

THE APPLICATION OF CONDITION BASED FACILITY MANAGEMENT ON CABLE DEHYDRATION SYSTEMS

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EXECUTIVE SUMMARY

The objective of this project was to investigate and develop a new maintenance strategy for the Total Facilities Management Company (TFMC) which would drastically improve the availability of the environmental equipment in a cost-effective manner.

In the study, a new Condition Based Facility Management (CBFM) strategy and methodology was developed that overcame the historical downfalls of Condition Based Maintenance and improved the value release of data encapsulated within Condition Monitoring.

At the outset, the different maintenance strategies that are in use today were examined and the best practices of each were selected for incorporation into a new approach. The concept of Condition Monitoring was then adapted to suit the Facility Manager. This included:

- Identification of equipment condition parameters representing a holistic view of the plant
- Identification of possible modes of failures with high severity consequence and high likelihood of occurrence
- Design or selection of sensors to measure the equipment parameters identified above
- Collection, and processing of data from these sensors into engineering values presenting the equipment condition

The current Remote Alarm Monitoring System was the ideal platform for collection of the equipment condition data. In order to complete the CBFM system, methods and modules were developed, to first convert engineering data into predicted failure data or un-optimised equipment performance data and then further convert this data into action plans.

In view of the importance of cables within the telecommunication chain, the Cable Dehydration System (CDH) was selected for the case study to apply and test the new CBFM strategy. The CBFM system immediately highlighted several problem areas within the current maintenance strategy which the previous Planned Preventative Maintenance system was not able to detect.

As a result implementation of the CDFM system, the availability of the cable dehydration system was improved from 90% to 98%, and costs were reduced. The current actual maintenance costs of R4,3 million could be reduced to R3,1 million, saving of 27%.

The case study demonstrated the success of the new CBFM approach and can now be used on other environmental equipment in TFMC.

SAMEVATTING

Hierdie studie se doelwit was om 'n nuwe onderhouds strategie te ontwikkel vir die Total Facility Management Company (TFMC). Die nuwe onderhouds strategie moet die beskikbaarheid van die omgewingstoerusting waarvoor TFMC verantwoordelik is, se koste effektiwiteit verbeter.

Die nuwe Kondisie Gebaseerde Fasiliteits Bestuurs strategie, voorkom die nadele wat met die vroeëre Kondiese Gebaseerde Onderhouds strategieë ondervind is. Verder verbeter die strategie en metodologie die vrystelling van die toegevoegde waarde wat opgesluit lê, binne die onverwerkde kondiese data.

As 'n vertrek punt is die verskillende onderhoudskonsepte en strategie, soos gebruik oor die laaste paar jaar, ondersoek. Sterk punte van die verskeie strategieë is uitgelig. Die nuwe kondiese gebaseerde onderhoudskonsep is toe aangepas om ook hierdie voordele van die ander konsepte in te sluit.

Die kondisie monitorings konsep is aangepas spesifiek vir toepassing in die fasiliteits bestuurs omgewing. Die volgende metodiek is gevolg:

- Identifikasie van toerusting kondisie eienskappe wat die globale werking van die stelsel omskryf
- Identifikasie van falings kondisies wat potensiële kritiese gevolge met 'n hoë waarskynlikheids faktor het
- Ontwerp of selekteering van meetinstrumente wat die kondisie eienskappe van bogenoemde toerusting kan meet
- Moniteer en verwerking van die gemete data, in ingenieurs terme weergee, wat bogenoemde toerusting kondisies beskryf

Die bestaande Sentraal Geleë Alarms Monitorings Stelsel bied die ideale infrastruktuur vir die monitoring van hierdie toerusting kondisie eienskappe. Om egter die volledige model van Kondisie Gebaseerde Fasiliteits Bestuurs te skep, moes daar addisionele modelle en metodes ontwikkel word. Hierdie modelle en metodes moet voorspelde falings data of nie-effektiewe toerusting data omskep in onderhoudsaksies en die inisiëring van sulke aksies.

Na aanleiding van die huidige klem op die belangrikheid van kabels in die totale telekomunikasie ketting is die Kabel Dehidreerders stelsel as 'n toepassings studieveld gekies. Tydens die toepassings studie is die effektiwiteit van die nuwe Kondisie Gebaseerde Fasiliteits Bestuurs konsep toegepas en getoets.

Die toegepaste konsep het onmiddelik verskeie probleem areas in die onderhoud van die Kabel Dehidreerder stelsel uitgewys wat nie voorheen moontlik was deur die Geskeduleerde Voorkomende Onderhouds stelsel nie.

Die resultaat van die nuwe Kondisie Gebaseerde Fasiliteits Bestuurs konsep was dat die beskikbaarheid van die toerusting van 90% na 98% verbeter het. Die koste van die totale onderhoud op al die Kabel Dehidreerder stelsels kan vanaf die huidige R4,3 miljoen vir Geskeduleerde Voorkomende Onderhoud stelsels, verlaag word na R3,1 miljoen met die Kondisie Gebaseerde Fasiliteits Bestuurs konsep, 'n besparing van 27%.

Die toepassings studie het die sukses van die nuwe Kondisie Gebaseerde Fasiliteits Bestuurs konsep bewys, en die' konsep kan nou met groot vrug op alle omgewings toerusting waarvoor TFMC verantwoordelik is toegepas word.

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LIST OF ABBREVIATIONS

BCC	Building Control Centre
BMS	Building Management Systems
BMSI	Building Management Systems Integration
CBM	Condition Based Maintenance
CDH	Cable Dehydrator
CM	Condition Monitoring
CMMS	Computerised Maintenance Management System
EM	Emergency Maintenance
EPS	Emergency Power Supply
FM	Facility Management
FMEA	Failure Mode, Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
HVACR	Heating, Ventilation, Air-conditioning and Refrigeration systems
MIMOSA	Machine Information Management Open System Alliances
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OSA	Open System Architecture
OSA-CBM	Open System Architecture for Condition Based Maintenance
OSA-EAI	Open System Architecture for Enterprise Application Integration
PcentM	Profit Centred Maintenance
PCB	Printed Circuit Board
PCM	Planned Corrective Maintenance
PM	Planned Maintenance
PPM	Predetermined Preventative Maintenance
RAMS	Remote Alarm Monitoring System
RBM	Risk Based Maintenance
RCA	Route Cause Analysis
RCM	Reliability Centred Maintenance
RCMS	Remote Condition Monitoring System
RUL	Remaining Useful Life.
SIC	Site Interface Controller
TBD	To Be Determined
TFMC	Total Facility Management Company
TPM	Total Productive Maintenance
UPS	Uninterruptible Power Supply

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CHAPTER 1. INTRODUCTION

1.1 Background

1.1.1 *Telkom and TFMC*

Telkom is the main supplier of fixed line telecommunication services in South Africa. In order to provide this service, Telkom has more than 22 900 facilities and 14 500 masts, of which 1 200 are critical in terms of revenue. These facilities vary from large multi-story buildings to containers equipped with telecommunication and support equipment. Within Telkom, the support equipment, or the so-called environmental equipment, is defined as the equipment which provides the correct environment for the telecommunications equipment [1].

The Total Facilities Management Company (TFMC) is responsible for the facility management of Telkom's South African facilities. The facilities cover a wide variety of telecommunication exchanges, masts and office buildings throughout South Africa.

TFMC's responsibility is to ensure that an ideal environment is provided for the telecommunication equipment in these facilities. The following is defined as typical environmental equipment:

- Electrical Power Supply systems (for the buildings and all equipment within the buildings)
- Emergency Power Supplies (EPS) / standby generators
- Uninterruptible Power Supplies (UPS)
- Heating, Ventilation, Air-conditioning and Refrigeration systems (HVACR)
- Fire Detection and Prevention systems
- Lift and Elevator systems
- Audio Building systems (PA, lift intercoms and fire phones)
- Domestic Water Supply and Sump Pump systems
- Cable dehydration or cable pressurisation systems
- Security systems (physical and electronic)
- Infrastructure and Gardening

Most of the mentioned equipment is electronically controlled requiring no human interface.

1.1.2 TFMC Maintenance Actions

In order to perform the facility management / maintenance task, TFMC has nine regional offices, 1 300 employees with 700 vehicles or maintenance teams. The ratio between telecommunication facilities and maintenance technicians is 50:1, which translates to an average of 4.5 maintenance man days per year per site. Refer to Paragraph 2.2.5 for more detail on TFMC's Historical Maintenance Strategy.

1.1.3 The Current Remote Alarm Monitoring System (RAMS)

Resulting from the low average maintenance man-hours per day, per site, when TFMC technicians were on site, the chances of detecting equipment failures were very low which relates to a slow Mean Time To Repair (MTTR) figure, which in turn relates to low availability of equipment.

To improve the MTTR and availability, the Remote Alarm Monitoring System (RAMS) was developed and implemented by TFMC on all Telkom's strategic sites. Thus, when equipment failure occurs, an alarm is sent to the Building Control Centre (BCC) in the Meersig building in Centurion from where the corrective restoration activities is initiated and tracked [2].

1.2 Problem Statement

Historically TFMC's maintenance strategy was based on a Predetermined Preventative Maintenance strategy. Refer to Paragraph 2.2 for an Overview on Maintenance Philosophy. At the same time, the workload in the facilities changes as Telkom's telecommunication requirements change [3], [4].

This resulted in all Predetermined Preventative Maintenance actions being regularly evaluated to ensure continuous effective maintenance. These re-evaluation processes require full-time team equipment specialists to constantly upgrade each site's maintenance plans and maintenance schedules. In the end, this maintenance strategy was found to be insufficient and still resulted in too many failures.

The mentioned RAMS system only triggered alarms when failures occurred. This resulted in many large failure-related costs such as client income loss, consequential damages to other equipment (environmental and telecommunication equipment), catastrophic failure replacement costs, unplanned maintenance overtime costs, etc [5].

High failure rates also occurred within the cable dehydrators. Initially cable dehydrators were not considered to be of a high priority for several reasons, discussed in Paragraph 4.1.

To conform to modern communication needs, Telkom re-evaluated the importance of the different telecommunication facilities and equipment within the telecommunication chain. This resulted in reprioritisation of their inter-exchange communication mediums (e.g. cables) and the associated environmental equipment (e.g. cable dehydrator systems) within the telecommunication chain.

The problem statement for this project was therefore to investigate and develop a new maintenance strategy which would drastically improve the availability of the environmental equipment in a cost-effective manner.

The cable dehydrator system was therefore selected as a suitable case study to ascertain whether the suggested process improves the situation in view of its historically bad availability status and its new elevated importance classification.

1.3 Objectives

The objective of the study was to transform TFMC's current maintenance strategy into a more effective strategy based on a Condition Based Maintenance (CBM) strategy. The following objectives were identified:

- Evaluation of the different maintenance strategies and determining the impact of a Condition Based Maintenance strategy to improve reliability and increase maintenance effectiveness.
- Evaluation of the different condition monitoring techniques and determining which of the different methods would contribute significantly to provide the required equipment condition data for implementation of Condition Based Maintenance.
- Development of a methodology to determine the critical equipment conditions which needs to be monitored.
- Investigation into the existence of standards for Condition Monitoring and Condition Based Maintenance and analysis of their applicability in the TFMC facility management environment.
- Implementation or application of Condition Monitoring and Condition Based Maintenance on a sample of Cable Dehydrator systems.

The study shall then comment on the way forward for application of the new Condition Based Maintenance strategy, to be applied on cable dehydration and the other environmental equipment for which TFMC is responsible.

1.4 Research Methodology

The aim of the study was to ensure a comprehensive understanding of international trends, concepts and applications concerning facility management, maintenance concepts and condition monitoring in order to improve system availability and cost-effective maintenance in the facility management industry. The study explored crucial aspects of facility management and maintenance strategies from a condition and alarm monitoring perspective.

The study was divided into several phases. Firstly, a literature study was launched to gather information on international trends pertaining to the problem statement and possible solutions that may have been previously explored or implemented. The information obtained was analysed and a new Maintenance Management strategy conceptualised.

The second phase of the study focused on methods and processes for implementation of the new Maintenance Management strategy. This led to a second literature study to search for tools which could assist in determining which equipment parameters should be monitored in order to gain maximum impact when applying Condition Based Maintenance in the facility management industry. The study also attempted to learn from the mistakes of others where similar strategies were implemented. Solutions to avoid similar mistakes were then proposed.

In the third phase, the principles, processes, tools and concepts were applied to a case study based on the Cable Dehydrator system. The study included the improvement of the current Alarm Monitoring system, the application of the tools on the chosen group of equipment, and the design of the complete maintenance system. The system was applied to a few prototype systems.

The results obtained from the implemented system were analysed over a three months period to determine whether the new maintenance strategy did indeed provide the required solution. The case study further reflects on additional work which must be performed to finalise the study, and ends with comments on the successful implementation of the system on the mentioned equipment.

Lastly, the study reflected on the usefulness of the new Maintenance Management strategy and all the tools, processes and solutions, as developed. The recommendation made is that the solution developed in this study should be implemented on all the environmental equipment managed by TFMC.

1.5 Outline of the Thesis

Through the study readers will be guided through the research process:

Chapter 1 sets the overview of the study. This includes the problem statement, the need and how the study was conducted.

Chapter 2 describes the literature search that was carried out in order to obtain a comprehensive understanding of the current status of the international trends within the fields of facility management, different maintenance philosophies, maintenance concepts and Maintenance Management strategies. The study also investigates Condition Based Maintenance and Condition Monitoring in more detail. From the above information a new Maintenance Management concept is described, based on Condition Based Maintenance but also incorporating key principles from the other strategies.

Chapter 3 describes ways and methods to implement the new strategy and investigates the implementation of the new strategy. During the research and analysis there is a closer look at the base technology and tools with which the condition monitoring data will be collected. The study also looks at tools to determine which equipment condition parameters should be collected, and which would have the highest impact. International Standards as applied on Condition Base Maintenance are also addressed.

Chapter 4 describes the Cable Dehydrator System (CDH), with its role and operational detail. The tools and standards, identified and evaluated in Chapter 3, were applied to the Cable Dehydration system and the most important equipment parameters were identified.

Chapter 5 addresses the detail design of the new Remote Condition Monitoring System (RCMS) and the Condition Based Facility Management system (CBFM). A few equipment health scenarios were evaluated with basic simulations to assist with the prediction of failures.

Chapter 6 looks at some of the results obtained from the system as implemented on eight Cable Dehydration systems. The CBFM's effectiveness to improve system availability and reduction in maintenance costs is described.

Chapter 7 draws conclusions on the implementation of the CBFM concept applied to the Cable Dehydrator Systems (including the RCMS, on the CDHs.) It is recommended that the newly developed CBFM can be implemented on the other environmental equipment managed by TFMC.

CHAPTER 2. FACILITY MANAGEMENT AND MAINTENANCE STRATEGIES

2.1 Facility Management

Productivity is a key issue for industrial companies to stay competitive in a continuously growing global market.

A few years ago, facility management companies were not very common. Most facility owners had their own maintenance departments looking after their facilities. As the economic climate changed and profitability became the main business driver, businesses started to focus more on their core business and all non-core business was outsourced.

It was and is still believed that specialist companies which focus on facility management as their core business would be more effective. TFMC is such a company which focuses on facility management [1], [6].

The main reason for the existence of facility management companies is thus to provide a better, more focused and more cost-effective service [7].

2.2 Overview on Maintenance Philosophies

It is vital for the Facility Manager to continuously evaluate his/her maintenance strategy to ensure that it delivers the most effective service for the changing business environment. Increased productivity can be achieved through increased availability of production equipment or tools.

This has directed focus on different maintenance concepts and Maintenance Management strategies.

