Implementing a remote condition monitoring system for South African gold mines

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Abstract

Title: Implementing a remote condition monitoring system for South African gold mines

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Keywords: Condition monitoring, Remote monitoring, Implementation process, Unattended condition monitoring system, Maintenance strategies, South African gold mines, Corrective maintenance, Preventative maintenance, Condition-based maintenance, Alarm limits, Automated alarm notifications, Remote data transmission, Fridge plants, Dewatering pumps, Ventilation fans, Compressors, Winder.

In a modern world, people and industries are increasingly using technology to automate and optimise systems and processes. This also applies to the field of condition monitoring on any level. Several recent academic studies focus on using advanced algorithms to do condition monitoring through feature extraction and to predict the remaining useful lifetime period of components accurately.

However, there is one industry in specific where condition monitoring is not being done at the same level as other industries, namely, the mining industry. Condition monitoring on South African gold mines is lacking in the sense that basic condition monitoring is not being done properly and consistently. The primary reason might be the absence of a detailed implementation process. Although there are specialised condition monitoring systems available on the market today, most are expensive and require constant supervision from specialised maintenance personnel.

There was thus a need to develop a generic process for implementing basic condition monitoring systems on South African gold mines. To make it more feasible to implement on mines, the process needed to be low cost, simple and reliable. There was also a need to prove the practical feasibility of the developed implementation process by applying it to several South African gold mines.

Therefore, the objective of this study was to develop a process for implementing a basic condition monitoring system on remote South African gold mines. This process would implement a condition monitoring system that required minimal additional costs and could be used on any size of mining operation. The secondary objective was to prove the usability of the developed implementation process by using it to initiate basic condition monitoring systems on various South African gold mines.

The developed implementation process was implemented on six different South African gold mines. The result was that the condition monitoring systems identified several critical machines with poor operating conditions. Maintenance personnel were notified of the urgent maintenance required on these machines before they failed critically.

The impact of the condition monitoring system was quantified by analysing the total number of monthly critical exceptions, which refers to the frequency at which monitored machine parameters exceed their defined limits. From the six gold mines where this process was applied, the results ranged from an 114% increase to a decrease of 83% in the total number of monthly critical exceptions generated for each mine. The implementation of this basic condition monitoring further resulted in an estimated R20 million cost saving by preventing machines from running into critical failure or incurring irreparable damage.

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Abbreviations

ANN	Artificial Neural Network
APM	Asset Performance Management
Assetguard CMB	Assetguard Circuit Breaker Monitoring
Assetguard GDM	Assetguard Gas Density Monitoring
Assetguard MVC	Assetguard Medium Voltage Switchgear Monitoring
Assetguard PDM	Assetguard Partial-discharge Monitoring
Assetguard TXM	Assetguard Online Transformer Monitoring
BAC	Bulk Air Cooler
CBM	Condition-Based Maintenance
CMS	Condition Monitoring System
COM	Component Object Model
CONMOW	Condition Monitoring for Offshore Wind Farms
DE	Drive End
DPIF	Design–Installation–Potential Failure–Failure
EDM	Engineering Data Management
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
GDP	Gross Domestic Product
GSM	Global System for Mobile (Communications)
ISCM	Integrated Substation Condition Monitoring
ISO	International Organization for Standardization
KPI	Key Performance Indicator
MCSA	Motor Current Signature Analysis
MSS	Mine Support System
MTB	Management Toolbox
NDE	Non-Drive End
OEM	Original Equipment Manufacturer
OPC	Open Platform Communications
PLC	Programmable Logic Controller
RBD	Reliability Block Diagram
RCAM	Reliability Centered Asset Management
RCM	Reliability-centred Maintenance
SCADA	Supervisory Control and Data Acquisition
SMS	Short Message Service
SOM	Self-Organising Map
Temp	Temperature
Vib	Vibration

Units of measure

Symbol	Unit	Description
A	Ampere	Current
°C	Celsius	Temperature
kV	Kilovolt	Voltage
ℓ	Litre	Volume
mm	Millimetre	Length
mm/s	Millimetre per second	Vibration
R	Rand	Currency
W	Watt	Power

CHAPTER 1

Introduction to Condition Monitoring in the Mining Industry

1.1 Background

The mining industry is one of South Africa's largest industries and primary economic contributors. The mining industry contributed 6.8% of the gross domestic product (GDP) in 2017 [1]. The South African government requires that employers provide and maintain a safe working environment for employees. It is also required that systems of work and machines are maintained in such a way that they are safe to employees and do not pose a risk to their health [2]. The conditions in underground working areas are harsh and need to be improved to make them safer for mineworkers. The underground conditions can only be improved by using various supporting systems.

In his thesis, Schutte referred to five individual support systems needed for production in gold mines. These support systems are compressed air, mine ventilation, refrigeration, mine dewatering, and winder systems. [3] Since these systems are of such high importance, it is imperative that they are always operational. The proper maintenance and reliability of machines driving these systems are thus a requirement for safe and continued mining operations.

1.1.1 Maintenance in the mining industry

The systems described by Schutte are primarily machine driven: the compressed air systems are driven by compressors, mine ventilation systems are driven by ventilation fans, mine refrigeration systems are driven by refrigeration (fridge) plants, mine dewatering systems are driven by water pumps, and winder systems are driven by winders.

Winder systems are critical for keeping deep-level mines running efficiently and profitable. Thus, winder systems can be considered as one of the most important systems in deep-level mines [4], [5]. The South African government legally requires mines to inspect winder systems daily [6]. As winder systems are already monitored closely, they will not be included in the condition monitoring implementation process.

The maintenance cost of machines in the mining industry can be as much as 20–50% of the total production or operational cost [7]. One of the world's biggest gold producers estimated that replacing a component only after it has failed can be as much as three to five times more expensive than replacing it before it fails. Early component failures are also one of the primary causes of unplanned maintenance costs and production losses [8].

The majority of South African gold mines do have preventative maintenance policies in place as part of their legal responsibilities. These policies are however mostly theoretical and are not always properly enforced by mine personnel. The implementation of such policies can also differ greatly between mines due to the different interpretations thereof.

1.1.2 Machine reliability

The period during which early failures occur is also known as the burn-in period. The reliability of components increases as they age and reaches a maximum during which failure rates are at a minimum. The failure rate stays at this low level for most of the component's life. This period is known as the useful life period. This period is followed by a period during which the component's failure rate increases significantly as it nears the end of its life, which is known as the wear-out period. These failure rates follow the form of a bathtub, which is illustrated in Figure 1 [9].

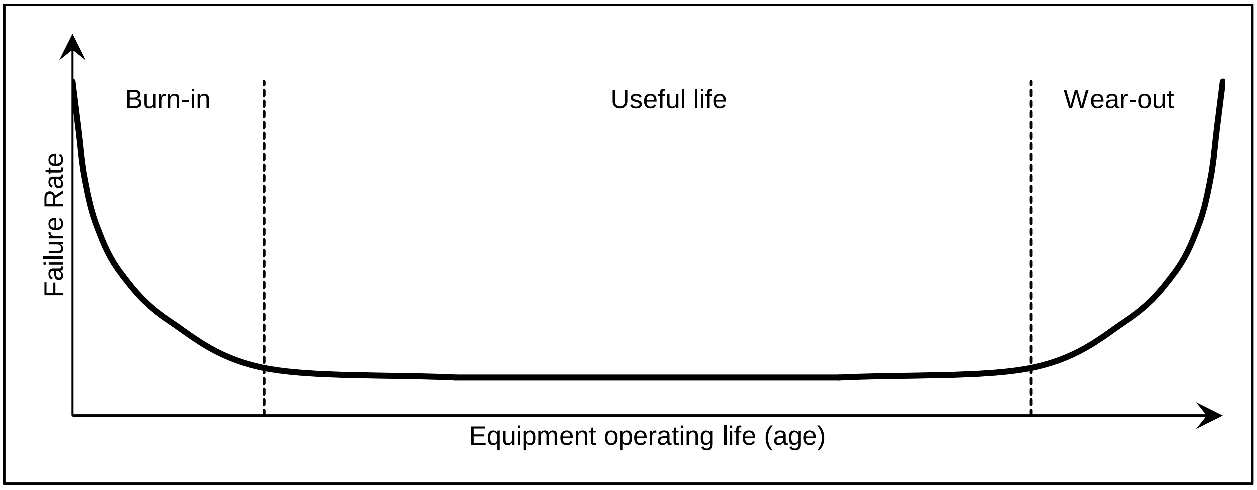


Figure 1: Bathtub curve (Adapted from [9], [10]**)**

Machine reliability can thus be defined as the probability that a machine will be able to perform a specific function without failing [11].

1.1.3 Reliability and criticality

A reliability block diagram (RBD) can be used to model the reliability of systems and analyse their performance [12], [13]. An RBD includes a graphical representation of the smallest entities or components of the system according to their logical relation of reliability [13]. RBDs can thus be used to identify focus areas for condition monitoring on machines and systems.

A criticality assessment can be used to identify potential risks and their impact on a system. The criticality assessment is done by plotting the probability of an event occurring against the size of its impact on the system [14]. The resulting risk matrix is used to prioritise machine components that should be monitored. The risk matrix is illustrated by Table 1.

Table 1: Example of a risk matrix (Adapted from [15])

Breakdown Description	Likelihood	Risk Rating			
Breakdown A	**4**	4	8	12	16
Breakdown B	**3**	3	6	9	12
Breakdown C	**2**	2	4	6	8
Breakdown D	**1**	1	2	3	4
Impact	**0**	**1**	**2**	**3**	**4**

1.1.4 Common maintenance strategies

The increased use of electronics and machinery to improve and automate processes has caused an increase in maintenance requirements. This increased mechanisation has helped to improve overall process efficiency, eliminate human error and decrease operating and manufacturing costs. The growth of technology and its use are increasing daily, which has also helped to automate and control processes in industries worldwide [15]. There are mainly two types of maintenance with respect to their occurrence, namely, preventative maintenance and corrective maintenance. Figure 2 shows the different types of maintenance.

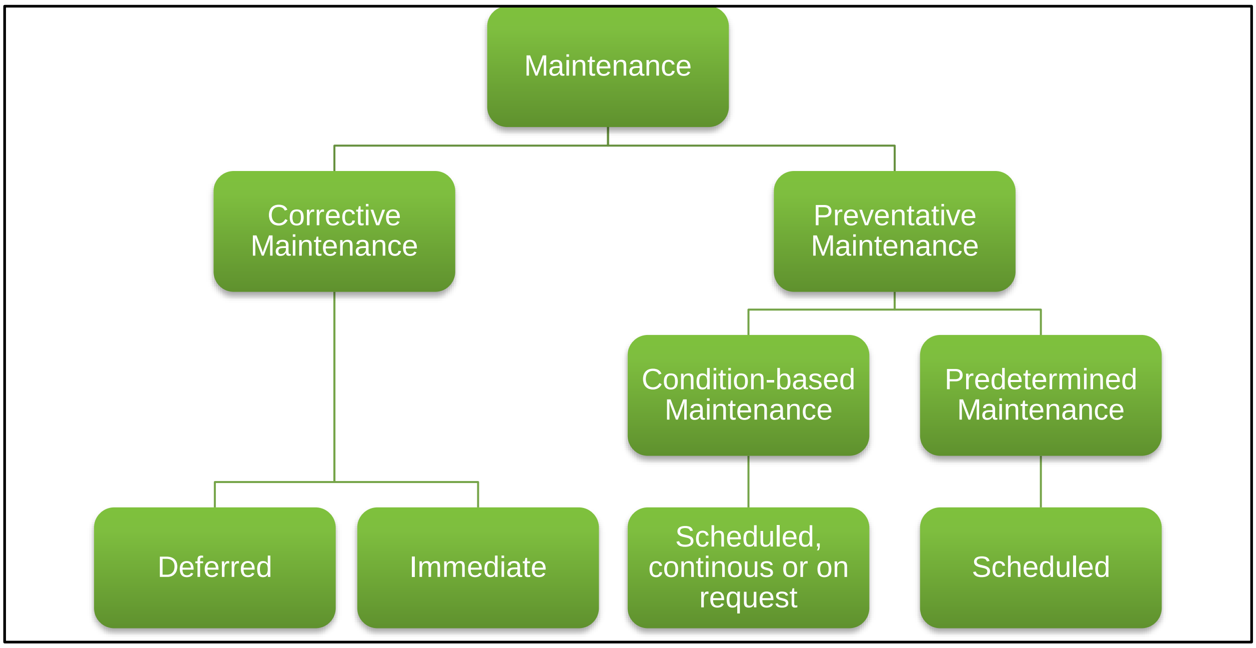


Figure 2: Types of maintenance (Adapted from [17])

Corrective maintenance is the unplanned repair or maintenance that is done on a machine only after it has failed in order to return it to a defined state. This type of maintenance cannot be planned or anticipated based on its occurrence. However, preventative maintenance is done at predetermined times and is used to keep machines in a good operating condition or to prevent them from failing unexpectedly [16]. These two types of maintenance are discussed in more detail in the subsections that follow.

a) Corrective maintenance

Corrective maintenance is urgent; it must either replace or be combined with any previously planned maintenance items. Corrective maintenance is done by maintenance personnel as soon as they become aware of a failure or deficiency [9]. This maintenance strategy can cause a significant amount of machine downtime or production losses, as well as expensive repair or replacement costs due to sudden failure [17]. In the case of the gold mining industry, the failure of some systems can bring production to a complete halt and even endanger the lives of mineworkers. This makes corrective maintenance strategies unadvisable on important support systems and machines in the South African gold mining industry. Corrective maintenance can be divided into five different categories as illustrated in Figure 3.

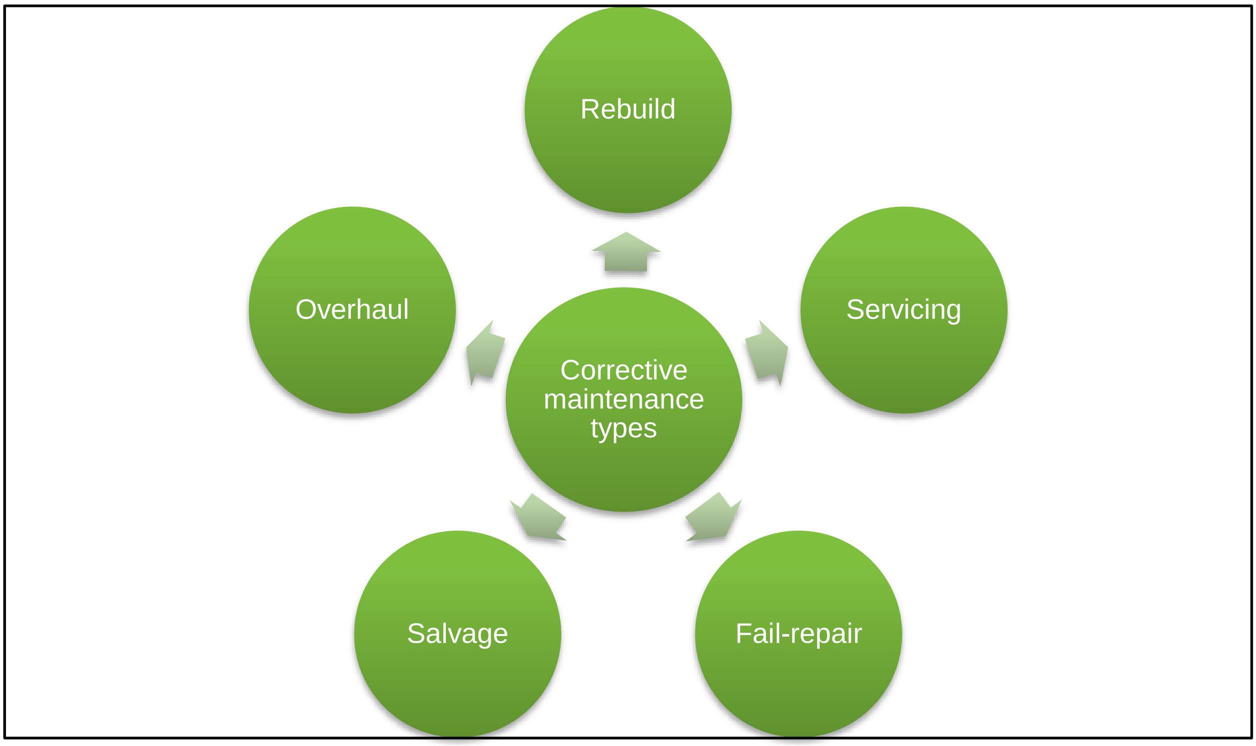


Figure 3: Types of corrective maintenance (Adapted from [9])

The different types of corrective maintenance can be described as [9]:

- **Rebuild:** Restoring a machine as close as possible to its original state in every aspect. This is achieved by completely disassembling the machine and repairing or replacing all parts to meet their original specifications before rebuilding and testing the machine.
- **Servicing:** Implementing corrective maintenance actions such as eliminating air from a fuel flow system after replacing a fuel filter.
- **Fail-repair:** Restoring an item or machine to its operational state.
- **Salvage:** Disposing of unusable material and using salvaged material from unrepairable items to repair machines.
- **Overhaul:** Returning a machine to an operational state by looking for and repairing any worn parts.

b) Preventative maintenance

Preventative maintenance can include fixing any impending failure before it occurs or develops into a major failure. This makes preventative maintenance a more suitable maintenance strategy for the South African gold mining industry. Preventative maintenance usually accounts for the larger part of a maintenance strategy. Upper management often does not support preventative maintenance because of unjustifiable costs or the long time it takes to get results. It is thus important to keep in mind that preventative maintenance is not worth doing if it is not going to reduce costs.

Preventative maintenance consists of seven elements needed to develop a good maintenance strategy. They are [9]:

- **Inspection:** Regularly checking the characteristics of a machine to determine its operational ability.
- **Servicing:** Preserving items by regularly cleaning and lubricating them to prevent failures from developing and occurring.
- **Calibration:** Comparing instruments to an instrument with a known and certified accuracy and adjusting any difference in the accuracy of the parameter being measured to establish a standard measurement.
- **Testing:** Determining the operational ability of a machine or item on a regular basis to detect any degradation thereof.
- **Alignment:** Changing a specified variable element of an item to optimise its performance.

- **Adjustment:** Periodically changing a specified variable element of a material to optimise its performance.
- **Installation:** Replacing parts that has a set lifetime or that are starting to get worn out to maintain a specified tolerance.

There are some indicators that can help identify an ineffective preventative maintenance strategy. Machines are not used regularly because of breakdowns and an increased repair cost due to poor servicing and installation. This can also decrease the expected lifetime of important machines significantly.

Preventative maintenance can be divided further into two categories, namely, precision maintenance and condition-based maintenance (CBM). Precision maintenance is done according to a schedule, which is generated at regular intervals without considering the machine condition. This schedule usually depends on conditions such as component age and prescribed dates, which are provided by the original equipment manufacturer (OEM). CBM is almost the opposite of precision maintenance since the condition of a machine is the deciding factor when scheduling preventative maintenance [16]. Since the degradation rate of machine condition is different for each machine, it makes more sense to focus on a CBM strategy than a predetermined maintenance strategy.

i) Precision maintenance

Precision maintenance can be considered as the most accurate type of maintenance as it maintains plants and equipment at the finest specifications. The main objective of precision maintenance is to minimise problems on machines during operation by rebuilding machines to the highest standard. It also focuses on keeping maintenance activities accurate and efficient. Precision maintenance can be considered profitable if done correctly due to minimal machine failures and lower operating costs [18].

ii) Condition-based maintenance

CBM is used to make maintenance decisions based on the current or future condition of assets. This means that maintenance activities are determined by a change in a machine’s performance or condition. The primary objective of CBM is to keep repair and inspection costs to a minimum through intermittent or continuous monitoring of the operating conditions of critical components. CBM can also provide adequate notice of impending failures, which results in lower maintenance cost than corrective or time-based maintenance [19].

The relationship between precision, predictive, preventative and corrective maintenance is illustrated by Figure 4.

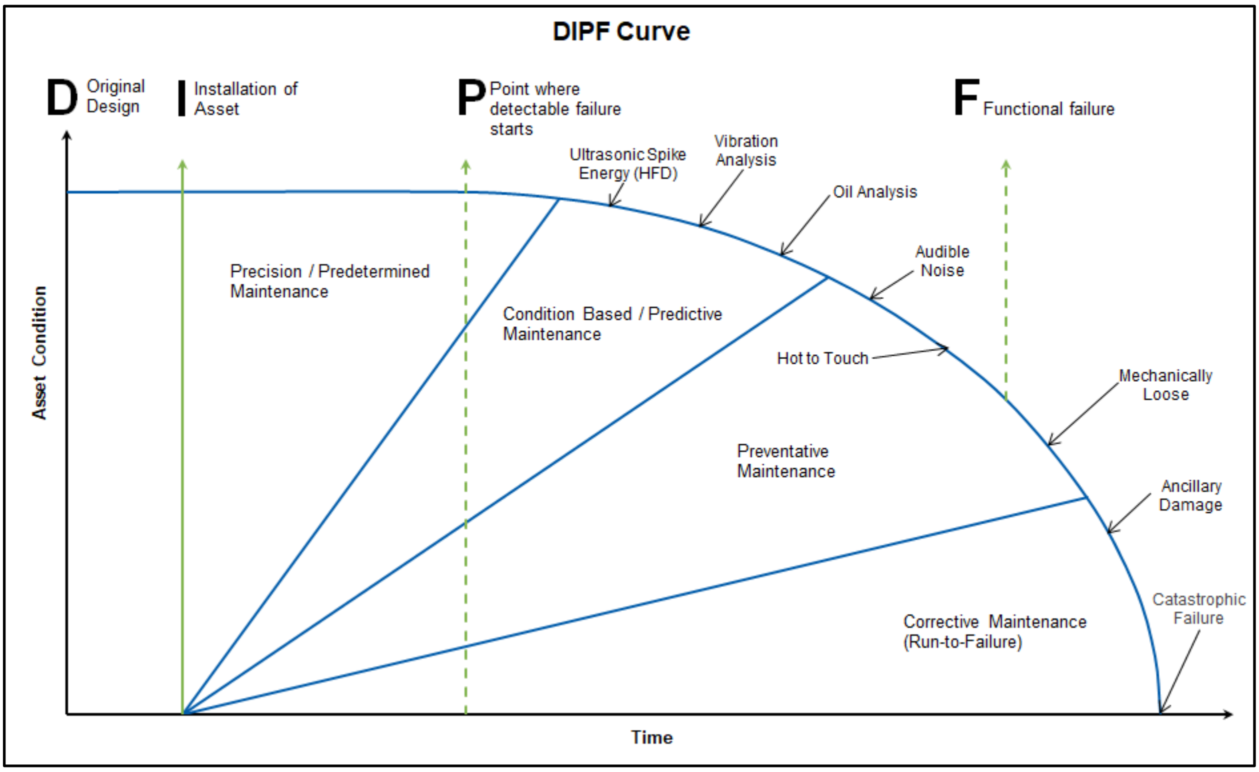


Figure 4: Design–installation–potential failure–failure (DIPF) curve (Adapted from [20]**)**

iii) Reliability-centred maintenance

In the case of large systems, the required preventative maintenance strategy would be too extensive to allow profitable operation. This has led to the development of a new maintenance strategy called reliability-centred maintenance (RCM). It was originally developed in the aircraft industry, but has since spread to various other industries [21]. Due to the difference in business models, the failure rate of implementing an RCM strategy is 90%. This is largely due to companies trying to implement an RCM strategy before they are ready [22].

RCM is a maintenance programme used to identify the requirements for a physical facility to keep operating according to its design. It focuses preventative maintenance on failure modes that are experienced frequently. RCM can be beneficial to any organisation where breakdowns make up 20% to 25% of all maintenance. RCM can lead to a maintenance strategy that focuses on preventative maintenance of specific failure modes and the probability of their occurrence [9].

1.1.5 Measurement methods

There are numerous different condition monitoring techniques available; each with their own area of optimal application. Some of these monitoring techniques are temperature monitoring (thermal monitoring), vibration monitoring, acoustic emission monitoring, motor current signature analysis (MCSA) and artificial neural networks (ANNs) [23]. These monitoring techniques will be discussed briefly in the following subsections.

a) Temperature monitoring

Temperature monitoring can be used to monitor the condition of induction motors and bearings [24]. Temperature monitoring can be done on electric machines using local temperature measurements. Shorted turns in the stator windings of an induction motor cause excessive temperature increases, which can be identified using temperature monitoring [23]. The temperature rises of bearings due to degrading grease or bearing condition can also be detected using temperature monitoring.

Temperature monitoring is considered as the traditional method for monitoring the condition of bearings [25]. Temperature sensors are generally used for temperature monitoring [26]. Since all mine support system (MSS) machines are rotational machines and are induction motor driven, temperature monitoring can be used as the primary type of condition monitoring.

b) Vibration monitoring

Vibration monitoring is used to detect mechanical faults such as bearing failures and mechanical imbalance. It is also considered one of the oldest and most popular condition monitoring techniques. Vibrations are measured by a piezo-electric transducer that gives a voltage output proportional to its acceleration [26], [27].

In the case of induction motors, vibrations are primarily caused by unbalanced supply voltage, uneven air gap, single-phasing and interturn winding faults. Improving vibration monitoring requires advanced signal processing techniques such as nonstationary recursive filters and wavelets [23], [27], [28]. This requires some degree of expertise as the user must be able to differentiate between normal operating conditions and potential failure modes. However, a failure monitoring system requires a consistent way of predicting possible failures from measurements [29]. Instead of monitoring the entire vibration spectra, only maximum displacement can be monitored and still provide a consistent measurement.

c) Acoustic emission monitoring

An acoustic emission is the rapid release of strain energy in the form of transient elastic waves. This strain energy is generated because of damage or deformation within the surface of a material. In rotating machines, acoustic emission can be caused by factors such as cyclic fatigue, friction, cavitation, impacting and material loss. The biggest disadvantage of acoustic emission monitoring is the attenuation of the signal, which can be minimised by moving the sensor closer to the source of emissions. Acoustic emission monitoring is used to monitor the condition of, for example, bearings, gearboxes, pumps and engines [30]. Acoustic emission monitoring can be less effective than vibration monitoring in high noise environments due to higher signal-to-noise ratios. Acoustic emission monitoring can have high system costs and require specialist expertise [25].

d) Motor current signature analysis

The analysis of variations in the electric current to an induction motor can be used to create trends over time to provide an indication of the condition of deterioration of the motor. This is known as motor current signature analysis (MCSA) [31]. MCSA is defined as a non-invasive online monitoring technique to diagnose problems in induction motors. Current MCSA systems consist of a combination of a front-end signal conditioner, spectrum analyser and computer. MCSA is mainly used to diagnose winding faults, shorted turns and air-gap eccentricities [32]. The focus is the behaviour of the motor current at the sideband associated with a fault. This requires a profound or detailed knowledge of the machine's construction [23].

e) Artificial neural networks

ANNs are designed to imitate the function of the biological neuron. ANNs are well known for their ability to identify and classify real data. ANNs can also be used to investigate bearing and gear failures by analysing vibration signals [33]. A processing algorithm is used to specify how calculations are done by neurons for input vectors and a specified set of weights. An ANN can adjust the weights being trained for the specific application so that the desired outputs are obtained from a specific set of inputs [34]. One of the primary disadvantages of ANNs is their black box nature. The relationship between model inputs and outputs is not developed by engineering judgement, which makes the model a black box [35]. An example of parameters that can be monitored for a range of machines is shown in Table 2.

Table 2: Examples of typical condition monitoring machine parameters (Adapted from [36])

Parameter	Machine Type				
	Electric Motor	Steam Turbine	Pump	Compressor	Fan
Temperature	✓	✓	✓	✓	✓
Pressure		✓	✓	✓	✓
Airflow				✓	✓
Fluid flow		✓	✓	✓	
Current	✓				
Vibration	✓	✓	✓	✓	✓
Speed	✓	✓	✓	✓	✓
Efficiency (derived)		✓	✓	✓	

The parameters that can be monitored for the different machines illustrated in Table 2 show that two of the most generic parameters for condition monitoring are temperature and vibration. A more comprehensive list of parameters for condition monitoring purposes can be found in Annexure A. Since temperature and vibration parameters are commonly monitored on machines as a legal requirement in the mining industry, they can be used to implement a condition monitoring system (CMS) with minimal additional cost for instrumentation [2].

1.1.6 Measurement positions

Commonly, two bearing positions are referred to when discussing rotating machines: these positions are called the drive end (DE) and non-drive end (NDE) positions, which refer to a location on a rotating shaft [37]. The DE position always refers to the position on the rotating shaft that is closest to the connection between the driving machine and the driven machine. Figure 5 illustrates these common bearing positions for an induction motor driving a multistage centrifugal air compressor.

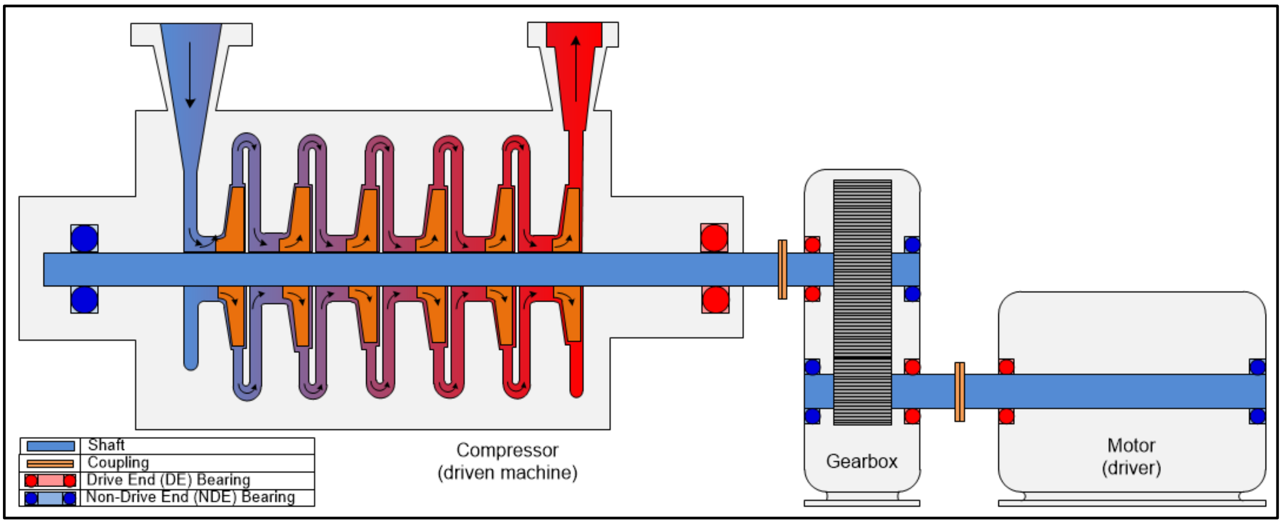


Figure 5: Common bearing positions

Temperature and vibration sensors are usually located next to the DE and NDE bearings. An example of a temperature sensor typically used in the mining industry to monitor bearing temperatures is shown in Figure 6.

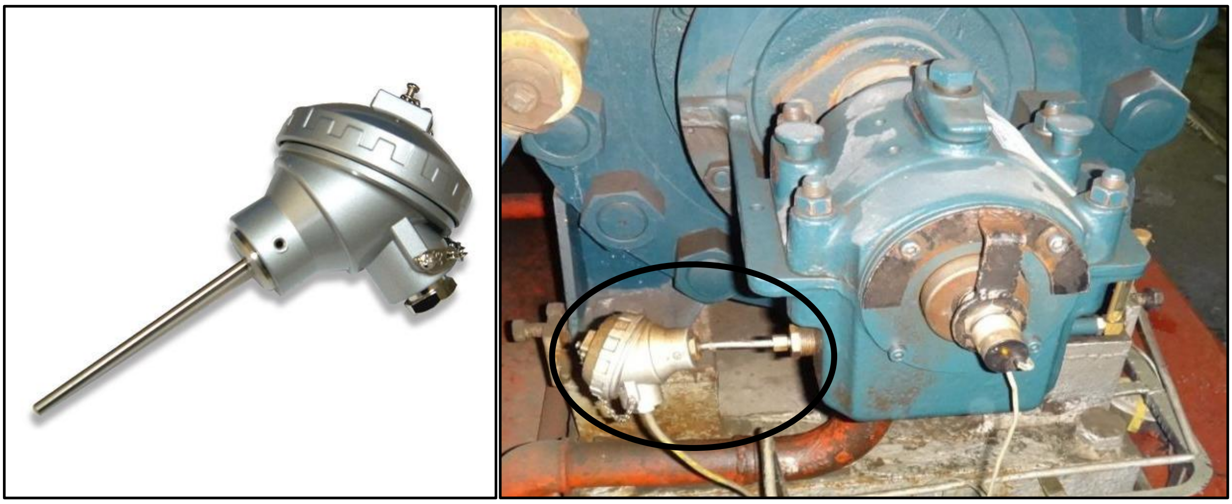


Figure 6: Temperature sensor [38], [39]

The picture on the left side of Figure 6 shows the temperature sensor itself, while the picture on the right shows an installed temperature sensor on the NDE bearing of a multistage centrifugal dewatering pump. In a similar way, accelerometers are used to monitor bearing vibration levels. An example of an accelerometer is shown in Figure 7.

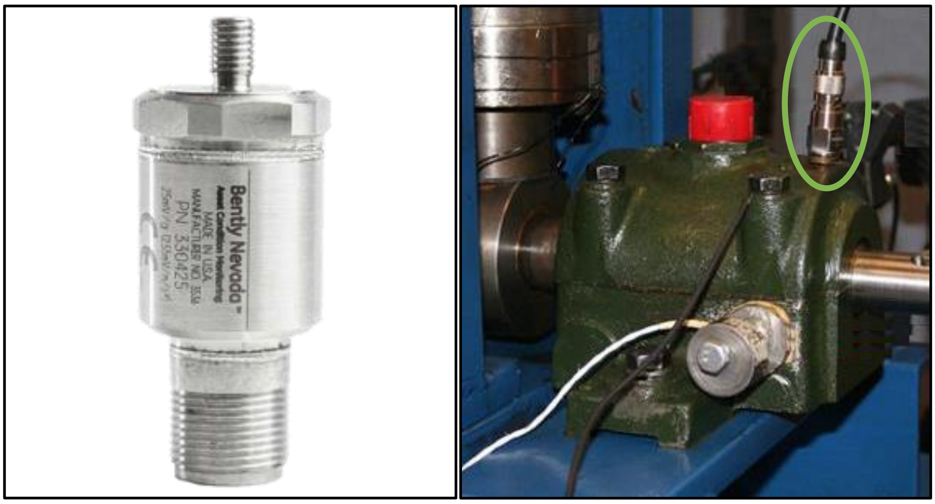


Figure 7: Accelerometer example [40], [41]

Looking at Figure 7, the image on the left is an example of an accelerometer used typically to monitor bearing vibrations. The image to the right shows an installed accelerometer on a bearing housing. The process of obtaining condition monitoring parameters is discussed in the next section.

1.1.7 Data communications

a) Software control and data acquisition systems

Machines in the mining industry are monitored by sensors that transmit parameter values to the centralised software control and data acquisition (SCADA) computer of each mine. A control system, such as a SCADA system, can be defined as one or more devices that are used to manage and control the function of other devices. SCADA systems are responsible for collecting and transferring information to a central location. They are also used to analyse and control some processes while displaying the relevant information to an operator. A typical SCADA system consists of three basic components, which are a master station, remote assets such as programmable logic controllers (PLCs) and a communication medium [42].

b) Open platform communications connections

Open platform communications (OPC) is a set of standards that allows for the reliable and secure data communication of devices from different vendors [43]. OPC has become the worldwide industry standard for facilitating the interoperability of information between PLCs, asset management systems, control systems, CMSs and production management systems.

The original OPC data access standard can bridge the gap between floor measurement, control and CMSs. The OPC data access standard thus specifies a required set of component object model (COM) objects, methods and properties to address the interoperability of plant automation, process control and condition monitoring applications. This means that any product with a built-in OPC server provides a standard interface to the OPC data access COM objects, thus allowing data exchange with any OPC client application. Therefore, computerised maintenance management systems and e-diagnostic applications can use OPC to monitor both real-time and historical data [44]. Some of the supported OPC interface functions include alarms and events, historical and process data access [45].

Online condition monitoring can be integrated into SCADA systems to automate alarms and notify personnel of problems. This can also provide personnel with long-term trends and short-term events while the machines are operational [46].

