, failing to cool the supplied water to the target temperature of 5 °C. This shortfall was particularly pronounced during the summer months, when higher inlet water temperatures placed additional demands on the chillers' cooling capacity. The increased cooling requirement during this period highlights the need for system refurbishment to ensure cooling demands are met.

The low cooling duty of Chiller 2 can be attributed to its reduced water flow rates, as shown in Figure 4-14. This was a result of Chiller 2's lower utilisation compared with Chiller 1, which significantly decreased its overall water flow requirements.

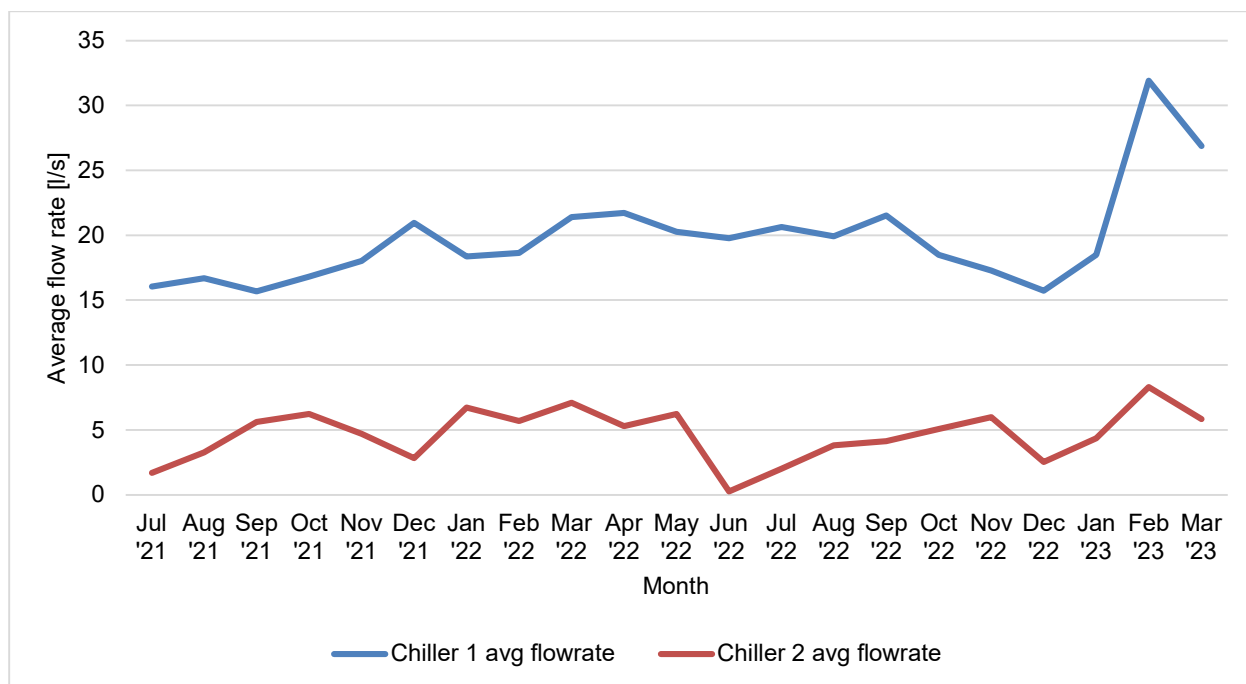


Figure 4-14: Average water inlet flow rates for Chillers 1 and 2

4.5.2 Development of possible solutions

A tailored solution was developed for each issue identified in Section 4.5.1, addressing the unique challenges that impact the ice plant's efficiency and performance. By targeting the root causes of each identified issue, the proposed solutions aimed to deliver measurable improvements across the plant's operations.

Leak water

Due to the ice plant's design, some water leakage is unavoidable and requires effective management, similar to standard practices for handling leaks at each level underground in a mine [36], [92]. The main issues with leaked water entering the system are its high temperature and contamination. By addressing these issues through cooling and filtering the leaked water, the performance of the KTIs receiving this water could be significantly improved.

There were two possible solutions to this problem. The first option was to filter out the contaminants and to send the water through Chiller 1 before being delivered to the KTIs. The other option was to remove the leak water from the ice plant network entirely.

Option 1 required the rerouting of pipes as shown in Figure 4-15. The leak water is pumped from the right-side spindle pump towards the left-side pump. The leak water would then be pumped from the left spindle pump back into the manifold as indicated in red. Before reaching the manifold,

the leak water must move through a filter to remove contaminants or hard minerals. From the manifold, the filtered leak water would return to the water network where it would be directed to numerous evaporative condensers as well as Chiller 1 and 2. The main problems of the leak water would thus be removed, and the ice production of the ice plant would be expected to improve.

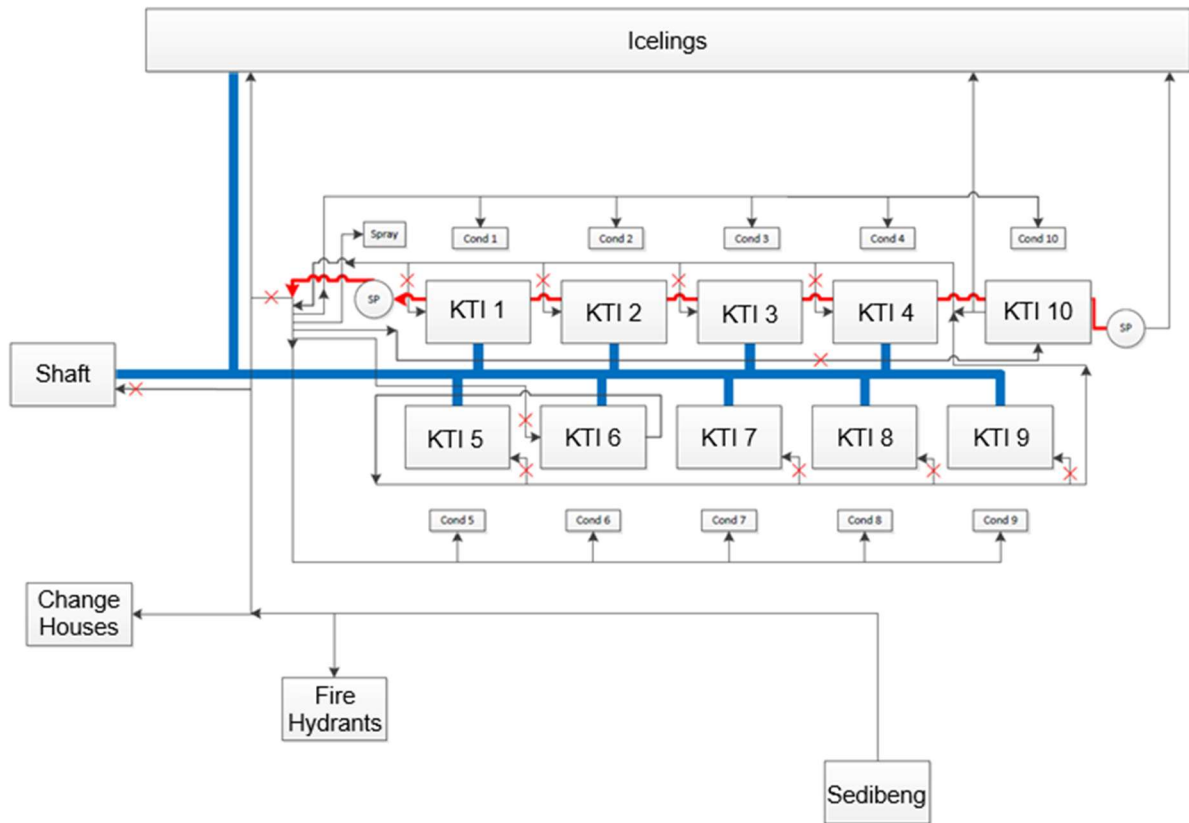


Figure 4-15: Diagram illustrating option 1's leak water rerouting

Option 2 focused on the removal of the leak water from the KTI ice plant. Due to environmental obligations, Mine A cannot remove the leak water from their grounds. The leak water must be re-introduced into the mining environment. The Icelings ice plants which are next to the KTI ice plants can handle high temperature water without having a reduction in ice output. This makes them a good candidate to receive the leak water. Figure 4-16 illustrates the rerouting of leak water towards a coffer dam before being fed to the Icelings. Although the temperature is not a problem, the water would be required to be filtered to reduce downtime. A filter could thus be installed between the coffer dam and the Icelings.