2.2.1 General Maintenance Concepts

Most maintenance philosophies contain both corrective maintenance activities as well as preventative maintenance activities. According to Swedish standard SS-EN 13306 [9], [10] maintenance can be broken down as shown in Figure 1:

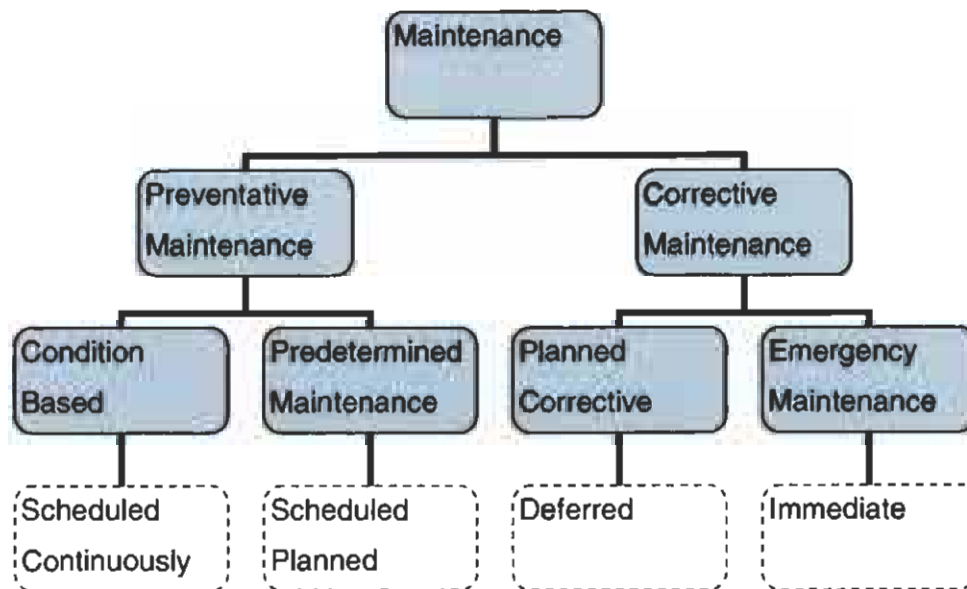


Figure 1: Maintenance Breakdown

The corrective maintenance strategy is common amongst all maintenance strategies. The major change in maintenance strategies occurred in preventative maintenance strategies, where several different strategies were developed over the past few decades.

Increased availability through efficient maintenance can be achieved through less corrective maintenance actions and more accurate preventive maintenance [8].

2.2.2 Corrective Maintenance

Corrective maintenance is performed after a breakdown or when an obvious fault has occurred. For some types of equipment the maintenance action must be performed immediately while for others the maintenance action can be deferred in time, depending on the equipment's function criticality [10]. The corrective maintenance activities could be defined as:

- Emergency Maintenance (EM) or immediate maintenance resulting from a failure. Some of these faults are detected through TFMC RAMS, the client's own monitoring system or by the client's employees who will inform the Facility Manager through logging a fault via the call centre.
- Planned Corrective Maintenance (PCM) or deferred maintenance is performed where part of the equipment needs to be replaced and is not immediately available. In this case a temporary repair will be executed. PCMs can also occur when major maintenance actions are required (e.g. where compressors or a bearing needs to be replaced) and the equipment will be out of service for a day or two.

These tasks were normally identified through the maintenance personnel during Planned Maintenance (PMs) or when temporary repairs were performed during EMs. Maintenance tasks can also be specified by the supplier of the equipment to be executed after a certain number of running hours.

2.2.3 Preventative Maintenance

Preventive maintenance is performed in order to prevent equipment breakdown. Typical preventative maintenance tasks are: servicing (replacing filters and oil), adjusting of the system to work optimally, replacing components and performing repairs which did not result from a failure. Another definition is, “the maintenance actions performed today which will prevent failures, tomorrow”.

The effectiveness of preventative maintenance was improved over several years. In order to understand a maintenance strategy like Condition Based Maintenance it is necessary to see it in context with other Maintenance Management strategies.

2.2.4 Maintenance Management Strategies



Figure 2: Maintenance Management Strategy Evolution

Figure 2 illustrates the evolution of Maintenance Management strategies and the acceptance thereof in the industry, in principle [50]. It should be noted that newer maintenance concepts are built on and incorporate earlier concepts, rather than replacing them. For example, Reliability Centred Maintenance still incorporates the concepts of repairs after failure,

inspections, scheduled and Condition Based Maintenance options, but now form part of a more holistic and rational decision framework.

Current leading Maintenance Management strategies are listed in Figure 2. The latest one can be defined as:

- Predetermined Preventative Maintenance strategy (PPM), aims to achieve preventative maintenance actions through a predetermined set of preventative maintenance tasks which were executed through a fixed schedule of maintenance activities.
- Condition Based Maintenance (CBM), aims to monitor and predict the optimum time when maintenance per individual piece of equipment is necessary, determined from the condition of the equipment in order to prevent failure of the equipment [11], [12].
CBM has been defined as "Maintenance actions based on actual condition (objective evidence of need) obtained from in-situ, non-invasive tests, operating and condition measurement" [13].
- Reliability Centred Maintenance (RCM), aims at reducing equipment failures by eliminating the root cause of failure through the use of failure mode analysis and selection of appropriate maintenance options [5], [14].
- Total Productive Maintenance (TPM), aims at maximising equipment efficiency by eliminating losses in the manufacturing process. These improvements could be obtained through a change in organisational culture as embodied in increased operator ownership, cross-functional performance improvement teams, visible senior management commitment and support to operational excellence [15], [16].
- Risk Based Maintenance (RBM), focuses on the risks associated with failures, as the primary basis for choosing appropriate maintenance options, rather than the failure itself as defined in the classical RCM approach. In this approach, risk, as determined by the combination of the probability of failure and the consequence of such failure, is used to identify maintenance critical equipment. These items are subjected to a formal RCM analysis [17], [18].
- Profit Centred Maintenance (PcentM), in which the maintenance of machinery, equipment and fixed assets are considered a profit activity and is optimised for maximum value rather than least cost. Profit Centred Maintenance combines best practice maintenance with re-engineering, maintenance, administration, modern information technology and empowered workers [19], [20].

2.2.5 TFMC's Historical Maintenance Strategy

TFMC's historical maintenance activities were based on a Predetermined Preventative Maintenance strategy (or Planned Preventative Maintenance strategy).

Their historical maintenance strategy included three maintenance activities which could be defined as:

- Predetermined / Planned Maintenance (PM) or scheduled maintenance, performed on a regular base. This normally only includes tasks like changing filters and oils, adjustments if necessary, and inspection to detect any other problems.
- Emergency Maintenance (EM) as previously defined.
- Planned Corrective Maintenance (PCM) as previously defined.

2.2.6 Most Important Principles within the Different Strategies

The most important principles in each of the Maintenance Management strategies can be summarised, as below. To improve TFMC's previous strategy it is important to build their new strategy on the principles which will contribute the most, within their environment. The principles are:

- Equipment should be maintained according to it's current condition (CBM).
- Maintenance should be done on equipment, only to ensure or improve reliability/availability (RCM).
- Equipment should be maintained or reengineered to maximise efficiency by eliminating losses (TPM).
- Maintenance focus should be concentrated on the risks associated with failures rather than the failure itself, as in the classical RCM approach described above (RBM).
- All maintenance actions should be focused on the equipment's function in order to generate or ensure profit (PcentM).

The fundamental principle, on which the new improved maintenance strategy is based, is to maintain equipment according to its true current condition. The other principles, as listed above, assist to focus the attention on specific equipment, which contribute to risk, efficiency and profitability.

2.3 Condition Based Maintenance (CBM)

Condition Based Maintenance (CBM) is a technology that strives to identify incipient faults, before they become critical. This enables more accurate planning of the preventative maintenance actions or tasks.

The following typical tasks must be performed within CBM:

- Obtain equipment condition data (Condition Monitoring).
- Determine the current health of the equipment.
- Predict if and when potential failures will occur.
- Develop maintenance actions to prevent these failures.
- Schedule and activate these preventative maintenance actions.

The accuracy of equipment health predictions and the tasks to follow are dependant on how the equipment conditions are monitored.

2.3.1 Condition Monitoring as Applied in Industry

The first step in CBM is generally known as Condition Monitoring (CM). CM means the use of advanced technologies in order to determine equipment condition and potentially predict failure [21]. It includes, but is not limited to, technologies such as:

- Vibration Measurement and Analysis [22], [23]
- Infrared Thermography [24]
- Oil Analysis and Tribology
- Ultrasonics [23]
- Motor Current Analysis [25]

Condition Monitoring is most frequently used as a Predictive or Condition-Based Maintenance technique. However, other Predictive Maintenance techniques can also be used, including:

- Human Senses (look, listen, feel, smell etc.).
- Machine Performance Monitoring [26]. (Machine Performance Monitoring is the one Condition Monitoring technique which allows optimum time for restorative maintenance to be determined where the deterioration results in increased fuel consumption, or in reduced output, or both).

2.3.2 Condition Based Maintenance (CBM) as Applied in Industry

CBM can be achieved by utilising complex technical systems or by utilising human experience to manually monitor the equipment and performing the necessary maintenance actions. Using humans is not always very successful as the maintenance technician servicing the equipment does not always have the necessary skills, or visits to the sites are not frequently enough.

Traditionally, the method used to collect data was to collect technical data, periodically, with a handheld data collector, by a CM technician. Even the sensors could be portable and the technician would move it from one machine to the next. The sensors could also be permanently installed on machines, in which case the technician would connect the handheld data collector to the sensors for capturing the condition data.

The condition data is then transferred from the handheld device to a PC with some analytical software, e.g. vibration analysis toolkit. Through the assistance of the software and the technician's skills, an equipment health and potential failure prediction is then made. The CM technician will then prescribe maintenance actions (CBM) to prevent the predicted failures.

During the data collection process, condition variations were not effectively taken into account, except perhaps in a qualitative manner. Thus the slight variations in the CM results, that appeared between surveys were assumed to be due to these "process condition variations", and were regarded as insignificant [27].

The diagnostic capability would become far more accurate and sensitive if it was possible to also collect the "process conditions" at the time of recording the equipment condition data.

Previously it was not possible to collect the "process data". The system therefore relied on the analyst's experience to arrive at an accurate fault detection and failure prediction.

Some CM suppliers started to offer integrated CM software which permits the effective integration of Oil Analysis, Vibration Analysis and other Condition Monitoring data into combined reports [28].

Computerised Maintenance Management System (CMMS) vendors also started to include a "Condition Monitoring" module within their software. However, this was generally limited to typical condition data like "running hours", thus the effectiveness of this integrated solution is still questionable [28].

Current, commonly used sensor technology only permits the most rudimentary form of signal processing and analysis within the sensor. To perform accurate and detailed failure prediction with Vibration Analysis, large quantities of data must be transmitted from the sensor to a separate, usually handheld, data collector, for subsequent processing and analysis [22].

In the past, the large amount of data transfer to remote systems was not economically viable and on-line vibration monitoring was thus limited to an overall vibration alarm. New technologies are currently emerging which increased "on-board" signal processing power dramatically. Some equipment vendors already provide permanently installed vibration sensors in some of their larger electric motors and other equipment [23].

Wilcoxon Research has already developed so-called fourth generation "Smart Sensors" that permit onboard signal processing and analysis, similar to that currently requiring a handheld data collector and/or a Personal Computer [29].

When fully implemented, the smart sensor technology will greatly reduce the complexity of linking the outputs of the sensors to current Process control systems.

More and more equipment will be capable to be monitored in real time, on-line, and control room operators will be able to quickly and easily tell the current condition of bearings or the alignment and balance of gears, on a machine [10].

2.3.3 Why did Previous Condition Based Maintenance (CBM) Fail?

When looking back since the concept of Condition Based Maintenance was introduced, it can be seen that the predicted growth at that time was not as astronomical as everybody had suggested. In fact, CBM has only grown at an average of 4% annum [12].

Although CBM holds a lot of benefits compared to other maintenance types, it is not yet commonly utilised in the general industry. CBM successes were mainly achieved in the technically advanced industries or where the consequence of failure could have serious implications, such as in the aircraft industry, power generation industry, especially nuclear power, etc.

The general industry will only accept CBM when it reaches an acceptable maturity level as required within the industry [12]. It is therefore necessary to understand why it failed or did not grow as expected, in order to know the way forward. These reasons for failure can be summarised as follows:

- The different CM data was not properly integrated (Vibration-, Oil-, Heat Analysis).
- CMMS did not cater properly for CM and CBM in the past, resulting in a lack of integration between CM or CBM and CMMS.
- Only on-site collection of CM data was possible, utilising highly skilled CM technicians.
- CM data did not take process data or equipment workload into consideration.
- CBM success was not visible as no failures occurred.
- CBM success could only be traced if compared with detailed pre-CBM maintenance data, which was not always available.
- The cost of CBM was highly visible.

The success of a CBM program was therefore greatly dependant on the effective integration of the CM data into the capturing of maintenance data (e.g. CMMS) and the integration of CBM into the business operation / productive process [30].

Sensor technology has improved to where a large quantity of pre processing of the raw data is possible in the sensor or within a small microprocessor close to the equipment. Telecommunication systems worldwide have also improved to the extent where enough bandwidth is now readily available for real-time remote CM [31] [32].

It is believed that in the first part of this century CM and CBM are going to be key success factors in the maintenance industry [27].

2.4 Conclusion - Condition Based Facility Management (CBFM)

From the Maintenance Management strategy analysis the most important maintenance principles, which are applicable in the Facility Management industry, were extracted (refer to Paragraph 2.2.6). CM was selected as the base principle, while the other principles assisted to focus on the most important equipment and functions. In Paragraph 2.3.3 the previous issues, which prevented CBM to achieve its full potential, were identified.

A new CBM concept applicable in the FM industry was formulated. The Condition Based Facility Management (CBFM) concept was built on the following principles:

- Condition Monitoring should be used to optimise maintenance actions, focus on equipment failures and equipment inefficiencies. (CBM performed on RBM and TPM principles).
- Maintenance actions should be focused towards preventing equipment failure which could have high risk and a big profit impact on the client.

- Maintenance should also be focused on equipment which is not working optimally and which could have high risk and a big profit impact on the client.
- CM should also capture process or workload data and integrate it in the equipment health assessment.
- CBFM should be properly integrated into CMMS to ensure proper capturing of maintenance actions and other maintenance data.
- CBFM should make use of remote, real-time monitoring, to improve timeous execution, trend analysis and ease to automate integration with CMMS.

CHAPTER 3. **CONDITION BASED FACILITY MANAGEMENT**

In Chapter 2, the new Condition Based Facility Management concept was developed. The CBM concept was enhanced with maintenance principles from other Maintenance Management strategies, providing a more specific focus.

The principles as listed in Paragraph 2.4 for CBFM were translated into tools, methodologies and standards, in this chapter, described as:

- The Remote Condition Monitoring System (RCMS) of facilities, a tool through which specific real-time equipment condition data was collected.
- The tools through which equipment condition data were collected, were focused. (Risk, equipment performance optimisation and process data or equipment workload).
- The CBM standards which would ensure open system architecture to convert all types of CM data into maintenance actions, without being restricted to one technology supplier.
- The implementation of maintenance actions to, prevent identified predicted failures.
- The integration of CM data and associated maintenance actions into CMMS for data capturing.
- The converting of CM data and associated maintenance actions into management information reports.

3.1 Condition Data Collection via a Remote Real-time data Collection System

New telecommunication technology has opened the world for transferring of data at very high speeds from almost anywhere to any place. This together with the Internet has made it economically possible to start optimising different systems in various factories or industrial plants all over the world (System-to-System Communication). Process information can now be exchanged in real-time, with which the different processes within plants can be optimised, the so called Machine-to-Machine (M2M) communication [31].

In previous CM systems data was collected via handheld devices at each machine. With the fast telecommunication systems, available today, CM data can now be collected from remote locations in real-time. The Remote Alarm Monitoring Systems (RAMS) based on this remote real-time technology creates the ideal platform for CM or CBFM. CM will be performed through enhanced RAMS.

3.1.1 RAMS Platform Capability

The RAMS platform has the following capabilities [33]:

- Relays alarms from the equipment to control room personnel
- Relays equipment alarm conditions to technical specialists
- Real-time trending of operating conditions
- Logs all alarms and operating conditions (events)
- Assists with energy management, without jeopardising the availability of environmental systems on sites
- Integrates existing, legacy and modern control systems
- Integrates various systems onto a single platform
- Graphical presentation of equipment and systems, in a user-friendly manner
- Has a hierarchical user interface (drill-down capability)
- Has a unified operator interface, that significantly reduces operator training requirements
- Is accessible anywhere throughout the company on the Intranet and if required on the Internet (e.g. Web based systems)
- Keeps a historical database of alarm and operating conditions
- Performs control functions

These RAMS systems were designed to integrate a variety of devices and protocols into a common distributed automation system. They incorporate software technology to integrate LonWorks™, BACnet™, Modbus and various Internet standards into a common object model, embedded at the controller level and supported by a standard Web browser interface.

A full range of low cost LonWorks™ and Modbus electronic controller cards were developed to form the current TFMC remote monitoring system. Additional interface drivers were also

developed for several controllers and systems, with the assistance of the manufacturers of these controllers and systems.

