Optimising mine cooling system performance through monitoring and analysis

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PREFACE

This dissertation was assembled and presented in **Article Format**. The appendices comprise of the two articles showing the results of this study. Each article contributed to the current field of knowledge and was submitted for publication to a journal. Each article presents a logical flow, highlighting the novel contributions to an integrated research goal of optimising mine cooling system performance through monitoring and analysis. The authors and all relevant parties provided permission for the use of the articles as part of this Master's degree.

I want to acknowledge the following, whose assistance, guidance and contributions were crucial to achieving success during this study:

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ABSTRACT

Title: Optimising mine cooling systems through monitoring and analysis

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Keywords: Mining; Cooling systems; DIKW; Cooling coil; Automatic reporting

The South African mining industry is under ever-increasing economic pressure. The lack of shallow resources forces mining companies to increase workplace depths to exploit mineral resources. The increased depth of workplaces poses significant environmental challenges due to increasing temperature resulting from auto-compression and higher virgin rock temperatures. Mines mitigate this heat load with large cooling systems to provide safe working conditions. These cooling systems are therefore critical in effective mine operations and are an area in need of optimisation through monitoring and analysis.

This study implemented a novel application of the Data, Information, Knowledge, Wisdom (DIKW) method on a deep-mine cooling system to monitor the cooling system performance. The method aggregated data available on the mine into an automatic daily report, which extracted valuable information and knowledge. This data maturity led to a wisdom-level understanding of cooling performance, enabling informed management decisions. The DIKW method facilitated an improvement of 55% in delivered cooling on a South African deep gold mine. This increase in cooling resulted in safer workplace environmental temperatures. However, a shortcoming of the methodology was the inability to account for the expected performance of the cooling systems at off-design conditions.

The changing nature of the underground environmental conditions resulted in a need to analyse the expected performance of mine cooling systems operating under off-design conditions. The study developed simulation models to predict the expected (normalised) performance of underground cooling systems operating under off-design conditions. The novel application of this method on tertiary cooling systems (cooling coils) showed that the conventional method of calculating cooling coil efficiency was 38% off. The use of simulation models in cooling coil analysis enabled a more accurate representation of their efficiencies. The results then enabled effective maintenance strategies aimed at the cooling coils, as well as the environmental conditions.

This research showed the importance of actual performance monitoring and reporting, as well as using normalised performance for accurate cooling system analysis. The developed monitoring and analysis methods form the building blocks for the current Industry 4.0 drive on deep-mine cooling systems. The research outcomes added substantial value for the future of optimising mine cooling system performance. This Master’s degree is in an article-based format, with the first article covering the DIKW approach, published in the International Journal of Mining Science and Technology. The second article, investigating the normalised performance of cooling coils, was submitted to Applied Energy.

LIST OF PAPERS

The articles listed below form the central part of this dissertation. This study is ordered in an article-based fashion. Roman numerals notate these two interconnected articles throughout the dissertation.

I. PRETORIUS, J.G., MATHEWS, M.J., MARé, P., KLEINGELD, M., VAN RENSBURG, J., "*Implementing a DIKW model on a deep mine cooling system*" International Journal of Mining Science and Technology, Available online: https://doi.org/10.1016/j.ijmst.2018.07.004 (26 July 2018).

II. PRETORIUS, J.G., MATHEWS, M.J., MARé, P., KLEINGELD, M., JANSE VAN RENSBURG, F., "*Performance analysis of cooling coils operating at off-design conditions using simulation models*" Applied Energy, 2018

The technical integrity of each paper was the responsibility of the student, J.G. Pretorius. The co-authors, Dr M.J. Mathews, Dr P. Maré, Dr M. Kleingeld, Dr J. van Rensburg and F. Janse van Rensburg, provided permission to submit the articles as part of this dissertation. Appendix A contains the permissions of all authors and relevant parties.

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ABBREVIATIONS

BAC	Bulk Air Cooler
CBM	Condition-based Maintenance
COP	Coefficient of Performance
DB	Dry-Bulb
DIKW	Data Information Knowledge Wisdom
HMI	Human-machine Interface
OEE	Overall Equipment Effectiveness
OHS	Occupational Health and Safety
SCADA	Supervisory Control and Data Acquisition
TPM	Total Productive Maintenance
WB	Wet-Bulb

CHAPTER 1 INTRODUCTION

10 MW Surface Fridge Plant [i]

Fridge plants provide chilled water for the use in air- and water cooling mine services to enable safe and productive deep mine operations [ii]

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[i] Photograph taken by author near Klerksdorp, North West, South Africa.
[ii] Subsurface ventilation engineering [11].

1.1. BACKGROUND

The South African mining sector is under ever-increasing economic pressure. The employment in this sector has decreased by a third between 1986 and 2012. The mining sector's contribution to the gross domestic product also reduced by 14.6% between 1980 and 2014. This relative decline may be a reflection of the growth experienced in the manufacturing and services sector, but it still points to a significant change in the mining sector [1]. This economic strain shows that mines cannot afford to lose production time due to any preventable stoppages.

The Department of Mineral Resources has the right to stop a mining operation in the event of a safety breach[iii]. These stoppages are known as Section 54 closures in terms of the Mine Health and Safety Act 1996. The cost incurred to the mining industry was R4.8 billion in 2015 with an average revenue loss of R13 million per stoppage per operation[iii]. It is evident from a financial perspective that the mines cannot afford to lose production shifts, especially not because of safety breaches, in an economically pressured time for the South African mining industry [1]. Some of these safety breaches are a result of dangerous environments caused by challenges found in deeper exploration of mineral resources [2].

The economic pressure and reduction in shallow mineral reserves result in mining operations developing deeper than ever before. Seven of the world's deepest mines are in the Witwatersrand Basin in South Africa. These mines are exploiting mineral resources to depths of 4 km below the surface [2]. These depths result in challenging environmental conditions. The geothermal gradient or virgin rock temperature and auto-compression are significant heat sources encountered in the deeper mines [3], [4]. The deep mines are susceptible to hot environments, which leads to safety risks. These safety risks, if unattended to, are grounds for Section 54 stoppages and loss of production. These hot environments carry significant health risks and are not suitable for humans due to the stress incurred on the body.

The South African heat stress index categorises the temperatures of underground working places according to risks of obtaining heat hazards [5]. Four main categories interpret environmental temperatures as having an unacceptable risk, potentially conducive, or only a negligible risk of obtaining a heat disorder. Figure 1-1 shows these categories according to the wet-bulb (WB) and dry-bulb (DB) temperatures [5]. The wet-bulb temperature indicates the level of moisture in the air and the dry-bulb shows the temperature isolated from moisture and radiation effects. Under

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[iii] D. McKay, "Section 54s cost SA mines R4.8bn in 2015, and 2016 may be worse," 2016. [Online]. Available: http://www.miningmx.com/opinion/columnists/27866-stoppages-lop-r4-8bn-off-2015-revenue-2016-worse/. [Accessed: 01-Jan-2017].

fully saturated conditions (100% relative humidity) the dry-bulb and wet-bulb temperatures will be the same. The wet-bulb temperatures thus show the extent of evaporative cooling on a surface. High wet-bulb temperatures, combined with high relative humidity levels, limit the body's ability to cool down using evaporative cooling, which results in dangerous internal body-heat build-up [6].

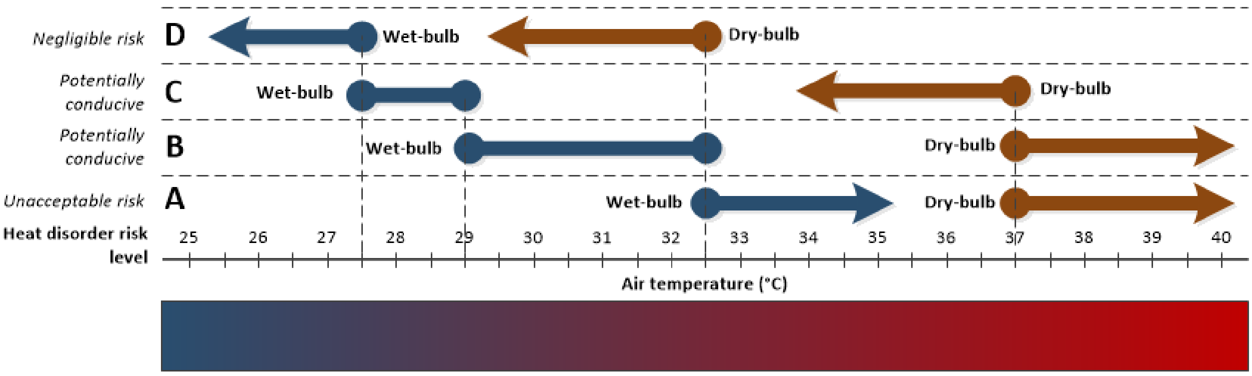

Figure 1-1: The South African Heat Stress Index[iv]

The hot environments of category A and B in Figure 1-1 have a high risk of affecting the thermoregulation of a person's core body temperature [7]. The external factors influencing the heat stress on a person's body include the ambient air temperature, radiant heat, air velocity and humidity. In high-risk categories, these factors enable conception of the following heat disorders in order of severity: transient heat fatigue, heat rash, heat cramps, heat syncope, heat exhaustion and heat stroke [7]. Heat stroke is a fatal hazard, and necessary protocols must be in place to prevent such exposure. A heat management program is necessary and proper engineering protocols, in conjunction with work practice controls, could alleviate high hazard exposure levels [4].

There exists a relationship between environmental conditions, productivity and accident rates [8], [9]. Working in sweltering conditions is very unhealthy, inefficient and unproductive. These high-heat areas affect a person's dexterity and coordination, alertness during lengthy and monotonous tasks, observation of irregular, faint optical signs and also the ability to make quick rational decisions [10].

The optimum range for workplace temperatures to achieve high productivity and low accident rates is 27.5 °C_{wb} to 29.0 °C_{wb} [8]. This temperature range, in conjunction with the South African heat stress index, shows that workplace temperatures should be sustained in category C and D in Figure 1-1 to ensure safe and productive workplace conditions. Proper heat management

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[iv] Developed from literature [5]

strategies achieve these workplace temperatures by using refrigeration systems, ventilation, administrative and engineering controls [2], [4], [9].

The cooling systems on mines provide the necessary services to enable safe workplace conditions. Figure 1-2 shows the hierarchy for cooling systems on a deep platinum mine. The hierarchy is also appropriate for other metalliferous mines. However, the depths of implementation will differ. The depth suitable for implementing bulk air coolers (BACs) is approximately 1400m and ice around 3000m for gold mines [8].

The general cooling methods under consideration include the use of ventilation only, surface BACs (primary cooling), underground BACs (secondary cooling) and tertiary or in-stope cooling (tertiary cooling) [9]. The BACs and tertiary cooling methods are usually direct or indirect contact water-to-air heat exchangers [11]. Vapour-compression refrigeration systems, also known as chillers or fridge plants, provide cold water to the primary, secondary and tertiary air cooling installations [9]. The hierarchy of implementing these systems are surface fridge plants, underground fridge plants (to improve positional efficiency) and surface ice plants in very deep mines [8], [9].

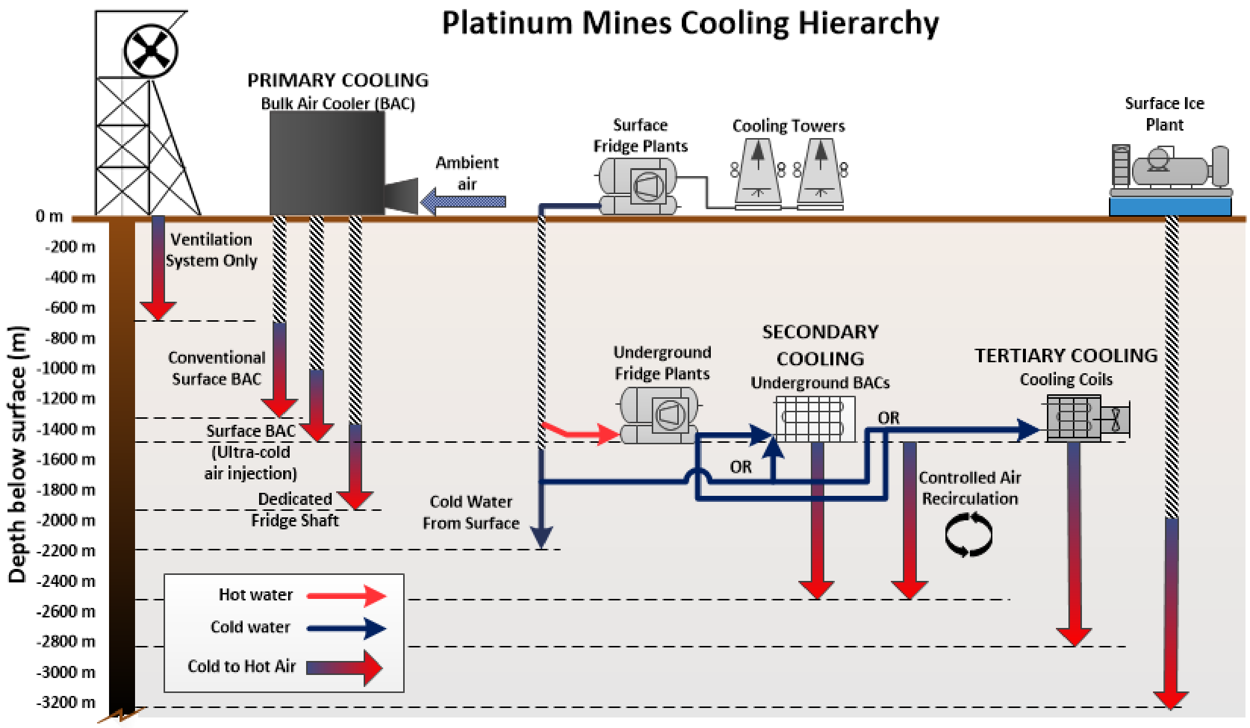

Figure 1-2: Platinum Mines Cooling Hierarchy[v]

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[v] Developed from literature [8], [9], [51], [52]

The cooling systems depicted in Figure 1-2, are large, complex and energy-intensive applications [11], [12]. A study on the use of variable speed drives for cost-effective energy savings in South African mine cooling systems analysed 20 sites during 2013. The combined installed refrigeration capacity for these mines was 239 MW of refrigeration, with a total energy consumption of 869 GWh/year [13]. The average energy usage per site exceeded 43 GWh/year. It is evident from these results that cooling systems are energy-intensive applications and should be well-maintained and managed for cost-effective operation.

Providing cooling for safe and productive workplace temperatures necessitates reliable cooling system performance [14]. An effective maintenance program will ensure this reliable and efficient cooling performance. The maintenance program will succeed when the information provided is accurate and trustworthy [15]. A study, spanning over four years, showed that managers of mines are usually not very involved in maintenance procedures. This study also showed that most mines have access to fully-integrated information systems. However, these systems are commonly under-utilised [16].

Mine management currently rely on their Supervisory Control and Data Acquisition (SCADA) systems to manage their systems from the surface [17], [18]. These systems typically log 15000+ data values, and mine management cannot react daily to an overdose of information. Monitoring the performance of this system is the responsibility of the appointed engineer and forms part of the engineer's monthly review pack. However, the data is rarely critically analysed due to time constraints and computational limitations held by the relevant employee [16]. The SCADA system must thus enable the manager to make informed decisions regarding maintenance procedures and improvement initiatives.

The SCADA system is crucial to the safe underground mining operation but has its shortcomings in providing management with actionable data for efficiency improvements, especially on cooling systems. These SCADA systems typically reflect only measured flows, temperatures and pressures [17]. It is difficult to track performance and obtain intelligible information from only these values, especially over time [19], [20]. It is thus likely that an improved monitoring solution, using the mine's installed instrumentation, combined with Industry 4.0[vi] data processing and visualisation techniques, will have a significant impact on the performance of these systems. From practical experience and literature, it is evident that mines could benefit from a data analysis system providing them with the necessary cooling performance information to react on [14].

[vi] Industry 4.0 is referred to as the fourth industrial revolution and includes the current trend for automation and data exchange in manufacturing technologies. It forms the basis for cyber-physical systems, Internet-of-Things, cloud computing and cognitive computing. *Industry 4.0 - Wikipedia. 2018. Industry 4.0 - Wikipedia. [ONLINE] Available at: https://en.wikipedia.org/wiki/Industry_4.0. [Accessed 12 October 2018].*

1.2. STUDY MOTIVATION

The South African mining industry is under increasing economic pressure. The shortage of shallow reserves, in conjunction with the challenging market, results in mines developing deeper to exploit mineral reserves. The deeper workplaces result in hot environments due to the magnified impact of auto-compression and geothermal heat. The health risks associated with these hot environments necessitate the use of cooling systems. These cooling systems are energy-intensive and require effective maintenance and management programs to provide reliable cooling. The successful implementation of maintenance programs on cooling systems relies on the information provided. However, most mines have access to fully integrated information systems but do not use them to their full potential.

It is evident from the literature that there exists a deficiency of a proper cooling system monitoring and analysis tool. The definite need lies in a solution which could enable clear-cut analysis of the deep-mine cooling system performance utilising the existing installed infrastructure. This study aims to provide monitoring and analysis techniques applicable to the cooling systems of deep mines for cooling reliability and optimisation.

1.3. PROBLEM STATEMENT

The deep mining sector could benefit from a cooling performance monitoring and analysis system during an economically stressed time. This system should enable managers of cooling systems to make informed decisions and increase the reliability and performance of their cooling systems. The increase in cooling reliability and performance is a necessity for safety and production.

The holistic research objectives are as follows:

- Development of a deep-mine cooling performance monitoring solution to increase system management effectiveness.
- A method of analysing the actual and expected performance of underground cooling systems using simulation models to assist in maintenance directives.

1.4. DISSERTATION OVERVIEW

The layout of the dissertation provides a logical flow which highlights the coherence between the two research articles. The core chapters forming a unified storyline are an introduction, article I and II summary, followed by a conclusion.

Chapter 1: Introduction

This section introduces the need for the study through a thorough background leading to the problem statement. Finally, an overview of the dissertation emphasises the dissertation structure to enable a clear-cut view of the holistic storyline binding the two articles.

Chapter 2: Article I

This chapter discusses the literature that enabled the formulation of the first research question in this dissertation. The survey presents the literature in a logical flow to emphasise the need for this study. An article summary then highlights the method and results addressing the need for optimising cooling system performance through monitoring. The study limitations and recommendations for further work of this article lead to the need for the second article.

Chapter 3: Article II

Article II is a necessary continuation stemming from the recommendations for further work from article I. The first section discusses the literature showing that more in-depth analysis is necessary when reporting on cooling system performance. An article summary then summarises the method and results used. The concluding remarks of the chapter include the study limitations and recommendations for further work.

Chapter 4: Conclusion

The conclusion summarises the findings of this research and provides recommendations for further study. The chapter summarises the connection and significance of each article’s findings contributing to the unified research goal of optimising mine cooling systems through monitoring and analysis.

CHAPTER 2 ARTICLE I

Primary cooling - Surface bulk air coolers [vii]

Surface bulk air coolers cool down fresh ambient air at the intake of the downcast shaft to enable safe and productive underground mining operations [viii]

[vii] Photograph taken by author near Klerksdorp, North West, South Africa.

[viii] Subsurface ventilation engineering [11], [52].

2.1. PREAMBLE

This chapter discusses the research procedure followed to reach the novel contribution described in article I (Appendix B). The literature survey follows a logical flow to show the need for mine cooling performance optimisation through monitoring. A publication summary highlights the method and results contributing to the solution proposed by this study. A discussion section then indicates the significance of article I to the holistic research goal of cooling performance optimisation through monitoring and analysis. The concluding remarks for this article also provide recommendations for further work leading to article II.

2.2. LITERATURE SURVEY

The level of insight into the cooling performance of the mine depends on the cognition of the individual analysing it. Analyses should consider the context of the operating conditions. Lack of understanding the context reduces the ability of an individual to fully comprehend the factors contributing to poor or reduced performance [14], [21]. Various data analyses and maintenance strategies exist to assist managers in large-scale industrial operations with improved management strategies [22]–[24]. However, not all are suitable for the deep-mining context.

There exists a relationship between understanding and context [20], [21], [25]. Figure 2-1 shows that this relationship increases with the maturity of data to information, knowledge and finally, wisdom (DIKW). The DIKW method is also known as the wisdom hierarchy [20]. The DIKW method is part of the knowledge management literature and looks at simplistic ways to extract knowledge from data [26]. This extraction allows for actionable decisions made through a method of developing data to wisdom.

The data level consists of values or symbols, such as sensor readings, from which no definite conclusion is yet possible [19], [27]. From an analysis point of view, only a limited amount of context and understanding is available. Data processing results in information. The information provides answers to the “who, what, where and when” questions [19]. The further analysis of information enables knowledge to offer even greater understanding and context. Knowledge assists in answering the “how” questions [27]. Analysis of knowledge by a competent person results in wisdom, which is evaluated understanding [19].

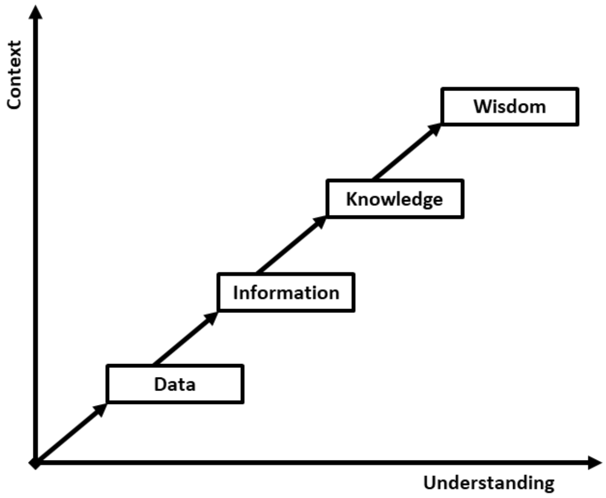

Figure 2-1: Relationship between context and understanding[ix]

Within the wisdom hierarchy steps, there is an increase in the level of added value, distillation, complexity, abstraction, integration, organisation, connectedness, relevance, meaningfulness, human input, applicability, contextualisation, learning and understanding [26]. This hierarchy could aid the knowledge management of performance monitoring on deep-mine cooling systems. It also shows the importance of data maturity to obtain the relevant context and understanding within an operational environment.

The most common practice in South African deep-level mines is to monitor all operational units on the mine from a centralised control room [28]. These control rooms have a SCADA human-machine interface (HMI) that enables operators to view and control the statuses of all instrumented processes on the mine. Figure 2-2 shows the typical layout of a mine's SCADA system.

Sensors such as actuators, pressure gauges, electromagnetic flow meters, turbidity and temperature probes automatically measure different types of energies and their subcomponents. Different types of interfaces, such as remote terminal units or programmable logic controllers, link these sensors to the SCADA mainframe via a computer network [17]. The trade-off between programmable logic controllers or remote terminal units lies in the control method, i.e. local or centralised respectively, required for the area. Finally, the HMI displays the entire network of sampled measurements and controllable units to a control-room operator in a centralised control room.

[ix] Developed from literature [20], [25]

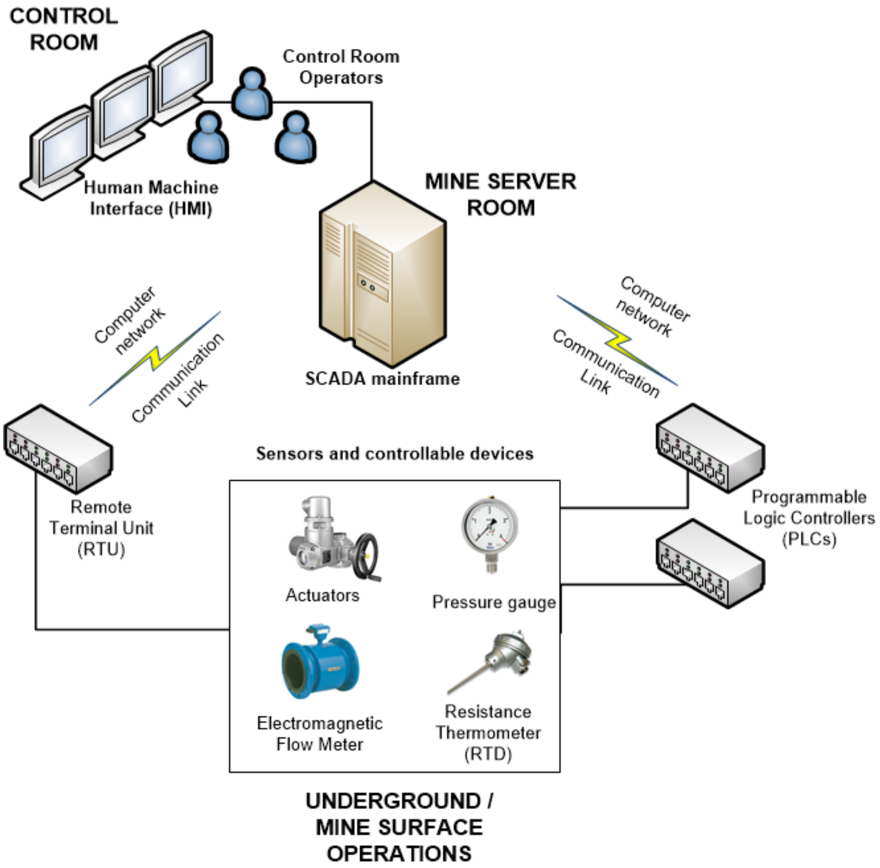

Figure 2-2: SCADA system infrastructure[x]

The SCADA mainframe enables a trained person to evaluate and control system processes in real time [28]. Due to the significant size of these networks, not all mines store the measured data for more than one to three months. However, some mines license a Historian database package to store data for more extended periods, such as 1 to 5 years. Monitoring performances from this system will typically form part of the responsible engineer's monthly review pack. The data is rarely critically analysed, due to time constraints and computational limitations held by the relevant employee [16]. The SCADA system should thus empower the relevant employee with automated data analysis, enabling rapid, actionable decisions.

The SCADA system is crucial to the safe mining operation but has its shortcomings to provide management with actionable data for efficiency improvements, especially on cooling systems. These systems typically operate at the data level and, at most, the information level of the DIKW hierarchy. There is room for additional data processing to progress towards the knowledge- and

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[x] Developed from literature [17]

even wisdom level. A trackable performance measurement and data evaluation system will add significant value to the management of these systems. There are implementations of such performance parameters in the industrial context, which may add value to the mining industry.

A well-known performance measurement parameter in the manufacturing industry is the overall equipment effectiveness (OEE) parameter [22]. The OEE factor considers the availability, performance and quality of a system's deliverables [29]. The implementations in the mining industry have various combinations between different key performance indicators (KPIs) and the OEE parameter for specific outcomes in maintenance or production monitoring. These evaluations include combinations between OEE and a reliability method for measuring machine effectiveness [30], mine production index to evaluate the effectiveness of mining machinery [31] or detect bottlenecks [32] and various other implementations. The OEE parameter operates at the information level and could quickly progress to the knowledge level of the wisdom hierarchy. However, the value for the OEE parameter for the mining industry is limited unless the underlying factors are thoroughly analysed [33].

The standalone use of the OEE parameter in the mining industry may be limited but combining it with optimised maintenance strategies may be successful. Advanced strategies for optimisation, such as total productive maintenance (TPM), widely use OEE as a basis [34]. TPM activities highlight three major activities, which are maximising equipment effectiveness, autonomous maintenance by operators and small group activities [35]. The core idea behind TPM is a company-wide approach to optimise the performance of the applicable system.

TPM strategies operate at the information- and knowledge level with the potential to develop wisdom-level decisions. However, advanced maintenance strategies such as TPM rarely succeed in the mining context [15]. There is an important observation made from the connection between OEE and TPM. The industrial use of maintenance strategies for improved throughput requires a performance measure, such as OEE, in measuring the performance thereof.

Condition-based maintenance (CBM) is another method to improve maintenance performance. CBM activities measure the vibration, temperatures and other available parameters on motors, compressors, fans and pumps in real time. Exception reports and alarms show the applicable maintenance foreman which unit operates above specified limits. CBM is quite useful when incorporated into the mine's planned maintenance strategies [24].

Other CBM implementations on mining conveyors [36], vibration monitoring in varying operational conditions in mines [37], wind-turbine gearbox fault-finding [38] and preventative maintenance based on the identification of actual state [39], showed the effectiveness of monitoring equipment and reacting on changes in operating condition. CBM operates at a knowledge level in the DIKW context, with a high dependency on data accuracy. However, CBM provides knowledge on reliability but is limited in operational efficiency data representations. The valuable lessons learned from CBM is the correct use and reporting of condition parameters, which may succeed with performance parameters as well.

The basis of processing data to information and even knowledge lies in the correct use of KPIs. Various other industries implement KPIs to extract valuable information from data within their system [40]. The use of system-specific KPIs could sustain an information-level basis for a DIKW implementation. Robust KPIs encapsulated within a DIKW approach to knowledge management on a deep-mine cooling system could result in a sustainable method to extract actionable decisions from processed data. The use of existing sensory data, combined with site-specific KPIs, could enable the implementation of the DIKW method.

