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## Implementing a DIKW model on a deep mine cooling system

Jan Gabriel Pretorius<sup>\*</sup>, Marc John Mathews, Philip Maré, Marius Kleingeld, Johann van Rensburg

Centre for Research and Continued Engineering Development, North-West University, Pretoria 0081, South Africa  
TEMM International (Pty) Ltd, Pretoria 0081, South Africa

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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.

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### 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,

<sup>\*</sup> Corresponding author at: Centre for Research and Continued Engineering Development, North-West University, Pretoria 0081, South Africa.

E-mail address: [jgpretorius@rems2.com](mailto:jgpretorius@rems2.com) (J.G. Pretorius).

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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.

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].

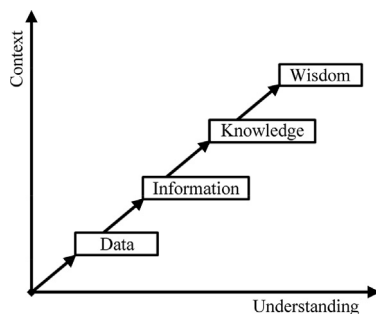


Fig. 1. Relationship between context and understanding [14,15].

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

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  $\Delta T$  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<sup>3</sup>/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; and  $\Delta S_a$  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 on-site 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.

### 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 Orchestra 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

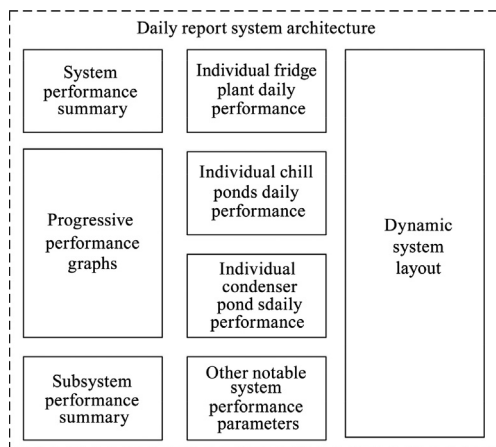


Fig. 2. Report system architecture.

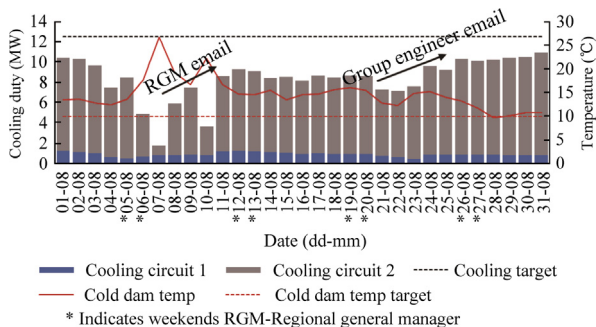


Fig. 3. Progressive cooling duty graph.

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

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.

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 <sup>a</sup>	5.2	105.1	2.6
FP2	0.0										
FP3	87.5	63.9	4566	4096	22.8 <sup>a</sup>	9.0	120.9	47.1 <sup>a</sup>	3.7 <sup>a</sup>	225.2	3.2
FP4	100.0	99.0	4863 <sup>b</sup>	2269	21.1	9.6	121.1 <sup>b</sup>	43.7 <sup>a</sup>	7.9	106.5	5.9 <sup>b</sup>
FP5	100.0	99.3	2130	2269	22.0 <sup>a</sup>	8.5	60.2	44.0 <sup>a</sup>	6.5	99.7	2.9
FP6	0.0										
FP7	0.0										
FP9	0.0										
FP10	100.0	89.8	1759 <sup>a</sup>	4096	23.7 <sup>a</sup>	3.1 <sup>a</sup>	138.1	43.4	7.4	106.3	2.4

<sup>a</sup> Critical values.  
<sup>b</sup> Questionable values.

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.

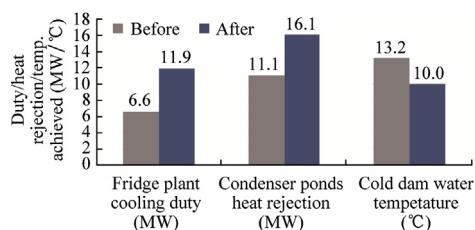


Fig. 4. Cooling system performance comparison.

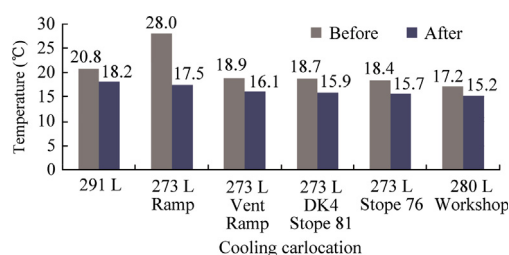


Fig. 5. Cooling car-inlet water temperatures.