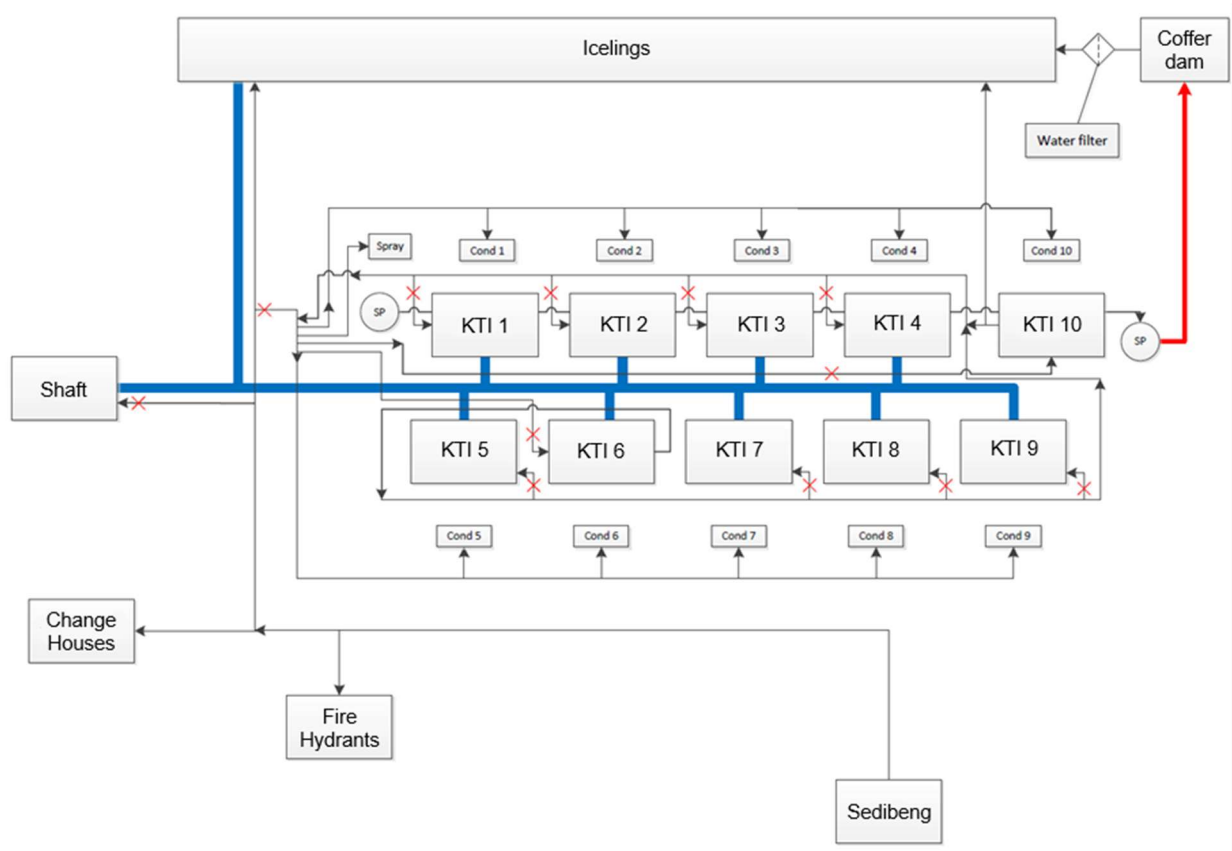


Figure 4-16: Diagram illustrating option 2's leak water rerouting

Cladding on chilled water pipes

To minimise heat entering the system, insulating cladding should be added to the chilled water pipelines. This insulation would reduce heat gain as the chilled water travels from the chiller to the ice making KTIs, resulting in a lower inlet temperature and increased ice production.

Chiller flow capacity

One chiller, which is rated to handle 15.75 l/s of water is unable to sufficiently cool down the measured flow rate of 18 l/s. The water flow rate must be reduced, or the available cooling capacity must be increased. The minimum water flow rate to produce the target tonnes of ice per day, which is 16.2 l/s, is larger than what the chiller can handle, so a reduction of water flow is unfeasible. The cooling capacity must thus be increased.

Chiller 2, which supplies chilled water to the Icelings, has a utilisation of 22%. This chiller can be used to supply the rest of the required chilled water. Figure 4-17 shows the required pipe rerouting to supply each KTI with sufficiently cooled water.

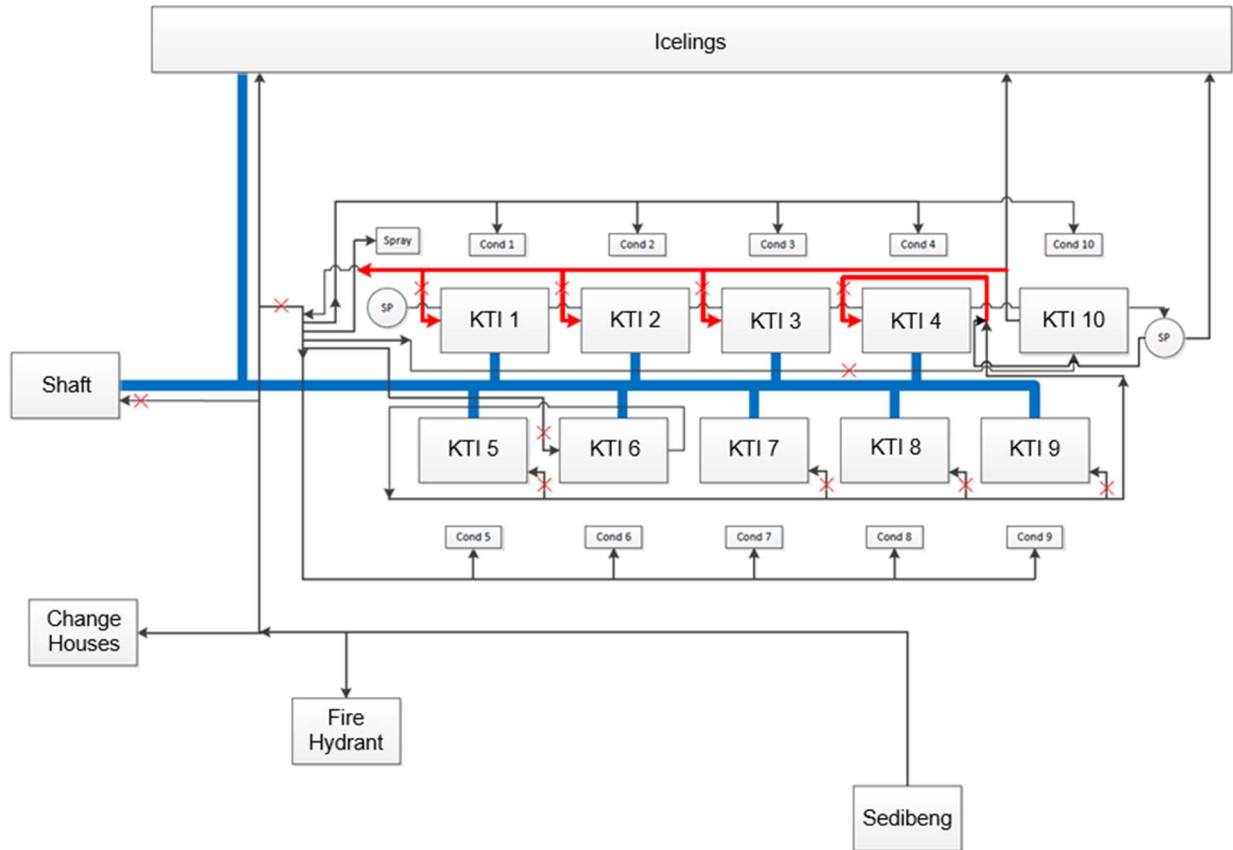


Figure 4-17: KTI network diagram with chiller rerouting

Chiller 1 (KTI 6) can be connected to five ice making units, requiring 11.575 l/s of chilled water, while Chiller 2 (KTI 10) can be connected to three ice making units, requiring 6.945 l/s of chilled water. This new configuration would ensure that Chiller 1 can adequately cool the water supplied to its connected KTIs, with some allowance for leaks. Meanwhile, Chiller 2 would utilise 44% of its cooling capacity for its KTIs while maintaining the ability to supply chilled water to the Icelings.

Component wear

Compressors operating beyond their recommended lifespan were performing below optimal efficiency and required more frequent maintenance than would be needed if they were within their service life. This increased downtime and reduced performance resulted in lower ice production. Refurbishing the compressors was necessary to address these inefficiencies; however, due to the high costs, priority was given to refurbishing the lowest-performing compressors first.

Before implementing any proposed solutions at Mine A, each option had to undergo thorough analysis to assess its feasibility, anticipated impact, and alignment with the project's objectives. This involved evaluating the practicality and potential benefits of each solution to predict how well it would improve ice production and overall system efficiency. Only those solutions demonstrating strong feasibility and positive outcomes were recommended for implementation, ensuring that resources were directed towards the most effective improvements.

4.5.3 Analysis of proposed solutions

Each proposed solution had to undergo a thorough feasibility assessment to determine its practicality and alignment with the operational requirements of the ice plant. This evaluation included analysing resource requirements, anticipated impact on ice production, compatibility with existing systems, and any associated risks or limitations. Only solutions that demonstrated strong feasibility—meaning they were achievable, effective, and economically viable—were recommended for implementation. Once these solutions had been validated as feasible, they were presented to Mine A for consideration.

Leak water

Removing the contaminated leak water offered a practical solution that can be implemented with relatively low additional costs and within a short timeframe. This approach involved straightforward modifications to the water management system to isolate and redirect the leak water before it mixed with the main chilled water supply. By filtering out contaminants and reducing the water's temperature prior to reintroduction, the solution would minimise operational disruptions while improving system efficiency. Given its cost-effectiveness and ease of integration, this solution presented an immediate improvement to the ice plant's overall performance with minimal resource demands.

Option 1 and 2, shown in Figure 4-15 and Figure 4-16, were both simulated to determine the effects of the rerouting on the ice plant network. The simulations revealed a limitation on the potential solution. In the simulation, the reintroduction of leak water into the chilled water line reduced the water flow through Chiller 1 by 4 l/s. By removing the leak water from the system, the water flow rate through the chiller increased up to 24 l/s. This was above the Chillers capacity; insufficient cooling was thus experienced on the KTI supply water, but both sets of KTIs received similar temperature water.

