A DYNAMIC SIMULATION MODEL FOR OPTIMAL DEEP-LEVEL MINE COOLING MANAGEMENT AND OPERATIONAL DECISION-MAKING FOR ESKOM'S LOAD CURTAILMENT

S.M. Sithole[1*], A.G.S. Gous[1] & C.S.L. Schutte[1]

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Contact details
* Corresponding author
shamymanchala@gmail.com

Author affiliations
1 Department of Industrial Engineering, Stellenbosch University, Stellenbosch, South Africa

ORCID® identifiers
S.M. Sithole
https://orcid.org/0000-0002-7463-4968

A.G.S. Gous
https://orcid.org/0000-0002-3195-1146

C.S.L. Schutte
https://orcid.org/0000-0002-0119-720X

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ABSTRACT

The South African mining sector depends on intensive energy usage to extract minerals. Most of this energy is used to enhance underground working conditions through cooling. Electricity costs have been on the rise, reducing the profitability of mines. Mines must invest in management systems that optimise energy usage while maintaining underground conditions. Dynamic simulation models are critical for systems analysis, optimal management, and improved decision-making. This paper presents an integrated dynamic simulation model for deep-level mine cooling systems. The model was developed using Process ToolBox simulation software, and a Mean Average Percentage Error of 3.53% was achieved. The impact of load curtailment on underground services was simulated. Eight working areas exceeded the legal limit of 32.5 °C, and the steady state simulation underestimated the impact, as only three working areas were affected. The simulation was sensitive to the ambient conditions; high temperatures were noted in the working areas when the ambient temperatures peaked.

OPSOMMING

Die Suid-Afrikaanse mynbousektor is afhanklik van intensiewe energieverbruik om minerale te ontgin. Die meeste van hierdie energie word gebruik om ondergrondse werksomstandighede deur verkoeling te verbeter. Elektrisiteitskoste is aan die toeneem, wat die winsgewendheid van myne verminder. Myne moet belê in bestuurstelsels wat energieverbruik optimeer terwyl ondergrondse toestande gehandhaaf word. Dinamiese simulasiemodelle is van kritieke belang vir stelselontleding, optimale bestuur en verbeterde besluitneming. Hierdie artikel bied 'n geïntegreerde dinamiese simulasiemodel vir diepvlakmynverkoelingstelsels aan. Die model is ontwikkel deur gebruik te maak van Process Toolbox simulasie sagteware, en 'n gemiddelde persentasie fout (MAPE) van 3.53 % is behaal. Die impak van vragbeperking op ondergrondse dienste is gesimuleer. Agt werkareas het die wettige perk van 32,5 °C oorskry, en die bestendige toestand-simulasie het die impak onderskat, aangesien slegs drie werksareas geraak is. Die simulasie was sensitief vir die omgewingstoestande; hoë temperature is in die werksareas opgemerk toe die omgewingstemperature 'n hoogtepunt bereik het.

1. INTRODUCTION

1.1. Energy constraints in deep-level mining

South Africa's energy and electricity are currently constrained. The country's main energy producer (Eskom) has seen increased power reductions ('load shedding') in the past five years. About 6 000 MW of load is removed from the grid for about six hours daily [1]. The South African mining industry spends about 30% of its total cash operating costs on electricity [2].

The South African mining industry is one of the most significant contributors to the country's gross domestic product (GDP) and to employment. South African mines are generally exposed to factors that negatively affect their economic growth. In the past 30 years, the mining industry has seen increased economic pressures, forcing the mines to optimise their operations. Because of variable mineral prices, the mines' uneconomical operations directly impact their production output and overall profits [3].

South African deep-level mines experience virgin rock temperatures of up to 60 °C [4] at increased mining depths, and are up to 4 km in depth [5]. Mines use cooling systems to maintain underground temperatures under the required threshold, but they use around 25% of a mine's total electricity consumption [6],[7]. With the rise in electrical costs, mines are forced to implement energy-saving initiatives to remain profitable. The challenge lies in ensuring that underground operational conditions are maintained by implementing several energy-saving initiatives.

1.2. Load curtailment as the new norm

The Eskom load curtailment programme is implemented in a total of four stages. The first and second stages require the mine to reduce their total load by 10%, the third stage requires a 15% reduction, and the fourth stage requires a maximum decrease of 20% of the total electricity consumption [8],[9]. Between January and August 2022, Eskom implemented 91 days of load-shedding, with 18 days of load curtailment at stage 2 and two days at stage 3 [10]. Load curtailment directly impacts mines' cooling systems, as they are the largest consumers of the mine's electrical load.

Any disturbance in the mine's cooling systems results in increased underground temperatures, resulting from several underground heat sources, such as geothermal energy, auto compression, mechanised equipment, explosives and blasting, mechanical processes, and light [3],[11]. The increased temperatures create several heat hazards, such as heat stroke, rushes, cramps, and exhaustion [12]. These heat hazards result in reduced mining performances; and in most cases, heat stroke may cause death. Heat stroke occurs when the internal body temperature exceeds 40 °C [12]. Government regulators closely monitor and regulate heat hazards; if the conditions are dangerous to mine personnel, the mine is issued a 'section 54', which requires a complete shutdown of the mining operation [13]. The regulation prohibits mine workers from being exposed to temperatures exceeding 32.5 °C in the wet bulb, as it is conducive to heat stroke [13].

Mines cannot afford to shut down operations, as that would add more strain to the current economic pressures. In 2015, underground stoppages issued by government regulators resulted in a total loss of 376 million USD. Most of these stoppages were owing to high workplace air temperatures [14].

Load curtailment is not announced well in advance. This gives the mines only limited time to plan for curtailments. The reduction in load on the cooling system directly impacts underground conditions, and so it is vital to ensure that the decisions made on the mine's cooling systems are guided by reliable data that ensures that the safety of the underground mine workers is maintained.