3.1.2 Remote Alarm Monitoring Integrated System Architecture

The remote monitoring system architecture as developed by the author and his engineering team is briefly described below:

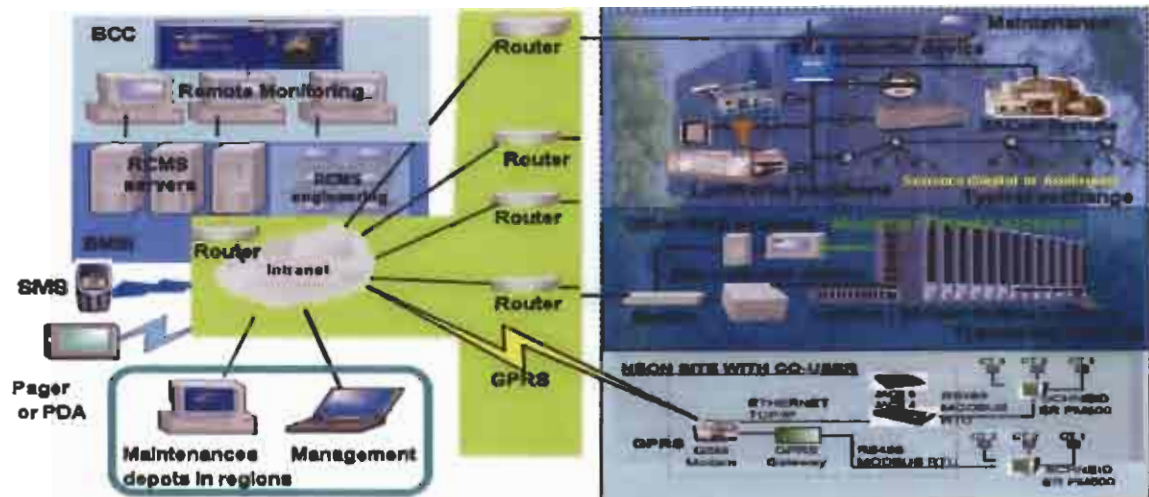


Figure 3: RCMS Architecture

The system comprises of the following:

The Building Control Centre (BCC) from where a 24x365 monitoring service is performed.

The engineering team to expand / rollout the system to additional sites or to add additional monitoring points to the current facilities. The team also performs support and maintenance functions on the system.

A countrywide communication network was established, connecting the sites to the BCC, through Diginet and Frame-relay networks for bigger sites and the GPRS network for smaller sites.

On site, a Site Interface Controller (SIC) gathers all the monitoring data from the local I/O nodes distributed throughout the site, via different building control networks (e.g. LonWorks, Modbus or propriety building control networks). This device will pass on all the information and data between the servers in the control room and the local SIC via the communication network.

Sites equipped with Building Management Systems (BMS) are linked directly to the local SIC through an intelligent protocol interface.

Alarm and fault data can be automatically dispatched to maintenance technicians through SMS.

Maintenance technicians and depots can access plant statuses through a standard Web browser over the company Intranet or Internet, if desired.

3.1.3 Transforming the RAMS into a Remote Condition Monitoring System (RCMS)

This RAMS was the ideal platform to expand, in order to become the RCMS. The transformation required only the development of additional interfaces to different controllers as required or through adding additional sensors on the LonWorks or Modbus networks.

The condition data was stored in different Log tables in the SIC and in Log and archive tables, in the monitoring servers at the BCC. Post processing was partially done in local controllers, in the plant rooms, in the SIC and in the monitoring servers.

The RCMS system needs to convert equipment condition data into equipment health statuses and eventually perform failure prediction. For this an additional database and processing was required, as discussed in Paragraph 3.3.

3.2 What Equipment, Condition Data must be Collected? - What to Monitor?

The CBFM system uses principles from RCM, TPM, RBM and PcentM to focus CBM. The following CM data must thus be collected:

- Monitor "What can go wrong" – potential failures (RCM) and "What is the associated risk" (RBM).
- Monitor equipment performance or efficiency including equipment workload (TPM).
- Replace inspections and similar tasks through remote condition monitoring.

Different tools were analysed to assist with the determination of important points to be monitored. Some of these tools are used in RCM, RBM and TPM. The different tools, and how they were adapted for the purpose of this study, are briefly discussed below:

- The Black Box approach only analyses the external factors e.g. inputs and outputs of the system.
- Failure Modes Effects and Criticality Analysis (FMECA) helps to identify potential failures, the modes in which the equipment can fail, the effect of such a failure and the criticality of the failure.

- Root Cause Analysis (RCA), analyses failures which have occurred. It also determines what really caused the failure and how it could have been prevented.
- Current Historical Maintenance data analysis. From this data the equipment replacement frequency and the current cost drivers can be determined.

3.2.1 *Plant Performance Analysis (Monitor if the system is working as it should)*

An important part of the Remote Condition Monitoring System is to make the operation of the systems easily visible to the monitoring operator. A holistic overview of the systems performance is thus required.

Each system is designed to perform one or more functions (e.g. provide dry, oil free compressed air). When the system or equipment can no longer perform this function to the required level (e.g. can not supply compressed air), the condition is defined as a functional failure (complete or limited failure). A functional failure normally results from an engineering failure (e.g. compressor bearings failed).

The Black Box approach is very effective to indication if the system is working and if it is functioning correctly and optimally. The complete system can be considered as a Black Box.



Figure 4: Complete System Black Box

This can be done by monitoring various parameters of the complete system. Firstly it is necessary to show the “Output” parameters which indicate if the system is delivering its intended function. Secondly, it must indicate if there are any “Input” parameters that are a prerequisite for the outputs to be delivered.

If the mentioned parameters are within predefined limits, the system performs its intended function and does not require any corrective maintenance.

If it is detected that the system is not performing its intended function, it is necessary to investigate in more detail, to determine “What is not working properly?” This information is required to send out the correct technician with the correct spares.

In order to determine what is wrong it is necessary to analyse the system in more detail. The Black Box approach can again be useful, but now on sub-systems level, as seen in Figure 5.

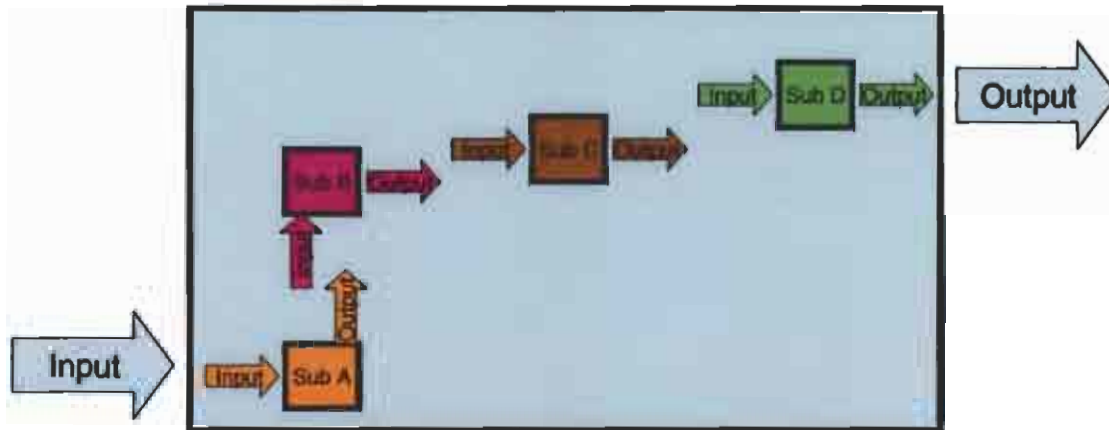


Figure 5: Sub-system Black Box Approach

3.2.2 Failure Mode, Effects and Criticality Analysis (FMECA)

Introduction to FMEA or FMECA

Failure Modes, Effects, and Criticality Analysis (FMECA) is one of the most widely used and effective tools for developing quality designs, processes, and services [34], [35], [36].

When FMECAs are developed during the design stage they are procedures by which potential failure modes of a system are analysed to determine the effect of failures on the system. This is done by classifying them according to their severity and probability of occurrence, which assists to prioritise them. Actions plans can then be recommended to either eliminate or compensate for unacceptable effects.

The principle objective of FMECAs is to anticipate the most important design problems early in the development process. These can then either be prevented from occurring, or their consequences can be minimised as cost effectively as possible.

Ideally the FMECA must begin early in the design phase and be maintained throughout the life of the system. The FMECA becomes a diary of the design and all changes that affect system quality and reliability.

FMECA - Bottom-up Approach for Facility Management / Maintenance Perspective

For many older systems the FMEACs were not formally used and the data or diaries were thus not available to the maintenance personnel. An alternative is the construction of a new FMECA from the bottom up. This method starts the analysis with the failure modes of the lowest level items (e.g. components level items) of the system, and then successively iterate up through the levels and ends at the system level.

The following FMECA steps were used:

Step A – The system, process or hardware is broken down into discrete elements. Thus, the system needs to be broken down into a number of assemblies or sub-systems and ultimately into individual components.

Step B - Failure mode analysis. The manner in which each element could potentially fail needs to be determined.

Step C - Failure Effect Analysis. Each failure mode must be independently evaluated for the effect of that failure at the current level and then on the entire system.

Step D - Criticality Analysis - There are some industry-adopted approaches to quantifying risk in FMECAs, as well as a number of user-defined approaches [34], [48].

The Risk Priority Number (RPN) criticality analysis approach was chosen, which is a numerical assessment of risk using the following definition of the RPN number:

- Risk Priority Number (RPN) = Severity * Occurrence * Detection
- RPN values range from 1 to 1 000. Each failure mode must be evaluated to determine its Severity, Occurrence, and Detection number.
- The Risk priority scores were adapted by the author to assist in the analysing of failure risks for a Remote Condition Monitoring application. Refer to Table 1 for the new Risk Priority score table.

Score	Severity	Occurrence	Detection
1	Small functional decrease with no cost implication to the system itself	Very seldom	Very easy to detect and predict with accuracy when it will occur
2	Small functional decrease with low cost implication to the system itself	Once in ten years	Easy to detect and predict with medium accuracy when it will occur
3	Medium functional decrease with low cost implication to the system itself	Once in five years	Can be detected and predicted with medium accuracy when it will occur
4	Medium functional decrease with medium cost implication to the system itself	Once in three years	Can be detected but difficult to predict when it will occur
5	Total functional decrease with low cost implication to the system itself	Once a year	Can be detected but cannot predict with accuracy when it will occur
6	Total functional decrease with medium cost implication to the system itself	Once in six months	Difficult to detect and to predict when it will occur
7	Total functional decrease with high cost implication to the system itself	Once in three months	Difficult to detect and cannot predict with accuracy when it will occur
8	Increased damage to other or client equipment, high cost implications	Once a month	Difficult to detect and cannot predict when it will occur
9	Catastrophic + injuries	Once in two weeks	Very difficult to detect and cannot predict when it will occur
10	Catastrophic + loss of life	Once a week	Cannot be detected and cannot predict when it will occur

Table 1: Risk Priority Score Table

Action Plans to Stop / Prevent Failure Modes and its Effects

A new three-stage action plan, was developed in this study, to reduce the associated risks from failures (as per FMECA) through a combination of remote real-time detection, redesigning the system / components or through the adding of redundant systems:

Stage 1, ensures that components with an individual severity score of 9 or higher, conform to the necessary safety requirements and statutory requirements.

Stage 2, ensures that components with a high “Severity * Occurrence Number” are monitored and conform to the CM action requirement as set out in Table 2. This stage ensures that the risk was significantly reduced through the implementation of the RCMS to predict potential failures.

S*O Number	Risk Classification	CM Action Required
49 -100	Critical high risk	Must be remotely monitored with a detection system with a value of not more than 3 and a backup or second sensing system
36 -48	Very high risk	Must be remotely monitored with a detection system with a value of not more than 4
25 - 35	High risk	Must be remotely monitored with a detection system with a value of not more than 5
12 - 24	Medium risk	Must be remotely monitored
0 - 11	Low risk	No actions

Table 2: Severity and Occurrence Risk Definitions and CM Actions

Stage 3, ensures that all components are within acceptable risk tolerances as seen in Table 3, and where necessary reduce the risk through redesign or adding of redundant systems.

RPN	Risk Classification	Risk Reduction Action Required
500 -1000	Very high risk	Needs to be redesigned or redundant system needs to be put in place in order to prevent these occurrences
150 - 500	High risk	Needs to be redesigned or redundant system needs to be put in place in order to prevent these occurrences
111 - 150	Medium Risk	Must be remotely monitored
0 - 110	Low risk	No actions

Table 3: Risk Priority Number Risk Definition

The CM system must thus reduce the total criticality of any failure to below 150 after which it can be classified as a low risk.

3.2.3 Root Cause Analysis (RCA) or Passed Failure Analysis

Root Cause Analysis (RCA) is a method which analyses failures which have already occurred, in order to prevent such failures in future.

The RCA must be performed by a group of knowledgeable people who can investigate the failure using evidence left behind from the fault. The team brainstorms to find as many causes of the fault as possible. By using what evidence remained after the fault and through discussions with people involved in the incident, all the non-contributing causes are removed and the contributing causes retained.

A fault tree is constructed starting with the final failure and progressively tracing each cause that led to the previous cause. This continues until the trail can be traced back no further. Each result of a cause must clearly flow from its predecessor. If it is clear that a step is missing between causes, it is added in and evidence is searched to support its presence.

Once the fault tree is completed and checked for logical flow, the team determines what changes to make, in order to prevent the sequence of causes and consequences from reoccurring.

It is not necessary to prevent the first, or root cause, from happening. It is merely necessary to break the chain of events at any point to prevent the final failure to reoccur. Often the fault tree leads to an initial design problem. In such a case, redesign is necessary.

Where the fault tree leads back to a failure of procedures, it is necessary either to address the procedural weakness or to install a method which can protect against the damage caused by the procedural failure [37], [38].

3.2.4 Historical Maintenance Data Analysis

Another valuable source of information, is the Computerised Maintenance Management System (CMMS). The maintenance cost drivers of specific equipment can be analysed to determine cost drivers and other important maintenance issues. The following typical analysis can be performed:

- Maintenance task analysis
- Maintenance task cost analysis
- Material and components used analysis
- Material and components used cost analysis
- Reliability and availability analysis

The maintenance as specified by the manufacturer and as applied must also be analysed. Some of the cost drivers, identified through the historical maintenance data analysis, originate from this previous maintenance strategy.

In some cases the cost drivers can be ignored as the new maintenance strategy will not include these costs. However, it remains a function of the new strategy and tasks to ensure that these costs are avoided or minimised, through better maintenance practices.

In other cases the analysis highlights current, unofficial maintenance practices that are not according to the manufacturer's or the facility management company's strategy. These practices must be investigated to ensure that the new strategy and tasks avoid these malpractices or incorporate those, which contribute positively towards the bottom-line result.

3.2.5 *Summary of Tools*

This study's focus was to initiate the implementation of a Condition Based Facility Management strategy, with the starting point of converting the RAMS to a RCMS. The analysis tools as described above must assist to identify the points to be monitored.

The Black Box tool gives a holistic view on the real-time operation of the system. This view is important for any remote user which could be the maintenance technician, his supervisor, the maintenance specialist, the remote monitoring personnel or even the client. The holistic view provides the baseline information from which any decisions are made.

The FMECA tool is preferred when starting the process of implementing a Condition Based Maintenance philosophy as it analyses the complete system and does not focus on individual incidents.

If the FMECA is used, it is not necessary to use the RCA, as it provides the same type of information, but only for specific failure incidents. It could, however, be a useful tool to be used when an incident occurred, which was not foreseen during the initial implementation.

The analysis of current practices and their associated cost also provides useful information on current cost drivers. This data is especially useful to identify costly maintenance practices and can identify areas where the Condition Monitoring system can assist with significant improvements.

This is however not a guarantee for optimum maintenance, continuous improvement will be required. These tools do, however, provide vital information for the initial design of a Condition Based Maintenance strategy.

3.3 **CBM Standards**

Several organisations are active in the CBM field and are busy setting up standards ~~in order~~ to promote and open the systems for easy integrations between plant and machinery maintenance information systems.

One such organisation is the Machine Information Management Open System Alliances (MIMOSA). They are promoting Open System Architectures (OSA), for example Open System Architecture for Enterprise Application Integration (OSA-EAI) [39].