Under the same conditions as in Jan–Apr 2022, the simulated temperature delta between KTI 1-4 and KTI 5,7-9 lessened, and the average inlet temperature for KTI 5,7-9 increased to 9.6 °C from 8.6 °C, as shown in Figure 4-18 . The overall average KTI inlet temperature decreased to 9.62 °C from 9.86 °C. This resulted in a predicted ice production increase of 10 tonnes per day, which is a 0.82% improvement.

The removal of leak water from the system would allow further improvements to be done on the ice plant network. Additionally, maintenance on KTI 1-4 could potentially decrease due to higher quality water being used.

Cladding on chilled water pipes

Implementing cladding on chilled water pipes is a cost-effective and low-risk intervention that provides incremental improvements in system performance. A modest 0.21 °C reduction in inlet temperatures was expected. This could increase the ice production with 8 tonnes per day which is a 0.71% improvement.

Cladding is best considered as part of a broader strategy to improve system performance, complementing higher-impact solutions like chiller refurbishment or the implementation of Chiller 2.

Chiller flow capacity

As discussed in Section 4.5.2, the proposed rerouting shown in Figure 4-17 reduced the water flow demand on Chiller 1 to below its design capacity of 15.75 l/s in the simulation. This was only the case if excess water usage caused by water leaks was removed from the system.

Utilising Chiller 2 was expected to significantly lower KTI inlet temperatures to 5.4 °C, resulting in a 15.88% increase in daily ice production, equivalent to an additional 191.92 tonnes of ice.

Additionally, in the simulation, the added chiller reduced the operational strain on Chiller 1 and other cooling components, leading to better system balance and reliability as shown by the cooling duty of each chiller shown in Table 4-12. This approach would not only maximise ice production, but would also support long-term system sustainability by distributing the workload across two chillers, reducing wear and tear on individual components.

Redistributing the flow rates through both chillers would only solve one part of the problem. Un-chilled water would still be fed into KTI 1-4. The leak water needs to be removed from the system to see positive results.

Component wear

The compressors were underperforming and required refurbishment. The underperforming compressors were causing inefficient operating conditions in Chiller 1. Chiller 1's underperformance is shown in Figure 4-13, alongside that of Chiller 2.

By refurbishing Chiller 1's compressors, several improvements could be expected. First, the refurbishment would lower the average KTI water inlet temperatures from 9.86 °C to 7.81 °C, as shown in Figure 4-18, which shows simulated possibilities. This reduction would significantly enhance cooling performance across the system. Second, ice production would be expected to increase by 8.51%, equating to an additional 102 tonnes of ice per day, which directly boosts operational output. Third, refurbished chillers typically consume less energy per tonne of ice produced, leading to improved energy efficiency and reduced operational costs. Finally, refurbishment enhances the reliability and longevity of the chiller, decreasing the risk of unexpected breakdowns and extending its lifespan. This improvement would minimise maintenance costs and downtime, ensuring consistent and efficient system performance.

Refurbishing Chiller 1 would be a high-impact, cost-effective solution for improving system performance. It would significantly reduce inlet temperatures, boosts ice production, improves energy efficiency, and enhances system reliability.

Summary

Figure 4-18 shows the expected KTI water inlet temperatures under different simulated scenarios for the months of January to April. A minimum chiller output temperature of 5 °C was set to match the chiller output target in Table 4-2 .Table 4-112 shows the duty done on the KTI inlet water by both chillers under the previously mentioned scenarios.

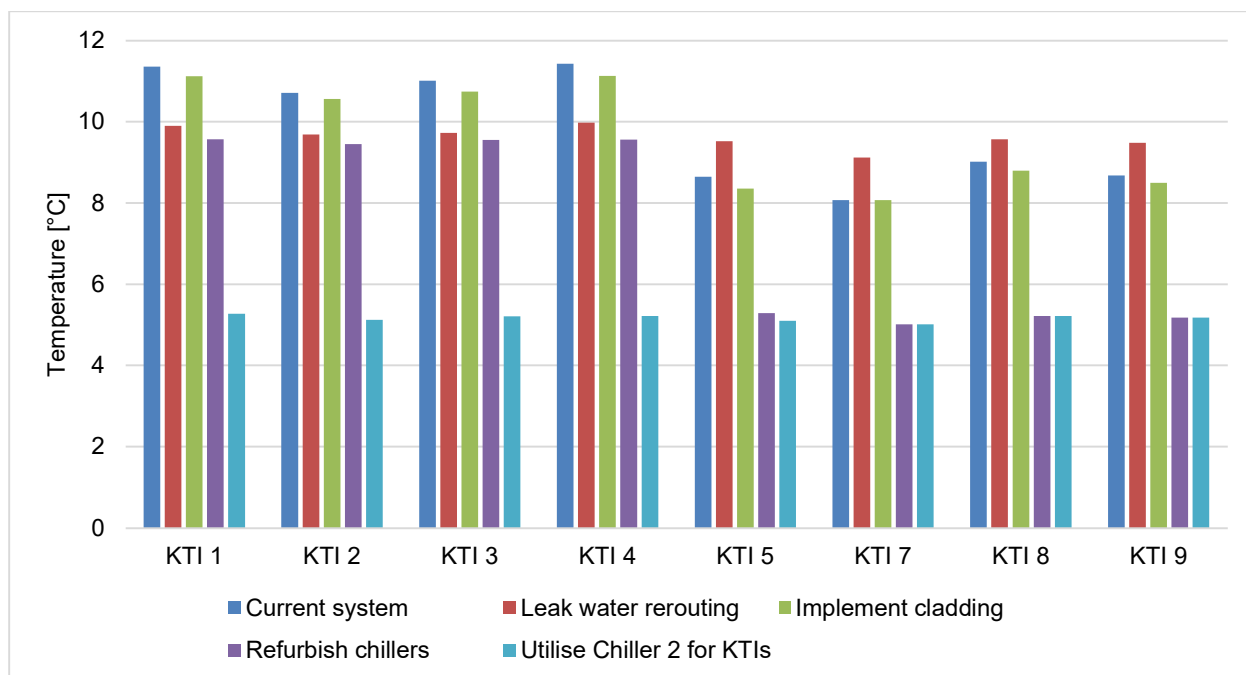


Figure 4-18: Effect of various solutions on KTI inlet temperature

Table 4-12: Chiller duty on KTI inlet water

	Chiller 1 duty [kW]	Chiller 2 duty [kW]
Current system	927.50	-
Refurbish chiller	1 519.19	-
Utilise Chiller 2 for KTIs	927.50	1 130.05

Figure 4-18 clearly demonstrates that utilising Chiller 2 would provide the most impactful improvement in cooling performance, making it the best single option for maximising ice production. Combining refurbishment and the utilisation of Chiller 2 is not required as the minimum temperature output stops at 5 °C. Cladding would further improve the KTI inlet temperature by removing heat gain during transport, but this would only have a marginal effect on the overall temperature.

4.6 Step 4: Solution implementation

The feasible solutions identified were presented to Mine A for implementation, with the responsibility for executing these improvements resting with Mine A's operational team. After reviewing the proposed solutions, Mine A opted to implement only the leak water redirection solution, specifically Option 2, which reroutes the water to a surface dam, despite the existing limitations of Chiller 1 as discussed in Section 4.5.1 and 4.5.3. The leak water rerouting to Icelings was implemented in December 2022.

This selective approach reflects Mine A's prioritisation strategy and available resources, focusing on addressing the immediate issues caused by high-temperature, contaminated leak water in the system. For the implementation phase, economical constraints as well as the current projects that the mine is focused on at any given time must also be considered when implementing the method. Although long-term improvements can be seen on other solutions, Mine A favoured low-cost implementations which will show immediate payback. The research process shown in Figure 1-7 indicates that improvements must be made on the constructed method where necessary. Because the mine's prioritisation strategy will influence the outcome of the method, it is recommended that future studies should take this into account.

It is acknowledged that, without addressing Chiller 1's limitations, further performance improvements may be constrained. Chiller 1 operated above maximum capacity during the evaluation period and by rerouting the leak water it will put additional strain on the chiller. By not addressing these inefficiencies, Chiller 1 and its limited cooling output would reduce the temperature improvements achievable across the KTIs, thereby diminishing the effectiveness of the rerouted leak water solution, as Chiller 1 cannot accommodate the larger amounts of water as discussed in the previous section. It can, therefore, be theorised that, had Chiller 1's performance constraints been mitigated, either through refurbishment or by operating a second chiller in parallel, the rerouting solution would have achieved a more substantial improvement in ice production by working in tandem with the chiller capacity solution.

4.7 Step 5: Evaluation

The effectiveness of the implemented solution was evaluated by measuring its impact on ice production, as the primary objective of this method was to increase the ice plant network's output.

In May 2024, four months after the implementation of the leak water rerouting solution, the evaluation took place.

Figure 4-19 shows the average daily ice production from January to April for the years 2021, 2022, and 2023. A comparison of these periods reveals that ice production has continued its declining trend, with a 2.8% decrease observed in 2023, decreasing from 1 284 tonnes per day in 2022 to 1 248 tonnes per day in 2023.