1.3. Current simulations and cooling strategies

Mine cooling systems are suitable for achieving energy savings and improving operations. The impact of load curtailment on the mines' underground conditions requires an integrated investigation in which the impact of each sub-component could be outlined. A dynamic simulation model of a complete mine cooling system is necessary to achieve this.

Dynamic simulations can provide a holistic view of a mine's cooling energy usage and the overall system service delivery. It can assist with outlining the impacts of changing one or a combination of sub-components on the system [15]. To make well-informed decisions about reducing the system's total energy consumption and improving overall service delivery, an integrated investigation is required to evaluate the impact on the overall cooling system. Each sub-component's contribution needs to be outlined and assessed. The ventilation and water system serves as a transportation medium for cooling, and thus forms part of the cooling system.

Simulation software is widely used on mine ventilation and cooling systems. Simulation systems are crucial for optimising energy use and mine planning [16]. Simulations allow for the exploration of 'what if' questions and the evaluation of different scenarios without experimenting with the system itself. Simulations help to identify system inefficiencies and material limitations, and to gain insight into which variables are the most important in the system [17]. Simulation software gives the ability to evaluate dynamic scenarios; unlike the analytical approach, most simulation software has built-in mathematical equations from first principles, and simplifies the systems. In most cases, the analysis depends on the model's quality and the modeller's skills, which require specialised training. Building a successful simulation model using simulation software can be time-consuming and expensive [17].

Studies have shown the limitations of using steady-state simulation model in underground ventilation networks as they over-predict high temperatures and under-predict low temperatures [18],[19]. Transient simulation software is required to simulate the dynamic scenarios of mine cooling systems [20],[21]. Various simulation software applications are available, such as VentSim, Vuma-3D, ClimS, m, DuctSim, VenPri, MineFire, Process Toolbox (PTB), VentGraph, and 3D-Canvent [16],[22]. PTB is a thermodynamic simulation software that can incorporate transient heat transfer processes. It has an intuitive setup with a three-dimensional (3D) visualiser to allow for a rapid assessment of the system [22].

PTB and other simulation software programs have not been applied to an integrated dynamic mine cooling system. Fair *et al*. [23] investigated simulating underground systems' sensitivity to fluctuating ambient conditions. PTB was applied to a case study, showing that transient software could be used for an entire mine ventilation system and could improve predicting the underground environment because of fluctuating ambient conditions. Vuma-transient can simulate temperature variations, but little literature exists on applying it to integrated cooling and ventilation systems [24],[25].

The studies of controlling and optimising mine cooling systems resulted in several energy savings and service delivery improvements [5],[26-30]. Crowford *et al*. [26] reduced power demands in a building sector's air conditioning and heating ventilation system by 45.7% through an optimised dynamic control strategy. Vosloo *et al*. [5] reduced the operational costs of a mine water reticulation system by 13%.

The studies on the cooling systems modelling approaches considered different simulation software such as TRNSYS modelling [34],[35], Modelica [32],[33], and Process Toolbox [43]. The models were constructed for mine cooling systems [36],[37], and some focused on cooling systems in commercial buildings [35]. Romero *et al*. [31] considered a black box approach to developing a simulation model that determined the outlet water temperatures of an HVAC system with constant condenser conditions. The model prediction accuracy ranged from 69% to 76%.

Du Plessis *et al*. [38] showed that a model accuracy error of 4.1% was attainable. Mofet and Zmeureanu [29] investigated the reduction in model accuracy over time; the study outlined that the model root mean square was less than 7% for the one-time frame of a summer season and less than 8% for the other. It was argued that the reduction was because of the change in cooling demand and ambient conditions being significantly different.

Decision-making is crucial in mine cooling and ventilation systems. Managers need to follow well-considered decision-making processes to make sound decisions about systems. Pretorius *et al*. [40] implemented a data information knowledge wisdom (DIKW) model to assist management in improving their deep mine cooling systems. The study achieved a cooling duty improvement of 55%, translating to an increase of 5.3 MW in refrigeration. The DIKW model was not integrated with the dynamic simulation model of the mines' cooling system, and the model could not be used to predict the impact of various changes on the system. The data received from the DIKW model could also be applied to construct a robust dynamic simulation model. The model could further draw wisdom from and guide managers through decision-making.

Load curtailment presents a dynamic problem to the overall mine cooling and ventilation reticulation system. For mines to comply, several components must be isolated or switched off. Relating to the cooling system, this paper focuses on the following components: ventilation fans, refrigeration plants and their auxiliaries, pre-cooling towers, bulk air coolers, and mobile spot coolers.

1.4. Need for the study, and its objective

A need still exists to study a cooling system's dynamic nature and to outline the impact of instantaneous change cooling systems on mine service delivery – i.e., gathering knowledge and wisdom. With load curtailment being the new norm, it is required that the instantaneous changes resulting from load curtailment of mine cooling systems be studied, and the impact be compared with the conventional steady-state method.

This study aims to develop a dynamic simulation model that can be used to predict the impact of load curtailment on mine service delivery in working areas, using an existing integrated energy modelling method from the literature [40],[41]. The dynamic simulation model should assist mine management by simulating the impact of unexpected energy changes on a mine's cooling system and on overall service delivery. The model is used to investigate and predict the impact of load curtailment (load shedding) on overall underground conditions, and outlines the possible evacuation time needed for underground mines until the conditions underground are unbearable. The model also considers the impact of dynamic ambient conditions throughout the day and its overall contribution to underground service delivery.

2. METHODOLOGY

In Section 1, a problem was identified and outlined, and the literature was defined and analysed. This section uses an integrated dynamic simulation method from the evaluated literature. A complete system integration is proposed to integrate mine refrigeration, ventilation, and water reticulation systems. A load curtailment prediction method is also presented. The DIKW method is included to assist with the construction of the dynamic simulation models and to outline the knowledge and wisdom that results from the analysis and simulation of the dynamic models. The case study methodology is suggested to outline the practicality of the systematic approach and to assist with a comprehensive system analysis [42].