1.1.8 Data specific requirements

There are some requirements for important functions to facilitate CBM. They can be summarised as follows [47]:

- Data collection,
- Signal processing,
- Alarm or notification generation,
- State detection or health assessment,
- Prognostic assessment,
- Decision aiding,
- Data flow management,
- Historical data storage,
- System configuration management, and
- A system interface.

1.2 Previous research on condition monitoring

During the literature survey, it was found that there is a significant amount of remote condition monitoring being done in the field of wind turbines. This might be attributed to a growing interest in renewable energy, the development of wind farms and high maintenance costs of wind mills. Unfortunately, very little literature was found with regard to remote condition monitoring or even the process of implementing remote condition monitoring systems on South African gold mines.

It was therefore decided to consider literature with similar objectives or elements from various industries for this thesis. The criteria used to identify literature for inclusion in this article are as follows:

- CMS operational cost impact,
- SCADA systems in condition monitoring applications,
- CMS personnel requirements,
- Condition monitoring applications in South African mining industry,
- Centralised monitoring of remote operations,
- Maintenance research in practical applications,
- Low implementation costs,
- Scalable to any size mining operation and
- Use standardised process.

To gain a better understanding of shortcomings in condition monitoring research, literature must be reviewed to establish what has been done and which problems have been identified by other authors. A few studies in the field of condition monitoring and maintenance are discussed briefly in the following subsections. The discussion includes a short description of the study, its primary objectives, the outcomes of each study, and some important notes. The last subsection emphasises problems identified by the author and includes important statements or other findings important to this thesis.

1.2.1 Ahmad and Kamaruddin, 2012 [48]

a) Study description

Ahmad and Kamaruddin conducted a study on two maintenance techniques, namely, CBM and time-based maintenance. The authors reviewed academic articles covering the application of these techniques.

b) Study objectives

The objectives of this article were to evaluate the way these maintenance techniques work in terms of decision-making and to compare the challenges for their practical implementation. The analysis of CBM data was also more helpful than time-based maintenance for evaluating equipment conditions through deterioration modelling. The decision process for CBM was found to be simpler than the process for time-based maintenance.

c) Study outcomes/results

This study found that the application of CBM is more realistic than the application of time-based maintenance from a concept/principle point of view. The conclusion was based on the fact that specific signs or indicators preceded most equipment failures.

d) Important notes

In this study, Ahmad and Kamaruddin mention that preventative maintenance can be approached either from recommendations drawn from experience, or from OEM recommendations. The main drawback of using experience recommendations from maintenance personnel is that they may not always be available to solve maintenance problems.

On the other hand, using OEM recommendations (scheduled maintenance) for preventative maintenance can lead to increased operational costs since machines work in different environments and would thus need specific preventative maintenance schedules. Machine designers might not experience machine failures and would thus lack knowledge in their prevention. Furthermore, OEMs could even have hidden agendas such as using preventative maintenance schedules to maximise part replacements.

1.2.2 Bengtsson, 2004 [49]

a) Study description

In his thesis, Bengtsson set out to find standards and standardisation proposals within CBM to see how they might affect future research.

b) Study objectives

Bengtsson reviewed the requirements for designing a comprehensive CBM system by considering different techniques, methods and the role of people within such a system. Bengtsson also studied the aspects that need to be considered by a company when implementing a CBM system.

c) Study outcomes/results

Bengtsson found that there are various existing standards and proposals for CBM systems that can be used. In his thesis, Bengtsson discussed seven modules for designing a comprehensive CBM system technically, namely, sensors, signal processing, condition monitoring, diagnosis, prognosis, decision support and presentation. He further found that some of the important aspects that need to be considered when implementing CBM are the support from management personnel, employee training, increased interdepartmental cooperation and pilot projects.

d) Important notes

Bengtsson noted that a maintenance strategy focusing on preventative maintenance and its planning, instead of corrective maintenance, could result in lower maintenance costs. The author also discussed some benefits of standardisation processes, which include facilitating flexibility through modularisation, enabling communication and facilitating technology collaboration.

1.2.3 Fouché, 2015 [22]

a) Study description

Fouché conducted a study on a hot strip mill to determine the feasibility of implementing an RCM process on an industrial level.

b) Study objectives

The first objective of this study was to gain a comprehensive understanding of the RCM process and its elements. The second objective was to determine why many RCM process implementations are unsuccessful. The third objective was to investigate the methods used in successful RCM implementations to ensure successful future implementations. The fourth and final objective was to determine the possibility of implementing RCM principles successfully on an old plant such as a hot strip mill.

c) Study outcomes/results

The RCM process is based on sound engineering practices. RCM enables users to manage the maintenance requirements of individual assets effectively, but RCM might be too resource intensive for industries such as steel, cement and mining. The study also recommended that a maintenance improvement programme should be implemented systematically.

d) Important notes

Fouché found that RCM covers almost all types of maintenance. However, the implementation of an RCM strategy has a 90% failure rate. The reason might be the considerable number of resources being wasted on conducting lengthy and intense criticality assessments.

1.2.4 Fraser, Hvolby and Tseng 2015 [50]

a) Study description

Fraser et al. highlighted the changing perspective of maintenance management from considering it as a “necessary evil” to considering it an important strategy for competitive organisations worldwide. This study offers two comprehensive literature reviews: firstly, to identify and categorise different maintenance management models and, secondly, to investigate the level of empirical evidence of common models in terms of real-world applications.

b) Study objectives

The objective of this study was to investigate the different maintenance management methods being used in real-world applications while exploring the gap between practical applications and academic research.

c) Study outcomes/results

Fraser et al. analysed almost 500 articles from journals that are “dedicated to maintenance” which resulted in an average empirical evidence rate of 8%. Thus, most articles have no links to practical examples or real-world applications.

d) Important notes

There were some other important statements in this study that should be noted. Maintenance costs can be very high and make up as much as 15% to 40% of an organisation’s production costs [51], [52]. This supports the statement that maintenance spending can make up the second-largest part of an operational budget [53]. Fraser et al. state that maintenance literature focus more on developing new computational methods with no verified practical value [54]. There were some interesting quotes from literature such as:

- “It is astonishing how little attention is paid either to make results worthwhile or understandable to practitioners, or to justify models on real problems.” [53]
- “There is more isolation between practitioners of maintenance and the researchers than in any other professional activity.” [55]

1.2.5 Hameed, Ahn and Cho, 2010 [56]

a) Study description

Hameed et al. investigated the role of a CMS on maximising potential energy production by wind turbines through reducing their downtime for maintenance.

b) Study objectives

The primary objective of this study was to determine the viability of CMSs on wind turbines. This was done by evaluating important parameters in the design, architecture and installation of CMSs.

c) Study outcomes/results

The study concludes that the implementation of a CMS as a whole and viable system requires a great deal of effort. Another study of CMS hardware and software indicates that the required architecture is quite complex, and that a thorough understanding of wind turbine operations is required. Hameed et al. state that the installation of a CMS is equally important as the design, and that successful implementation relies on reliable and robust testing procedures.

d) Important notes

The study points out that a CMS can be evaluated by monitoring the efficiency at which a signal/alarm regarding a potential failure is conveyed. Hameed et al. further state that online condition monitoring can help identify problems that might not be noticeable with spot checks. The study notes that the cost of installing a CMS must be justified by the usefulness of the information. Hameed et al. state that different CMSs have their own respective user interfaces and alarm systems, which require more experience to operate.

1.2.6 Pan, Li and Cheng, 2008 [57]

a) Study description

Pan et al. investigated making remote condition monitoring possible by using a system that is built on the architecture of internet transmission communication and software-developing environment. Pan et al. mention that the complexity of faulty features embedded in recorded data is not considered for various case-based CMSs.

b) Study objectives

The primary objective of this study was to create a remote CMS based on the architectures of Borland C++ Builder and internet transmission communication.

c) Study outcomes/results

Pan et al. propose that raw data be sent to a central processing server that analyses the condition monitoring data through data processing techniques such as signal processing, feature extraction and ANNs. This remote server is thus also responsible for sending operational commands and making decisions by processing the raw data received. Pan et al. conclude that such a setup can be used to monitor machines at different physical locations by using in-house coded analysis modules.

d) Important notes

Unfortunately, a setup such as this depends on a reliable internet connection between the processing server and remote computers for recording data, evaluating machine conditions and executing operating commands. A connection failure will thus disable the CMS since decision-making and control are being done remotely. This system also uses a high data resolution and transmits high data volumes to be processed, which can increase exponentially with additional remote machines. This can significantly increase operating costs in terms of data transmission and the required processing power.

1.2.7 Van Jaarsveld, 2017 [58]

a) Study description

South African deep-level mines rely on several important systems to keep operations sustainable and safe. It is not feasible to inspect these systems manually on a regular basis due to the size of these operations. An automated tool is thus required to analyse the large volumes of data and generate risk notifications. Due to the high operational costs of South African deep-level mines, this tool needs to be able to utilise the existing infrastructure as far as possible.

b) Study objectives

The primary objective of this study was to develop a maintenance tool with the following capabilities:

- Automatically collect, structure and analyse machine and process data,

- Automatically find operational risks from collected data,
- Automatically create notifications and evaluations (reports) for identified operational risks,
- Promote transparency of maintenance operations,
- Integrate CBM into current maintenance strategies, and
- Improve the safety of mining activities through increased awareness.

c) Study outcomes/results

Van Jaarsveld reviewed various South African mines to develop this system. Data from various systems on these mines was logged and sent for processing by dedicated servers. An innovative methodology was developed to calculate the risk scores for individual machines. Parameters with high risk scores were used to generate automated reports that were sent to mine personnel daily. These daily analysis results were made available to mine personnel via an online platform. The solutions developed in this study were incorporated into the mining group's maintenance strategy.

d) Important notes

Van Jaarsveld found that although there is a big focus on the energy consumption of mining equipment, their operating conditions are not evaluated properly. This would result in a lack of adequate maintenance and machines being run to failure. It is important to note that this study only developed a tool for processing condition monitoring data and did not consider the steps required to implement such a system on remote gold mines.

1.2.8 Wilkinson et al., 2014 [59]

a) Study description

The reliability of wind turbines is particularly important for owners, operators and manufacturers, which can justify the need for condition monitoring.

b) Study objectives

This study was conducted on SCADA data to investigate the reliability of various SCADA-based condition monitoring methods on wind farms. The SCADA-based monitoring methods investigated in this study were signal trending, self-organising maps (SOM) and physical model.

c) Study outcomes/results

The signal trending method, which was used to create trends to compare measurements from different periods or turbines with each other, could be readily applied to many data sets due to its simplicity. This method was not sufficiently accurate in comparison and could not account for changes in operating conditions such as external temperature or operational modes of turbines.

The SOM method proved to be more sensitive to faults, which could help in investigating wind turbine health. This method as well as other ANNs can unfortunately not identify the nature of a fault, thus making it difficult to find impending failures.

The last method, which was the physical model, provided the most accurate results although it was the most complicated regarding setup and training. This method was validated by conducting blind tests on 472 turbine-years of data from turbines ranging from 2.5 to 7 operational years. This method was able to detect 67% of major component failures. It had a failure prediction period of between one and 24 months.

d) Important notes

This study proved that SCADA-based condition monitoring can be used to improve reliability and reduce the downtime of wind turbines, thus decreasing operational costs. There are also some advantages of using SCADA data for condition monitoring, such as the data being readily available, and that no additional instrumentation being required. The biggest shortfall of this study, however, is that it was done on historical SCADA data, which means that machine conditions could only be evaluated after critical failures have occurred and have even been corrected.

1.2.9 Wiggelinkhuizen et al., 2007 [60]

a) Study description

A small wind farm consisting of five turbines was instrumented with different condition monitoring and measurement systems.

b) Study objectives

The objective of this study was to determine if a basic and cost-effective CMS could be implemented practically on the Condition Monitoring for Offshore Wind Farms (CONMOW) project. The analysis of data obtained from the implemented monitoring systems would be used to develop algorithms that could be integrated into SCADA systems. This would reduce the cost of CMSs and provide more accurate information.

c) Study outcomes/results

The important outcomes from this paper can be summarised as follows: The failure mode and effect analysis (FMEA) proved to be an effective way of identifying the correct CMS for specific component failures. The developed processing methods and algorithms were able to process 10-minute averaged SCADA data effectively. The different measurement types used in the study produced large amounts of data, which were difficult for operators to interpret and thus required a dedicated expert.

d) Important notes

An FMEA was used to identify possible failures, the likelihood of their occurrence as well as their consequences. The measurement systems that were used produced data at frequencies ranging between 4 Hz and 32 Hz depending on the system. The measurement data and its analysis could be accessed via the internet. Two of the CMSs used displacement sensors at low speed sections due to their superiority over vibration sensors at slow rotational speeds.

1.2.10 Summary

From the preceding sections, we have found some interesting facts about condition monitoring research and applications, which are summarised in the following sections.

Maintenance strategy overview

- The operating conditions of machines are not monitored properly in the mining industry [58].
- Maintenance costs can make up as much as 40% of an organisation’s production budget [50].
- Properly planned preventative maintenance can reduce corrective maintenance and result in lower maintenance costs [49].
- The application of CBM is more practical than time-based maintenance [48].
- Scheduled maintenance can lead to increased maintenance and thus increased operational costs [48].
- Although there is a significant amount of research on maintenance; in most cases, it is not linked to real-world applications [50].

Reliability-centred maintenance

- Most RCM implementation attempts fail due to resources being wasted on intense criticality assessments [22].
- RCM can be very resource intensive – especially in industries such as mining [22].

Implementing condition monitoring

- Maintenance improvement programmes should be implemented systematically [22].
- The benefits of standardisation include flexibility, enabling communication and facilitating technology collaboration [49].
- Condition monitoring requires a thorough understanding of how monitored machines work [56].
- CMSs can produce large amounts of data, which require dedicated and experienced personnel to interpret [59], [61].
- The implementation of an entire CMS requires a great deal of effort [56].
- The required architecture for a CMS is quite complex [56].
- There are seven modules required for a comprehensive CBM system, namely, sensors, signal processing, condition monitoring, diagnosis, prognosis, decision support and presentation [49].
- A combination of internet transmission communication and a software development environment can be used to monitor machines at different physical locations [57], [62].
- Condition monitoring can be done using SCADA data to improve reliability and reduce operational costs [59], [62].
- SCADA-based condition monitoring can have advantages such as readily available data and minimal additional instrumentation costs [59].
- A CMS can be evaluated by the efficiency at which an alarm/notification regarding a potential failure is conveyed [56], [61].

Other

- Vibrations can be monitored by displacement sensors in machines with low rotational speeds [59].

The articles that were discussed can be categorised broadly according to their objectives and/or methodology. The first is the impact that CMSs can have on the operational cost of an organisation. This can be described more specifically as the impact of CMSs on maintenance costs, which form part of an organisation's operational costs.

Another category is using SCADA systems or SCADA data for condition monitoring applications. Since SCADA systems are used in all industries, these systems already have direct access to the required condition monitoring data – either in real-time or as historical data. Therefore, minimal capital expenditure would be required to implement a CMS.

The fourth category for the studies, is used to identify those that did research or made contributions to the maintenance or condition monitoring field with specific reference to the South African mining industry. Another category that can be used for these studies is for those that looked at CMSs that made specific reference to the remote monitoring of machines and systems, or at least the ability to access condition monitoring data remotely.

The last category is articles that researched maintenance strategies or CMS in practical scenarios or with the specific objective of applying the study outcomes practically. The focus areas of the studies that were discussed are summarised in Table 3. This table also outlines the need for a process to implement low cost CMSs in the South African mining industry.

Table 3: Studies relating to remote CMSs

Author	CMS operational cost impact	SCADA systems in condition monitoring applications	CMS personnel requirements	Condition monitoring applications in South African mining industry	Data gathering and notification methods	Centralised monitoring of remote operations	Maintenance research in practical applications	Need		
								Low implementation costs	Scalable to any size mining operation	Use standardised process
Ahmed and Kamaruddin [48]										
Bengtsson [49]										
Fouché [22]										
Fraser et al. [50]										
Hameed et al. [56]										
Pan et al. [57]										
Van Jaarsveld [58]										
Wilkinson et al. [59]										
Wiggelinkhuizen et al. [60]										

1.3 Condition monitoring standards

There are a great variety of standardisation documents, each with a specific objective. These documents are generated by organizations and companies that specialise in documenting guidelines to help people in different industries use widely accepted methods. One such organization is the International Organization for Standardization, which was established in 1947 and has published over 22 542 international standards in various technology and manufacturing aspects. [63]

They have published several condition monitoring standards, but only the ISO 17359 document focus on the process for implementing a CMS. These standards are also regularly updated with the latest revision being released in 2018. This section discusses the implementation of a condition monitoring programme as specified by the ISO 17359 standard (condition monitoring and diagnostics of machines). This is an international standard designed to provide guidance when setting up a condition monitoring programme for all machines. ISO 17359 provides an overview of the recommended generic procedure that is used to implement a condition monitoring programme [36].

The ISO 17359 standard provides more information on the important steps that should be followed when implementing the programme. The standard recommends that condition monitoring activities are directed at finding and preventing root cause failure modes. An overview of the generic procedure for implementing a CMS is shown in Figure 8 [36].

Cost benefit analysis

- Life cycle cost
- Cost of production
- Consequential damage
- Warranty and insurance

Equipment audit

- Identify equipment
- Identify equipment function

Reliability and criticality audit

- Produce reliability block diagram
- Establish equipment criticality
- Identify failure modes, effects and criticality [FMEA and failure mode effect and criticality analysis (FMECA)]

Select appropriat maintenance tasks

- Measurable?

Select measurement method

- Identify parameters to be measured
- Select measurement technique
- Select measurement location
- Set or review alert/alarm criteria

Data collection and analysis

- Take measurements and trend readings
- Compare with alert/alarm criteria
- Outside alert/alarm criteria
- Perform diagnosis and prognosis
- Confidence in desicion?

Determine maintenance action, carry it out, feed back to history

- Detimine required maintenance action
- Carry out maintenance action
- Feed back results to history record

Review

- Review

Figure 8: Steps for implementing a condition monitoring programme (Adapted from [36]**)**

The different steps in the implementation process are discussed in more detail in the following subsections.

1.3.1 Cost benefit analysis

It is important to start the implementation process by determining key performance indicators (KPIs) and benchmarks to evaluate the efficiency of any condition monitoring programme. This can be done through an initial feasibility and cost benefit analysis. Some of the items that should be considered are life cycle costs, cost of lost production, consequential damage, warranty and insurance [36].

1.3.2 Equipment audit

An equipment audit is the next step in the implementation process and consists of two actions, namely, Identify Equipment and Identify Equipment Function. The goals are to identify and list all the equipment that should be included in the condition monitoring programme. Some examples of components typically considered for monitoring by a CMS are illustrated in Annexure B. During these actions, the function of the equipment as well as their operating conditions should be determined [36].

1.3.3 Reliability and criticality audit

A reliability and criticality audit follows the equipment audit. A high-level RBD can be useful to determine whether equipment has a parallel or serial reliability effect. ISO 17359 also recommends using reliability and availability factors areas for condition monitoring processes [36].

Another recommendation made by ISO 17359 is using a criticality assessment. This can help to prioritise machines that must be included in the condition monitoring programme. The criticality can be a rating that is calculated from factors such as life cycle costs, cost of production loss, cost of machine replacement, cost of machine components and failure rates. These factors can be included and weighted in a formula that can be used to calculate machine priorities [36].

The standard further recommends that an FMEA or FMECA is used to determine expected faults, symptoms and parameters that can be used to indicate the occurrence of faults.

1.3.4 Appropriate maintenance tasks

In cases where a failure mode cannot be detected from measurements, it is recommended that alternative maintenance strategies are applied [36].

1.3.5 Measurement method

The parameters identified for monitoring the condition of the relevant machines as discussed in Section 1.3.3 can be measured using one or more measurement techniques. It is thus important to select the appropriate measurement technique, which can use permanently installed, semi-permanent or portable instrumentation [36].

The accuracy required for routine condition monitoring is not as high as the accuracy required for performance testing. It is more important to obtain repeatable rather than accurate measurements for methods that create trends of the parameter values [36].

Another important factor to consider when selecting a measurement method is the availability of parameter data. Factors that should be considered include existing measurement instrumentation, data accessibility, required data processing, cost and current parameter monitoring systems [36].

It is also important to determine the operating conditions of monitored machines. This means identifying the normal parameter ranges when machines are operational. These parameter values can thus be trended to form a baseline to which subsequent measurements can be compared in order to identify changes [36].

Parameter measurement intervals should also be considered, and sampling can either be done periodically or continuously. The primary deciding factors for determining the correct measurement interval are the type of fault and the parameter’s rate of change. Secondary deciding factors should not be excluded and can include criticality and measurement cost [36].

The rate of data acquisition should also be considered, which should be fast enough to reflect changes in conditions. Parameter data archives should contain important information about the parameter such as a machine description, measurement location, unit of measurement, measurement interval and the date and time of the measurement [36].

The standard further recommends that measurement locations are identified uniquely and labelled or marked properly. Locations should also be positioned for optimal fault detection while considering factors such as safety, sensitivity to a fault condition, interference from unwanted sources, accessibility and measurement cost [36].

Alarm criteria must be set to give the earliest possible indication of fault conditions and can either be a single value or multiple levels. Alarm values can be obtained by processing several parameter measurements, which should be optimised iteratively over time [36].

Baselines should be established for parameters of machines operating under normal conditions. The baselines can be used to detect changes. These baselines should define the machine's initial condition under normal operating conditions. It is important to note that these parameter baselines can change during a machine's wear-in period and should thus only be measured after the baselines have stabilised [36].

1.3.6 Data collection and analysis

The objective of data collection is to get measurements to compare with historical data or baselines for similar machines. It is recommended that the data collection procedure is managed by organising measurements in a logical order [36].

Measured parameter values should be compared constantly with their respective alarm criteria. When the parameter values are within the acceptable range, no action is needed, and the data should only be recorded. In cases where parameter values do exceed acceptable ranges, a diagnosis process should be initiated [36].

There are two possible approaches when diagnosing a machine, which are a symptoms approach and a casual approach. Condition monitoring can also be used to indicate the expected outcomes of current or future faults, which is known as prognosis. In cases of low confidence in the diagnosis or prognosis, further investigation is required; otherwise corrective maintenance can be initiated immediately [36].

The ISO 17359 standard provides suggested actions that can improve confidence in diagnosis or prognosis. Actions include verifying parameter measurements and alarm conditions, analysing historical trends, increasing data measurement frequency or using alternative techniques for correlation [36].

1.3.7 Determine maintenance action

Maintenance actions can be determined by evaluating circumstances such as machine criticality, the level of confidence in the fault diagnosis or fault severity. This can result in actions ranging from continued monitoring at normal intervals to a reduced machine load or speed, to an immediate shutdown [36].

The standard recommends that a proper record is kept of machine details, maintenance activities performed, changes made to the machine, and other faults discovered during maintenance activities. These records can help with future diagnostics and are useful when reviewing the condition monitoring process [36].

1.3.8 Review

Since the condition monitoring process is an ongoing process, it is important to evaluate the feasibility of condition monitoring techniques constantly. This will help identify techniques that might have been too costly or complicated in the past, which can become feasible on review. The same approach should also be taken to evaluate the efficiency of current techniques [36].

The alarm criteria for machines should also be reviewed regularly along with baseline values to account for changes resulting from maintenance activities, progressive wear and ageing [36].

1.3.9 ISO deficiencies

Although ISO 17359 can be helpful when implementing a CMS, it can be considered insufficient or lacking when it comes to practical implementation. Some of the deficiencies in the ISO standard regarding the practical implementation of a CMS in the South African gold mining industry are:

- The theoretical work required for reliability and criticality analysis as suggested by the standard is unnecessarily specific and time-consuming. This discourages the implementation of a basic CMS on predetermined systems and machines.
- A criticality assessment has to be done for individual machines since their breakdown likelihood and reliability can differ significantly even for similar machines. This process can also be time-consuming if it needs to be done for numerous machines.
- The reliability of machines and components is not generic and needs to be adapted to historical maintenance records. This implies that comprehensive and accurate maintenance records are readily available for each of the machines considered. This is however not practically feasible in the mining industry.
- Although the ISO standard lists possible parameters that can be used for condition monitoring of some types of machines, it is not industry specific.
- Even though several of the parameters listed in the ISO standard are applicable to machines in the mining industry, the acquisition of the required infrastructure to monitor them can be capital intensive.

- The ISO standard discusses the importance of the correct measurement intervals but does not make any recommendations applicable to the mining industry.
- Furthermore, the ISO standard does mention some condition monitoring techniques, but their feasibility in the mining industry are not considered or discussed.
- The ISO standard is very vague in terms of communicating alarm notifications to relevant parties with no suggestions on communication channels.
- The ISO standard explains the management of monitored parameter data, but this seems to be more applicable to manual condition monitoring techniques than continuous condition monitoring.
- The ISO standard discusses the implementation and optimisation of condition monitoring diagnostics and prognostics, but this can complicate the successful implementation of a basic CMS.

1.4 Need for this study

A critical review of existing literature found that although a great variety of CMSs have been implemented across various industries, there is no generic step-by-step implementation process. This seems to be even more applicable to the South African gold mining industry since no relevant case studies were found in literature.

Some studies were found in literature that considered the requirements for implementing remote CMSs in other industries. These studies even referenced case studies but could not combine these two aspects into a generic implementation process. Furthermore, these studies were specific to their respective case studies and not applicable to other case studies of different industries and sizes.

The case studies found in literature were case specific as mentioned and were either a proof of concept or experimental application of a CMS. This means that these studies did not consider the sustainability of the system and these systems were not meant to be operated without constant user input or adjustments.

Even though some case studies were found in literature that were proven to be implementable on remote locations, there were no cases where CMSs were implemented from a generic process and maintained on remote gold mines.

While some case studies found in literature did consider the possibility of communication between a remote monitoring system and relevant personnel, none of these were able to implement an automated notification system that could notify personnel of arising matters that might require their attention.

1.5 Study objectives

The first objective of this thesis is thus to develop a step-by-step implementation process for implementing a basic CMS on a South African gold mine. The term basic CMS will be considered in the context of this thesis as a CMS that only monitors the four primary MSSs needed to ensure sustainable deep-level mining operations on South African gold mines. It will also be considered as a system that only monitors the vibration, or maximum vibration displacement, and temperature levels of the rotational machines included in these MSSs. This will keep the required additional instrumentation costs low due to the common availability of temperature and vibration monitoring on South African gold mines (as discussed in the last part of Section 1.1.5).

The second objective of this thesis will be to apply the developed implementation process practically to set up basic CMSs of different remote South African gold mines. This will ensure that the same implementation process is followed irrespective of the mine’s location, size or complexity. The application of the developed process will furthermore be used to prove that the developed process is not just an academic result but that it can be applied successfully to real-world cases and be used for extensive time periods.

1.6 Novel Contribution of this study

The two primary contribution to the field are discussed briefly in the following subsections. This contribution can be considered in two parts, one which is the theoretical development of an implementation process for CMSs on South African gold mines, while the other focuses more on the real-world application of the developed process through its application on South African gold mines.

1.6.1 Part 1 (Theoretical process)

Develop a simplified process for implementing a basic CMS on South African gold mines that:

- Uses generic data gathering and notification methods,
- Has a low implementation cost,
- Is scalable to be used on any size of mining operation,
- Uses a standardised process to enable implementation on any kind of mining operation, and

- Provides centralised monitoring of remote mining operations.

a) Current situation

Although condition monitoring is already being done on South African gold mines, it is not being implemented according to a standardised process. The scope and refinement of CMSs are unique to each mine since personnel configure CMSs as they feel necessary. In some cases, this can end up leaning towards convenience and away from efficiency. The implementation of specialised CMSs on South African gold mines is not feasible due to excessive implementation and operating costs.

b) Shortcomings

The result of such uncontrolled implementation of CMSs is that some critical machines are excluded from the CMS. It also causes machine conditions to be determined from different parameters and parameter limits. The monitoring intervals and frequency of these parameters are also different for each mine. This results in inconsistent maintenance of critical machines and more unexpected breakdowns.

c) Description of contribution

A process will be developed to ensure that CMSs on South African gold mines can be implemented consistently and with minimal capital expenditure. This will ensure that the same critical machines are monitored and that their condition is determined by the same parameters and parameter limits. The implemented CMS will also be centralised to provide transparency and feedback on the efficiency of maintenance strategies.

1.6.2 Part 2 (Real-World application)

Practical application of a simplified process for a basic CMS on South African gold mines.

a) Current situation

There is a wide variety of literature on how to do condition monitoring on critical machines. This includes discussions of critical machine parameters and condition monitoring techniques such as machine learning. Furthermore, there is some literature on the theoretical implementation of CMSs in general, but nothing on real-world or actual implementation of CMSs in the mining industry.

b) Shortcomings

The lack of practical implementation of CMSs in the mining industry leaves some important aspects for discussion. This includes the implementation and operating costs of CMSs. Implemented CMSs are also not optimised and are thus not necessarily sustainable. Another important aspect is utilising existing infrastructure and identifying infrastructure needed to implement a CMS sufficiently.

c) Description of contribution

This thesis will look at implementing CMSs on different South African gold mines by using the same implementation process. This will help ensure that important aspects such as sustainability, operational costs and infrastructure availability are considered. It will also help optimise the implementation process and identify common obstacles.

1.7 Thesis layout

Chapter 1 – The first chapter has shown that there are several important support systems being used in South African gold mines and that maintenance of these systems is essential. This chapter further reviewed contributions of previous studies relevant to the field of condition monitoring implementations. It included literature relevant to the implementation process of a CMS. The ISO 17539 standard's guideline and its shortcomings with respect to condition monitoring in the South African gold mining industry were discussed briefly. This information was used to motivate the need for this study and formulate the study objectives. The study objectives in turn were used to formulate and define the novel contributions that will be made by this study.

Chapter 2 – The methodology of this thesis is discussed in detail in this chapter. The information gained from the previous chapter is applied to develop a condition monitoring implementation process for South African gold mines. The developed process considers implementation scenarios that are typical to South African gold mines to develop the process up to a step-by-step implementation.

Chapter 3 – The third chapter of this thesis discusses the application of the developed implementation process with reference to two case study mines. The different steps of the implementation process are explained and illustrated with examples from the case study mines where deemed necessary. This chapter also discusses the results obtained from implementing the developed implementation process on several other South African gold mines.

Chapter 4 – The final chapter in this thesis concludes with a summary of the outcomes from the previous chapters. It discusses the results obtained from the implementation in terms of lessons learned and potential focus areas for future studies.

CHAPTER 2

Implementation Process development

2.1 Introduction

This chapter discusses the implementation process of a basic CMS. The need for developing a basic and low-cost remote CMS for South African gold mines was defined by identifying the required objectives of such a system.

These objectives were further optimised by consulting with mine personnel on different gold mines which are actively involved in the monitoring and maintenance of machines on a daily basis. This includes people like:

- Quality control engineers,
- Engineering managers,
- Services engineers,
- Instrumentation technicians,
- Electrical foremen and
- Mechanical foremen

This information was then used to develop and optimise an implementation process for CMS systems on South African gold mines. This was achieved by evaluating real-world CMS implementations in terms of simplicity, practicality, required costs and long-term reliability.

The ISO 17359 standard document structure is combined with this experience gained from the implementation of CMSs on South African gold mines to develop a basic layout of the implementation process. In order to simplify the implementation process, the implementation guidelines provided by the ISO document, is reduced and simplified. This simplified implementation process is divided into several sections, namely, investigation, data gathering, data interpretation and reporting. The four sections will each be divided into a pair of processes. The process simplification and resulting implementation process that make up this chapter is illustrated in Figure 9.

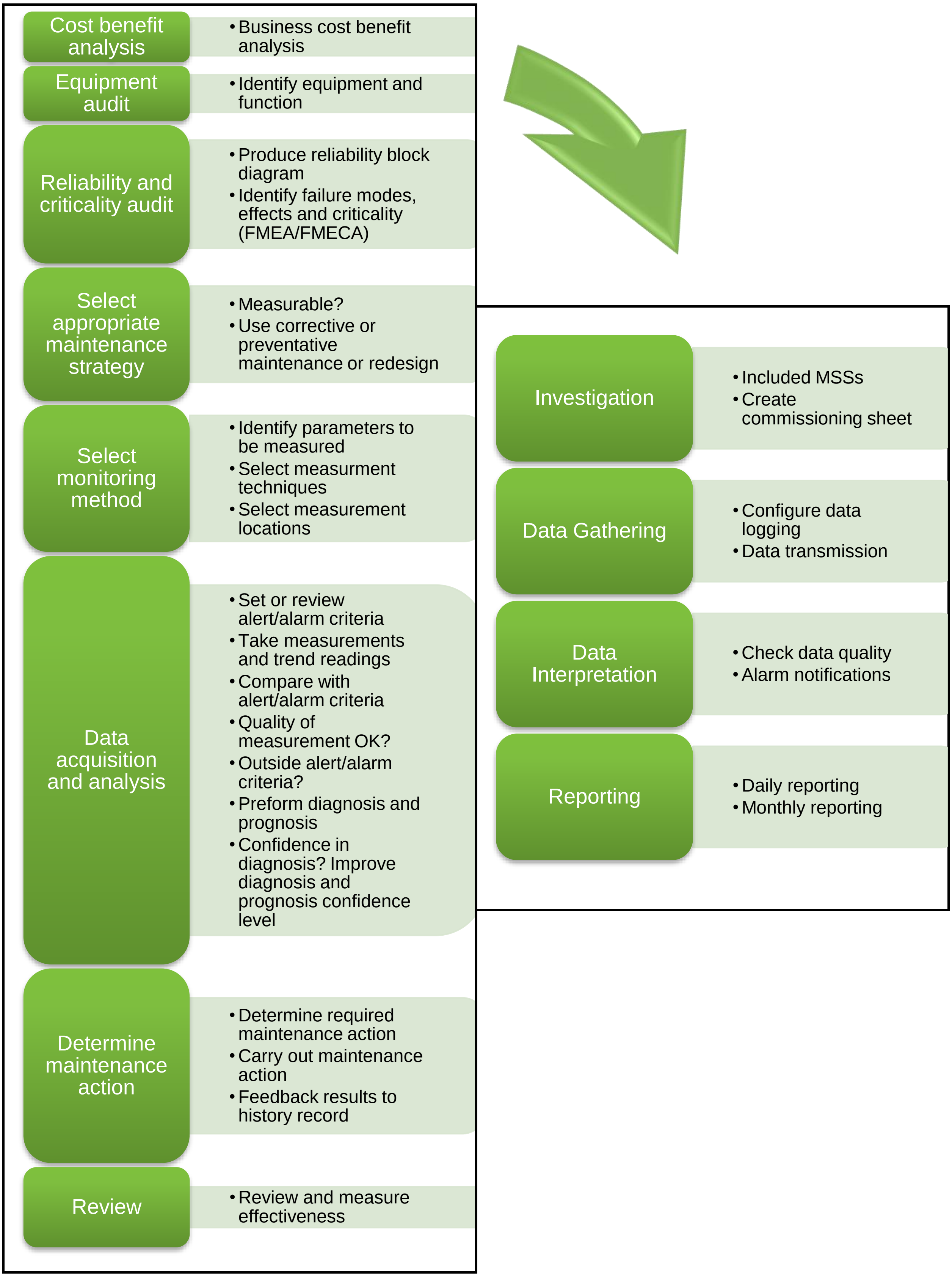


Figure 9: Simplified methodology

The first section in the implementation is the investigation section, and starts with an evaluation process, which consists primarily of evaluating the extent of condition monitoring on a gold mine. This means determining how many systems, and how many machines per system will be included in the condition monitoring of the mine. The second process focuses the steps required to create a commissioning sheet. This includes a list of common parameters, parameter names and parameter limits.

The third process explains the steps needed to configure data loggers from the commissioning sheet in an organised fashion. The forth process gives a brief overview of the implementation of data transmission on remote condition monitoring sites. The fifth process concerns the different steps that need to be done to verify the data quality. The sixth process looks at the steps in implementing and updating an alarm notification system for parameters exceeding their limits. The final process focuses on the automated daily exception reports, monthly reports and quantifying the impact of the CMS.

2.2 Investigation

There are various aspects that need to be determined before implementing a CMS. Some are illustrated by the investigation process shown in Figure 10. The elements of this flow diagram are discussed in more detail after the figure.