The Open System Architecture for Condition Based Maintenance (OSA-CBM) was developed as a *de facto* standard that encompasses the entire range of functions of which a CBM system needs to consist [23]. The different functions can be depicted as seen in Figure 6. For the purposes of this study the different processes are divided into Condition Monitoring functions and Maintenance Optimisation functions.

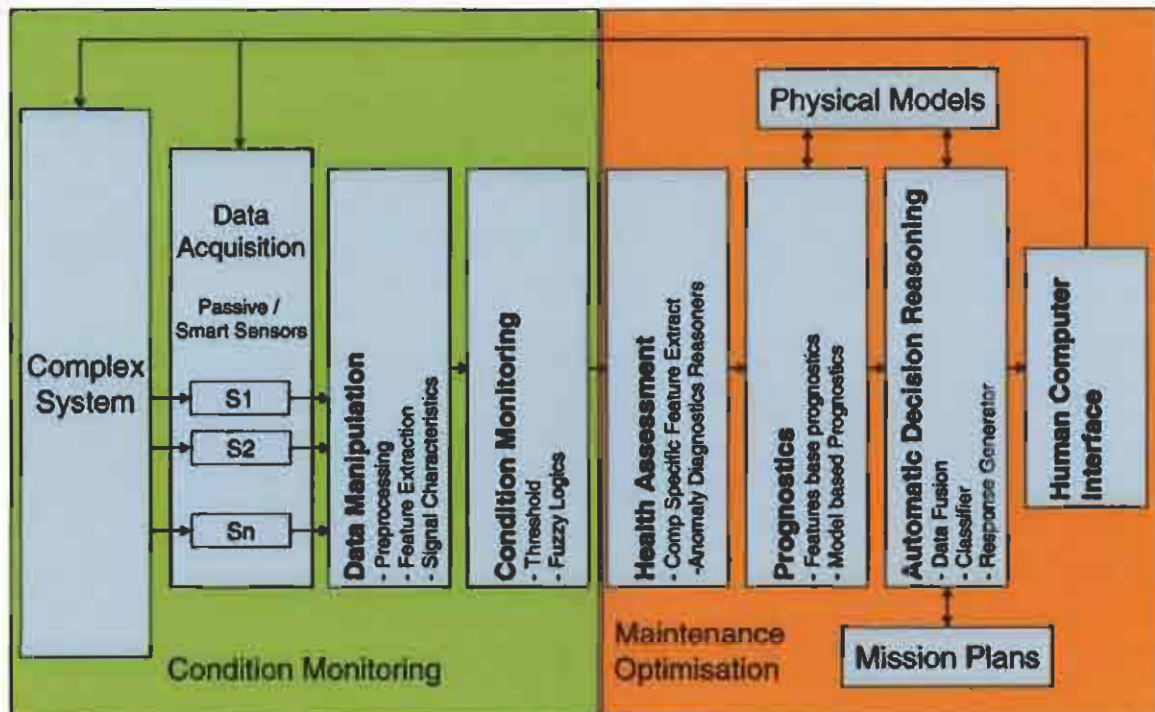


Figure 6: Open System Architecture for Condition Based Maintenance

OSA-CBM defines the following standard functions for CBM [23].

1 Sensor Module: The sensor module provides the CBM system with digitised sensor or transducer data. (Applicable standard IEEE Std 1451).

2 Signal Processing: The signal processing module receives signals and data from the sensors or other signal processing modules. The output from these signal processing modules includes digitally filtered sensor data, frequency spectra, virtual sensor signals and other CBM features.

3 Condition Monitor: The condition monitor receives data from the sensor modules, the signal processing modules and other condition monitors. Its primary focus is to compare data, to expected values. The condition monitor should also be able to generate alerts based on preset operational limits (applicable standard ISO 13373-1).

The degree of automation in assessing the condition can vary from human visual inspection to fully automated systems with sensors, data manipulation, condition monitoring, diagnosis, and prognosis.

4 Health Assessment: The health assessment module receives data from different condition monitors or from other health assessment modules. The primary focus of this module is to describe degradation in the health of the monitored component, sub-system or system.

The health assessment module should be able to generate diagnostic records and predict fault possibilities. The diagnosing should be based upon trends in the health history, operational status and loading, and maintenance history (applicable standards IEEE 1232 and ISO 13373-1).

5 Prognostics: The prognostic module should have the possibility to take into account, data from all the prior layers. The primary focus of the prognostic module is to calculate the future health of an asset, taking into account the future usage profiles. The module should report the expected health status over a specified time, or the Remaining Useful Life (RUL).

6 Decision Support: The decision support module receives data from the health assessment module and the prognostic module. Its primary focus is to generate recommended actions and alternatives. The actions can be related to maintenance or how to operate the asset, until the current mission is completed without occurrence of breakdown.

7 Presentation: The presentation module should present data from all previous modules with emphasis on the health assessment, prognostic and decision support modules as well as alerts generated from the condition monitors. The ability to look even further down in the layers should be a possibility. The presentation module could be built into a regular machine interface.

3.4 Integration of CM Data into CMMS

The CMMS system integrates and manages all maintenance activities [40]. These maintenance activities typically include data: from the asset register, the planned maintenance activities, the execution of maintenance tasks (both preventative and corrective maintenance), costing and the tracking of maintenance statistics e.g. MTBF, MTTR, etc.

Raw data within the CM system needs to be transformed into useful information as prescribed within the OSA-CBM standard [23]. Most of the processing will be performed outside the CMMS, but at least the final answer on the equipment condition, health status

and failure prediction needs to be recorded within the CMMS from where maintenance actions must be initiated.

All data obtained via the CM system must end within the CMMS in a raw or processed format as all activation and tracking of maintenance activities are managed by CMMS [28].

3.5 Management Information – Maximising the Value of CBFM

Another critical success factor of CM and CBFM is the generation of reports which must be sent to all relevant personnel on all levels of the business.

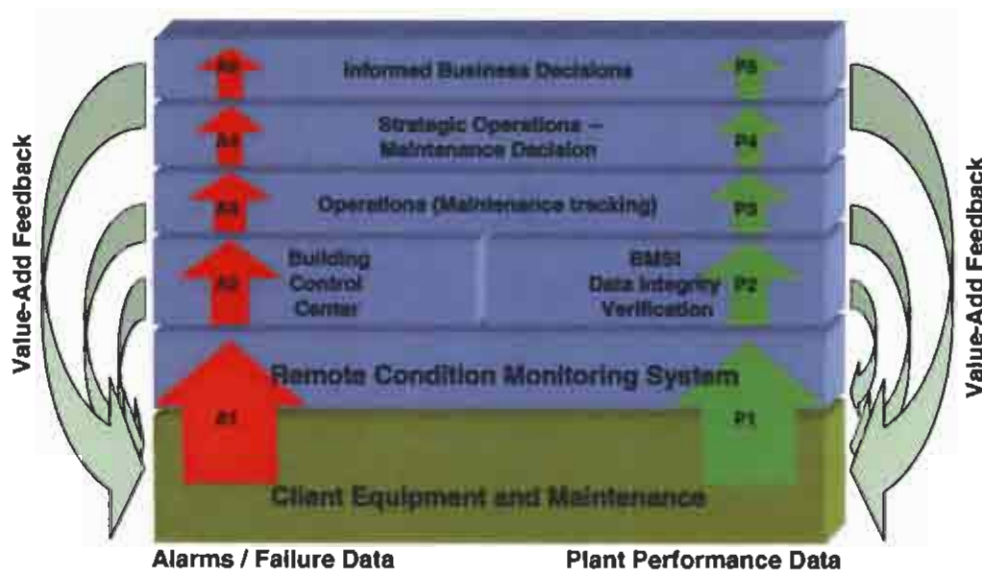


Figure 7: Data to Management Information to Knowledge

With the remote Condition Monitoring system, large quantities of equipment and condition data are collected. If this data is only stored in the servers and used by the control room personnel to initiate corrective or predictive maintenance, the true value of the CBFM system is limited.

All the equipment data (e.g. condition data, health assessment data and predicted failure data) must be converted or extracted into management information for the different levels within the facility management organisation.

In Figure 7, two separate information paths have been identified, namely Alarms / Failure data and, Plant Performance or Condition Data. As the data is passed through the FM organisation, each level can analyse the data.

Thus, with the correct condition and failure data each level within the organisation can make informed decisions at their level to improve or optimise the availability and cost effectiveness of the client's equipment.

The following is a list of typical reports which must be generated for the different levels:

- Building Control Centre Manager
 - Alarms received per month/week/shift
 - Alarms that received priority classification distribution
 - Unattended alarms per shift/hour/15 minutes
 - Emergency Maintenance actions in progress during shift/hour
 - Average MTTR alarm per priority classification
 - Alarms active for more than month/2 weeks/week/day
- Maintenance specialist in region
 - Average – MTBF, MTTR and Equipment Performance Factor on specific function equipment group (e.g. CDH or HVACR)
 - Average - MTBF, MTTR and Equipment Performance Factor on all equipment in specialist field (e.g. Chiller, Cooling Tower, CDH, Flow panel, etc) outside acceptable levels or change more than x% from previous months values
 - MTBF, MTTR and Equipment Performance Factor on each individual piece of equipment in specialist field (e.g. Rosebank/1st floor/Chiller3, Rosebank/Roof/Cooling Tower1, etc) outside acceptable levels or change more than x% from previous months values
 - Energy optimisation report, displaying trends on critical energy saving parameters per building and equipment.
- Operational Manager:
 - Failure trends on all functional equipment groups (e.g. HVACR, UPS, CDH, etc)
 - Average - MTBF, MTTR and Equipment Performance Factor on all functional equipment groups (e.g. HVACR, UPS, CDH, etc)
 - Average - MTBF, MTTR and Equipment Performance Factor on all equipment groups (e.g. Chiller, Cooling tower, CDH, Flow panel, etc) outside acceptable levels or change more than x% from previous months values

- Maintenance specialist in Head Office:
 - Average – MTBF, MTTR and Equipment Performance Factor on specific function, equipment group (e.g. CDH or HVACR)
 - Average - MTBF, MTTR and Equipment Performance Factor on all equipment in specialist field (e.g. Chiller, Cooling Tower, CDH, Flow panel, etc) outside acceptable levels or change more than x% from previous months values
 - Yearly trends on MTBF, MTTR and Equipment Performance Factor on each individual manufacturer's equipment in specialist field (e.g. UniFlair/Chillers/model xxx, PolarAir/CDH/CCD800 series, Nicotra Sistemi Spa/CDH/DSA160 series, etc)
 - Energy optimisation report, displaying trends on critical energy saving parameters per region per building and per equipment
- Executives and directors
 - Alarms received per month
 - Alarms received, priority classification, distribution
 - Average MTTR alarm per priority classification
 - Failures Trends on all functional equipment groups (e.g. HVACR, UPS, CDH, etc)
 - Average - MTBF, MTTR and Equipment Performance Factor on all functional equipment groups (e.g. HVACR, UPS, CDH, etc)
- Equipment manufacturer
 - Annual trends on MTBF, MTTR and Equipment Performance Factors on each individual manufacturer's equipment (e.g. UniFlair/Chillers/model xxx, PolarAir/CDH/CCD800 series, Nicotra Sistemi Spa/CDH/DSA160 series, etc)

3.6 Conclusion

The RAMS is the ideal platform to collect equipment condition data. The RCMS system will thus collect remote real-time condition data, which will include alarms.

The study has developed a methodology to overcome historical downfalls of CBM and to improve the value release of data, encapsulated within CM for the FM industry.

- Different tools were evaluated and three were selected to pinpoint which important parameters of the equipment need to be monitored, in order to predict critical failures and to improve equipment performance.
- The study defined the methodology to convert the failure modes and its effects, as obtained through the FMECA tool into an action plan, in order to stop / prevent failure modes and associated effects.
- The CBM standard as set by OSA-CBM was selected as a base for the CBFM design.
- The study identified the importance of integrating with the CMMS as all maintenance activities are executed, managed and tracked through it.
- To improve the value which the CBFM system can add to a FM business, the data as obtained and used in CBFM must be converted into management information reports, relevant to the different organisational levels and different departments within the business.

CHAPTER 4. THE APPLICATION OF CONDITION BASED FACILITY MANAGEMENT ON CABLE DEHYDRATION SYSTEMS

4.1 Telecommunication Cable Background

To complete the telecommunication network, Telkom uses cable networks or microwave systems to inter connect the telecommunication exchanges and to finally connect users, telephonically.

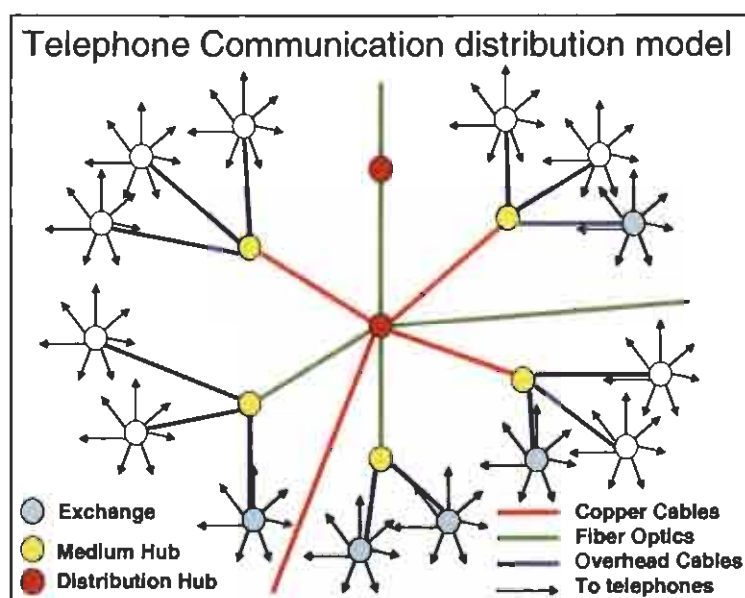


Figure 8: Telephone Communication Distribution Model

Modern needs for better and faster communication foresees all telecommunication providers to move towards better communication mediums for example, fibre optic cables in place of copper cables. Telkom is therefore installing fibre optic cables in most new installations and are replacing copper cables where necessary.

However, a very large percentage of communication in South Africa is still running through copper cables. The ratio between copper and fibre optics is changing fast but it is too costly to replace all copper cables over a short period of time.

The need for better communication thus requires new technology with better bandwidth to run on the existing copper cables. Telkom has recently upgraded their philosophy on cables and the protection thereof, thus the emphasis on the importance of the cables has been highlighted [41].

Some of these copper cables run underground, sometimes below the water table. These cables are protected by cable housings, from corrosion and deterioration. These housings are not flawless and subjected to erosion and deterioration.

To counteract the outside water, the cables housings are pressurised from the inside, in order to force air out of the holes, cracks and joints, preventing moisture from entering the cable housings and damaging / corroding the copper cables. As a result of the high pressures and the low temperatures, underground, any excessive moisture in the compressed air will form dew in the cables. Thus, the air entering the cable housings must be at the correct pressure and humidity not to form any dew inside the housing.

Several incidents occurred, where the CDH malfunctioned and pumped no, or moist air, into the cable housings. These malfunctions were not detected by the maintenance team, as the systems appeared to be working correctly at first sight, e.g. the compressors were pumping. Such incidents resulted in costly replacement of cables.

4.2 The Cable Dehydration System (CDH)

4.2.1 What is a Cable Dehydration System (CDH) and for what is it used?

The Cables Dehydration systems (CDH) pumps dry compressed air into the cables housing to prevent moisture from entering the housings. To ensure that the CDH has the required availability of 97% [42], TFMC must ensure that the CDH is fit for purpose. This means that the CDH capacity must match the expected workload and that proper maintenance is performed on the CDH.

The workload on each Cable Dehydration system varies, due to the variation in demand and different operation conditions for each system (e.g. number of cables housings per CDH, housing lengths, distances below water table, leakages in cable housings, etc).