Sensory data combined with the correct KPIs may enable identification of improvement opportunities and prioritisation of resources [33]. These KPIs should form the basis of a management strategy to improve the reliability of the system [24], [35]. The correct use of the installed sensory capacity could enable data maturity to wisdom, which will enable actionable decisions from management [20]. The performance monitoring parameters should allow tracking of system improvement initiatives and management directives [41].

The DIKW hierarchy, as a method for knowledge management of data, has been shown as a suitable approach in the industrial context [21], [42], [43]. It is thus likely that a novel application on mine cooling systems could allow for robust cooling performance monitoring. This DIKW implementation will allow for progress and efficiency tracking regarding improvement initiatives on mine cooling systems.

Figure 2-3 shows a typical mine cooling system which comprises fridge plants (chillers), evaporator- and condenser circuits. The aim is to move heat (energy) from the evaporator side to the condenser side. A typical mine chiller would utilise a vapour compression refrigeration system. This system uses electrical energy to operate a refrigerant cycle, where indirect heat exchange between refrigerant and evaporator- or condenser water respectively carries heat from the evaporator vessel to the condenser vessel [11], [12], [44].

The Coefficient of Performance (COP) is a KPI indicating the cooling performance of a fridge plant. The COP of a plant relates the electrical input to the evaporator cooling duty achieved. The cooling duty is a function of water mass flow and change of water temperature before and after heat exchange occurs within the vessel. The cooling duty and COP reflect the actual performance of the fridge plant [11], [12], [45].

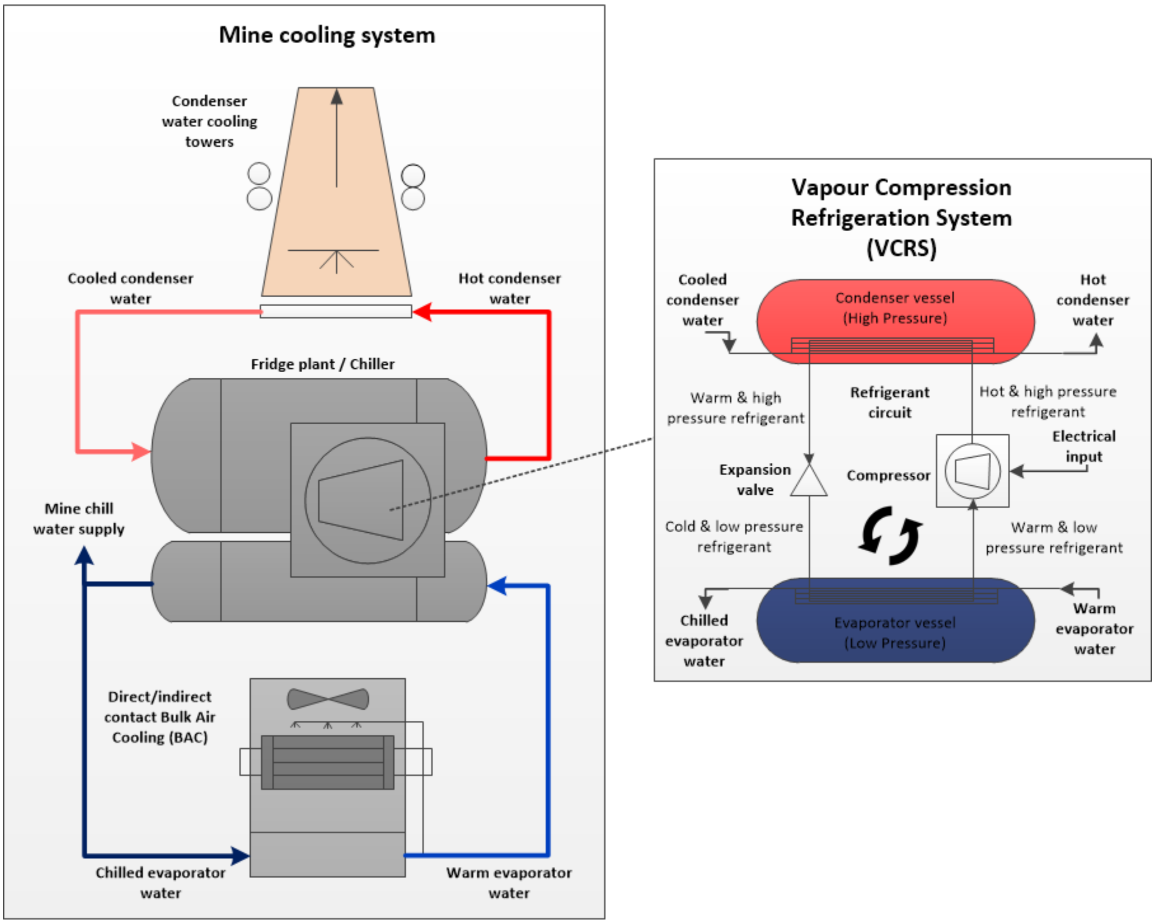

Figure 2-3: Components of a Vapour Compression Refrigeration System[xi]

The performance monitoring of a cooling system should indicate the level of work output (cooling duty) in comparison to work input (electrical power). This COP relationship could form the basis of robust performance monitoring. However, a crucial component to consider is the normalised cooling performance. The normalised cooling performance shows the performance expected of a cooling unit at the given environmental inputs [12]. Chapter 3 discusses the impact of normalised cooling performance on efficiency calculations.

Literature shows that deep-mine cooling systems are complex, and it is crucial to evaluate their performance regularly. The level of insight into the cooling performance depends on a person's contextual understanding of the prevailing operating conditions. The relationship between context and understanding increases as data matures to wisdom. The current use of SCADA systems

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[xi] Developed from literature [11], [12]

provides understanding on a data level and, at most, information level. Parameters such as OEE could develop that information to knowledge.

The industrial use of TPM in conjunction with OEE shows the importance of using KPIs together with maintenance strategies. This phenomenon is supported by the increased impact of combining condition-based maintenance with planned maintenance strategies. It is shown that site-specific KPIs could provide relevant knowledge, of which the cooling system KPIs include COPs and cooling duty.

The successful implementation of the DIKW model in other industries indicates that a novel application thereof will likely succeed on mine cooling systems. This study aims to show that the DIKW method could successfully lay the foundation for a cooling-system monitoring method. This method addresses the first research objective of increasing cooling-system management effectiveness and performance through monitoring.

First research objective:
Development of a deep-mine cooling performance monitoring solution to increase system management effectiveness.

The subsequent section discusses the method and results obtained from implementing a DIKW method on a deep-mine cooling system for the first time.

2.3. PUBLICATION SUMMARY

The first article addresses the first part of the holistic research goal to optimise deep-mine cooling system performance through monitoring and analysis. Article I was successfully published in an international peer-reviewed journal and forms part of the appendices. The details of this publication are as follows [14]:

Pretorius JG et al. Implementing a DIKW model on a deep mine cooling system. Int. J. Min. Sci. Technol. (2018), https://doi.org/10.1016/j.ijmst.2018.07.004

The literature survey showed that a DIKW method could enable data maturity to wisdom. This section discusses how the DIKW method was implemented on a deep-mine cooling system for the first time. The hierarchy steps follow a logical flow where data measurements are automatically logged, and automatic analyses develop the data to information and wisdom. The wisdom level is then evident from the human interaction resulting from the use of the daily cooling-efficiency report.

The data acquisition phase consists of determining the site layout, acquiring the available data, determining any data constraints and verifying the site instrumentation [14]. The first phase enables one to understand the site layout, measurement locations and interconnections between various cooling subsystems. The initial site inspection should source design specifications, layouts and any other information to support an understanding of the cooling system operation.

The data level is the sensory data logged and referenced as SCADA tags [14], [17]. The SCADA data was logged with a real-time energy management system over an open platform connection. The installed SCADA infrastructure sampled sensor measurements every two seconds. However, due to the non-volatile operation of the cooling system, the sample period was set to two minutes on the real-time energy management system.

A communication system called HERMES enabled automatic relaying of these sample bundles using a simple mail transfer protocol to a centralised cloud-based Mongo database every 30 minutes. An automated reporting system then empowered automatic daily calculations and analyses, which were then sent to mine personnel recipients.

The identification of the data constraints and the validity of data samples forms the last part of the data acquisition phase. The automatic data validation procedure checked the sensor measurement ranges, ensured values are in a local predetermined local realistic range, not constant and implemented any material redundancy [14], [46], [47].

The data level was followed by an on-site information audit where key measurements were performed to validate instrumentation further. The implementation of the automatic data validation resulted in recommendations, which mine personnel used, to fix and calibrate installed sensors. This phase is critical, as the data accuracy is of the utmost importance for the remainder of the DIKW method. This information audit also assisted in baselining the current system state [14].

Automatic monitoring and reporting form the basis for the knowledge level of the DIKW in this study. This continuous process makes use of system-specific KPIs. These KPIs reflect the cooling-system operation by analyses of fridge plant cooling duty, COP, condenser circuit heat rejection, cold-dam temperatures and cold-water mass flows [12], [14]. These KPIs were then organised in a compact report showing the recent cooling performance statistics.

Figure 2-4 shows the automatic report system architecture. This specific layout was developed with the inputs from mine personnel to increase the impact thereof. The first page reflects the holistic system and subsystem performance, combined with 30-day and monthly progressive cooling duty and cold-water temperature graphs. The second page analyses the individual fridge plants and evaporator- and condenser circuits, as well as other notable system parameters. The third page reflects the water consumption and temperatures relative to the hot- and cold dams. The final page displays the system layout obtained in the data acquisition page, together with average values on system parameters, to provide a snapshot of the daily performance.

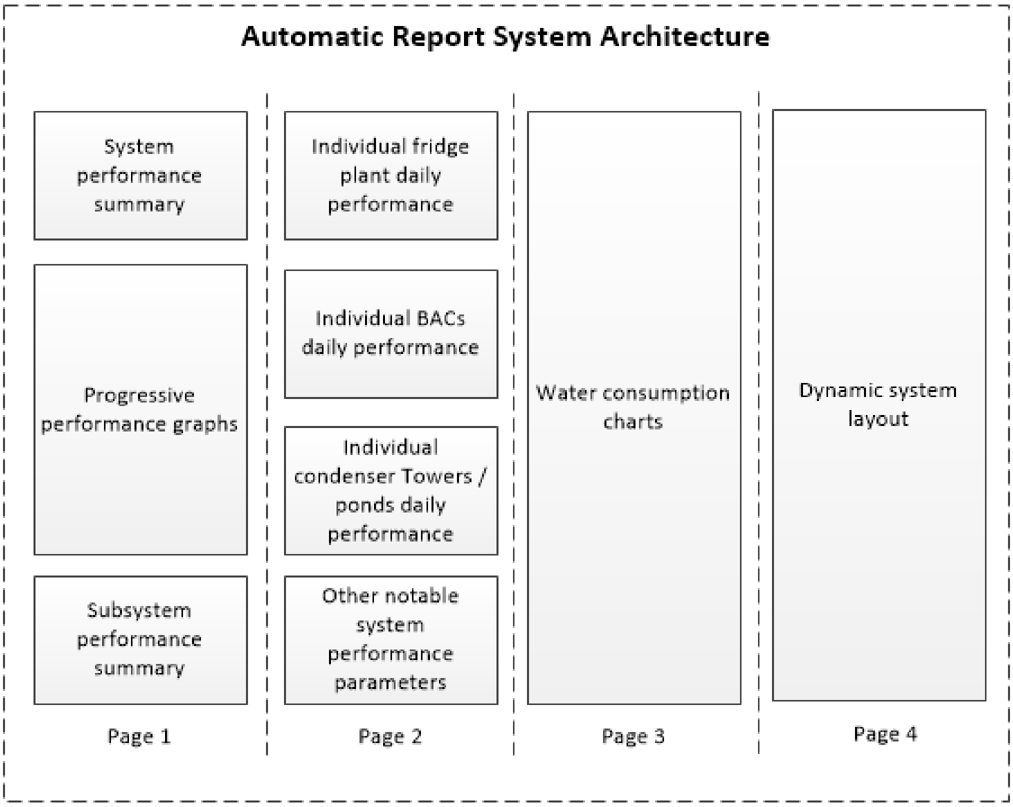

Figure 2-4: Automated report system architecture[xii]

The final stage of the DIKW method is the maturity of knowledge to wisdom. This level requires report interpretation by a person. The daily report delivery to all cooling-system role players enabled a centralised and shared platform for cooling performance. The mine management could reflect on the previous day's performance, as well as the progressive trend.

The case study for the DIKW method implementation was on Mine A[xiii]. Mine A's entire cooling system is approximately 2 km underground. The limiting factor for cooling on Mine A was the heat rejection capacity and old cooling infrastructure. The challenging monitoring conditions and the

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[xii] This is an updated version to the architecture available in the first article [14]

[xiii] This is the same Mine A used in Article II.

absence of a centralised platform to access summarised cooling performance data led to a great need for a cooling performance monitoring platform requested by Mine A's management.

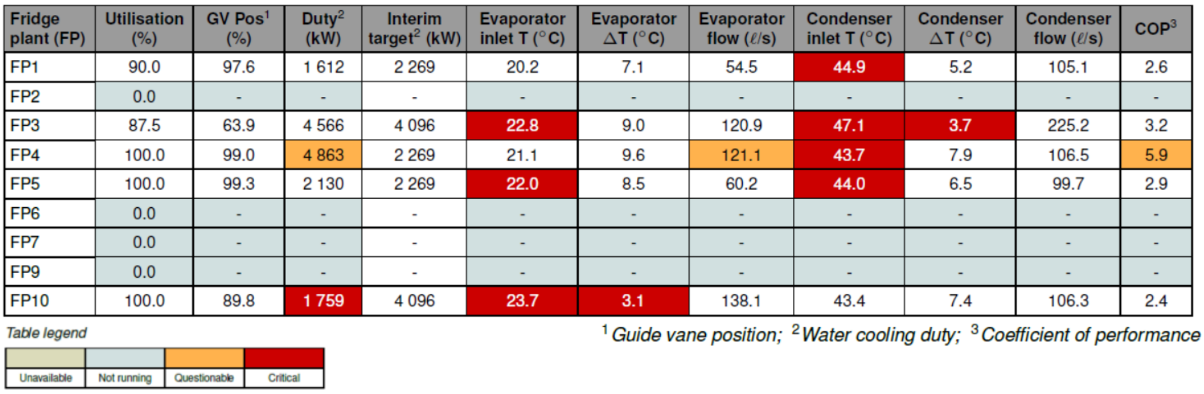
The DIKW method resulted in an instrumentation recommendation report to replace or calibrate faulty instruments (data level). Table 2-1 shows the results for one of the fridge plants during the instrumentation audit. These instrumentation audits ensured the accuracy of the sensors through validation measurements, as well as sensor measurement range, local realistic range, constant values and material redundancy checks.

Table 2-1: Instrumentation verification

Description	SCADA reading	Sensor measurement range	Local realistic range	Constant values check	Material redundancy check	Measured value	Tolerance (%)	Recommendation	Result
FP01 Current (A)	63.0	0-200	0-120	Pass	Not possible	64.3	2.0	Acceptable	N/A
FP01 Evap. flow (kg/s)	58.4	0-350	0-100	Pass	Not possible	68.0	14.1	Questionable: calibrate	Flow meter sent for calibration
FP01 Evap. temp in (°C)	16.7	-10-100	5-25	Pass	Not possible	18.0	7.2	Calibrate	Calibrated
FP01 Evap. temp out (°C)	12.7	-10-100	5-25	Pass	Not possible	9.9	28.3	Questionable: calibrate	Replaced
FP01 Cond. flow (kg/s)	78.6	0-350	0-250	Pass	Possible	111.0	29.2	Questionable: calibrate	Flow meter replaced
FP01 Cond. temp in (°C)	37.8	-10-100	30-60	Pass	Possible	38.5	1.8	Acceptable	N/A
FP01 Cond. temp out (°C)	42.8	-10-100	30-60	Pass	Possible	43.3	1.2	Acceptable	N/A

The daily cooling efficiency report followed, as seen in Appendix C, after these recommendations (information level). The conditional formatting and analysis of the information provided in the report indicated questionable, critical and good performance. These analyses enabled rapid system fault finding such as instrumentation errors, and questionable system behaviour like gas leaks (knowledge level). Table 2-2 shows the conditional formatting which implemented automatic data analytics such as in Table 2-1. Table 2-2 shows a real event where fridge plant 4 experienced a rapid decrease in its evaporator flow accuracy. The report indicated this by highlighting the flow, duty and COP blocks in orange as questionable. Further investigation led to the re-calibration of the flow meter. The report also showed critical operational values in red, which prompted additional investigations.

Table 2-2: Fridge plant performances – daily averages while running



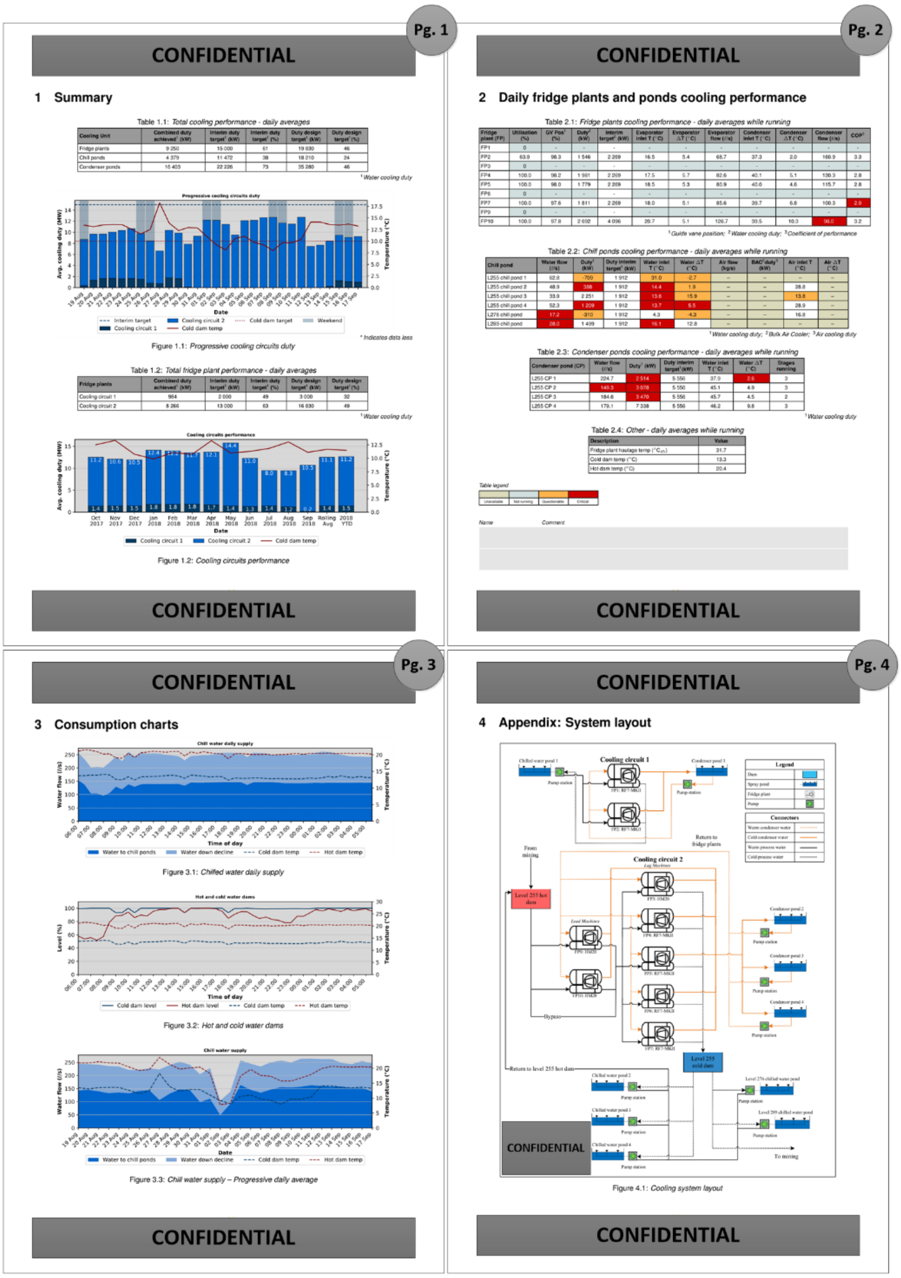
Fridge plant (FP)	Utilisation (%)	GV Pos[1] (%)	Duty[2] (kW)	Interim target[2] (kW)	Evaporator inlet T (°C)	Evaporator ΔT (°C)	Evaporator flow (ℓ/s)	Condenser inlet T (°C)	Condenser ΔT (°C)	Condenser flow (ℓ/s)	COP[3]
FP1	90.0	97.6	1 612	2 269	20.2	7.1	54.5	44.9	5.2	105.1	2.6
FP2	0.0	-	-	-	-	-	-	-	-	-	-
FP3	87.5	63.9	4 566	4 096	22.8	9.0	120.9	47.1	3.7	225.2	3.2
FP4	100.0	99.0	4 863	2 269	21.1	9.6	121.1	43.7	7.9	106.5	5.9
FP5	100.0	99.3	2 130	2 269	22.0	8.5	60.2	44.0	6.5	99.7	2.9
FP6	0.0	-	-	-	-	-	-	-	-	-	-
FP7	0.0	-	-	-	-	-	-	-	-	-	-
FP9	0.0	-	-	-	-	-	-	-	-	-	-
FP10	100.0	89.8	1 759	4 096	23.7	3.1	138.1	43.4	7.4	106.3	2.4

Table legend

🟨	⬜	🟧	🟥
Unavailable	Not running	Questionable	Critical

[1] *Guide vane position;* [2] *Water cooling duty;* [3] *Coefficient of performance*

Figure 2-5 shows the pages of the daily cooling efficiency report. Page 1 clearly shows the progressive cooling duty graphs for the system. Figure 2-6 shows the 30-day progressive cooling graph. It was necessary to include the cold-dam temperature on these graphs. Cooling duty is a function of water mass flow, and operators increased the flow to reflect a higher duty. This increase in flow would then result in a higher cold-dam temperature due to a reduced heat exchange time. The addition of the cold-dam temperature to the graphs mitigated this problem. These graphs indicate the relationship between cooling duty and cold-water temperature.



Pg. 1

CONFIDENTIAL

1 Summary

Table 1.1: *Total cooling performance - daily averages*

Cooling Unit	Combined duty achieved[1] (kW)	Interim duty target[1] (kW)	Interim duty target[1] (%)	Duty design target[1] (kW)	Duty design target[1] (%)
Fridge plants	9 250	15 000	61	19 830	46
Chill ponds	4 379	11 472	38	18 210	24
Condenser ponds	16 403	22 226	73	35 280	46

[1] *Water cooling duty*

* *Indicates data loss*

Figure 1.1: *Progressive cooling circuits duty*

Table 1.2: *Total fridge plant performance - daily averages*

Fridge plants	Combined duty achieved[1] (kW)	Interim duty target[1] (kW)	Interim duty target[1] (%)	Duty design target[1] (kW)	Duty design target[1] (%)
Cooling circuit 1	984	2 000	49	3 000	32
Cooling circuit 2	8 266	13 000	63	16 830	49

[1] *Water cooling duty*

Figure 1.2: *Cooling circuits performance*

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Pg. 2

CONFIDENTIAL

2 Daily fridge plants and ponds cooling performance

Table 2.1: *Fridge plants cooling performance - daily averages while running*

Fridge plant (FP)	Utilisation (%)	GV Pos[1] (%)	Duty[2] (kW)	Interim target[2] (kW)	Evaporator inlet T (°C)	Evaporator ΔT (°C)	Evaporator flow (ℓ/s)	Condenser inlet T (°C)	Condenser ΔT (°C)	Condenser flow (ℓ/s)	COP[3]
FP1	0	-	-	-	-	-	-	-	-	-	-
FP2	63.9	98.3	1 546	2 269	16.5	5.4	68.7	37.3	2.0	160.9	3.3
FP3	0	-	-	-	-	-	-	-	-	-	-
FP4	100.0	98.2	1 981	2 269	17.5	5.7	82.6	40.1	5.1	130.3	2.8
FP5	100.0	98.0	1 779	2 269	18.5	5.3	80.9	40.0	4.6	115.7	2.8
FP6	0	-	-	-	-	-	-	-	-	-	-
FP7	100.0	97.6	1 811	2 269	18.0	5.1	85.6	39.7	6.8	100.3	2.0
FP9	0	-	-	-	-	-	-	-	-	-	-
FP10	100.0	97.8	2 692	4 096	20.7	5.1	126.7	39.5	10.3	96.0	3.2

[1] *Guide vane position;* [2] *Water cooling duty;* [3] *Coefficient of performance*

Table 2.2: *Chill ponds cooling performance - daily averages while running*

Chill pond	Water flow (ℓ/s)	Duty[1] (kW)	Duty interim target[1] (kW)	Water inlet T (°C)	Water ΔT (°C)	Air flow (kg/s)	BAC[2] duty[3] (kW)	Air inlet T (°C)	Air ΔT (°C)
L255 chill pond 1	62.8	-709	1 912	31.0	-2.7	–	–	–	–
L255 chill pond 2	48.9	388	1 912	14.4	1.9	–	–	28.8	–
L255 chill pond 3	33.9	2 251	1 912	13.6	15.9	–	–	13.8	–
L255 chill pond 4	52.3	1 209	1 912	13.7	5.5	–	–	28.9	–
L276 chill pond	17.2	-310	1 912	4.3	-4.3	–	–	16.8	–
L289 chill pond	28.0	1 499	1 912	16.1	12.8	–	–	–	–

[1] *Water cooling duty;* [2] *Bulk Air Cooler;* [3] *Air cooling duty*

Table 2.3: *Condenser ponds cooling performance - daily averages while running*

Condenser pond (CP)	Water flow (ℓ/s)	Duty[1] (kW)	Duty interim target[1] (kW)	Water inlet T (°C)	Water ΔT (°C)	Stages running
L255 CP 1	224.7	2 514	5 556	37.9	2.6	3
L255 CP 2	149.3	3 078	5 556	45.1	4.9	3
L255 CP 3	184.6	3 470	5 556	45.7	4.5	2
L255 CP 4	179.1	7 338	5 556	46.2	9.8	3

[1] *Water cooling duty*

Table 2.4: *Other - daily averages while running*

Description	Value
Fridge plant haulage temp (°C$_{wb}$)	31.7
Cold dam temp (°C)	13.3
Hot dam temp (°C)	20.4

Table legend

Unavailable	Not running	Questionable	Critical

Name *Comment*

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Pg. 3

CONFIDENTIAL

3 Consumption charts

Figure 3.1: *Chilled water daily supply*

Figure 3.2: *Hot and cold water dams*

Figure 3.3: *Chill water supply – Progressive daily average*

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4 Appendix: System layout

Figure 4.1: *Cooling system layout*

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Figure 2-5: Automated daily cooling performance report[xiv]

[xiv] The full report is shown in Appendix C

The second page elaborates on the cooling performance of the individual fridge plants, evaporator- and condenser circuits, as well as other notable system parameters. The third page shows the water consumption charts of the main hot- and cold dams. The fourth page shows the cooling system layout.

The literature showed that the development to the wisdom level of the hierarchy shows an increase in human involvement and reaction [26]. This involvement was seen by the reaction on performance enquiries from top-level management. In Figure 2-6, the bars indicate the cooling duty achieved, and the solid red line shows the cold-dam temperature. A disturbance in the cooling duty also influences the cold-dam temperature. Management could act on a decrease in performance, whether sudden or over a few days, by prompting the relevant personnel. Figure 2-6 shows that there was a significant response after an email from the regional general manager and the group engineer on two separate occasions [14].

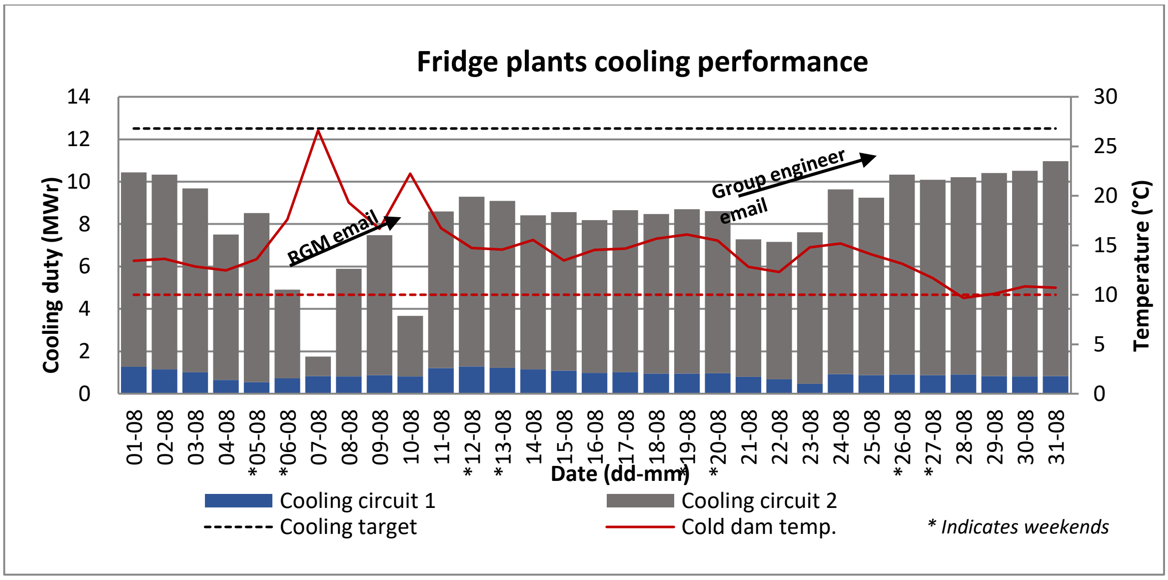


Figure 2-6: Progressive cooling performance graph[xv]

An increase of 55% relating to 5.3 MW of refrigeration was witnessed before and after implementation of this methodology. The heat rejection improved with more than 5.0 MW and the cold-dam temperature reduced with 3.2 °C. Verification of this improvement was done through conducting manual audits of the cooling coils near the workplaces before and after implementation of the DIKW method. On average, the cooling coils' inlet water temperature improved by 13% [14].