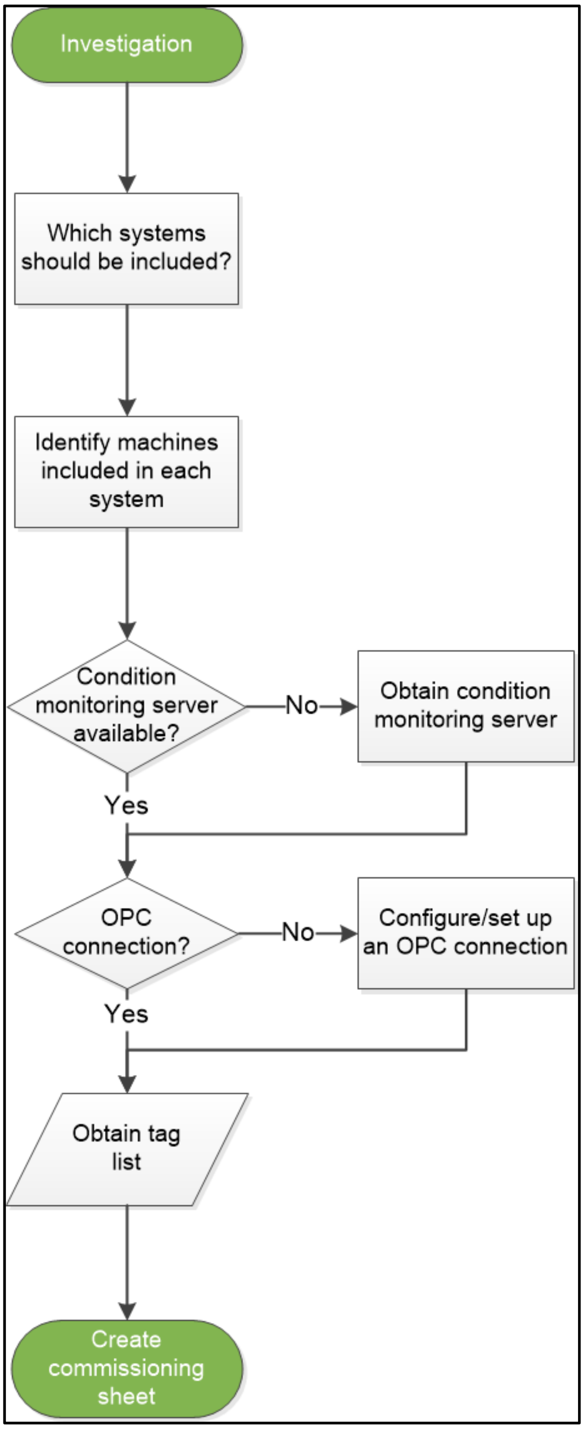


Figure 10: Condition monitoring: Investigation process

2.2.1 Mine support systems

As shown in Figure 10, the first step is to determine which of the major MSSs will be monitored by the CMS and the number of machines they each contain. The primary deciding factors for inclusion in the CMS are system reliability, instrumentation availability and remote monitoring infrastructure available. Consistent monitoring of unreliable systems can help identify causes of failures and provide information on how to improve reliability. A well-instrumented MSS can be beneficial towards monitoring and improving its reliability. The included systems are usually mine ventilation, mine dewatering, refrigeration and compressed air systems (as discussed in Section 1.1.1). Each MSS is primarily driven by specific machines. It is thus important to determine how many machines will be monitored in each of these systems, which is discussed in the next section.

2.2.2 Machines in mine support systems

The machines from the MSSs usually have a total of about ten parameters being recorded. From the experience gained as discussed at the start of this chapter, it was found that the recorded parameters typically include four vibration measurements, four temperature measurements, a running status, and an energy or current measurement.

The vibrations are typically the DE and NDE bearing vibrations of the motor and driven machine (e.g. pump). Temperature parameters usually include the DE and NDE bearing temperatures of the motor and driven machine. In some cases, only one vibration sensor is installed on the casings of each of the motors and driven machines. These vibration sensors are monitored in the absence of vibration sensors on the DE and NDE bearings.

The recorded parameters for air compressors, on the other hand, can be a great deal more. The example in Figure 11 illustrates the typical number of recorded parameters per system for condition monitoring.

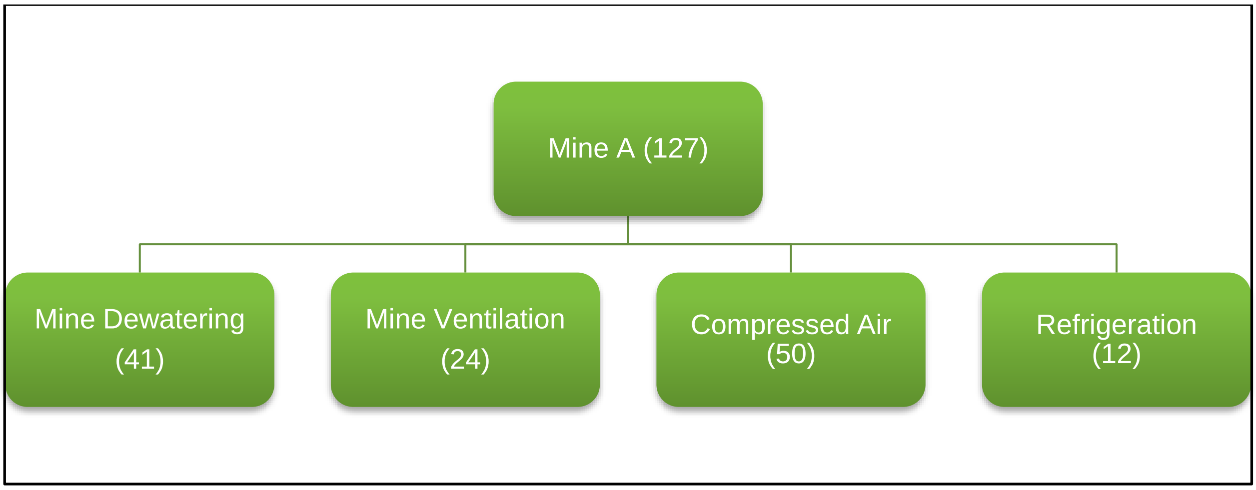


Figure 11: Number of recorded parameters on a typical gold mine

Figure 11 illustrates that a typical gold mine can have more than 120 condition monitoring parameters, but in some cases can exceed 500 parameters. These systems can be divided into the individual machines that make up the systems as illustrated in Figure 12.

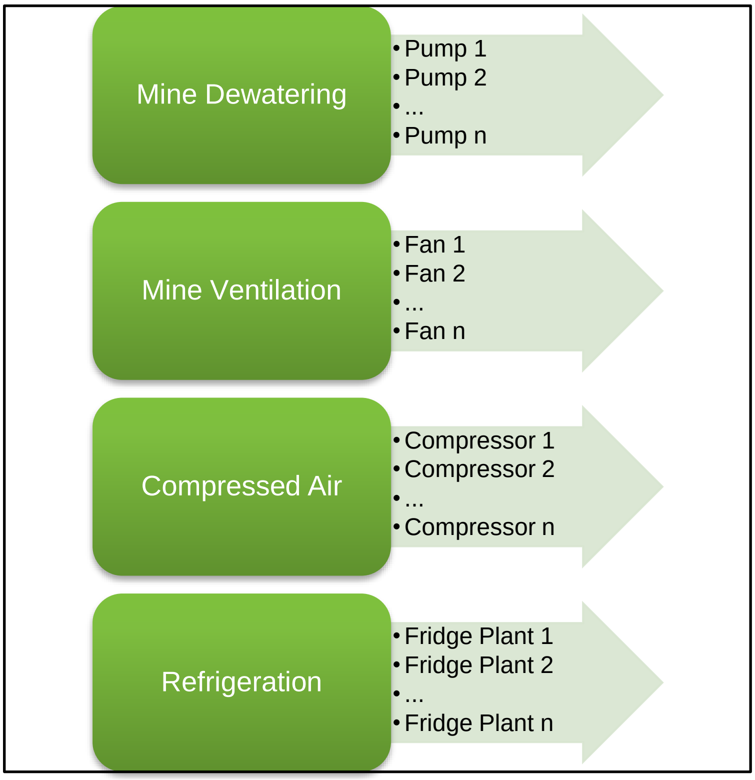


Figure 12: Individual MSS machines

The number of machines in each system illustrated in Figure 12 includes all the machines for that specific system on the entire gold mine – even if they are at different locations on the mine. These individual machines can be subdivided into their primary components as illustrated in Figure 13.

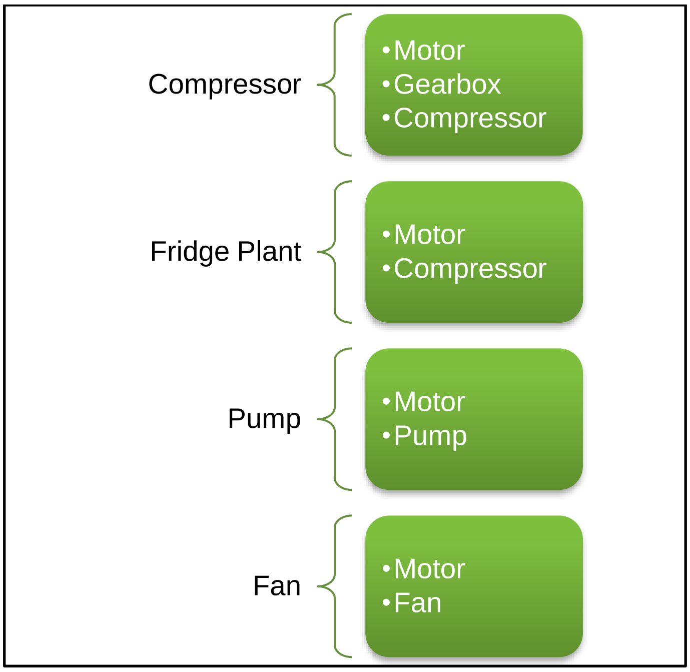


Figure 13: Components of individual machines

The machines in Figure 13 are non-specific, and the illustrated components are valid for all machines in their respective MSSs. The same common parameters are monitored for condition monitoring on these components. Since they are all rotational machines, the monitored parameters are bearing temperatures and vibrations on the ends of the rotational shaft (as mentioned in Section 1.1.5). In some cases, there are only one vibration parameter available, which measures the entire component's vibration.

2.2.3 Condition monitoring server connection

An OPC connection is used to synchronise parameter data between the SCADA computer and the condition monitoring computer. In cases where no dedicated condition monitoring computer is available, one should be obtained. This also enables personnel responsible for condition monitoring to actively maintain and update the condition monitoring platform without sacrificing the performance and reliability of the SCADA computer and related mining operations.

The OPC connection is used by a software package on the condition monitoring server to record the required parameter values at regular intervals. Most parameters for machines used in the South African gold mining industry are monitored centrally by a SCADA system. A list of all the parameters available on the SCADA system can be downloaded over the OPC connection, which is referred to as a tag list. This tag list will be used to create and populate a commissioning sheet, which is used to document all relevant parameter information. The process of creating a commissioning sheet is discussed in the following section.

2.2.4 Commissioning sheet

The commissioning sheet can be used at a later stage to verify tag names, indicate parameter limits, and identify unmonitored parameters. It is important to note that the processes described later on in this section need to be done twice: the first time to document and initiate data logging of the condition monitoring parameters, and the second time to document and implement the alarm notifications.

First, make sure that all the MSSs that will be included in the CMS are represented in the commissioning sheet. Furthermore, it is important to ensure that all the relevant machines from the MSSs are defined in the commissioning sheet. These steps are illustrated in Figure 14. The elements of this flow diagram are discussed in more detail after the figure.

The steps illustrated in Figure 14 should be followed when creating a new commissioning sheet as well as updating an existing commissioning sheet. The next section discusses the steps to create a new commissioning sheet.

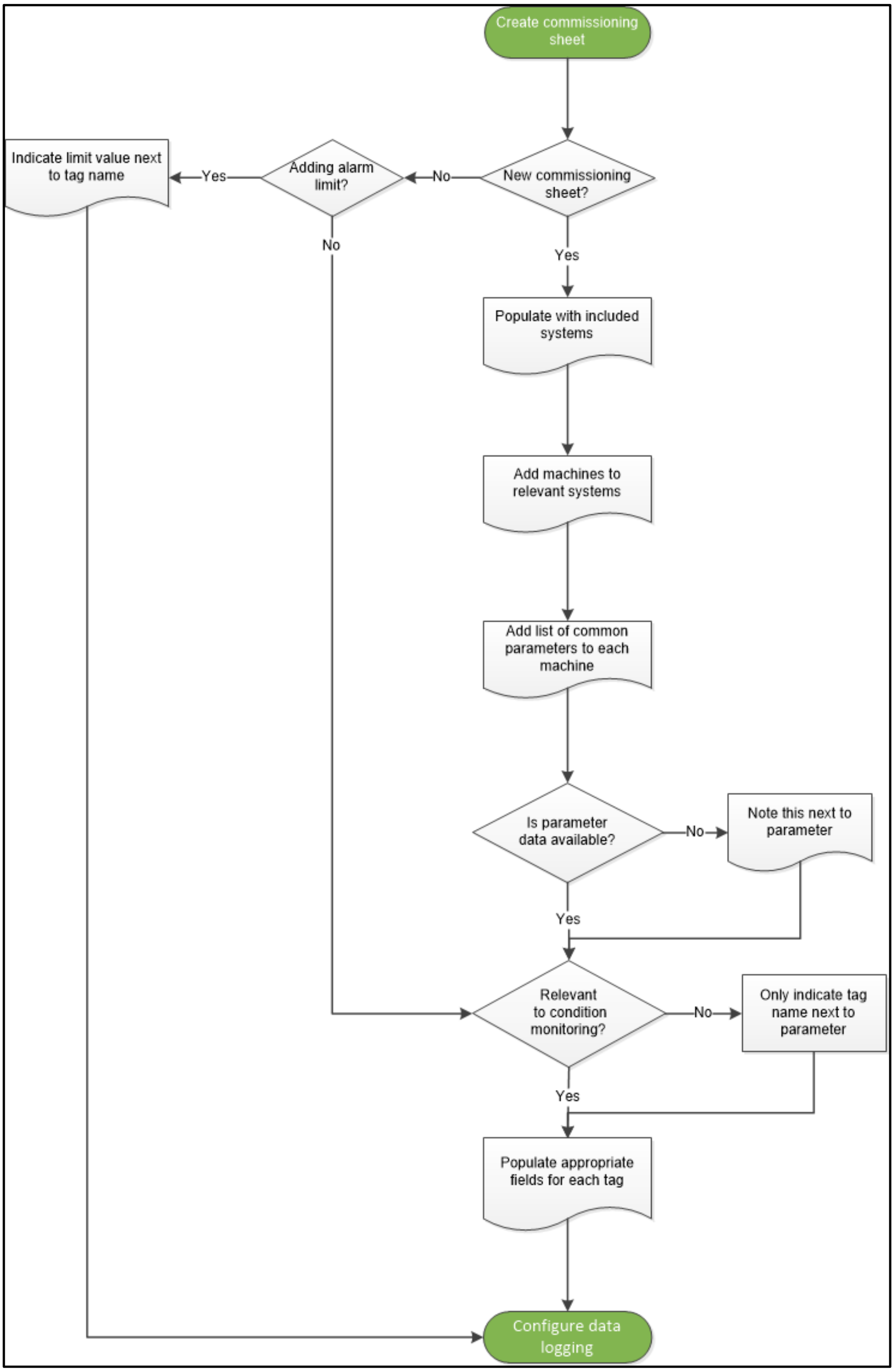
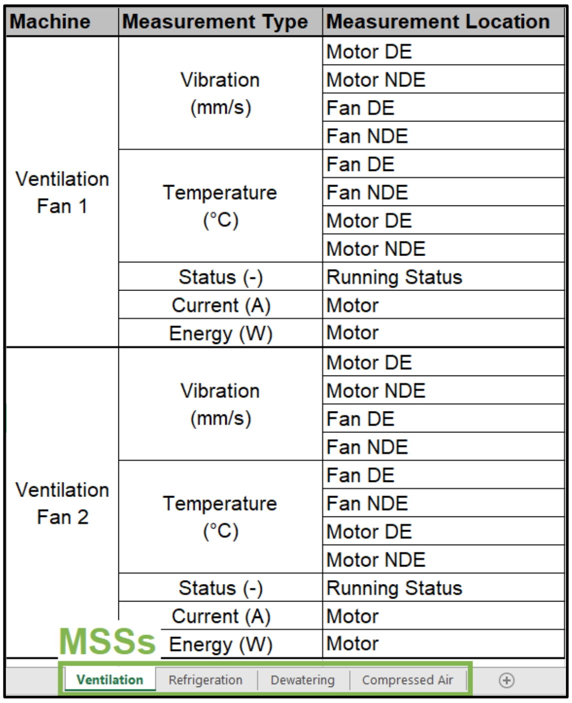


Figure 14: Steps to create a commissioning sheet

a) Parameter list

The commissioning sheet should have separate sections for each of the MSSs that will be monitored by the CMS. A good example is using separate worksheets in a Microsoft® Excel workbook – one for each MSS. Add a list of the machines in each MSS to the relevant section along with an appropriate heading. Next, list the parameters of each machine that will be monitored according to their measurement locations on the machine. It is recommended that these parameters are grouped by measurement type to keep the list organised. The result of these steps is illustrated for the ventilation system of a gold mine in Figure 15.



Machine	Measurement Type	Measurement Location
Ventilation Fan 1	Vibration (mm/s)	Motor DE
		Motor NDE
		Fan DE
		Fan NDE
	Temperature (°C)	Fan DE
		Fan NDE
		Motor DE
		Motor NDE
	Status (-)	Running Status
	Current (A)	Motor
	Energy (W)	Motor
Ventilation Fan 2	Vibration (mm/s)	Motor DE
		Motor NDE
		Fan DE
		Fan NDE
	Temperature (°C)	Fan DE
		Fan NDE
		Motor DE
		Motor NDE
	Status (-)	Running Status
	Current (A)	Motor
	Energy (W)	Motor

Figure 15: Example parameter list for ventilation system

b) Populate parameter list

For future reference, populate the tag names (if they are available) from the downloaded tag list into the corresponding measurement type and location fields for each machine. It is also important to make a note of missing or outstanding measurements and supply an explanation. The tag names needed for condition monitoring can now be filled out for the populated SCADA tag names by using a universal naming convention. This will help identify parameters from various machines in various MSSs from different gold mines within the same mining group. It would also make it easier to find parameter data without knowing the exact parameter name. A convention was thus developed that would include relevant information as illustrated in Table 4.

Table 4: Tag naming convention fields

Information	Description	Example
Client group	Mining group name	Gauteng Gold
Site	Gold mine name	Mine B
Section description	System name	Ventilation
System description	Description of machine	MainFan3
Measurement description	Measurement location and parameter type	Fan DE Bearing Temp
Measurement symbol	Temperature, pressure, flow, etc.	T

The resulting tag name for the parameter described in the Example column of Table 4 would be:

Gauteng Gold_Mine B_Ventilation_MainFan3_Fan DE Bearing Temp_T

It is important to document the tag name of each recorded parameter and make provision for alarm notifications. This requires a warning and alarm value. The warning value is used to determine when a parameter is getting close its limit, while the alarm value is used to define the parameter limits. These two fields will be populated at a later stage of the implementation process. Table 5 shows an example of the completed commissioning sheet for two mine ventilation fans.

Table 5: Example of a commissioning sheet

Measurement Location	SCADA Tag Name	Warning Value	Alarm Value	Condition Monitoring Tag Name
Motor DE	vfan1_mot_de_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Motor DE Bearing Vib_V
Motor NDE	vfan1_mot_nde_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Motor NDE Bearing Vib_V
Fan DE	vfan1_fan_de_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Fan DE Bearing Vib_V
Fan NDE	vfan1_fan_nde_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Fan NDE Bearing Vib_V
Fan DE	vfan1_fan_de_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Fan DE Bearing Temp_T
Fan NDE	vfan1_fan_nde_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Fan NDE Bearing Temp_T
Motor DE	vfan1_mot_de_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Motor DE Temp_T
Motor NDE	vfan1_mot_nde_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Motor NDE Temp_T
Running Status	vfan1.sfp_mp_diginput_1.dig11.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Running_Y
Motor	vfan1_mot_current.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Current_I
Motor	vfan1_total_active_power.value			Gauteng Gold_Mine B_Ventilation_MainFan1__Total Active Power_J
Motor DE	vfan2_mot_de_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Motor DE Bearing Vib_V
Motor NDE	vfan2_mot_nde_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Motor NDE Bearing Vib_V
Fan DE	vfan2_fan_de_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Fan DE Bearing Vib_V
Fan NDE	vfan2_fan_nde_vibration.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Fan NDE Bearing Vib_V
Fan DE	vfan2_fan_de_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Fan DE Bearing Temp_T
Fan NDE	vfan2_fan_nde_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Fan NDE Bearing Temp_T
Motor DE	vfan2_mot_de_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Motor DE Temp_T
Motor NDE	vfan2_mot_nde_temp.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Motor NDE Temp_T
Running Status	vfan2.sfp_mp_diginput_1.dig13.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Running_Y
Motor	vfan2_mot_current.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Current_I
Motor	vfan2_total_active_power.value			Gauteng Gold_Mine B_Ventilation_MainFan2__Total Active Power_J

An example of a complete commissioning sheet for the dewatering system of a mine can be found in Annexure C.

2.3 Data gathering

The data gathering section of the implementation process can be divided into two processes, which are data logging and data transmission. Data logging refers to the process of recording individual parameter values continuously at constant intervals. Data transmission refers to the process of transmitting the recorded parameter values to a central location where data can be archived and processed. These two parts are discussed in more detail in the following subsections.

2.3.1 Data logging

Data logging can either be done manually or automatically by an electronic system. It is however recommended that data logging is automated to save time and to prevent logging errors. From the experience gained as discussed earlier, it is recommended that each of these parameter values are recorded at two-minute intervals, their average values are calculated every 30 minutes, and sent to a remote server via e-mail. This can add up to a significant number of parameter values that need to be processed every 30 minutes for a total of five remote gold mines. The recorded parameters are also saved daily on the condition monitoring server to serve as backup in case of data loss during transmission or processing.

For the purposes of this thesis, a software package called REMS™ is used for data logging. This package is used due to its simplicity in terms of data logging and availability on South African gold mines. Alternative software packages can be used as long as they provide the capability to automatically log various parameter values at regular intervals. The process of configuring the data logging platform is illustrated in Figure 16. The elements of this flow diagram are discussed in more detail after the figure.

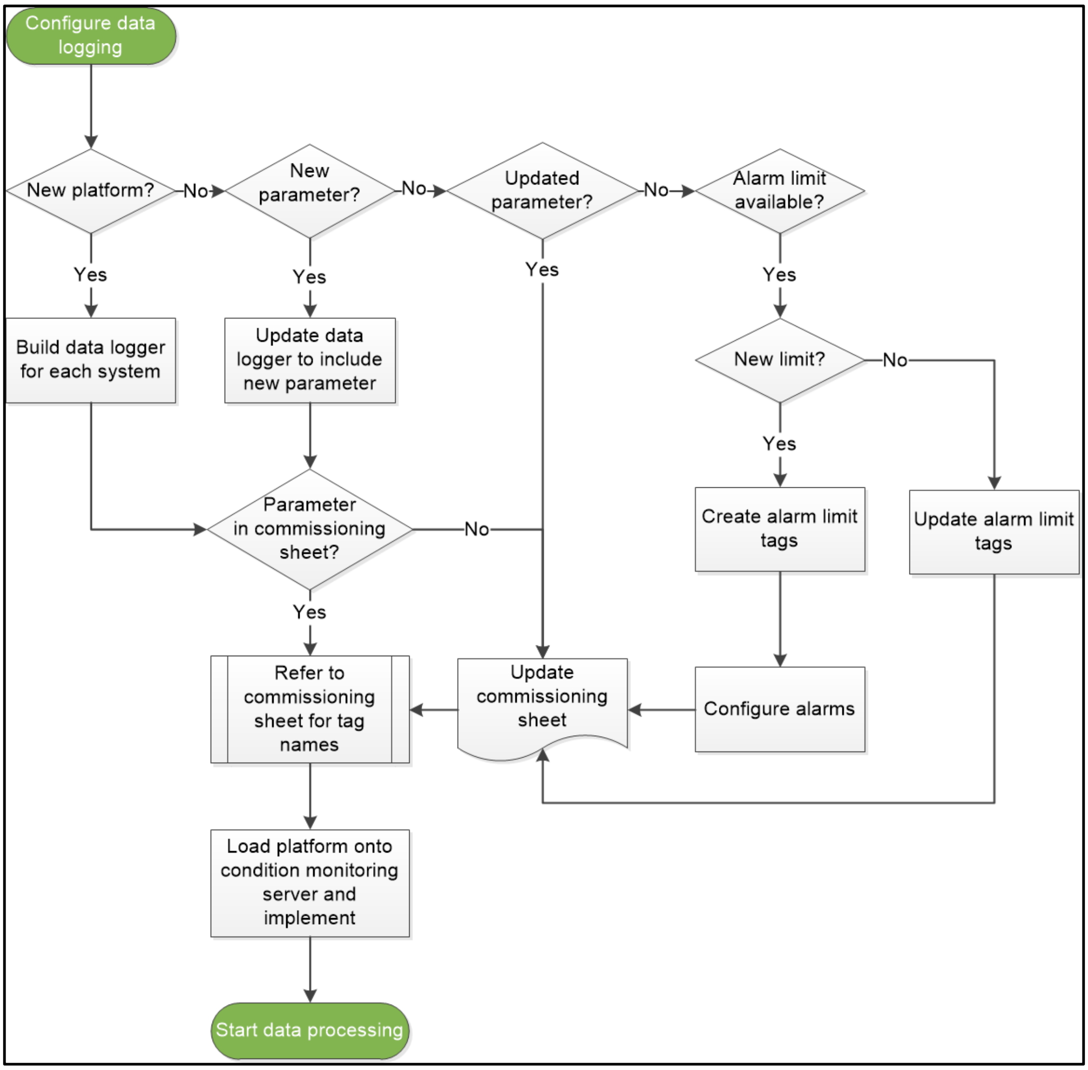


Figure 16: Steps in configuring a data logging platform

Individual data logger configurations are recommended for each MSS on the mine. If a gold mine has two ventilation fans, the data logger configuration for its ventilation system will contain information similar to that shown in Table 5. This will also be applicable to the other MSS systems included in the CMS of the gold mine.

The first step is to configure a data logger for each of the MSSs as mentioned earlier. The next step is to populate the data logger with all the SCADA tags added to the commissioning sheet for condition monitoring. Following this, provide corresponding condition monitoring tags as defined in the commissioning sheet.

It is recommended that the platform is developed on a computer that is easily accessible at all times such as a laptop or desktop computer at the office. This eliminates the need to travel to individual mines for software configurations or maintenance. Developing and maintaining the condition monitoring software from a central location can save significant amounts of time and minimise travel costs.

It can be frustrating to develop and maintain the data logging software remotely via a poor network connection, but a familiar environment might increase productivity. The data logging configurations can thus be sent to remote condition monitoring servers and loaded when needed.

Regular backups of the platform configuration are important. Backups should be stored locally and at a remote location to ensure that the configuration is not lost during an unexpected hardware failure, or to enable the user to revert to a previous configuration if necessary for any reason. The data being logged by the data loggers needs to be processed and archived to simplify its use, which is done by a centrally located server. This is illustrated in Figure 17.

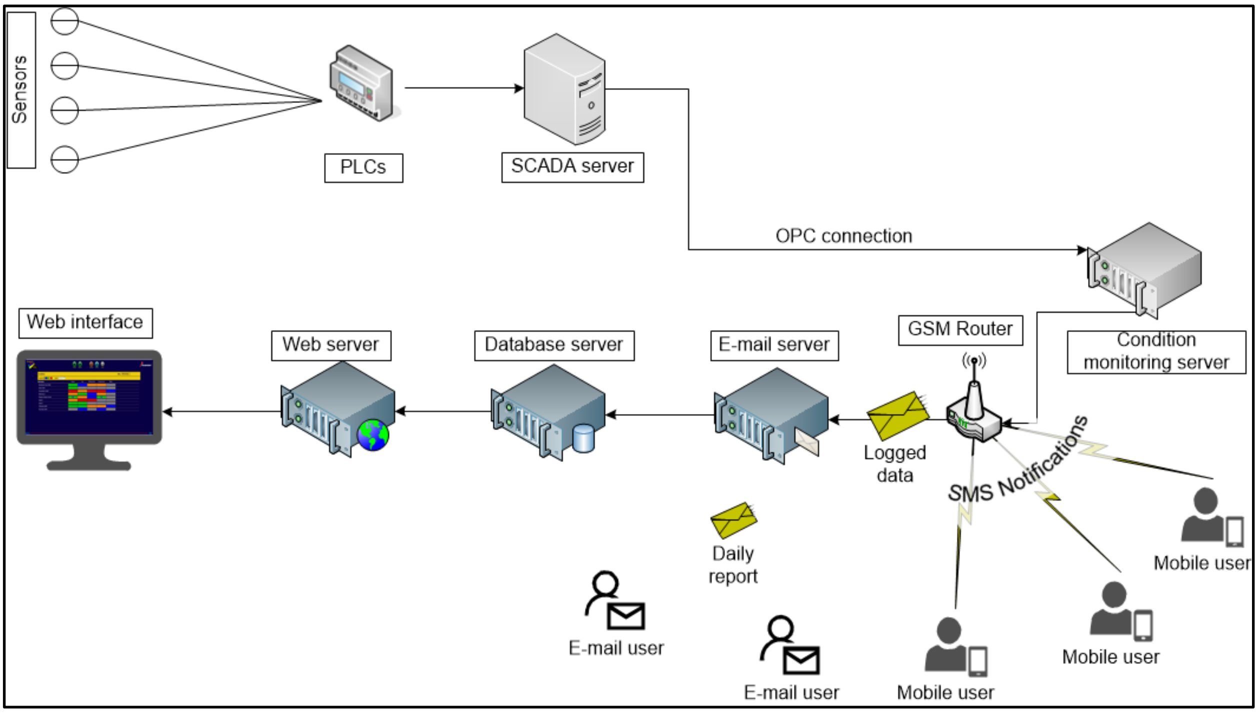


Figure 17: Condition monitoring data communications

2.3.2 Data transmission

The server responsible for data transmission receives the data via e-mail from the remote condition monitoring sites. It is recommended that the condition monitoring servers on the remote sites use Global System for Mobile Communications (GSM) routers to transmit data over a secured mobile broadband network. This provides flexibility on the physical location of the remote condition monitoring servers while keeping transmitted data and the mine’s control network secure. Alternative methods can be used the transmit data, but the main objectives are centralising the logged data and keeping it secure. The data transmission process for using a GSM router and a secure mobile network is illustrated in Figure 18.

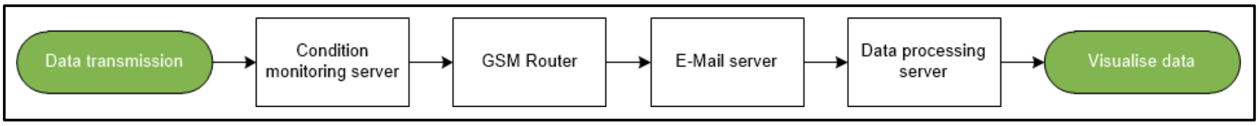


Figure 18: Data transmission process

The data files are logged, zipped and sent to the remote processing server as an e-mail attachment. This remote server sorts the data, writes it to a database and makes the new data available for display on a web interface. The database enables historical data to be analysed or processed further for reporting purposes. Since data needs to be transmitted to a remote server, processed and archived, it would be unpractical to record and send all available data.

A higher data resolution for each parameter will result in larger data volumes being transmitted and an increased processing cost. The increased cost of the higher data resolution does not justify the increased benefit to condition monitoring. It is thus important to only record parameters that will help determine a machine's condition, and at such a resolution that will create an accurate depiction of the changing operational condition of a machine. It is recommended that data is aggregated by calculating the parameter averages. The difference between using two-minute intervals for a mine dewatering pump and using half-hourly average values calculated from the two-minute intervals is illustrated by the graph in Figure 19.

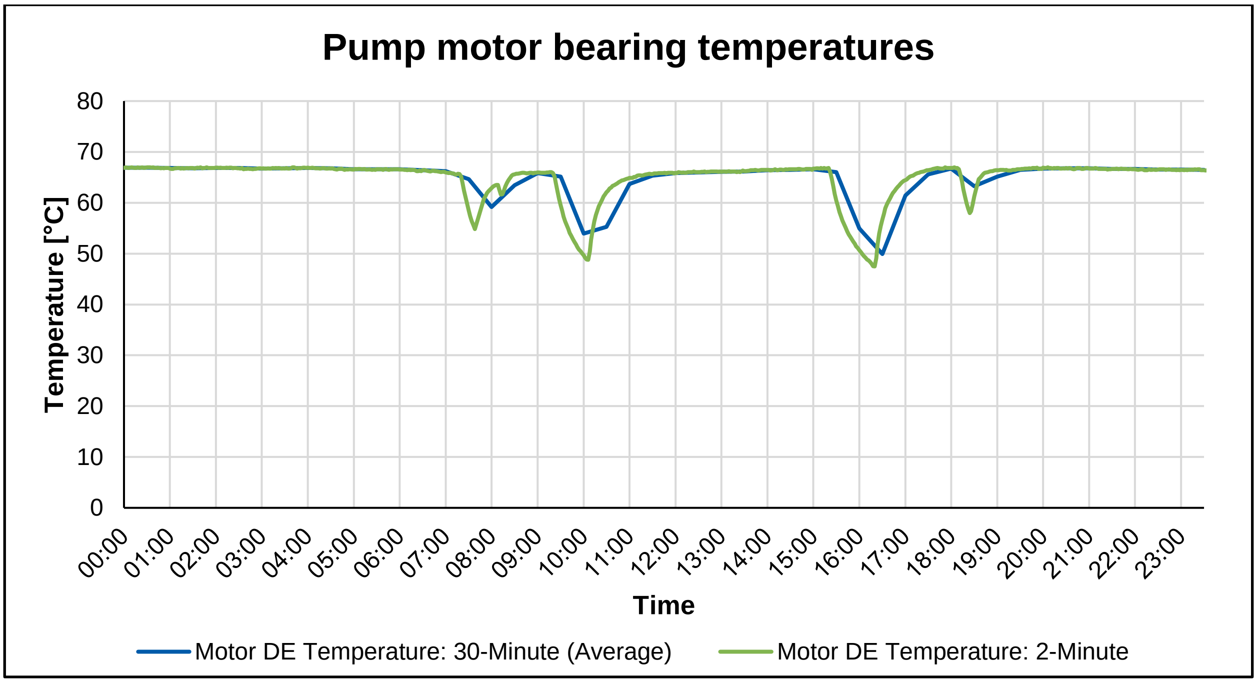


Figure 19: Data resolution comparison

The trends in Figure 19 show that although the high-resolution data provides more precision, the aggregated data is still able to indicate temperature increases and decreases when the pump is started or stopped. Although there is a time delay between the aggregated minimum temperatures and the two-minute temperature minimums, which will never be more than 30 minutes, the data is accurate enough for basic condition monitoring. The gathered data is processed and visually represented by trends of daily data per parameter. A visual presentation of the logged data can provide a good indication of their respective historical values and behaviour. It can also be used to easily check data quality of the monitored machines on different remote mines. The steps in the data quality checking process are discussed in the section that follows.

2.4 Data interpretation

There are two parts of the data interpretation step, namely, data quality and alarm notifications. The objective of the data quality step is to make sure that credible data is being logged by comparing the logged parameter values against some specific conditions. The alarm notifications part of this step focuses on generating useful alarm notifications when parameters exceed their defined limits. Data quality and alarm notifications are discussed in more detail in the following subsections.

2.4.1 Data quality

Steps can be taken to make sure that the data quality is acceptable, which are illustrated in Figure 20. The elements of this flow diagram are discussed in more detail after the figure.