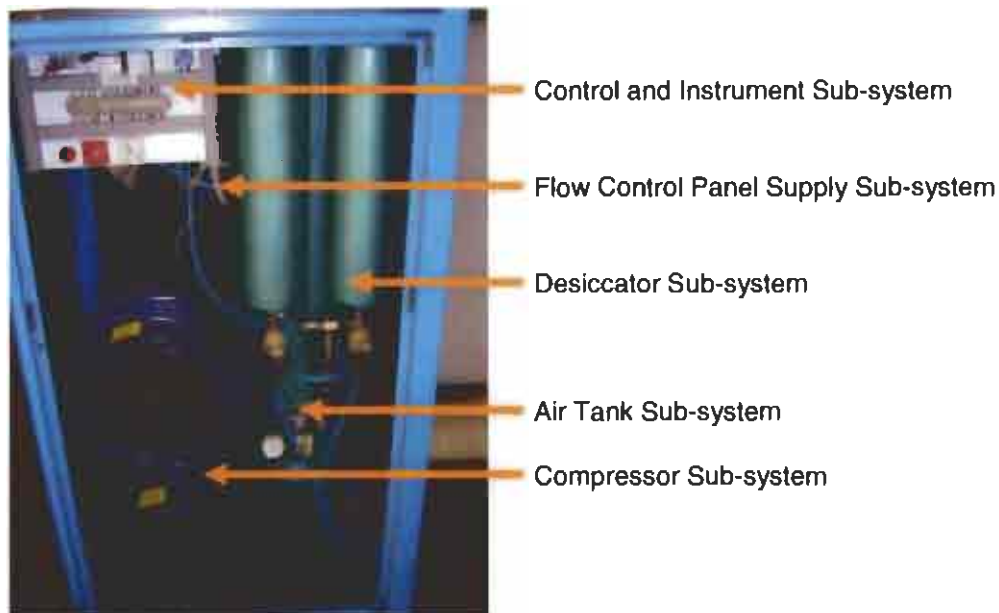


Figure 9: Polar Air Cable Dehydrator (CCD800)

4.2.2 Basic Operations of a Cable Dehydration System

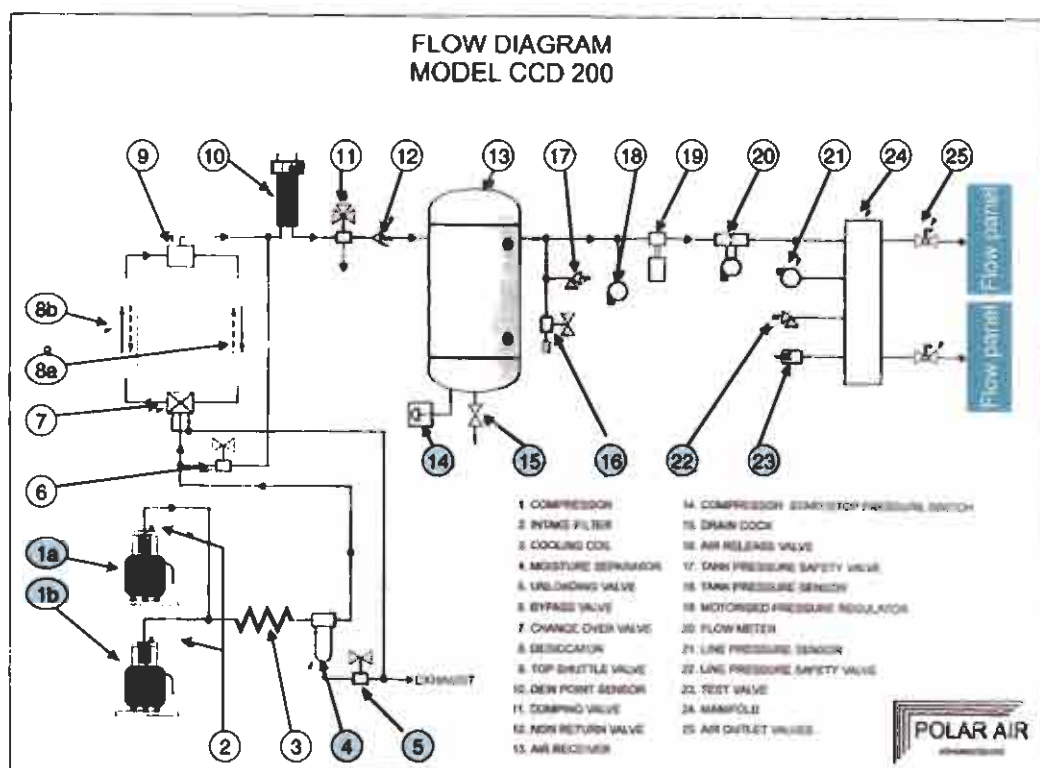


Figure 10: Flow Diagram for Polar Air Cable Dehydrator

The compressor (1) sucks in air through the intake filter (2) from its direct surroundings. The air is then compressed before it is moved through the cooling coil (3) to lower the compressed air temperature. The moisture separator (4) removes the excess moisture from the compressed air.

From the moisture separator the air is routed via the bottom change over valve (7) to one of the two desiccators (8). The chemical crystals of the desiccators dry the air by principle of absorbing moisture under pressure.

One of the desiccants absorbs moisture from the air while a small amount of dry air flows back through the top shuttle valve (9) to the other desiccant under low pressure. This extremely dry air absorbs the moisture from the crystals thus drying (or purging) the other desiccant. This process alternates under control of an independent timer.

The dew point sensor (10) tests the moisture level of the dried air. If the dew point is higher than -18°C the dumping valve (11) opens, ensuring that no moist air can enter the air-receiver tank (13).

The air receiver tank (13) then stores the dry compressed air. The tank pressure is regulated by the stop/start pressure switch (14) which starts and stops the compressor between the preset values of $\pm 300\text{kPa}$ and $\pm 550\text{kPa}$.

The air tank is protected by a tank pressure safety valve (17). The air tank is also equipped with a pressure sensor (18) and a drain cock (15). The air receiver tank continuously feeds dry compressed air to the distribution manifold (24) and flow panels, during both the "on" and "off" phase of the compressor.

If the tank reaches its preferred maximum set-point pressure, but the desiccant has not finished its cycle, the compressor will keep on running until the desiccant cycle is complete. While the cycles are being completed, the dumping valve (11) releases the surplus air. Thus the system will start on a different desiccant every time the compressor starts.

The motorised pressure regulator (19) delivers the correct pressure to the distribution manifold (24) to pressurise the various cables. The manifold is also equipped with a flow meter (20), manifold pressure sensor (21), a pressure safety valve (22) and a test valve (23) [42], [44].

The duty cycle is the percentage of time the compressor is running, relative to the time it is not running. The non- running cycle is important in order to allow the compressor to cool down. The compressors are oil free and many parts are Teflon coated to reduce wear. Cooling is vital for the compressors to ensure that the Teflon coated parts are not running at higher than intended temperatures, where its effectiveness is reduced and excessive wear takes place.

4.3 What to Monitor

The following type of equipment condition data must be monitored: equipment performance, equipment workload and, equipment risk or potential failures.

4.3.1 Plant Performance Analysis (Monitor if the System is Working as it Should)

An important part of the RCMS was to make the operation of the CDH easily visible to the monitoring operator. A holistic overview of the CDH system's performance is thus required.

The CDH has three important output parameters namely; supply dry air at the required volumes and at the required pressure to the flow panels. The inputs to the CDH are electrical power and air (110 litre at nominal pressure if both compressors are running).

The Cable Dehydration system can be divided in the Compressor Sub-system, Desiccator Sub-system, Air Tank Sub-system, Flow Control Panel Supply Sub-system and the Control and Instrument Sub-system. As all of these sub-systems are in series, it is only necessary to monitor each sub-system's output, as the first sub-system's output is the following sub-system's input.

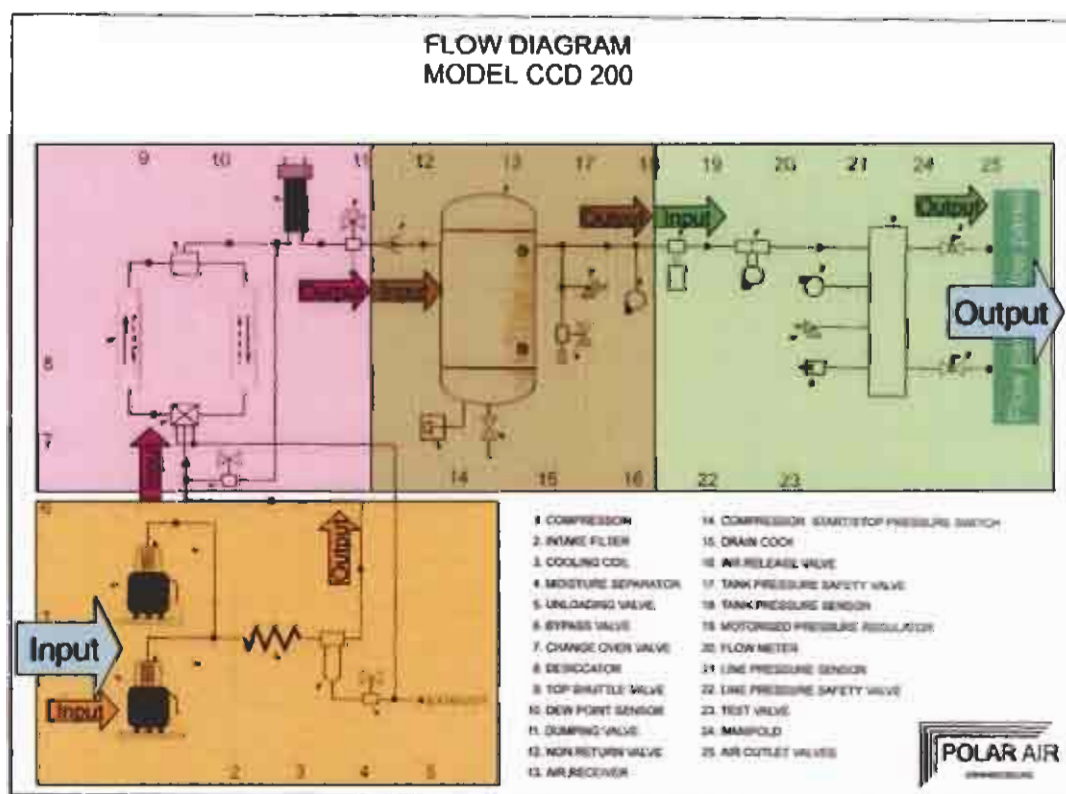


Figure 11: Sub-system Black Box's Detail

- **Compressor Sub-system**

The first sub-system's input is equal to the complete system's input as described above. The compressor sub-system's output is the compressed air, at pressure and volume as required in the air tank, minus pressure loss due to resistance through the system, at an acceptable temperature and without any moisture droplets.

- **Desiccator Sub-system**

For this sub-system the output is the compressed air, at the pressure and volume as required in the air tank, minus pressure loss through the dew point sensors and one way valve and at an acceptable degree of dryness.

- **Air Tank Sub-system**

The air tank sub-system's output is again the compressed air, at the required pressure and volume and at an acceptable degree of dryness.

- **Flow Control Panel Supply Sub-system**

The final output of the flow control panel sub-system is equal to the complete systems output and is the compressed air (line pressure and volume required) and at an acceptable degree of dryness.

- **Control and Instrument Sub-system**

The only sub-system not in series is the system's electronic controller, which controls and monitors the performance of the complete system. The sub-system outputs are the controlling functions and equipment operational data as measured by its sensors. The sensors provide most of the condition data as required for this research project. The input to this system is the sensor data and electrical power.

To have a holistic view of the CDH performance and operation the following information available within the CDH control sub-system was selected:

Compressor 1 and 2 are running, change over valve position, dew point sensor reading, tank pressure profile, pressure and airflow supply to flow panels. Also refer to Figure 12 and Figure 13 for the dynamics of the CDH.

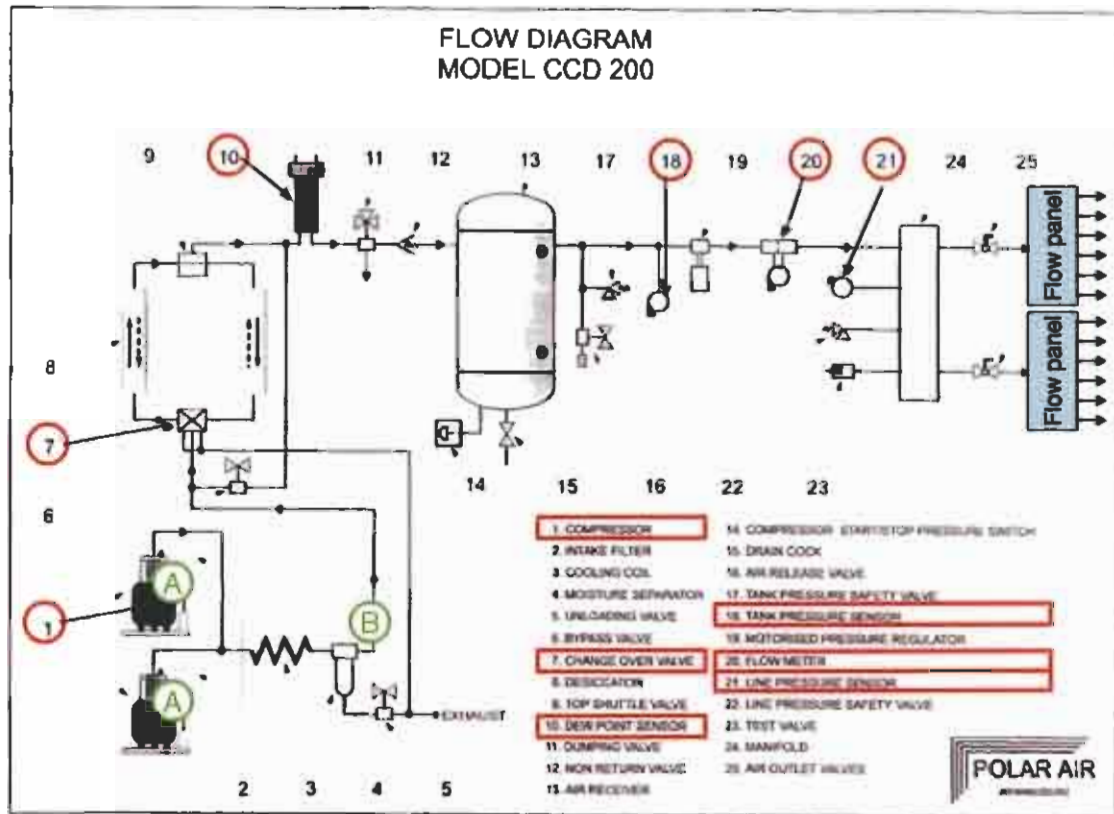
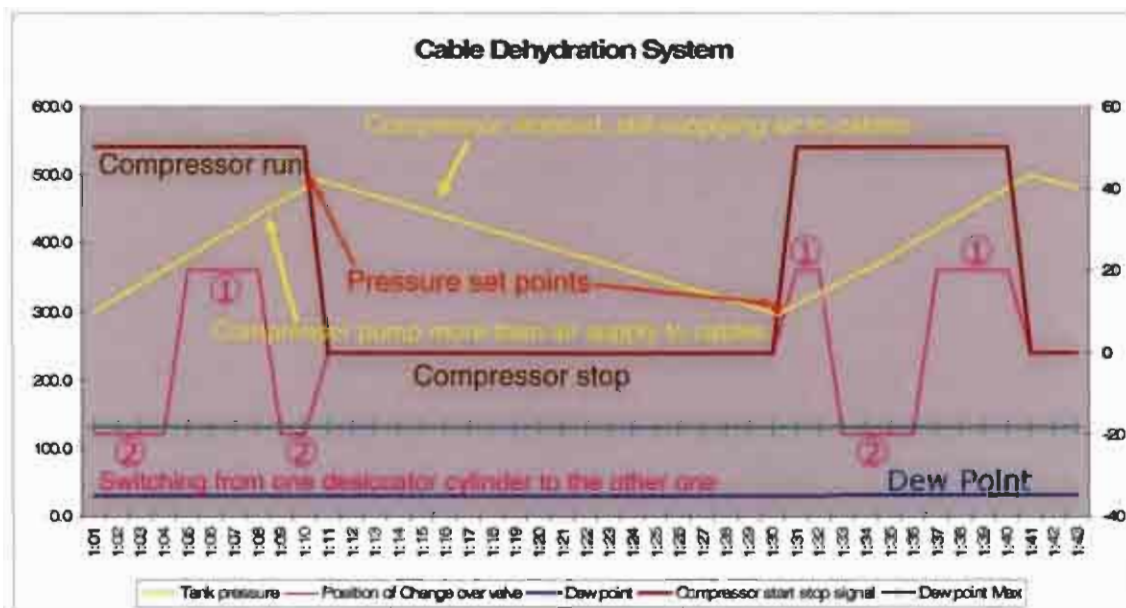


Figure 12: CDH Equipment Condition Data



4.3.2 Results of a FMECA as Performed on the CDH

Table 4 lists a few of the important results from the FMECA analysis. Refer to Annexure A for detailed results of the FMECA analysis.