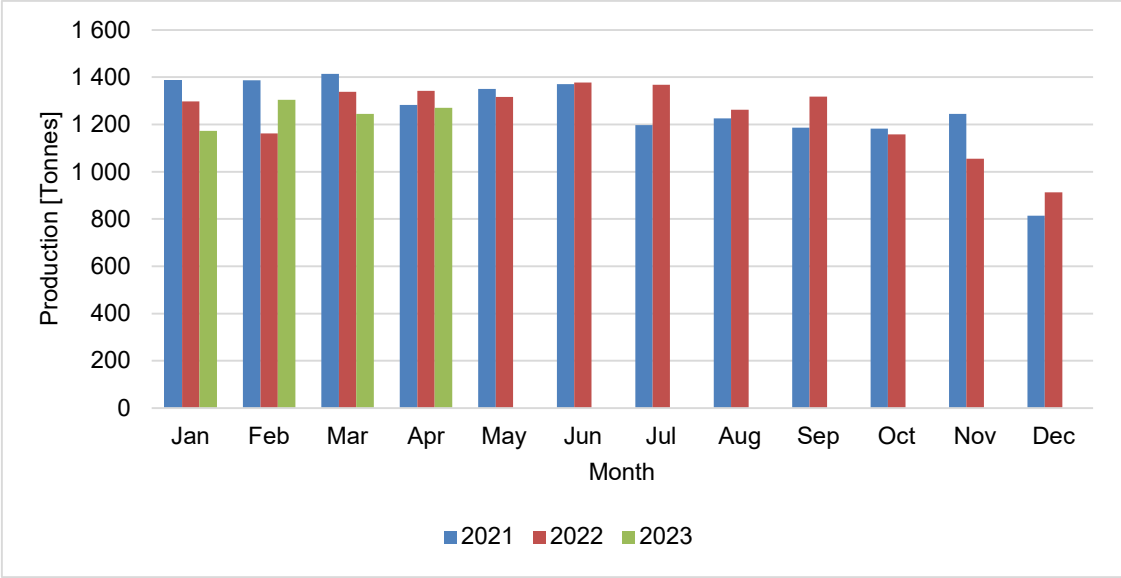


Figure 4-19: KTI ice plant production after solution implementation

The effects of the leak water rerouting can be seen in Figure 4-20. As expected, the temperature peaks decreased, as well as the temperature delta between the two sets of KTIs. This came with the downside of a slightly higher average water inlet temperature of 10.97 °C compared to 2022’s 9.86 °C (January to April). This increase can be attributed to the warmer summer conditions in 2023, coupled with a higher chiller inlet temperature of 19.8 °C compared to 17.9 °C in 2022. Additionally, elevated ambient temperatures during the summer of 2023 reduced the heat rejection efficiency of the condensers, further impacting system performance.

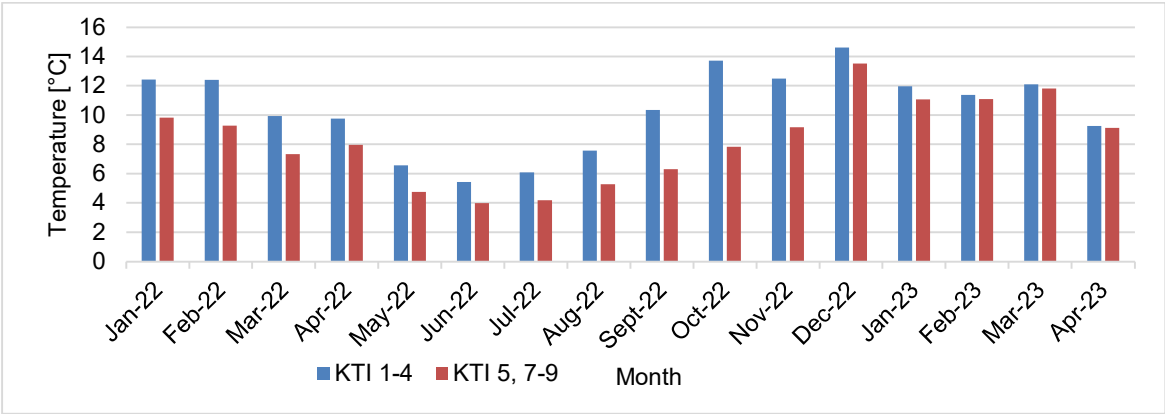


Figure 4-20: KTI average inlet temperature comparison after leak water rerouting

The increased KTI water inlet temperature explains the decrease in ice production as predicted in Figure 4-10. Figure 4-20 supports the prediction made in Section 4.5.3, which emphasised that improving chiller flow capacity, in addition to implementing leak water rerouting, is essential to achieve greater reductions in KTI inlet temperatures. The theoretical evaluation of the other proposed implementations are further discussed below.

4.7.1 Theoretical evaluation

When plotting the average KTI water inlet temperatures and the daily ice production on Figure 4-10, a prediction error of only 6.9% was observed. This validates the accuracy of the graph and suggests that the method can reliably predict expected ice production under different conditions. Using the graph, the expected outcomes of additional solutions proposed in Section 3.5 can be estimated under conditions similar to the summer of 2022, given in Table 4-13.

Table 4-13: Expected ice production for different scenarios

Scenario	Average KTI inlet temperature [°C]	Expected daily ice production [Tonnes]	Increase	Annual energy cost equivalent
Original System	9.86	1 207.00	-	
Implement Cladding	9.19	1 215.56	0.71 %	R 224 200
Refurbish Chiller	7.81	1 309.64	8.51 %	R 2 688 311
Utilise Chiller 2 for KTIs	5.40	1 398.92	15.88 %	R 5 026 703

By enhancing the efficiency of the ice plants, it is possible to produce more ice while using the same amount of energy, thanks to continuous operation of the plants. This increased ice production can be translated to significant cost savings by comparing the energy required to produce the same amount of ice with a separate unit operating under standard conditions.

The findings in Table 4-13 demonstrate that, while the implemented solution of leak water rerouting addressed some inefficiencies, it was not sufficient on its own to counteract the challenges posed by external factors, such as warmer ambient temperatures and higher chiller inlet temperatures. To achieve significant improvements in ice production, additional solutions such as chiller refurbishment or the use of a second chiller, will be required. The method remains theoretically successful, as it provides accurate predictions and a clear pathway for achieving enhanced performance when multiple solutions are applied in combination.

When the simulation results were adjusted for these elevated ambient conditions, the predicted inlet temperature aligned with the measured data to within 5% as shown in Table 4-14, indicating that the method's predictive capability remains accurate despite the differing environmental conditions. This comparison validates the reliability of the developed optimisation method and demonstrates its potential to predict realistic outcomes under varying operating environments, provided that accurate environmental data are incorporated into the simulations.

Table 4-14: Actual inlet temperatures compared to simulated temperatures after implementation

	Actual inlet temperature [°C]	Simulated inlet temperature [°C]	Percentage error [%]
KTI 1	9.76	9.91	1.53
KTI 2	9.9	9.69	2.12
KTI 3	10.09	9.73	3.57
KTI 4	9.59	9.98	4.07
KTI 5	9.64	9.52	1.24
KTI 7	9.64	9.12	5.39
KTI 8	9.23	9.56	3.58
KTI 9	9.32	9.48	1.72

4.8 Limitation of the case study

During the case study various limitations have been noted which will influence the outcome of this study. These limitations will be named and discussed here.

4.8.1 Unreliable measurement equipment

At Mine A, a significant limitation identified during the study was the unreliability and inaccuracy of the installed measurement equipment. The existing instrumentation does not consistently provide dependable data, which introduces uncertainty into the analysis and subsequent optimisation efforts.

To mitigate this issue, manual measurements were conducted using a calibrated instrument. While this approach improved measurement accuracy at specific points, it introduced several practical constraints. Manual measurements are time-consuming and can only be performed at

one location at a time. As a result, it is not feasible to capture simultaneous system-wide data across the complex network.

In an ideal scenario, accurate and reliable instrumentation would be installed at all relevant measurement points across the network. Continuous, synchronized data collection would improve validation accuracy and allow for higher-confidence optimisation decisions.

4.8.2 Limited implementation

Another limitation of this study is that only a single proposed solution has been implemented at the mine. Although this implementation is sufficient to validate the developed method, it limits the scope of validation.

4.9 Method Validation

Table 4-15 below highlights the alignment between the study's objectives and the steps of the method. It demonstrates that the proposed method is comprehensive and systematically addresses the goals of the study.

Table 4-15: Study objectives validation

Criterion	Criterion satisfied in	
Objectives (Section 1.7)		
Optimise ice plant production,	Step 5	Section 4.7
For deep-level mining operations,	Step 1	Section 4.3
By applying a simulation-based approach	Step 2-3	Section 4.4-4.5
Using a structured method	Step 1-5	Section 4.3-4.7
Focused on the water pre-cooling (refrigeration) network	Step 1-4	Section 4.3-4.6
To improve service delivery	Step 4-5	Section 4.6-4.7

4.9.1 Results comparison to previous studies

To increase the validity of the presented study, previous studies and their results were consulted and compared with the presented study. The goal of this section was to prove that the results in

Section 4 were within realistic expectations. The studies considered focused mostly on pre-cooling, as this part of the refrigeration network was improved upon in the results.

Two studies were identified of which the goals were closely related to the refrigeration network and methods used to improve the network.

4.9.1.1 Study one

Title: Improving deep-level mining refrigeration through increasing pre-cooling efficiency [89]

The first study considered in the comparison focused on improving a refrigeration network by increasing its pre-cooling efficiency, as previously discussed in Section 2.3.8. The study improved refrigeration plant service delivery by reducing the temperature of water supplied to the refrigeration plants by 4.7 °C, which resulted in a 24.4% increase in efficiency. The use of chilled water allowed the refrigeration plants to produce colder water in greater quantities. These findings align with the results presented in Sections 4.5.3 and 4.7, where it was predicted that supplying cooler water, with a reduction of 4.46 °C, would enhance ice plant performance and lead to increased ice production.