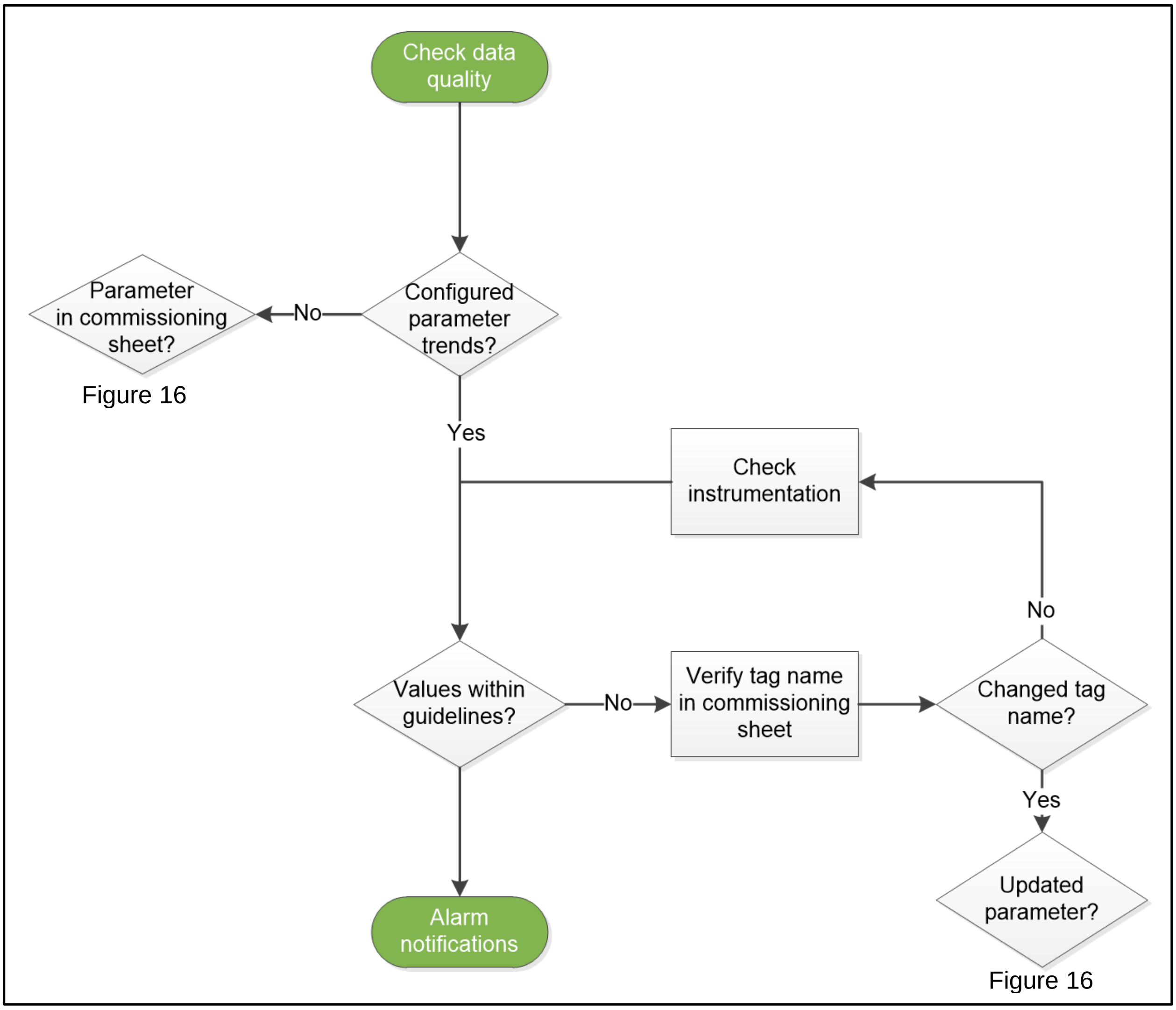


Figure 20: Steps to check data quality

The first step is to check that all the condition monitoring parameters are visualised by graphs and that the tag data is shown and actively updated. If the parameters are not visualised, make sure that they are within the CMS scope by referring to the commissioning sheet discussed in Section 2.2.4.

If the graphs are visible but the data is not updated actively, a check should be done to ensure that the tag data is being received by the processing server. The tag name should also be verified against the commissioning sheet and by mine personnel. There might be cases where graphs are configured and data is actively updated, but the values are unrealistically high, low or even constant. This might indicate a faulty measuring instrument, which should be communicated to mine personnel for further investigation. It is therefore recommended that any bearing temperatures below 10°C or bearing vibrations more than 10 mm/s be investigated. From gained experience, these guidelines (Refer to Figure 20) have proven to be successful in identifying faulty parameter readings. These guidelines will be discussed in more detail in 2.4.2. An example of constant parameter values is illustrated in Figure 21.

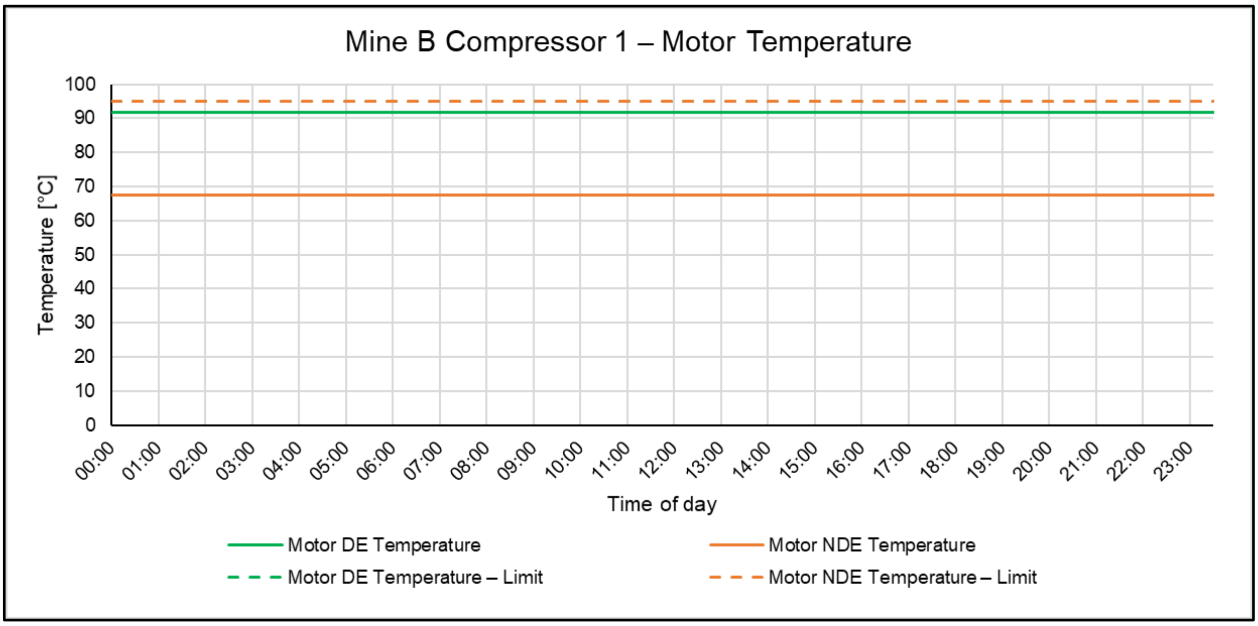


Figure 21: Example of static tag values

If faulty tag values are logged in condition monitoring, as shown in Figure 21, they cannot be used for machine condition monitoring. It is therefore necessary to ensure that the quality of the data being logged is adequate for condition monitoring purposes. This means that the data should give a realistic representation of the actual parameter values.

Adding a parameter limit to a parameter value trend can significantly clarify visualised data. It can furthermore help quantify the operating condition of a machine and make it easier to compare the parameters of different machines. These parameter limits can also be used to trigger notifications for parameters that are approaching or that have reached their limits. The alarm notification system used for condition monitoring is discussed in the following subsection.

2.4.2 Alarm notifications

The steps needed to identify parameter limits and implement a notification system are illustrated in Figure 22. The elements of this flow diagram are discussed in more detail after the figure.

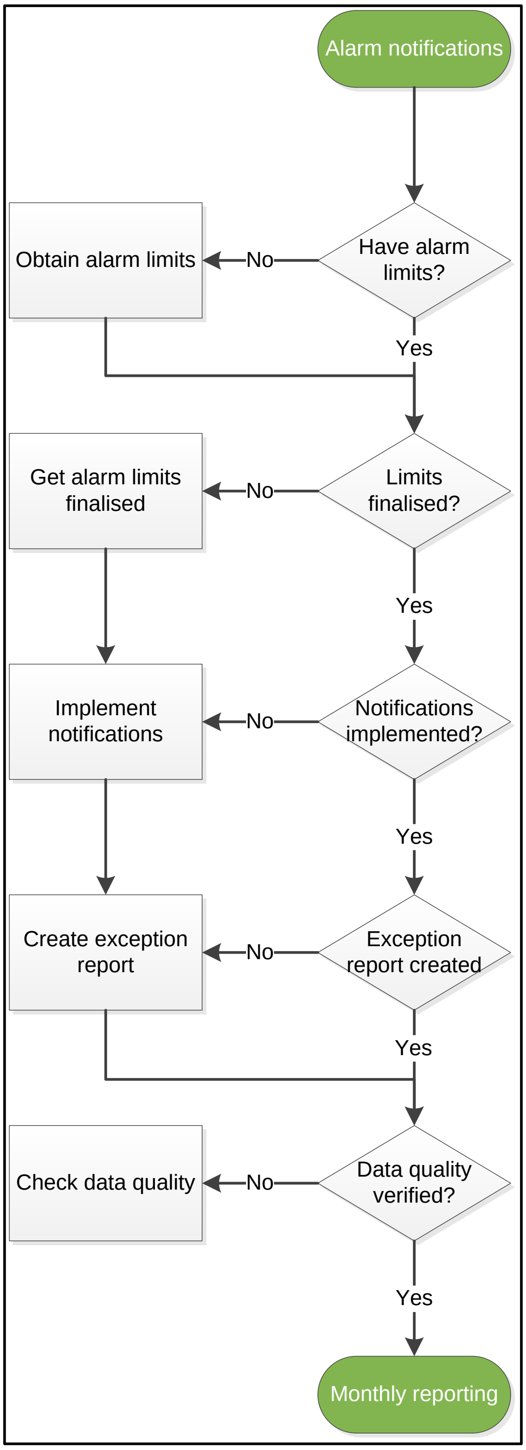


Figure 22: Implementing an alarm notification system

The first step in initiating alarm notifications is to obtain and document all the required parameter limits as illustrated in Figure 22. This is followed by configuring the alarm notifications. The process is discussed in this order.

a) Parameter limits

There are primarily three ways of determining parameter limits:

- Statistical analysis of historical data;
- Technical specifications from the OEM, and
- From experienced maintenance personnel.

The statistical analysis method is by processing historical data for machines in good operational condition to find an average range for each parameter over a specific time period. The biggest drawback to this method is that all machines are at different operational conditions and run under different environmental conditions. The installation of machines, their maintenance history and physical size are not identical, resulting in different acceptable ranges for the same parameter of similar machines. These differences can be taken into account and normalised, but in most cases not all this data is recorded.

In many cases, machines are unique in maintenance history and thus also acceptable operating conditions. The acceptable range for their parameters would thus also never be identical. Historical data for each individual machine would thus need to be analysed to determine the normal parameter ranges for each. This would need to be updated continuously as the machine changes over time, which would not justify the small benefit to the CMS.

Parameter ranges for machines from the OEM would be better suited for determining parameter limits, because they are designed for optimal operation. These ranges are determined by the OEM through extensive testing, but the test conditions might differ greatly from real-world operating conditions, thus rendering the OEM specified parameter ranges inaccurate. These ranges on the other hand can be used as a goal to get machines as close as possible to running within the parameter ranges. Unfortunately, the OEM specifications for machines are not always available or easily obtainable due to their advanced age.

The parameter limits can also be obtained from experienced people in the industry. Instrumentation and maintenance personnel on different mines have hands-on experience on the operating conditions of these machines. Such people work with these machines daily and they know what the acceptable parameter ranges are for their respective operating environments. For the purposes of this study, alarm limits are obtained from mine personnel since they have significant experience regarding the machines' normal operating conditions.

The first step in parameter limit identification is to obtain interim alarm limits for the required parameters from mine personnel. The instrumentation technicians of the various gold mines are responsible for specifying the parameter limits for their machines. A document containing all the required parameter limits for the CMS is provided to the instrumentation technician to complete. An example of such a document can be seen in Annexure D.

These parameter limits are used to quantify machine condition and to implement an alarm notification system. The alarm notification system is only implemented after the parameter limits obtained from instrumentation technicians are finalised by the mining group's quality control engineer.

These parameter limits need to be finalised by the representative of a mine group who is responsible for maintenance on all mines within the mining group. Once the parameter or alarm limits have been finalised, the alarm notifications can be configured and updated. This process has to be done for all existing and updated parameter limits. The implementation of the alarm notification system is discussed in the next subsection.

b) Alarm notification system

The SCADA systems on South African gold mines are configured to alert the control room operator when some parameters exceed their pre-set limits. The control room operators, however, do not always realise the significance of these alerts or alarms. Faulty machines that are reported do not always get the needed attention in time. It is often the case on South African gold mines that machines are run until they fail catastrophically, which is also known as a corrective or run-to-failure maintenance strategy.

This lack of timeous maintenance is partly due to a lack of funding for maintenance purposes, because personnel in management positions are not always properly aware of the need for maintenance funding. In other cases, management personnel feel that they do not see the results of maintenance. The results of an efficient maintenance strategy, however, can be seen as the lack of significant events such as machine failures or breakdowns. However, if management are notified of current problems, they might even be able to anticipate increased maintenance costs.

The notification to personnel about parameter limit violations furthermore creates transparency regarding the efficiency of the maintenance strategy. This transparency can propagate to a mining group level, where one person can accurately track and compare maintenance strategies of various gold mines within the same mining group. A reduction in notifications can thus be seen as an improved maintenance strategy. Since the same source of alarm notifications is used for everyone, the data integrity is not compromised.

There are some requirements for making alarm notifications as informative as possible. They must:

- Reach the recipient timeously;
- Be accessible irrespective of the recipient's location;
- Be recipient hardware independent;
- Have low operating cost;
- Automated, and
- Include relevant information such as:
    - Site name;
    - Machine name;
    - Measurement description, and
    - Measured value.

The easiest methods of sending alarm notifications are thus either via Short Message Service (SMS) or e-mail messages directly from the CMS on site. Both methods are low cost and communicate directly to mine personnel irrespective of their location. Since most mining personnel are not always in their offices with immediate access to their e-mails, and as they are already receiving a significant number of e-mails daily, they prefer to get alarm notifications via SMS messages.

The alarm notification frequency should not be too high for parameters that regularly exceed their defined parameter limits. The purpose is to notify mine personnel about undesired parameter values and not annoy them. When people get annoyed by notifications, they tend to start ignoring them. Therefore, a higher notification frequency does not necessarily mean that notifications will result in faster maintenance.

2.5 Reporting

This section of the implementation process discusses feedback generated by the CMS in the form of reports. The first report is a daily report that is automatically generated daily, while the second report is a monthly report that is generated by the CMS at the end of each month.

2.5.1 Daily reporting

A report that combines the parameter violations for all the systems of each site should be generated automatically every day and sent to the maintenance personnel. Reports provide personnel with an overview of the previous day's noteworthy events in terms of machine operating conditions. Reports help personnel prioritise maintenance tasks and plan maintenance more efficiently. Additionally, this report should also include warnings of machines operating with parameters that are close to their defined limits but do not exceed them. A warning limit, which is just lower than the parameter limit is used to this. The difference between these limit values is primarily influenced by the rate of change of the monitored parameter. This can be helpful in assisting maintenance personnel with planning preventative maintenance tasks and obtaining the necessary replacement parts that might be needed to do proper maintenance before machines break down. A typical example of such a report can be found in Annexure E.

It is also important to keep track of the overall CMS and provide mine personnel with regular feedback. This will enable personnel to adjust the maintenance time allocation accordingly and focus on problem areas. It will also aid in quantifying the impact and efficiency of the CMS. An overview report of monthly critical exceptions is generated and discussed with mining personnel monthly. These monthly reports will be discussed in the next section.

2.5.2 Monthly reporting

The tracking of a CMS impact is difficult to quantify, since improvements are not always instantly or directly observable. The tracking needs to be dependent on the overall condition of MSSs. The system condition was evaluated by analysing the number of parameter limit violations for each machine. Therefore, if a machine parameter limit is violated once a day by the averaged or aggregated parameter value, it will give a count of one towards the system total. In a similar fashion, a machine can add a count for each monitored parameter daily if all its parameters exceed their defined limits. These violation events are referred to as critical exceptions. The total for each MSS is calculated monthly and added to obtain a total number of critical exceptions per gold mine.

Figure 23 shows an example of the parameter violation count for a monthly report of a gold mine.

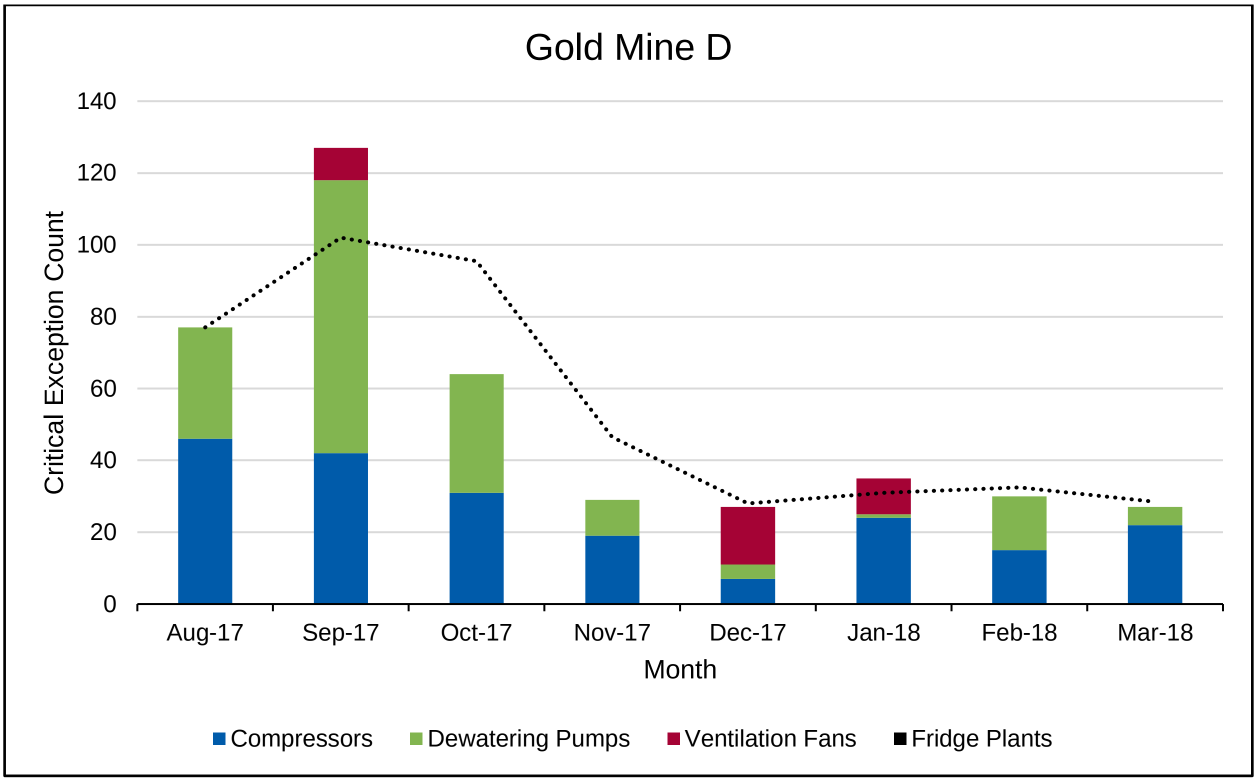


Figure 23: Monthly MSS critical exception count

A reduction in the critical exception count of a gold mine could indicate that more preventative maintenance is being done by mine personnel. Preventative maintenance is thus being done by mine personnel to prevent parameters from exceeding their defined parameter limits.

2.6 Summary

In this chapter, a generic process for implementing a CMS on South African gold mines was developed. The basic elements of this developed process were then discussed individually. This included a discussion on how parameter data can be obtained from the mine's SCADA system, which is recorded at 30-minute intervals. The naming convention for recorded tag data was also reviewed along with the computers involved in processing recorded data.

The methods of determining parameter limits were discussed as well as the impact that the presence of a parameter limit can have on the visual representation thereof. The function of an alarm notification system was discussed along with its benefits on the awareness of deteriorating machine conditions. Furthermore, a brief overview was given on how the impact of the CMS is being quantified and reported to mining personnel.

CHAPTER 3

Case Studies

3.1 Introduction

This chapter discusses the implementation of a CMS on a number of gold mines, which is done in a step-by-step method to make it easier to follow. The concepts discussed in the previous chapter are applied in the implementation process. Two case studies are used to illustrate the implementation process that was developed. The case studies include some of the first gold mines where this process was applied, which are discussed in the following paragraphs.

3.2 Case studies

Two South African gold mines are used as case studies to illustrate the developed implementation process. They are referred to as Mine A and Mine B.

Mine A

Mine A is a gold mine located in the Free State Province about 270 km southwest of Johannesburg. It has a depth of around 3 000 m. Mechanised mining is the primary ore extraction technique.

Mine B

Mine B is a gold mine located in the Free State Province. It is one of the mines mining the Basal Reef. The mine is around 2 500 m deep and is being expanded to increase its capacity. It has a monthly capacity of more than 90 000 tonnes [64].

3.2.1 <u>Step 1</u> → Investigation

The first step in the implementation process is to identify which MSSs should be included in the CMS. The machines that make up these systems should be identified and listed. Only machines with at least temperature or vibration parameters that are being monitored on the SCADA system will be considered as having sufficient instrumentation.

There are four MSSs on each of these mines that must be considered. They are the ventilation system, dewatering system, compressed air system and refrigeration system. The machines that make up these systems on Mine A are summarised in Figure 24, which are all primary MSS machines. These machines are marked with green, while the machines marked in red do not have sufficient instrumentation. These machines will therefore be excluded from the CMS and its implementation. Since the compressors on Mine A lack temperature and vibration sensors, the only MSSs that will be monitored are the ventilation, pumping and refrigeration systems.

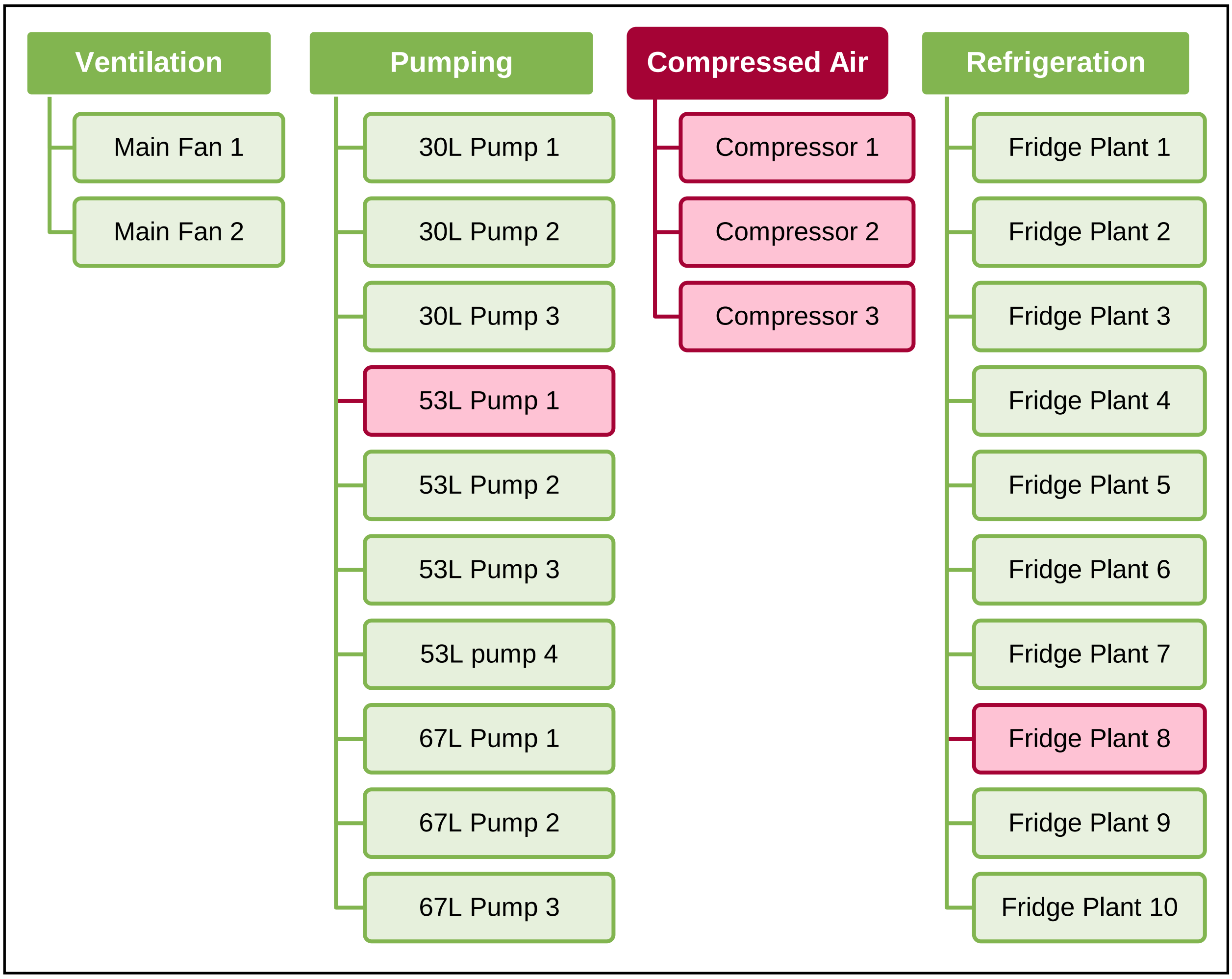


Figure 24: Summary of machines per MSS on Mine A

In a similar way, the machines that make up the MSSs on Mine B can be summarised as shown by Figure 25.

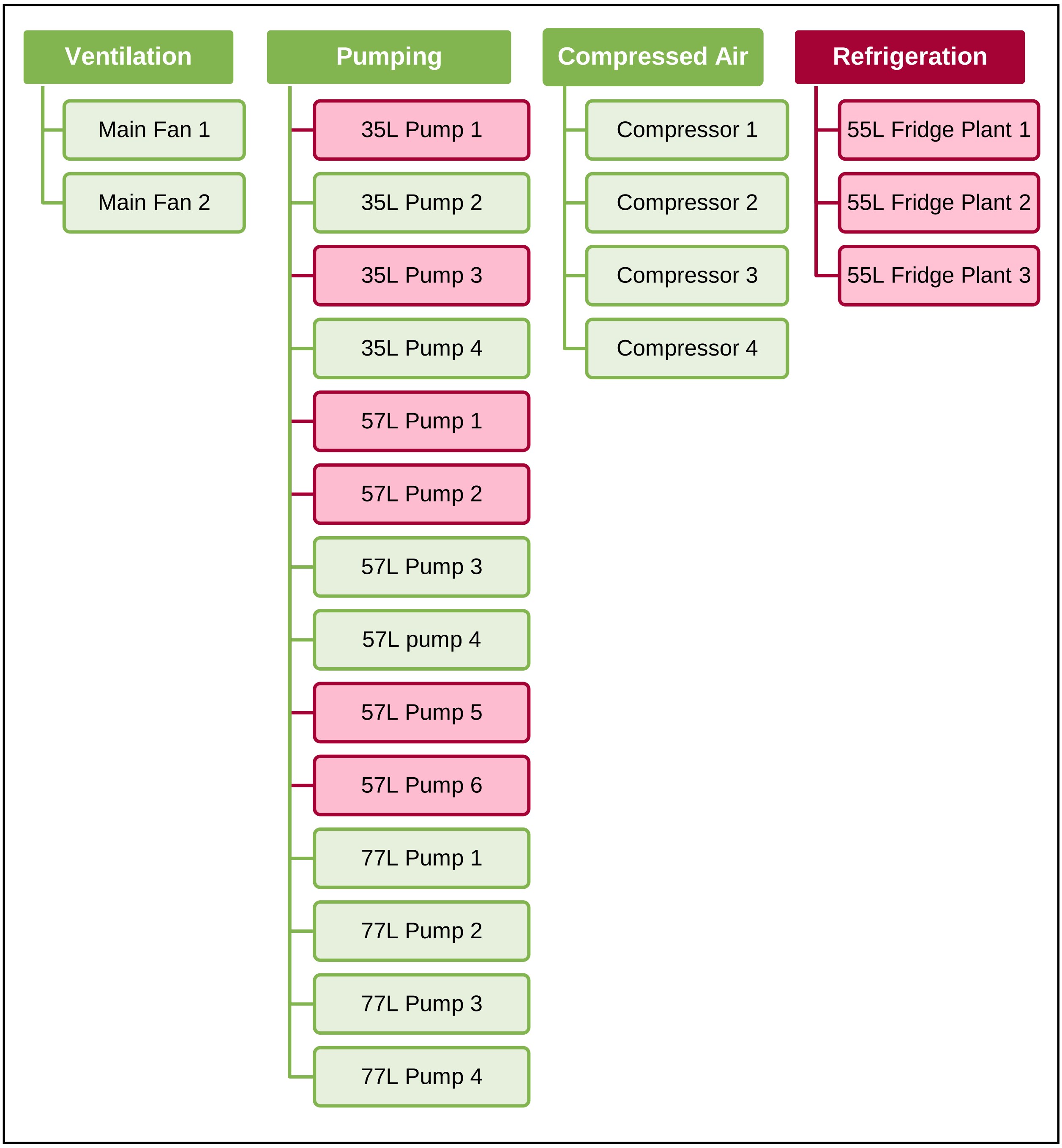


Figure 25: Summary of machines per MSS on Mine B

In the case of Mine B, all the fridge plants as well as several pumps lack instrumentation for remote condition monitoring. Therefore, these pumps and the refrigeration system will be excluded from the condition monitoring implementation process. These machines are marked in red and will be included in the CMS once they become operational again.

There is no dedicated condition monitoring server available on Mine A, and one will need to be installed. There is a server available on Mine B that can be reconfigured to be a dedicated condition monitoring server. This also means that an OPC connection will need to be established to the SCADA computer. The details of the server installation and configuration required to establish an OPC connection will not be discussed since they are not deemed relevant to the implementation process.

The next step in the investigation process is to obtain a tag list. A tag list provides a more accurate and detailed indication of relevant parameters being monitored for each machine. The easiest and most reliable way of obtaining the tag list is to download it as a text file either directly from the SCADA computer or on the condition monitoring server via the OPC connection that was established.

The last step in this part of the implementation process is to create a commissioning sheet that contains all the parameters that will be monitored. There is some basic information that needs to be indicated in this sheet for each monitored machine. The required information includes aspects such as the MSS the machine is part of, the machine name, the measurement locations of the monitored parameters and the type of parameters that are being measured.

It is recommended that the commissioning sheet be partitioned according to the MSS being monitored. In the case of Mine A, there are three partitions, which are ventilation, pumping and refrigeration. The commissioning sheet for Mine B also only has three partitions, which are ventilation, pumping and compressed air. Partitions make it easier to navigate the commissioning sheet and find specific machines.

Monitored parameters should be grouped according to their type such as temperatures, vibrations and pressures. Furthermore, it is a good idea to indicate the unit of measurement for each measurement type. Examples of the recommended parameter layout for a machine from each MSS of Mine A and Mine B are shown in Figure 26.

Note that the compressed air system for Mine A and the refrigeration system for Mine B in Figure 26 have been greyed as they are excluded from the CMS. The basic blocks shown in Figure 26 should be created for each machine included in the CMS. The measurement locations and measurement types shown in Figure 26 can be expanded or reduced according to the machine being monitored and the parameters available for that machine.

Mine A											
Ventilation			Pumping			Refrigeration			Compressed Air		
Machine	Measurement Type	Measurement Location	Machine	Measurement Type	Measurement Location	Machine	Measurement Type	Measurement Location	Machine	Measurement Type	Measurement Location
Main Fan 1	Vibration (mm/s)	Motor DE	30L Pump 1	Vibration (mm/s)	Motor DE	Fridge Plant 1	Vibration (mm/s)	Motor DE		Vibration (mm/s)	
		Motor NDE			Motor NDE			Motor NDE			
		Fan DE			Pump DE			Compressor DE			
		Fan NDE			Pump NDE			Compressor NDE			
	Temperature (°C)	Motor DE		Temperature (°C)	Motor DE		Temperature (°C)	Motor DE		Temperature (°C)	
		Motor NDE			Motor NDE			Motor NDE			
		Fan DE			Pump DE			Compressor DE			
		Fan NDE			Pump NDE			Compressor NDE			
	Status (-)	Running Status		Status (-)	Running Status		Status (-)	Running Status		Status (-)	
	Current (A)	Motor		Current (A)	Motor		Current (A)	Motor		Current (A)	
	Energy (W)	Motor		Energy (W)	Motor		Energy (W)	Motor		Energy (W)	

Mine B											
Ventilation			Pumping			Refrigeration			Compressed Air		
Machine	Measurement Type	Measurement Location	Machine	Measurement Type	Measurement Location	Machine	Measurement Type	Measurement Location	Machine	Measurement Type	Measurement Location
Main Fan 1	Vibration (mm/s)	Motor DE	30L Pump 1	Vibration (mm/s)	Motor DE	Fridge Plant 1	Vibration (mm/s)		Compressor 1	Vibration (mm/s)	Motor DE
		Motor NDE			Motor NDE						Motor NDE
		Fan DE			Pump DE						Compressor DE
		Fan NDE			Pump NDE						Compressor NDE
	Temperature (°C)	Motor DE		Temperature (°C)	Motor DE		Temperature (°C)			Temperature (°C)	Motor DE
		Motor NDE			Motor NDE						Motor NDE
		Fan DE			Pump DE						Compressor DE
		Fan NDE			Pump NDE						Compressor NDE
	Status (-)	Running Status		Status (-)	Running Status		Status (-)			Status (-)	Running Status
	Current (A)	Motor		Current (A)	Motor		Current (A)			Current (A)	Motor
	Energy (W)	Motor		Energy (W)	Motor		Energy (W)			Energy (W)	Motor

Figure 26: Basic commissioning sheet information layout

Once the basic blocks have been created for all the machines, the relevant tag names (SCADA tag names) for each of the measurement locations can be added. The most reliable way is by referring to the tag list downloaded earlier to ensure that the tag names and their spelling are correct.

The next step is to assign new, more descriptive tag names to the parameters by using the naming convention discussed earlier. This makes it easier to organise and find monitored parameters according to their tag names. Figure 27 gives an example of the added tag names and their corresponding new tag names for a ventilation fan on Mine A.

Machine	Measurement Type	Measurement Location	SCADA Tag Name	Condition Monitoring Tag Name
Main Fan 1	Vibration (mm/s)	Motor	T4_000VS01.T4_000VS01_MTR01_VT01	Gauteng Gold_Mine A_Ventilation_MainFan1_Motor Vib_V
		Fan	T4_000VS01.T4_000VS01_FAN01_VT01	Gauteng Gold_Mine A_Ventilation_MainFan1_Fan Vib_V
	Temperature (°C)	Motor DE	T4_000VS01.T4_000VS01_MTR01_TT01	Gauteng Gold_Mine A_Ventilation_MainFan1_Motor DE Bearing Temp_T
		Motor NDE	T4_000VS01.T4_000VS01_MTR01_TT02	Gauteng Gold_Mine A_Ventilation_MainFan1_Motor NDE Bearing Temp_T
		Fan DE	T4_000VS01.T4_000VS01_FAN01_TT01	Gauteng Gold_Mine A_Ventilation_MainFan1_Fan DE Bearing Temp_T
		Fan NDE	T4_000VS01.T4_000VS01_FAN01_TT02	Gauteng Gold_Mine A_Ventilation_MainFan1_Fan NDE Bearing Temp_T
	Status (-)	Running Status	T4_000VS01.T4_000VS01_FAN01_XS01	Gauteng Gold_Mine A_Ventilation_MainFan1_Running_Y
	Current (A)	Motor	T4_000VS01.T4_000VS01_MTR01_IT01	Gauteng Gold_Mine A_Ventilation_MainFan1_Motor Cur_I
	Energy (W)	Motor	Not Being Measured	

Figure 27: Adding tag names to the commissioning sheet for Mine A

Note that there is only one vibration tag in the commissioning sheet shown in Figure 27 as there is only one vibration sensor mounted on each machine to indicate the entire machine's vibration.

The process of adding tag names should be repeated for each machine in the CMS until the entire sheet is populated. Figure 28 gives an example of the added tag names for a ventilation fan on Mine B.