Most Important Results from the FMECA Sorted to the Highest Monitoring Importance Factor

Parts	Failure mode (Cause of failure)	Failure Effect (What happens when it fails)	Severity	Adjusted Severity	Occurrence	Monitor Importance	Detection	RPN
Cylinder sleeve	Cease with piston	No compression, no pressure and airflow	8	8	6	40	4	100
	Overheat - lost tension	Loss of compression, low pressure and airflow, energy wast	8	8	5	40	3	120
	Dew point sensor failure to below minus 23 degC	System will still continue to supply air, but no guarantee that system supply dry air to Telkom	8	8	5	40	2	80
	See compressor 1	Resulting from hard work it one fail the wear on the other one is increase with several factors, this one can not cool down properly	6	6	6	36	4	144
Compressor bearings	Break	High cost to repair, No compression, no pressure and Air flow	7	7	5	35	4	140
	Power failure	Reduced Airflow over cooling coil - reduced heat dissipating - energy wast - damage to chemicals	5	5	7	35	4	140
Piston rod assembly	Overheating - cease	No compression, no pressure and Air flow	7	7	5	35	3	105
	Bearings Cease	No compression, no pressure and Air flow	7	7	5	35	3	105
Motor	Power failure	No compression, no pressure and Air flow	5	5	7	35	2	70
Intake Air Filter	Removed	Rapid increase wear on compressor rings and sleeves, contamination and blocking of desiccator chemical	8	8	4	32	8	256
	Compressor body	Internal damage due to component breakage	8	8	4	32	5	160
Dumping valve	Internal damage due to component breakage	No compression, no pressure and Air flow	8	8	4	32	5	160
	Dump valve fail to close	System still supply air to tank - no guarantee that system supply dry air to Telkom	8	8	4	32	3	96
Motor bearings	Bearings Cease	No compression, no pressure and Air flow	6	6	6	30	5	150
Piston rod assembly	Bearings Overheat - Cease	No compression, no pressure and Air flow	7	7	4	28	3	84
	Motorize pressure regulator	Could result into damage to cable or cable housing joints	7	7	4	28	1	28
Compressor bearings	Overheating - cease eventually	Eventually No compression, no pressure and Air flow	5	5	5	25	6	150
Cylinder sleeve	Overheat - Scratch marks - loss compression	Reduced compression, reduced pressure and airflow	5	5	5	25	4	100
	Motor bearings	Overheating - cease eventually	5	5	5	25	4	100
Dew point Sensor	Dew point sensor failure to above minus 18degC	Dump valve open, no supply dry air to tank	5	5	5	25	2	50
	Desiccator change	Wet - Can not dry air, no air to tank - no supply of dry air	5	5	5	25	1	25

Table 4: Summary of CDH FMECA Results

4.3.3 Results from a RCA Performed on the CDH

Part affected	Mode of degradation	Comments	Suitable condition monitoring
Top Shuttle valve	Dirty - Stuck - Failed in position to one dessicator	Cannot switch to be in sync with bottom shuttle valve, will only supply air to tank for 50% of the time.	Monitoring of tank pressure, will see fluctuating increase in tank pressure during pumping phase, resulting from air from only one desiccator.
Top Shuttle valve	Bleeding hole dirty	Does not dry non-working desiccator - dump valve will open and results in no airflow.	Dew point will increase as desiccant is not drying properly and air dryness reduces.
Dew point Sensor	Dew point sensor failure to below -60 °C	System will continue to supply air, but no guarantee that system supplies dry air to Telkom.	When dew point censored indicates a dew point below -55°C the technician should be dispatched as this represents a functional failure. Technician to perform desiccator bypass tested to check the functioning of the sensor, the sensor should indicate wet air (above -18°C) when the desiccant is bypassed.
Dew point Sensor	Dew point sensor failure to above -18°C	Dump valve opens, no supply of dry air to tank.	When dew point censored indicates a dew point above -18°C the technician should be dispatched as this represents a functional failure, as the dump valve should dump all air
Compressor Piston ring	Overheat - lost tension	Loss of compression, low pressure and airflow, energy waste.	The compressor pumping cycle should be monitored, when the duty cycle is higher than 65% the compressor will not cool down sufficient and a temperature build up will occur. The compressor body temperature should be the most accurate monitoring method.
Compressor bearings	Bearings Cease	Bearing can cease from no proper lubrication, excessive heat, no proper installation or excessive wear. Results in no compression, no pressure and airflow.	Monitoring can vary from monitoring running hours, bearing temperature or bearing vibration analysis. With the last two the most effective.
Desiccator charge (Chemical)	Wet	Drying cycle was not performed effectively. This could result from top shuttle valve bleeding hole blockage or pumping of excessive humid air for long periods. Results in wet air – (cannot dry air), no air to tank - no supply of dry air.	The dew point censored will indicate that air is gradually drifting towards the -18°C.
Valve plate	Dirty - partially working	Leak - reduced compression - reduced pressure and airflow	The increasing of the compressor duty cycle and or the increasing of pumping time will indicate problems with the compressor if the dew point and line airflow is within acceptable limits.

Table 5: Summary of CDH Rout Cause Analysis

4.3.4 Historical Maintenance Data Analysis

The historical maintenance data as stored in CMMS (Maximo) for the last year was analysed. The maintenance cost drivers on CDH can be summarised as follows. Refer to Annexure C for more detail.

Availability Analysis

No availability values were available from any of the environmental equipment from the CMMS system. Availability values could be calculated for critical systems (e.g. electricity supply to the exchanges), where a service interruption is immediately noticed by everybody. For the analysis period, the RAMS system was not monitoring the CDH as TFMC's focus was still concentrated on exchange-related equipment.

Without RAMS / RCMS, availability can only be calculated from maintenance tasks such as those recorded in CMMS. The capturing of the data was not very accurate (e.g. when exactly the service was interrupted and failure occurred until the service was restored). This resulted in very inaccurate availability figures.

With Telkom's new, higher emphasis on the cables and their supporting equipment, this needed to change. Availability values MTBF/A, MTTR, must be calculated within RAMS / RCMS and then exported to CMMS.

Maintenance Task Category Analysis

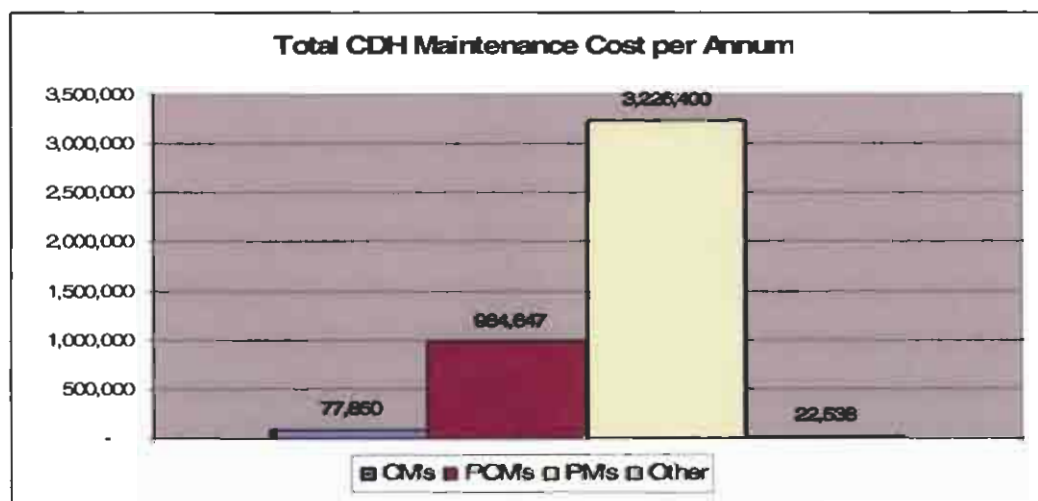


Figure 14: CDH Maintenance Cost per Annum

The Maintenance Task Category analysis performed on data provided by CMMS, indicated that 75% of all cost on CDH maintenance was for Planned Maintenance (PM's), 22% was used for Planned Corrective Maintenance (PCMs) and only 3% was used for Emergency

Maintenance (EMs), which is not a true reflection of the expected low availability of the CDH. No real corrective maintenance was performed during EMs, as this work mostly related to emergency short-term restoration of the air supply to the Telkom cables. The real corrective maintenance was thus performed afterwards, during PCMs.

Maintenance Task Analysis

When analysing the cost breakdown of the Planned Maintenance tasks, 62.5% of costs were found to be travel-related while 37% of all Planned Maintenance costs were for performing of physical PM work, and 0.5% for material, as seen in Figure 15.

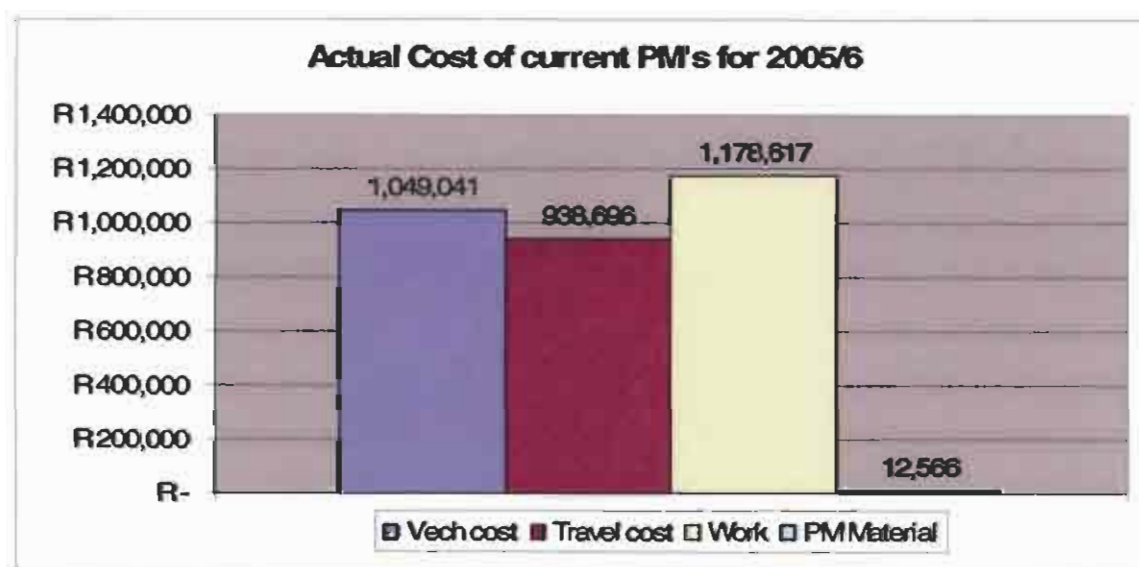


Figure 15: Actual PM Cost Breakdown

Refer to Annexure C1 for details of the Corrective Maintenance (Non-PM) analysis. The results from the complete analysis can be summarised as follows:

Cost Type	Preventative Maintenance (PM activities 75%)	Corrective Maintenance (Non-PM activities 22%+3%)	Total
Traveling cost	62.5%	27%	53%
Material cost	0.5%	50%	14%
Work (Labor) cost	37%	23%	33%

Table 6: Summary of maintenance tasks cost analysis

From Table 6, it can be seen that travelling related cost for CDH, is equal to 53% of total maintenance cost, of which most is contributed during Planned Maintenance.

If RCMS can assist to minimise travelling, considerable savings could be achieved.

Material and Components Used

The following results were obtained through analysing the material or components used during the maintenance process.

Figure 16 indicates that the desiccant agent and the compressor contributed towards 40% of the total material cost used. According to the manufacturer, if proper maintenance was performed, these two components should last much longer, in fact it should normally last for at least 10 years.

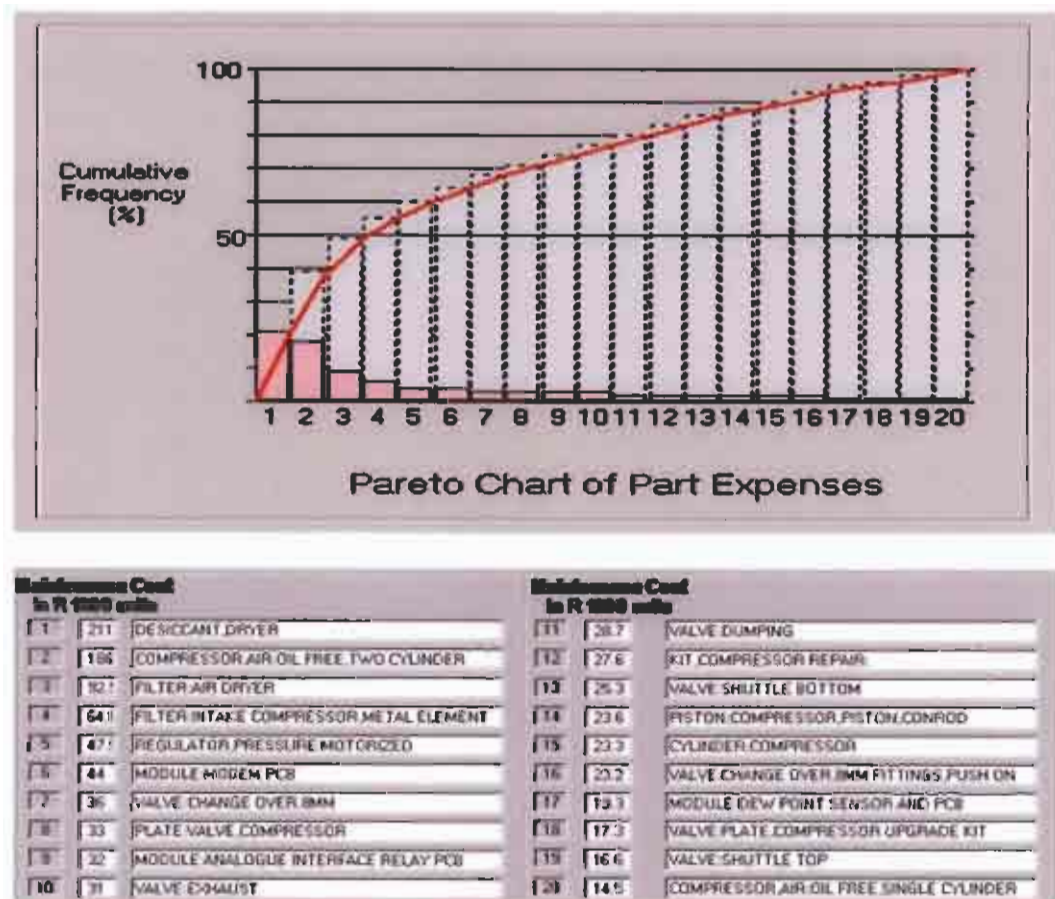


Figure 16: Pareto Chart of CDH Parts being used During Maintenance

The desiccant chemical needs to be replaced when the desiccant becomes totally saturated (wet). This failure only occurred when the “top shuttle valve” bleeding hole was blocked or partially blocked. The CDH kept on running unnoticed while the desiccant did not dry itself. Long before the desiccant chemical was totally wet, the dew point sensor should have detected that the air was not dry enough and the dump valve should have opened as described in Paragraph 4.2.2. This failure led to the next failure where the compressor was running continuously, as the compressor “stop/start switch” never reached the maximum pressure set point.

The main reason for compressor replacements is due to high duty cycle or dirty air through the air intake filter. Refer to detail FMECA or RCA, higher wear occurs, resulting in unnecessary reduction in compressor Remaining Useful Life (RUL).

These failures can only be prevented with regular inspections (every second day) or through RCMS. When a minor fault occurred and the problems weren't detected the system kept on running. The minor failures which weren't corrected quick enough would escalate until the specific equipment, or other components, were damaged to the extent that it was necessary to be replaced. The normal control system of the CDH only protects the equipment when major failures occur.

4.3.5 Current Maintenance Procedures for Cable Dehydration Systems

Maintenance as Specified by the Manufacturer

According to the manufacturer's operating manual the following maintenance needs to be performed [42], [44]:

- Regular inspections or remote inspections through dial-in modem (on new equipment) to check for alarms on the instrument panel
- 1000 running hour's - Minor service
 - Inspection of the machine to detect any problems (e.g. air leakages) or future problems (e.g. noisy bearings which can lead to future failure)
 - Replacement of the air intake filters of the compressors
 - Testing if all functions and system modes are working properly
- 2000 running hour's Minor service (same as 1000 hour's - Minor service)
- 3000 running hour's - Major service
 - Replace compressor components (piston rings, expander rings, and valve plates)
 - Perform maintenance actions as for 1000 hour's - Minor service
- 4000 running hour's minor service (same as 1000 hour's - Minor service)
- 5000 running hour's - Major service
 - Replace compressor components (motor bearings piston rings, expander rings, valve plates, cylinder sleeves and piston rod assemblies)
 - Perform maintenance actions as for 1000 hour's - Minor service

TFMC's maintenance tasks according to the TFMC CMMS job cards are very similar to that which was specified by the manufacturer.