2.1. Model development

The method describes how the dynamic simulation model is developed and integrated with the DIKW model. Sections of the DIKW model are used to construct and develop an accurate dynamic simulation model. Later, the calibrated dynamic simulation model is used to investigate several scenarios. The remaining section of the DIKW method extracts knowledge and wisdom from the outputs/results of the simulation model to make critical decisions about the mining block.

Figure 1 outlines a systematic approach and an integrated method to build a dynamic simulation model, and to use the DIKW model to assist mine managers with decision-making. A detailed method for investigating the impact of system energy changes is outlined later in the study.

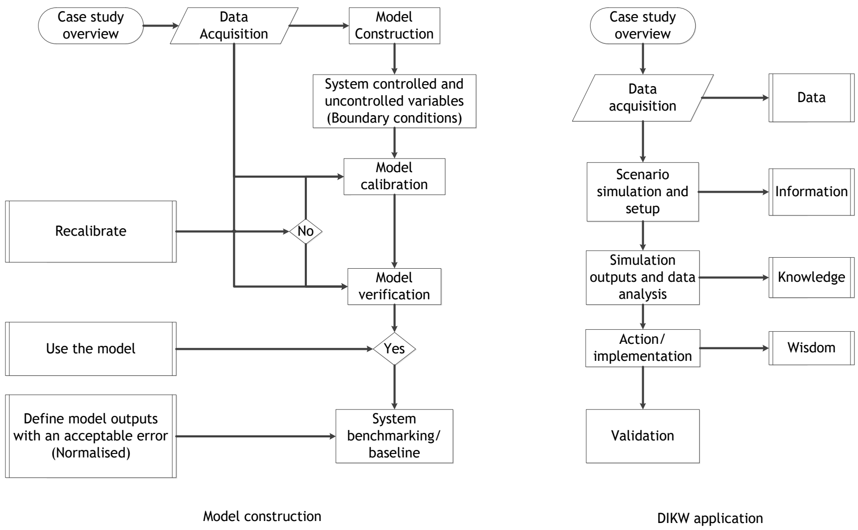


Figure 1: Dynamic simulation development method/framework

The cooling system consists of three sub-systems: refrigeration, water reticulation, and ventilation. The refrigeration system consists of water chillers, bulk air coolers, and precooling towers to cool down the cooling mediums and to eject heat into the atmosphere. The cooling medium is usually in the form of water or air; water is supplied to underground areas through underground pipes, which are also used for cooling through mobile spot coolers and underground bulk air coolers. In cases where the cooling from the refrigeration system is added to the system through surface bulk air coolers, the cooling is distributed through the ventilation system, which is maintained through forced fans. Figure 2 outlines the general integration between refrigeration, water reticulation, and ventilation systems.

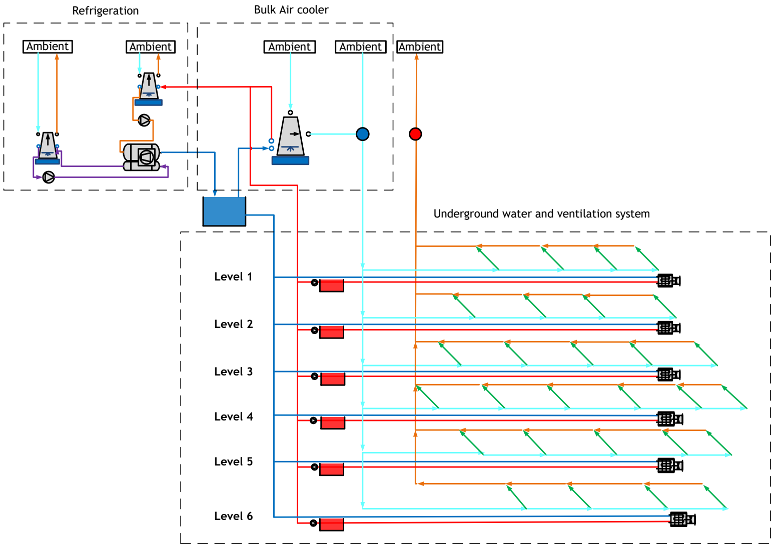


Figure 2: Deep-level gold mine refrigeration, ventilation, and water network integration

The systems share the thermal characteristics outlined above. The refrigeration system feeds into the ventilation and water reticulation systems, which are connected underground as they continue to exchange heat; the uncladded pipes and leakages transfer cooling to the ventilation air; and the heat removed from the air goes into the water, which eventually returns to the refrigeration cycle to eject the heat.

The transient and dynamic nature of all three systems needs to be considered. The systematic approach will therefore be applied to all of the sub-systems.

2.1.1. Data acquisition

Data acquisition is the most crucial part of developing a dynamic simulation model. Data inputs are required to build and calibrate the model. The collected data includes the cooling systems' operation measurements, the operational energy supply, the system energy demand, the temperature, air flows, barometric pressures, pipe sizes and lengths, and the design specifications of all system sub-components.

The collected data is used to calibrate the cooling system simulation model accurately. Different data collection methods exist; these include using the SCADA system, in which instrumentation is placed on strategic points to collect data.

The mining industry still needs to catch up with the digitisation of the system; some mines still rely on manual measurements for data collection. The instruments used for manual measurements need to be accurate and calibrated. Unwil *et al.* [43] completed a review of underground mine instruments and outlined the accuracies associated with the instruments.

2.1.2. Model construction

Model construction often depends on the software used for the simulation. Simulation software simplifies construction using a component-based drag-and-drop graphical user interface (GUI) [44]. Although the building process is simplified, the user needs to be familiar with the software, as it is easy to make a lot of fundamental errors. The user also needs to be familiar with the mathematical modelling system. Simulation software has user guidelines that outline the type of equations and standards used to define different components of the system.