Machine	Measurement Type	Measurement Location	SCADA Tag Name	Condition Monitoring Tag Name
Main Fan 1	Vibration (mm/s)	Motor DE	analog.vent1_mot_de_vibration	Gauteng Gold_Mine B_Ventilation_MainFan1_Motor DE Bearing Vib_V
		Motor NDE	analog.vent1_mot_nde_vibration	Gauteng Gold_Mine B_Ventilation_MainFan1_Motor NDE Bearing Vib_V
		Fan DE	analog.vent1_fan_de_vibration	Gauteng Gold_Mine B_Ventilation_MainFan1_Fan DE Bearing Vib_V
		Fan NDE	analog.vent1_fan_nde_vibration	Gauteng Gold_Mine B_Ventilation_MainFan1_Fan NDE Bearing Vib_V
	Temperature (°C)	Motor DE	analog.vent1_mot_de_temp	Gauteng Gold_Mine B_Ventilation_MainFan1_Motor DE Bearing Temp_T
		Motor NDE	analog.vent1_mot_nde_temp	Gauteng Gold_Mine B_Ventilation_MainFan1_Motor NDE Bearing Temp_T
		Fan DE	analog.vent1_fan_de_temp	Gauteng Gold_Mine B_Ventilation_MainFan1_Fan DE Bearing Temp_T
		Fan NDE	analog.vent1_fan_nde_temp	Gauteng Gold_Mine B_Ventilation_MainFan1_Fan NDE Bearing Temp_T
	Status (-)	Running Status	digital.vent1_motor_running	Gauteng Gold_Mine B_Ventilation_MainFan1_Running_Y
	Current (A)	Motor	Not Being Measured	
	Energy (W)	Motor	Not Being Measured	

Figure 28: Adding tag names to the commissioning sheet for Mine B

Take note that there are no tags added for the fan's motor current and energy usage for Mine B as shown in Figure 28 as there is no instrumentation on Mine B for monitoring the energy consumption of the ventilation fans. This should be indicated accordingly on the commissioning sheet and a similar approach should be used for other machines on the commissioning sheet.

This step concludes the investigation part of the process. The next step, namely, data gathering is discussed in the next subsection.

3.2.2 Step 2 → Data gathering

The primary objective of this part of the implementation process is as the name implies, to collect data. In other words, this part of the implementation process focuses on initiating a process of collecting or gathering the monitored parameter values for the various machines.

For this thesis, a software package called REMS® was used to record parameter values. This program allows the user to configure software components dedicated to condition monitoring for data logging purposes. The parameter values are refreshed every two minutes, which means that an average is calculated every 30 minutes for 15 values for each parameter in the logger.

Individual data loggers have to be created for each MSS included in the CMS of the mine. This makes it easier to maintain and update these loggers when needed.

The parameter data for the mines was logged as the average values of two-minute data intervals every 30 minutes. This means that 15 values were averaged and logged at half-hourly intervals for each parameter. This average value logging helped reduce the data volume significantly, which also resulted in reduced processing required by the central server responsible for data archiving and reporting. The vibration sensors on all the monitored machines on this mine were limited to one per machine. Mine A had a total of 130 parameters monitored by the CMS, which resulted in 6 200 parameter values being monitored and logged daily.

The condition monitoring parameter values for Mine B were calculated and logged in the same way as Mine A. The CMS of Mine B monitored 125 parameters, which resulted in 6 000 parameter values being monitored on a daily basis. The ventilation system of this mine was well instrumented, and four vibration parameters and four temperature parameters could be monitored for the two ventilation fans.

Each logger creates a file every 30 minutes containing the calculated average parameter values, which is then sent to a central processing server. This processing server extracts the data from the e-mails, sorts the data according to their tag names, and updates the database with the latest parameter values from Mine A. This gathered data needs to be visualised to simplify its interpretation. This is discussed in the next section.

3.2.3 Step 3 → Data interpretation

It is important to ensure that users interpret the data logged by the CMS correctly. A visual representation of this logged data ensures that it is used correctly, which can save significant amounts of time when this is an automated process. An example of a visual data representation system is discussed in the following sections to emphasise the importance of visual data representation and illustrate the advantages of having such an automated process.

In the case of this thesis, a web-based user interface developed for condition monitoring was used. This user interface for the CMS makes it easy for any authorised person to log in and view or analyse condition monitoring data. It provides access to all recorded historical data for the relevant machines on different gold mines. This interface is also known as Management Toolbox™ or MTB. The following subsections discuss the individual interface layouts and functions.

a) Site overview screen

The function of the site overview screen is to provide a quick overview of the machine conditions of the various systems on the different gold mines. This list is unique for different people; it differs depending on the mines they can access. Figure 29 provides an illustration of the screen.

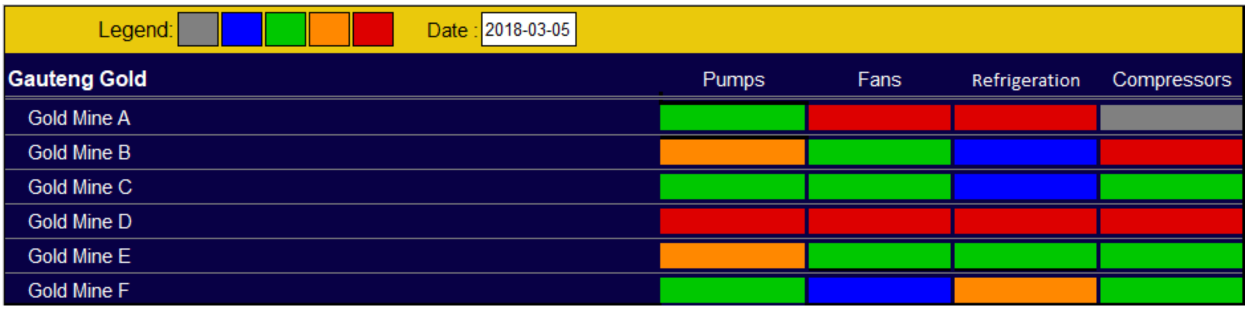


Figure 29: Condition monitoring overview of sites

This overview screen provides the user with a relative indication of the operating condition of machines from various systems included in the condition monitoring. The overview indicates the overall system condition on a specific date, which can be changed by the user. The machine condition is indicated by the coloured blocks that correspond to the status of a specific system of a gold mine. There are five different possible block colours, namely, grey, blue, green, orange and red:

- The grey blocks represent a system that is not included in the scope of the condition monitoring or is not logging data due to a lack of instrumentation, which is the case for the compressors on Mine A.
- The blue blocks represent systems where the limits for logged parameters have not been specified and the condition of the machines can thus not be quantified accordingly. These machines are also not considered when indicating the overall condition of a system.
- The green blocks represent systems where the machines are operating within parameter limits.
- The orange blocks represent systems where machines are operating close to their parameter limits.
- The overview screen indicates that there are machines within the system that require some maintenance to prevent unexpected failure. The red blocks represent machines that are already operating beyond their parameter limits and are close to failure. Such machines need maintenance urgently.

The overview block colour is determined according to the worst parameter in that specific system. This means if all machine parameters in that system are indicated as green except for one red parameter, the system condition is indicated as red on the overview page. This same visual indication is used for the system overview screen.

b) System overview screen

The system overview screen can be accessed by selecting (clicking) any one of the blocks on the site overview screen. Figure 30 illustrates the system overview screen when the “Pumps” option is selected for Mine A.

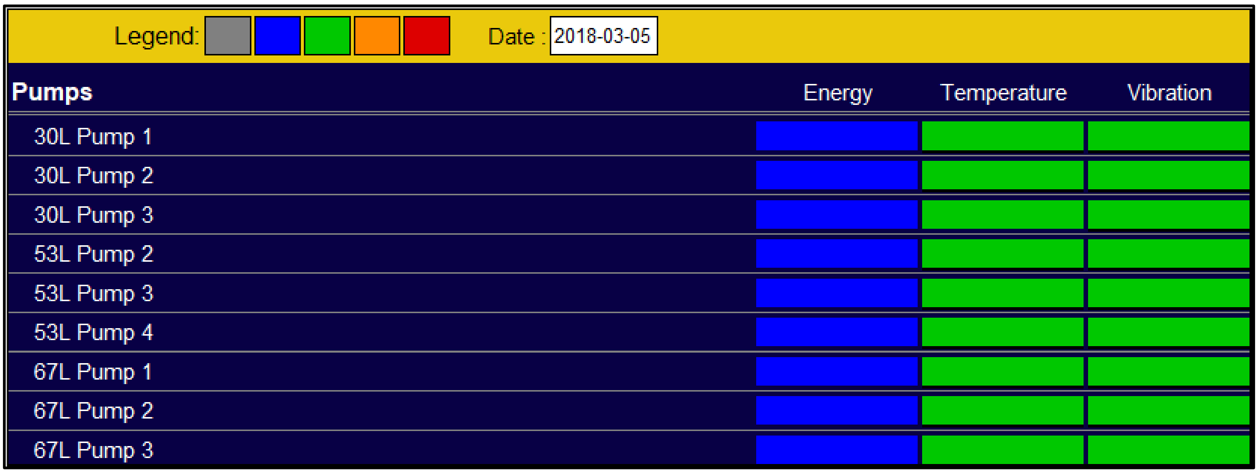


Figure 30: Condition monitoring overview of an MSS on Mine A

Take note of the absence of a “53L Pump 1” from the system overview screen in Figure 30. This pump was excluded from the CMS due to a lack of instrumentation. The system overview screen provides the user with a list of machines being monitored under the selected system of the corresponding gold mine. It does differ from the site overview screen discussed in Paragraph a) as the different systems for each site have now been replaced by the monitored parameter types for each machine. The site names have also been replaced by the machine descriptions in the specific system. In the case of Mine A, the condition of the pumping system will be indicated as green on the site overview screen.

Selecting the “Compressors” option for Mine B results in a similar system overview screen as shown in Figure 31.

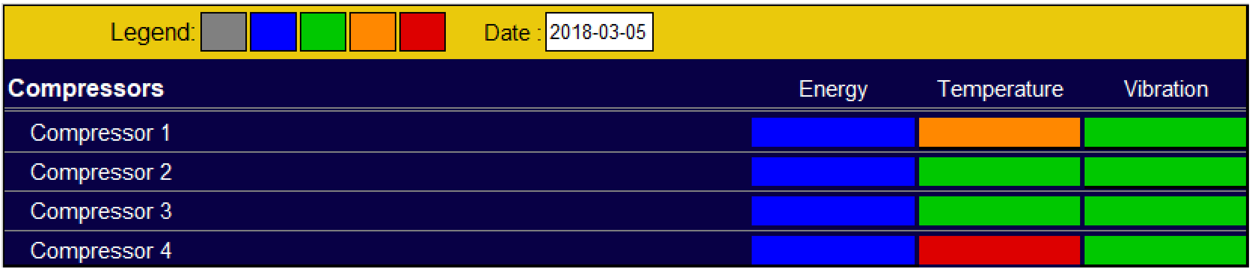


Figure 31: Condition monitoring overview of an MSS on Mine B

The overall condition of the system is dictated by the machine parameter with the value relative to its specified limit. In the case on Mine B, the system overview screen shown in Figure 31 will result in a red block on the site overview screen as shown in Figure 29. The user can select a block on the system overview screen to access the parameter overview screen.

c) Parameter overview screen

The parameter overview screen is used to view a 24-hour trend of the parameters of a specific type for an individual machine. The date range for these graphs can be specified by the user to a maximum range of 14 consecutive days. The end date of this range can also be specified by the user. An example of the parameter overview screen for a dewatering pump on Mine A is shown in Figure 32.

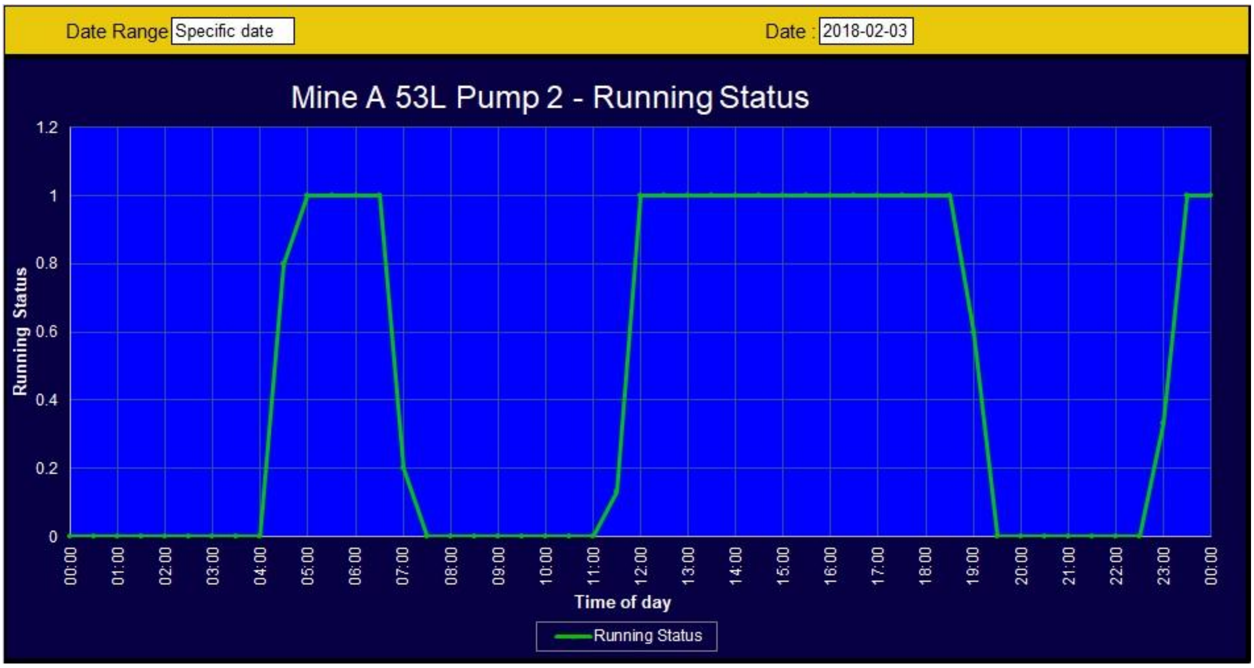


Figure 32: Example of a machine's 24-hour running status

The graph in Figure 32 shows the 24-hour running status trend of 53L Pump 2. The running status graph of each machine is included in every parameter overview screen. The running status graph is followed by the recorded parameters for the specific parameter type. An example of a parameter graph is shown in Figure 33, which is the 24-hour temperature trends of the pump’s DE and NDE bearing temperatures. When the trend from Figure 32 is cross-referenced with the trend in Figure 33, it can be seen that the bearing temperatures correspond with the machine’s running status. These graphs contain 48 half-hourly data points for each daily trend. The data in Figure 33 shows that the bearings are operating well below their specified operating limit. This explains the green colour indication on the system overview screen shown in Figure 30.

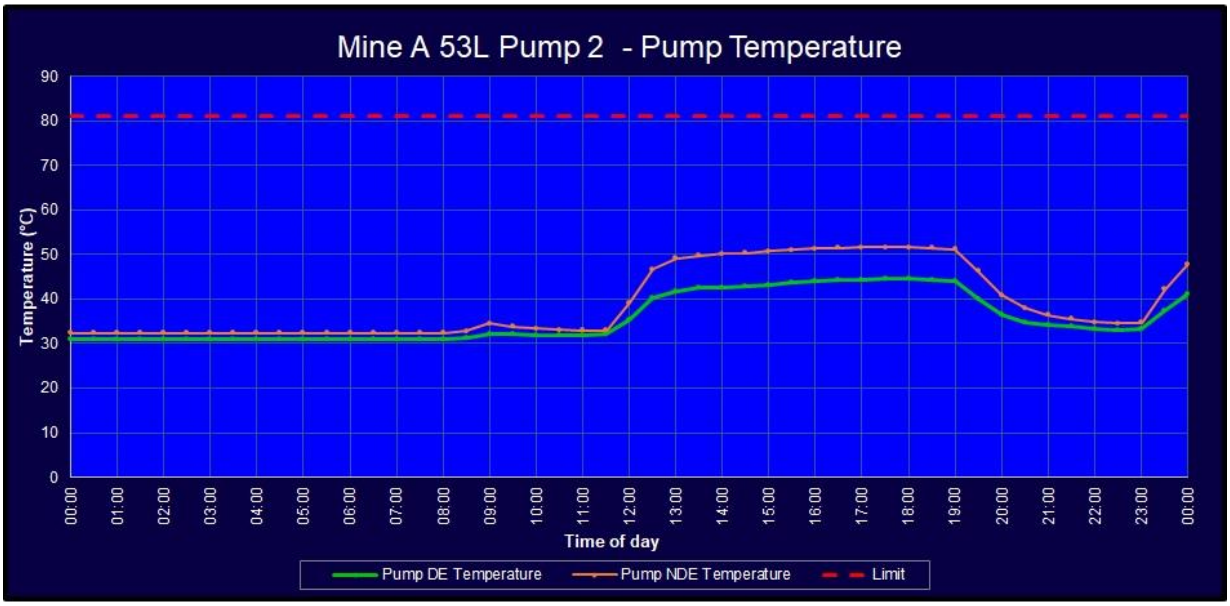


Figure 33: Pump 24-hour bearing temperature trend

Selecting compressor 2's temperature block on Mine B's system overview screen results in a similar parameter overview screen as illustrated in Figure 34. Due to the compressor running constantly for the day, the running status is not illustrated even though it is shown on the parameter overview screen.

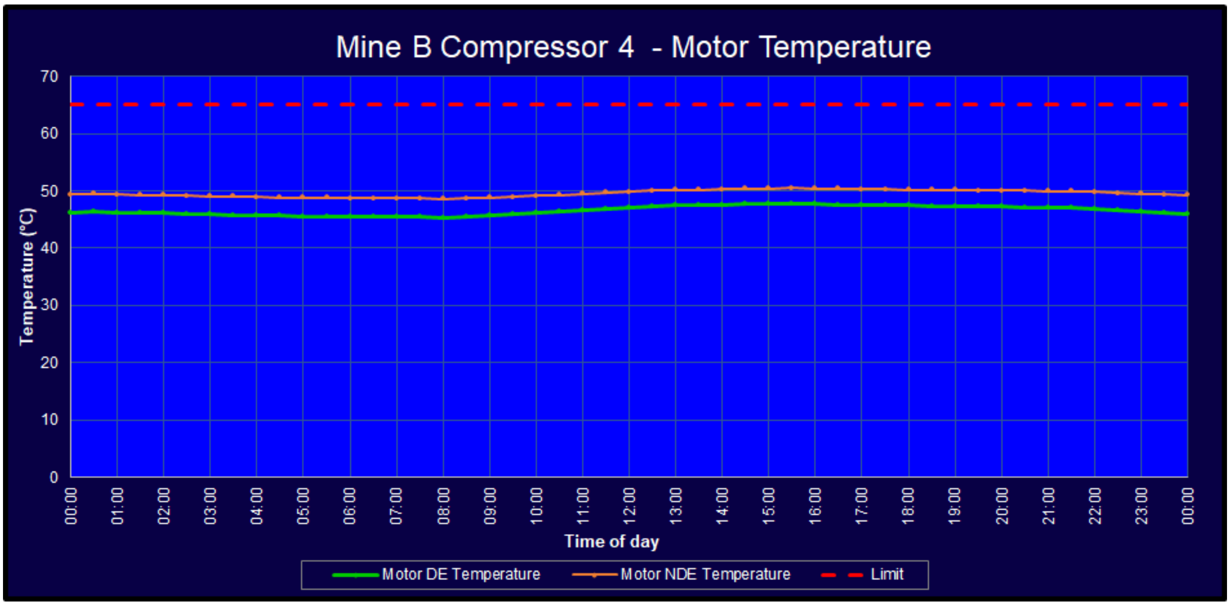


Figure 34: Compressor motor 24-hour bearing temperature trend

Similar trends apply to all the monitored parameters of machines in the CMS. It makes the web-based user interface useful. However, personnel do not always have the time to comb through each monitored parameter on a regular basis. Therefore, CMS reporting is important, which is discussed in the following subsection.

d) Alarm notifications

It is important to choose the alarm frequency so that the CMS is able to notify maintenance personnel of parameter limit violations before it is too late. The alarms were thus required to satisfy some important conditions to initiate alarm notifications. These conditions were that:

- The monitored machine has to be running.
- The monitored parameter has to exceed its parameter limit continuously for five minutes.
- Only one alarm notification could be sent daily for each monitored parameter.
- The notification has to include a complete description of the monitored parameter as well as its value at the time of the notification being generated.

Examples of SMS alarm notifications, being sent by the CMS system, are shown for Mine A and Mine B in Figure 35.

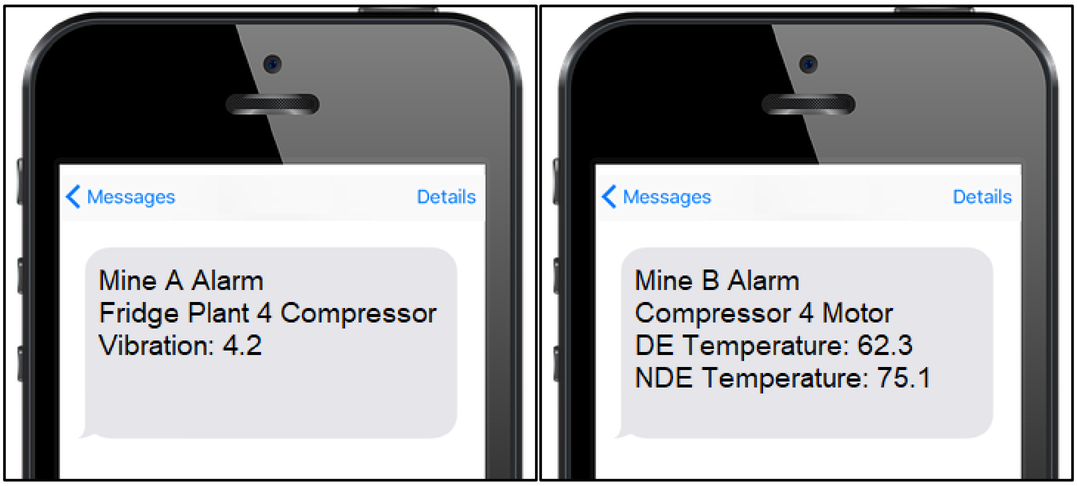


Figure 35: Examples of an alarm notification SMS message

The message on the left in Figure 35 indicates that the vibration of the fridge plant compressor exceeded the parameter limit and is currently at 4.2 mm/s. The message on the right of Figure 35 shows that one of Mine B's compressor 4 motor bearing temperatures exceeded its defined limit and is currently at 75.1°C. Parameter limit violations are also included in a daily exception report sent to mine personnel, which is discussed in the next section.

3.2.4 <u>Step 4</u> → Reporting

The condition monitoring reporting is discussed at the hand of critical exceptions generated by individual CMS on the two example mines.

a) Feedback and results

In the event of a parameter exceeding its predefined limit, a notification is sent to the relevant recipients. If the half-hourly average parameter value also exceeds the parameter limit, a red indication is given on the web-based user interface, which is referred to as a critical exception. A critical exception can only occur once daily for each monitored parameter. This means that a machine with six monitored parameters can have a maximum critical exception count of six per day.

A critical exception report, which indicates the critical exceptions from the previous day, is automatically generated daily for each gold mine. This report lists machine parameters that were operating close to their parameter limits. The report shows the parameter name, parameter or critical limit, violation duration and violation period average. In the case of warning exceptions, the critical limit is replaced by the warning limit. In this case the warning limits was specified a 1 mm/s or 5 °C lower than the parameter or critical limit. A trend of the parameter value for the previous day is only shown for critical exceptions. An example of the critical and warning exceptions for Mine A is shown in Figure 36.

Summary of critical exceptions

Parameter	Critical Limit	Violation duration (hours)	Violation period average
Main Fan 2 Motor Vibration	6.0 mm/s	22.5	9.22 mm/s
Main Fan 2 Fan DE Vibration	6.0 mm/s	22.5	8.25 mm/s
FP 4 Compressor Vibration	4.0 mm/s	10.5	4.41 mm/s
FP 10 Compressor DE Temperature	76.0 °C	8	78.06 °C

Summary of warning exceptions

Parameter	Warning Limit	Violation duration (hours)	Violation period average
Main Fan 1 Fan NDE Vibration	5.0 mm/s	24	5.67 mm/s
FP 3 Motor Vibration	3.0 mm/s	20	3.46 mm/s
FP 10 Compressor NDE Temperature	71.0 °C	8.5	75.03 °C

Figure 36: List of warning and critical exceptions

The critical exception count of the individual MSS on a gold mine can be used to quantify the overall operating conditions of machines in these MSSs. The critical exception count of each mine is reported monthly to the relevant mining personnel. A reduction in the total monthly critical exceptions means that more preventative maintenance was done on machines, which in turn means that fewer critical exceptions were created.

Figure 37 shows an example of the total number of monthly critical exceptions created by each of Mine A's support systems. The bars in Figure 37 represent the number of critical exceptions created monthly by the individual MSSs. The critical exception count for each system is stacked to indicate a monthly total critical exception count for the entire gold mine.

The data in Figure 37 suggests that there was a decrease in critical exceptions from the second month of implementation, but an increase started in the fifth month after implementation. One of the reasons for this increase is that the maintenance planner of the mine was relocated. As a result, the condition of the machines started deteriorating due to a different approach to maintenance being done by his successor.

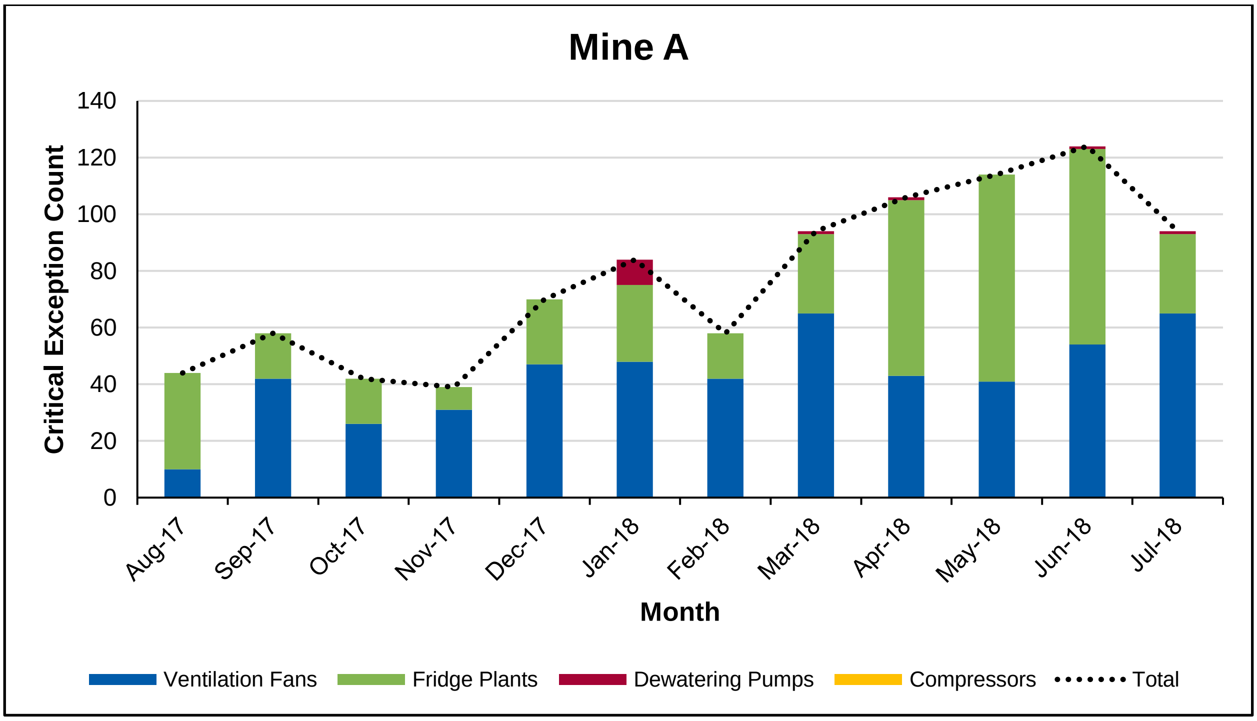


Figure 37: Total monthly exceptions – Mine A

Figure 38 shows the total number of critical exceptions created by the machines from Mine B's support systems.

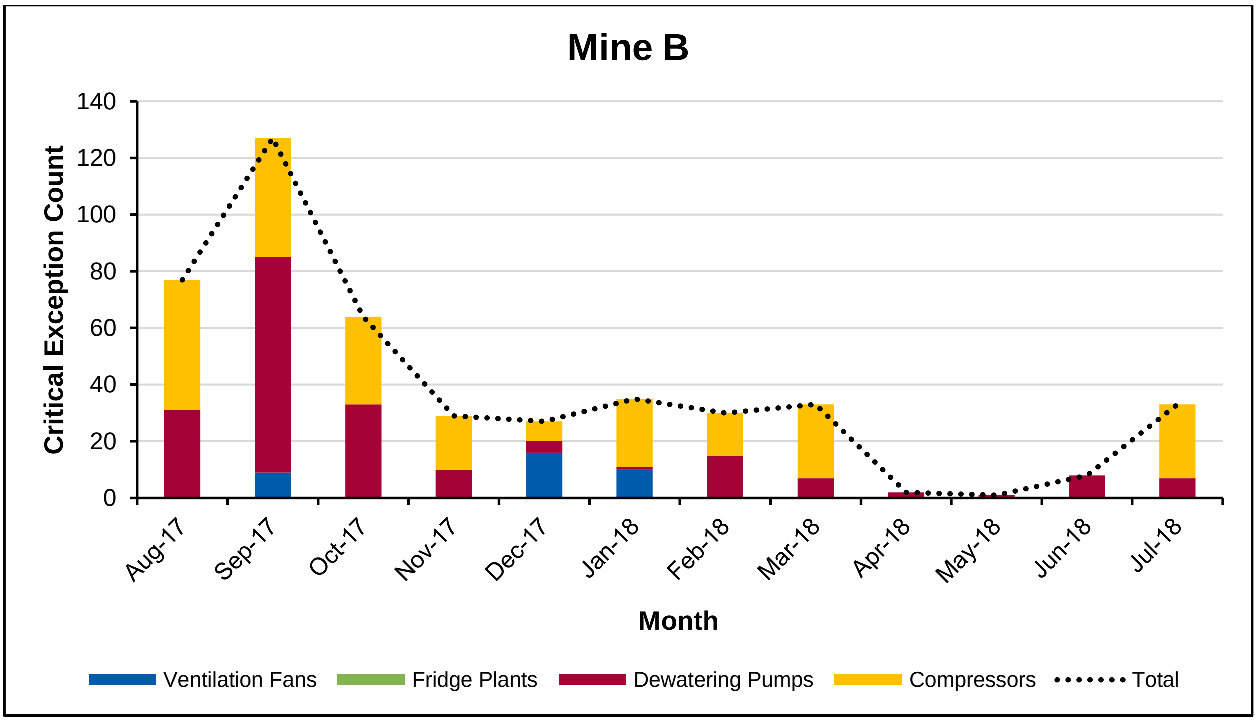


Figure 38: Total monthly exceptions – Mine B

The data in Figure 38 shows that the number of monthly critical exceptions decreased significantly until June 2018, although it increased significantly during the second month after the CMS was implemented. This can be attributed to the CMS operation being optimised and a slow adoption rate by mine personnel. It is also evident from the data that the cause of the increase in critical exceptions from June 2018 to July 2018 is the number of critical exceptions from the compressors. This suggests that the maintenance strategy for this MSS needs to be revised.

The goal of a CMS is firstly to reduce the number of critical exceptions by encouraging preventative maintenance. The secondary goal is to minimise parameter warning exceptions through early machine condition deterioration notifications.

3.3 Condition monitoring system group roll-out

This CMS was implemented on six different South African gold mines within the same mining group. The MSSs included in the CMS are mine dewatering, mine ventilation, mine refrigeration, and compressed air systems. These systems are not fully instrumented on all the mines, and only the systems with sufficient infrastructure were included in the CMS. The various systems on each of the gold mines are shown in Table 6.

Table 6: Summary of MSSs where condition monitoring was implemented

MSS	Ventilation Fans	Dewatering Pumps	Compressors	Refrigeration Plants (Fridge Plants)
Gold Mine A	✓	✓	✗	✓
Gold Mine B	✓	✓	✓	✗
Gold Mine C	✓	✓	✓	✗
Gold Mine D	✓	✓	✓	✓
Gold Mine E	✓	✓	✓	✓
Gold Mine F	✗	✓	✓	✓

The names of the mining group and gold mines where the CMS was implemented are substituted, as shown in Table 6, for confidentiality reasons. The primary parameters monitored for all the MSS machines were bearing vibrations and temperatures. This would help keep the CMS from becoming too large and complex to manage and optimise properly while still maintaining the feasibility thereof. The CMS was implemented incrementally on one gold mine at a time. This implementation process was the same for each gold mine. The total number of machines included in the CMS on the different gold mines is shown in Figure 39.

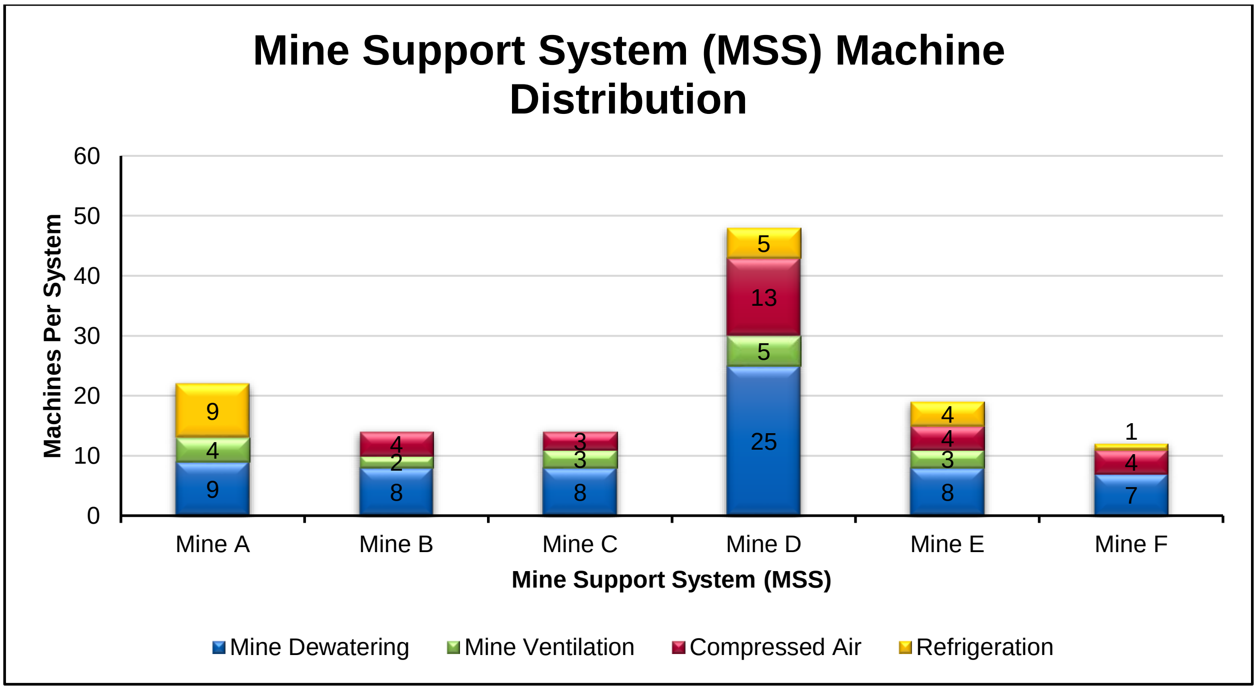


Figure 39: Machines per MSS

The data in Figure 39 indicates that the number of machines per MSS is closely matched between most mines, with the exception of the refrigeration systems, since not all mines have sufficient instrumentation on their fridge plants. Furthermore, Figure 39 shows that Gold Mine D has significantly more machines per MSS being monitored by the CMS. The results of implementing a remote CMS on these mines using the developed process is discussed in the next section.

The total monthly critical exception count of the six gold mines included in this system are summarised in Table 7 below.