4.3.6 *Current Maintenance Practices as Applied in TFMC*

From the work which needs to be performed during PM tasks (as listed in paragraph 4.3.5), it is clear that material cost forms a substantial portion of a Major service. Table 6 reflects that only 0.5% of the PM cost is used for material during PMs, and the majority of material cost (97% of total material cost) is used during EMs or PCMs.

Discussions with the maintenance technicians and the above material usage trends confirms that current maintenance practice is only, to do an Inspections or Minor Services as part of PMs. Major Service are performed as PCMs, but the more likely scenario is that the Major Service is skipped and the CDH is maintained with a "Run to Fail" strategy in this regard.

With no remote dial-in capability (which is only possible for a very low percentage of the CDHs), the running hours can only be collected during a visit to the CDH for inspection. This explains the cost breakdown for PMs as mentioned in Table 6.

The issuing of PCM job cards to perform Major services, (e.g. replace expensive components - piston rings, expander rings, and valve plates) were manipulated by the service leaders and the maintenance budget managers, to provide an escape route for poor budget management. When availability of funds is restricted, the issuing of PCMs or Major services is limited by the service managers.

From the CMMS (Maximo) TFMC is maintaining 947 CDH, while from the manufactures records they have sold more than 1600 CDH to Telkom over the last 20 years. This indicates that 40% of the CDH have been replaced during this period or there are some CDH of which TFMC don't know and therefore do not maintain.

4.4 **Conclusion: What is Important to monitor on a Cable Dehydration System?**

Paragraph 3.2 describes the goals - What needs to be monitored? and in Paragraph 4.3 the tools which were applied on the CDH are described. The following measuring points were selected:

- To provide a holistic view of the CDH performance:
 - Dew point value (+40°C to -60°C)
 - Demand air pressure (0kPa to 100kPa)
 - Demand airflow (0 L/min to 380 L/min)
- To provide a view of the CDH internal optimal performance:
 - Compressor 1 (running/stopped)

- Running hours compressor 1
- Compressor 2 (running/stopped)
- Running hours compressor 2
- Desiccator 1 (active / self drying/ no activity)
- Desiccator 2 (active / self drying/ no activity)
- Dew point value (+40°C to -60°C)
- Air receiver tank pressure profile (0kPa to 800kPa)
- Maximum air receiver tank pressure (500kPa to 600kPa)
- Minimum air receiver tank pressure (250kPa to 350kPa)
- To provide a view of CDH predicted failure:
 - Compressor Duty Cycle (%)
 - Compressor operational (both cycling / only one in running condition)
 - Compressor 1 running temperature (-10°C to +150°C)
 - Compressor 2 running temperature (-10°C to +150°C)
 - Dew point value desiccator 1 (+40°C to -60°C)
 - Dew point value desiccator 2 (+40°C to -60°C)
 - Dew point value profile (+40°C to – 60°C)
 - Desiccators cycle change (0min-10min)
 - Air receiver tank pressure (0kPa to 800kPa)
 - Energy consumption (0kW – 5kW)
 - Compressor 1 vibration (bearing and compressor overall)
 - Compressor 2 vibration (bearing and compressor overall)
 - CDH vibration (CDH overall)
- To reduce travelling time for inspections and ensure timely maintenance of all items as listed above.

Also refer to Table 7 for a summary of the above.

The total effectiveness of the current maintenance strategy is far from optimal and the introduction of CBFM could have a major impact on the total effectiveness of the CDH maintenance.

Real-time Condition data	Units	Expected Value	CDH Performance	Internal Optimal Performance	Prediction of Failure	Reduce Travelling
Demand cable pressure	kPa	0kPa to 100kPa	X		X	X
Demand airflow	l/min	0 L/min to 380 L/min	X		X	X
Dew point	°C	+40°C to -60°C	X	X	Desiccator 1 + 2	X
Compressor 1	digital	Running/Stopped		X		X
Running hours Compressor 1	hours	0 to 50 000 hours			X	X
Compressor 2	digital	Running/stopped		X		X
Running hours Compressor 2	hours	0 to 50 000 hours			X	X
Desiccator 1	digital	Active / Self drying / not activity		X		X
Desiccator 2	digital	Active / Self drying / not activity		X		X
Tank Pressure	kPa	0kPa to 800kPa		X	X	X
Tank pressure Maximum Value	kPa	500kPa to 600kPa		X		X
Tank pressure Minimum Value	kPa	250kPa to 350kPa		X		X
Compressor Duty Cycle	%	0% to 100%			X	X
Pump-cycle time	min	To calculate Compressor Duty Cycle			X	
Pump Off Cycle Set point	min	To calculate Compressor Duty Cycle			X	
Compressors Operational	digital	Both cycling / only one running			X	X
Current Compressor cycle time	Hours				X	
Average Compressor 1 cycle time	Hours				X	
Average Compressor 2 cycle time	Hours				X	
Desiccators cycle change	Min				X	X
Compressor 1 Temperature	°C	-10°C to +150°C			X	X
Compressor 2 Temperature	°C	- 10°C to + 150°C			X	X
Energy consumption	kWh	0kW to 5kW			X	X
Compressor 1 vibration	Hz	Bearing and compressor overall			N	N
Compressor 2 vibration	Hz	Bearing and compressor overall			N	N
CDH Vibration		Overall frame			N	N

Table 7: Points to Monitor - Summary of Analysis Tools

CHAPTER 5. THE ACTUAL DESIGN OF THE CONDITION BASED FACILITY MANAGEMENT SYSTEM

The RCMS was structured according to OSA-CBM standard, as described in Paragraph 3.3.

5.1 Sensor Module

Table 8 lists the condition data which was obtained from the CDH microcontroller.

Real-time Condition Data	Units	Expected Value	Display Value
Demand cable pressure	kPa	0kPa to 100kPa	Real-time value
Demand Airflow	l/min	0 L/min to 380 L/min	Real-time value
Dew point	°C	+40°C to -60°C	Real-time value
Compressor 1	Digital	Run / stopped	Real-time value
Running hours Compressor 1	Hours	0 to 50 000 hours	Real-time value
Compressor 2	Digital	Run / stopped	Real-time value
Running hours Compressor 2	Hours	0 to 50 000 hours	Real-time value
Desiccator 1	Digital	Active / Self drying / no activity	Real-time value
Desiccator 2	Digital	Active / Self drying / no activity	Real-time value
Tank Pressure	kPa	0kPa to 800kPa	Real-time value

Table 8: Condition Data Obtained from CDH Microcontrollers

Table 9 lists the condition data which was calculated from data collected through the CDH microcontroller.

Real-time Condition data	Units	Expected value	Display value
Running hours Compressor 1	Hours	0 to 50 000 hours	Calculated from compressor run status
Running hours Compressor 2	Hours	0 to 50 000 hours	Calculated from compressor run status
Tank pressure Maximum Value	kPa	500kPa to 600kPa	Calculated from pressure profile
Tank pressure Minimum Value	kPa	250kPa to 350kPa	Calculated from pressure profile
Compressor Duty Cycle	%	0% to 100%	Calculated from stop/start signal
Pump-cycle time	Min	To calculate compressor duty cycle	Calculated from stop/start signal
Pump Off Cycle Time	Min	To calculate compressor duty cycle	Calculated from stop/start signal

Real-time Condition data	Units	Expected value	Display value
Compressors Operational	Digital	Both cycling / only one running	Calculated from Compressor 1 and 2 run/stop
Current Compressor cycle time	Hours	1 to 5 hours	Calculated from stop/start signal
Average Compressor 1 cycle time	Hours	1 to 5 hours	Calculated from compressor cycle time
Average Compressor 2 cycle time	Hours	1 to 5 hours	Calculated from compressor cycle time

Table 9: Condition data Calculated

Table 10 lists the condition data which was obtained through additional sensors installed on the CDH and monitored directly by the SIC.

Real-time Condition data	Units	Expected value	Display value
Desiccators cycle change	Min	Between 2 and 4 minutes	Real-time value
Compressor 1 Temperature	°C	-10°C to + 150°C	Real-time value
Compressor 2 Temperature	°C	-10°C to + 150°C	Real-time value
Energy consumption	kWh	0kW to 5kW	Real-time value
Compressor 1 vibration	Hz	bearing and compressor overall	Real-time value
Compressor 2 vibration	Hz	bearing and compressor overall	Real-time value
CDH Vibration		overall frame	Real-time value

Table 10: Condition Data Obtained through Additional Sensors

The condition data was obtained via the Modbus interface developed by the CDH manufacturer (Polar Air) and BMSI.

5.2 Signal Processing

The condition data points contain analogue and digital values. The Cable Dehydrator's analogue interface PCB and the dew point PCB provide the data values and are converted with the CDH microcontroller into digital word values, which are stored in the different Modbus registers.

The compressors are directly controlled from the stop/start switch on the pressure tank. The microcontroller monitors the signal from the stop/start switch and makes the data available in a Modbus register. From the compressor cycle setup the microcontroller determines which compressor needs to run.

The Site Interface Controller (SIC) requested the values from the Cable Dehydrator's microprocessor through a RS485 communication network with a Modbus RTU communication protocol. The condition data was then further relayed to the Web-supervisory platform in the remote control room.

Refer to Table 11 for a detailed list of the signal processing.

Sensor		Sensor output	Signal processing	Sampling rate	Communication to SIC	Communication to Remote Control Servers
i.	Demand cable pressure	0-20 mA	CDH Microprocessor	10 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
ii.	Demand Airflow	0-20 mA	CDH Microprocessor	2 Hz	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
iii.	Dew point	0-20 mA	CDH Microprocessor	10 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
iv.	Tank pressure	0-20 mA	CDH Microprocessor	10 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
v.	Compressor 1 running status (command signal)	Digital-dry contact	CDH Microprocessor	10 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
vi.	Compressor 2 running status (command signal)	Digital-dry contact	CDH Microprocessor	10 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
vii.	Change over valve position (command signal)	Digital-dry contact	CDH Microprocessor	10 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
viii.	Compressor 1 running hours		CDH Microprocessor	60 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
ix.	Compressor 2 running hours		CDH Microprocessor	60 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
x.	Time to next minor service		CDH Microprocessor	60 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
xi.	Time to next major service		CDH Microprocessor	60 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
xii.	Compressor 1 temperatures	°C	Digital and Analogue input modules	30 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
xiii.	Compressor 2 temperatures	°C	Digital and Analogue input modules	30 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol
xiv.	Energy consumption (Compressor)	kWh	Lovato DM32 Power Meter	60 seconds	RS485 via Modbus RTU protocol	Ethernet via the TCP/IP Niagara protocol

Table 11: RCMS Signal Processing

The Tank pressure profile provides an easy visible picture of the CDH performance. The effectiveness of the complete CDH could be obtained from this indicator. Several potential failures can be derived from this pressure profile. Refer to Figure 17, paragraph 5.5 Scenario 3 and paragraph 6.2.2.

The maximum and minimum actual tank pressures need to be captured. The Compressor pump-cycle time and compressor off-cycle time can be determined from the compressor stop/start signal.

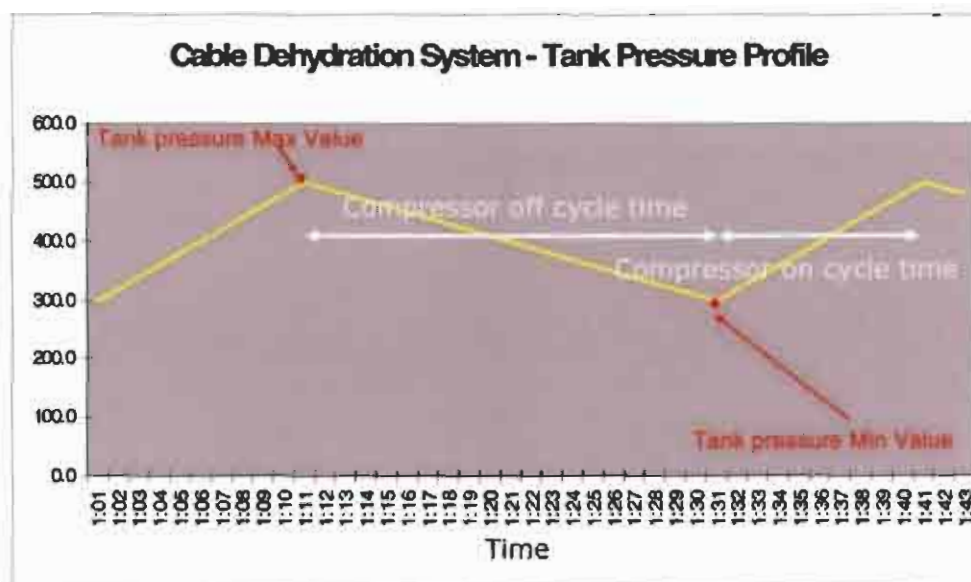


Figure 17: Tank Pressure Profile

5.3 Condition Monitor

To assist the control room operators in determining the condition of the CDH, the current real-time values were compared with predetermined values. When any of these compared values are exceeded it indicates that the CDH either is not performing optimally or a failure condition is approaching. The RCMS was configured to raise an alarm when any of these conditions were exceeded.

Real-time Condition data	Expected value	Display value	Alarm Low	Alarm High	Units	Log intervals	Set point for each machine
Demand cable pressure	0kPa to 100kPa	Real-time value	65	80	kPa	30min	
Demand Airflow	0 L/min to 380 L/min	Real-time value	90% from set point	100% from set point	l/min	30min	52
Dew point	+40°C to -60°C	Real-time value	-23	-55	°C	5 seconds	-40
Compressor 1	Run / stop	Real-time value			Run / Stop	Poled every 5 seconds	
Running hours Compressor 1	0 to 50 000 hours	Real-time value		every 1000	hours	Calculates every 30 minutes	
Compressor 2	Run/stopped	Real-time value			Run / Stop	Poled every 5 seconds	
Running hours Compressor 2	0 to 50 000 hours	Real-time value		every 1000	hours	Calculates every 30 minutes	
Desiccator 1	Active / self drying / no activity	Real-time value			Active / Self drying / not activity	Poled every 5 seconds	
Desiccator 2	Active / self drying / no activity	Real-time value			Active / Self drying / not activity	Poled every 5 seconds	
Tank Pressure	0kPa to 800kPa	Real-time value			kPa	Change of value 20kPa	
Desiccators cycle change		Real-time value	90% from set point	100% from set point	Min	Calculates every 5 seconds	3

Table 12: Condition Monitoring Alarms and Logging Intervals - CDH Microcontroller

Real-time Condition data	Expected value	Display value	Alarm Low	Alarm High	Units	Log Intervals	Set point for each machine
Tank pressure Maximum Value	500kPa to 600kPa	Calculated from pressure profile	90% from set point	100% from set point	kPa	Calculates every 5 seconds	530
Tank pressure Minimum Value	250kPa to 350kPa	Calculated from pressure profile	90% from set point	100% from set point	kPa	Calculates every 5 seconds	320
Compressor Duty Cycle	0% to 100%	Calculated from stop/start signal	10%	90%	%	Calculates every 5 seconds	50%
Pump-cycle time	To calculate compressor duty cycle	Calculated from stop/start signal	90% from set point	100% from set point	min	Calculates every 5 seconds	6.7
Pump off cycle Time	To calculate compressor duty cycle	Calculated from stop/start signal	90% from set point	100% from set point	min	Calculates every 5 seconds	6.7
Compressors Operational	Both cycling / only one running	Calculated from Compressor 1 and 2 run / stop	Compressor 1 or 2 less than 1 hour	Compressor 1 or 2 more than 6 hours	Both cycle / only one	Calculates every 5 seconds	
Current Compressor cycle time	1 to 5 hours	Calculated from pump / Off cycle times	90% from set point	100% from set point	Hours	Calculates every 5 seconds	2
Average Compressor 1 cycle time	2 to 5 hours	Calculated from compressor cycle time	90% from set point	100% from set point	Hours	Calculates every 5 seconds	2
Average Compressor 2 cycle time	3 to 5 hours	Calculated from compressor cycle time	90% from set point	100% from set point	Hours	Calculates every 5 seconds	2

Table 13: Condition Monitoring Alarms and Logging intervals - Calculated Alarms

Real-time Condition data	Expected value	Display value	Alarm Low	Alarm High	Units	Log Intervals	Set point for each machine
Compressor 1 Temperature	-10°C to +150°C	Real-time value		80	°C	10min	
Compressor 2 Temperature	-10°C to +150°C	Real-time value		80	°C	10min	
Energy consumption	0kW to 5kW	Real-time value		2.2	kWh	10min	2.2 kW
Compressor 1 vibration	Bearing and compressor overall	Real-time value	TBD	TBD	Hz	10min	TBD
Compressor 2 vibration	Bearing and compressor overall	Real-time value	TBD	TBD	Hz	10min	TBD
CDH Vibration	Overall frame	Real-time value	TBD	TBD	Hz	10min	TBD

Table 14: Condition Monitoring Alarms and Logging Intervals - Additional Condition Sensors

5.4 Health Assessment

The primary focus of the health assessment module is to describe if the health of the monitored component, sub-system or system has degraded.