Software such as Process Toolbox (PTB) allows the user to create three-dimensional (3D) networks using digital mine survey plans [45],[46]. The software consists of mathematically modelled components such as air tunnels, water–air heat exchangers, ice dams, water pipes, water pumps, cooling towers, water–water chillers, and public water demand to model other water users underground.

Cooling systems have set control philosophies put in place to optimise the day-to-day operation of the mine. The control philosophies are usually guided by the production cycle; it is essential also to outline the set control of the system when building the model, as this would significantly influence the calibration of the model. Simulation software consists of basic control tools that allow for dynamic control of the system components, including the step controller, calibration controller, or direct input control into the details.

2.1.3. Model calibration

The model needs to be calibrated on the basis of the current operating conditions. Model calibration is vital in decision-making about mine cooling systems [47]. Depending on the nature and complexity of the model being constructed, model calibration can range from changing the pipe sizes in the system to changing and confirming the sub-components' inputs to the system. It is essential to build a model like the existing system.

Different calibration methods are used, depending on the simulation software that is used. Manual iterations are usually used to determine unknown parameters [48]. A dimensionless calibration factor is sometimes applied to the model sub-components [49].

Model calibration is a continuous process throughout the development of the model. Accurate data often results in a precise model [49]. The model calibration process repeatedly involves data acquisition, model construction, and verification processes.

Refrigeration models do not usually change significantly over time, and the model's accuracy does not vary much. In most cases, the model needs to be recalibrated if there is a change in the performance of the system's sub-components. The ventilation model is sensitive, and needs to be calibrated frequently; it is usually affected by the expansions and addition of heat sources in the system. Sometimes the ventilation model changes when old mining areas are closed and ventilation fans in the system are added or removed. The model must be updated to ensure that the accuracy level is always maintained.

2.1.4. Model verification

To verify the accuracy of a cooling system model, the simulation outputs of the model are compared with the actual measurements. Since the model is dynamic and transient, the verification method will need to consider the time-dependent nature of the system. The output averages will be compared over time [50],[18]. The accuracy of the model can also be determined using statistical estimators such as mean absolute percentage error (MAPE) [51],[53].

A simulation accuracy of at least 95% ensures an accurate representation of the actual system [52]. Studies have shown that a mean absolute percentage error of 4.1% is achievable for mine cooling systems [38], and that the mean absolute percentage error of 7% is also possible after a few iterations and reusing the models after a specific time [39].

The MAPE is calculated with Equation 1 [53]:

$$MAP\left(\frac{1}{N}\sum_{t=1}^{N}\left|\frac{A_t-F_t}{A_t}\right|\right)\times 100 \qquad (1)$$

where:

A_t is the actual measured result,

F_t is the simulated result,

N is the number of data points.

DIKW & load curtailment investigation method

Figure 1 above outlined the high-level implementation of a DIKW method to make decisions about cooling systems using a calibrated model. Load curtailment is usually unexpected, and it is easier to make decisions if the impact of the changes on the entire mine system is known. Figure 3 outlines a step-by-step approach to assist with decision-making about load curtailment.

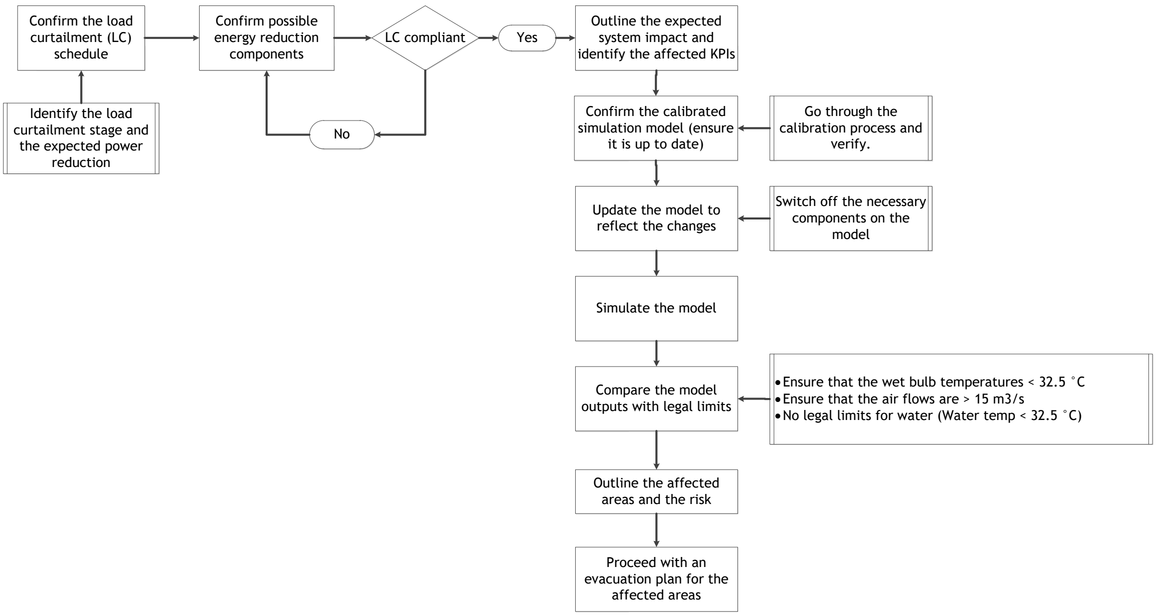


Figure 3: Load curtailment handling/decision-making method

Managers require a step-by-step guide to deciding which cooling components to switch off during load curtailment. Energy-intensive parts affect the operation. Mines usually rank the details in order of importance and their ability to influence the operation; they also aim to remain profitable during load curtailment times. The areas directly linked to production are usually left for last. Depending on the time of the load curtailment, some of the components can be turned off. The mine has hoisting components, ventilation fans, chiller plants, and dewatering pumps.