Table 7: Gold mine monthly critical exception count

Components	Gold Mine A	Gold Mine B	Gold Mine C	Gold Mine D	Gold Mine E	Gold Mine F
Aug-17	44	77	0	247	8	23
Sep-17	58	127	0	222	15	18
Oct-17	42	64	0	255	11	14
Nov-17	39	29	0	239	6	5
Dec-17	70	27	0	282	1	23
Jan-18	84	35	1	274	1	29
Feb-18	58	30	1	221	8	6
Mar-18	94	33	0	248	12	4
Apr-18	106	2	0	161	15	0
May-18	114	1	1	203	20	27
Jun-18	124	8	1	134	21	4
Jul-18	94	33	0	248	12	4
Reduction	−114 %	57 %	N/A	0 %	−50 %	83 %

From the data shown in Table 7, three of the six gold mines showed a reduction in the monthly critical exception count. Mine A showed an increase in critical exceptions of 114%, which could be interpreted as a deteriorating maintenance strategy by the maintenance personnel of this mine.

The maintenance strategy of Mine B showed an initial increase after the CMS was implemented but experienced a significant reduction in the total number of critical exceptions. This is an example of a mine where the maintenance personnel embraced the CMS as an additional resource towards improved maintenance.

Mine C did not have any critical exceptions that could be reduced, which means that either the maintenance strategy on this mine was highly efficient or that instrumentation was not reflecting the true operating conditions of the machines for some reason. It is highly unlikely that all instrumentation on the mine was faulty, which means that the lack of critical exceptions might be the result of monitored parameters being manipulated.

Mine D is the largest mine where the CMS was implemented in terms of the number of monitored machines. This mine unfortunately did not show any improvement in the total number of monthly exceptions, which might be due to internal conflict between maintenance personnel and engineers on the mine.

Mine E showed a 50% increase in critical exceptions, which could also be interpreted as a reduction of preventative maintenance efforts, which could lead to more machine failures and increased maintenance and operational costs.

Mine F showed the best improvement in the number of monthly critical exceptions with an improvement of 83%. This was due to the maintenance personnel actively participating in the implementation and development of the CMS on this mine. Maintenance personnel were also highly motivated to keep machines in proper running condition.

The involved mining group’s quality control engineer required the maintenance planners of each mine to initiate maintenance tasks for all alarm notifications generated by the CMS. This would serve as a link between the CMS and the maintenance personnel, which would identify machines that required urgent preventative maintenance interventions. The success of this link formed by the mines’ maintenance planners could unfortunately not be evaluated since feedback on maintenance tasks was not communicated properly. There was unfortunately also no enforcement of this rule from the mine personnel’s side.

The involvement of maintenance personnel and their attitude towards such a condition monitoring implementation is essential. It can result in an overall improvement of machines’ operation conditions, or it can result in deteriorating machine operating conditions. One such case was identified on Mine F where the foreman responsible for maintenance on the mine’s fridge plants was relocated. His successor unfortunately did not manage maintenance activities as efficiently, which resulted in deteriorating operating conditions on the fridge plants. He did however find a way to optimise the maintenance management strategy, which was also reflected in the number of exceptions triggered by the fridge plants from February 2018. The change in maintenance management strategy efficiency can be seen from the total critical exceptions created monthly by the condition monitoring system as shown in Figure 40 below.

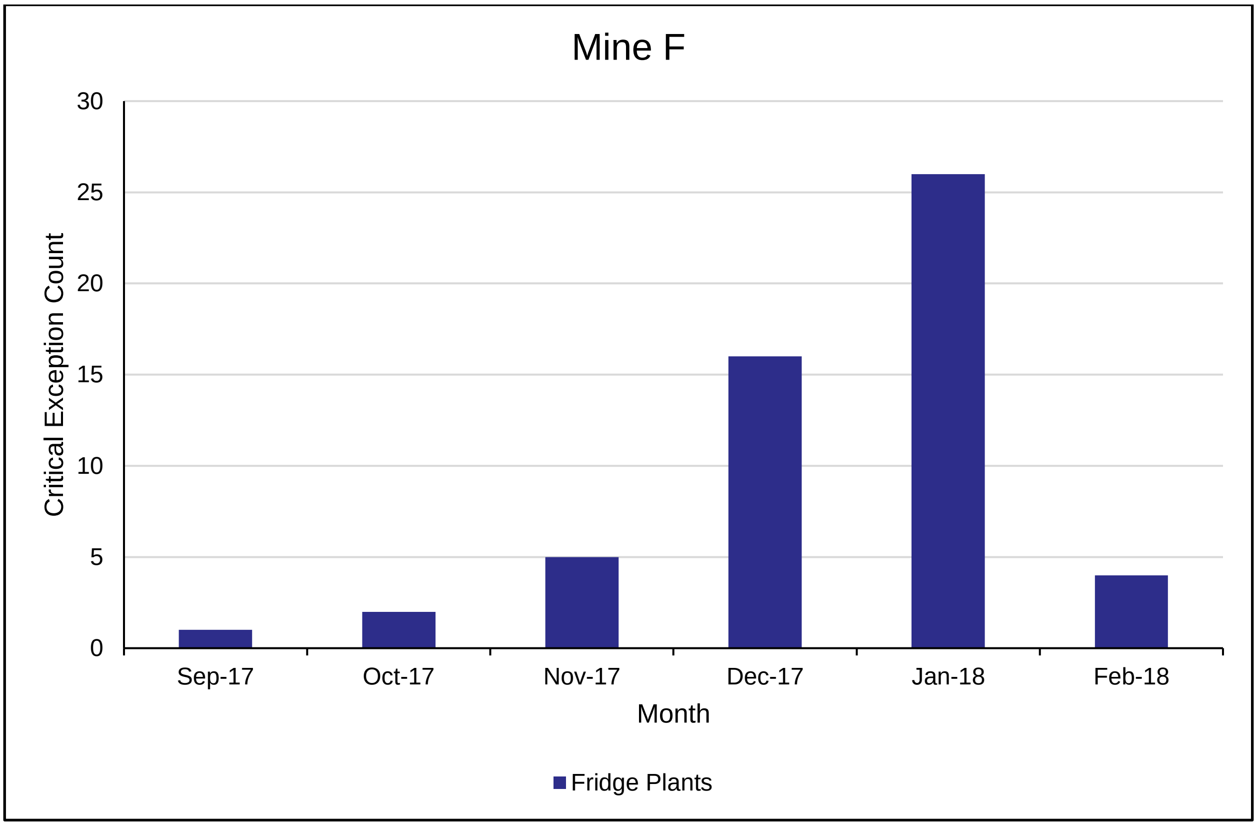


Figure 40: Deteriorating maintenance strategy efficiency

Looking at the total number of exceptions generated for the MSS's on the mines included in the implementation process shows the overall impact of the condition monitoring system on the machine operating conditions. The refrigeration systems and ventilation systems showed an overall increase in the total monthly exceptions triggered, while the compressed air systems and dewatering systems showed an overall decrease in the total monthly exceptions triggered. This is shown by the trendlines for the individual MSS's in Figure 41 below.

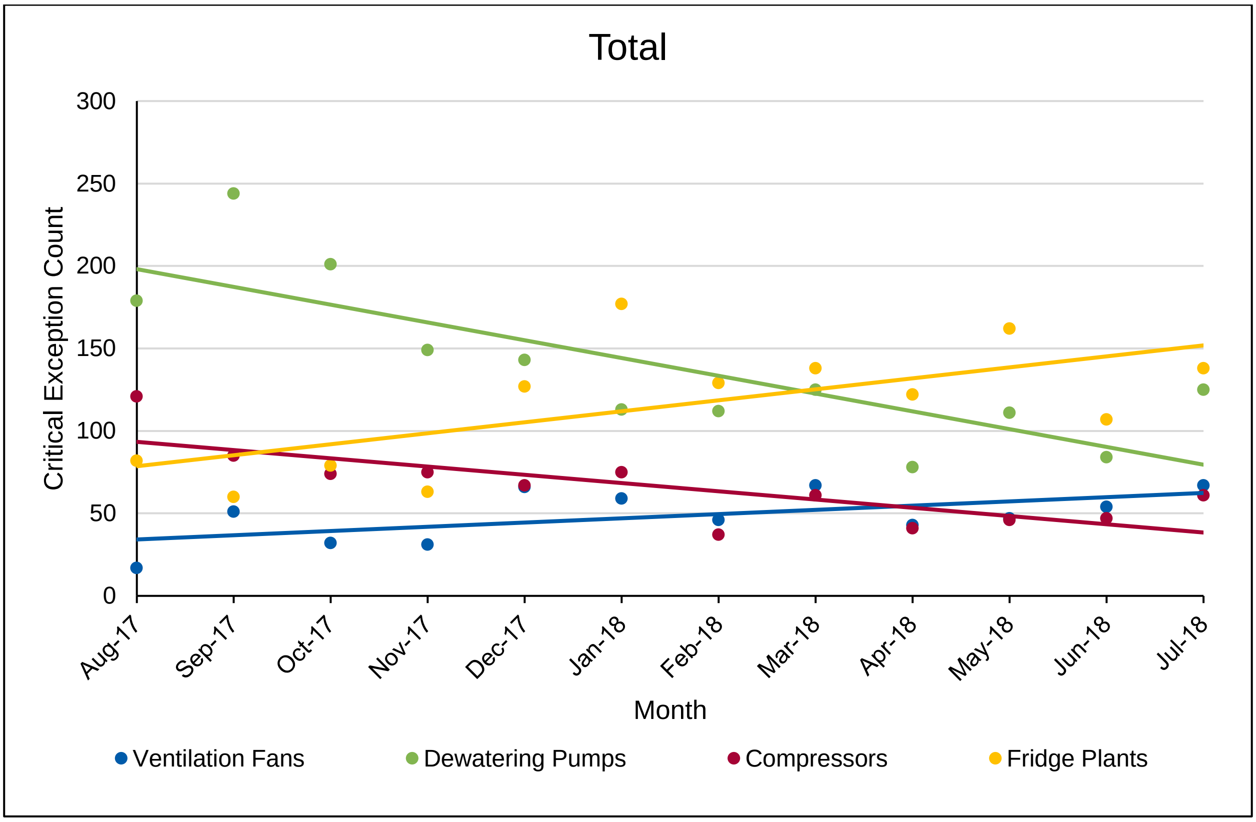


Figure 41: Critical exceptions per MSS

One of the main contributors to the MSS's with increased monthly critical exceptions, is Mine A. The majority of the critical exceptions generated for the ventilation systems of mines in the mining group originated from Mine A and can be seen in Figure 42 below.

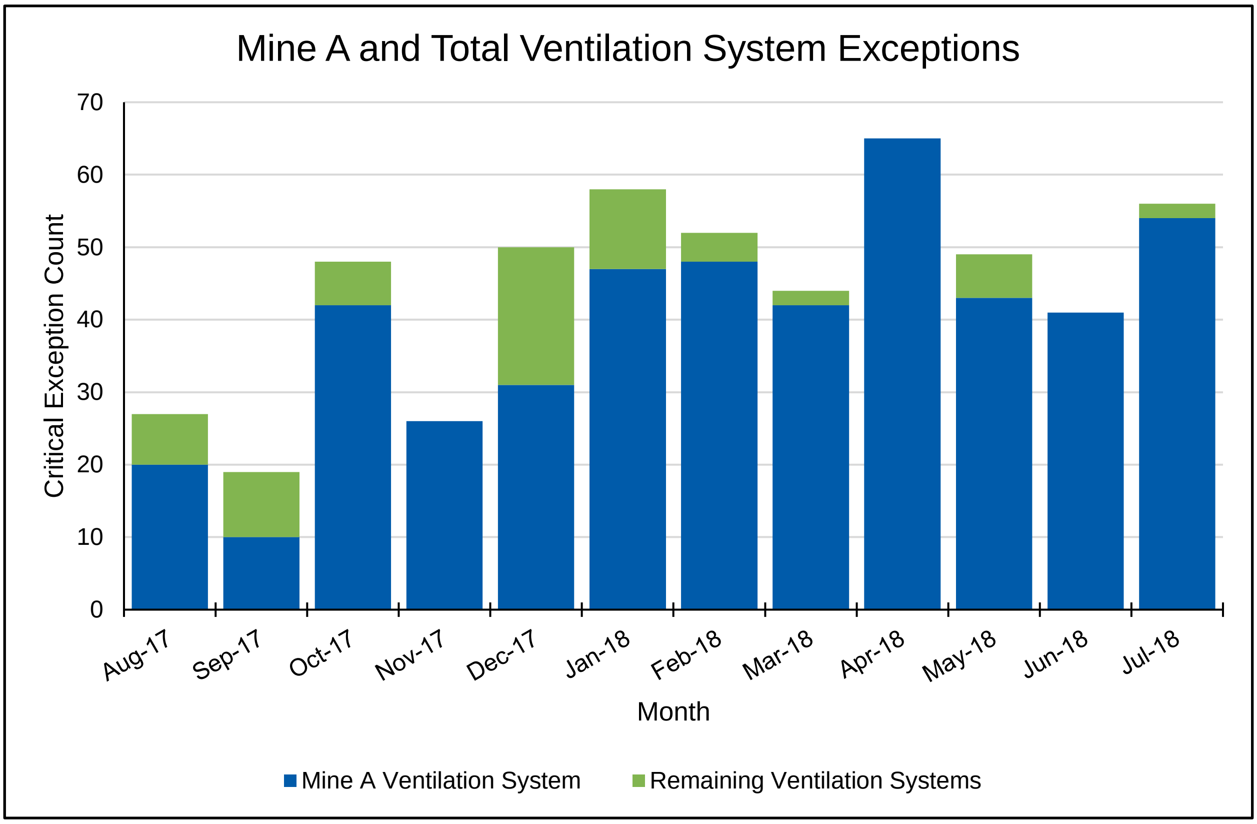


Figure 42: Effect a poor maintenance strategy on overall impact

This shows that an inefficient maintenance strategy of one mine can have a significant impact on the overall efficiency of maintenance strategies within the mining group.

The total operational cost savings achieved by the CMS for these mines over a period of one year was estimated by the quality control engineer of the relevant mining group to be more than R20 million. This cost saving is only an estimation of the replacement cost of machines identified by the CMS to be in critical operating condition. The potential losses in terms of lost production is thus not included in this amount. It is important to note that a CMS can only notify personnel of degrading operational conditions on machines, but it cannot enforce a maintenance strategy. This is still the responsibility of the maintenance personnel of each gold mine.

3.4 Machine condition improvements

Some instances of poor machine operating conditions identified by the implemented CMS resulted in cost saving maintenance interventions. These cost saving interventions refer to the maintenance being done on machines before critical failures occurred, which would have been more expensive to rectify. Some examples are discussed briefly in the following subsections according to their relevant MSSs.

3.4.1 Mine dewatering system

The CMS identified a mine dewatering pump on Mine E where the driving motor's bearing temperatures constantly exceeded the defined alarm limit. Notifications were generated by the CMS and sent to mine personnel. The abnormal bearing temperatures are shown in Figure 43.

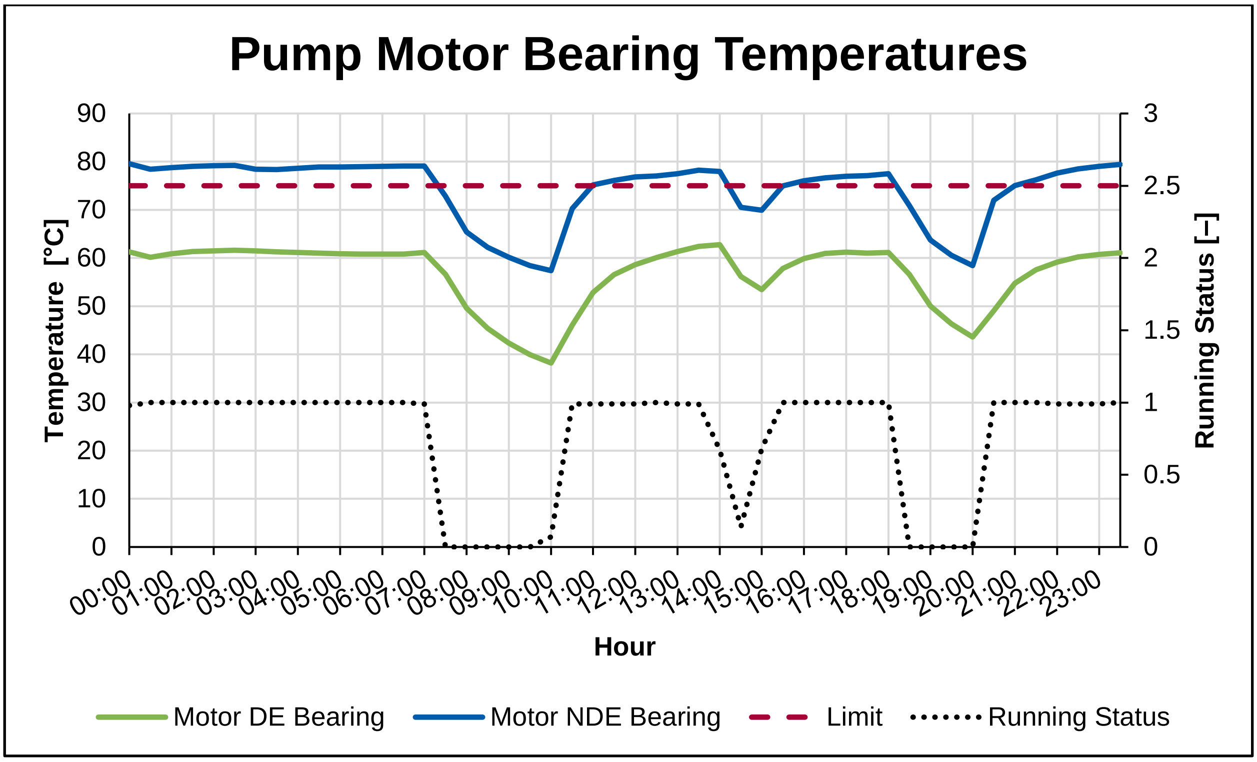


Figure 43: Excessive pump motor bearing temperatures

Figure 43 shows the half-hourly average bearing temperatures for an entire day for both the DE and NDE bearings of the motor. When looking at the pump's running status, it can be seen that both bearing temperatures decrease when the pump is stopped while they increase when it is started. The defined maximum temperature for these bearings is also shown. The graph clearly shows how the NDE bearing temperature repeatedly exceeded this alarm limit.

The cause of these high temperatures was investigated by the maintenance personnel and it was found that the motor was not installed correctly. More specifically, the motor alignment, coupling gap and magnetic centre were not determined correctly. This was corrected and the motor was restarted, which resulted in lower bearing operating temperatures. The improved bearing operating temperatures can be seen in Figure 44.

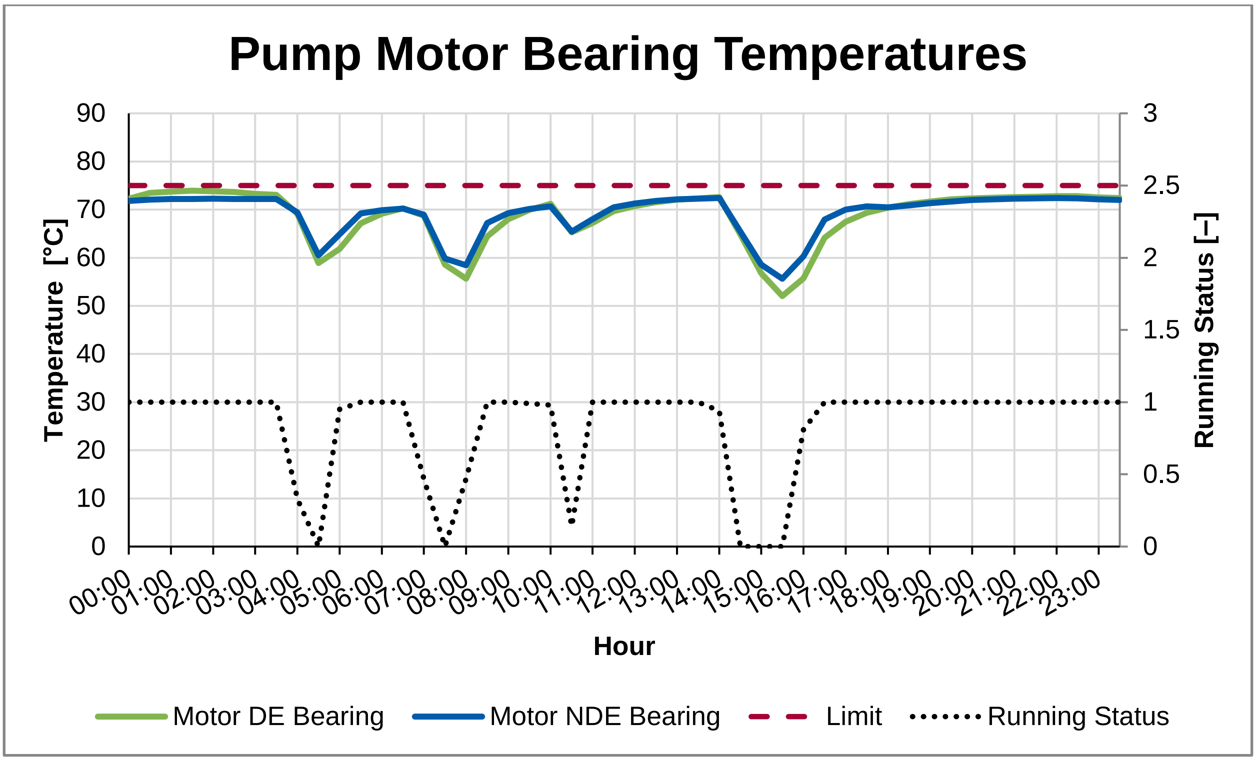


Figure 44: Improved motor bearing temperatures

The data shows both bearing temperatures stayed below the defined temperature limit after the maintenance intervention. The graph in Figure 44 also indicates the correspondence between the bearing temperatures and the pump's running status. Although the DE bearing temperature is higher after the maintenance was done, this can be attributed to a more distributed load. This means that the DE bearing is handling an increased load while the load on the NDE bearing has decreased.

3.4.2 Mine ventilation system

The next incident is that of a booster fan on Mine B. Booster fans are used to improve air circulation in deeper mining levels that are far away from the main ventilation fans, thus lacking sufficient air circulation. Therefore, a failed booster fan can lead to decreased mine production, or even bring mining operations to a complete stop. In this case, the vibrations on the fan bearing were significantly more than they should have been according to the defined alarm limit for the CMS. The high fan bearing vibrations are shown by the graph in Figure 45.

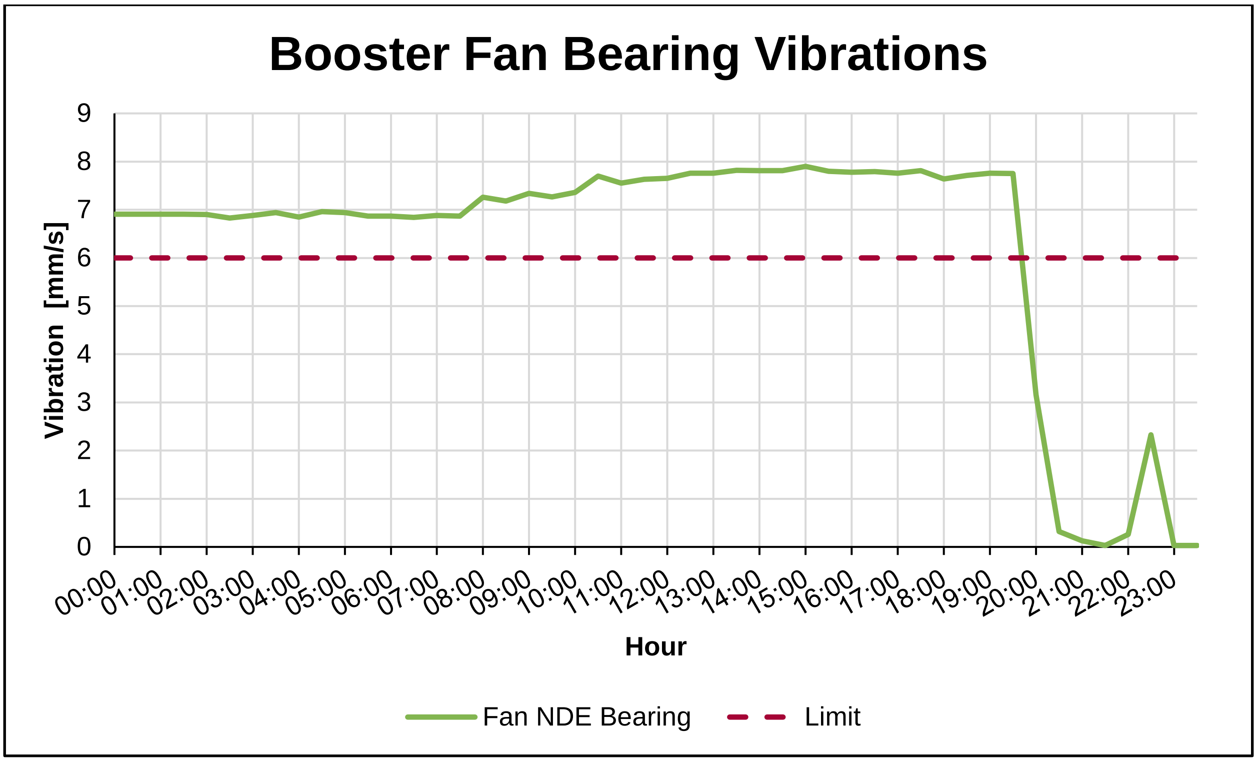


Figure 45: Excessive fan bearing vibrations

Figure 45 shows the half-hourly average vibrations for the NDE bearings of the fan for an entire day. The reason for the absence of a DE vibration parameter is the lack of a vibration sensor. The trend shows that the NDE vibrations were definitively higher than the alarm limit, which resulted in notifications being generated and sent to the mine's maintenance personnel. The problem was investigated, and it was found that the bearing was in a critical condition, which resulted in the fan's shaft being damaged by the faulty bearing. Further deterioration of the bearing would have caused the fan to seize and destroy its shaft. This would have resulted in a longer repair time for the booster fan, which could result in higher maintenance costs and lead to decreased production by mining operations. Figure 46 shows the damage to the fan's shaft because of the faulty bearing.

Figure 46: Damaged booster fan shaft

The bearing was replaced, and the vibrations were corrected. Figure 47 shows the resulting vibrations for an entire day.

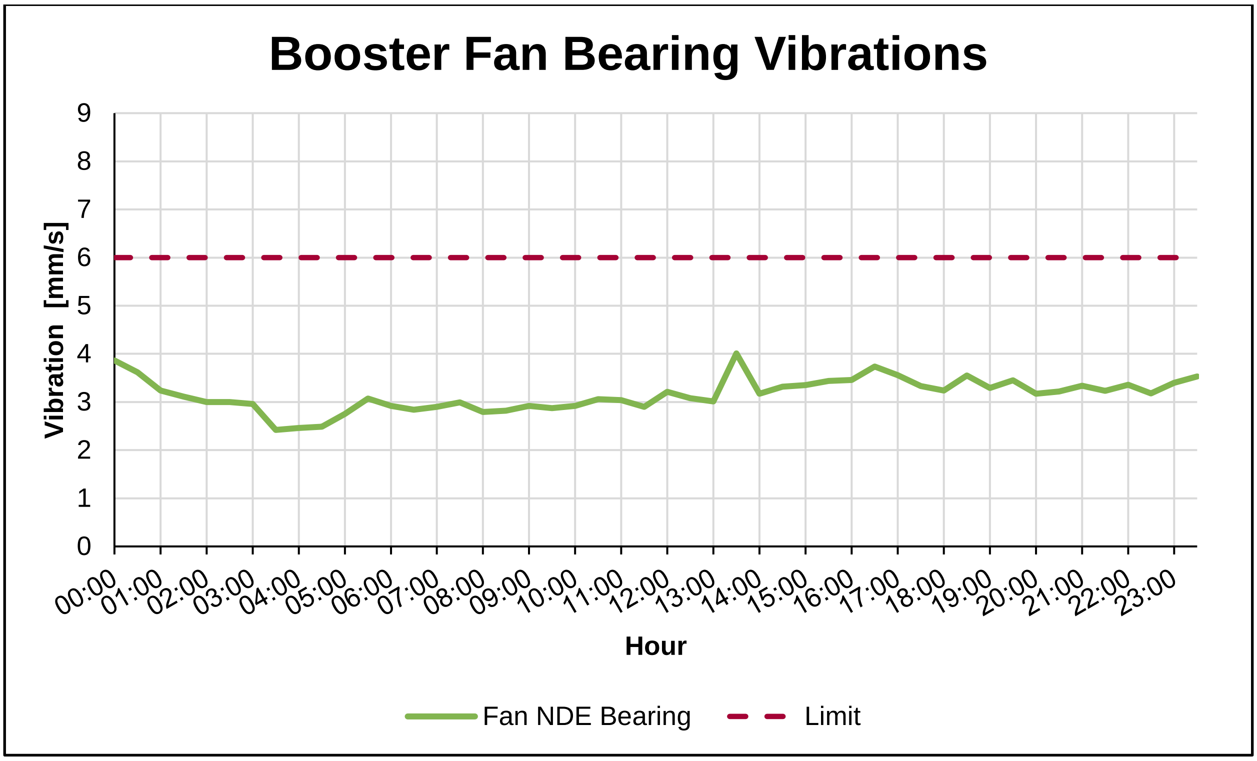


Figure 47: Improved fan bearing vibrations

The trended data in Figure 47 indicates that the vibration levels of the NDE fan bearings decreased significantly after maintenance was done.

3.4.3 Refrigeration system (fridge plants)

The third incident was on Mine F, where the CMS identified poor machine operating conditions, which were the thrust bearing temperatures on the compressor of a refrigeration machine (fridge plant). The bearing temperature got so high that it exceeded the maximum measurable temperature of the sensor. This resulted in the temperature sensor reading its maximum value for all these excessive temperatures. The high temperature readings are shown by the trend lines in Figure 48.

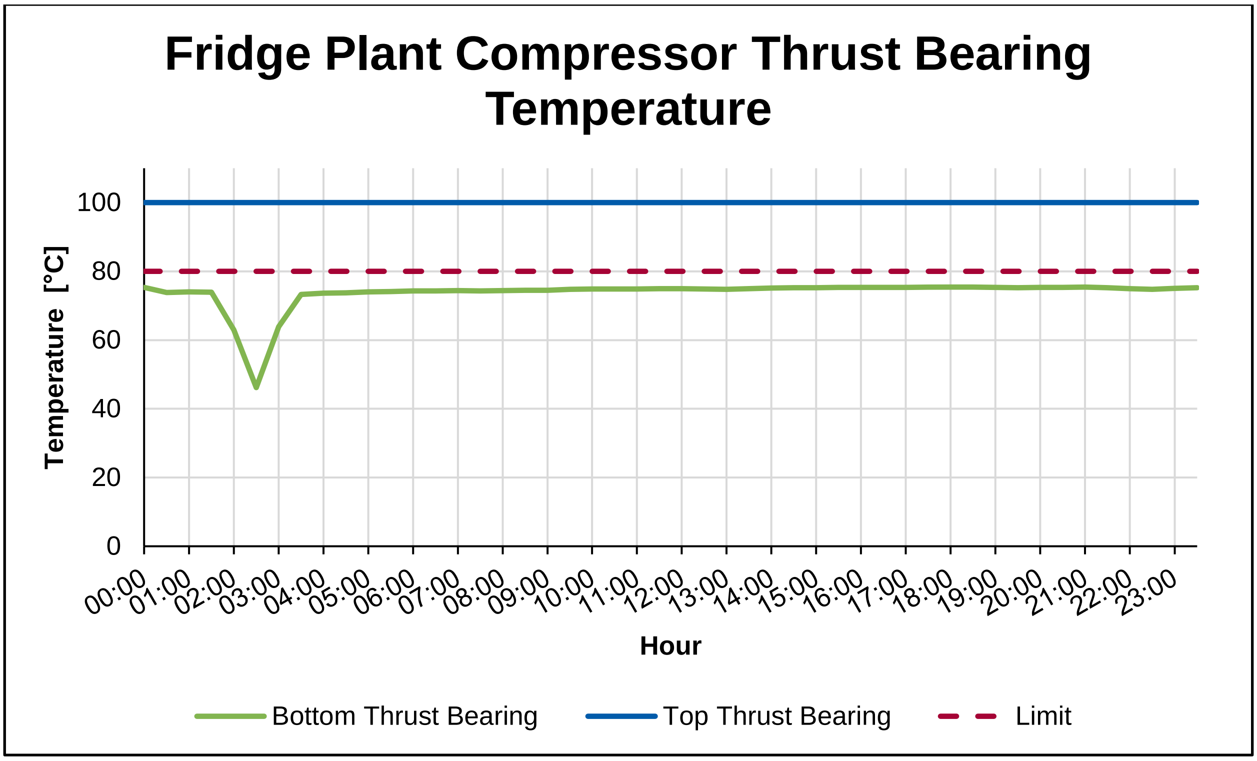


Figure 48: Excessive thrust bearing temperatures

Figure 48 shows the half-hourly average temperature values of both the top and bottom thrust bearing temperatures. The data in Figure 48 shows that the temperature of the top thrust bearing was constantly over the maximum measurable temperature of the sensor, which was 100°C. The bearing temperature stayed above this maximum even when the fridge plant was switched off around 02:00 in the morning. This means that the bearing temperature was so high that it did not even cool to below 100°C during this time.

The CMS notified mine personnel via e-mail and SMS and the problem was investigated. Corrective measures were taken, and the fridge plant was restarted. This maintenance intervention resulted in the top thrust bearing operating at a significantly lower temperature. Figure 49 shows the improved bearing temperatures for an entire day.

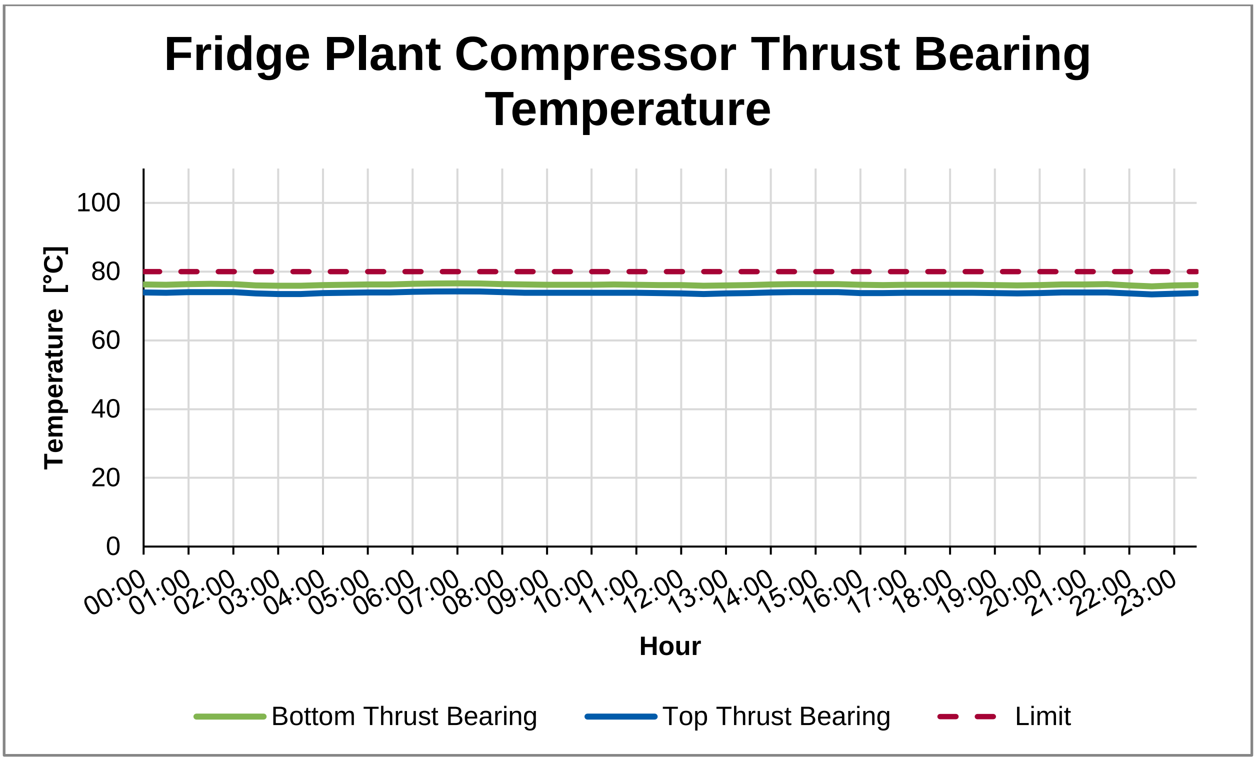


Figure 49: Improved compressor thrust bearing temperatures

The trends in Figure 49 show that the top thrust bearing temperature was similar to the bottom thrust bearing temperature after the maintenance interventions.