[xv] Available in the first article [14]

2.4. DISCUSSION

The publication section highlighted the DIKW steps followed and the results obtained. This section discusses the relevance of this study to the holistic research objective of developing a cooling system performance monitoring tool to increase system management effectiveness.

The data-acquisition phase is the foundation for this DIKW implementation on a deep-level mine cooling system. Various studies show that the use of performance measurements to analyse system state and improvements are highly dependent on data accuracy [14], [24], [39]–[41]. This implementation of approaching each DIKW-level chronologically addresses the data integrity issue. Building in automatic smart-analysis features enabled the real-time identification of communication losses and deteriorating instrumentation accuracy, based on material redundancy or heat imbalances between the electrical, evaporator and condenser duties.

Lessons learned in the data phase included the timeous reporting and constant follow-up of instrumentation requiring calibration or replacement to the correct management representative. Experience gained through the implementation of this project showed that the harsh underground environment makes it extremely challenging to keep instrumentation in good condition. The solution implemented in the data phase showed that a further study, incorporating condition-based maintenance for instrumentation, could add significant value to the mining community. There is room for improvement at this level. However, the current data-acquisition phase was suitable for this study.

The literature showed that site-specific KPIs contribute to effective maintenance procedures and improvement initiatives [33], [40], [48]. This study focused on the KPIs relevant to mine cooling systems. These KPIs included cooling duties and COPs. The core focus of the automatic daily report, developed together with insightful inputs from mine management, was the cooling duty and cold-dam temperatures. Operators soon increased the evaporator water flow to indicate a higher cooling duty, but it resulted in warmer cold-dam temperatures. Development of an indicator taking both cooling duty and cold-dam temperature into account was a consideration. However, this unknown parameter was not greatly accepted and adopted by mining personnel. Lessons learned in the information phase included reporting of cooling performance measures known and accepted by the on-site personnel.

The information level of the DIKW hierarchy showed that choosing the correct performance indicators assisted in the significant impact of the cooling system monitoring tool. This phase created the basis for analysing the direction of performance trends. The performance trends enabled the initial reflection of knowledge by the daily report. It quickly showed the direction of the performance trend, and one could easily see the impact of improvement initiatives. It also created transparency between different engineering and mining departments regarding the cooling services provided.

The knowledge reflected daily by the report enabled management to make informed decisions regarding improvement initiatives. One of these initiatives that stemmed from the use of the report was the construction of another condenser pond. Mine management quickly realised that the current cooling capacity was hindered due to the limited heat rejection capacity. The limited heat rejection capacity was indicated by the report when the guide vanes on the fridge plants cut back due to increased condenser vessel pressure. This pressure was a result of higher condenser water temperature in the cases where additional fridge plants were operating to increase the cooling duty. The impact of the new pond will not be assessed in this study due to the construction period exceeding two years.

The highest level of the DIKW hierarchy aims to assess data at the maximum level of context and understanding. The daily automatic implementation of the report showed a significant increase of awareness between mine management and cooling system performance. This was quite evident from the use of the report in management meetings and the reaction of upper-level management to cooling performance drops, as seen in Figure 2-6. The long-term impact of the daily performance report showed an increase of 55% relating to 5.3 MW of refrigeration. The daily use of the report helped facilitate the continual improvement on performance.

The results are promising due to the significant size and complexity of these systems. The DIKW method assisted in developing a unique Industry 4.0[xvi] implementation on deep-mine cooling systems. This DIKW method could also add considerable value to other mining systems such as compressed air, pumping and ventilation.

[xvi] The fourth industrial revolution incorporates smart technologies to predict performance reduction, autonomously manage and optimise product services [52].

2.5. CONCLUSION AND RECOMMENDATIONS

The deeper mines require cooling systems to mitigate the increased heat load of the mine. These cooling systems are large interconnected circuits requiring well-timed maintenance to ensure sustainable operation. The research objective was to provide mine management with a cooling system monitoring tool. Implementing a DIKW model on a deep-mine cooling system showed that the automatic daily analysis and reporting of the available data on the cooling system resulted in better awareness and facilitation of improvement directives.

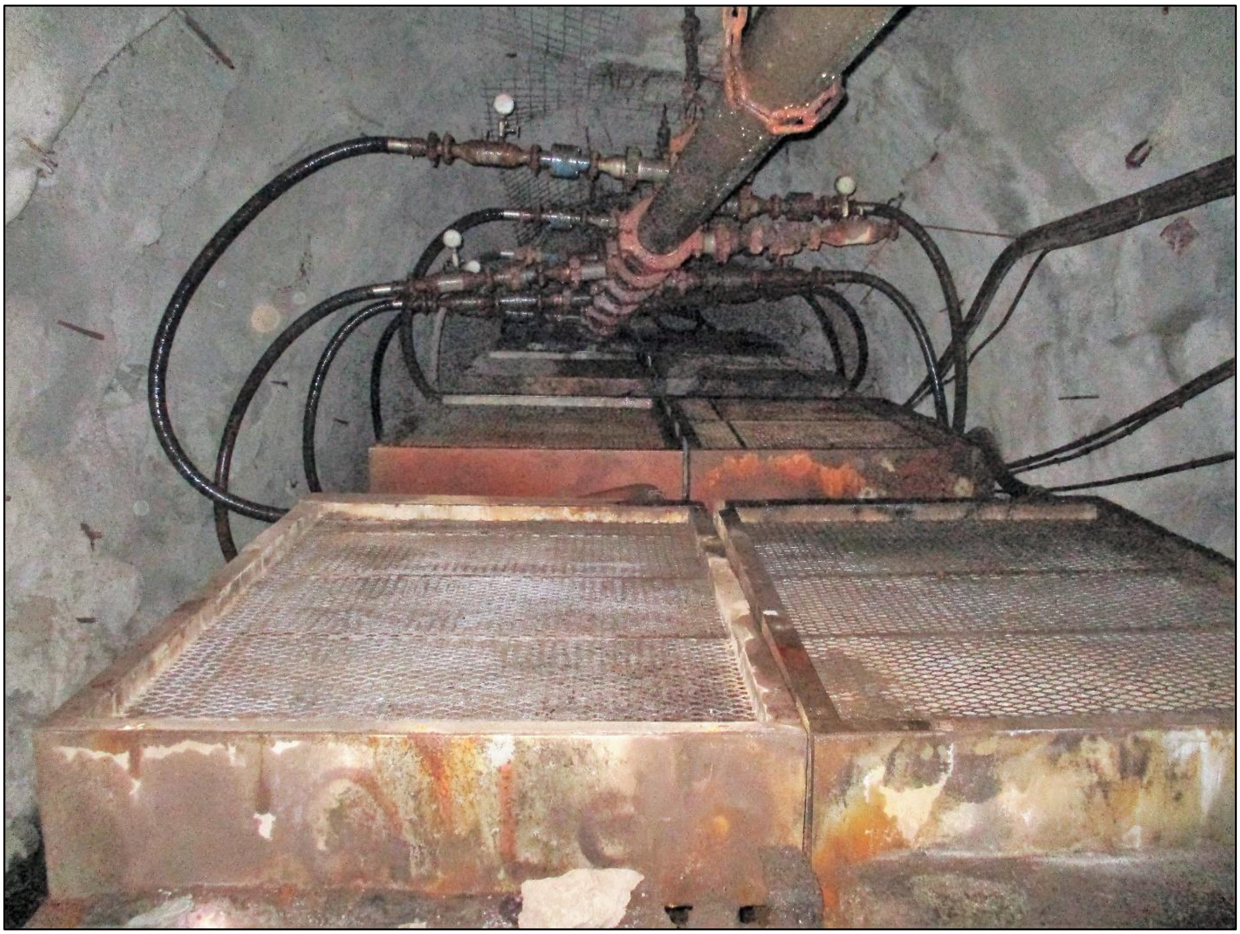
The DIKW implementation was done with zero capital expenditure by using the mine's installed infrastructure. The full maturity of data to wisdom facilitated a 5.3 MW refrigeration improvement, which resulted in a 13% reduction in cooling cars' water inlet temperature. The results show that the DIKW model is an appropriate method to optimise management on deep mines, using their already installed infrastructure.

The implementation of the DIKW method was promising. However, there were a few challenges and lessons learned during this study. The study limitations and recommendations for further work are listed below:

- Instrumentation accuracy and availability posed a significant challenge. The instrumentation forms the backbone of the hierarchy, as the data level is highly dependent on this. The reporting system had built-in smart features, which enabled rapid detection of instrumentation errors. However, quarterly or biannual instrumentation audits are recommended to ensure data accuracy. As discussed in the previous section, further work could add substantial value to the mining community by providing a condition-based maintenance method for instrumentation technicians to keep their sensors in excellent condition.
- Report interpretation depended on the level of the reader's competency. The level of wisdom extracted from the report was equivalent to an individual's capacity to analyse the information and knowledge reflected by the report. On-site training mitigated this problem to a certain extent. Further work could address this by adopting better visualisation techniques [49]. Lessons learned from environmental reporting set out by the Global Reporting Initiative also shows that disclosing data and using set standards could also lead to better report interpretation [50].
- Daily report delivery was only confirmed by on-site interaction with mining personnel or feedback on the reports via email communication. Further work could address this via a web-based delivery method to confirm delivery and reading of the reports.

- High reporting frequency has many advantages, but it also has a few disadvantages. A study on world-class maintenance showed that the overuse of performance indices start enthusiastically. However, they soon lose their appeal [15]. This study also experienced a similar start. The danger of daily reporting losing its appeal cannot be ignored. Further work should address this by developing a standard reporting system rolled out over multiple sites and well-adopted into mine management procedures.
- Actual performance reporting lacks the capability of assessing expected performance. The daily assessing of actual cooling performance had a significant impact. The question remains whether the performance was suitable under the current environmental conditions. The study found that mine management set impossible cooling performance targets, based on design cooling duties. Further work should address this by analysing the expected performance of the cooling systems operating under off-design conditions.

CHAPTER 3   ARTICLE II



Secondary cooling – Underground bulk air cooler [xvii]

Underground bulk air coolers cool down air entering the underground level to enable safe and productive workplace environments [xviii]

[xvii] Photograph taken by author 3.1 km underground near Klerksdorp, North West, South Africa.
[xviii] Subsurface ventilation engineering [11], [52].

3.1. PREAMBLE

This chapter discusses the research procedure followed to reach the novel contribution described in article II (Appendix D). The first article showed that further work should provide solutions for calculating the expected performance of a cooling system operating under off-design conditions. The challenge encountered within industry is the lack of realistic cooling performance targets. This was found during implementation of cooling performance monitoring in Article I. The rated cooling capacity of these installations are not applicable under off-design conditions and hence further study should address this problem. The literature survey follows a logical flow to show the need for analysing the expected cooling performance of mine cooling systems operating at off-design conditions. A publication summary highlights the method and results contributing to the solution proposed by this study.

A discussion section then indicates the significance of article II to the holistic research goal of cooling performance optimisation through monitoring and analysis. This article aims to develop a method that analyses the actual and expected performance of underground cooling systems operating at off-design conditions to assist in maintenance directives. The concluding remarks for this article also provide recommendations for further work.

3.2. LITERATURE SURVEY

The introduction showed that the deeper exploration of mineral resources results in hot workplaces [2], [3]. These deep mines use cooling systems to mitigate the heat. Figure 3-1 shows the typical cooling hierarchy, including primary air-cooling systems (surface BACs), secondary air-cooling systems (underground BACs) and tertiary air-cooling systems (cooling coils) [8], [9], [51], [52].

Fridge plants provide cold water to these air-cooling systems. The first article showed the significance of calculating and daily reporting of actual cooling performance regarding these systems [14]. However, the actual performance does not indicate the level of performance expected under the current environmental inputs such as water- and air temperatures, mass flows and pressures. These systems operate on certain design performance curves with specific inputs. The actual cooling divided by the design cooling rarely provides the correct efficiency. It is thus not possible to determine the efficiency of the system correctly without taking the expected performance of the cooling system under those environmental conditions into account [12].

The expected performance of a heat exchanger at the given environmental inputs is the normalised performance [12]. The actual performance divided by the normalised performance results in the real efficiency of the cooling system [12], [53]. Accounting for normalised performance in efficiency calculations provides accurate results and realistic cooling targets. The conventional methods for dividing actual performance by the design performance is only applicable when these systems operate within their design specifications. The mine cooling systems operate on a performance curve, and design performance cannot be expected under off-design inlet water- and air temperatures, pressures and mass flows [12]. It is thus crucial to account for normalised performance when setting cooling targets or analysing the efficiency of the cooling systems.

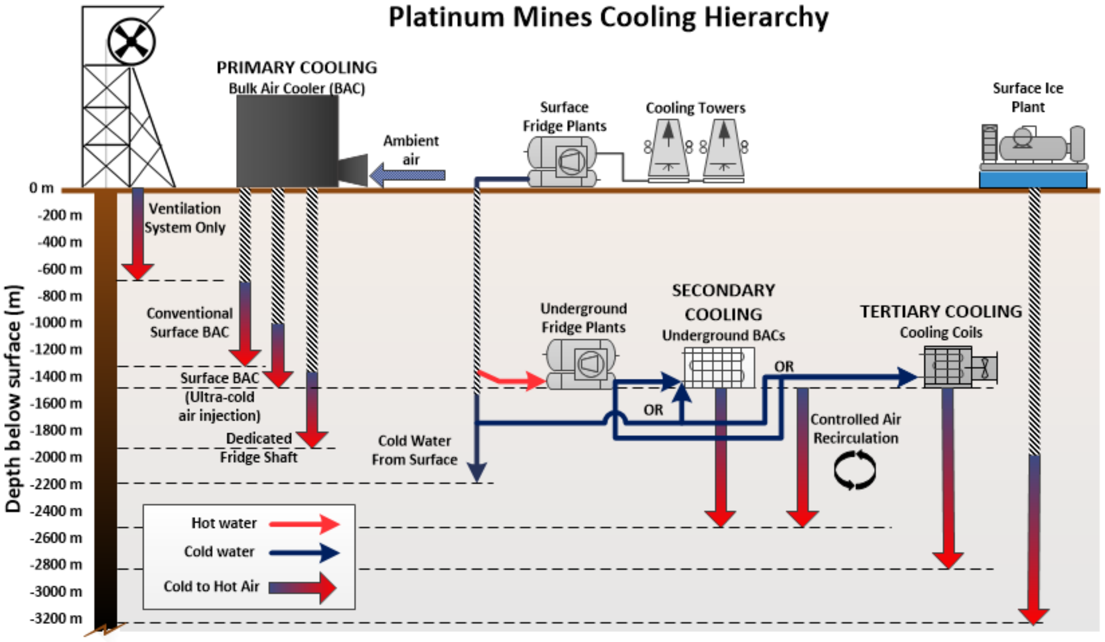


Figure 3-1: Platinum Mines Cooling Hierarchy[xix]

The focus of this study is limited to the performance analysis of cooling coils. These types of tertiary air-cooling methods are the most common and thus the focus of this study. However, the lessons learned from this apply to most of the deep-mine cooling system components. This section highlights the literature applicable to obtaining the actual and normalised performance of cooling coils.

Cooling coils are also known as spot coolers, decentralised, tertiary or in-stope cooling systems [51]. Anglo American made use of cooling coils since the 1950s [9], [51]. Due to the

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[xix] This figure is a repeat of Figure 1-2.

deeper mines and developments further away from central haulages, the need for tertiary cooling constantly increases [52]. The most common tertiary cooling methods include vortex tubes, spot cooling coils, venturi cannons, in-stope spray systems and mobile refrigeration air-cooling units [9], [11], [51], [52], [54], [55]. Cooling coils are considered the better alternative to vortex tubes or in-stope spray systems [52].

A cooling coil is an air-to-water heat exchanger [11]. A tube-and-fin heat exchanger transfers the hot ventilation air to the cold service water from the fridge plants. The cooling coil rejects the heat into the dewatering system of the mine. Ventilation ducting then directs air to the working area to mitigate localised heat [51]. Figure 3-2 shows a 500-kW rated cooling coil removed from underground for maintenance. The tube-and-fin plates, water inlet- and outlet connections, as well as air inlet and outlet, are visible.

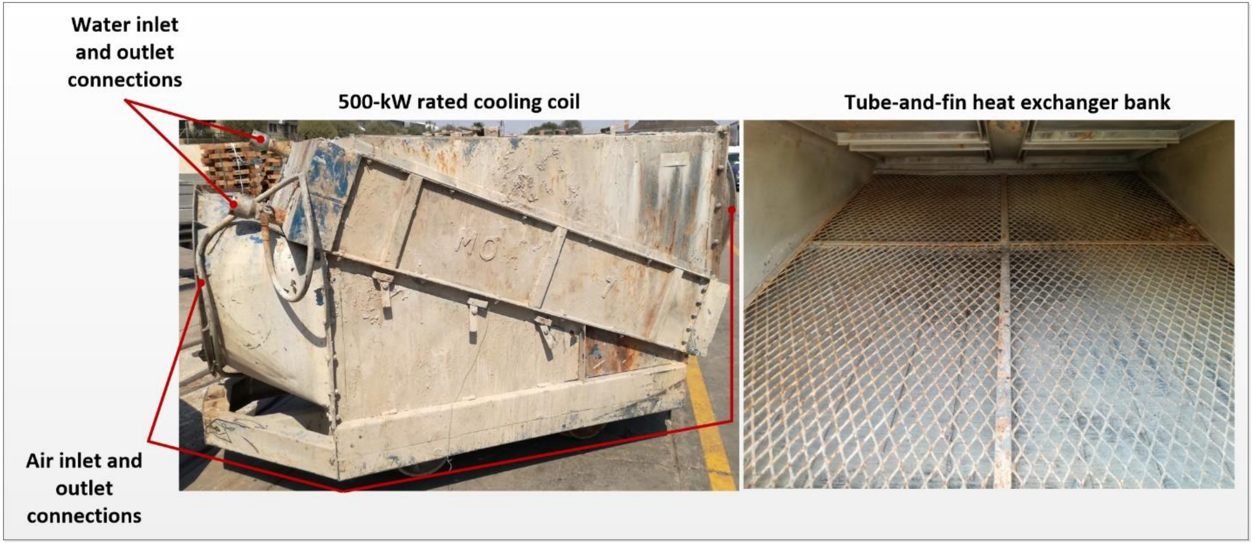

Figure 3-2: 500-kW rated cooling coil[xx]

Several calculations evaluate the effectiveness of a cooling coil [11], [12], [56]. Most calculations use manual or automated measurements as inputs. The water duty and air duty of a cooling coil are calculated parameters that reflect its actual performance [12]. The measurements also enable assessment of the cooling coil's overall heat transfer coefficient (UA product). The UA product is a calculated parameter which reflects the degree of heat exchange effectiveness [11], [12], [53].

A clean cooling coil's UA product ranges between 10 to 25 kW/°C. There are methods to calculate the cooling coil's clean UA product [45], [56]. Comparing the actual UA product to the clean UA

[xx] Photographs taken by author near Klerksdorp, North West, South Africa.

product provides insight into the cooling potential of the cooling coil. However, the required inputs for these calculations are not always available [12]. A heat transfer effectiveness calculation is useful if the cooling coil is in a closed system configuration. During the on-site research, this was found to be a rare case. The alternative is to compare the actual performance to the normalised performance [12].

There are several methods to calculate the normalised or expected performance of a cooling coil operating under off-design conditions. The methods include the use of performance curves issued by the original equipment manufacturer [12], utilising historical performance data [12], [57], straightforward mathematical modelling [12], [58] and calibrated simulation models based on either comprehensive or straightforward mathematical modelling [59].

The first approach entails original equipment manufacturer involvement. The success of this method depends on the alacrity of the manufacturer to provide performance curves for various operating conditions [12]. The challenge to obtain these curves from the manufacturer is a result of intellectual property concerns. In theory, the performance curves will indicate the expected performance of the cooling coil at the measured environmental conditions [11]. The shortcomings in this method include the range of environmental conditions, which necessitates a substantial range of operating curves from the manufacturer [8], [12].

A historical data model could also enable the successful prediction of normalised performance. However, the shortcoming in this approach lies in the high dependence on comprehensive and accurate historical datasets [11], [57]. A straightforward mathematical model is also an option and has been implemented on refrigeration machines [59], [60]. The shortcomings in these straightforward mathematical models include the availability of specific required parameters, practical applicability in the mining environment and that these models need expansion for use on cooling coils [12].

A few studies made use of simulation programs, based on straightforward or comprehensive mathematical modelling, to analyse the performance of air-handling units on surface buildings [61], [62]. These studies show that modelling heat exchangers with simulation methods has its benefits. However, they use proprietary software and assume all parameters are measured or provided by the manufacturer. The expansion of simulation models to underground cooling coils could enable the prediction of normalised performance. Other studies successfully made use of simulation software for performance analyses of refrigeration plants [60]. It thus seems likely that an underground cooling coil simulation model could successfully evaluate its normalised performance.

Figure 3-3 shows a typical cooling coil installation. These installations are usually far from central haulages [51]. The cooling coils' installation areas make automated performance measurements infeasible. Thus, robust performance analysis on underground cooling coils will be successful when it is implementable with the minimum amount of accurate measurements.

Figure 3-3: A 500-kW rated cooling coil installed underground[xxi]

The mining industry will benefit from a cooling coil performance analysis method. This method should enable higher accurate efficiency calculations to assist in ventilation planning and maintenance strategies near workplaces. This method should be practical and evaluate cooling coils operating at off-design conditions with the minimum amount of data available. Literature shows that there are several methods to calculate the actual and normalised performance of a cooling coil. The literature survey also shows that a simulation model will most likely succeed.

The first article developed a novel deep-mine cooling performance real-time monitoring and daily reporting method. The implementation thereof suggested that the normalised performance of underground conditions should be considered when stating system efficiencies. This literature section focused on tertiary cooling methods, as they are mostly exposed to off-design conditions.

[xxi] Photograph taken by author 2.1 km underground near Welkom, Free State, South Africa

The literature findings showed that a simulation model would likely succeed in estimating normalised performance.

This method addresses the second research objective of analysing the actual and expected performance of underground cooling systems to assist in maintenance directives.

Second research objective:
A method of analysing the actual and expected performance of underground cooling systems using simulation models to assist in maintenance directives.

The subsequent section summarises article II, where simulation models are used to analyse the performance of cooling coils operating at off-design conditions.

3.3. PUBLICATION SUMMARY

Article II focuses on the analysis methods applicable to cooling coils. Article II was submitted at an international peer-reviewed journal. Article II forms part of Appendix D. The details of this publication are as follows:

Pretorius JG et al. “Performance analysis of cooling coils operating at off-design conditions using simulation models” Applied Energy, 2018

The deeper mines and distant workplaces from central haulages necessitate the use of cooling coils [9]. Mining personnel use these coils to mitigate the localised heat. The Occupational Health and Safety (OHS) department of the mine determines the heat load of the workplace and need to supply the correct amount of cooling for safe environmental conditions.

During the on-site research work, it quickly became evident that the OHS departments use the design duties in cooling strategies. The OHS departments also made use of the design duties in the cooling coil efficiency calculations. These incorrect use of design duties at off-design conditions lead to ill decision-making for cooling coil maintenance strategies (The results in Figure 3-9 clearly illustrate this). The need for a method, which incorporates normalised performance into efficiency calculations and results in maintenance strategies, were supported by on-site findings and interaction with mining personnel.

The first step was to identify the minimum measurements required for full analysis of both actual and normalised performance. Figure 3-4 indicates the measurements as inlet and outlet water temperature, water mass flow, air ducting diameter, air velocity, air inlet and air outlet temperature [11], [12]. Figure 3-4 also shows the suitable measurement locations for each parameter.

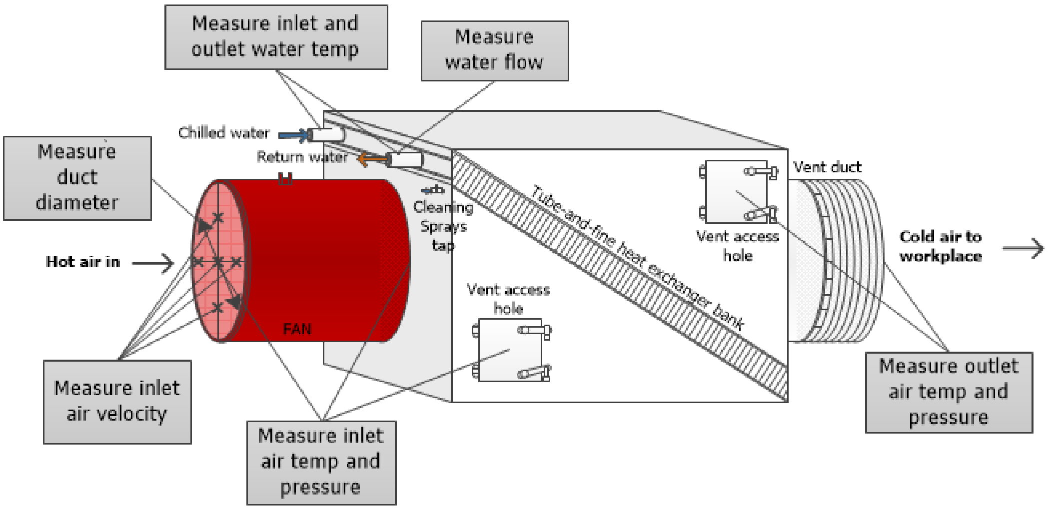

Figure 3-4: Cooling coil measurement locations[xxii]

There are several considerations to account for when conducting these measurements. These considerations include cooling coil type, fan size, fan configuration, whether the cleaning sprays are activated, water leaks, ventilation ducting condition and cooling coil type. Some measurements may be impossible to take, as shown in Figure 3-4. However, there are alternative locations for measuring specific parameters. Not all the parameters are measurable, depending on the cooling coil installation location. Hence, some modifications to the cooling coil may be necessary to allow for measurements. These modifications include:

- installation of water-isolating valves and quick-connect camlock-type hose fittings to enable safe and easy water flow measurements (applicable to low-pressure cooling coils);
- thermowells for water temperature measurements; and
- ventilation ducting access holes for airflow, pressure and temperature measurements.

The calculations of actual performance follow the completion of the manual measurements. The equations for water duty and air duty were thoroughly reviewed from literature [11], [12], [63]. A necessary calculation to make in cooling coil analysis includes the log mean temperature difference. The log mean temperature difference is a proper calculation for use in heat exchanger analysis [53]. The overall heat transfer coefficient (UA product) results from the use of the log

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[xxii] Developed from multiple resources and used in article II [11], [12], [53], [64].

mean temperature difference combined with water duty [11], [12], [53]. An important note on this method is its suitability for only parallel-flow and counter-flow heat exchangers [53]. The typical underground cooling coil uses a cross-flow configuration [11], [52]. The calculation for the log mean temperature difference in the cross-flow configuration is too complex, but a correction factor can be used. Literature shows that either a graphical or a numerical method can provide the correction factor [53], [64], [65].

The method for calculating all the applicable actual performance parameters is concluded in an important note on fan-induced temperature gain. Figure 3-5 shows a conventional cooling coil fan connection configuration found underground. The fan is directly connected to the cooling coil. The ventilation access holes, as shown in Figure 3-4, are sometimes rusted shut and the only possible measurement location is before the fan. In these scenarios, it is essential to account for the fan-induced temperature gain. The calculation of enthalpy before and after the fan is a suitable solution to estimate a more accurate dry-bulb inlet temperature for these scenarios.