The load curtailment schedule determines the expected load reduction and how long the load needs to remain reduced. With the known expected power reduction, the components that need to be switched off can be identified to ensure that the mine complies with the requirements. A preliminary risk assessment must be completed to outline the potentially affected areas in the mining block. The most recent calibrated cooling model is then used to simulate the impact of the energy changes on the cooling system. The simulation output is then compared with the general legal limits.

3. RESULTS AND DISCUSSION

3.1. Case study overview

A gold mine was selected as a case study (Mine A). The mine is mining at an average depth of 2.9 km underground, with an average radial distance of 10 km from the shaft collar.

As outlined in Section 2, the cooling system consists of three systems: the refrigeration system, the ventilation system, and the water reticulation system. The refrigeration system consists of four water chillers, condenser towers, underground water-pre-cooling towers, refrigeration water circulation pumps, and surface chilled water storage dams on the surface. The mine also has three surface bulk air coolers that cool down ambient air using the chill water, and send it underground for cooling.

Chilled water in the surface chilled water storage dams is sent underground for underground mining services and cooling. The mine has underground chilled water storage capacity, and water is sent from the dam to the respective levels. To enhance the cooling, the mine has underground bulk air coolers and mobile tertiary spot coolers, where the chilled water cools the underground air further. The return water from underground is pumped to the surface through multistage pumps and a three-pipe system.

The ventilation system consists of a single downcast shaft and an upcast shaft. The upcast shaft has three ventilation fans that create negative system pressure for continuous ventilation flow. The ventilation circuit consists of the ventilation-forced fans in the mining block where air cannot flow naturally or through the surface vent fans.

The overall system control philosophy, ambient conditions, and several heat sources underground influence the underground conditions. The case study mine was selected owing to the dynamic nature of the refrigeration system, which plays a bigger role in underground cooling.

3.2. Data acquisition

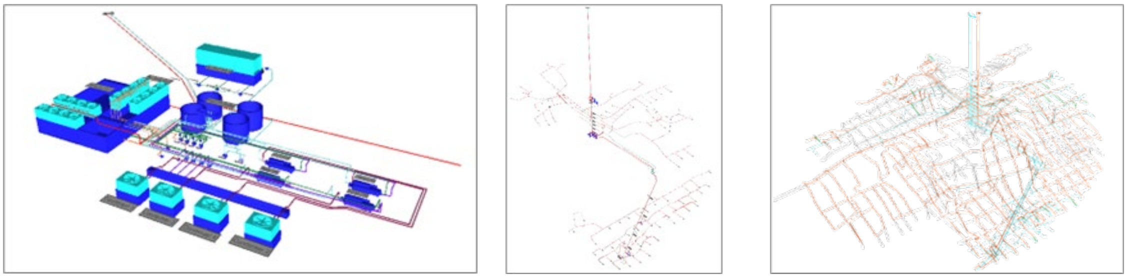
The critical components' design specifications were collected from the existing data sheets and nameplates. The refrigeration system was already advanced; all of the essential measuring points had instrumentation, and fewer manual measurements were required. Most of the time, manual measurements were done to verify some of the instruments. The water reticulation system also had enough instrumentation for temperature and flow calibration. The water flows on specific working stopes and tertiary spot coolers had to be measured.

The ventilation system had continuous surface measuring instrumentation; the airflow and temperature underground were known, and the temperature inlets to the mining levels were instrumented. Manual measurements were taken to verify the data from the installed instruments before being used for calibration.

Several site inspections were conducted to construct the surface refrigeration model as close as possible to specification. All the pipe lengths and sizes were noted for the model's construction, and process and instrumentation diagrams and process flow diagrams were completed to outline the configuration of the existing systems. Underground visits were also done; all of the ventilation auxiliaries were noted, and layouts were prepared with all of the data collected from underground. Volume surveys conducted by mine ventilation officers were used to update the collected data continuously.

3.3. Model construction

PTB simulation software was used to build the dynamic surface refrigeration system, the underground water reticulation system, and the ventilation system according to the mine plans, volume surveys, and the acquired system data. All known design specifications, current operation points, and data inputs were programmed into the models. Figure 4 shows screenshots of the dynamic refrigeration model (a), the water reticulation model (b), and the ventilation network (c).



(a) (b) (c)

Figure 4: Mine A's refrigeration (a), water reticulation (b), and ventilation network (c)

The final mine dynamic model included the active integration of the refrigeration model, the water reticulation, and the ventilation. Fair [41] noted that one of the limitations of that study was the integration of the water pipes and the ventilation air. The current model reduced the limitation by treating all of the uncladded areas as small indirect contact heat exchangers, allowing continuous interaction between the chilled water pipes and the ventilation haulages.

3.4. Model calibration and verification

After building the blueprint of the sub-systems of the cooling system, the collected operational data was used as inputs to the models. The data was collected for a week, and was used to calibrate the model. Figure 5 outlines the managed ambient temperatures for a week.

First, the refrigeration model was calibrated in isolation. The control philosophy of the mine was also used together with the collected data. Ambient temperatures were used as a controlled variable and as inputs to the fridge plant condenser towers, the pre-cooling towers, and the surface bulk air cooler inlet conditions. The refrigeration system was sensitive to ambient temperatures. The water chillers, pre-cooling towers, return water, and surface chill dam inputs and outputs were used to verify the accuracy of the refrigeration model.