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

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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#### References

- [1] Macmillan H. Plus ça change? Mining in South Africa in the last 30 years – an overview. *Rev Afr Polit Econ* 2017;44:272–91.
- [2] Donoghue AM. Occupational health hazards in mining: an overview. *Occup Med (Chic Ill)* 2004;54:283–9.
- [3] Gloy M. The use of Section 54 stoppage orders in terms of the Mine Health and Safety Act. Potchefstroom campus of the North. West University; 2014.
- [4] McKay D. Section 54s cost SA mines R4.8bn in 2015, and 2016 may be worse 2016 [accessed January 1, 2017].
- [5] Maurya T, Karena K, Vardhan H, Aruna M, Raj MG. Potential sources of heat in underground mines – a review. *Proc Earth Planet Sci* 2015;11:463–8.
- [6] Tshibalo AE, Dhansay T, Nyabeze P, Chevallier L, Musekiwa C, Oliver J. Chevallier Evaluation of the geothermal energy potential for South Africa. *World Geotherm Congr* 2015:8.
- [7] Ryan A, Euler DS. Heat stress management in underground mines. *Int J Min Sci Technol* 2017;27(4):651–5.
- [8] Webber RCW, Franz RM, Marx WM, Schutte PC. A review of local and international heat stress indices, standards and limits with reference to ultra-deep mining. *South Afr Inst Min Metall* 2003;1:313–24.
- [9] McEwan MB. Mine refrigeration machinery and performance assessment. 1st ed. Johannesburg, South Africa: Mine Ventilation Society of South Africa; 2016.
- [10] Tomlinsqon PD. Achieving world class maintenance status. *Eng Min J* 2007;208:38–40.
- [11] Tomlinsqon PD. Maintenance information: value added? *Eng Min J* 2005;206:54–6.
- [12] Plant R, Air M, Systems C, McPherson MJ. *Subsurface Ventilation Engineering*. M J McPherson; 2015. p. 905.
- [13] Tomlinsqon P. Achieving world-class mining maintenance: Step 6-evaluate. *Coal Age* 2016;121:26–9.
- [14] Ahsan S, Shah A. Data, information, knowledge, wisdom: a doubly linked chain? *Int Conf Inf Knowl Eng* 2006:270–8.
- [15] Rowley J. The wisdom hierarchy: representations of the DIKW hierarchy. *J Inf Sci* 2007;33:163–80.
- [16] Conger S, Probst J. Knowledge management in ITSM: applying the DIKW model. *Intell Syst Ref Libr* 2014;55:1–18.
- [17] Kirsch P, Hine A, Maybury T. A model for the implementation of industry-wide knowledge sharing to improve risk management practice. *Saf Sci* 2015;80:66–76.
- [18] Tomita Y, Watanabe K, Shirasaka S, Maeno T. Applying design thinking in systems engineering process as an extended version of DIKW model. In: *INCOSE Int. Symp.*, vol. 27; 2017. p. 858–70.
- [19] Ardolino M, Rapaccini M, Sacconi N, Gaiardelli P, Crespi G, Ruggeri C. The role of digital technologies for the service transformation of industrial companies. *Int J Prod Res* 2017:1–17.
- [20] Almeanazel OTR. Total productive maintenance review and overall equipment. *Jordan J Mech Ind Eng* 2010;4:517–22.
- [21] Du Plessis GE, Liebenberg L, Mathews EH, Du Plessis JN. A versatile energy management system for large integrated cooling systems. *Energy Convers Manag* 2013;66:312–25.
- [22] Kirti M. Scada: supervisory control and data acquisition. *Int J Eng Comput Sci* 2014;3:3743–51.
- [23] Astolfi D, Scappaticci L, Terzi L. Fault diagnosis of wind turbine gearboxes through temperature and vibration data. *Int J Renew Energy Res* 2017;7.
- [24] Paraszczak J. Understanding and assessment of mining equipment effectiveness. *Min Technol* 2005;114:147–51.
- [25] Ugwu OO, Haupt TC. Key performance indicators and assessment methods for infrastructure sustainability – a South African construction industry perspective. *Build Environ* 2007;42:665–80.
- [26] Branisavljević N, Kapelan Z, Prodanović D. Improved real-time data anomaly detection using context classification. *J Hydroinform* 2011;13. 307 LP-323.
- [27] Mourad M, Bertrand-Krajewski J-L. A method for automatic validation of long time series of data in urban hydrology. *Water Sci Technol* 2002;45. 263 LP-270.
- [28] du Plessis JLL, Whillier A. *Elementary Thermodynamics*. Vent. Occup. Environ. Eng. Mines. 3rd ed., Pretoria, South Africa: Mine Ventilation Society of South Africa; 2014.
- [29] Kebede G. Knowledge management: an information science perspective. *Int J Inf Manage* 2010;30:416–24.
- [30] Karsten M, Mackay L. Underground environmental challenges in deep platinum mining and some suggested solutions. *South Afr Inst Min Metall* 2012:177–92.
- [31] Maré P, Kriel CJR, Marais JH. Energy efficiency improvements through the integration of underground mine water reticulation and cooling systems. In: 2016 Int Conf Ind Commer use energy; 2016. p. 112–7.
- [32] Brand HG, Kleingeld M, Maré P, Schutte AJ. The effect of surface Bulk Air Cooler water flow on deep-level mine temperatures. In: 2017 Int Conf Ind Commer use energy; 2017. p. 1–6.
- [33] Wallace K, Prosser B, Stinnette JD. The practice of mine ventilation engineering. *Int J Min Sci Technol* 2015;25(2):165–9.
- [34] Chen C. *Information visualisation and virtual environments*. Springer Science & Business Media; 2013.
- [35] Northey S, Haque N, Mudd G. Using sustainability reporting to assess the environmental footprint of copper mining. *J Clean Prod* 2013;40:118–28.