3.4.4 Compressed air system

The final case of the CMS identifying a machine that required urgent maintenance is that of a compressor on Mine C. The CMS identified a compressor that was experiencing increasing levels of vibration on its bearings, which could lead to a critical failure if left unattended. This was communicated to maintenance personnel on the mine via both SMS and e-mail messages. The high vibrations are shown by the graph in Figure 50.

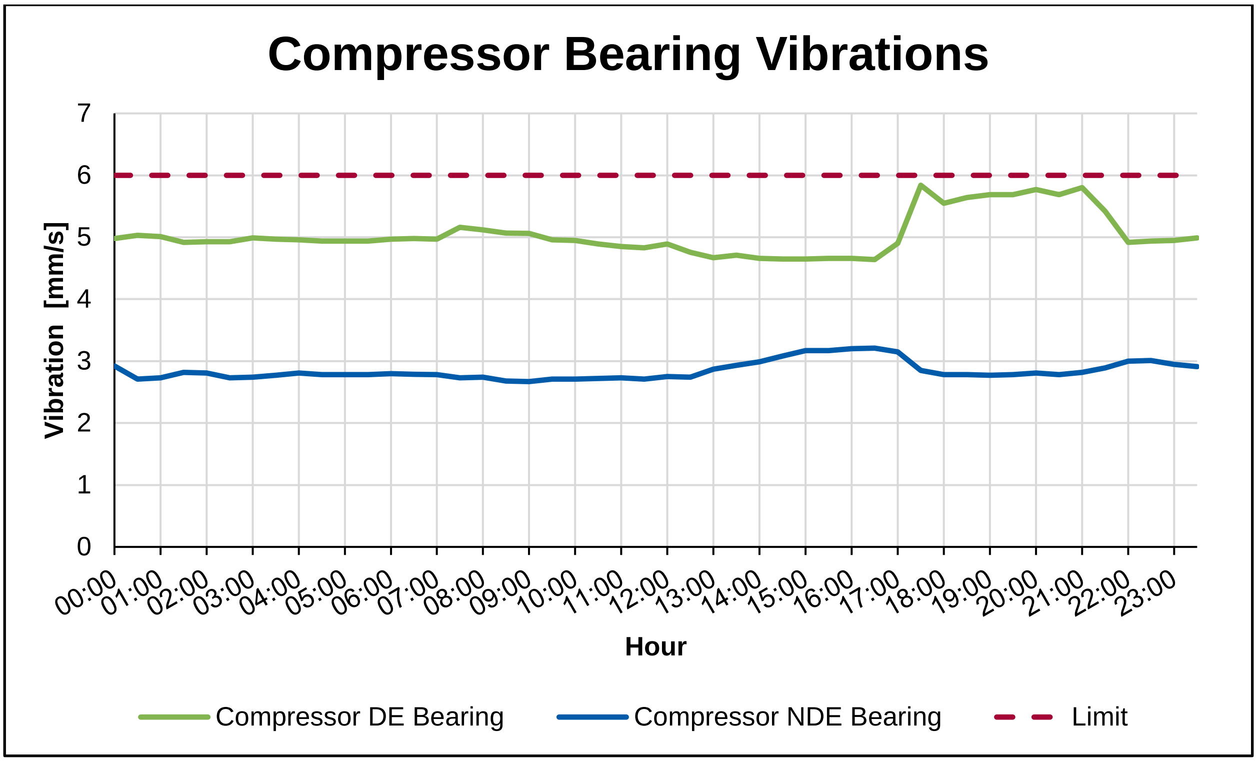


Figure 50: Excessive compressor bearing vibrations

It is important to keep in mind that SMS alarms are sent if a parameter consistently violates its pre-set limit for a short time period, which is five minutes in this case. The parameter trends being used in daily reports however makes use of half-hourly average values. This means that alarm SMSs can be sent even though the daily report will only indicate that the parameter is getting close to its pre-set limit as shown in Figure 50. The half-hourly average vibrations for both DE and NDE bearings of the compressor are shown in Figure 50. The cause of these high vibrations was investigated by the mine’s maintenance personnel. The data in the trend also shows increased vibration levels on the DE bearing from 17:00 until 22:00. This was due to another compressor in the compressed air system being unloaded (pressure set point being lowered) during the electricity peak-tariff periods to reduce total electricity consumption and costs. This translated to a higher compressed air volume being required from the running compressor. The higher volume requirement meant that the compressor experienced an increased load, which put more strain on its components. From this observation, it could be assumed that components are more likely to fail when they experience increased strain or load.

The investigation revealed that the intercoolers were leaking onto the compressor impellers, which caused an imbalance on the compressor impellers. The results were that the impellers were damaged when the compressor was in operation. After the intercooler leak was fixed, the vibration levels decreased significantly on both the DE and NDE bearings of the compressor. The improved bearing vibrations for an entire day are illustrated by the graph in Figure 51.

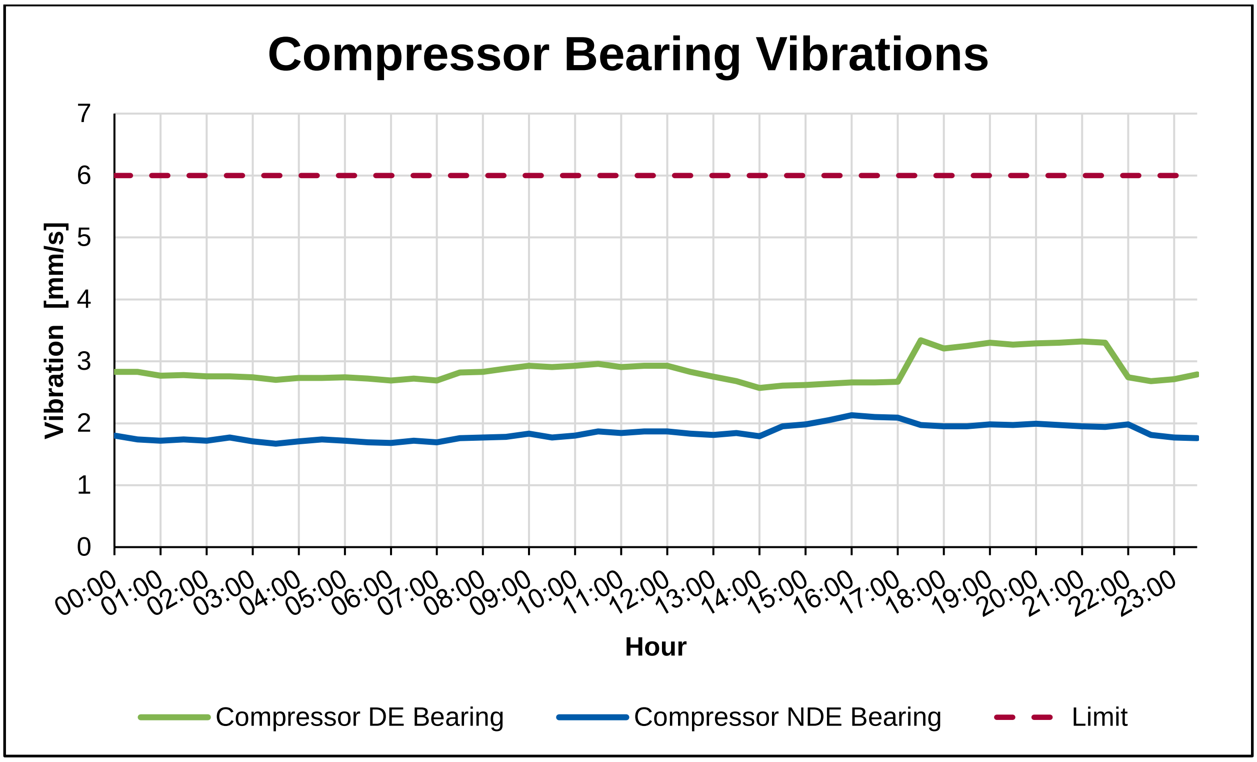


Figure 51: Improved compressor bearing vibrations

The half-hourly data in Figure 51 shows that both the bearing vibrations decreased significantly and were only half of their alarm limits as defined for the CMS. The increased vibration levels on the DE bearing can still be seen during the time of 17:00 until 21:00. After maintenance was done, the overall vibrations on the DE bearing were significantly lower.

3.5 Summary

In this chapter, we have seen how the developed implementation process was applied to two case study mines. The four different sections of the implementation process were discussed individually. The investigation process illustrated the selection of MSSs to be included in the CMS based on available instrumentation. The documentation of important parameter information for the monitored machines in a commissioning sheet was also discussed and illustrated.

This chapter included a discussion of how parameter values were calculated, recorded and sent to a central server for processing. Furthermore, the function of a web-based interface was discussed to illustrate how automated data processing and visualisation could ensure the correct interpretation of data.

In the last step of the implementation process, the configuration of alarm notifications and exception reports was discussed and illustrated. The results from implementing a remote CMS on other mines using the developed implementation process were summarised and discussed briefly. The critical exceptions from these mines were used to quantify the impact of the CMS on maintenance strategies. It was seen that almost half of the mines where the CMS was implemented reflected an improved maintenance efficiency.

CHAPTER 4

Conclusion and Recommendations

4.1 Summary

This thesis showed that South African gold mines are under financial pressure due to volatile exchange rates, increasing wages and low production rates. It was shown that South African gold mines rely on four support systems to ensure safe and sustainable production. These systems are compressed air, ventilation, refrigeration and dewatering systems. It was found that preventative maintenance can reduce maintenance costs significantly. Condition monitoring was thus identified as a way to optimise existing maintenance strategies.

A critical literature review indicated that a generic implementation process for a basic CMS was required to meet specific criteria for deployment in South African gold mines. It needed to use durable yet simple sensors, which did not require excessive maintenance, and which could be installed with minimal capital expenditure. The literature review also revealed that most research being done in the field of maintenance was not translated into real-world applications. There was therefore a need to prove the practical feasibility of the developed implementation process by applying it to several South African gold mines. The contributions of this thesis to the field can thus be summarised as:

- Develop a simplified process for implementing a CMS on South African gold mines, and
- Apply the developed process to implement a CMS practically on multiple South African gold mines to validate its feasibility.

A generic process was developed to implement a basic CMS on South African gold mines with minimal additional cost requirements. The developed implementation process was applied to the machines from the MSSs of six different South African gold mines. This provided the opportunity to evaluate and compare the efficiency of the maintenance strategies used by the mines on a month-to-month basis.

The guidelines set out by the ISO 17359 document was used to structure the development of the implementation process while continuously evaluating the feasibility of the guidelines on South African gold mines.

The basic protection sensors on the machines that were monitored were identified as suitable instrumentation. The sensors were already in use in South African gold mines and needed regular maintenance for mines to comply with national regulations.

In an effort to simplify the implementation and development of a CMS while keeping implementation costs to a minimum, only vibrations and temperatures were monitored by the CMS. Data was recorded as 30-minute averages for the machines of various South African gold mines and sent to a remote processing server. These recorded parameter values were processed, stored and visually presented on a central web-based user interface. Machine parameters were presented in three categories, namely, energy, temperature, and vibrations.

A web-based user interface quantified the overall condition of an MSS or the condition of individual machines by using a colour coding system. Individual parameter limits were used to quantify machine conditions. Parameter limits were obtained from mine personnel at each gold mine since the specifications from the OEM were unavailable and machines were operating under different environmental conditions. These parameter limits were indicated on the web-based user interface, which was used to notify mine personnel of machine parameters exceeding these limits. Mine personnel were notified either via SMS or e-mail. Daily exception reports were generated automatically and sent to mine personnel to indicate parameters that exceeded their predetermined limits and parameters that were getting close to their limits for the previous day.

The impact of the CMS on the gold mines were quantified by analysing the monthly total of critical exceptions created for each mine. A reduction in the number of monthly critical exceptions indicates that mine personnel are focusing more on preventative maintenance, which means that they would action maintenance before machine parameters exceed their limits. The results of the CMS were reductions in monthly critical exceptions ranging from 57% to 83%. Two mines showed increases in critical exceptions of 50% and 114% respectively. These increases should not be seen as the CMS failing, but rather of maintenance personnel failing to react on feedback and notifications created by the CMS.

The mining group’s quality control engineer estimated that the total operational cost saving was in excess of R20 million. This saving refers to the cost of replacing machines that were identified by the CMS as being critical. Such breakdowns might have led to reduced production in some cases and could incur significant additional costs as lost production.

It can thus be concluded that a process for implementing a CMS on South African gold mines was developed successfully. The developed process can be implemented on any South African gold mine, or other similar operation irrespective of its size and location. Lastly, it was seen that more reliable data from instrumentation can provide the opportunity for further development of such a CMS into a more dynamic and user independent system.

Furthermore, this thesis identified some shortfalls and recommendations for future studies. They are discussed in the following section.

4.2 Limitations of this study and recommendations

The most important shortfall of the system is the inability to identify inaccurate parameter values. There were incidents where instrumentation was manipulated and prevented from providing correct measurements in an effort to keep exceptions form being triggered. This was not done to create a false indication of improvement, but rather to delay corrective maintenance further. Such events can be identified by looking at suspicious parameter trends.

Another opportunity for future research is to establish baseline temperature increase and decrease rates for bearings in different applications. This will allow users to find bearing temperature limits irrespective of the operating temperature of their environment. It will also help identify deteriorating bearings by looking for abnormal temperature increase rates during operation.

This implementation process generates significant amounts of data, which can be utilised for predictive maintenance. A great number of industries is entering an era referred to as the 4^{th} industrial revolution, which essentially uses the available data to improve process efficiency and also reduce operating costs. This data can also be combined with artificial intelligence methods and machine learning projects to make statistical predictions towards future machine failure that can thus be prevented. In other words, the implementation of such a CMS can provide significant potential for future development and optimisation in the field of maintenance and condition monitoring in the gold mining industry.

In the case studies, the quality control engineer of the mining group required maintenance planners to generate maintenance tasks for all notifications generated by the CMS. One of the biggest obstacles encountered in the implementation of the developed process for condition monitoring on South African gold mines was the lack of feedback from maintenance personnel regarding maintenance actions on the monitored machines. Therefore, there is a need to find a way of improving feedback from maintenance tasks and to keep a proper maintenance record of maintenance actions taken per machine.

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Annexure A – Examples of condition monitoring parameters

Parameter	Aero gas turbine	Compressor	Electric generator	Electric motor	Fan	Industrial gas turbine	Power transformer	Pump	RIC engine	Steam turbine
Acoustic emission	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Angular position	✓	✓				✓				✓
Current			✓	✓			✓			
Efficiency – derived	✓	✓				✓		✓	✓	✓
Electrical phase			✓	✓						
Flow – air	✓	✓			✓	✓			✓	
Flow – fluid		✓						✓		✓
Flow – fuel	✓					✓			✓	
Length										✓
Noise	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Oil – consumption	✓	✓	✓	✓	✓	✓		✓	✓	✓
Oil – pressure	✓	✓	✓	✓	✓	✓		✓	✓	✓
Oil – tribology	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Power – input		✓	✓	✓			✓	✓		
Power – output	✓		✓	✓		✓	✓		✓	✓
Pressure	✓	✓			✓	✓	✓	✓	✓	✓
Pressure – head								✓		
Pressure – ratio	✓	✓				✓				
Pressure – vacuum								✓		✓
Resistance			✓	✓			✓			
Speed	✓	✓	✓	✓	✓	✓		✓	✓	✓
Temperature	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Thermography	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Torque		✓	✓	✓		✓			✓	✓
Ultrasonics	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Vibration	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Voltage			✓	✓			✓			

Annexure B – ISO 17359:2018 Examples and Illustrations

Figure 52 shows the typical components and processes monitored by a condition monitoring management process as specified in the ISO 17359 standard.

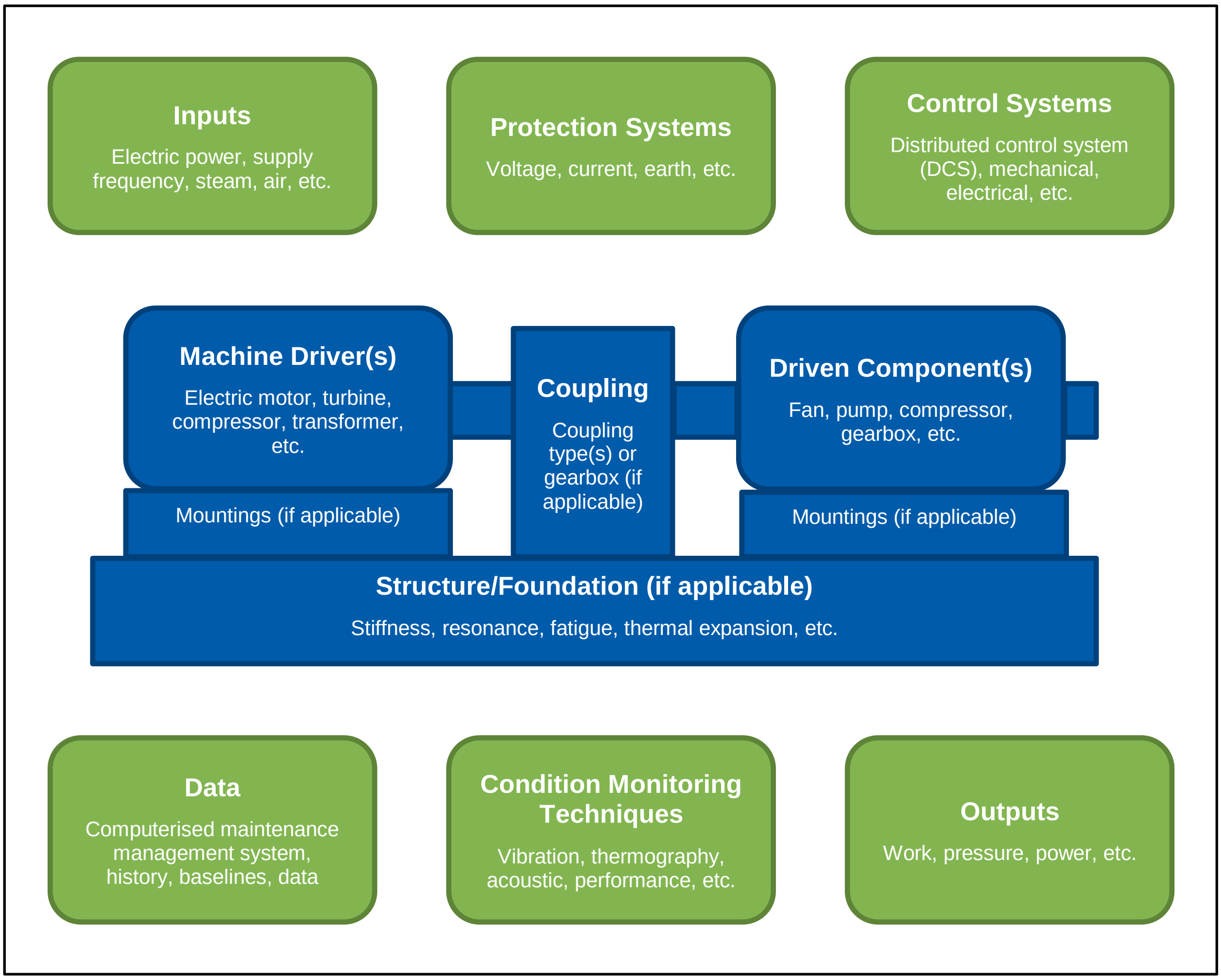

Figure 52: Typical components and processes monitored in condition monitoring (Adapted from [36]**)**

Annexure C – Example Commissioning Sheet for MSS

Machine	Measurement Type	Measurement Location	SCADA Tag Name	Calculation type	PDI Logger	Alarm Value	Trip value	Condition Monitoring Tag Name
Ventilation Fan 1	Vibration (mm/s)	Motor DE	INDUSTRIALNET.NIAHF0121	30 Min Average	Vent Fans Vibrations	4	5	Gauteng Gold_Mine E_Vent Fan 1_Motor DE Vibration_V
		Motor NDE	No Instrumentation					
		Fan DE	No Instrumentation					
		Fan NDE	INDUSTRIALNET.NIAHF0105	30 Min Average	Vent Fans Vibrations	4	5	Gauteng Gold_Mine E_Vent Fan 1_Fan NDE Vibration_V
	Temperature (°C)	Fan DE	INDUSTRIALNET.TIAHF0106	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 1_Fan DE Bearing Temp_T
		Fan NDE	INDUSTRIALNET.TIAHF0109	30 Min Average	Tshepong Vent Fan Data	81	85	Gauteng Gold_Mine E_Ventilation_Vent Fan 1_Fan NDE Bearing Temp_T
		Motor DE	INDUSTRIALNET.TIAHF0114	30 Min Average	Tshepong Vent Fan Data	81	85	Gauteng Gold_Mine E_Ventilation_Vent Fan 1_Motor DE Bearing Temp_T
		Motor NDE	INDUSTRIALNET.TIAHF0120	30 Min Average	Tshepong Vent Fan Data	81	85	Gauteng Gold_Mine E_Ventilation_Vent Fan 1_Motor NDE Bearing Temp_T
	Status (-)	Running Status	INDUSTRIALNET.UCF0115_RS	30 Min Average	Tshepong Vent Fan Data			Gauteng Gold_Mine E_Ventilation_Vent Fan 1_Fan Status_Y
	Current (A)	Motor	INDUSTRIALNET.IIF1001	30 Min Average	Tshepong Vent Fan Data			Gauteng Gold_Mine E_Ventilation_Vent Fan 1_Motor Current_I
	Energy (W)	Motor	No Instrumentation					
Ventilation Fan 2	Vibration (mm/s)	Motor DE	INDUSTRIALNET.NIAHF0221	30 Min Average	Vent Fans Vibrations	4	5	Gauteng Gold_Mine E_Vent Fan 2_Motor DE Vibration_V
		Motor NDE	No Instrumentation					
		Fan DE	No Instrumentation					
		Fan NDE	INDUSTRIALNET.NIAHF0205	30 Min Average	Vent Fans Vibrations	4	5	Gauteng Gold_Mine E_Vent Fan 2_Fan NDE Vibration_V
	Temperature (°C)	Fan DE	INDUSTRIALNET.TIAHF0206	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 2_Fan DE Bearing Temp_T
		Fan NDE	INDUSTRIALNET.TIAHF0209	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 2_Fan NDE Bearing Temp_T
		Motor DE	INDUSTRIALNET.TIAHF0214	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 2_Motor DE Bearing Temp_T
		Motor NDE	INDUSTRIALNET.TIAHF0220	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 2_Motor NDE Bearing Temp_T
	Status (-)	Running Status	INDUSTRIALNET.UCF0215_RS	30 Min Average	Tshepong Vent Fan Data			Gauteng Gold_Mine E_Ventilation_Vent Fan 2_Fan Status_Y
	Current (A)	Motor	INDUSTRIALNET.IIF2001	30 Min Average	Tshepong Vent Fan Data			Gauteng Gold_Mine E_Ventilation_Vent Fan 2_Motor Current_I
	Energy (W)	Motor	No Instrumentation					
Ventilation Fan 3	Vibration (mm/s)	Motor DE	INDUSTRIALNET.NIAHF0321	30 Min Average	Vent Fans Vibrations	4	5	Gauteng Gold_Mine E_Vent Fan 3_Motor DE Vibration_V
		Motor NDE	No Instrumentation					
		Fan DE	No Instrumentation					
		Fan NDE	INDUSTRIALNET.NIAHF0305	30 Min Average	Vent Fans Vibrations	4	5	Gauteng Gold_Mine E_Vent Fan 3_Fan NDE Vibration_V
	Temperature (°C)	Fan DE	INDUSTRIALNET.TIAHF0306	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 3_Fan DE Bearing Temp_T
		Fan NDE	INDUSTRIALNET.TIAHF0309	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 3_Fan NDE Bearing Temp_T
		Motor DE	INDUSTRIALNET.TIAHF0314	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 3_Motor DE Bearing Temp_T
		Motor NDE	INDUSTRIALNET.TIAHF0320	30 Min Average	Tshepong Vent Fan Data	75	80	Gauteng Gold_Mine E_Ventilation_Vent Fan 3_Motor NDE Bearing Temp_T
	Status (-)	Running Status	INDUSTRIALNET.UCF0315_RS	30 Min Average	Tshepong Vent Fan Data			Gauteng Gold_Mine E_Ventilation_Vent Fan 3_Fan Status_Y
	Current (A)	Motor	INDUSTRIALNET.IIF3001	30 Min Average	Tshepong Vent Fan Data			Gauteng Gold_Mine E_Ventilation_Vent Fan 3_Motor Current_I
	Energy (W)	Motor	No Instrumentation					

Figure 53: Example of a complete ventilation system commissioning sheet

Machine	Measurement Type	Measurement Location	SCADA Tag Name	Calculation type	PDI Logger	Alarm Value	Trip value	Condition Monitoring Tag Name
45L Pump 1	Vibration (mm/s)	Motor DE	INDUSTRIALNET.NI_CK0616	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump1 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.NI_AK0616	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump1 Motor NDE Vibration_V
		Pump NDE	INDUSTRIALNET.NI_AK0602	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump1 Pump NDE Vibration_V
		Pump DE	INDUSTRIALNET.NI_CK0602	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump1 Pump DE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.TI_AK0604	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump1 Motor DE Bear Temperature_T
		Motor NDE	INDUSTRIALNET.TI_BK0604	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump1 Motor NDE Bear Temperature_T
		Pump NDE	INDUSTRIALNET.TI_BK0603	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump1 Pump NDE Bear Temperature_T
		Pump DE	INDUSTRIALNET.TI_AK0603	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump1 Pump DE Bear Temperature_T
	Status (-)	Running Status	INDUSTRIALNET.UCK0601_RS	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump1_Running Status_Y
	Current (A)	Motor	INDUSTRIALNET.P1_Current	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump1_Motor Current_I
	Energy (W)	Motor	INDUSTRIALNET.P1_KW	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump1 Energy_J
45L Pump 2	Vibration (mm/s)	Motor DE	INDUSTRIALNET.NI_CK0716	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump2 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.NI_AK0716	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump2 Motor NDE Vibration_V
		Pump NDE	INDUSTRIALNET.NI_AK0702	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump2 Pump NDE Vibration_V
		Pump DE	INDUSTRIALNET.NI_CK0702	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump2 Pump DE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.TI_AK0704	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump2 Motor DE Bear Temperature_T
		Motor NDE	INDUSTRIALNET.TI_BK0704	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump2 Motor NDE Bear Temperature_T
		Pump NDE	INDUSTRIALNET.TI_BK0703	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump2 Pump NDE Bear Temperature_T
		Pump DE	INDUSTRIALNET.TI_AK0703	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump2 Pump DE Bear Temperature_T
	Status (-)	Running Status	INDUSTRIALNET.UCK0701_RS	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump2_Running Status_Y
	Current (A)	Motor	INDUSTRIALNET.P2_Current	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump2_Motor Current_I
	Energy (W)	Motor	INDUSTRIALNET.P2_KW	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump2 Energy_J
45L Pump 3	Vibration (mm/s)	Motor DE	INDUSTRIALNET.NI_CK0816	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump3 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.NI_AK0816	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump3 Motor NDE Vibration_V
		Pump NDE	INDUSTRIALNET.NI_AK0802	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump3 Pump NDE Vibration_V
		Pump DE	INDUSTRIALNET.NI_CK0802	30 Min Average	Pumping Vibration	6	7	Gauteng Gold_Mine EPumping_35L Pump3 Pump DE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.TI_AK0804	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump3 Motor DE Bear Temperature_T
		Motor NDE	INDUSTRIALNET.TI_BK0804	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump3 Motor NDE Bear Temperature_T
		Pump NDE	INDUSTRIALNET.TI_BK0803	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump3 Pump NDE Bear Temperature_T
		Pump DE	INDUSTRIALNET.TI_AK0803	30 Min Average	Pumping Temperatures	75	80	Gauteng Gold_Mine EPumping_35L Pump3 Pump DE Bear Temperature_T
	Status (-)	Running Status	INDUSTRIALNET.UCK0801_RS	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump3_Running Status_Y
	Current (A)	Motor	INDUSTRIALNET.P3_Current	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump3_Motor Current_I
	Energy (W)	Motor	INDUSTRIALNET.P3_KW	30 Min Average	Pumping Temperatures			Gauteng Gold_Mine EPumping_35L Pump3 Energy_J

Figure 54: Example of one pump station's dewatering system commissioning sheet

Equipment	Measurement Type	Measurement Location	REMS Tag	PDI Logger	Calculation Type	Alarm Value	Trip Value Tag	ASTIR Tag
Compressor 1	Vibration (mm/s)	Motor DE	INDUSTRIALNET.Comp1 Motor DE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 1 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.Comp1 Motor NDE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 1 Motor NDE Vibration_V
		Compressor DE	INDUSTRIALNET.Comp1 Comp DE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 1 DE Vibration_V
		Compressor NDE	INDUSTRIALNET.Comp1 Comp NDE Vibr	Compressor Vibration	30 Min Average	6	7	Gauten Gold_Mine E_Compressors_Compressor 1 NDE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.Comp1 Motor DE Temp Bear	Compressors	30 Min Average	67	70	Gauten Gold_Mine E_Compressors_Compressor 1 Motor DE Temperature_T
		Motor NDE	INDUSTRIALNET.Comp1 Motor NDE Temp Bear	Compressors	30 Min Average	67	70	Gauten Gold_Mine E_Compressors_Compressor 1 Motor NDE Temperature_T
		Compressor DE	INDUSTRIALNET.Comp1 DE Temp	Compressors	30 Min Average	76	80	Gauten Gold_Mine E_Compressors_Compressor 1 DE Temperature_T__
		Compressor NDE	INDUSTRIALNET.Comp1 NDE Temp	Compressors	30 Min Average	71	75	Gauten Gold_Mine E_Compressors_Compressor 1 NDE Temperature_T__
		Gearbox Pin DE	INDUSTRIALNET.Comp1 Gearbox Pin DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 1 Gearbox Pin DE Temperature_T
		Gearbox Pin NDE	INDUSTRIALNET.Comp1 Gearbox Pin NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 1 Gearbox Pin NDE Temperature_T
		Gearbox Thrust DE	INDUSTRIALNET.Comp1 Gearbox Thrust DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 1 Gearbox Thrust DE Temperature_T
		Gearbox Thrust NDE	INDUSTRIALNET.Comp1 Gearbox Thrust NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 1 Gearbox Thrust NDE Temperature_T
		Gearbox DE	INDUSTRIALNET.Comp1 Gearbox DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 1 Gearbox DE Temperature_T
		Gearbox NDE	INDUSTRIALNET.Comp1 Gearbox NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 1 Gearbox NDE Temperature_T
	Status (-)	Running Status	INDUSTRIALNET.UACY1707	Compressors	30 Min Average			Gauten Gold_Mine E_Compressors_Compressor 1_Status_Y
	Current (A)	Motor	No Instrumentation					
	Energy (W)	Motor	INDUSTRIALNET.Cmp1_Power	Compressors	30 Min Average			Gauten Gold_Mine E_Compressors_Compressor 1 Power_J
Compressor 2	Vibration (mm/s)	Motor DE	INDUSTRIALNET.Comp2 Motor DE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 2 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.Comp2 Motor NDE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 2 Motor NDE Vibration_V
		Compressor DE	INDUSTRIALNET.Comp2 Comp DE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 2 DE Vibration_V
		Compressor NDE	INDUSTRIALNET.Comp2 Comp NDE Vibr	Compressor Vibration	30 Min Average	6	7	Gauten Gold_Mine E_Compressors_Compressor 2 NDE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.Comp2 Motor DE Temp Bear	Compressors	30 Min Average	67	70	Gauten Gold_Mine E_Compressors_Compressor 2 Motor DE Temperature_T
		Motor NDE	INDUSTRIALNET.Comp2 Motor NDE Temp	Compressors	30 Min Average	67	70	Gauten Gold_Mine E_Compressors_Compressor 2 Motor NDE Temperature_T
		Compressor DE	INDUSTRIALNET.Comp2 Comp DE Temp	Compressors	30 Min Average	76	80	Gauten Gold_Mine E_Compressors_Compressor 2 DE Temperature_T
		Compressor NDE	INDUSTRIALNET.Comp2 Comp NDE Temp	Compressors	30 Min Average	71	75	Gauten Gold_Mine E_Compressors_Compressor 2 NDE Temperature_T
		Gearbox Pin DE	INDUSTRIALNET.Comp2 Gearbox Pin DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 2 Gearbox Pin DE Temperature_T
		Gearbox Pin NDE	INDUSTRIALNET.Comp2 Gearbox Pin NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 2 Gearbox Pin NDE Temperature_T
		Gearbox Thrust DE	INDUSTRIALNET.Comp2 Gearbox Thrust DE Temp	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 2 Gearbox Thrust DE Temperature_T
		Gearbox Thrust NDE	INDUSTRIALNET.Comp2 Gearbox Thrust NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 2 Gearbox Thrust NDE Temperature_T
		Gearbox DE	INDUSTRIALNET.Comp2 Gearbox DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 2 Gearbox DE Temperature_T
		Gearbox NDE	INDUSTRIALNET.Comp2 Gearbox NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 2 Gearbox NDE Temperature_T
	Status (-)	Running Status	INDUSTRIALNET.UACY2707	Compressors	30 Min Average			Gauten Gold_Mine E_Compressors_Compressor 2_Status_Y
	Current (A)	Motor	No Instrumentation					
	Energy (W)	Motor	INDUSTRIALNET.Cmp2_Power	Compressors	30 Min Average			Gauten Gold_Mine E_Compressors_Compressor 2 Power_J
Compressor 3	Vibration (mm/s)	Motor DE	INDUSTRIALNET.Comp3 Motor DE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 3 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.Comp3 Motor NDE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 3 Motor NDE Vibration_V
		Compressor DE	INDUSTRIALNET.Comp3 Comp DE Vibr	Compressor Vibration	30 Min Average	5	6	Gauten Gold_Mine E_Compressors_Compressor 3 DE Vibration_V
		Compressor NDE	INDUSTRIALNET.Comp3 Comp NDE Vibr	Compressor Vibration	30 Min Average	6	7	Gauten Gold_Mine E_Compressors_Compressor 3 NDE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.Comp3 Motor DE Temp Bear	Compressors	30 Min Average	67	70	Gauten Gold_Mine E_Compressors_Compressor 3 Motor DE Temperature_T
		Motor NDE	INDUSTRIALNET.Comp3 Motor NDE Temp Bear	Compressors	30 Min Average	67	70	Gauten Gold_Mine E_Compressors_Compressor 3 Motor NDE Temperature_T
		Compressor DE	INDUSTRIALNET.Comp3 Comp DE Temp	Compressors	30 Min Average	76	80	Gauten Gold_Mine E_Compressors_Compressor 3 DE Temperature_T
		Compressor NDE	INDUSTRIALNET.Comp3 Comp NDE Temp	Compressors	30 Min Average	71	75	Gauten Gold_Mine E_Compressors_Compressor 3 NDE Temperature_T
		Gearbox Pin DE	INDUSTRIALNET.Comp3 Gearbox Pin DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 3 Gearbox Pin DE Temperature_T
		Gearbox Pin NDE	INDUSTRIALNET.Comp3 Gearbox Pin NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 3 Gearbox Pin NDE Temperature_T
		Gearbox Thrust DE	INDUSTRIALNET.Comp3 Gearbox Thrust DE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 3 Gearbox Thrust DE Temperature_T
		Gearbox Thrust NDE	INDUSTRIALNET.Comp3 Gearbox Thrust NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 3 Gearbox Thrust NDE Temperature_T
		Gearbox DE	INDUSTRIALNET.Comp3 Gearbox DE Temp	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 3 Gearbox DE Temperature_T
		Gearbox NDE	INDUSTRIALNET.Comp3 Gearbox NDE Temp Bear	Compressors	30 Min Average	81	85	Gauten Gold_Mine E_Compressors_Compressor 3 Gearbox NDE Temperature_T
	Status (-)	Running Status	INDUSTRIALNET.UACY3707	Compressors	30 Min Average			Gauten Gold_Mine E_Compressors_Compressor 3_Status_Y
	Current (A)	Motor	No Instrumentation					
	Energy (W)	Motor	INDUSTRIALNET.Cmp3_Power	Compressors	30 Min Average			Gauten Gold_Mine E_Compressors_Compressor 3 Power_J