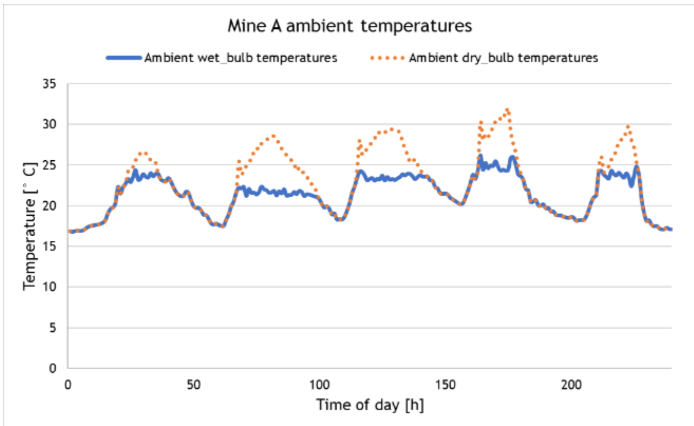


Figure 5: Mine A's ambient surface temperatures

The average mean error for all of the individual components was evaluated, and the simulated output results were compared with the current operational data. Figure 6 shows the results of the refrigeration model. One bulk air cooler showed the highest average MAPE of 7.1%, and the average MAPE for the refrigeration model was evaluated to be 2.8%. The refrigeration model was seen to be 97.2% accurate.

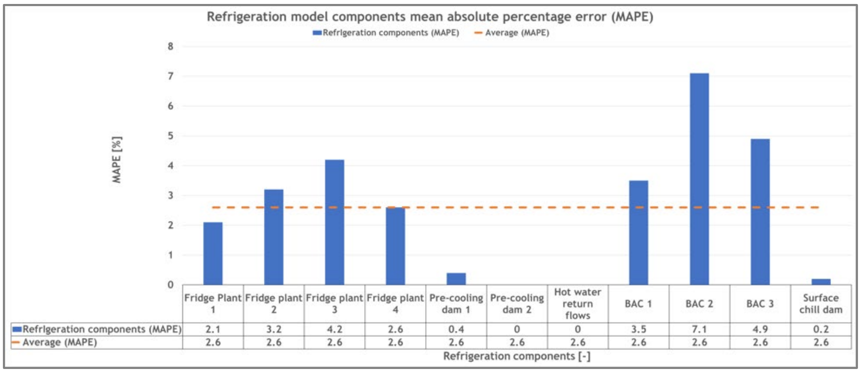


Figure 6: Refrigeration components' mean absolute percentage error

Figure 7 shows the results for all of the critical components of the water reticulation system (water supply and dewatering). The dewatering pumps showed the highest MAPE of 5%, and the average MAPE for the entire water reticulation model was 3%; the accuracy of the water reticulation model was 97%.

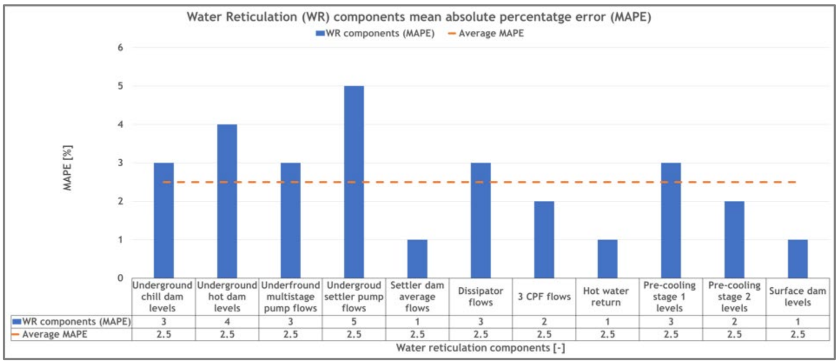


Figure 7: Water reticulation MAPE

Mine A has line-of-sight instrumentation that measures wet bulb temperatures, dry-bulb temperatures, relative humidity, and velocities at strategic points of the ventilation network. Points with complete instrumentation and quality data were selected to verify the model. Tiny tag equipment was installed on several points to verify the instruments, and most of the data was within a 2% error difference. Figure 8 outlines the calculated MAPE for the selected data points; the highest MAPE was recorded on two cross-cuts, and the average MAPE for the model was estimated to be 4.42%. The accuracy of the model was evaluated to be 95.6%.

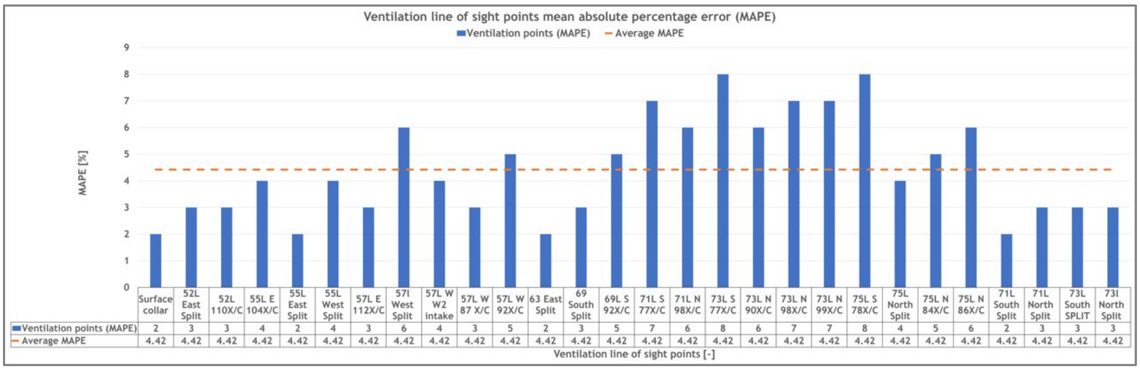


Figure 8: Ventilation system MAPE

Based on the evaluated individual mean square error for the sub-systems of the cooling system, the final integrated cooling system average MAPE was evaluated to be 3.17%, resulting in an accuracy of 96.8%.