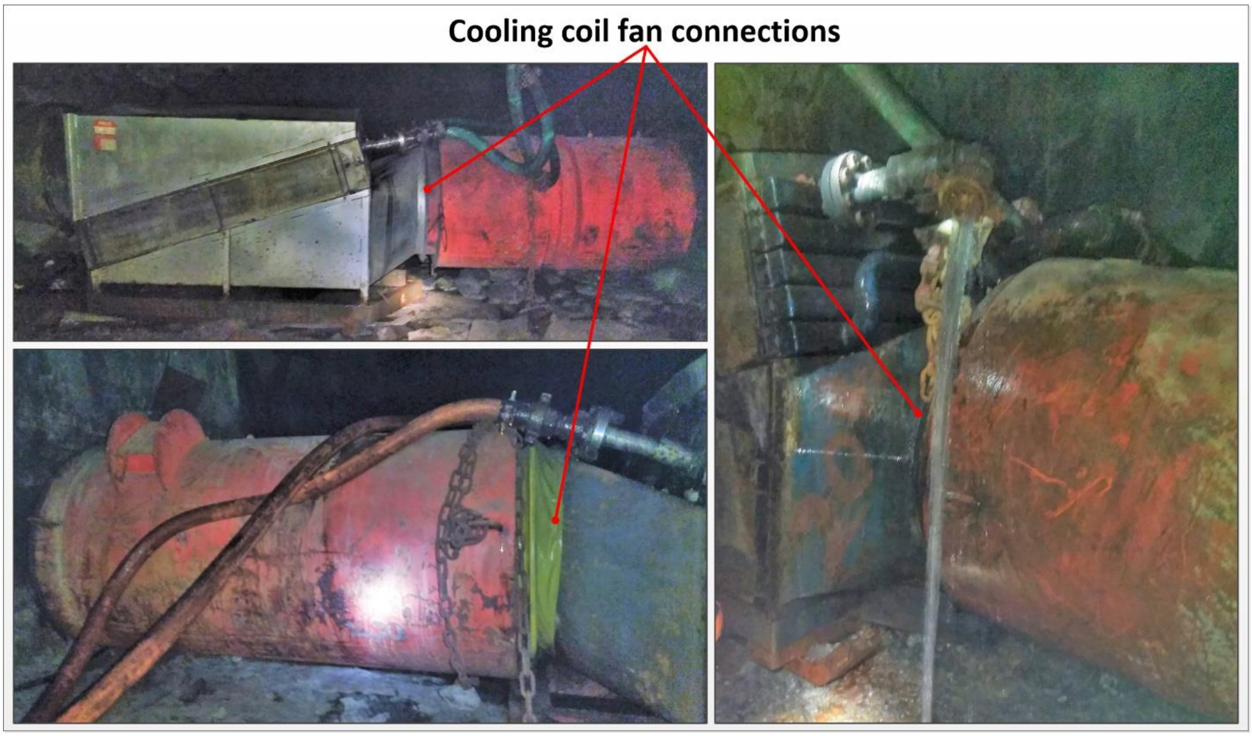

Figure 3-5: Cooling coil fan connections[xxiii]

The methodology up to this point allows one to calculate the actual performance parameters relevant to the cooling coil performance analysis. It is essential to evaluate the actual performance

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[xxiii] Photographs taken by author 2.3 km underground near Welkom, Free State, South Africa

against the normalised performance to enable an accurate reflection of cooling efficiency [12]. Figure 3-6 shows the methodology followed to obtain the normalised performance of a cooling coil using simulation models.

The first step is to obtain all available design performance curves from the manufacturer. In the scenario where no curve is available, use the best-case 25 kW/°C found in the literature [11], [12]. The second step involves the construction of a water-to-air heat exchanger model using the appropriate simulation software. Market available software packages include Flownex®, Comsol® or Simscale®. This study made use of Process Toolbox™, a thermal-hydraulic simulation software package. The next step involves the calibration of the model according to the actual measurement results. Once the model is accurately calibrated, the overall heat transfer coefficient (UA product) can be changed to the design or best-case value. The performance of the design/best-case heat exchanger under the current environmental conditions will provide the normalised performance.

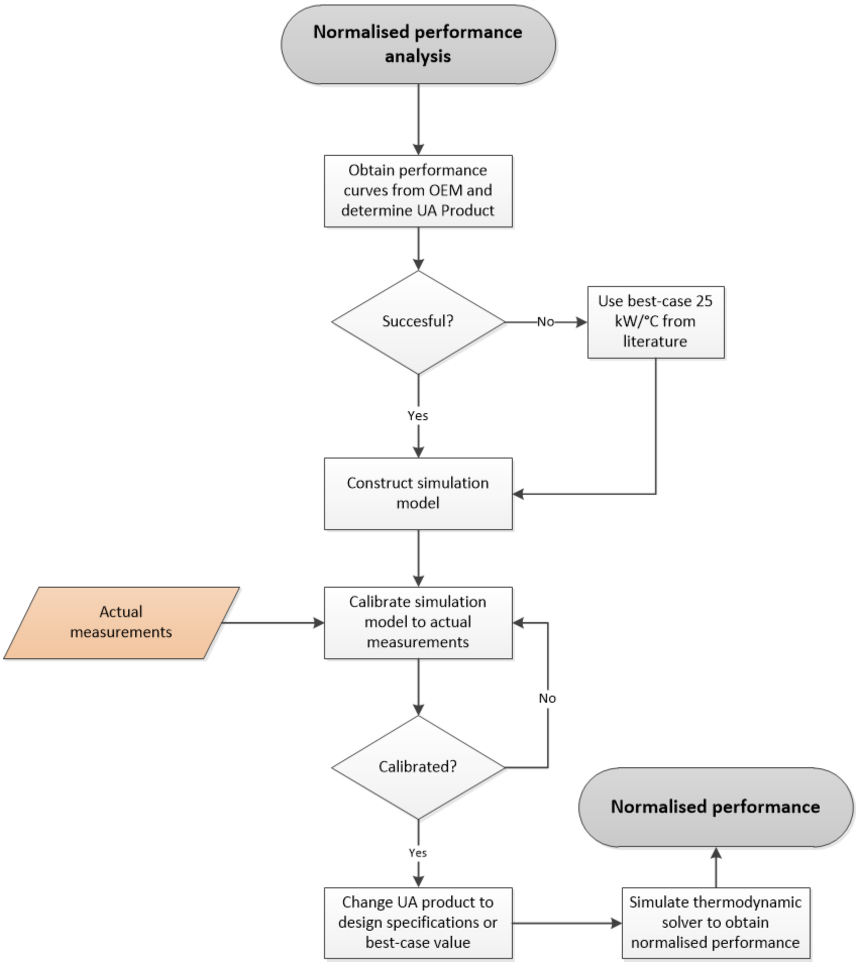

Figure 3-6: Normalised performance methodology[xxiv]

[xxiv] Methodology as used in Article II

Data measurements from two separate deep-level mines formed part of the case study implementations of this methodology. Mine A's[xxv] entire refrigeration system is located 2 km underground and does not use any surface air-cooling. Mine B's refrigeration system is located on the surface and utilises primary surface air-cooling. The great distance of the workplaces from the central fresh air intakes and secondary air-cooling necessitates the use of tertiary cooling on Mine A. The workplaces of Mine B are also far from the secondary air-cooling (BACs) and thus require tertiary cooling to mitigate the localised heat. Both Mine A and Mine B have several ventilation challenges, such as mechanised equipment, high virgin rock temperatures, ventilation air restraints, changing environmental conditions and various other problems which necessitate the use of tertiary cooling. These mines were thus deemed appropriate for this study.

The measurements were taken as shown in Figure 3-4 and discussed in article II (Appendix D). The actual performance parameters were calculated, and the normalised performance simulated. Seven 500-kW cooling coils from Mine A and three 300-kW cooling coils from Mine B were analysed. Due to challenges encountered when measuring the required parameters, such as transient air-flow conditions and also recommendations from literature [11], the waterside measurements were deemed more reliable. Article II elaborates on the instrumentation used in this study and their accuracy. The average measurement accuracy to consider is approximately 5%.

During the on-site research, it was found that the OHS departments use an Excel sheet to calculate their cooling coil efficiencies. This sheet was found on multiple sites. The Excel sheet would use their air-side measurements and calculate the water mass flow. The calculated duties would be compared against the design duty to reflect the efficiency of the cooling coil. The calculation of the OHS departments never took normalised performance into account. This finding supported the need to evaluate the normalised performance of their cooling coils.

Mine A provided the performance curves for their 500-kW cooling coils. After analysis of the curves and the findings underground, it was soon concluded that the curves did not match the installed cooling coils. This finding was due to retrofitting, refurbishment and different types of coils in operation. The suppliers of the cooling coils were highly reluctant to share any performance curves on each type of coil installed for the purposes of this study. However, the design environmental conditions were evident from the curves. Mine B could not supply any design curves for their cooling coils. This study utilised a best-case of 25 kW/°C for all the cooling coils analysed.

[xxv] This is the same Mine A used in Article I.

The simulation model for each cooling coil was constructed in Process Toolbox™. The models were calibrated to within 6% of the actual measurements. For this study, it was not feasible to move cooling coils or install new cooling coils, due to capital constraints. This comparison between the actual measurements and the simulation model thus acted as the verification to this study. Figure 3-7 shows the simulation model of cooling coil A3, shown in Figure 3-9, calibrated to within 6% of the measured environmental conditions. The simulation model also shows that the simulated actual performance of this cooling coil is 67.8 kW, which is within 1.2% of the calculated value in Figure 3-9.

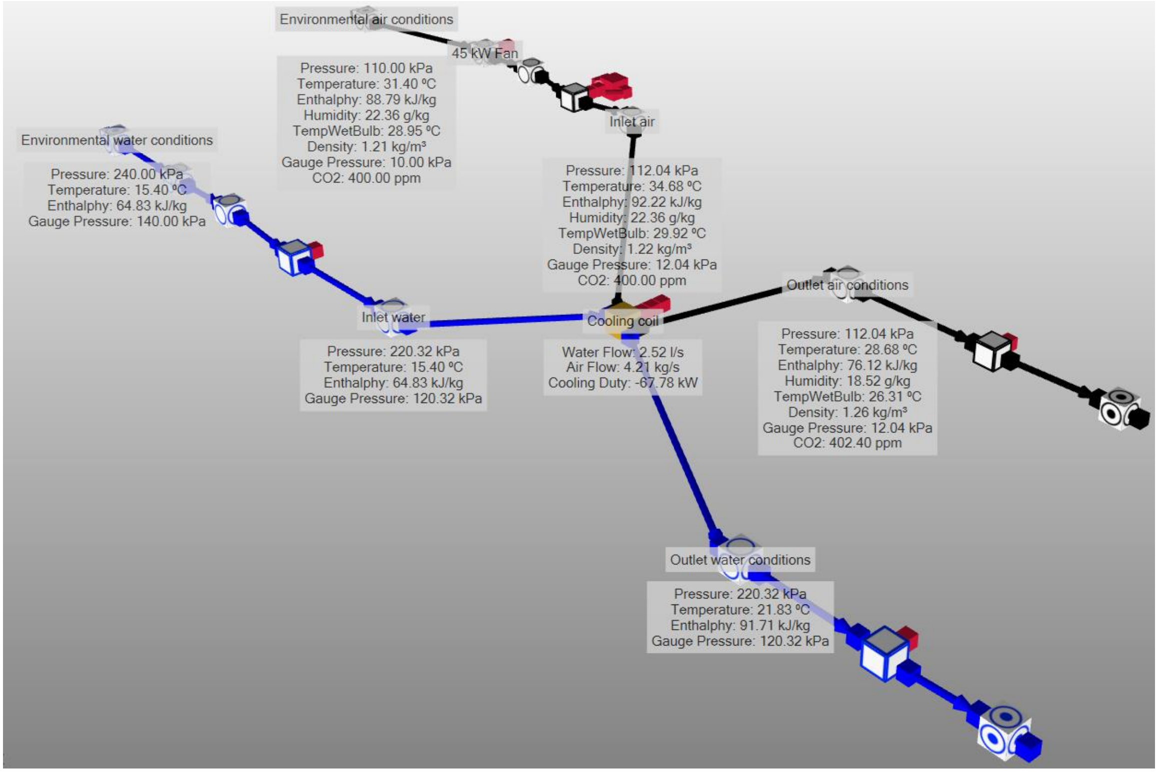

Figure 3-7: Calibrated actual performance simulation model[xxvi]

The UA product of this calibrated simulation model was then changed to the best-case UA product of 25 kW/°C. Figure 3-8 shows the best-case expected performance of the cooling coil under the current environmental conditions as 121.3 kW.

[xxvi] Cooling coil simulation model showing actual performance as described in article II

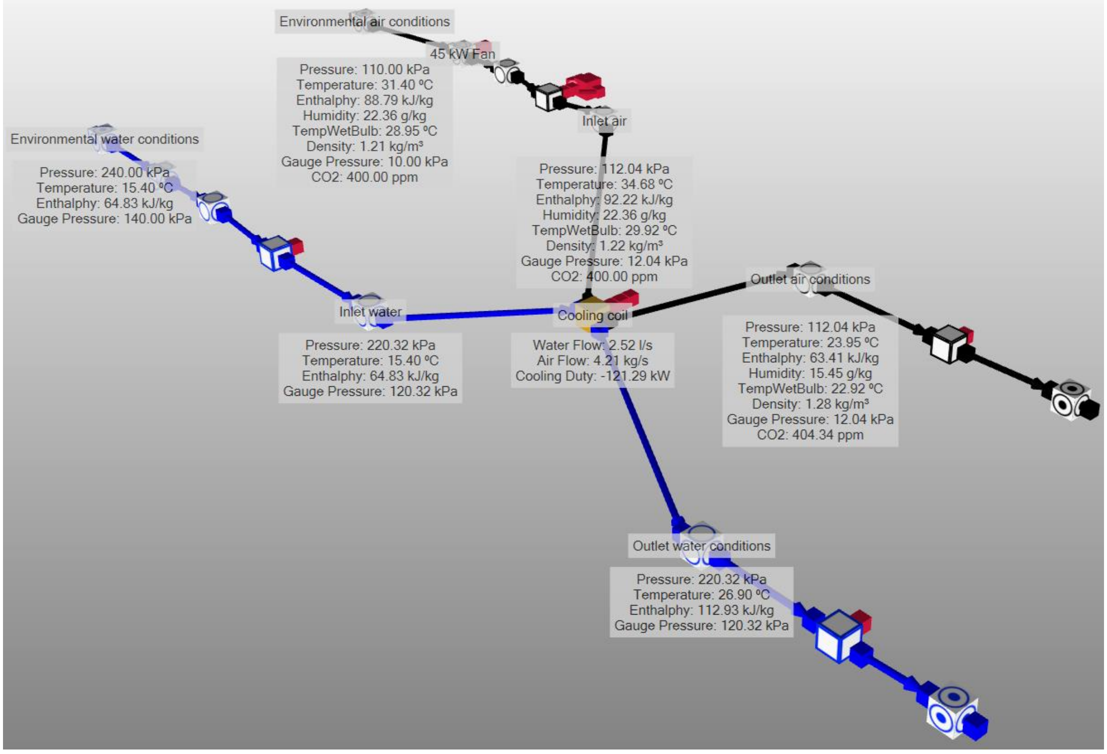

Figure 3-8: Normalised performance simulation model[xxvii]

Simulation models were constructed, calibrated and simulated for each of the cooling coils. If the design environmental conditions were known, such as for Mine A, then another simulation scenario was compiled. This additional simulation scenario evaluated the current cooling coil overall heat transfer coefficient at the design environmental conditions. Figure 3-9 shows the actual, normalised and actual at design conditions results for all the cooling coils.

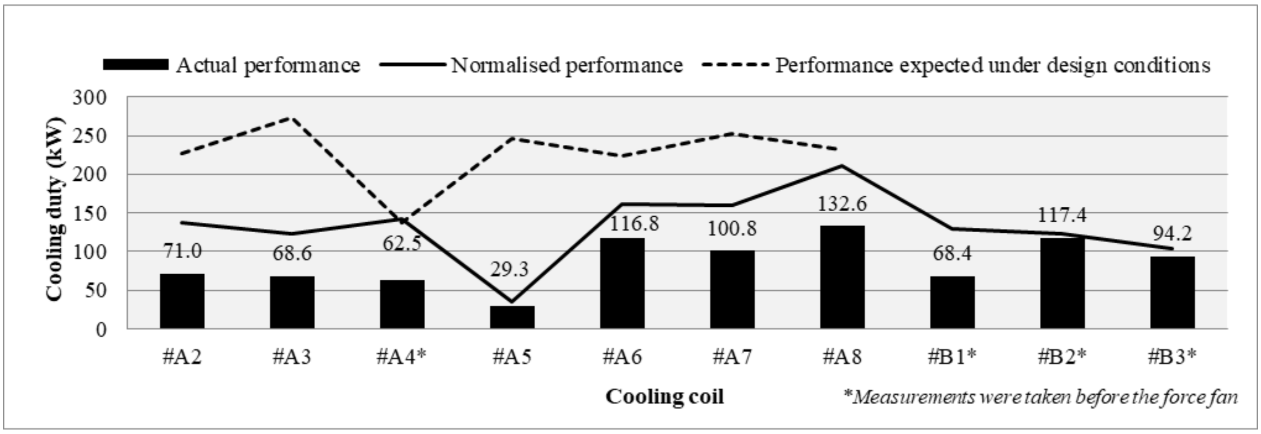

Figure 3-9: Normalised and actual cooling performance[xxviii]

[xxvii] Cooling coil simulation model showing normalised performance as described in article II

[xxviii] Cooling coil simulation results showing actual and normalised performance as used in article II

Figure 3-9 indicates the actual performance for each cooling coil with a bar, the normalised performance with a solid line, and the expected performance of the actual cooling coil when operating at its design conditions (if design conditions were available from the original equipment manufacturer). The subsequent section discusses the significance of the results towards cooling coil performance analysis and the research objective of analysing the actual and expected performance of underground cooling systems to assist in maintenance directives.

3.4. DISCUSSION

Article II (Appendix D) provides and discusses in depth the actual measurements, performance calculations and simulation results. The observations on the actual measurements showed that the activation of cleaning sprays during or before the measurements were taken, resulted in saturated outlet air conditions. Figure 3-10 shows the position of the cleaning sprays up-stream of the tube-and-fin heat exchanger bank. The results and literature showed that the cleaning sprays provide additional cooling due to direct-contact heat exchange [11]. However, leaving these sprays open results in clogging of fins caused by dust particle entrapment, as shown on the right in Figure 3-10.

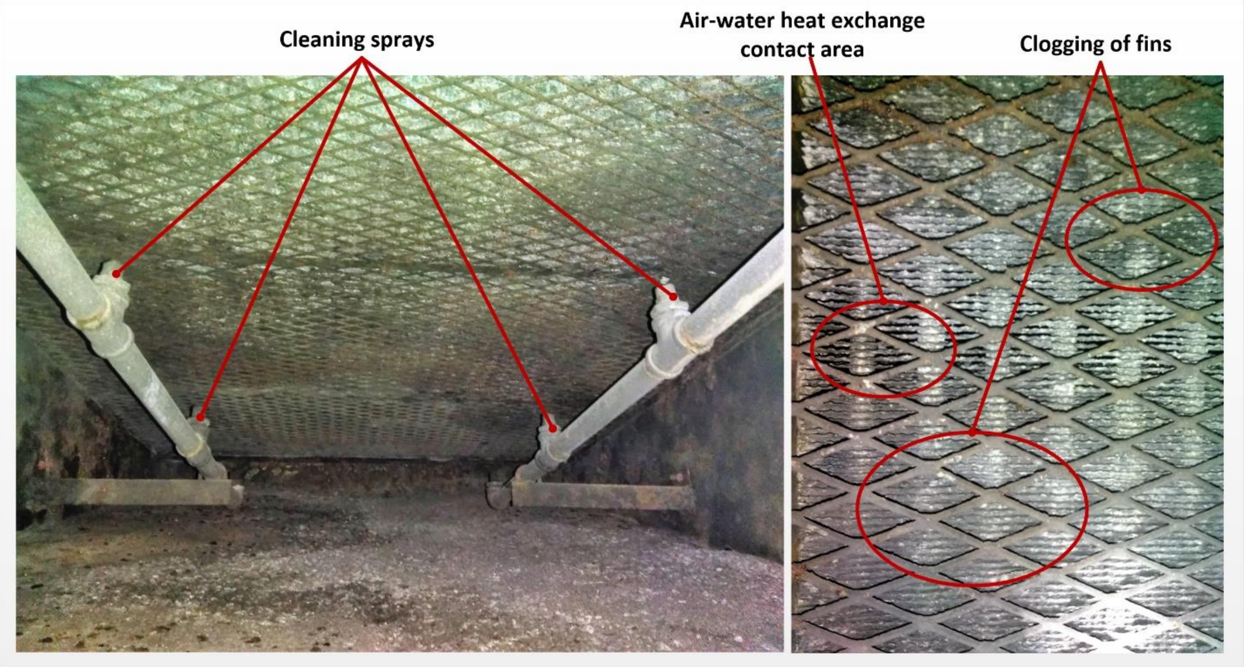

Figure 3-10: Cooling coil cleaning sprays and fin clogging[xxix]

[xxix] Photographs taken by author 2.3 km underground near Welkom, Free State, South Africa

The additional cooling from open water sprays and condensation resulted in a variation between measured air- and water duty. The measurements on the water side cannot be considered a closed-loop in this case. The methodology considered the air- and water side as a closed loop, although the additional cooling can be accounted for in the simulation program. The recommendation was to close the water sprays well in advance of taking the measurements. This assessment will enable the clear-cut analysis of the actual cooling coil conditions.

Table 3-1 shows the performance ratios depicted in Figure 3-9. The ratio between the actual performance and the design duty shows the typical efficiency reported on by the mine's OHS department. The actual performance compared to the normalised performance indicates the real performance of the cooling coil. This performance also indicates the maximum scope for improvement by cleaning the coil, which on average was 32% for Mine A and Mine B. The ratio between the cooling coil performance at design environmental conditions indicates the scope of improvement by changing the environmental conditions.

The ratios in Table 3-1 prioritise the maintenance of the cooling coil or the improvement of the environmental conditions of the cooling coil. This shows the significance of this methodology for cooling coil performance analysis. The results for poor performance easily differentiate between the cooling coil condition itself, or inadequate environmental conditions, such as air flow, water flow, air inlet and water inlet temperatures and pressures.

Table 3-1: Cooling coil performance ratios

Description	Unit	#A2	#A3	#A4*	#A5	#A6	#A7	#A8	#B1*	#B2*	#B3*
Actual vs. Design (300/500)	%	23.7	22.9	20.8	9.8	38.9	33.6	44.2	22.8	39.1	31.4
Actual vs. Normalised	%	51.5	56.0	44.0	84.4	72.6	63.0	62.7	52.9	95.5	90.6
Performance at design conditions vs. Actual	-	3.2	4.0	2.2	8.4	1.9	2.5	1.7	-	-	-

**Measurements were taken before the force fan*

Article II provides different strategies for the maintenance of the cooling coil and improvement of the environmental conditions. These strategies will assist in the upkeep of the tertiary cooling installations and help OHS departments make informed decisions regarding cooling coils. Table 3-1 shows that reporting on cooling coil efficiencies using actual performance versus design was on average 38% lower than accounting for normalised performance. This is significant because the low efficiencies of cooling coils are usually the drivers for replacing cooling coils.

During the on-site research, cooling coil A5 was one of the worst performing cooling coils according to the mine's OHS department. The mine replaced the cooling coil with another one, to only realise that the water pressure was the actual problem. The pressure relief valve system reduced the high pressure to that area too much. The replaced cooling coil was moved to a workshop where the cooling coil operated much more efficiently due to the increased water pressure supplied to it. Table 3-1 clearly shows that the environmental conditions were at fault. A new 500-kW cooling coil typically costs R500k. The correct implementation of this method could have resulted in significant cost avoidance if the mine followed its recommendations. Nevertheless, as found in article I, this analysis and recommendations should form part of the maintenance strategies adopted by the mining personnel [14], [66].

Another important outcome of this study was the use of the methodology in ventilation planning. This methodology provides insight into the expected cooling from the tertiary cooling installation to mitigate the calculated workplace heat load. During the on-site research, it was found that the ventilation strategies bargained in advance on the full design duties for these areas. The false expectation of these design duties leads to unsafe workplace ventilation conditions. The question remains if this method will still apply to mobile air-cooling units, where the design duty is easier achieved and bargained for due to more efficient heat rejection method [55].

The recent developments in localised vapour compression refrigeration systems show implementations of mobile air-cooling units [55]. The concept of using these mobile air-cooling units near workplaces are not new, but the need for it grows with the expansion of deep mines [44]. The manufacturer shows that it is only economically feasible to implement localised refrigeration technology below 4 km. The manufacturer also recommends the use of cooling coils on its condenser circuit to reject heat into return airways as the optimal configuration [55]. The advancement in localised cooling technologies still show the need for cooling coils and thus establishes the longevity of this method.

3.5. CONCLUSION AND RECOMMENDATIONS

The deeper exploration of remnant ore reserves results in hot environmental conditions. The increase is mainly due to high virgin rock temperatures and auto-compression. Cooling systems mitigate these heat loads from the surface with primary air-cooling up to tertiary air-cooling at the workplaces. These tertiary air-cooling installations have become a necessity for safe workplace conditions. The underground cooling systems typically operate outside of their design environmental conditions. This operation results in incorrect cooling performance efficiency calculations when neglecting the normalised performance for the off-design conditions. Article II focused on tertiary cooling coils and found that a simulations approach is a feasible method to obtain the normalised performance at those off-design conditions.

The actual performance calculations relevant to underground cooling coils were reviewed and implemented. The simulation models were then calibrated to within 6% of the actual results. These calibrated simulation models also acted as the verification of the study. The case study implementation found that the general method of calculating cooling coil efficiency, by comparing actual performance against design conditions, were on average 38% lower than comparison to normalised performance. The results also differentiated between changing the environmental conditions or cooling coil maintenance for the best improvement in cooling performance. The results showed that an average of 32% improvement in cooling performance was feasible for the case study cooling coils.

This methodology could be highly beneficial to other deep-mine cooling systems. The method successfully addressed the second research objective of analysing the actual and expected performance of underground cooling systems to assist in maintenance directives. The focus was on cooling coils to prove the concept of using simulation models for normalised performance calculations, although the applicability to primary- and secondary cooling, as well as refrigeration systems, still holds and forms part of the recommendations for further study. The study limitations and recommendations for further study are listed below:

- The accuracy of manual measurements was a big challenge to sustain. The installation areas for the cooling coils are usually far from central haulages [51]. These areas experience harsh environmental conditions with high pressures, humidities and temperatures. The equipment which enabled the measurements, as discussed in article II, sometimes malfunctioned due to these environmental conditions. Further work could address this challenge by installing proper measurement points and using more robust non-electronic or high ingress protection-rated equipment.
- The unavailability of measurement points on some cooling coils affected the parameter estimations, e.g. on cooling coils with no thermowells, a cold-water supply valve would enable a rough reflection on the inlet water temperatures, or the use of an infrared temperature gun on a piece of uninsulated pipe into the cooling coil. However, these temperatures provide an estimation of the temperature and not necessarily the correct value. Further work should address this by installing proper measurement points for all parameters necessary to measure during the analysis.
- The manual measurements on the cooling coils are not taken regularly. Even though the mine’s OHS department must do audits as part of their scope of work, the audits are still infrequent and not at constant intervals. This may not be the case at all mines, but for the maturity of this study and a resultant increase in analysis effectiveness, a higher frequency of audits on a monthly, bi-monthly, or at the most three-monthly basis, forms part of the

recommendations. This recommendation also includes proper cooling coil audit training to the relevant mining personnel.

- One of the challenges experienced during the research period was the change of environmental conditions and cooling coil positions between audits. These changes made it difficult to analyse the same cooling coil over a period, especially when not taking normalised performance into account. Further study should implement this method with an increase in audit frequency on the same coils to analyse the effects of maintenance, time of use and degradation of environmental conditions over time. This recommendation for further work, which implements the use of normalised performance, will add significant value to this research field.
- The alacrity of original equipment manufacturers to provide performance curves and the use of best-case UA product values require further work. The use of best-case UA products is an assumption of the cooling coil due to the absence of coil-specific design performance data. Some cooling coils are old and unbranded, which adds to the challenge of finding design performance data. Further work should address this by developing models for accurate design UA product estimation applicable to underground cooling coils, or the buy-in of original equipment manufacturers to release lab performance data.

The implementation of simulation models in the analysis of cooling coils operating under off-design conditions showed great promise. The results of this analysis method on tertiary cooling installations showed that it would most likely succeed when further developed to refrigeration machines, cooling towers and primary- and secondary cooling systems. The following chapter concludes the study through a detailed collage of both articles' contributions and interdependencies towards the holistic research goal.

CHAPTER 4 CONCLUSION

Tertiary cooling - Underground cooling coil [xxx]

Cooling coils provide localised air cooling at the workplaces to enable safe and productive workplace environments [xxxi]

[xxx] Photograph taken by author 2.3 km underground near Welkom, Free State, South Africa.
[xxxi] Subsurface ventilation engineering [11], [52].

4.1. PREAMBLE

This final chapter aims to provide an overview of the research and logically condense the successes and shortcomings thereof. The first section summarises the events leading up to the research need and resulting objectives. The subsequent sections then emphasise the connectedness between both articles and how each contributed to reaching the research goals. These sections logically flow into the next, which describes the benefits and contributions of this research. Finally, the shortcomings of the entire study towards optimising mine cooling performance with monitoring and analysis are listed, and recommendations for further work made.