Furthermore, the study applied the same simulation software, PTB, to test its proposed solutions and predicted the inlet pre-chilled water temperatures to within 2.2% accuracy. This is comparable to the method used in the present study, which achieved a maximum error of 4.29% (see Section 4.4).

The main distinction between the two studies is that the earlier improvements were implemented via a cooling tower, whereas the present study focused on a chiller. Nonetheless, the purpose of both components, namely cooling water, remains the same.

4.9.1.2 Study two

Title: Analysing the impact of refurbishing precooling towers on a deep-level mine [91]

Study two developed a refurbishment strategy for PCTs and verified the proposed solutions through simulations before implementing them on a mine, similar to the approach taken in the present study.

The refurbishment strategy enhanced PCT performance by 29.5%, which reduced the inlet temperature to the refrigeration plants, increased their effectiveness by 2.6%, and improved the

overall refrigeration network efficiency by 12.3%. These outcomes are consistent with the more conservative improvements reported in the present study, where the effectiveness of refrigeration units was shown to increase by 0.71–15.88% when appropriate solutions were applied.

As with Study one, Study two focused on pre-cooling towers rather than a chiller. Nevertheless, both components serve the same objective: supplying cooler water to the refrigeration units and thereby enhancing the performance of the refrigeration network.

4.9.1.3 Summary

Table 4-16 summarises relevant aspects of the present study compared with the two previous studies, followed by Figure 4-21, which visually compares the studies.

Table 4-16: Result comparison to previous studies

	Study 1	Study 2	Present Study
Objective	Reduce water supply temperature to improve refrigeration plant efficiency	Enhance PCT performance to improve refrigeration effectiveness	Increase ice production and network efficiency
System Component Studied	Cooling tower and refrigeration plant	Pre-cooling towers and refrigeration plant	Chiller and ice making network
Temperature Reduction Achieved	4.7 °C	3.7 °C	4.46 °C
Performance / Efficiency Improvement	24.4 % increase in refrigeration efficiency	29.5 % PCT performance, 2.6 % refrigeration effectiveness, 12.3 % network efficiency	0.71 % – 15.88 % improvement in ice maker effectiveness
Simulation Tool	PTB software	PTB software	PTB software
Prediction Accuracy	2.2 % error	8.4 % error	4.29 % error
Implementations	Cooling tower improvements implemented	PCT refurbishment strategy implemented and validated on site	Leak water rerouting implemented; chiller-related improvements not yet applied

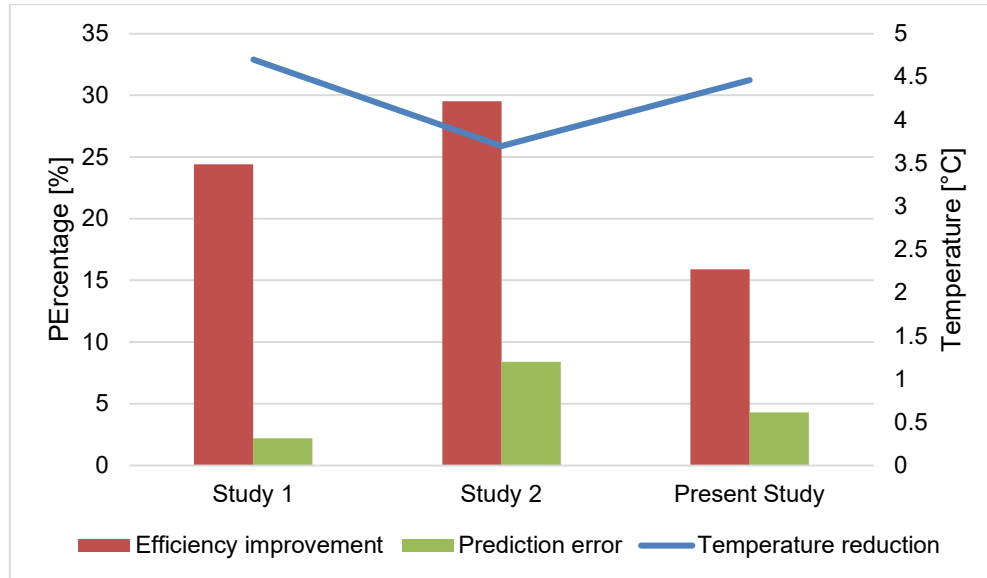


Figure 4-21: Results comparison between present study and previous studies

4.10 Conclusion

The developed method was applied to an ice plant network consisting of eight ice making units, one active chiller, and one inactive chiller. The method identified multiple potential improvements that could enhance the network's performance and increase ice production. Among these, the combination of utilising a second chiller and rerouting leak water was found to yield the highest production increase. However, Mine A implemented only the leak water rerouting solution, which resulted in a 2.8% decrease in ice production due to the warmer summer season of 2023. Under conditions similar to those in the summer of 2022, an increase of 0.82% in ice production could be expected from the rerouting solution alone, whereas implementing the second chiller could increase production by 15.88%. This improvement corresponds to an annual energy cost saving of up to R 5.03 million, based on the energy required to produce the same quantity of ice. When extrapolated to Mine B, the largest ice producer in South Africa with a peak production of 4 800 tonnes of ice per day, and assuming similar conditions to those at Mine A, an annual energy saving of up to R 15.09 million could be expected. Additionally, the method itself can be improved on by considering the mine's prioritisation strategy when developing solutions.

CHAPTER 5: CONSLUSION

5.1 Preamble

This chapter concludes the case study research methodology by discussing the outcome of the study as shown in Figure 5-1 below.

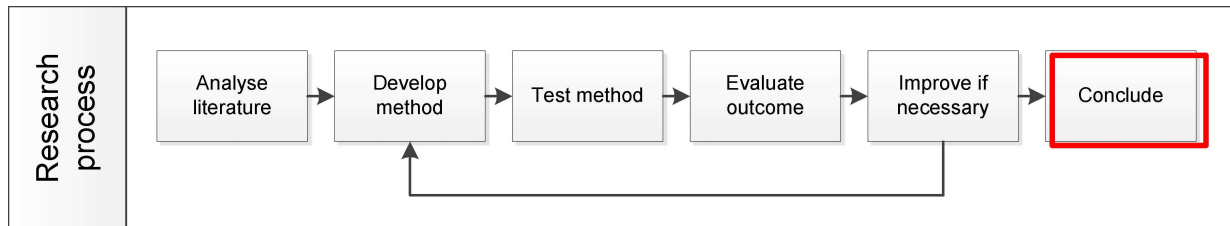


Figure 5-1: Conclude stage in research methodology

The study is concluded in Section 5.2. Afterwards, recommendations are given for future research in Section 5.3. The chapter concludes with a reflection on the method and objectives in Section 5.4.

5.2 Conclusions

South Africa's gold production has been consistently decreasing since its peak in 1970, partly due to the depletion of high-grade reserves. The increasing depths of gold mines in South Africa results in higher ambient air temperatures in working places. This challenge, coupled with the increasing energy tariffs, forces mines to adopt more efficient practices in order to make a profit.

Mines in South Africa are legally required to maintain safe working conditions underground by keeping air wet-bulb temperatures below 32.5 °C. This is achieved by making use of deep-level mining cooling systems. In extreme depths of over 2 000 m, ice becomes a feasible method to provide the necessary cooling.

A problem facing mines equipped with ice plant networks is that they lose efficiency over time, and due to their complexity, it is difficult to identify the causes. Ice plants will therefore have lowered production, which reduces their overall cooling capacity in mines that are often increasing their depths and heat demands. A method to identify and solve these problems is needed to increase the cooling capacity of ice plants to combat the increasing heat loads in mines. A case-study research methodology was used in this study to create and analyse this method.

Chilled water produced by the refrigeration plant serves multiple critical functions throughout the mine. Heat exchangers utilise the chilled water to cool the surrounding air, ensuring a safe and comfortable working environment in the mine's operating underground areas. Additionally, drills rely on chilled water for effective cooling during operation, preventing overheating and maintaining performance. The water is also used for dust suppression, minimising airborne particulates and improving air quality. In some mines, high-pressure hoses use the chilled water to transport broken rock efficiently.

Ice plants, a type of refrigeration plant, is mostly seen in mines deeper than 1 900–2 300 m, as this is where they start to perform similarly on a cost front than their refrigeration plant counterparts that produce chilled water instead of ice. These ice plants produce large amounts of ice which is then transported underground to a chilled water dam from where it is distributed to users.

Due to their high complexity, refrigeration plant networks are time consuming and difficult to analyse holistically. Digital simulations have been used to analyse refrigeration plant networks, and similar methods can be applied to ice plants networks. These simulations can be used to identify and correct problems while exploring different options with a much lower turnaround time.

The method to improve ice production in ice plant networks on deep-level mines was constructed by considering the study objectives, simulation-based optimisation methods and previously used methods implemented on refrigeration plants.

The constructed method was applied to a case study mine, Mine A. This mine is a conventional deep-level gold mine in South Africa that makes use of an ice plant network to provide for most of its cooling requirements. This ice plant network has been producing lower amounts of ice each year.

The method was split into five steps. The investigation (Step 1) focused on collecting and analysing relevant data to be used to build a simulation model of the ice plant network in Step 2. The ice plant network was also visually inspected to identify visual problems and to get a better understanding of the system.