Figure 55: Example of a compressed air system commissioning sheet

Machine	Measurement Type	Measurement Location	SCADA Tag Name	Calculation type	PDI Logger	Alarm Value	Trip value	Condition Monitoring Tag Name
Fridge Plant 1	Vibration (mm/s)	Motor DE	INDUSTRIALNET.FP1 Motor DE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 1 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.FP1 Motor NDE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 1 Motor NDE Vibration_V
		Compressor DE	INDUSTRIALNET.FP1 Comp DE Vibr	30 Min Average	FP Vibrations	3	4	Gauteng Gold_Mine E_Refrigeration_FP 1 Comp DE Vibration_V
		Compressor NDE	INDUSTRIALNET.FP1 Comp NDE Vibr	30 Min Average	FP Vibrations	3	4	Gauteng Gold_Mine E_Refrigeration_FP 1 Comp NDE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.FP1 Motor DE Temp Bear	30 Min Average	FP Temperatures	81	85	Gauteng Gold_Mine E_Refrigeration_FP 1 Motor DE Temperature_T
		Motor NDE	INDUSTRIALNET.FP1 Motor NDE Temp Bear	30 Min Average	FP Temperatures	81	85	Gauteng Gold_Mine E_Refrigeration_FP 1 Motor NDE Temperature_T
		Compressor DE	No Instrumentation					
		Compressor NDE	No Instrumentation					
		Gearbox DE	Integrally Geared					
		Gearbox NDE	Integrally Geared					
	Status (-)	Running Status	INDUSTRIALNET.UCD0401_RS	30 Min Average	FP Temperatures			Gauteng Gold_Mine E_Refrigeration_FP 1_Running Status_Y
	Current (A)	Motor	No Instrumentation					
	Energy (W)	Motor	INDUSTRIALNET.FP1_Power	30 Min Average	FP Temperatures			Gauteng Gold_Mine E_Refrigeration_FP 1 Power_J
Fridge Plant 2	Vibration (mm/s)	Motor DE	INDUSTRIALNET.FP2 Motor DE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 2 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.FP2 Motor NDE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 2 Motor NDE Vibration_V
		Compressor DE	INDUSTRIALNET.FP2 Comp DE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 2 Comp DE Vibration_V
		Compressor NDE	INDUSTRIALNET.FP2 Comp NDE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 2 Comp NDE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.FP2 Motor DE Temp Bear	30 Min Average	FP Temperatures	81	85	Gauteng Gold_Mine E_Refrigeration_FP 2 Motor DE Temperature_T
		Motor NDE	INDUSTRIALNET.FP2 Motor NDE Temp Bear	30 Min Average	FP Temperatures	81	85	Gauteng Gold_Mine E_Refrigeration_FP 2 Motor NDE Temperature_T
		Compressor DE	No Instrumentation					
		Compressor NDE	No Instrumentation					
		Gearbox DE	Integrally Geared					
		Gearbox NDE	Integrally Geared					
	Status (-)	Running Status	INDUSTRIALNET.U2D0401_RS	30 Min Average	FP Temperatures			Gauteng Gold_Mine E_Refrigeration_FP 2_Running Status_Y
	Current (A)	Motor	No Instrumentation					
	Energy (W)	Motor	INDUSTRIALNET.FP2_Power	30 Min Average	FP Temperatures			Gauteng Gold_Mine E_Refrigeration_FP 2 Power_J
Fridge Plant 3	Vibration (mm/s)	Motor DE	INDUSTRIALNET.FP3 Motor DE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 3 Motor DE Vibration_V
		Motor NDE	INDUSTRIALNET.FP3 Motor NDE Vibr	30 Min Average	FP Vibrations	5	6	Gauteng Gold_Mine E_Refrigeration_FP 3 Motor NDE Vibration_V
		Compressor DE	INDUSTRIALNET.FP3 Comp DE Vibr	30 Min Average	FP Vibrations	4	5	Gauteng Gold_Mine E_Refrigeration_FP 3 Comp DE Vibration_V
		Compressor NDE	INDUSTRIALNET.FP3 Comp NDE Vibr	30 Min Average	FP Vibrations	4	5	Gauteng Gold_Mine E_Refrigeration_FP 3 Comp NDE Vibration_V
	Temperature (°C)	Motor DE	INDUSTRIALNET.FP3 Motor DE Temp Bear	30 Min Average	FP Temperatures	81	85	Gauteng Gold_Mine E_Refrigeration_FP 3 Motor DE Temperature_T
		Motor NDE	INDUSTRIALNET.FP3 Motor NDE Temp Bear	30 Min Average	FP Temperatures	81	85	Gauteng Gold_Mine E_Refrigeration_FP 3 Motor NDE Temperature_T
		Compressor DE	No Instrumentation					
		Compressor NDE	No Instrumentation					
		Gearbox DE	Integrally Geared					
		Gearbox NDE	Integrally Geared					
	Status (-)	Running Status	INDUSTRIALNET.U3D0401_RS	30 Min Average	FP Temperatures			Gauteng Gold_Mine E_Refrigeration_FP 3_Running Status_Y
	Current (A)	Motor	No Instrumentation					
	Energy (W)	Motor	INDUSTRIALNET.FP3_Power	30 Min Average	FP Temperatures			Gauteng Gold_Mine E_Refrigeration_FP 3 Power_J

Figure 56: Example of a refrigeration system commissioning sheet

Annexure D – Example Alarm Limit Sign-Off Sheet

ESCo

Mine D Condition Monitoring

Alarm Limit Sign-off

Version: 5

Published on: 2017-10-06

Gauteng Gold

Document control

	Name	Tel.	E-mail	Date	Signed
Compiled	A. Compiler	555-112	a.compiler@gpowers.c	2017-10-06	
Checked	C. Checker	555-153	c.checker@gpowers.co	2017-10-06	
Checked	J. Checker	555-143	j.checker@gpowers.co.	2017-10-06	
Approved	D. Client	555-155	d.client@ggold.co.za	2017-10-06	

Distribution list

Name	Designation
L. Client	Engineering Manager
N. Client	Shaft Engineer
A. Client	Senior Instrumentation Technician
T. Client	Chief Instrumentation Technician
D. Client	Quality Control Engineer

Alarm Limit Sign-off

Mineshaft Representative

Name	Designation
Signature	Date

Quality Control Representative

Name	Designation
Signature	Date

ESCo Representative

Name	Designation
Signature	Date

Nomenclature

DE	Drive End
NDE	Non-Drive End
Comp	Compressor
FP	Fridge Plant

Contents

This report summarises the limits and notification strategy for the condition monitoring at Mine D. The three major systems being monitored are: compressors, fridge plants and dewatering pumps.

Parameter	Measurement	Fan 1		Fan 2	
		Alarm	Trip	Alarm	Trip
Vibration [mm/s]	Motor DE	6	7	6	7
	Motor NDE	6	7	6	7
	Fan DE	6	7	6	7
	Fan NDE	6	7	6	7
Temperature [°C]	Motor DE	65	72	65	72
	Motor NDE	65	72	65	72
	Fan DE	65	72	65	72
	Fan NDE	65	72	65	72
	Motor Winding Temp 1	81	85	81	85
	Motor Winding Temp 2	81	85	81	85
	Motor Winding Temp 3	81	85	81	85

Parameter	Measurement	Comp 1		Comp 2		Comp 3	
		Alarm	Trip	Alarm	Trip	Alarm	Trip
Vibration [mm/s]	Motor DE	4	6	4	6	4	6
	Motor NDE	4	6	4	6	4	6
	Comp DE	4	6	4	6	4	6
	Comp NDE	4	6	4	6	4	6
	Gearbox Main Gear DE	5	7	5	7	5	7
	Gearbox Pin DE	5	7	5	7	5	7
Temperature [°C]	Motor DE	65	70	65	70	65	70
	Motor NDE	65	70	65	70	65	70
	Comp DE	65	70	65	70	65	70
	Comp NDE	65	70	65	70	65	70
	Gearbox Pin DE	65	70	65	70	65	70
	Gearbox Pin NDE	65	70	65	70	65	70
	Gearbox Main Gear DE	65	70	65	70	65	70
	Gearbox Main Gear NDE	65	70	65	70	65	70
	Cooling Water Inlet	40	45	40	45	40	45
	Cooling Water Outlet	55	60	55	60	55	60

e	Measurement	Surface FP 1		Surface FP 2		Surface FP 3	
		Alarm	Trip	Alarm	Trip	Alarm	Trip
Vibration [mm/s]	Motor DE	4	6	4	6	4	6
	Comp DE	4	6	4	6	4	6
Temperature [°C]	Motor DE	70	75	70	75	70	75
	Motor NDE	70	75	70	75	70	75
	Comp DE	75	80	75	80	75	80
	Comp NDE	75	80	75	80	75	80

Parameter	Measurement	Pump 2		Pump 4	
		Alarm	Trip	Alarm	Trip
Vibration [mm/s]	Motor DE	4	6	4	6
	Pump DE	6	8	6	8
Temperature [°C]	Motor DE	70	75	70	75
	Motor NDE	70	75	70	75
	Pump DE	70	75	70	75
	Pump NDE	70	75	70	75

Parameter	Measurement	Pump 3		Pump 4	
		Alarm	Trip	Alarm	Trip
Vibration [mm/s]	Motor DE	4	6	4	6
	Pump DE	5	8	5	8
Temperature [°C]	Motor DE	70	75	70	75
	Motor NDE	70	75	70	75
	Pump DE	70	75	70	75
	Pump NDE	70	75	70	75

Parameter	Measurement	Pump 1		Pump 2		Pump 3	
		Alarm	Trip	Alarm	Trip	Alarm	Trip
Vibration [mm/s]	Motor DE	4	6	4	6	4	6
	Pump DE	4	6	4	6	4	6
Temperature [°C]	Motor DE	87	92	87	92	87	92
	Motor NDE	87	92	87	92	87	92
	Pump DE	70	75	70	75	70	75
	Pump NDE	70	75	70	75	70	75

Due to a lack of alarm tag availability, the alarm limits for the following components are excluded from this document:

- 31L Pump 1
- 31L Pump 3
- 64L Pump 1
- 64L Pump 2

Alarms are sent via SMS or e-mail when temperatures and vibrations exceed alarm limits for more than 5 minutes. The alarms are sent to the following recipients:

Recipient	Designation	Notification details
L. Client	Engineering Manager	l.client@ggold.co.za
N. Client	Shaft Engineer	n.client@ggold.co.za
A. Client	Senior Instrumentation Technician	a.client@ggold.co.za
D. Client	Quality Control Engineer	d.client@ggold.co.za

ESCo also monitors the systematics worsening of equipment and will notify Mine D when certain equipment needs maintenance. These e-mail notifications will be sent to the following recipients:

Recipient	Designation	Notification details
L. Client	Engineering Manager	l.client@ggold.co.za
N. Client	Shaft Engineer	n.client@ggold.co.za
D. Client	Quality Control Engineer	d.client@ggold.co.za

User	MineDCM
Password	GG@MineD

Annexure E – Daily Condition monitoring Report

Exception Report

02 August 2018

Generated on 03 August 2018 for:

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Summary of critical exceptions

Parameter	Critical Limit	Violation duration (hours)	Violation period average
100L FP3 Motor DE Temp	80°C	24	81.03°C
71L FP4 Motor DE Vib	4 mm/s	24	4.31 mm/s
85L BFan Fan NDE Vib	4 mm/s	24	5.06 mm/s
85L BFan Motor DE Vib	4 mm/s	24	4.90 mm/s
102L BFan Fan NDE Vib	4 mm/s	23.5	5.52 mm/s
Comp3 Gbox Pin NDE Temp	65°C	6.5	67.76°C
52L P4 Motor Vib	4.5 mm/s	4.5	4.79 mm/s
75L P5 Pump Vib	4 mm/s	2	6.59 mm/s

Summary of warning exceptions

Parameter	Warning Limit	Violation duration (hours)	Violation period average
DK MainFan 2 Fan Vib	3 mm/s	24	3.71 mm/s
75L P3 Pump Vib	3 mm/s	21.5	3.83 mm/s
75L P3 Motor Vib	3 mm/s	6.5	3.29 mm/s
115L P3 Motor NDE Temp	70°C	18	71.47°C
115L P3 Pump NDE Temp	70°C	18	71.52°C
100L FP3 Motor NDE Temp	75°C	17.5	75.17°C
SFP2 Motor NDE Temp	70°C	7.5	72.94°C
Comp4 Gbox Thrust Temp	60°C	7.5	60.73°C
Comp3 Comp DE Temp	60°C	4	60.84°C
Comp3 Gbox Thrust Temp	60°C	1.5	60.07°C
29L P1 Pump Vib	3.5 mm/s	3	4.15 mm/s
29L P1 Motor DE Temp	70°C	2	73.87°C
75L P5 Motor DE Temp	70°C	1.5	73.48°C
Comp1 Comp DE Temp	60°C	1	60.08°C
Comp1 Gbox DE Temp	55°C	1	55.19°C

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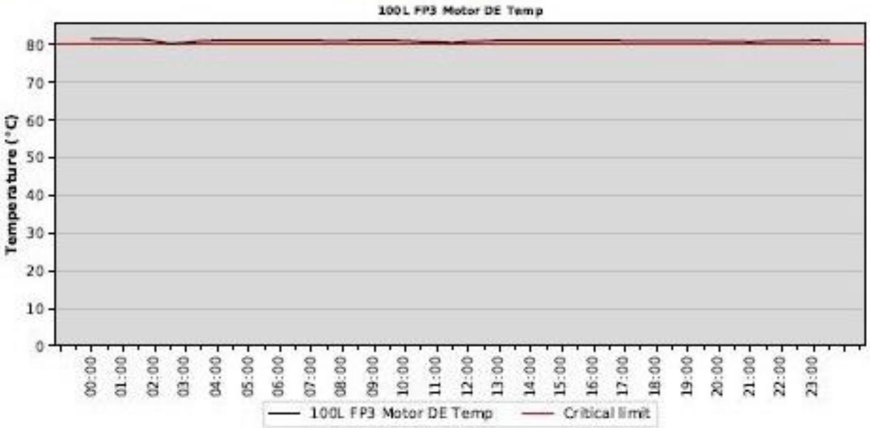
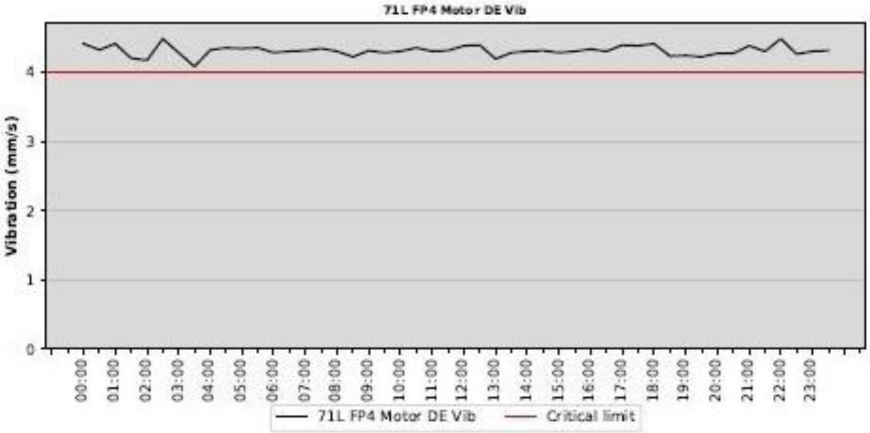
Template ID: 2017-08-30_MTB_TMP_01A.dotx

Appendix: Critical exception graphs





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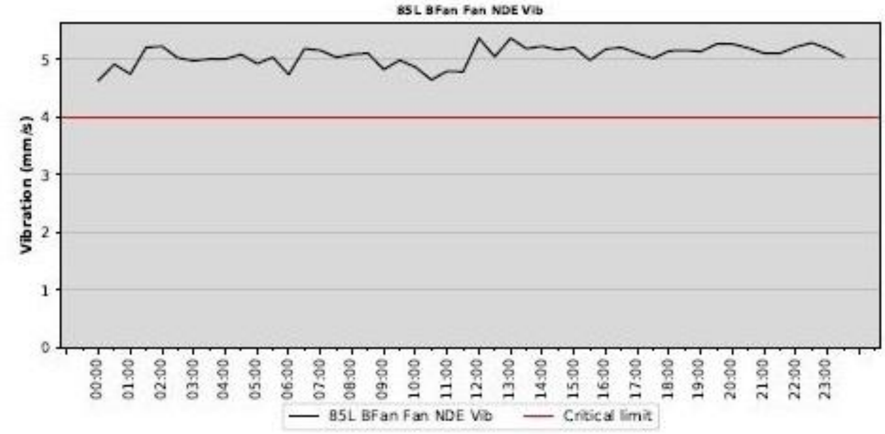
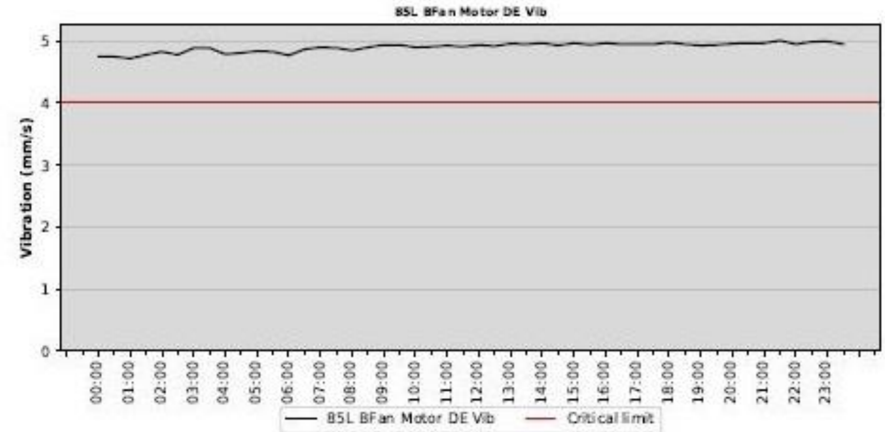
Template ID: 2017-08-30_MTB_TMP_01A.dotx





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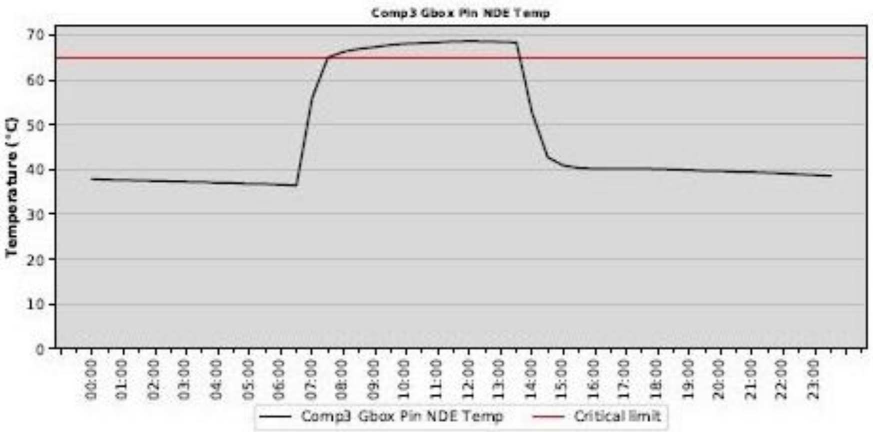
Document ID: Exception Report 2018-08-03 01_41_02-920.pdf
Template ID: 2017-08-30_MTB_TMP_01A.dotx



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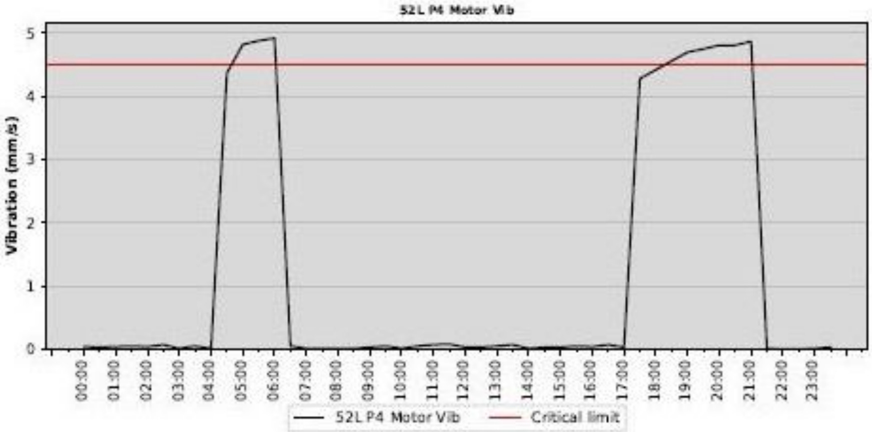
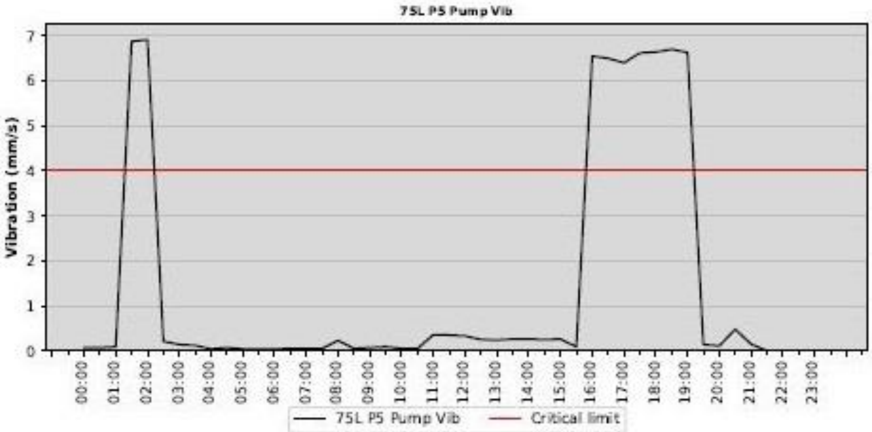
Template ID: 2017-08-30_MTB_TMP_01A.dotx





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Template ID: 2017-08-30_MTB_TMP_01A.dotx

Comments

Name:

Notes:

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Annexure F – Existing CMSs

Crystal Instruments

Spider-80X [65]

This CMS is aimed at machine condition monitoring. The system is housed in a single but scalable chassis and can accept a variety of input types. Multiple Spider-80X front ends can be connected via a Spider-HUB to form a condition monitoring network. This system can be expanded further by combining it with the company's Engineering Data Management (EDM) Cloud product. This enables maintenance personnel to run condition monitoring tests remotely and get results in real time. This system provides access to historical or real-time data via a web interface. Typical applications of this system include condition monitoring, bridge and railway vibration monitoring, wind turbine status monitoring, and tunnel sound monitoring.

Multotec [66]

Multotec provides several different condition monitoring products that monitor machine wear rates against productivity in real time. The different condition monitoring products from Multotec are Hawkeye®, MultoScan and PIG-I.

- Hawkeye™ [67]: This CMS is a web-based system designed to monitor the wear and life data of components such as mill liners, cyclone components and screen panels. The monitoring of component wear is used to predict their expected lifespans, which can help prevent unplanned failures or breakdowns. The web-based system allows maintenance personnel to access the relevant data easily from anywhere.
- MultoScan [68]: This condition monitoring product aims to minimise overall downtime. It uses a laser measurement to monitor the condition of liners in mills continuously and predict their expected life and changeouts.
- PIG-i [69]: The PIG-i gauge is a specialised condition monitoring device that can be used for condition-based monitoring of pipelines with diameters of 150–350 mm in various industries. It uses LED lights and a low-light camera to provide the operator with feedback during pipeline inspections.

National Instruments

InsightCM™

This CMS uses online asset monitoring software to provide personnel with accurate data and different connectivity options. Additionally, it offers different alarm configurations and data management options [70].

There are different CMS components available to expand the system's functionality. Some of these components are integration into an existing information technology infrastructure, monitoring devices, a software development kit and software add-ons for extended functionality [71].

Rockwell Automation [72]

Rockwell Automation offers a comprehensive range of condition monitoring products from sensors to portable instruments, real-time protection modules and monitoring software.

Dynamix™ 1444 [73]

The Dynamix™ Integrated CMS provides machine protection by integrating with its control software. This system provides a single control architecture to protect both reciprocating and rotating machinery.

Bulletin Emonitor® [74]

The Bulletin 9309 Emonitor® condition monitoring software can be used with the company's monitors and portable data collectors to develop and implement a CBM strategy.

Siemens

Siemens offers a variety of CMSs across various industries. Most of their condition monitoring solutions are modular in design to allow for easy expansion, but all these systems are sold as products. This means that the configuration of data processing and resulting system outputs is "purchased" from a supplier. Although it can be integrated into SCADA systems, the active management and development of these systems require additional training and, in some cases, even additional costs.

Assetguard

- Assetguard GDM (Gas Density Monitoring) [75], [76]**:** The Siemens Assetguard GDM is used to monitor high-voltage gas-insulated switchgear. This system uses density transducers to provide a full gas inventory management system.

- Assetguard PDM (Partial-discharge Monitoring) [76]: The Siemens Assetguard PDM is also used to monitor high-voltage gas-insulated switchgear. This system facilitates measurements from ultrahigh frequency sensors and supports compliance with the international electrotechnical commission's requirements for high-voltage on-site testing by using PDM.

- Assetguard MVC (Medium Voltage Switchgear Monitoring) [77]: This system is used to monitor the condition of circuit breakers as well as functionality and contact wear. It can transmit alarms when maintenance is needed and can be used to monitor many circuit breakers. All the system components, such as power supply and data storage, are also combined into a single housing. This system can be integrated into a SCADA if required.

- Assetguard TXM (Online Transformer Monitoring) [76], [78]: Siemens Assetguard TXM is used for online transformer monitoring. It can be used as a standalone product or integrated into a substation monitoring system. It detects failures such as dissolved gas in various locations. This system stores recorded data locally or forwards it over protocol to be displayed by a web human machine interface.

- Assetguard Circuit Breaker Monitoring [79], [80]: The Assetguard Circuit Breaker Monitoring system can be used on both air insulated switchgear as well as gas-insulated switchgear. This specific system is better suited for the monitoring of ageing equipment.

Sitram Condition Monitoring [76]

This system can be used on transformers of any age or manufacturer. Sitram condition monitoring is a modular monitoring system that allows operators to oversee different types of sensors, protocols and parameters to achieve cost-specific objectives. This can be done by integrating the solutions from a monitoring system called Integrated Substation Condition Monitoring (ISCM).

Integrated Substation Condition Monitoring [76]

The Siemens ISCM system can be seen as a host for all monitored substation equipment. It processes the data from monitored equipment for further analysis and diagnostics. It has a simple user interface that can indicate possible faults to users without any condition monitoring expertise. The functionality of this system can be expanded further by adding available add-ons to each system.

Asset Performance Management (APM) [76]

Asset performance management can be optimised by integrating online condition monitoring data. This forms part of asset data management, which helps operators to interpret data collected from online condition monitoring into useful knowledge. This system can also predict the behaviour of assets by combining online condition monitoring data and Siemens' Reliability Centered Asset Management (RCAM) system.

The RCAM system predicts the future conditions of assets to help increase and maximise asset life while reducing operating costs. It also combines different types of data to make predictions and risk assessments.

SIPLUS CMS Family [81]

This product series is primarily aimed at the continuous monitoring of mechanical components in machinery. It can analyse mechanical variables and assists maintenance personnel with decision-making. Furthermore, it is able to compare measurements from machines to identify problems. The SIPLUS CMS family consists of three members, namely, SIPLUS CMS1200, SIPLUS CMS2000 and SIPLUS CMS4000. Each of these have different degrees of complexity.

- SIPLUS CMS1200: This is the most basic member of the family and can be used to monitor critical mechanical components continuously. This system can monitor up to 28 vibrations without additional software, but additional modules are required to monitor variables such as temperature and pressure. Recorded data is analysed by software on an internal module.

- SIPLUS CMS2000: This system is a bit more complex and can be used to record data from vibration sensors. It can analyse, diagnose and visualise this data in a web browser without any additional software requirements. This system is able to measure parameters such as temperature without the requirement of additional modules.

- SIPLUS CMS4000: This system is the last and most complex CMS in the family and can monitor anything from individual machine components to complex plants.

SKF [82]

SKF @ptitude

The SKF @ptitude Monitoring Suite comprise three applications, namely, SKF @ptitude Inspector, which is used for operator driven reliability, SKF @ptitude Analyst for SKF Microlog Analyzer and SKF @ptitude Analyst.

This system can use data from portable and online devices as well as OPC servers to monitor the conditions of machines. It enables the user to determine the appropriate limits for condition monitoring alarms. This system can be configured to use SMS or e-mail messages to communicate alarm notifications.

TAS Online [83]

TAS Online is a pump company that specialises in pump reliability and efficiency optimisation. The objective of these optimisations is reducing maintenance and energy costs while improving productivity. Some of the company's target industries include the mining, water utility and industrial sectors. The company offers various services, which include pump testing, remote monitoring, pump system assessments and pump station audits.

In the mining industry, this company provides monthly reports on the operating conditions of mine dewatering pumps. The primary KPIs in these reports are the pump utilisation in terms of running hours, average discharge flow rates in terms of ℓ/s, annual costs incurred by energy losses, pump refurbishment costs and pump replacement costs. These reports also contain detailed asset registries of pump installations and removals as well as a combined operating cost for each installed pump expressed as Rand/Mℓ of pumped water.

WearCheck [84]

WearCheck is a specialist company that offers condition monitoring through various different condition monitoring techniques. Their condition monitoring program includes audits and the implementation of the program. They offer different degrees of vibration monitoring and transient analysis. Their condition monitoring program also includes monitoring techniques such as MCSA, thermography (thermal imaging) and ultrasonic monitoring.

Literature survey

A literature survey was done on existing CMSs and solutions and the results of the survey can be summarised according to their intended areas of application as shown in Table 8. The table shows that there is a deficiency on condition monitoring in common machines found in MSSs.

Table 8: Existing condition monitoring solutions

Product	**High-voltage Gas-insulated Switchgear**	**Online Transformer Monitoring**	**High-voltage Switchgear Monitoring**	**Medium-voltage Switchgear Monitoring**	**Circuit Breaker Monitoring**	**Performance Monitoring**	**Water Pump Monitoring**	**Unspecific Condition Monitoring**	**Mill Liners**	**Cyclone Components**	**Screen Panels**	**Pipeline Monitoring (Condition-based)**	**Ventilation Fan Monitoring**	**Compressor Monitoring**	**Refrigeration Plant Monitoring**	**Unattended Monitoring System**
Crystal Instruments Spider-80X								■								
Multotec Hawkeye									■	■	■					
Multotec MultoScan									■							
Multotec PIG-I												■				
National Instruments InsightCM								■								
Rockwell Automation								■								
Siemens APM						■										
Siemens ISCM			■													
Siemens SIPLUS CMS Family								■								
Siemens Assetguard CBM (Circuit Breaker Monitoring)					■											
Siemens Assetguard GDM	■															
Siemens Assetguard MVC				■												
Siemens Assetguard PDM	■															
Siemens Assetguard TXM		■														
SKF @ptitude Asset Management System								■								
TAS Online							■									
WearCheck									■							
This Study							■						■	■	■	■

Annexure G – Common Machine Failures

Most machines are driven by induction motors due to their reliability and simplistic construction [85]. Although induction motors may be reliable, they also fail from time to time. The most common failures are summarised in Table 9.

Table 9: Common induction motor failures (Adapted from [26], [86]**)**

Component	Rate of Failure (%)
Bearing	40
Stator	38
Rotor	10
Other	12

Failures in gearboxes can be very costly, and the most expensive gearbox failures are [87]:

- High speed shaft bearing failure;
- Broken intermediate shaft;
- Intermediate shaft bearing failure;
- Planet bearing failure; and
- Broken centre post.

This is supported by a similar study on wind turbine gearbox failures [88]. The following sections provide more information on the significance of the support systems used in the mining industry. The typical failures experienced by the primary machines responsible for these MSSs is discussed briefly in the following sections.

Compressors

According to a study, the most common causes of failure in compressors can be summarised as shown in Table 10. [89], [90]

Table 10: Common causes of failures in compressors (Adapted from [89], [90]**)**

Component	Rate of Failure (%)
Valve	28
Packing	24
Process cooler	10
Other	38

Fans

Common fan failures can be summarised by the data shown in Table 11.

Table 11: Common causes of fan failures (Adapted from [91]**)**

Component	Rate of Failure (%)
Mechanical	24
Electrical	24
Fan installation	24
Vibration	15
Other	13

Air is chilled by bulk air coolers (BACs) on surface before entering the mine. These BACs use chilled water provided by fridge plants to cool the ventilation air [92]. The fridge plants form part of the refrigeration system.

Fridge plants

According to a survey, the most common problems on fridge plants are: [93]

- Reduced evaporator water flow;
- Refrigerant leakage;
- Excess oil;
- Condenser fouling; and
- Non-condensables in refrigerant.

Pumps

The most common component failures on multistage dewatering pumps can be summarised by Table 12.

Table 12: Common problems on centrifugal pumps (Adapted from [94]**)**

Component	Rate of Failure (%)
Sliding ring seal	31
Roller bearing	22
Leakage	10
Driving motor	10
Other	27

Induction motor failures

Bearing faults

Bearings are a common component of any electric machine. Bearing failures account for more than 40% of all machine failures [23]. The basic components of a typical bearing are shown in Figure 57.

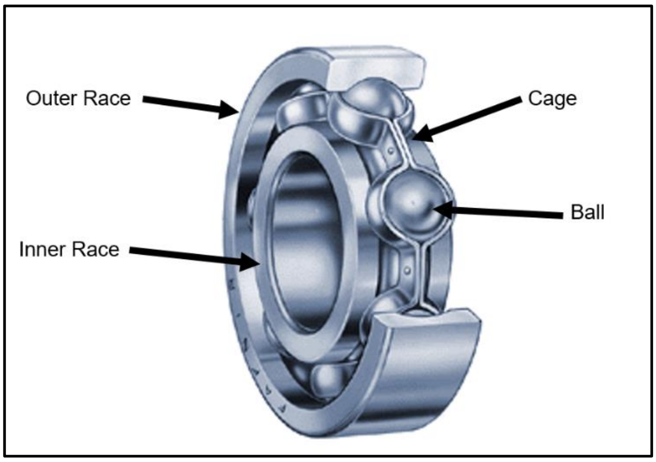

Figure 57: Basic components of a bearing [95]

As illustrated in Figure 57, a bearing consists of an inner and outer race, which are separated by a set of rolling elements. Fatigue failure is the result of continuous stress on the bearing, which can even occur under normal operating conditions with good alignment and a balanced load. Fatigue can cause spalling or flaking of the bearing, where small pieces of the bearing break loose, which cause it to run roughly. The rough running of bearings is detectable as vibrations and increased noise levels [23], [96].

Bearing lubrication often gets contaminated by dirt and other foreign matter. This prevents the rolling elements from rotating properly, resulting in increased levels of heating. Excessive temperatures in turn causes the lubricant to break down, which decreases its ability to lubricate the bearing elements and increases its rate of failure [97].

Stator faults

Stator faults are generally linked to interturn faults caused by insulation failure. [27] These faults are also known as phase-to-phase or ground-to-phase faults. A survey has found that 37% of all induction motor failures are caused by stator windings [28]. Common causes of stator failure include:

- High winding temperatures;
- Starting stresses;
- Electrical discharges; and

- Contamination.

It has been found that online partial-discharge test methods are very reliable for detecting stator faults for motor stator windings that are rated at 4 kV and higher [96]. Stator current signature analysis has become a popular method for detecting stator winding faults [27]. Winding problems for motors and generators are very similar and a turbine generator analyser test can thus be used to detect insulation deterioration [28].

Rotor faults

One of the most common rotor faults in induction motors is broken bars, which can be caused by pulsating loads or direct online starting. Broken bars in turn can lead to [27]:

- Torque pulsation;
- Speed fluctuation;
- Vibration;
- Overheating in the rotor;
- Acoustic noise; and
- Damaged rotor laminations.

One of the most common methods for rotor fault detection is stator current analysis [98]. Rotor faults can be detected by using vibration or air-gap monitoring [28], [99].