4.2. RESEARCH NEED AND OBJECTIVES

The South African deep-mining industry is under ever-increasing pressure for production. The shortage of shallow gold and platinum reserves forces mining companies to exploit mineral resources deeper than ever before. The deeper mining is crucial to stay competitive during the current stressed economic times. The deep mines have challenging environmental conditions. Due to the magnified impact of geothermal heat and auto-compression at increased depths, mine cooling systems are needed. These cooling systems are large, complex, inter-connected and energy-intensive. Maintenance and efficient operation of these systems keep the mines operational and productive. The literature showed that collaboration between departments and effective utilisation of the mine’s information systems might improve maintenance and assist in improvement initiatives.

The literature showed that the mine SCADA systems are typically under-utilised. This statement was substantially supported by upper-level management from one of South Africa’s deep-mining conglomerates. The need for this research stemmed from this interaction with management and literature background to optimise deep-mine cooling systems through monitoring and analysis techniques. The current monitoring techniques fell short due to immature knowledge management techniques, and an inability to evaluate not only the actual cooling performance but also the expected performance of these systems.

4.3. ARTICLE I

There are large amounts of data on a typical mine cooling system. The mine installs sensors to measure various flows, pressures and temperatures through their refrigeration plants and the rest of the cooling system. However, these data values are not always used to their full extent. The SCADA system reflects specific performance parameters but is rarely communicated and widely shared in a compact form between different departments and management. Article I presented a wisdom hierarchy (DIKW) implementation of knowledge management, which facilitated cooling system improvements and increased the management effectiveness thereof.

The wisdom hierarchy showed that there exists a coherence between data, information, knowledge and wisdom. The maturity of data towards wisdom exploited the greater contextual understanding of system cooling performances. The novel implementation of the DIKW method on a deep-mine cooling system, focussed on each step in the hierarchy to allow for full extraction of the knowledge within these large datasets. The focus on each hierarchy level assisted in developing a robust system for performance monitoring while using the mine’s installed infrastructure.

In article I, a novel implementation of the data, information, knowledge, wisdom (DIKW) hierarchy showed great promise for optimising cooling system management on deep mines. The DIKW method emphasised the maturity of data towards wisdom. This knowledge management method of developing data, captured by the existing mine instrumentation backbone, to information, knowledge and finally, wisdom, assisted mine management in actionable decisions and improvement directives. The daily reporting facilitated a cooling performance improvement of 55% (5.3 MW of refrigeration). The daily reports automatically calculated KPIs for specific system parameters to monitor and track system cooling performance. The value of the system was in the use of existing tools and techniques to add significant value to the performance of mine cooling systems. This same method could also be applied to other mines or other components on a mining system.

4.4. ARTICLE II

Article I addressed the first research objective to provide a performance monitoring solution for deep-mine cooling systems. Article II stemmed from the shortcomings of article I, where a solution was needed to estimate the expected performance of the cooling systems when operating under off-design conditions. Figure 1-2 shows the three levels of air-cooling systems, with each level closer to the working areas. Primary cooling usually consists of surface bulk air cooling. Secondary air cooling consists of underground bulk air cooling on a level basis, and tertiary cooling entails localised workplace cooling. The tertiary cooling locations experience the most extreme environmental conditions. Ventilation and cold-water services provided to these areas usually experience changes over time. For this study, the development of the solution for expected performance at off-design conditions was performed at the most extreme, tertiary cooling level.

Article II presented a method to calculate the normalised performance of cooling coils operating under off-design conditions, using simulation models. The article reviewed the actual performance calculations and provided the methodology to estimate the normalised performance of a cooling coil operating outside of its design environmental inputs. The comparison between actual and normalised performance indicated the real efficiency of the cooling coil and provided insight into maintenance strategies for these coils.

The insight gained by the analysis method of exploiting normalised performance showed the significance of discerning between cooling coil condition and environmental inputs. The comparison between normalised performance and actual performance showed that a maximum performance improvement of 32% was feasible for the cooling coils forming part of the case study.

The results also showed that the current method of using only design performance when calculating efficiency reported, on average, 38% lower than when accounting for normalised performance. This was significant because the cooling coil efficiency is usually the driver for cooling coil replacements, refurbishments and additional capital expenditure. Comparing the actual and normalised performance in Figure 3-9 helped to identify the causes of poor performance, i.e. coil or environmental conditions. Maintenance procedures were then recommended for both these cases.

The results also showed promise for workplace ventilation strategies and promoted safer ventilation planning. The successful application of simulation models to predict normalised performance on cooling coils with limited data availability and cooling coil specifications proved the power of these digital models. Article II addressed the second research objective of analysing the actual and expected performance of cooling systems operating at off-design conditions to assist in maintenance directives. The positive findings on the tertiary cooling systems show that this methodology would most likely succeed in the rest of the cooling system as well. The value of this method was the use of minimal information to estimate the normalised cooling performance of a cooling system. The expansion of this method to other mines and cooling systems could be highly beneficial to the mining community.

4.5. RESEARCH BENEFITS AND CONTRIBUTIONS

This research had a beneficial impact on the case study mines and could add value to the rest of the mining community. The list below discusses the main benefits of this study at the hand of the contributions made:

- A method to audit instrumentation and ensure data quality for deep-mine instrumentation networks. The method developed as part of the DIKW implementation carries substantial value.
- A cooling performance monitoring method. This Industry 4.0 implementation had a significant impact on the management of these systems and actual performance monitoring based on system-specific performance indices.
- A novel implementation of simulation models to calculate the expected performance of cooling systems under off-design conditions.
- Maintenance methods for cooling coils. The results of the off-design cooling system analysis method assisted in discerning between environmental or cooling system conditions with a limited amount of data availability.

4.6. STUDY LIMITATIONS AND RECOMMENDATIONS FOR FURTHER STUDY

The research provided adequate solutions to the research objectives. However, there still exists some limitations to the holistic study goal not listed in section 2.5 and 3.5. The study limitations and recommendations for further work are listed below:

- The DIKW method was developed on a single mine as a case study. This mine had a great need for a performance monitoring method and had adequate instrumentation to enable implementation thereof. Even though the results were positive, the roll-out of this report to other sites may or may not experience the same results. Recommendations for further study include the implementation and effectiveness evaluation of daily cooling performance reporting on other mines.
- The DIKW solution was highly dependent on instrumentation accuracy and availability. The report would reflect instrumentation errors quickly, but the fixing of these sensors was quite challenging. The mining environment made it very difficult to ensure consistent instrumentation accuracy and installation of additional sensors. The roll-out of this implementation may thus be difficult on mines with no instrumentation backbone, and even

impossible. Further study could address this by evaluating DIKW solutions, which are highly dependent on operator inputs.

- The simulation models were calibrated successfully to the actual measurements. However, there was no feasible way to verify the normalised performance of the coils. The normalised performance is thus based solely on comprehensive mathematical modelling built into the simulation software. Further study should address this by a lab experiment, working together with the suppliers.
- The simulation models were successful on an individual cooling coil basis. However, the simulation models of larger systems such as BACs, and even refrigeration machines, are more complex and may not experience the same success. Further study should address these other systems individually and explore different options to ascertain expected performance for these cooling systems at off-design conditions.
- The monitoring method did not include the use of normalised performance. The actual performance monitoring method showed promising results, but it does not reflect the missed opportunities for cooling. This led to impossible cooling targets set by management. Further study should address this by combining both these methods into a daily evaluation of actual and normalised performance for the entire cooling system.

Overall the study was a huge success, and various lessons were learned working on these large cooling systems. The insight gained by extracting the knowledge contained within data using the DIKW facilitated great system improvements. The analysis method of expected performance showed realistic performance targets and provided a suitable method to predict the normalised performance in the mining environment. The successful publication of the first article in an international peer-reviewed journal and the current publication process of the second article show that the novel contributions of this research hold excellent value for the global mining community.

CHAPTER 5 REFERENCES

Heat rejection – Surface cooling towers [xxxii]

Cooling towers reject the heat removed from underground into the atmosphere to enable safe and productive underground mining operations [xxxiii]

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APPENDIX A CO-AUTHOR STATEMENT

I, **Marc John Mathews**, hereby provides consent that the articles listed below (**I to II**), may be used as part of Jan Gabriel Pretorius's M.Eng. dissertation.

Signature: Date: 2018-10-26

I, **Philip Maré**, hereby provides consent that the articles listed below (**I to II**), may be used as part of Jan Gabriel Pretorius's M.Eng. dissertation.

Signature: Date: 2018-10-26.

I, **Marius Kleingeld**, hereby provides consent that the articles listed below (**I to II**), may be used as part of Jan Gabriel Pretorius's M.Eng.. dissertation.

Signature: Date: 2018-10-26

I, **Johann van Rensburg**, hereby provides consent that the articles listed below (**I**), may be used as part of Jan Gabriel Pretorius's M.Eng. dissertation.

Signature: Date: 2018-10-29

I, **Francois Janse van Rensburg**, hereby provides consent that the articles listed below (**II**), may be used as part of Jan Gabriel Pretorius's M.Eng. dissertation.

Signature: Date: 2018/10/30

Articles:

I. PRETORIUS, J.G., MATHEWS, M.J., MARé, P., KLEINGELD, M., VAN RENSBURG, J., "*Implementing a DIKW model on a deep mine cooling system*" International Journal of Mining Science and Technology, Available online: https://doi.org/10.1016/j.ijmst.2018.07.004 (26 July 2018).

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APPENDIX B: ARTICLE I

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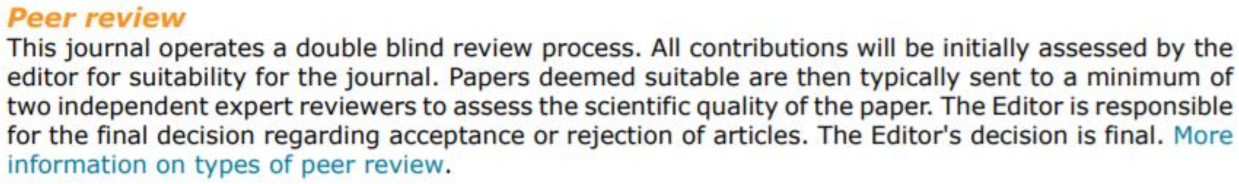

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Implementing a DIKW model on a deep mine cooling system

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ABSTRACT

The South African mining industry has been experiencing increasing economic pressure. Deep mines also suffer from very hot workplaces, which leads to safety risks. These factors place stress on managers to reach their production targets while providing safe workplace conditions. The data information knowledge wisdom (DIKW) model, also known as the wisdom hierarchy, was implemented on a deep mine cooling system. This study aims to show that a simple model such as the DIKW model can assist managers in improving their deep mine cooling system's performance. The study found that the DIKW approach is a suitable approach for use on mine cooling systems to facilitate operational improvements. Applying the DIKW approach to a case study on a mine cooling system created substantial awareness and facilitated a cooling duty improvement of 55% which relates to an increase of 5.3 MW of refrigeration. The results of this study indicate that the DIKW approach may be a suitable approach to optimise management on deep mines using their existing infrastructure.

1. Background

According to Macmillan, the South African mining industry has been experiencing increasing economic pressure over the past 30 years [1]. The mining industry's contribution to the gross domestic product (GDP) and employment, continuously decreased during this time [1]. The decline of mining in the South African economy can be due to various reasons but emphasises that the mining sector cannot afford to operate uneconomically in a progressively competitive market.

Mining in deep-level mines occurs under hazardous conditions which include physical hazards such as rock falls, fires, explosions, mobile equipment accidents, falls from a height, entrapment, electrocution and most importantly significantly high underground temperatures [2]. Government regulators closely monitor these hazardous conditions and if conditions are dangerous to mine personnel, will typically result in the shutdown of the mine's operations [3]. In South Africa, it was estimated that these stoppages resulted in a loss to the industry of approximately 376 million USD during 2015 [4]. These stoppages add extra strain on the existing economic pressure. From experience, many of these stoppages in deep-level mines are due to extreme workplace air temperatures.

The most common heat sources for underground mining include geothermal energy, auto-compression, mechanised equipment, explosives and blasting, mechanical processes and light [5]. Of these heat sources, geothermal energy and auto-compression of ventilation air are usually the most significant contributors to the heat load in deep mines [5]. The geothermal energy of the earth results in warmer strata temperatures also referred to as virgin rock temperatures (VRT). According to geological research, the VRT of deep mines can easily reach above 50 °C [6].

The above-mentioned high temperatures result in heat hazards such as heat rashes, heat cramps, heat exhaustion and heat stroke [7]. Heat stroke occurs when the body's internal temperature exceeds 40 °C, and it is the most dangerous form of heat stress as it can result in death [7]. Regulations prohibit persons from working in conditions in excess of 32.5 °C wet-bulb air temperature as it is conducive to heat stroke [8]. Thus, it is of the utmost importance for deep mines to manage these heat risks.

Deep mines use refrigeration and cooling systems to provide cold air to workplaces [9]. The production and safety of a mine will thus depend on the reliability of the refrigeration equipment to cool the mine down. An effective maintenance program will result in the reliable performance of the equipment. This program is sustainable when the information provided is accurate and complete [10]. The correct maintenance strategies will thus depend on accurate information regarding the cooling system performance.

It is common to see mine managers under tremendous pressure to meet their production targets. A study, spanning over 4-years,

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found that mine managers are usually not very involved in maintenance procedures or progress [11]. Management also showed little interest in preventative maintenance programs. The lack of understanding regarding the mining system and its current state could lead to production losses and possible safety risks [10]. Usually, such systems deteriorate over time until maintenance cannot keep up with equipment failure.

A deep-mine cooling system is a complex interconnected circuit. If maintenance teams apply the necessary maintenance of refrigeration systems at the right time, the system can operate efficiently [9,12]. However, a lack of labour, as well as management involvement, could lead to ill-timed maintenance or even the lack thereof. From a maintenance perspective, there exists a need for management to regularly evaluate the performance of their improvement and maintenance initiatives to achieve world-class maintenance [10,13].

As a manager of a cooling system, it is essential to have a great understanding of the problems that occur. It is also important to consider the context of the aforementioned problems [14]. Fig. 1 depicts the relationship between context and understanding in terms of data, information, knowledge and wisdom (DIKW). There exists an increasing growth in the relationship between context and understanding when data develops to information, knowledge and wisdom [14,15]. The DIKW model looks at simple ways to extract insight from all sorts of data to make useful decisions [15].

The first principle of the DIKW model is that data must be analyzed to be meaningful [14]. When data is analysed, it results in information which is structured data and reveals relationships hidden within the data [14,15]. The further interpretation of this information leads to knowledge which highlights patterns and gives context to the data captured [14]. Further interpretation of knowledge, by a skilled person, leads to wisdom. Wisdom results in actionable decisions made with the right understanding as well as in the correct context [15]. The deep mining industry could benefit from the full maturity of data towards wisdom by enabling management to make informed decisions regarding their cooling system's maintenance plans, and improvement directives.

The DIKW model implementation in the information technology service management, safety information management in the Australian coal industry, the systems engineering process and various industrial companies, showed great potential [16–19]. This study aims to test the DIKW approach on a complex mining system. The research aims to show that this simple hierarchy of wisdom can supply managers of deep mine cooling systems with valuable context and understanding.

Although there are large amounts of data on mines, it does not always proceed to information, knowledge and wisdom. A thorough study done on the use of maintenance information suggests that most mines have access to fully-integrated information systems, but do not utilise them to their full potential [11]. Managers in large industries, such as deep mines, need to keep track of and manage hundreds of resources on a given day [20]. From practical experience, this is conducted in challenging conditions where underground accessibility to the equipment is very limited. The implementation of a DIKW methodology could yield significant results because deep-mine cooling installations underground usually have travel times exceeding 30–60 min, placing extra pressure on mine management to access these locations due to tight schedules. This limited access combined with old equipment makes data an issue in deep mines. It is thus difficult to understand the system as well as the context of the underground conditions.

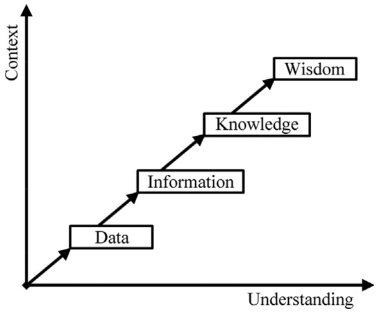

Fig. 1. Relationship between context and understanding [14,15].

Mine management currently relies on their supervisor control and data acquisition (SCADA) systems to evaluate their underground systems from the surface [21,22]. These systems typically operate at the data level of the DIKW context but can enable the implementation of data interpretation systems to convert the data to more useful knowledge.

Various data interpretation methods exist, but not all are appropriate for the mining environment. Condition monitoring has been used on surface installations, such as wind turbine gearbox fault detection [23]. It is a highly effective system to indicate system state, with a high dependence on accurate performance data.

Another data interpretation system, the overall equipment effectiveness (OEE) parameter, is a widely known parameter in the manufacturing industry. The shortcoming for OEE use on mines is that the value for mining is limited unless contributing factors are measured and analyzed [24].

Total productive maintenance (TPM) is a company-wide approach to maximise equipment effectiveness. However, the shortcoming of this approach is a data collection issue. Manual data is not always possible and computerised data is not always reliable [20].

Key performance indicators (KPIs) are utilised in various other industries [25]. Robust KPIs together with the right methodology could achieve positive outcomes [25]. Site-specific KPIs could be sustainable in representing data as information [25].

The focus of sensory data should be to improve equipment effectiveness monitoring. Combined with a thorough analysis of key performance indicators, it may allow one to identify viable opportunities and prioritisation of resources. This, in turn, will lead to a robust assessment of the progress and performance regarding improvement initiatives [24].

The DIKW model has been shown as a suitable model for decision making in the industrial context [19]. Thus, it seems likely that a novel application on mine cooling systems of the DIKW model could provide the basis for system specific decision making on these systems of deep-level mines, as these are central to safe and efficient mining [9].

A mine cooling system usually consists of a chiller/refrigeration plant, a condenser circuit and an evaporator circuit. The aim is to move heat (energy) from the evaporator side and reject at the condenser side [9]. There are two performance measurement classes of a refrigeration system. The first type is measures of effectiveness such as inlet and outlet temperatures. The second type is measures of quality such as electrical power usage and calculated KPIs such as a coefficient of performance (COP) [9].

Assessing a refrigeration machine's performance requires the determination of its steady state (actual) performance, its normal performance under the given operating conditions and then comparing these two. The actual performance calculation depends on the following key measurements: flows, inlet and outlet temperatures of the water being cooled, as well as electrical input power to the compressors and auxiliary devices of the system [9]. Verification of the performance calculation lies in confirming measurements such as flow-rate and inlet and outlet temperatures of the condenser and evaporator circuit. It is essential that the circuit is in a well-maintained state when utilising confirming measurements [9].

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More in-depth surveys are required to verify the actual performance calculated from key measurements. One or two persons generally carry out these surveys on a bi-quarterly basis [9]. However, a continuous performance assessment could support maintenance initiatives as well as management directives implemented on the system. A method exists to verify the key measurements based on a heat balance. The heat balance of a chiller system states that the sum of the evaporator duty and electrical input power and condenser heat rejection should equal zero. There are scenarios presented in literature where faulty measurements can be identified using relative heat imbalance, COPs and an acceptability plot [9]. However, these techniques require more measurement points not usually installed or maintained on a mine cooling system.

Mines are responsible for the aforementioned necessary performance measurements or surveys [9]. How effectively the surveyors portray the measured data to the relevant management personnel of the system, would lead to the best actionable decisions [11]. The performance measurements made by mines typically make part of their SCADA systems or manual measurements [9,21]. However, as mentioned above these information systems are typically underutilised [11]. SCADA systems provide information regarding key points only at a data or at most information level [22]. Therefore, it is difficult to see trends only from key data or information whereas system specific KPIs could increase performance analysis ability [25]. There is a definite need to develop a centralised tool which enables operation at least on the knowledge and wisdom level. This tool should also facilitate clear-cut decision making from mine management, and so increase their involvement in maintenance procedures and system performance.

Literature shows that a wisdom hierarchy, such as in Fig. 1, could assist in transforming data on a mine to useful knowledge. This data evaluation model depends on the data integrity and effective data analysis. This paper will test whether the application of the DIKW principles on a mine cooling system could act as a catalyst to improve the performance of that system.

2. Method

The method describes how the DIKW model was applied to an underground cooling system in the mining environment for the first time [15]. This was done to determine if the DIKW model could provide the basis for system specific decision making on these systems. The method followed the general DIKW model of obtaining and converting data into usable information. Data was acquired and audited to ensure accurate information. Knowledge was then gained through using the information for efficiency monitoring and reporting. Finally, the reports allowed for wisdom in taking the correct actions based on the information available. The impact of applying the DIKW model on the system was then validated by comparing system performance before and after implementation.

2.1. Data acquisition (data)

This subsection focuses on how the mine cooling system was approached to ascertain a greater understanding of the system. The outcome was reliable data of the cooling system parameters.

2.1.1. Determination of site layout

An initial inspection was conducted to determine the site layout. This was achieved by conducting interviews with site personnel and sourcing design layouts and specifications by doing a site visit. The site layout quantifies the number of components and measuring equipment in the system, and their interconnections and locations.

2.1.2. Acquiring available data

The next step was to get the design specifications of the refrigeration plant, condenser and evaporator circuits. We needed to confirm whether they use direct contact heat exchangers (spray ponds) or indirect (coil) heat exchangers, and determine what data is available from instrumentation readings. Table 1 shows the minimum data requirements, marked by "X", to characterise the waterside of a mine cooling system [9].

Table 2 shows the minimum data requirements, marked by "X", to characterise the airside of a mine cooling system.

The data was acquired by using software with logging capabilities such as a real-time energy management system (REMS) in conjunction with the mine's SCADA system. Manual on-site measurements discussed later verified the captured data [21].

2.1.3. Determination of data constraints

The third step was to determine the data constraints and for which parameters these constraints were valid. This step tested the feasibility of acquiring the necessary readings as in Tables 1 and 2. The constraints were grouped into one of the following categories: measurability (can the parameter be measured with the installed sensors?), sample time required (how frequent should

Table 1
Minimum data requirements for the waterside of a cooling system.

System	Type	Water Temp. in (°C)	Water Temp. out (°C)	Water flow (kg/s)	Water pressure (kPa)	Refrigerant pressure (kPa)	Guide vane position (%)	Dam level (%)	Power usage (kW)	Designed duty (MW)
Fridge plant	Evaporator side	X	X	X	Optional	Optional	Optional	N/A	X	X
Fridge plant	Condenser side	X	X	X	Optional	Optional	Optional	N/A	X	X
Direct heat exchanger	Bulk air coolers	X	X	X	Optional	N/A	N/A	Optional	N/A	X
Indirect heat exchanger	Cooling towers	X	X	X	Optional	N/A	N/A	Optional	N/A	X

Table 2
Minimum data requirements for the airside of a cooling system.

System	Type	Air Temp. in and out (°C)	RH in and out (%)	Air mass flow (kg/s)	Barometric pressure (kPa)
Fridge plant	Evaporator side	N/A	N/A	N/A	N/A
Fridge plant	Condenser side	N/A	N/A	N/A	N/A
Direct heat exchanger	Bulk air coolers	X	X	Optional	X
Indirect heat exchanger	Cooling towers	X	X	Optional	X

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samples of the parameter be taken?), and dependent/independent parameter (can this parameter be calculated from other variables?).

2.1.4. Site instrumentation validation

This subsection focuses on the data validation procedure for the installed instrumentation. As noted in the background, the underground environment is challenging to access. This harsh environment also results in sensory equipment failure. The data integrity is of the utmost importance to ensure reliable monitoring as data is the lowest level of the DIKW methodology. Errors here will lead to inaccuracies or incorrect decisions in later steps. Data validation methods used consist of simple test-based methods and physical or mathematical model-based methods. A study done on automatic data collection errors on SCADA systems showed the following main considerations when validating data: zero value and flat line detection, and minimum and maximum boundaries detection based on geometric and data quality constraints as well as historical values [26].

In-depth data validation techniques are beyond the scope of this study. A practical method was required for the mining environment. Thus, a simple test-based method will result in a sustainable solution in the mining environment. This method identifies sensory data as acceptable or questionable. Acceptable values are values that adhere to the points mentioned above. The following tests were used to ensure data integrity.

(1) Sensor measurement range check [27]. Values thus fall into the range that the installed sensor can measure. A negative value from a sensor only measuring positive values will thus be erroneous.
(2) Values are located in a predetermined local realistic range [27]. A 5 °C measurement for a water temperature usually above 20 °C will be erroneous.
(3) Constant values check [26]. When the measured variable was constant for a predefined period, it will be erroneous.
(4) Material redundancy check [27]. When two sensors are redundant, their readings provide a comparison as an accuracy check. For example, when two water temperature sensors on the same pipeline reflect values differing with more than a predetermined threshold, then one of the values is erroneous.

2.2. Information audit

This sub-section discusses the in-depth audit of the mine cooling system. The purpose of this section was to determine the current system state. The objectives included validating installed instrumentation readings with on-site measurements and benchmarking the current system operation.

2.2.1. Measurements

A site inspection was conducted to determine the measurement points for all the parameters of the available data determined in Section 2.1.2. This sub-section elaborates on the measurement of these parameters. This subsection is categorised into water measurements and air measurements. Calibrated instruments ensured accurate measurements. These measurements formed part of the installed sensors validation. The calculation of water duty and air duty provided valuable information regarding the efficiency and state of the cooling installation.

2.2.2. Water measurements

There were three measurements required to calculate water duty: water flow (kg/s), water inlet temperature (°C), and water outlet temperature (°C).

A non-intrusive water flow meter, such as an ultrasonic water flow meter, was adequate for water flow measurements. Many mines have thermowells (probe pockets) installed to enable water temperature measurements. A digital thermometer allowed the measurement of water temperature. If there were no installed thermowells, a temperature gun reading on uninsulated pipes reflected a suitable temperature.

The calculation for water duty (Q_w) in kilowatts was one of the KPIs used. The calculation is

$$Q_w = \dot{m}_w c_p \Delta T$$

where $\dot{m}_w$ is the water mass flow rate, kg/s; c_p the specific heat of water, kJ/kg at a constant of 4.187; and ΔT the difference between the inlet and outlet water temperature, °C.

2.2.3. Air measurements

The air measurements were primarily on the heat rejection (condenser side) and air-cooling infrastructure (evaporator side). The following measurements were required to calculate the air duty: air volumetric flow (m^3/s), air inlet and outlet dry-bulb temperature (°C), air inlet and outlet wet-bulb temperature (°C) or relative humidity (%), and barometric pressure (kPa).

Air temperature measuring equipment such as a whirling hygrometer, a barometer and airflow measuring equipment, was required. A vane anemometer (to calculate air velocity) and a distance meter (to calculate flow area) enabled the measurement of airflow. The installed sensors did not measure all of these parameters, and the manual measurements were used in the calculations.

The calculation for air duty (Q_a) in kilowatts was one of the KPIs used. The calculation is

$$Q_a = \dot{m}_a \Delta S_a$$

where $\dot{m}_a$ is the air mass flow rate, kg/s; andΔS_a the change on sigma energies across the heat exchanger, kJ/kg. Sigma energy is a function of relative humidity, air dry-bulb temperature and barometric pressure. In mining applications, the air duty of direct contact heat exchangers depends on sigma energy. The air duty calculation for indirect heat exchangers depends on enthalpy even though enthalpy is applicable for both [28].

2.2.4. Instrumentation recommendation

A full-scale audit of all the relevant measuring equipment onsite was conducted to ensure that all sensors provide accurate readings. The full-scale audit of the measuring equipment determined the unavailable instrumentation required for sustainable system monitoring. A list of instrumentation operating accurately, sensors requiring calibration and outstanding sensors to install, were provided to the mine.

2.2.5. System state

The initial system audit results were compared with the system design benchmark. This comparison indicated how much the system had deteriorated. This allowed for the identification of improvement initiatives to get the specific deteriorated system parameters back to or at least near to design. The results of this comparison identified the critical system parameters required to monitor for effective system state tracking.

2.3. Knowledge through effectiveness monitoring and reporting

The system state was continuously monitored and reported on to make the most out of the information gathered in the previous step.

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2.3.1. Performance indicators

KPIs were chosen to transform the information and data regarding the critical system parameters into useful knowledge and wisdom daily. For an underground mine cooling system, the following KPIs were used:

(1) Fridge plant cooling duty and COP – these KPIs indicate how much cooling is achieved and at what performance rate.
(2) Condenser pond heat rejection and evaporator pond cooling duty – these KPIs indicate how much air-cooling is achieved and how much heat is removed from the mine ventilation system.
(3) Cold dam water temperature – this parameter shows the deliverable product of a mine cooling system and is essential to track. Cold water is necessary for mine drill operators, cooling cars, dust suppression and various other activities.

2.3.2. Automatic reporting

The data and information were consolidated in an automated report to facilitate the continuous use of the DIKW method described. The existing SCADA installation was used in conjunction with an open platform connection (OPC) setup for communication between a data logger system and the mine's instrumentation network. The SCADA system's Archestra platform acted as the tag manager on the mine's side. The data logger system used was real-time energy management system (REMS), which enabled automatic logging on the user side of the OPC [21]. REMS sent data to a central server which provided data analysis based on the KPIs described, and the required automatic daily reports.