A baseline simulation model of the ice plant water network was built in Step 2 using Process Toolbox. This model was validated with the current ice plant network, which showed an accuracy of higher than 95%. The model was considered accurate and was acceptable to be used in the rest of the method.

The solution development step (Step 3) was used to identify various issues on the ice plant network and to determine their feasibility by making use of the model built in Step 2. In this step, four independent solutions were developed and analysed where it was determined that using a second chiller unit while rerouting leak water will result in the best ice production improvement of 15.88% while having a low cost of implementation.

The implementation step (Step 4) outlined which of the proposed solutions have been adopted and put into practice by the mine. In the case of Mine A, only the leak water rerouting solution was selected for implementation. This decision was made in December 2022, reflecting the mine's focus on addressing water management inefficiencies as a priority.

The final step, evaluation, focused on quantifying the improvements made to the system. The January to April periods of 2022 and 2023 were compared with each other. With only the leak water rerouting solution implemented, the daily average ice production decreased with 2.8%. This reduction can be attributed to the warmer summer season of 2023, which increased water temperatures and reduced heat rejection efficiencies.

The new average daily ice production matches predicted values with only a 6.9% error. Using a similar method, the predicted ice production amounts of the other proposed solutions can be theoretically proven to be accurate and an ice production increase of 15.88% is predicted under similar conditions as January to April 2022 if the solutions were implemented.

When extrapolated to Mine B, the largest ice producer in South Africa with a peak production of 4 800 tonnes of ice per day, and assuming similar conditions to those at Mine A, an annual energy saving of up to R 15.09 million could be expected.

The constructed method was shown to satisfy all objectives and requirements refined in the study. With the study objectives met, the study can be considered successful.

5.3 Recommendations

Based on the findings and experiences gained throughout this study, several recommendations are proposed to support future research and practical implementation aimed at improving ice plant performance on deep-level gold mines. These recommendations are grouped into three key areas: data and monitoring, method implementation, and system optimisation focus.

5.3.1 Data quality and ambient condition analysis

Future studies should prioritise the acquisition of accurate and continuous data from the ice plant network. During this study, unreliable instrumentation and missing measurements limited the ability to validate results with high precision. It is recommended that future projects include an initial data audit phase to assess the reliability of all sensors and measurement devices before modelling begins. Additionally, a detailed investigation into the influence of ambient air conditions on ice plant performance should be undertaken. This includes temperature, humidity, and barometric pressure. Comparing performance under different environmental conditions remains challenging, as identical ambient scenarios rarely occur. By developing correction factors or normalisation techniques, researchers can better isolate the effects of operational changes from environmental variability. This will enhance the accuracy of model validation and allow for more meaningful comparisons across time periods and sites.

5.3.2 Implementation and validation of multiple solutions

Only one proposed solution, the rerouting of leak water, was implemented in this study. While this provided valuable insights, it limited the scope for validation. Future research should aim to implement and monitor multiple improvement strategies simultaneously or sequentially. Doing so would expand the dataset and enable a more comprehensive understanding of how various interventions interact and influence overall system behaviour. It is also recommended that collaboration between research institutions and mining operations be strengthened to facilitate pilot studies, ensuring that practical constraints such as budget limitations, maintenance schedules, and production demands are considered early in the planning phase. Establishing such partnerships could improve both the feasibility and long-term impact of optimisation initiatives.

5.3.3 Broader optimisation focus

While this study primarily focused on increasing ice production, future work should adopt a broader optimisation perspective that includes energy efficiency. Ice production is inherently energy-intensive, and with rising electricity costs, improving system efficiency is equally critical. Researchers should investigate the incorporation of energy-efficient components, such as advanced chillers, improved heat exchangers, or variable-speed drives, and evaluate their impact on overall system performance. Integrating predictive control or machine-learning-based optimisation tools could offer dynamic adjustments to operating conditions, further reducing energy costs while maintaining desired production levels.

5.3.4 Future outlook

It is recommended that future studies build upon the developed method to establish a standardised framework for ice plant optimisation applicable across multiple mines. In doing so, the method should also account for each mine's prioritisation strategy and implementation capacity, as operational and financial constraints often determine which solutions can realistically be executed. Mines typically favour improvements that provide immediate returns or “low-hanging fruit” with minimal disruption to production. They also prioritise low-cost implementation; therefore, it is recommended that a cost analysis of potential solutions be conducted in future studies. Recognising and integrating this decision-making behaviour into the optimisation framework will enhance its practicality and adoption potential. With improved data collection, broader collaboration, and a dual focus on production and efficiency, the mining industry can significantly enhance its cooling operations. In the long term, incorporating such optimisation frameworks into digital mine management systems could contribute to substantial energy savings, reduced operational costs, and improved sustainability in South African deep-level mining.

5.4 Reflection on method and objectives

The development of the proposed optimisation method presented several challenges—the most significant being data limitations. Although the mine had a well-established system for monitoring its ice plants, numerous measurement devices were either faulty or produced large errors that required correction. Considerable time was devoted to verifying and calibrating these measurements using manual readings with reliable instruments to establish their accuracy. In addition, the mine's decision to discontinue its internal data-tracking license restricted access to recent operational data, which limited the overall dataset available for analysis. Validation of the method was also constrained, as only one of the proposed solutions could be implemented during the study period. A broader implementation would have provided a more robust dataset and greater insight into the method's full potential.

Collaboration with the mine's engineering staff was largely positive during the investigation phase. They facilitated access to the site, provided historical data upon request, and allowed space for measurements after the required safety procedures were completed. However, during the implementation phase, enthusiasm from operational staff was limited. Discussions with technicians and foremen revealed that the ice plants received minimal budget allocation, which contributed to maintenance issues and reluctance to engage with modification work. These practical constraints underscored the importance of organisational support and financial prioritisation when introducing optimisation strategies in an industrial environment.

The implementation process itself was relatively straightforward due to the method's adaptive and case-dependent design. Despite data quality issues, the method could be applied effectively, and its flexibility allowed for practical adjustments based on the available information. With higher-quality data and broader implementation, the method's potential for improving ice production efficiency could be demonstrated more clearly.

All of the objectives set out at the start of the study were achieved. The ice plant production process was investigated in detail, a simulation-based optimisation method for deep-level mines was developed, and the method was successfully implemented and evaluated. Nonetheless, numerous lessons were learned throughout the process. Unforeseen challenges frequently arose, requiring creative and pragmatic solutions. The importance of collaboration with on-site personnel also became evident, as their support and expertise were vital for obtaining accurate data and executing field measurements.

Looking forward, there is significant potential for further research into ice production systems and the role of ice as a cooling medium in deep-level mines. Currently, only a few studies focus specifically on the optimisation and performance improvement of ice plants. As mining depths increase and energy costs continue to rise, ice plants will play an increasingly critical role in the mine cooling cycle. Continued research and collaboration between academia and industry could therefore provide substantial benefits to the South African mining sector by improving operational efficiency and reducing energy consumption.

REFERENCES

- [1] P. Richardson and J.-J. Van Helten, "The Development of the South African Gold-Mining Industry, 1895-1918," *The Economic History Review*, vol. 37, no. 3, p. 23, 1984.
- [2] D. Michaud, "Witwatersrand Gold Deposits." Accessed: Oct. 25, 2023. [Online]. Available: <https://www.911metallurgist.com/blog/witwatersrand-gold-deposits#:~:text=The Witwatersrand deposits have produced,world class solid gold elephants.>
- [3] "Discovery of Gold in 1884." Accessed: Sep. 23, 2023. [Online]. Available: <https://www.sahistory.org.za/article/discovery-gold-1884>
- [4] Minerals Council South Africa, "Facts and figures 2021," 2021. Accessed: Sep. 23, 2023. [Online]. Available: <https://www.mineralscouncil.org.za/industry-news/publications/facts-and-figures>
- [5] C. J. H. Hartnady, "South Africa's gold production and reserves," *S Afr J Sci*, vol. 105, no. 9–10, pp. 328–329, 2009, doi: 10.4102/sajs.v105i9/10.101.
- [6] "Gold production in South Africa and major projects." Accessed: Sep. 23, 2023. [Online]. Available: <https://www.mining-technology.com/data-insights/gold-in-south-africa/?cf-view&cf-closed>
- [7] P. N. Neingo and T. Tholana, "Trends in productivity in the South African gold mining industry," *J South Afr Inst Min Metall*, vol. 116, no. 3, pp. 283–290, 2016, doi: 10.17159/2411-9717/2016/v116n3a10.
- [8] PWC, "SA Mine 2023," 2023. Accessed: Nov. 08, 2023 [Online]. Available: <https://www.pwc.co.za/en/publications/sa-mine.html>
- [9] PWC, "SA Mine 2022," 2022. Accessed: Nov. 08, 2023 [Online]. Available: <https://www.pwc.co.za/en/publications/sa-mine.html>
- [10] G. Harvey, R., "Why is labour strife so persistent in South Africa's mining industry?," *Extr Ind Soc*, vol. 3, no. 3, pp. 832–842, 2016.
- [11] S. Moolman, "2022 update: Eskom tariff increases vs inflation since 1988 (with projections to 2024)," *Power Optimal*. Accessed: Nov. 08, 2023. [Online]. Available:

<https://poweroptimal.com/2021-update-eskom-tariff-increases-vs-inflation-since-1988/#:~:text=From 2007 to 2022%2C electricity,money terms in 14 years.>