3.5. Load curtailment schedule and energy reductions

As outlined in the literature, in terms of its licence conditions, Eskom is required to comply with NRS 048-9:2019 (Edition 2). Eskom has the right to interrupt or reduce the electricity supply to its customers temporarily. The case study mine chose the curtailment option in terms of NRS 048-9:2019 (Edition 2); thus Eskom expects the mine to reduce its load by a minimum of 10%, 15%, or 20%, and those reductions need to be maintained for the duration of the emergency.

By complying with the licence conditions, the mine is removed from load-shedding schedules. Failure to comply with the licence would result in Eskom putting the mine back on the load-shedding schedules, which would result in unplanned or short-notice cut-offs for the mine. Eskom uses the baseload of the previous three days or when the mine does not experience any load curtailment.

3.6. Cooling system set-up and planned components turned off

When a reduction of 20% is required, the mine usually prioritises systems where the load curtailment can be implemented without affecting its production and the safety of the employees. Mine A is a vertical shaft that uses belts and skips for ore hoisting, and depends on water pumps to ensure that the mine is not flooded. Generally, the mining schedule does not change, as this would also affect the mine workers' routine and could affect the production targets.

Sometimes mines are forced to fill their silos to increase capacity and only hoist when they are out of the load curtailment schedule. Even with the reduction options mentioned above, the mine requires further load reduction. The cooling system consumes close to 30% of the mine's total energy; thus its load will still need to be reduced during load curtailment. Table 1 outlines the scenario to be evaluated and the planned components to reduce the load.

Table 1: Breakdown of load curtailment scenario

	Fridge plants (FPs)	Bulk air coolers (BACs)	Load reduction	Compliant
Baseline	All FPS operating	All 3 BACs operating	0 MW	Not applicable
Scenario 1	Only 3 of 4 FPs operating	All 3 BACs operating	1.50 MW	Yes (only for stages 1 & 2)
Scenario 2	Only 3 of 4 FPs operating	Only 2 of 3 BACs operating	1.78 MW	Yes (only for stages 1 & 2)
Scenario 3	Only 2 of 4 FPs operating	Only 1 of 3 BACs operating	3.55 MW	Yes (only for stages 1,2 & 3)
Scenario 4	Only 1 of 4 FPs operating	Only 1 of 3 BACs operating	5.05 MW	Yes (only for stages 1, 2 & 3)

This study focuses on stage 4 load-shedding, in which 20% of the load needs to be reduced. Figure 9 outlines the baseload of the cooling load and the total expected operational load during load curtailment at 20% reduction. The average maximum load reduction of 6.5 MW is required; it is suggested that 5 MW be reduced from the cooling system, and the remaining 1.5 MW be reduced from pumping and other mining auxiliaries.

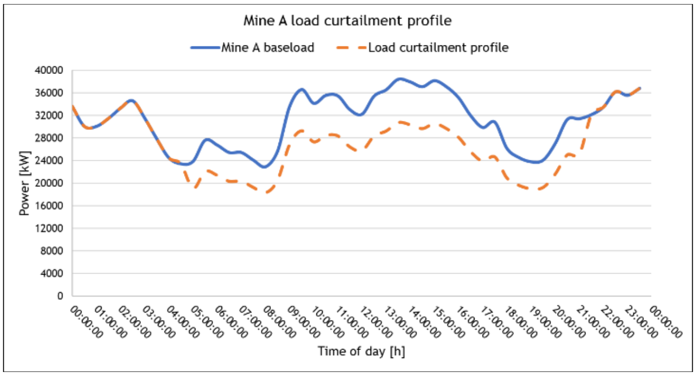


Figure 9: Load curtailment baseload

3.7. Simulation results and discussion

The components required for load curtailment were isolated in the model, and the model was simulated. The load curtailment was assumed to run from 05:00 to 21:00. Figure 10 outlines the ambient input in the simulation model. The surface temperatures increased during the day.

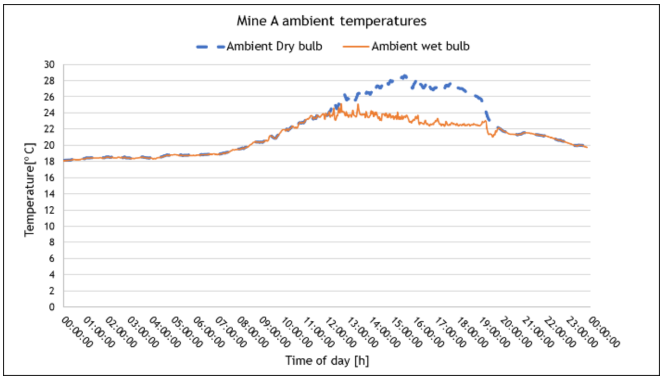
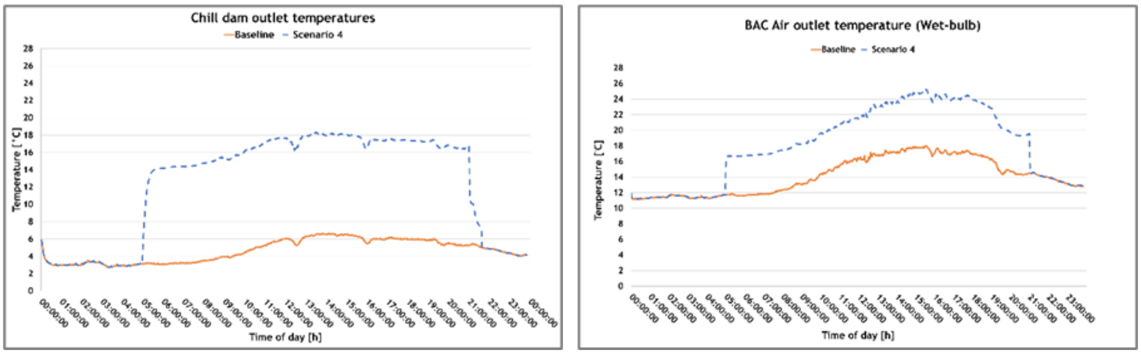