2.4. Wisdom through report interpretation

The cooling installation of a deep mine mainly consists of the fridge plants, evaporator and condenser heat rejection circuits [9]. The daily efficiency report reported on each section's performance. The server sent the report to each role player and relevant manager daily. This allowed for reflection on the previous day's performance and a quick reaction from management to take place. Further interpretation leads to the necessary wisdom in the identification of improvement initiatives and tracking thereof. This resulted in better decision making and prompting of the relevant action. This action will quantify the effect of the DIKW approach.

2.5. Impact of the DIKW model

The DIKW model was used to facilitate system improvement on the cooling system of a deep-level gold mine. This implementation of the DIKW model was a first on mine cooling systems. We quantified this impact using two measured aspects. The first was comparing the KPIs before and after implementation of the DIKW model. The second method was an independent validation done by comparing the in-stope cooling car water temperatures before and after implementation of the DIKW model on the cooling system. The in-stope cooling car water temperatures are the final product of improving cooling performance.

3. Results and discussion

This section discusses the implementation of the DIKW methodology on a deep-level mine for the first time (Mine A). This mine's refrigeration system is located approximately 2 km underground. It consists of nine fridge plants, four condenser ponds and six evaporator ponds. The mining operations stretch as deep as 2.4 km. The mine also has a very high VRT of about 64 °C. The shaft and executive management had no platform to access cooling performance data in a compact format. They needed a tool to increase their involvement in cooling performance improvements while utilising existing infrastructure.

3.1. Data

The data integrity of Mine A was verified with the steps explained in Section 2.1.4. Table 3 shows the result of this implementation on the case study. The results are only shown for fridge plant 1 (FP) as an example.

The results show that there were some instruments installed that had questionable values. The temperature probes installed were resistance temperature detection (RTD) PT100 probes. These probes were replaced or calibrated. However, to replace the installed Krohne water flow meters was much more tedious. For the purpose of this study, one was replaced and the other calibrated. This step was crucial for accurate reporting.

Table 3 also indicates what corrective action took place.

3.2. Information

3.2.1. System effectiveness report

Once the data was verified the next step was to convert the data into usable information. This was achieved by developing a daily report. Fig. 2 shows an overview of the system architecture for the developed daily report.

The system performance summary includes a summary of each section's performance. The progressive performance graph includes daily average graphs for the evaporator cooling duty of the fridge plants. It is necessary to include the cold dam temperature on the graph, as shown in Fig. 3, to ensure proper reflection of system performance. This will prevent plant operators from increasing flow to display an improved fridge plants cooling duty performance. The cold dam temperature will increase in the aforementioned case.

The second page reflects on the performance of each subsection. The fridge plant section includes water cooling duty (kW), design

Table 3
Instrumentation verification.

Description	SCADA reading	Sensor measurement range	Local realistic range	Constant value check	Material redundancy check	Measured value	Tolerance (%)	Recommendation	Result
FP01 Current (A)	63.0	0–200	0–120	Pass	Not possible	64.3	2.0	Acceptable	N/A
FP01 evap. flow (kg/s)	58.4	0–350	0–100	Pass	Not possible	68.0	14.1	Questionable: calibrate	Flow meter sent for calibration
FP01 evap. temp in (°C)	16.7	−10 to 100	5–25	Pass	Not possible	18.0	7.2	Calibrate	Calibrated
FP01 evap. temp out (°C)	12.7	−10 to 100	5–25	Pass	Not possible	9.9	28.3	Questionable: calibrate	Replaced
FP01 cond. flow (kg/s)	78.6	0–350	0–250	Pass	Possible	111.0	29.2	Questionable: calibrate	Flow meter replaced
FP01 cond. temp in (°C)	37.8	−10 to 100	30–60	Pass	Possible	38.5	1.8	Acceptable	N/A
FP01 cond. temp out (°C)	42.8	−10 to 100	30–60	Pass	Possible	43.3	1.2	Acceptable	N/A

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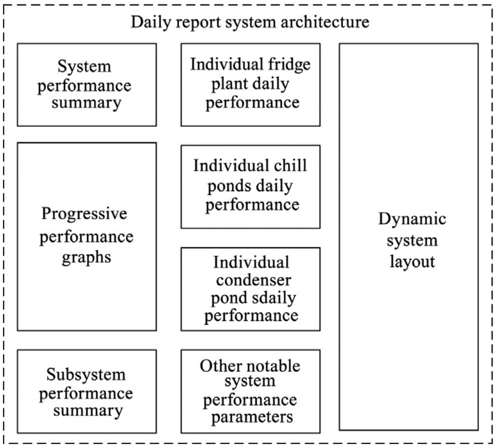

Fig. 2. Report system architecture.

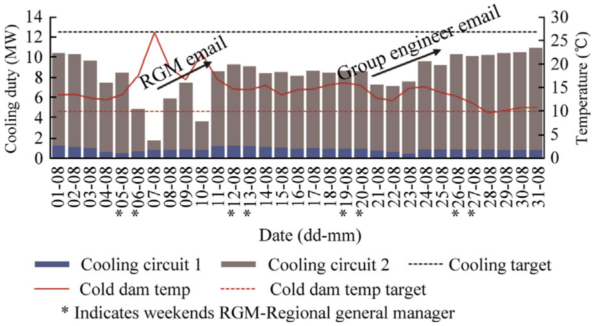

Fig. 3. Progressive cooling duty graph.

cooling duty (kW), evaporator inlet and delta temperature (°C), condenser inlet and delta temperature (°C), condenser and evaporator flows (kg/s) as well as COP. The COP and cooling duty act as the KPIs for this section. The evaporator and condenser sections include water and air cooling duty (kW), water flow (kg/s) and inlet and delta temperatures (°C). In the case of using direct contact heat exchangers (spray ponds), the water loading KPI is also added to the ponds section.

The dynamic system layout includes the layout together with daily averages on dam levels, temperatures, column flows, fridge plant performances, pond performances and all the possible system parameters to provide a snapshot of the daily system performance.

The report transforms the sensory data into information daily. Table 4 depicts the information acquired from the daily individual fridge plant analysis.

3.3. Knowledge

The implementation of the report showed that the essential sections differ for each position of appointment. The upper-level management uses the progressive performance graphs more than the individual fridge plants, condenser ponds and chill ponds performance sections. The fridge plant supervisor uses each section. The progressive performance graphs include the daily evaporator water cooling duty of all the plants. The graph also includes the cold dam temperature. Both indicators have a target line. This graph easily shows trend developments.

The individual fridge plant table helps identify when a plant is depreciating in performance. Usually, this is an indicator of fouling in the tubes, dirty strainer boxes and even gas leaks. The report helped identify each of these cases. Management acted and the next day's daily report indicated normal operation. The individual chill ponds and condenser ponds sections showed the impact of cleaning the ponds. The report could indicate the impact of operational directives in terms of heat rejection and cooling duty to management.

Conditional formatting of each value in the table according to the expected value as well as other checks as performed in the instrumentation check, lead to rapid action. The report indicated instrumentation faults and the instrumentation technicians could easily rectify the erroneous instrumentation. Most commonly the faulty readings were due to temperature probes not properly pushed back into their respective thermowell. Table 4 shows an instance where Fridge plant 4 had a questionable flow. After further investigation, the flow meter was found faulty and replaced.

3.4. Successes, challenges and actions (Wisdom)

The on-site impact of the report included increased awareness of the system's performance. The recipient list for the daily report includes 22 recipients. The recipients are from low-level to high-level mine management. All the recipients requested that they receive the report. The report quickly became the backbone of meeting discussions. The report also helped identify instrumentation errors, which were then quickly rectified. This reporting system also enabled quick identification of questionable system behavior such as refrigerant gas leaks. This system provided a measuring stick by which to track the performance of improvement initiatives. The report also enabled the identification of new initiatives.

The report is highly dependent on the condition of the site instrumentation. This poses a significant challenge for accurate reporting. This also shows the importance of building in smart data integrity testing features as mentioned in Section 2.1.4. Other challenges include report interpretation. The mining personnel do not always understand how the report works. It requires a thorough

Table 4
Fridge plants cooling performance–averages while running.

Fridge plant (FP)	Utilisation (%)	Guide vane position (%)	Cooling duty (kW)	Interim duty target (kW)	Evap. inlet temp. (°C)	Evap. Δtemp. (°C)	Evap. flow (kg/s)	Cond. inlet temp. (°C)	Cond. Δtemp. (°C)	Cond. flow (kg/s)	COP
FP1	90.0	97.6	1612	2269	20.2	7.1	54.5	44.9[a]	5.2	105.1	2.6
FP2	0.0										
FP3	87.5	63.9	4566	4096	22.8[a]	9.0	120.9	47.1[a]	3.7[a]	225.2	3.2
FP4	100.0	99.0	4863[b]	2269	21.1	9.6	121.1[b]	43.7[a]	7.9	106.5	5.9[b]
FP5	100.0	99.3	2130	2269	22.0[a]	8.5	60.2	44.0[a]	6.5	99.7	2.9
FP6	0.0										
FP7	0.0										
FP9	0.0										
FP10	100.0	89.8	1759[a]	4096	23.7[a]	3.1[a]	138.1	43.4	7.4	106.3	2.4

[a] Critical values.

[b] Questionable values.

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explanation of the report structure to all of the personnel. Instances also occurred where the daily email was forwarded to the personnel's spam folder. This report delivery issue also posed the challenge of ensuring the mining personnel to receive the report. Development of a generic report is also very challenging. Every site has a unique setup and requires a unique report. However, the reporting method is still valid for multiple sites.

The lack of previous studies relating to the DIKW approach to mine cooling systems resulted in the last challenge which was to quantify the impact of such a report. As discussed in the introduction of this paper, data needs to develop to wisdom. A study on knowledge management emphasised that the level of human contribution increase as data develop to information and knowledge [29]. Thus, a practical way is to show that action followed on the data recorded. Fig. 3 shows the improvement in average cooling duty of the cooling circuits as well as colder water temperatures after upper-level management initiated action. In both these cases, the report led upper management to question the decrease in cooling performance of the refrigeration system. An increase in cooling duty resulted directly in a few days after these email communications.

Overall the report was well received by mine personnel. The actions taken on the report are also evident from the long-term system performance.

3.5. Impact of the DIKW approach

Since the implementation of the report, system performance has increased. Fig. 4 shows values obtained from the daily report before it was made available to mining personnel and three months after implementation. There was an increase in fridge plants cooling duty of 5.3 MW; condenser ponds heat rejection of 5.0 MW and an improved cold dam temperature of 3.2 °C.

A separate investigation on the cooling cars in the mining block provided extra verification of these results. The cold dam feeds the cooling cars with cold water which act as spot air coolers in the mining block. Colder inlet water to the cooling cars results in colder air to the working areas. Fig. 5 shows that there was a reduction in the cooling car inlet water temperature after the implementation of the DIKW methodology. On average the inlet water temperature to the cooling cars improved by 13%, with a standard deviation of 1.06 °C.

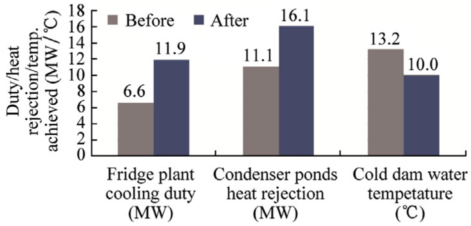

Fig. 4. Cooling system performance comparison.

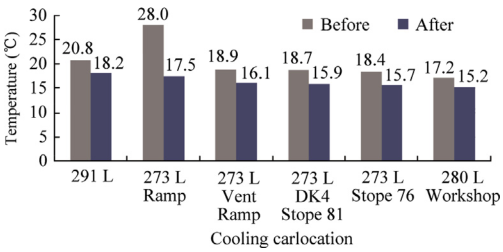

Fig. 5. Cooling car-inlet water temperatures.

These lower cold-water temperatures to the cooling cars enable colder workplace air temperatures. This results in safer working place temperatures and relates to an increase in production [30]. The implementation of the DIKW methodology on a mining refrigeration system facilitated significant operational improvement with a cooling performance improvement of 55% or 5.3 MW observed.

The results are promising because a deep mine cooling system is complex with many interconnected components and the same DIKW model approach can be applied to the other systems on the mines. A daily report could add substantial value to the management and improvement of compressed air systems, dewatering and other pumping systems, ventilation systems and various mechanical and electrical systems on a mine.

A DIKW approach could lead to sustainable energy efficiency projects such as implemented on mine water reticulation and cooling integration projects [31]. It could help managers monitor the effect of water flow control on bulk air coolers [32]. A DIKW approach could help managers monitor crucial points in a mine's ventilation network, and a daily report could enable day-to-day reflection on the underground environmental conditions, which is crucial for mine ventilation engineering [33]. These results show promise for management and informative monitoring and decision making in the mining industry.

3.6. Study limitations and further work

The implementation of the DIKW method on a deep mine cooling system showed great promise. However, this study encountered a few challenges, as discussed in Section 3.4, which highlighted the limitations listed below:

(1) The dependence on instrumentation availability and accuracy posed a significant challenge. Although we implemented smart data integrity features into the reporting, it still required significant maintenance and upkeep to ensure the reliability of the results. Quarterly, biannual or annual instrumentation audits are recommended to ensure operators do not tamper with or neglect to maintain the installed sensors. This limitation creates a need for further work whereas the reporting system should provide the instrumentation technicians with a dynamic list of sensors requiring maintenance. The quality of the installed sensors acts as the backbone of the reporting system, and further work should address this problem.

(2) Report interpretation depended on the competency of the reader. We noticed that the level of an individual's competency to understand the underlying factors, contributing to the performance reflected by the report, had a significant impact on how effectively a person utilised the daily report. Training of mine personnel eradicated this problem to a certain extent, but it still happened that personnel ignored individual sections of the report. This step is crucial in extracting wisdom from the knowledge provided in the report. Further work to increase report interpretation of the DIKW method will be to adopt better information visualisation techniques [34]. It is also evident, from environmental reporting supported by standards set out by the global reporting initiative (GRI), that adopting global standards on reporting and even disclosing performance data enhances reporting techniques and interpretation [35].

(3) Report delivery and reading on a daily basis were unconfirmed. The reports were delivered automatically to all the recipients. However, whether the report was read, deleted or ignored was challenging to measure. Although we received a lot of positive feedback and reaction on the

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report, the daily use of it by all parties could not be quantified. A web-based delivery method to confirm report delivery and reading could enable further work to address this issue.

(4) High reporting frequency had its advantages and disadvantages. A study on world-class maintenance suggested that overly frequent evaluation of performance indices start out enthusiastically but are ultimately abandoned [10]. Our implementation of the report also experienced a very enthusiastic start, as stated in the study above. However, the daily evaluation of cooling performance has many benefits, but this danger of losing its appeal cannot be ignored. The implementation of a generic report on multiple sites or systems could help prevent this. Therefore, suggestions for further work should be to create a standard of reporting which is rolled-out over multiple systems and sites which is well accepted and used by the mine personnel.

4. Conclusions

In a highly competitive market, mines cannot afford to operate inefficiently. The DIKW model was implemented on a deep mine cooling system for the first time to gain knowledge and wisdom pertaining to the data available on the mine on a daily basis. Data was aggregated into information in a daily report which aided managers in improving their mine cooling systems by reacting to the information given. The full maturity of the data to wisdom resulted in prompt corrective action by mining personnel. The DIKW approach facilitated the overall cooling improvement of the refrigeration system by 55% or 5.3 MW observed. The improved cooling performance led to cooler workplace temperatures and a safer working environment. The results showed that this wisdom hierarchy could be beneficial on a deep mine cooling system when implemented daily. The results also indicated that the DIKW approach might be a suitable approach to optimise management on deep mines using their existing infrastructure.

Declaration of interest statement

None.

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APPENDIX C: DAILY COOLING EFFICIENCY REPORT

CONFIDENTIAL

Daily cooling performance summary
Target 1#

22 May 2018

Generated on 23 May 2018 for:

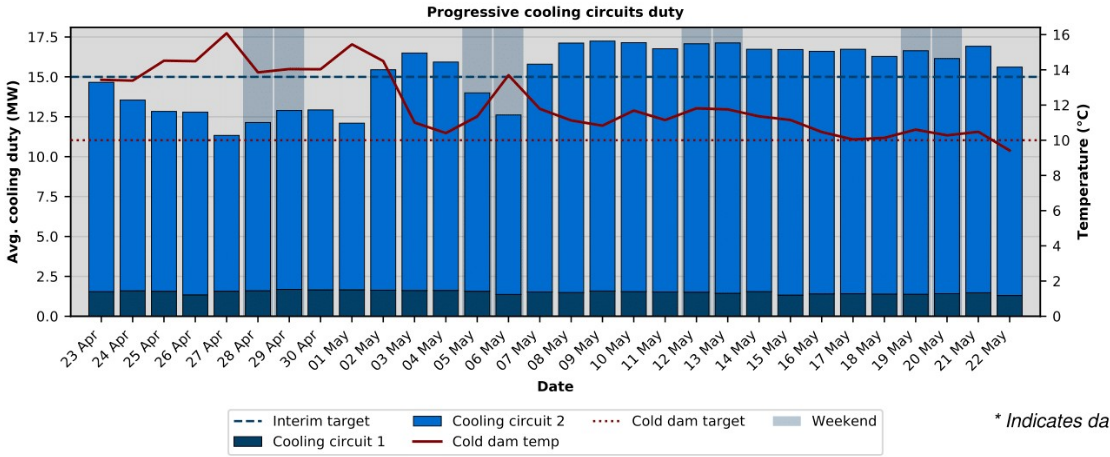
CONFIDENTIAL

1 Summary

Table 1.1: *Total cooling performance - daily averages*

Cooling Unit	**Combined duty achieved[1] (kW)**	**Interim duty target[1] (kW)**	**Interim duty target[1] (%)**	**Duty design target[1] (kW)**	**Duty design target[1] (%)**
Fridge plants	15 613	15 000	104	19 830	78
Chill ponds	7 915	11 472	68	18 210	43
Condenser ponds	19 031	22 226	85	35 280	53

[1] *Water cooling duty*



** Indicates data loss*

Figure 1.1: *Progressive cooling circuits duty*

Table 1.2: *Total fridge plant performance - daily averages*

Fridge plants	**Combined duty achieved[1] (kW)**	**Interim duty target[1] (kW)**	**Interim duty target[1] (%)**	**Duty design target[1] (kW)**	**Duty design target[1] (%)**
Cooling circuit 1	1 298	2 000	64	3 000	43
Cooling circuit 2	14 315	13 000	110	16 830	85

[1] *Water cooling duty*

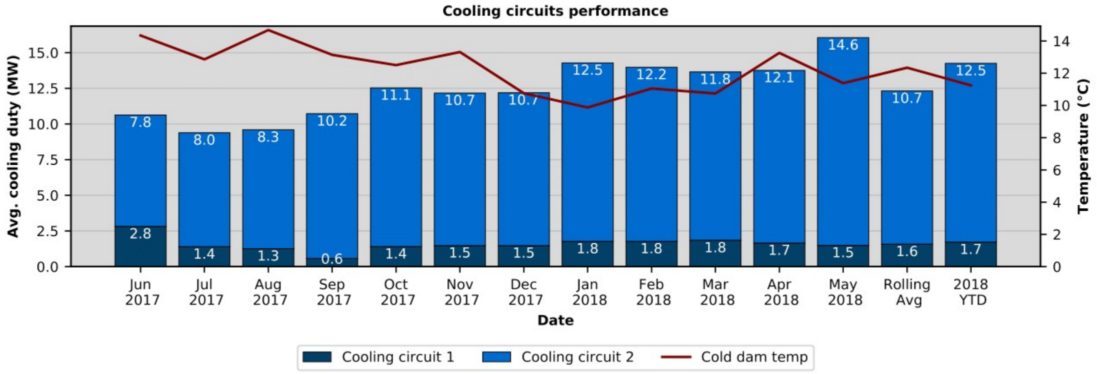


Figure 1.2: *Cooling circuits performance*

2 Daily fridge plants and ponds cooling performance

Table 2.1: *Fridge plants cooling performance - daily averages while running*

Fridge plant (FP)	Utilisation (%)	GV Pos[1] (%)	Duty[2] (kW)	Interim target[2] (kW)	Evaporator inlet T ($^\circ$C)	Evaporator ΔT ($^\circ$C)	Evaporator flow (ℓ/s)	Condenser inlet T ($^\circ$C)	Condenser ΔT ($^\circ$C)	Condenser flow (ℓ/s)	COP[3]
FP1	100.0	57.4	1 298	2 269	21.6	5.6	55.2	38.9	2.2	147.6	2.3
FP2	0	-	-	-	-	-	-	-	-	-	-
FP3	100.0	62.7	3 557	4 096	17.6	7.3	117.3	43.7	2.7	122.9	3.1
FP4	100.0	99.5	1 392	2 269	14.2	6.2	53.3	42.2	5.4	95.7	2.1
FP5	100.0	99.8	1 502	2 269	15.2	6.9	52.0	42.3	4.7	100.3	2.3
FP6	0	-	-	-	-	-	-	-	-	-	-
FP7	100.0	99.4	1 754	2 269	14.6	6.0	69.9	41.9	6.4	98.6	2.1
FP9	100.0	98.8	6 106	4 096	18.5	11.0	132.4	42.0	11.5	137.4	3.4
FP10	0	-	-	-	-	-	-	-	-	-	-

[1] *Guide vane position;* [2] *Water cooling duty;* [3] *Coefficient of performance*

Table 2.2: *Chill ponds cooling performance - daily averages while running*

Chill pond	Water flow (ℓ/s)	Duty[1] (kW)	Duty interim target (kW)	Water inlet T ($^\circ$C)	Water ΔT ($^\circ$C)	Air flow (kg/s)	BAC[2]duty[3] (kW)	Air inlet T ($^\circ$C)	Air ΔT ($^\circ$C)
L255 chill pond 1	55.2	1 298.9	1 912	16.0	5.6	–	–	0	–
L255 chill pond 2	50.3	1 890.4	1 912	11.1	9.0	–	–	31.9	–
L255 chill pond 3	42.0	2 861.3	1 912	10.0	16.3	–	–	32.8	–
L255 chill pond 4	46.3	1 798.9	1 912	10.1	9.3	–	–	31.8	–
L276 chill pond	11.5	-322.3	1 912	6.7	-6.7	–	–	0.0	–
L289 chill pond	27.0	388.4	1 912	7.8	3.4	–	–	0	–

[1] *Water cooling duty;* [2] *Bulk Air Cooler;* [3] *Air cooling duty*

Table 2.3: *Condenser ponds cooling performance - daily averages while running*

Condenser pond (CP)	Water flow (ℓ/s)	Duty[1] (kW)	Duty interim target[1] (kW)	Water inlet T ($^\circ$C)	Water ΔT ($^\circ$C)	Stages running
L255 CP 1	234.4	2 351.5	5 556	41.3	2.4	2
L255 CP 2	200.9	5 517.1	5 556	48.4	6.6	2
L255 CP 3	176.9	4 610.1	5 556	49.2	6.2	3
L255 CP 4	193.2	6 552.7	5 556	49.5	8.1	3

[1] *Water cooling duty*

Table 2.4: *Other - daily averages while running*

Description	Value
Fridge plant haulage temp ($^\circ$C$_{db}$)	-
Cold dam temp ($^\circ$C)	9.4
Hot dam temp ($^\circ$C)	18.1

Table legend

🟨	🟦	🟧	🟥
Unavailable	Not running	Questionable	Critical

Name	*Comment*

3 Consumption charts

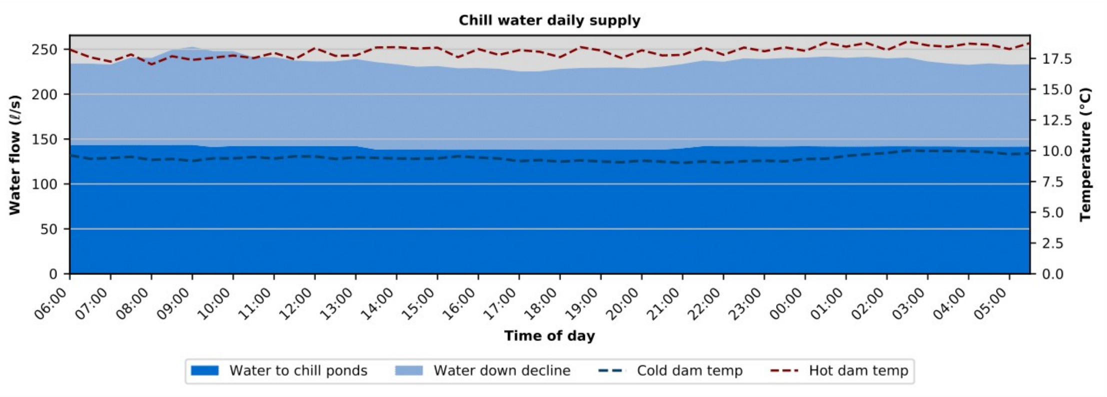


Figure 3.1: *Chilled water daily supply*

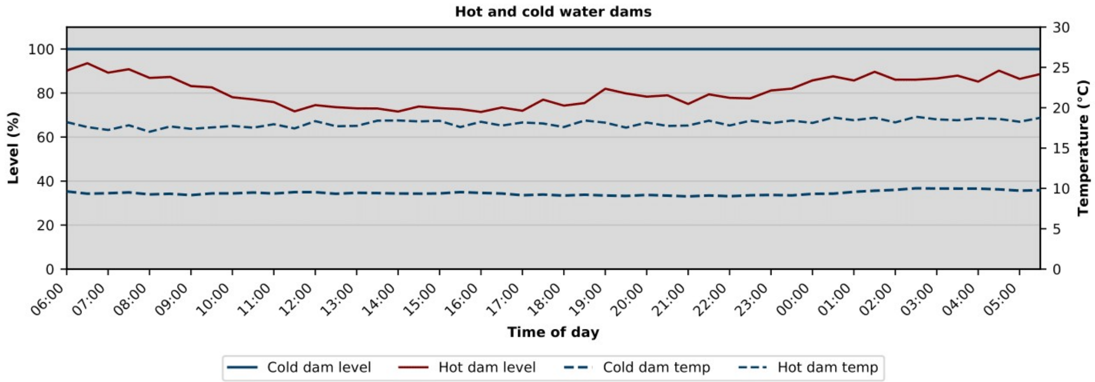


Figure 3.2: *Hot and cold water dams*

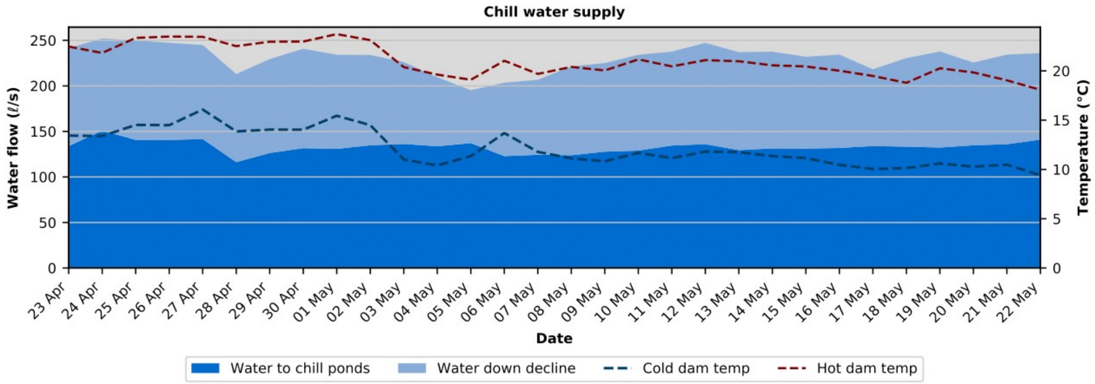


Figure 3.3: *Chill water supply – Progressive daily average*

4 Appendix: System layout

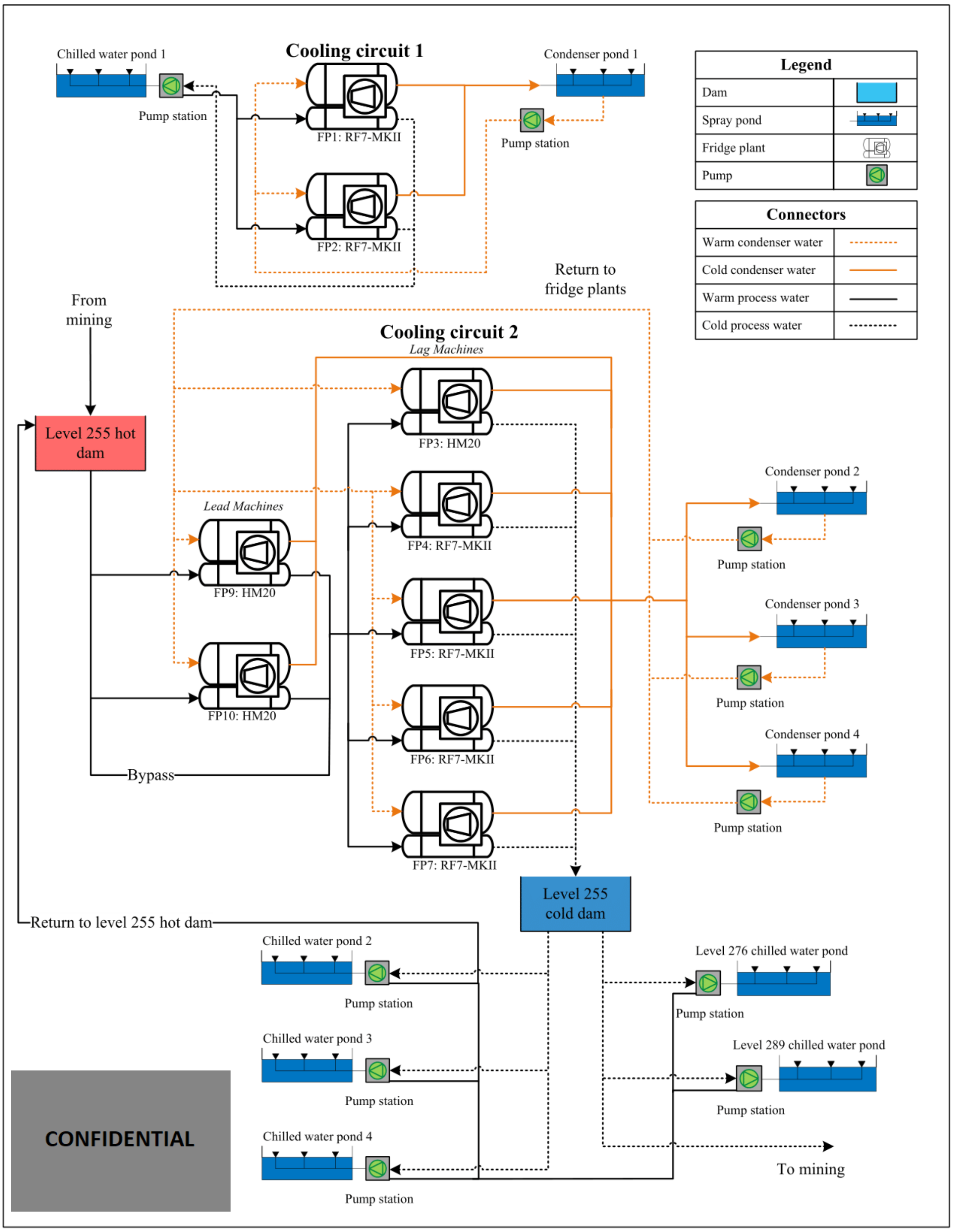
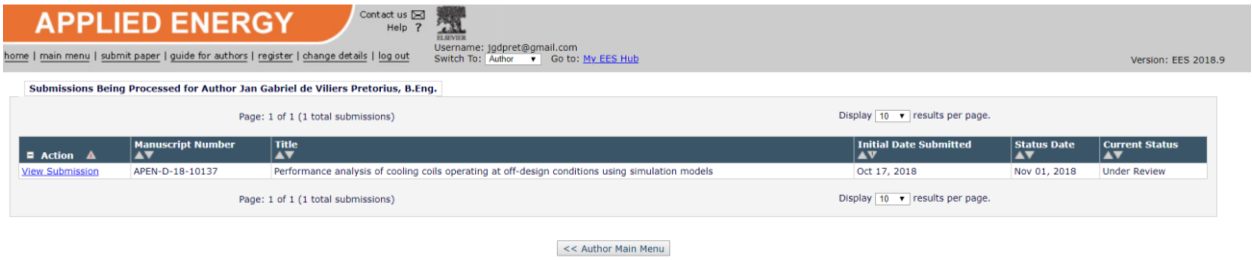


Figure 4.1: *Cooling system layout*

APPENDIX D: ARTICLE II

ARTICLE	Performance analysis of cooling coils operating at off-design conditions using simulation models
INITIAL DATE SUBMITTED	17 October 2018
JOURNAL	Applied Energy
STATUS	Under review (As on 1 November 2018)



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Submissions Being Processed for Author Jan Gabriel de Viliers Pretorius, B.Eng.