- [12] Global Green Growth Institute, “The impact of electricity price increases on the competitiveness of selected mining sector and smelting value chains in South Africa (Commissioned for the Economic Development Department, EDD),” Trade and Industrial Policy Strategies (TIPS) Global Green Growth Institute (GGGI), no. August, pp. 5–63, 2014.
- [13] L. F. Van Der Zee, “Modelling of electricity cost risks and opportunities in the gold mining industry,” PHD thesis, NWU, Potchefstroom, 2014.
- [14] J.-J. Calitz, “Research and implementation of a load reduction system for a mine refrigeration system J Calitz,” Masters Dissertation, NWU, Potchefstroom, 2006.
- [15] L. Zietsman, “Identification model for cost-effective electricity savings on a mine cooling system,” Masters, North-West University, 2018.
- [16] P. Peach, J. Bredenkamp, and J. van Rensburg, “Dynamic Optimisation of Deep-Level Mine Refrigeration Control,” South African Journal of Industrial Engineering, vol. 29, no. 3, pp. 202–216, 2018, doi: 10.7166/29-3-2060.
- [17] R. Hemp, “Sources of heat in mines,” Ventilation and Occupational Environment Engineering in Mines, pp. 569–612, 1982.
- [18] L. Mackat, S. Bluhm, and J. Van Rensburg, “Refrigeration and cooling concepts for ultra-deep platinum mining,” The Southern African Institute of Mining and Metallurgy, vol. 4, pp. 285–292, 2010.
- [19] D. Mishra and N. Sahay, “Effect of auto compression on ventilation system of deep shaft coal mines in jharia coal field –A case study,” no. June, 2015.
- [20] H. J. van Staden, J. F. van Rensburg, and H. J. Groenewald, “Optimal use of mobile cooling units in a deep-level gold mine,” Int J Min Sci Technol, vol. 30, no. 4, pp. 547–553, 2020, doi: 10.1016/j.ijmst.2020.03.004.
- [21] Department of mineral resources, “Guidelines for the compilation of a mandatory code of practice for an occupational health programme on thermal stress,” 2016.

- [22] J. Reason and A. Hobbs, *Managing Maintenance Error: A Practical Guide*. CRC Press, 2003.
- [23] L. Mackat, S. Bluhm, and J. Van Rensburg, "Refrigeration and cooling concepts for ultra-deep platinum mining," *The Southern African Institute of Mining and Metallurgy*, vol. 4, pp. 285–292, 2010, [Online]. Available: http://www.saimm.co.za/Conferences/Pt2010/285-292_MacKay.pdf
- [24] J. J. L. du Plessis, "Ventilation and Occupational Environment Engineering in Mines," *Mine Ventilation Society of South Africa*, vol. 1, p. 950, Aug. 2014.
- [25] A. Schutte, M. Kleingeld, and H. Groenewald, "A holistic energy-cost evaluation of ice vs chilled water in mining; A holistic energy-cost evaluation of ice vs chilled water in mining," 2016.
- [26] D. Cluff, G. Kennedy, and P. Foster, "Liquid air for energy storage, auto-compression, compressed air and ventilation in deep mining," in *Proceedings of the Seventh International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, 2014, pp. 757–770. doi: 10.36487/acg_rep/1410_54_cluff.
- [27] J. Vermeulen, J. F. Van Rensburg, and A. J. Schutte, "Cost Effective Management Strategies of Platinum Mine Cooling Systems," in *Industrial and Commercial Use of Energy*, Cape Town: IEEE, Oct. 2016, pp. 76–83.
- [28] D. G. Kröger, "Air-cooled heat exchangers and cooling towers," in *Thermal power plants*, vol. 3, University of Stellenbosch, 1998.
- [29] N. Szlązak, D. Obracaj, and M. Korzec, "Analysis of connecting a forcing fan to a multiple fan ventilation network of a real-life mine," *Process Safety and Environmental Protection*, vol. 107, pp. 468–479, 2017, doi: 10.1016/j.psep.2017.03.001.
- [30] Z. Lei and M. Zaheeruddin, "Dynamic simulation and analysis of a water chiller refrigeration system," *Appl Therm Eng*, vol. 25, no. 14–15, pp. 2258–2271, Oct. 2005, doi: 10.1016/j.applthermaleng.2005.01.002.
- [31] X. Zhou, B. Wang, L. Liang, J. Yan, and D. Pan, "An operational parameter optimization method based on association rules mining for chiller plant," *Journal of Building Engineering*, vol. 26, no. July, p. 100870, 2019, doi: 10.1016/j.jobbe.2019.100870.

- [32] S. A. Ghoreishi-Madiseh, A. Fahrettin Kuyuk, H. Kalantari, and A. P. Sasmito, "Ice versus battery storage; a case for integration of renewable.pdf," 2019.
- [33] N. M. Ashmead, "A holistic approach to evaluate the feasibility of implementing ice thermal storage on deep mines," NWU, 2020.
- [34] H. J. van Staden, J. F. van Rensburg, and H. J. Groenewald, "Optimal use of mobile cooling units in a deep-level gold mine," *Int J Min Sci Technol*, vol. 30, no. 4, pp. 547–553, 2020, doi: 10.1016/j.ijmst.2020.03.004.
- [35] J. de Wet, L. Mackay, S. Bluhm, and K. Walter, "Refrigeration and ventilation systems for ultra-deep platinum mining in the bushveld igneous complex," *Proceedings of the 10th International Mine Ventilation Congress*, no. 2010, pp. 1–8, 2014, [Online]. Available: [https://www.vuma3d.com/Data/Whitepapers/network/10 IMVC - Refrigeration and ventilation systems fro ultra-deep mining in the bushveld igneous complex.pdf](https://www.vuma3d.com/Data/Whitepapers/network/10_IMVC_-_Refrigeration_and_ventilation_systems_fro_ultra-deep_mining_in_the_bushveld_igneous_complex.pdf)
- [36] M. Le Roux, "Identifying water wastage in deep-level mines using novel simulation-based zero-waste baselines," Stellenbosch University, 2024. [Online]. Available: <https://scholar.sun.ac.za>
- [37] E. C. Hunger and G. T. C. Emere, "The use of cylindro-conical settlers for the clarification of underground water," *Journal of the south african institute of mining and metallurgy*, pp. 201–206, May 1977.
- [38] R. Venter, "Reconfiguring deep-level mine dewatering systems for increased water volumes," Master, North West University, 2020.
- [39] F. G. J. Van Rensburg, J. I. G. Bredenkamp, and J. F. Van Rensburg, "Optimising load management on a deep-level Mine's refrigeration systems through maintenance and operational improvements," *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, 2017, doi: 10.23919/ICUE.2017.8067997.
- [40] C. K. Kocsis, R. Hall, and S. G. Hardcastle, "The integration of mine simulation and ventilation simulation to develop a 'Life-Cycle' mine ventilation system," *South African Institute of Mining and Metallurgy*, pp. 223–229, 2003.
- [41] M. P. Pandey and A. B. Agrwal, "Performance analysis of ice plant using ecofriendly refrigerants," *International Journal of Advanced Technology & Engineering Research (IJATER)*, vol. 5, no. 1, 2015, [Online]. Available: www.ijater.com

- [42] S. M. Thu, T. Z. Win, and H. L. T. Kyi, "A Study on COP of Existing Ice Plant," *International Journal of Science and Engineering Applications*, vol. 8, no. 8, pp. 348–352, 2019, [Online]. Available: www.ijsea.com348
- [43] J. Yadav and B. R. Singh, "A Study on Analysis and Fabrication of an Ice Plant Model," *SAMRIDDHI : A Journal of Physical Sciences, Engineering and Technology*, vol. 2, no. 01, pp. 61–70, 2011, doi: 10.18090/samriddhi.v2i1.1599.
- [44] J. Tomczyk, "The Professor: Hard Ice vs. Soft Ice," *ACHR News*. Accessed: Jul. 06, 2024. [Online]. Available: <https://www.achrnews.com/articles/120119-the-professor--hard-ice-vs--soft-ice>
- [45] Howden, Hard ice technology delivers cost savings. 2015. [Online]. Available: www.howden.com
- [46] A. Nasir, A. Mohammed, A. S. Adegoke, and H. T. Abdulkarim, "Design and Performance Evaluation of an Ice Block Making Machine," *ARPN Journal of Science and Technology*, vol. 3, no. 4, pp. 332–339, Apr. 2013, [Online]. Available: <http://www.ejournalofscience.org>
- [47] KTI, "Plate Ice Plants (PLIP)." Accessed: Aug. 12, 2022. [Online]. Available: <https://www.kti-plersch.com/en/product/plate-ice-plants/>
- [48] J. D. Zhao, N. Liu, and Y. M. Kang, "Optimization of ice making period for ice storage system with flake ice maker," *Energy Build*, vol. 40, no. 9, pp. 1623–1627, 2008, doi: 10.1016/j.enbuild.2008.01.008.
- [49] M. Y. You, "Predictive component availability optimization with degradation correlated maintainability," *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, vol. 227, no. 4, pp. 243–253, 2013, doi: 10.1177/0954408912456661.
- [50] C. Ming Tan and N. Raghavan, "A framework to practical predictive maintenance modeling for multi-state systems," *Reliab Eng Syst Saf*, vol. 93, no. 8, pp. 1138–1150, Aug. 2008, doi: 10.1016/j.ress.2007.09.003.
- [51] A. J. H. Nel, J. F. van Rensburg, and C. Cilliers, "Improving existing DSM initiatives on mine refrigeration systems for sustainable performance".