Figure 10: Ambient conditions for load curtailment simulation

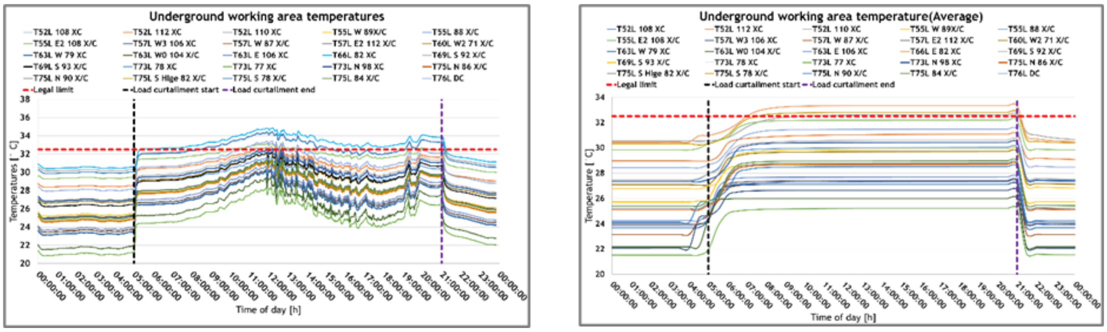
Three fridge plants and two BACs were switched off. Figure 11 outlines the outlet chill water temperature (a) and the BAC outlet air temperatures (b). The temperatures were higher than the baseline temperature; the BACs air temperatures were also affected by the increased chill water temperature and the reduced number of bulk air coolers.



(a) **(b)**

Figure 11: Refrigeration outlet water temperatures (a) and outlet BAC temperatures (b)

Several underground working areas were also evaluated. Figure 12 outlines the dynamic (a) and steady-state (b) underground wet-bulb temperatures per working area. A total of eight working areas exceeded the legal limit of 32.5 °C in the dynamic simulation.



(a) (b)

Figure 12: Dynamic (a) and steady-state (b) underground wet bulb temperatures

A steady-state simulation outlined the difference between dynamic and steady-state simulation. Figure 12 (b) summarises the steady-state simulation results of the respective working areas. From the results, only three working areas were affected, compared with the eight outlined in the dynamic simulation in Figure 12 (a).

3.8. Discussion

A dynamic simulation model for deep-level mine cooling systems was developed and calibrated. The resultant mean absolute percentage error for the sub-systems of the cooling system was evaluated to be 3%, 4.42%, and 3.17% respectively. The overall cooling systems MAPE was 3.53%, less than the MAPE found in the literature of 4.1% and 7%. The model accuracy was 96.47%. The model was used to simulate the impact of load curtailment on underground mine working areas, and steady-state and dynamic simulations were completed.

Steady-state simulations underestimate the impact of the change in temperatures, and cannot be used to make critical decisions in deep-level gold mines. The dynamic simulation outlines the true impact of load curtailment on working areas. The mine has an average of four hours from implementing load curtailment until the eight working areas exceed the legal limit. The implementation of load curtailment on the cooling system also depends on ambient temperatures; from the simulations, most working areas exceed the legal limit when the ambient temperatures peak.

Using the steady-state simulation to make decisions would have resulted in the under-prediction of the affected working areas; this would have meant that the mine workers would have been exposed to temperatures above the legal limit. Dynamic simulations have an advantage in decision-making because management can make better decisions and plans.

From the analysis of the results, there is potential to treat load curtailment as the new norm. The mine can afford constantly to save energy by adopting load curtailment as the new control philosophy. A 20% energy reduction leads to more working areas being isolated. The model can further evaluate the right combination for energy reduction with fewer working areas being affected.

The study met the objectives outlined in Section 1: the dynamic simulation resulted in usable knowledge as an output that could assist mine managers with decision-making. The model outlined the affected working areas underground and how long it would take for the areas to be affected after the implementation of load curtailment. The dynamic model was sensitive to the ambient temperatures, as the resulting profile in the working areas followed that of the ambient temperatures.

4. CONCLUSION

The need to apply integrated dynamic simulation in deep-level gold mines was outlined in the literature. This study's objective was to develop an integrated dynamic cooling system model using the methods found in the literature. The model needed to represent the entire cooling circuit of the mine.

A thermodynamic simulation was used to develop an integrated mine cooling system in which the refrigeration system, water reticulation, and ventilation systems were integrated. The mean absolute percentage error (MAPE) method was used to verify the simulation. The refrigeration, water, and ventilation models resulted in MAPEs of 3%, 4.42%, and 3.17% respectively.

The method was then used to investigate the impact of load curtailment on the mine's working areas. Stage 4 load curtailment was implemented, in which the mine's baseload had to be reduced by 20%. The dynamic simulation showed that eight working areas were affected by load curtailment. This gave the mine additional wisdom to prioritise specific working areas during load curtailment; localised cooling could also be implemented in the affected working areas to allow the mine to reach its production targets during load curtailment. A steady-state simulation was also considered; only three working areas were affected, and the steady-state simulation underestimated the peak results of the simulation.

The study showed the importance of integrated dynamic simulations in decision-making. Decision-making should also be supported by convincing data that accurately predicts the outcome of underground conditions.

With load curtailments as South Africa's new norm, different deep-level gold mines should urgently need this study and its integrated dynamic cooling simulation; this would enhance their decision-making procedures. The application of the study to different mine configurations with different dynamic cooling systems, depths, geographical locations, and seasons would reveal the possibilities of further reducing mines' energy load without affecting their underground working areas or service delivery.

There is also great potential to investigate the impact of infrastructure changes for energy management on mines' service delivery. This would improve the safety outcome of every decision that is made in deep-level gold mines.

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