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Action	Manuscript Number	Title	Initial Date Submitted	Status Date	Current Status
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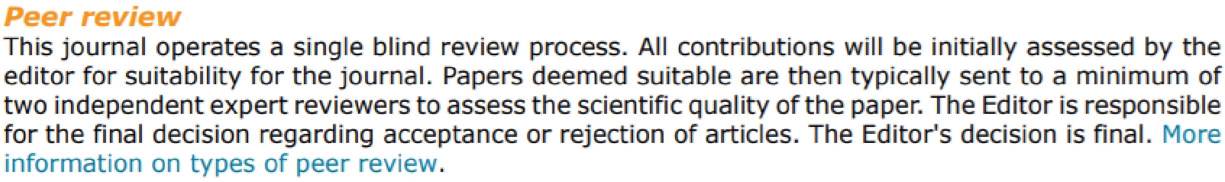

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This journal operates a single blind review process. All contributions will be initially assessed by the editor for suitability for the journal. Papers deemed suitable are then typically sent to a minimum of two independent expert reviewers to assess the scientific quality of the paper. The Editor is responsible for the final decision regarding acceptance or rejection of articles. The Editor's decision is final. More information on types of peer review.

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Note: Between the time of the examination and the master's feedback review changes, the article was submitted again after the review changes was implemented as suggested by the reviewers of Applied Energy. The Article was resubmitted to the international journal: Simulation Modelling Practice and Theory (SMPT). The article is currently under review.

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Manuscript Number: SIMPAT-D-19--105

Title: Performance analysis of cooling coils operating at off-design conditions using simulation models

Article Type: Regular Article

Keywords: Mine cooling systems; Cooling coils; Actual cooling performance; Normalised cooling performance; Cooling efficiency

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First Author: Jan Gabriel de Viliers Pretorius, B.Eng.

Order of Authors: Jan Gabriel de Viliers Pretorius, B.Eng.; Marc J Mathews, PhD; Philip Maré, PhD; Marius Kleingeld, PhD; Francois janse van Rensburg, B. Eng. MBA

Abstract: Deeper mine workplaces require localised mobile cooling coils to provide safe workplace air temperatures. The optimal use of these cooling coils necessitates practical performance analysis techniques. Key measurements determine the actual performance of the cooling coils, but the ever-changing environmental conditions make it difficult to quantify the normalised performance. This study uses a practical method in conjunction with simulation models to achieve a robust performance analysis method. A case study implementation shows that the analyses of both actual and normalised performance provide operational insight into the real performance of such cooling coils. These insights offer practical strategies for planned maintenance on these cooling coils. The case study results showed that the conventional efficiency calculations, which neglect normalised performance, were erroneous by 38% on average.

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05 February 2019

Helen D. Karatza
Editor-in-Chief
Simulation Modelling Practice and Theory

Dear Professor Helen D. Karatza

SUBMISSION: "Performance analysis of cooling coils operating at off-design conditions using simulation models"

Please find an article prepared for your journal.

We understand the importance of health and safety in the mining industry. Therefore, we focus on the effective management of energy intensive cooling systems in deep underground mines. We developed a methodology which makes use of simulations to determine the performance of cooling coils at off-design conditions. We found that there can be discrepancies as large as 38% between current performance analysis techniques and our proposed method. Such discrepancies could lead to poor decision making on the part of mine management and ultimately inefficient cooling. This novel work bridges the gap between simulation models and management of underground cooling coils resulting in safe mining practices through proper understanding of these systems.

Thank you for considering our manuscript.

Sincerely,

JAN GABRIEL PRETORIUS

Performance analysis of cooling coils operating at off-design conditions using simulation models.

Jan Gabriel Pretorius[a,b], Marc John Mathews[a], Philip Maré[a], Marius Kleingeld[a], Francois Janse van Rensburg[c]

Words: 5950 (*Excluding tables and references*)

Tables: 6

Figures: 5

Abstract

Deeper mine workplaces require localised mobile cooling coils to provide safe workplace air temperatures. The optimal use of these cooling coils necessitates practical performance analysis techniques. Key measurements determine the actual performance of the cooling coils, but the ever-changing environmental conditions make it difficult to quantify the normalised performance. This study uses a practical method in conjunction with simulation models to achieve a robust performance analysis method. A case study implementation shows that the analyses of both actual and normalised performance provide operational insight into the real performance of such cooling coils. These insights offer practical strategies for planned maintenance on these cooling coils. The case study results showed that the conventional efficiency calculations, which neglect normalised performance, were erroneous by 38% on average.

1 Introduction

Mining operations are increasing in depth to continue the extraction of mineral resources. Seven of the world's deepest mines are in the Witwatersrand Basin of South Africa with depths approaching 4 km below the surface [1]. One of the major challenges of mining at these depths are the high environmental temperatures [2]. The most significant heat sources for deep underground mines are the geothermal gradient or virgin rock temperature (VRT) and auto compression which both increase with increasing depth [3], [4]. Thus, the successful extraction of mineral resources in deep mines depends on overcoming these challenges through the proper operation of refrigeration and ventilation systems [2].

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It is well known that hot environments are conducive to heat stress [5] which numerous studies have shown to be correlated with productivity and accident rates [6], [7]. These studies found that the optimum range of workplace air temperatures is typically 27.5 $°C_{wb}$ to 29.0 $°C_{wb}$ [6]. However, there is a substantial financial impact in providing cooling at depths to obtain these optimum temperatures [6]. Thus, the correct cooling method is required to ensure safe working conditions, a limited amount of accidents and increased production.

The cooling systems on mines provide cold air to underground workplaces [7]. Figure 1 shows the different cooling methods appropriate for different depths in deep platinum mines [6]–[9]. This hierarchy of cooling methods is the same for other metalliferous mines, but the depths of implementation will differ. For example, the depths for introducing surface bulk air coolers (BACs) is around 1400m and ice around 3000m in gold mines [6].

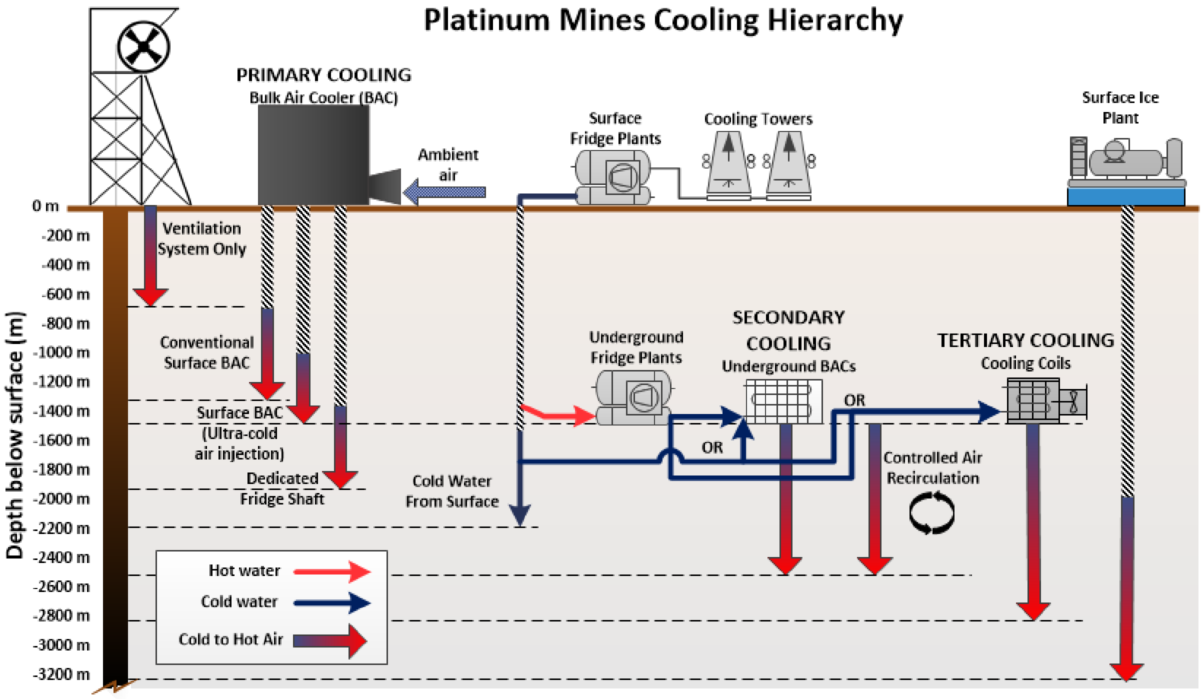

Figure 1: Cooling methods at different depths for deep level platinum mines

Developed from literature [6]–[9]

The cooling methods to consider, as in Figure 1, are ventilation only, surface BACs, underground BACs, tertiary or in-stope cooling and a surface ice plant [7]. The deeper mines call for underground refrigeration plants and BACs to increase positional efficiency [6]. However, the development of workplaces further away from central haulages and the increase in mechanisation for higher production, call for even higher positionally effective cooling methods or even ventilation on demand [6], [10]. Spot cooling coils are the most appropriate for areas far away from central airways with localised heat problems [8]. The use of tertiary cooling methods such as spot cooling coils has both its advantages and disadvantages, but it is evident that in some workplaces tertiary cooling strategies are a necessity for safe in-stope working conditions.

Mobile spot cooling coils are also known as decentralised, tertiary or in-stope cooling systems [8]. Anglo American gold and platinum mines utilised portable spot coolers since 1950 [7], [8]. The proven method of spot cooling is necessary to cool newly exposed rock. This method is also inevitable for future Australian coal mines as they expand and experience high virgin rock temperatures [7]. The deep gold mining industry suffers the same problem. The increase in air temperatures along the stope back, due to high virgin rock temperatures, necessitates tertiary cooling.

The use of an in-stope cooling system was not widely implemented in the past by all gold mines, but the need is growing as expansion projects in the deep gold mining industry advances [9]. The industry made use of tertiary cooling methods in the past and will require efficient tertiary cooling methods for safe mining practices in the future. The most common tertiary cooling methods are vortex tubes, spot cooling coils, venturi cannons, in-stope spray systems and mobile refrigeration air cooling units (ACUs) [7]–[9], [11]–[13].

A spot cooler is typically an indirect heat exchanger [9]. The spot cooling coil utilises a water-to-air indirect heat exchanger. The cold service water from the refrigeration system cools down the hot ventilation air flowing to the working area. A tube-and-fin heat exchanger bank transfers the heat from the air to the water. The cooling coil rejects the heat into the dewatering system of the mine. The cooled air is directed via ventilation ducting towards the working area to mitigate the localised heat [12]. The mobility of spot coolers increases their positional efficiency especially in deep mines [8], [14]. Spot cooling coils are considered the better alternative to in-stope spray systems or Venturi cannons [9]. However, the limitation to spot coolers are the availability of chilled water and maintained water reticulation systems nearby [7].

It is clear that cooling in general and spot cooling specifically is of utmost importance to deep mines. Therefore, mines typically try and monitor the performance of these systems where possible [15]. The performance analysis techniques for cooling coils should consist of determining actual cooling performance from manual or automated measurements and compare to the system’s expected performance under those conditions. These performance analyses should identify the substandard performance of any cooling system as soon as possible and ensure the implementation of proper maintenance and mitigation measures [16].

The water- and air duty of a cooling coil expresses its actual performance. These calculations also enable the estimation of the cooling coil’s overall heat transfer coefficient (UA product) which usually indicates the degree of effectiveness for a cooling coil. A clean cooling coil’s UA product ranges between 10 and 25 kW/°C [12].

There are methods to calculate a cooling coil's clean UA value [17], [18]. The clean UA value compared to the actual UA value provides insight into the cooling potential of the cooling coil. These calculations are lengthy and require coil specifications which from personal experience are not always available [16]. A heat transfer effectiveness calculation can also assist in providing insight into the cooling performance of the cooling coil if the cooling coil is in a closed system configuration [19]. However, from experience in analysing underground cooling systems, it is evident that these methods are limited by the available data for underground cooling coils.

As an alternative, the actual performance compared to the normalised performance of a cooling coil under those environmental conditions could ensure proper performance analysis [16]. The normalised performance entails the possible or expected performance of the cooling system under off-design conditions. The normalised performance calculation is possible from original equipment manufacturer (OEM) datasheets [16], predicting performance from historical data [16], [20], using more straightforward fundamental mathematical modelling [16], [21] and through calibrated simulation models based on comprehensive or straightforward mathematical modelling [16], [22].

The normalised performance obtained from OEM information is limited because it depends on user-defined environmental conditions and the alacrity of the manufacturer to provide a full range of operational performance data [16]. The shortcomings of predicting normalised performance from past data are that a reliable and comprehensive set of previous measurements is needed [12], [20].

A normalised performance calculation based on more straightforward fundamental mathematical modelling has been implemented on refrigeration machines but needs expansion for cooling coils. [22], [23]. The mathematical model still lacks the practical applicability to calculate the normalised performance for cooling coils in the mining environment. A few studies on Air Handling Units (AHUs) of surface buildings studied the use of simulation models based on straightforward mathematical modelling [24], [25]. However, the simulation programs are proprietary software and assume all parameters are measured or provided by the manufacturer.

Figure 2 shows a cooling coil installed near a workplace in a deep gold mine. These installations are usually far from central haulages [8]. This installation area makes it challenging to attain automated measurements and even maintain the cooling coils and instrumentation. For this reason, simulation programs cannot rely only on data capturing as in the study mentioned above [24]. The performance analysis should thus be implementable using the minimum amount of actual measurements.

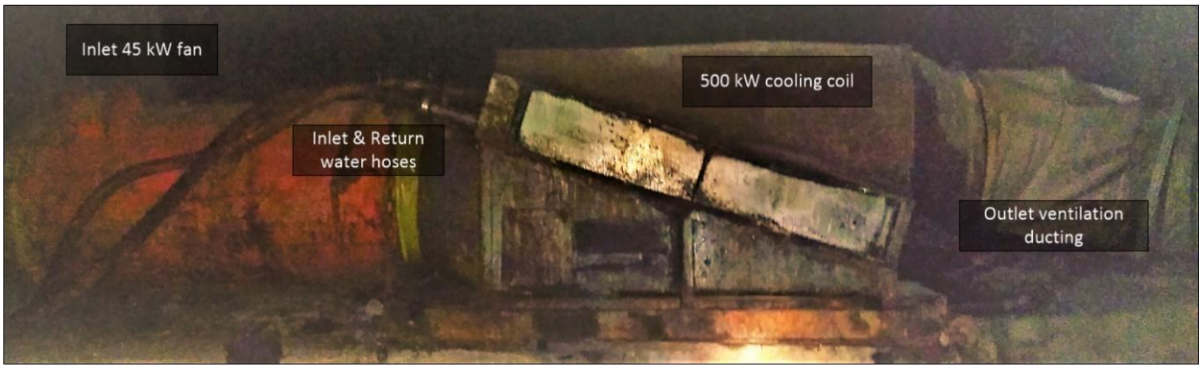

Figure 2: Underground cooling coil installation

The mining industry could benefit from a realistic method for determining cooling coil efficiency. This will enable proper cooling strategies to mitigate calculated heat loads and ensure safe environmental conditions. From personal experience, underground cooling strategies are based on design performance. The cooling efficiencies are also evaluated against design, which could lead to erroneous maintenance decisions. A robust method to provide normalised performance for cooling methods could add significant value to the analysis of cooling coils.

Literature shows that there are methods to calculate the actual performance of a heat exchanger based on a thermodynamic energy balance. The calculation of the UA product for the cooling coil is also generally used for the actual performance of this type of heat exchanger. However, the need exists to determine the normalised performance of a cooling coil in off-design conditions. Accounting for both normalised and actual performance will enable proper cooling performance analysis of underground cooling coils. This study aims to properly analyse cooling coils in the underground environment with a novel approach to performance analysis of these types of tertiary cooling methods using simulation models.

2 Method

This section elaborates on the mathematical models and measurements required to enable actual and normalised performance calculations. Table 1 shows the symbols and units used in the Method and the Results sections.

Table 1: List of symbols

Symbol	**Value / Unit**	**Description**	**Symbol**	**Value / Unit**	**Description**
Alphabets			***Subscripts***		
T	$°C$	Temperature	i		Inlet
P	kPa	Pressure	o		Outlet
P_{sat}	kPa	Saturated pressure	w		Water
P_m	kW	Motor power	a		Air
RH	%	Relative humidity	wi		Water inlet
Q	kW	Duty	wo		Water outlet
v_a	m/s	Air velocity	aiw		Air inlet wet-bulb
$\dot{v}_a$	m^3/s	Air volumetric flow rate	aow		Air outlet wet-bulb
$\dot{m}$	kg/s	Mass flow rate	aid		Air inlet dry-bulb
UA	$kW/°C$	The overall heat transfer coefficient	aod		Air outlet dry-bulb
H	kJ/kg	Enthalpy	adb		Air dry-bulb
A	m^2	Area	db		Dry-bulb
V	m^3/kg	Specific volume of moist air	wb		Wet-bulb
Q_{hl}	$kW\ (kJ/s)$	Total heat loss into air			
η_m	%	Motor efficiency			
η_f	%	Fan efficiency			
F	Decimal	LMTD correction factor			
Constants			***Greek letters***		
C_{pw}	4.187 $J/kg \cdot °C$	Specific heat of water at constant pressure	ΔT	$°C$	Change in temperature
C_{pa}	1.006 $kJ/kg \cdot K$	Specific heat of air	ΔT_{aw}	$°C_{wb}$	Change in wet bulb air temperature
C_{Pvap}	1.805 $kJ/kg \cdot K$	Specific heat of water vapour	ΔT_{ad}	$°C_{db}$	Change in dry bulb air temperature
R_{air}	287.05 $J/kg \cdot K$	Ideal gas constant for air	ΔP_a	kPa	Change in air pressure
R_{mol}	0.62198	The ratio of the molecular mass of water vapour to air	ρ_a	kg/m^3	Air density
K_t	273.15 K	Absolute temperature	ϕ	m	Fan / ventilation ducting diameter
h_{fg}	2501000 J/kg	Latent heat of vaporisation of water	η	%	Efficiency
C_1	-5800.2206				
C_2	-5.516256				
C_3	-0.048640239				
C_4	0.000041764768				
C_5	-0.000000014452093				
C_6	6.5449673				

2.1 Measurements

The minimum measurements required to calculate the actual and normalised performance of a cooling coil are listed in Table 2 [12], [16]. Table 2 also shows the instruments which were used in this study together with their operational characteristics. Figure 3 shows the appropriate areas for measuring the relevant parameters.

Table 2: Measurements for actual and normalised performance

Description	Unit	Instrument	Measurement Error	Resolution	Range
Inlet and outlet water temperature	$°C$	Gemini Tinytag View 2 with Thermistor Probe	0.25%	0.02	-40.0 ~ +125.0
Inlet and outlet air temperature	$°C_{wb}/°C_{db}$	Whirling Hygrometer	2%	0.5	-5.0 ~ 50.0
Inlet and outlet air pressure	kPa	Tenmar-404 Anemometer	± 0.2	0.1	0.35 ~ 110.0
Water mass flow	kg/s	Bucket method	5%	0.25	0.0 ~ 14.0
Air velocity into the cooling coil	m/s	Tenmar-404 Anemometer	± 2 % + 0.2	0.1	0.4 ~ 20.0
Inlet fan/ventilation ducting diameter	m	Bosch PLR-25 laser distance meter	2.0	0.001	0.05 ~ 25.0

Cooling coils usually have thermowells, also known as probe pockets, installed on the inlet and return water columns. The thermowells enable non-invasive water temperature measurements with a thermometer as shown in Figure 3. If there are no thermowells installed, an alternative solution is to measure the inlet water temperature (T_{wi} in $°C$) in the supply column at an openable valve near the cooling coil, and the return water temperature (T_{wo} in $°C$) at the water discharge onto the footwall or into the drain dam.

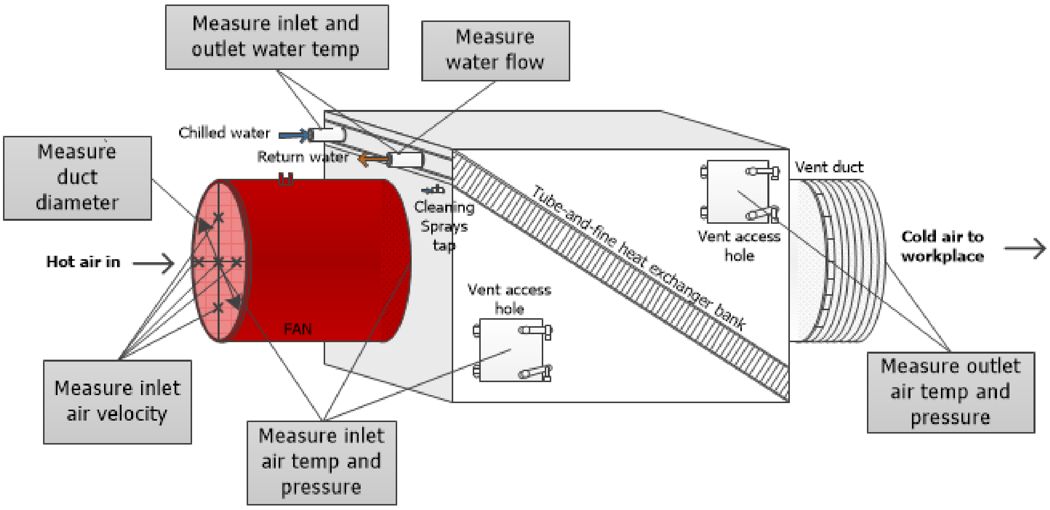

Figure 3: Cooling coil measurement locations

The mining industry widely uses whirling hygrometers for air temperature measurements [12], [26]. A calibrated whirling hygrometer provides wet bulb and dry bulb air temperatures and is suitable to measure the inlet (T_{aiw} / T_{aid} in $°C_{wb}$ / $°C_{db}$) and outlet (T_{aow} / T_{aod} in $°C_{wb}$ / $°C_{db}$) air conditions of the cooling coil as shown in Figure 3. The cooling coils usually have small access doors on both sides of the heat exchanger plate, which is a suitable area for the inlet and outlet air temperature measurements. Make sure that the cooling coil cleaning sprays, if installed, are closed during the measurement. In some cases, the access doors may have rusted shut or cannot be opened due to other circumstances. Therefore, alternative measurement locations include before and after the cooling coil in the ventilation ducting. If the force fan is attached to the cooling coil, the inlet air measurement location is before the fan. During this scenario, account for the fan induced air temperature gain in the inlet air to the cooling coil, as discussed in a later section.

The use of a barometer will enable the measurement of the inlet barometric pressure (P_i in kPa) and outlet barometric pressure (P_o in kPa) of the cooling coil. The cooling coils cause an air pressure reduction (ΔP_a in kPa) obtained by measuring the inlet and outlet air pressure with a barometer, utilising a manometer or using the manufacturer’s specification sheets. Figure 3 shows the suitable areas for measuring pressure.

A portable ultrasonic water flow meter enables a non-intrusive method to determine the water mass flow ($\dot{m}_a$ in kg/s) through the cooling coil. A bucket method is also a practical and simplistic method, where a bucket with known volume is filled with the return column hose. Measure the time it takes for the bucket to fill up and divide the bucket volume by the time elapsed to calculate water mass flow. However, the bucket method may not be feasible or safe to perform with high-pressure cooling coils.

The measurement of air velocity (v_a in m/s) into the cooling coil requires an air velocity meter such as a vane anemometer. Measure the air velocity inside the ducting or the fan intake before the cooling coil. It is essential to measure the ducting diameter (ϕ in m) with a distance meter or measuring tape to calculate the volumetric flow ($\dot{v}_a$ in m^3/s) through the cooling coil, as discussed in the subsequent sections.

2.2 Actual performance

This section elaborates on the calculation of the actual performance of the cooling coils. The parameters calculated for this section include the water- and air duty as well as the UA product.

2.2.1 Water duty

The calculation for water duty, Q_w in kilowatt, is as follows [12], [16]:

$$Q_w = C_{pw}\dot{m}_w\Delta T \qquad \text{[E.1]}$$

where C_{pw} is the specific heat of water at a constant pressure equal to $4.187\, J/kg\cdot°C$, $\dot{m}_w$ the water mass flow rate in kg/s and ΔT the difference between the inlet water temperature T_{wi} and the outlet water temperature T_{wo} in $°C$.