- [52] D. Goldsman, R. E. Nance, and J. R. Wilson, "A brief history of simulation revisited," in *Proceedings - Winter Simulation Conference*, 2010, pp. 567–574. doi: 10.1109/WSC.2010.5679129.
- [53] D. Stephenson, "Computer simulation of mine water pipeflow including transients," *Journal of the Mine Ventilation Society of South Africa*, vol. 38, no. 12, pp. 141–144, 1985.
- [54] N. T. B. Tram, "Simulation modeling-An effective method in doing business and management research," *Ho Chi Minh City Open University Journal of Science - Economics and Business Administration*, vol. 12, no. 1, pp. 108–124, 2021, doi: 10.46223/HCMCOUJS.
- [55] P. Maré, "Novel simulations for energy management of mine cooling systems," PhD Dissertation, North-West University, 2017.
- [56] L. Wright and S. Davidson, "How to tell the difference between a model and a digital twin," *Adv Model Simul Eng Sci*, vol. 7, no. 1, Dec. 2020, doi: 10.1186/s40323-020-00147-4.
- [57] C. Davis and A. Yadav, "Case Studies in Engineering," in *Cambridge Handbook of Engineering Education Research*, Cambridge University Press, 2014, ch. 9, pp. 161–180. doi: 10.1017/CBO9781139013451.013.
- [58] A. Priya, "Case Study Methodology of Qualitative Research: Key Attributes and Navigating the Conundrums in Its Application," *Sociol Bull*, vol. 70, no. 1, pp. 94–110, Jan. 2021, doi: 10.1177/0038022920970318.
- [59] P. Baxter and S. Jack, "Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers," *The Qualitative Report*, Jan. 2015, doi: 10.46743/2160-3715/2008.1573.
- [60] F. Lau and C. Kuziemsky, "Methods for Literature Reviews," in *Handbook of eHealth Evaluation: An Evidence-based Approach*, University of Victoria, 2017, ch. 9.
- [61] R. F. Baumeister and M. R. Leary, "Writing Narrative Literature Reviews," *Review of General Psychology*, vol. 1, no. 3, pp. 311–320, 1997.
- [62] D. le Roux, "Energy recovery from incoming high pressure cold water in deep level mines," in *Industrial and Commercial Use of Energy (ICUE)*, Cape Town: IEEE, Aug. 2012.

- [63] E. Price, G. R. Abhijith, and A. Ostfeld, "Pressure management in water distribution systems through PRVs optimal placement and settings," *Water Res*, vol. 226, pp. 119–236, Nov. 2022, doi: 10.1016/j.watres.2022.119236.
- [64] W. Pulles, D. Howie, D. Otto, and J. Easton, "A manual on mine water treatment and management practices in South Africa," Water Research Commission, 1995.
- [65] D. Stanton, "Development and testing of an underground remote refrigeration plant," International Platinum Conference "Platinum Adding Value," pp. 187–205, 2004, [Online]. Available: http://www.saimm.co.za/Conferences/Pt2004/187_Stanton.pdf
- [66] T. S. Moropa and J. H. Marais, "Cost and energy savings on mine surface cooling systems," Master of Engineering, North-West University, 2017. doi: 10.23919/ICUE.2017.8068001.
- [67] A. Whillier, "The design of underground cooling towers," *Journal of the South African institute of mining and metallurgy*, pp. 85–92, 1971.
- [68] M. L. Michelsen, "Saturation point calculations," Elsevier Science Publishers B.V, 1985.
- [69] N. Q. Minh, N. J. Hewitt, and P. C. Eames, "Improved Vapour Compression Refrigeration Cycles: Literature Review and Their Application to Heat Pumps," in *International Refrigeration and air conditioning conference*, Jul. 2006. [Online]. Available: <http://docs.lib.purdue.edu/iracc/795>
- [70] R. Gouws, "Measurement and verification of load shifting interventions for a fridge plant system in south africa," *Journal of Energy in Southern Africa*, vol. 24, no. 1, pp. 9–14, Feb. 2013.
- [71] J. Vermeulen, "Cost effective management strategies for platinum mine cooling systems," Masters, North-West University, 2015.
- [72] D. C. Uys, M. Kleingeld, and C. Cilliers, "Converting an ice storage facility to a chilled water system for energy efficiency on a deep level gold mine," *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, vol. 2015-Septe, pp. 76–83, 2015, doi: 10.1109/ICUE.2015.7280250.
- [73] G. E. Du Plessis, L. Liebenberg, and E. H. Mathews, "The use of variable speed drives for cost-effective energy savings in South African mine cooling systems," *Appl Energy*, vol. 111, pp. 16–27, 2013, doi: 10.1016/j.apenergy.2013.04.061.

- [74] W. Bornman, "Energy optimisation for mine cooling systems through flow control," 2017.
- [75] B. A. Qureshi and S. M. Zubair, "The impact of fouling on performance evaluation of evaporative coolers and condensers," *Int J Energy Res*, vol. 29, no. 14, pp. 1313–1330, Nov. 2005, doi: 10.1002/er.1120.
- [76] M. G. Vrachopoulos, A. E. Filios, G. T. Kotsiovelos, and E. D. Kravvaritis, "Incorporated evaporative condenser," *Appl Therm Eng*, vol. 27, no. 5–6, pp. 823–828, Apr. 2007, doi: 10.1016/j.applthermaleng.2006.09.021.
- [77] J. Van Der Walt and E. M. De Kock, "Developments in the engineering of refrigeration installations for cooling mines," *International Journal of Refrigeration*, vol. 7, no. 1, pp. 27–40, Jan. 1984.
- [78] A. Greth, P. Roghanchi, and K. C. Kocsis, "A review of cooling system practices and their applicability to deep and hot underground US mines," *16th North American Mine Ventilation Symposium*, vol. 11, no. June, pp. 1–9, 2017.
- [79] S. Van Jaarsveld, J. N. Du Plessis, and R. Pelzer, "A Control System for the Efficient Operation of Bulk Air Coolers on a Mine," in *Industrial and commercial use of energy (ICUE)*, Cape Town: IEEE, Aug. 2015. doi: 10.1109/icue.2015.7280259.
- [80] L. Messaoud, "Drilling technology in mining industry," 2006.
- [81] P. Pal Roy, "Emerging trends in drilling and blasting technology: concerns and commitments," *Arabian Journal of Geosciences*, vol. 14, no. 7, Apr. 2021, doi: 10.1007/s12517-021-06949-z.
- [82] R. G. B. Pickering, "The optimization of mining method and equipment," in *International Platinum Conference*, The South African Institute of Mining and Metallurgy, 2004.
- [83] U.S. Centers for disease control and prevention, "Mining Topic: Respiratory Diseases." Accessed: Jul. 24, 2024. [Online]. Available: [https://www.cdc.gov/niosh/mining/topics/respiratorydiseases.html#:~:text=Pneumoconioses%20\(meaning%20dusty%20lung\)%20can,affects%20workers%20in%20coal%20mining.](https://www.cdc.gov/niosh/mining/topics/respiratorydiseases.html#:~:text=Pneumoconioses%20(meaning%20dusty%20lung)%20can,affects%20workers%20in%20coal%20mining.)
- [84] K. Oberholzer, "Reconfiguring mine cooling auxiliaries for optimal operation" 2016.

- [85] P. Peach, J. Bredenkamp, and J. van Rensburg, "Dynamic Optimisation of Deep-Level Mine Refrigeration Control" *South African Journal of Industrial Engineering*, vol. 29, no. 3, pp. 202–216, 2018, doi: 10.7166/29-3-2060.
- [86] I. Mathews, E. H. Mathews, J. H. van Laar, W. Hamer, and M. Kleingeld, "A simulation-based prediction model for coal-fired power plant condenser maintenance" *Appl Therm Eng*, vol. 174, no. March, p. 115294, 2020, doi: 10.1016/j.applthermaleng.2020.115294.
- [87] P. F. H. Peach, M. Kleingeld, and J. I. G. Bredenkamp, "Optimising deep-level mine refrigeration control for sustainable cost savings" *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, 2017, doi: 10.23919/ICUE.2017.8068000.
- [88] H. Murgham et al., "Simulation Model of an Automatic Commercial Ice Machine" *International Refrigeration and Air Conditioning*, 2016. [Online]. Available: <http://docs.lib.purdue.edu/iracc/1686><http://docs.lib.purdue.edu/iracc/1686>
- [89] B. G. G. Terblanche, J. F. Van Rensburg, and W. Biermann, "Improving deep-level mining refrigeration through increasing pre-cooling efficiency" *Proceedings of the Conference on the Industrial and Commercial Use of Energy, ICUE*, vol. 2018-Augus, 2019.
- [90] W. Bornman, J. Dirker, D. C. Arndt, and J. P. Meyer, "Integrated energy simulation of a deep level mine cooling system through a combination of forward and first-principle models applied to system-side parameters" *Appl Therm Eng*, vol. 123, pp. 1166–1180, 2017, doi: 10.1016/j.applthermaleng.2017.05.163.
- [91] S. Jerling, "Analysing the impact of refurbishing precooling towers on a deep-level mine" *PHD dissertation*, North-West University, 2020.
- [92] M. Girard and R. A. Stewart, "Implementation of Pressure and Leakage Management Strategies on the Gold Coast, Australia: Case Study," *J Water Resour Plan Manag*, vol. 133, no. 3, pp. 210–217, May 2007, doi: 10.1061/(asce)0733-9496(2007)133:3(210).