2.2.2 Air duty

Sigma energies are commonly used in mining applications for air duty calculations, especially for direct contact heat exchangers. Enthalpy also enables air duty calculation and applies to both direct and indirect heat exchangers. The air duty, Q_a in kilowatt, is calculated as follows [27]:

$$Q_a = \dot{m}_a(H_o - H_i) \qquad \text{[E.2]}$$

where $\dot{m}_a$ is the air mass flow rate in kg/s, H_o the outlet and H_i the inlet enthalpy respectively in kJ/kg. The air mass flow rate is calculated by

$$\dot{m}_a = \rho_a \dot{v}_a \qquad \text{[E.3]}$$

where ρ_a is the air density in kg/m^3 and $\dot{v}_a$ is the air volumetric flow in m^3/s. The air volumetric flow is calculated by

$$\dot{v}_a = v_a A \qquad \text{[E.4]}$$

where v_a is the air velocity in m/s and A the air flow area in m^2 calculated by

$$A = \frac{\pi}{4}\phi^2 \qquad \text{[E.5]}$$

with ϕ the measured ducting diameter in m. The air density, ρ_a, is calculated as follows:

$$\rho_a = \left(\frac{1}{V}\right) \cdot (1 + RH) \qquad \text{[E.6]}$$

where V is the specific volume of moist air in m^3/kg and RH the relative humidity of the air. The Specific volume of moist air is calculated by

$$V = R_{air}(T_{adb} + K_t)/(P \cdot P_{sat} \cdot RH) \qquad \text{[E.7]}$$

Where R_{air} is the ideal gas constant equal to $287.05\, J/kg \cdot K$, T_{adb} the air dry-bulb temperature in $°C$, P the pressure in kPa and P_{sat} the saturated pressure of the air calculated by

$$Psat = e^{\left(\frac{C_1}{T} + C_2 + TC_3 + T^2C_4 + T^3C_5 + C_6 \log T\right)} \qquad \text{[E.8]}$$

where the C_x constants are extracted from the Hyland and Wexler correlation defined as in Table 1 and T is

$$T = T_{adb} + K_t \qquad \text{[E.9]}$$

The equation which enables the calculation of relative humidity RH is

$$RH = \frac{(P \times W)}{P_{sat(db)}(R_{mol} + W)}; \qquad \text{[E.10]}$$

$$W = \frac{\left(\left(\frac{R_{mol}P_{sat(wb)}}{P-P_{sat(wb)}}\right)\left(h_{fg}-T_{wb}\left(C_{pw}-C_{Pvap}\right)\right)-C_{pa}\left(T_{db}-T_{wb}\right)\right)}{h_{fg}+C_{Pvap}T_{db}-C_{pw}T_{wb}} \qquad \text{[E.11]}$$

Where R_{mol} is the ratio of the molecular mass of water vapour to air equal to 0.62198, h_{fg} is the heat of evaporation at $0\ °C$ equal to $2501000\ J/kg \cdot K$, C_{pa} the specific heat of air equal to $1.006\ kJ/kg \cdot K$ and C_{Pvap} the specific heat of water vapour equal to $1.805\ kJ/kg \cdot K$.

Equation E.12 below depicts the calculation for enthalpy (H) in kJ/kg.

$$H = C_{pa}T_{db} + \left(\frac{R_{mol}P_{sat(db)}RH}{P-P_{sat(db)}RH}\right)\left(h_{fg} + C_{Pvap}T_{db}\right) \qquad \text{[E.12]}$$

2.2.3 UA Product

The log mean temperature difference (LMTD) is a suitable form for use in the analysis of heat exchangers [19]. The LMTD and the water duty provides the UA product. The calculation of the overall heat transfer coefficient, UA in $kW/°C$, of the cooling coil is defined by [12], [16], [19]:

$$UA = Q_w \cdot LMTD = Q_w \cdot \frac{\ln(\Delta T_1/\Delta T_2)}{(\Delta T_1-\Delta T_2)} \qquad \text{[E.13]}$$

where Q_w is the water duty in kW, ln the natural logarithm, ΔT_1 and ΔT_2 the temperature differences of the fluids at each end of the cooling coil calculated by:

$$\Delta T_1 = T_{aiw} - T_{wo} \qquad \text{[E.14]}$$

$$\Delta T_2 = T_{aow} - T_{wi} \qquad \text{[E.15]}$$

The UA value for a clean coil is between $10 - 25\ kW/\ °C$ [12]. This method to calculate the LMTD is suitable for parallel-flow and counter-flow heat exchangers [19]. However, the typical cooling coils utilised in the mining industry use a cross-flow configuration [9], [12]. The calculation of the UA product for cross-flow conditions is too complicated because of the complex flow conditions. However, a correction factor (F) is a suitable alternative to use and can be obtained from a correction factor chart for one-shell pass and even number tube passes [19], [28]. The following equations are required to navigate these charts:

$$R_F = \frac{T_{airIN(wb)}-T_{airOUT(wb)}}{t_{waterOUT}-t_{waterIN}} \qquad \text{[E.16]}$$

$$P_F = \frac{t_{waterOUT}-t_{waterIN}}{T_{airIN(wb)}-t_{waterIN}} \qquad \text{[E.17]}$$

There also exists a suitable numerical calculation method for the correction factor F given in [29] as follows:

$$F_{1,2} = \begin{cases} \dfrac{\frac{\sqrt{1+R^2}}{(R-1)}\log_{10}\left(\frac{1-P}{1-PR}\right)}{\log_{10}\left(\frac{\frac{2}{P}-1-R+\sqrt{1+R^2}}{\frac{2}{P}-1-R-\sqrt{1+R^2}}\right)}, R < 1 \\ \dfrac{\frac{P\sqrt{1+R^2}}{2.3(1-P)}}{\log_{10}\left(\frac{\frac{2}{P}-1-R+\sqrt{1+R^2}}{\frac{2}{P}-1-R-\sqrt{1+R^2}}\right)}, R = 1 \end{cases} \quad \text{[E.18]}$$

where R is R_f and P is P_f from equations E.16 and E.17 respectively.

2.2.4 Fan induced air temperature gain

There are scenarios where the force fan is connected to the cooling coil, as in Figure 2. This poses a challenge as the input conditions in the actual performance calculations isolate the conditions around the cooling coil. If the cooling coil has restricted accessibility before the tube-and-fin heat exchanger plate (which in practice is always the case), then a mathematical approach can provide an estimation of the fan-induced air temperature gain. The heat added to the inlet cooling coil air stream is shown by:

$$Q_{hl} = P_m(1 - \eta_m) + (P_m\eta_m)(1 - \eta_f) \quad \text{[E.19]}$$

where Q_{hl} is the total heat loss into the air in kilowatt (kW or kJ/s), P_m is the motor power in kilowatt (kW), η_m is the motor efficiency and η_f the fan efficiency. The enthalpy into the cooling coil H in kJ/kg uses equation E.12, which calculates the enthalpy into the fan, in conjunction with Q_{hl} (kJ/s) and $\dot{m}$ (kg/s) as follows:

$$H = H_i + Q_{hl}/\dot{m} \quad \text{[E.20]}$$

The dry-bulb cooling car inlet temperature calculation depends on solving the enthalpy equation E.12 for T_{db} and using all the other inputs as measured before the fan together with the value obtained from equation E.20. This calculated temperature, if applicable to the scenario, is a more accurate representation of the cooling coil's inlet dry-bulb air temperature.

2.2.5 Actual performance summary

The water duty, air duty and UA product are all evaluation parameters for actual performance. These values provide valuable information regarding the condition of the cooling coils and the available cooling capacity. However, the questions arise whether poor cooling capacity is due to the environmental inputs to the cooling coil or the condition of the cooling coil? Thus, the following section will elaborate on the normalised performance analysis of the cooling coil.

2.3 Normalised performance

The normalised performance of a cooling coil evaluates the performance expected at off-design conditions. This enables the calculation of a more accurate efficiency as the actual performance is not compared to the design performance of 300 kW or 500 kW depending on the cooling coil under consideration. However, as noted in the introduction, it is a complex task to calculate normalised performance. The use of heat transfer effectiveness, obtained by dividing the actual heat transfer rate by the maximum possible heat transfer rate, would have been suitable if the systems did not experience any ventilation and water leaks or open water sprays circuits [19]. In this section, we will discuss how to use a thermodynamic solver to simulate the expected normalised performance. The steps required are listed below:

1. Obtain the performance curves, or design specifications, from the manufacturer. The cooling coils are designed for operation on a specific curve. If no specifications are acquirable, then use the best-case UA product of $25\ kW/°C$ from literature [12], [16].
2. Build an indirect heat exchanger simulation model with air and waterside calibrated according to the actual measurements. Thermal simulation software packages such as Flownex®, Comsol®, Process Toolbox® or Simscale® can enable these simulation models.
3. Verify the heat exchanger outputs against the actual measurements and calibrate until accurate.
4. Change the UA product of the coil to the design specifications or the best-case $25\ kW/°C.$
5. Solve the thermodynamic problem to obtain the normalised performance at those conditions.

The designed cooling coil operating at the actual environmental conditions will provide the normalised performance expected. This value compared to the actual performance provides a more accurate efficiency of the cooling coil.

3 Results

A case study implementation of the method on Mine A enabled most of the results in this section. Mine A’s entire refrigeration system is located underground to improve positional efficiency. The air travel distance to the mining and development areas are more than 4 km away from the primary and secondary cooling installations. The mine also utilises trackless equipment and has a high VRT of 60 °C. The production region stretches as deep as 2.4 km below the surface. The cooling installation of Mine B uses surface refrigeration as well as primary and secondary cooling. The lengthy air travel distance from the secondary and primary cooling on Mine B also necessitates the use of tertiary cooling.

The high VRT and various other ventilation challenges at Mine A and Mine B necessitate the use of tertiary cooling. It is of utmost importance for the mine to baseline the performance of their tertiary cooling coils as this enables safe and productive mining. The performance measurements of the cooling coils were taken as discussed in section 2.1. The actual performance parameters were calculated by the equations discussed in section 2.2 and the normalised performance as in section 2.3.

3.1 Measurements

We conducted numerous surveys on Mine A and Mine B of the cooling coils installed. Table 3 shows an example of measurements taken on seven different 500 kW rated cooling coils from Mine A and three 300 kW cooling coils installed at Mine B.

Table 3: Cooling coils survey measurements

Description	Unit	#A2	#A3	#A4*	#A5	#A6	#A7	#A8	#B1*	#B2*	#B3*
Survey date	-	07-Dec	15-May	12-Oct	07-Dec	07-Dec	15-May	15-May	02-Feb	02-Feb	02-Feb
Depth below surface	m	-2225	-2225	-2215	-2243	-2214	-2214	-2214	-1676	-2164	-2225
Fan size	kW	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0	45.0
Air temp. in (wb)	°C$_{wb}$	32.5	30.0	32.5	34.0	33.0	31.5	31.5	28.2	23.8	26.8
Air temp. in (db)	°C$_{db}$	40.5	34.5	36.5	44.5	39.5	33.0	33.0	33.3	25.0	30.1
Air temp. out (wb)	°C$_{wb}$	27.0	26.5	31.5	29.0	29.0	28.0	27.5	26.7	20.2	23.5
Air temp. out (db)	°C$_{db}$	27.0	28.0	33.5	29.0	29.5	30.0	28.0	31.1	21.1	24.7
Barometric pressure in	kPa	110.8	113.1	109.7	110.8	110.5	112.9	112.9	103.3	109.8	110.5
Fan diameter	m	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76	0.76
Fan velocity	m/s	8.0	7.4	14.8	4.5	15.6	11.1	16.3	14.5	21.0	13.0
Water temp. in	°C	16.7	15.4	20.2	18.8	15.9	14.9	14.9	18.0	17.1	19.1
Water temp. out	°C	23.3	21.9	24.6	32.8	26.5	23.3	21.6	21.8	20.4	24.1
Water flow	kg/s	2.6	2.5	3.4	0.5	2.6	2.9	4.7	4.3	8.5	4.5

**Measurements were taken before the force fan*

There are scenarios where not all measurements are practical. Some cooling coils do not have thermowells, air access holes or other challenges as described in section 2.1.

3.2 Actual performance

The cooling coil's actual performances depend on the equations in section 2.2. We programmed the equations into a Microsoft® Excel worksheet to enable streamlined measurement inputs and results. Table 4 shows the results of these calculations for the measurements in Table 3.

Table 4: Cooling coils actual performance

Description	Unit	#A2	#A3	#A4*	#A5	#A6	#A7	#A8	#B1*	#B2*	#B3*
Enthalpy in	kJ/kg	105.8	92.0	109.5	114.0	108.8	99.6	99.6	91.9	69.2	82.2
Enthalpy out	kJ/kg	80.1	76.8	101.9	88.8	89.2	83.2	81.3	82.8	55.1	66.0
Fan air dry-bulb temp. gain	°C	N/A	N/A	2.6	N/A	N/A	N/A	N/A	2.8	1.8	2.9
Air duty	kW	113.0	64.1	61.8	61.4	168.3	104.5	170.8	69.4	171.2	119.6
Water duty	kW	71.0	68.6	62.5	29.3	116.8	100.8	132.6	68.4	117.4	94.2
Corrected UA Product	kW/°C	6.8	6.9	6.5	-	11.3	9.2	11.4	9.0	27.0	18.6

**Measurements were taken before the force fan*

The measurement instruments have an average error of approximately 5% for these areas. The air pressure drop across the cooling coil could be measured or read from the manufacturer's specifications sheets. For six of these cooling coils, it was not necessary to calculate the fan air dry-bulb temperature gain as in section 2.2.4. In all the measurements, the water flow measurement was accepted as more reliable than the air flow measurements. The subsequent sections accept the water duty as acceptable duties for these cooling coils. The actual UA product calculation was still accurate because it omits the air flow.

3.3 Normalised performance

The calculation of cooling efficiency is only useful when taking actual and normalised performance into account [16]. The normalised performance is the expected cooling at the current off-design underground conditions. This section elaborates on the normalised performance calculation of the cooling coils as in section 2.3.

3.3.1 Design specifications

The manufacturer of the cooling coil can provide the performance curves of the cooling coil. However, from personal experience, manufacturers are reluctant to provide performance curves for a wide range of operating conditions. We obtained the design specifications for the coils installed at Mine A of $30.5°C_{wb}/34.0°C_{db}$ inlet air temperature, $7.0°C$ water inlet temperature, $110.0\ kPa$ inlet barometric pressure, $12\ m^3/s$ airflow rate, $10.0\ kg/s$ water flow rate and $524\ kW$ cooling duty.

However, we found that the design specifications did not match our survey findings. The design specifications were thus not used to calculate the design UA product. The expected best case of 25 kW/°C from the literature was used for the design cooling coil's overall heat transfer coefficient in the normalised performance simulation model [12], [16].

3.3.2 Simulation model

We used Process Toolbox©, a thermal simulation software package, to enable modelling of an indirect water-to-air heat exchanger. If additional design conditions are available from the manufacturer, this model can be tested against the manufacturer's performance curves. The environmental conditions at tertiary cooling locations are seldom according to the design specifications. A calibrated simulation model for each cooling coil surveyed on Mine A and Mine B provided the normalised performance at each installed area under the applicable measured input conditions. Figure 4 shows the actual calibrated simulation model on the left. The model was calibrated according to the actual measurements, in this case cooling coil B1 from Table 3. Figure 4 on the right shows the normalised performance obtained through altering the overall heat transfer coefficient to a best-case or design value under the same environmental conditions.

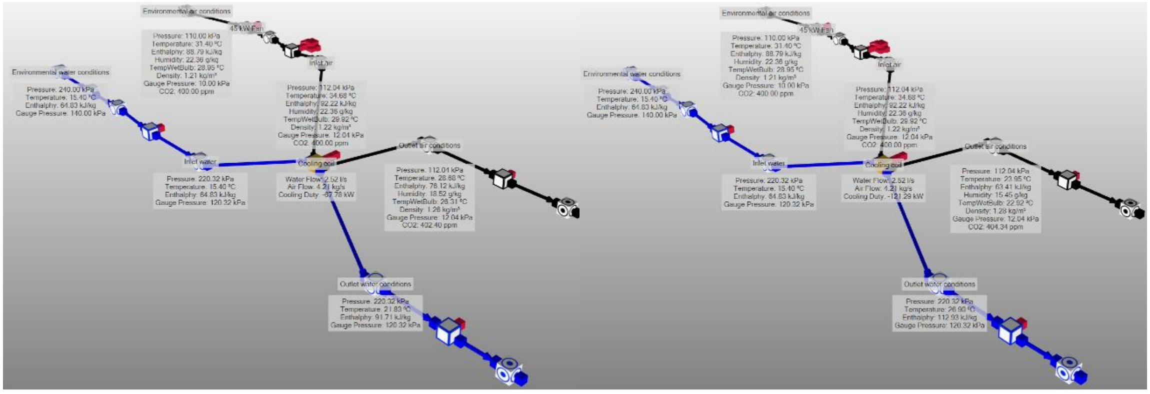

Figure 4: Calibrated actual performance model (left), Normalised performance model (right)

3.3.3 Simulation results and verification

The simulation model for each cooling coil has three components which provide insight into maintenance strategies discussed in section 4:

- A calibrated cooling coil model of the actual cooling coil at the actual conditions as in Figure 4 on the left.
- The design (normalised) cooling coil performance at the actual environmental conditions (If the correct performance curves are available. Otherwise, a best-case UA product is used) shown in Figure 4 on the right.
- The actual cooling coil under design environmental conditions (If design conditions are obtainable from the supplier).

Table 5 shows the comparison between the actual measurements and calculations versus the simulated model. This acts as the verification of the method as it is not financially feasible to replace a cooling coil with a new one at the same location or move the current cooling coil to a design environment.

Table 5: Difference between calibrated simulation model values and actual measurements

Description	**Unit**	**#A2**	**#A3**	**#A4***	**#A5**	**#A6**	**#A7**	**#A8**	**#B1***	**#B2***	**#B3***
Water flow	kg/s	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Air temp. out (wb)	°C$_{wb}$	9%	1%	1%	9%	5%	1%	4%	1%	8%	4%
Air temp. out (db)	°C$_{db}$	27%	2%	9%	35%	18%	6%	3%	4%	11%	10%
Air mass flow	kg/s	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Enthalpy in	kJ/kg	1%	1%	1%	1%	0%	0%	0%	1%	1%	0%
Enthalpy out	kJ/kg	13%	0%	0%	15%	7%	1%	5%	1%	10%	5%
Air duty	kW	37%	7%	2%	48%	31%	3%	22%	1%	31%	21%
Water ΔTemp.	°C	0%	0%	1%	0%	0%	0%	0%	0%	0%	0%
Water duty	kW	0%	0%	1%	10%	0%	0%	0%	0%	0%	0%
UA Product	kW/°C	11%	1%	4%	6%	5%	1%	4%	6%	27%	21%

**Measurements were taken before the force fan*

The average calibrated simulation model parameters in terms of outlet air temperatures, mass flow, enthalpy in and out, air duty, water duty and UA product were within 6 % of the actual measurements. The red values indicate questionable measurements due to difficult measuring circumstances discussed in section 4.

3.4 Efficiency calculations

The actual and normalised performance comparison provides the real efficiency of each cooling coil at those conditions. Figure 5 shows both normalised and the actual performance of each cooling coil. These results indicate the cooling coils with the highest potential for improvement. The design conditions were only available on Mine A, and the actual cooling coil performance at design conditions was therefore not calculated for the cooling coils at Mine B.

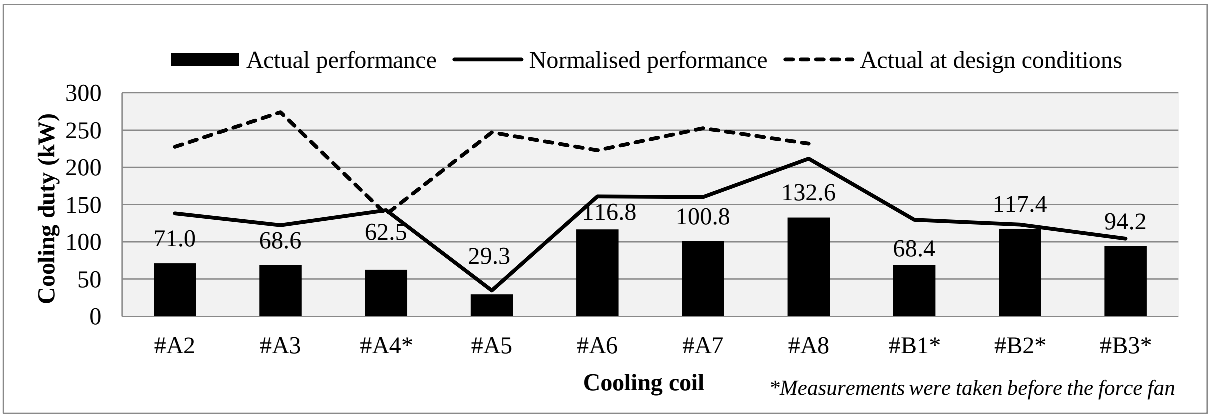

Figure 5: Normalised and actual cooling performance

Figure 5 indicates the actual cooling duty achieved with the bar, the normalised performance with the solid line and the expected performance of the current cooling coil when operated under its design environmental conditions with the dashed line. The subsequent section discusses the significance of the results.

4 Discussion

The difference between the air- and water duty in Table 4 is at an acceptable level only for unit A3, A4, A7 and B1. The measurements of the other cooling coils undoubtedly comprise some questionable readings. This is quite common because of the various challenges of the underground measurements such as equipment malfunction due to high humidity, inability to measure specific parameters due to cooling coil configuration and inaccessibility of cooling coil inlet/outlet due to the installation location.

One of the reasons for differing air- and water duty is due to activated water cleaning sprays located upstream from the cooling coil heat exchanger bank [12]. It is clear from the saturated outlet air of unit A2, A5, A6 and A8 that these sprays acted as a direct contact heat exchanger to provide additional cooling. However, these sprays should not be left open as it speeds up clogging of the fins due to dust particles. These cooling coils cannot be considered as a closed system and show the need for a robust method to assess these cooling coil performances. In conjunction with the activated cleaning sprays, the condensation of air during the process also contributes to the saturated outlet air temperatures [12], [27]. The robustness of using simulation models to obtain normalised performance still correctly evaluates these scenarios and shows significant results during the assessment of their performances.

The differing air duty in Table 5 for the cooling coils shows that the simulation model predicts the air duty expected in the case of a closed loop configuration. The conditions of the installation should be noted for the assessment. The simulation model enables the isolated heat exchange analysis of the cooling coils with higher accuracy by excluding factors influencing cooling duties such as cleaning sprays or condensation.

The cooling coils A6 and A8 in Table 4 has the highest UA Product for Mine A. These cooling coils were also the newest cooling coils during the surveys. The cooling coil specifications necessary for the calculation of the clean UA product, as in [17], [18], were not available for any of the cooling coils surveyed on Mine A or Mine B. This also highlights the need to accurately evaluate tertiary cooling installations with the least amount of information.

The low UA product for cooling coils A2, A3, A4, A5, A7 and B1 necessitates further analysis of the underlying performance factors. Figure 5 shows the actual performance of all the cooling coils surveyed. From personal experience, this is also the ventilation department of the mines’ limit to their evaluation. Usually, they also use the installed design capacity of the cooling coil to calculate its efficiency.

Analysis of Figure 5 shows that A5 has the highest efficiency for the environmental conditions under consideration at Mine A. This analysis provides the insight necessary for accurate maintenance procedures. Table 6 shows the ratios obtained from Figure 5.

Table 6: Cooling coil performance ratios

Description	**Unit**	**#A2**	**#A3**	**#A4***	**#A5**	**#A6**	**#A7**	**#A8**	**#B1***	**#B2***	**#B3***
Actual vs. Design (300/500)	%	23.7	22.9	20.8	9.8	38.9	33.6	44.2	22.8	39.1	31.4
Actual vs. Normalised	%	51.5	56.0	44.0	84.4	72.6	63.0	62.7	52.9	95.5	90.6
Performance at design conditions vs. Actual	-	3.2	4.0	2.2	8.4	1.9	2.5	1.7	-	-	-

**Measurements were taken before the force fan*

The ratio between the actual performance and the design shows the typical efficiency calculation done by the mine’s ventilation department. The ratio between the actual performance and the normalised performance indicates the real efficiency of the cooling coil. This shows the scope for improvement by cleaning and maintenance of the cooling coil, which is on average a maximum of 32%. The ratio between the performance at design conditions and the actual performance shows the maximum range for improvement obtained by better environmental conditions. Current methods do not differentiate between cooling coil maintenance or environmental conditions improvements. This is not as effective as it will not result in improved cooling performance.

For example, consider cooling coil A5, which would be noted as inefficient based on actual performance vs designed performance (9.8%). However, it is an efficient (84.4%) cooling coil operating in poor environmental conditions. This validates the need for normalised performance monitoring of mine coiling coils. Maintenance strategies include periodic manual brushing of the tubes, reverse flushing with brush inserts or ultrasonic vibration. High-pressure water jets could assist in external tube-and-fin cleaning or the correct use of upstream cleaning sprays. Chemical treatment reduces tube fouling and keeping the tubes clean will maximise the surface contact area [12].

Improvement of the environmental conditions includes maintenance of the inlet and outlet ventilation ducting and water supply pressure and temperature. The cladding of transfer pipes can improve the water temperature from the central refrigeration system. The supply pressure improvements include maintenance on upstream pipe leaks and installation/upkeep of the proper pressure relief valve (PRV) systems. If feasible, an increase to the PRV system's discharge pressure will enable a higher water flow through the cooling coil. However, it is recommended to use a flow limiting orifice when implementing such system changes.

Table 6 shows reporting on cooling coil efficiencies through comparing actual performance against design leads to a 38% lower cooling efficiency. This is significant because low efficiencies are usually the drivers for replacing cooling coils. Changing the analysis method could assist in unnecessary capital expenditure and focusing on the correct maintenance strategy.

Another important finding of this method is providing insight into cooling expected when developing ventilation strategies for working areas. We found that mine ventilation personnel generally expect the design cooling performance when planning for workplace ventilation. This is not feasible due to the non-design environmental conditions. The false expectation of a typical 500/300 kW design cooling duty at off-design conditions leads to poor and unsafe ventilation strategies. This method aims to achieve transparency in this regard.

5 Study limitations and further work

The outcomes of this study show promise for the accurate performance analysis of cooling coils operating at off-design conditions in deep mines. The simulation models assist in improving the accuracy of the manual measurements or the estimation of parameters not measurable. Mine personnel can therefore effectively start addressing the decrease in cooling coil performance. However, this study encountered a few challenges, which necessitates further work as listed below:

- The accuracy of the manual measurements posed a significant challenge in this study. Digital equipment sometimes malfunctioned due to the high humidity and temperatures encountered at these installation areas. Further work could address this by working in conjunction with the mine to install proper measurement points on the cooling coils and acquiring more robust measuring equipment.
- A higher frequency of manual measurements on the same cooling coils was challenging to obtain due to the travelling constraints to these underground areas. The information provided by the mines were quite limited, and we had to measure the cooling coils ourselves. Further work could alleviate this problem with proper training provided to the mine personnel.
- The underground water and ventilation supply to the cooling coils changed between underground visits. The cooling coils in operation at working areas also differed with the installation of new/additional cooling coils or removal thereof due to the closure of working areas between audits. Further studies could implement the method in this paper by evaluating new cooling coils at the same location or old cooling coils at new locations.
- The unavailability of design UA products from the manufacturer or of old unbranded cooling coils. The use of the best-case UA product, as shown in the literature, was suitable for the use of this study. However, further study must investigate more accurate solutions to identify the design UA product for the cooling coils under consideration.

Suggestions for further work includes the implementation of this method on other mine cooling systems. The daily implementation of refrigeration systems could support early identification of arising problems and strengthen system management [15]. This method could also assist in calculating the optimal water flow to BACs, especially for underground systems [30]. A further implementation to quantify the benefit of this method is to assess the effectiveness of this method on refrigeration machines [22], [23].

The mobile refrigeration ACU is one of the latest technologies in tertiary cooling methods [13]. The conceptual use thereof is not new, but the need for it grows with the deeper mines [14]. Further work should also assess the impact and applicability of this method on ACU units.

The application of localised vapour compression technology has its benefits. The ACU does not require cold service water. It can use water with temperatures of up to 45°C to reject heat from the air into the water. However, from an economic perspective, this investment is only feasible for depths below 4000m [13]. The use of ACUs on the return water from conventional spot coolers provides the maximum cooling achievable and economically feasible option recommended by the manufacturer [13]. The advancement in localised vapour compression technology still shows that spot cooling coil applications are advantageous. Thus, establishing the longevity of this method in the current and near-future mining industry.

6 Conclusion

South African mines are developing deeper than ever before. This poses significant challenges regarding ventilation and cooling strategies. Tertiary cooling methods such as cooling coils enable safe workplace temperatures. The methods to calculate cooling coil efficiencies on mines have been inadequately used, and a robust method was needed to take normalised performance into account. The method reviewed the actual performance calculations used in literature and simulation models were calibrated within 6% of the actual measurements. The simulation models enabled evaluation of the cooling coils under the current environmental conditions to obtain the normalised performance.

The case study results showed that the conventional efficiency calculations, which neglects normalised performance, were erroneous by 38% on average. The results showed that normalised performance evaluation could assist in decision-making in maintenance strategies. Cooling coils with the highest range for improvement were identified and maintenance strategies differentiated between environmental and cooling coil conditions. The results showed that a maximum average improvement of 32% in cooling performance was feasible by cleaning and maintenance of the coils. This method could also be beneficial when further developed to other mine cooling systems, such as refrigeration machines.

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8 Declaration of interest statement

None

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SUBMISSION: "PERFORMANCE ANALYSIS OF COOLING COILS OPERATING AT OFF-DESIGN CONDITIONS USING SIMULATION MODELS"

HIGHLIGHTS:

- Deep mines necessitate the use of cooling systems due to hot environments.
- Conventional cooling coil efficiency calculations are erroneous by 38% on average.
- Simulation models provide rapid estimation of expected performances.
- Normalised performance differentiates between cooling coil and environmental maintenance procedures.