- The system output is healthy when:
 - The demand cable pressure is delivering at a pressure between 70kPa and 90kPa.
 - The demand cable pressure is not deviating from preset set points with more than $\pm 10\%$ (preset value determined for CDH workload and set once).
 - The demand air volume to flow panel is within the CDH specification limits, e.g. for CCD 800 series maximum 160 nominal l/min for one compressor and 340 nominal l/min for both compressors running simultaneously during an emergency condition (only for short periods).
 - Dew point value must be within specification (lower than -23°C).
 - Dew point value does not deviate with more than $\pm 20\%$ from preset values **.
- The system input is healthy when:
 - Power supply 380V $\pm 10\%$ three phase at 50Hz $\pm 3\%$.
 - Room temperature -5°C $+50^{\circ}\text{C}$.
 - Air quality "good".
- Compressor Sub-system is healthy when:
 - Compressor delivers the required maximum pressure, as per equipment specification e.g. CCD 800 series ± 700 kPa.
 - Compressor temperature is within specification (between -5°C and 80°C)
 - Compressor bearings are healthy within vibration spectrum specification.
 - Inlet air filter is in place and only allows air to enter compressor through filter.
 - Inlet air filter is "clean".
 - Compressor pump-cycle time is within $\pm 5\%$ of preset value and all other inputs / outputs of the CDH are static (e.g. demand cable pressure, demand airflow and electrical supply voltage).

- Desiccator Sub-system is healthy when:
 - Bottom shuttle value cycle as per preset value.
 - Dew point value, within -30°C and -55°C .
 - Dew point value does not deviate with more than $\pm 10\%$ from preset (or average value) values **.
 - Dew point value does not deviate with more than $\pm 10\%$ from preset (or average value) values between desiccators **.
 - Compressor pump time within $\pm 5\%$ of preset value and all other inputs / outputs of the CDH are static (e.g. demand cable pressure, demand airflow and electrical supply voltage).
- No air leakages when:
 - Compressor pump time within $\pm 5\%$ of preset value and all other inputs / outputs of the CDH are static (e.g. demand cable pressure, demand airflow and electrical supply voltage).
 - Compressor pump off time within $\pm 5\%$ of preset value and all other inputs / outputs of the CDH are static (e.g. demand cable pressure, demand airflow and electrical supply voltage).
- Air Tank Sub-system is healthy when:
 - Maximum and minimum air tank pressure within $\pm 5\%$ of preset value and all other inputs / outputs of the CDH are static (e.g. demand cable pressure, demand airflow and electrical supply voltage).
 - Maximum air tank pressure never rises above ± 800 kPa.
- Flow Control Panel Supply Sub-system is healthy when:
 - The Demand cable pressure is delivering at a stable pressure with fluctuations of no more than 5% from stable long-term value.
- Control and Instrument Sub-system is healthy when:
 - Provides all the required condition data.

****→** Preset values are values which are determined by the equipment specialist for each specific machine which will assist RCMS to notify the BCC when any change in the working condition of the CDH occurs.

5.5 Prognostics

The primary focus of the prognostic module is to calculate the future health of an asset with account taken of the future usage profiles.

To fully understand the CDH operation and the interdependencies of the different sub-systems, a model was developed; refer to Figure 11, paragraph 4.3.1 and Annexure B for detail. Different scenarios were simulated to determine the importance of the different parameters. The simulation was also used to investigate typical equipment conditions and failure. A few typical scenarios are described below.

Scenario 1a: CDH Service to Cables (CDH Output) and Possible Failure Predictions

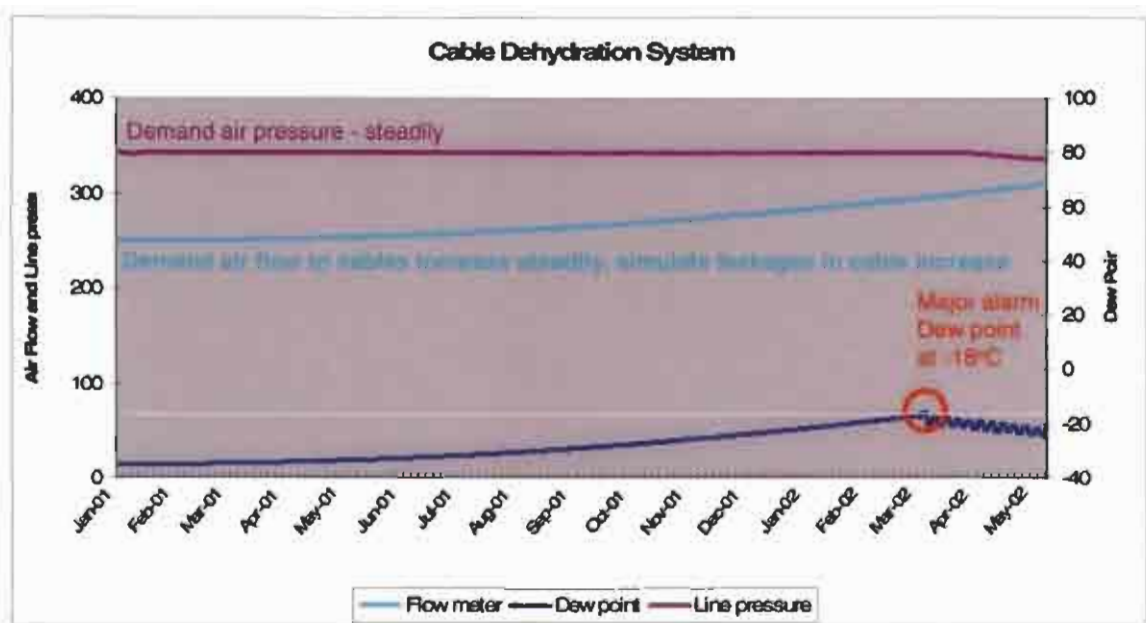
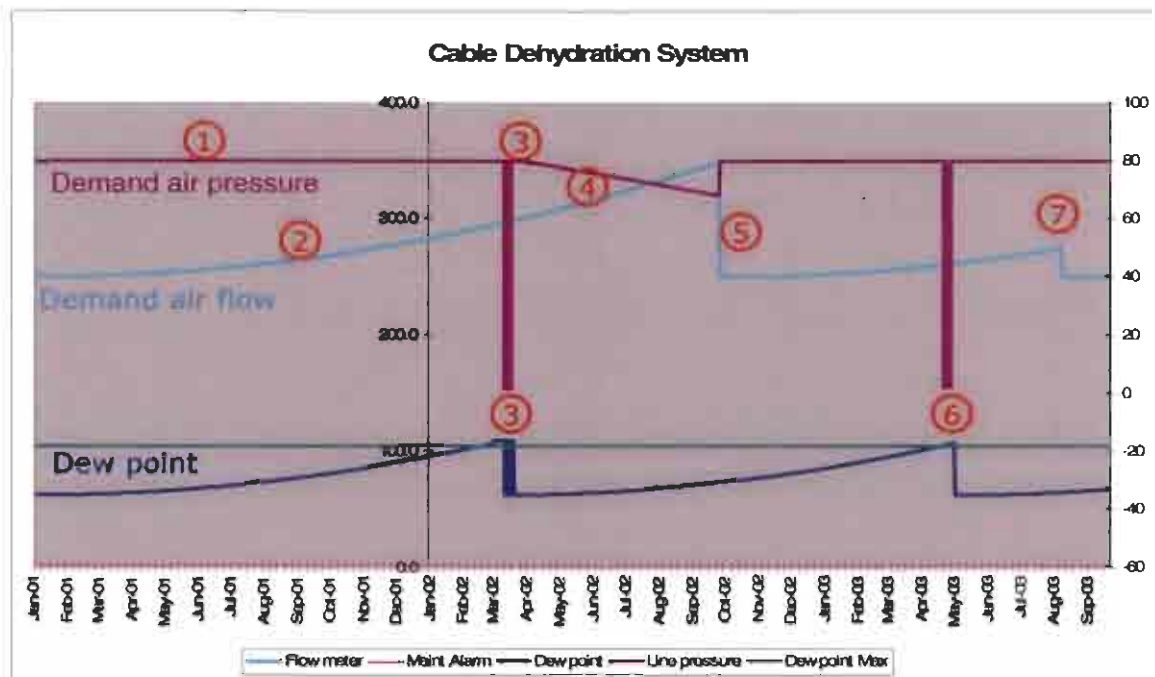
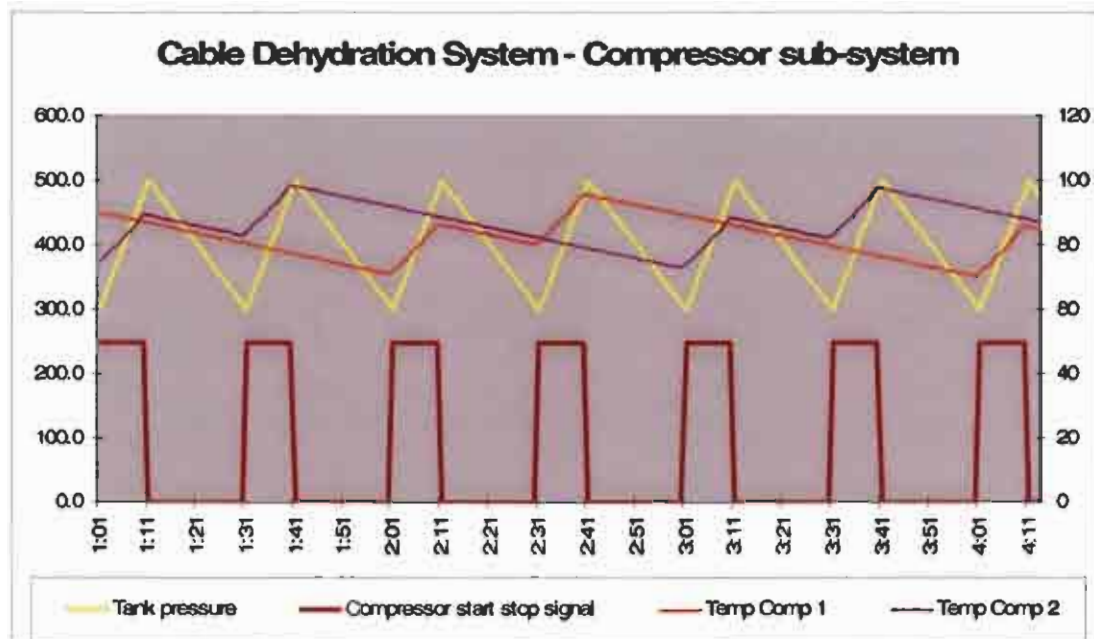


Figure 18: CDH Output Fault Conditions

- The Demand airflow values (air supply to cables) increase, as a result of an increase in cable leakages, which increases the workload for the CDH.
- The Demand line pressure values (air supply to cables) are steady, indicating that the CDH can accommodate the higher workload.
- The dew point value is increasing, indicating that the desiccators are becoming saturated, which could be a result of the additional workload on the CDH as discussed above, or faulty equipment condition (e.g. top shuttle valve bleeding hole being partially blocked).
- Dew point value reaches the alarm value, the dump valve will open to ensure that no “wet” air reaches the cables.

Scenario 1b: CDH Workload and Failure Conditions**Figure 19: CDH Workload and Fault Conditions**

- (1+2) The demand air pressure is stable but the demand airflow is increasing slightly resulting in a higher workload on CDH. The dew point that increases could be a result of the higher airflow required or a partially blocked "top shuttle valve bleeding hole".
- (3) The dew point indicates that the air is too wet, allowing the dump valve to open, resulting in the air receiver tank pressure dropping and within a few minutes the demand air pressure will also drop. The fault is corrected.
- (4) The increasing demand airflow reaches a critical stage where the CDH is operating at its maximum capability. The demand air pressure will start to drop as CDH cannot supply the required demand.
- (5) The client repairs leaks in cables, demand airflow decreases drastically to normal levels, demand air pressure rises back to normal levels as CDH can supply the required demand. Maintenance activities back to normal.
- (6) Dew point indicates that the air is too wet, the dump valve will open resulting in the air receiver tank pressure to drop and eventually (within a few minutes) the demand air pressure will also drop.
- (7) Telkom repaired more leakages on the cable housings and the demand airflow drops to normal levels.

Scenario 2a: Duty Cycle and Compressor Temperature for Alternating Compressor Cycle**Figure 20: CDH Compressor Temperatures**

- The stop/start switch (on the air receiver tank) controls the compressors, ensuring that the tank pressure is kept between the maximum and minimum pressure set points.
- The temperature of compressor 1 is cooling down while compressor 2 is working and vice versa.

Scenario 2b: Duty cycle and Compressor Temperature for Alternating Compressor Cycle

- In this scenario Compressor 2 becomes faulty (Time = 4:31) and Compressor 1 is running constantly.
- The temperature is rising far above the maximum allowable value, resulting in the shortening of the compressors Remaining Useful Life (RUL) as discussed in the last point of Paragraph 4.2.2. The faulty compressor needs to be replaced as soon as possible.

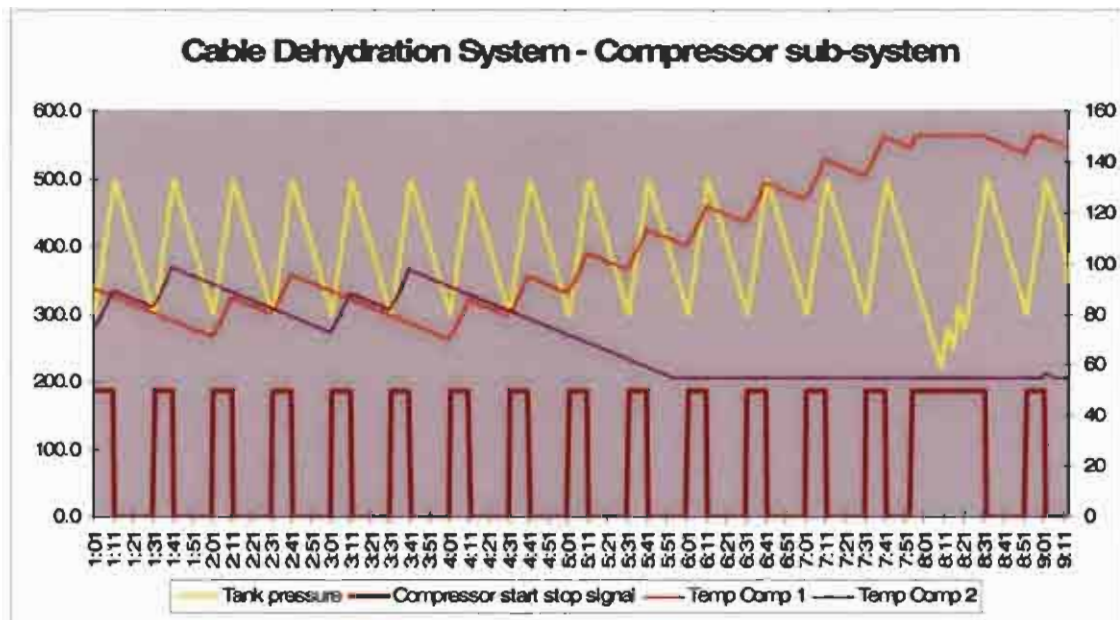


Figure 21: CDH Compressor Temperature Fault Condition

Scenario 3a: Simulating of an Expected Equipment Fault Condition

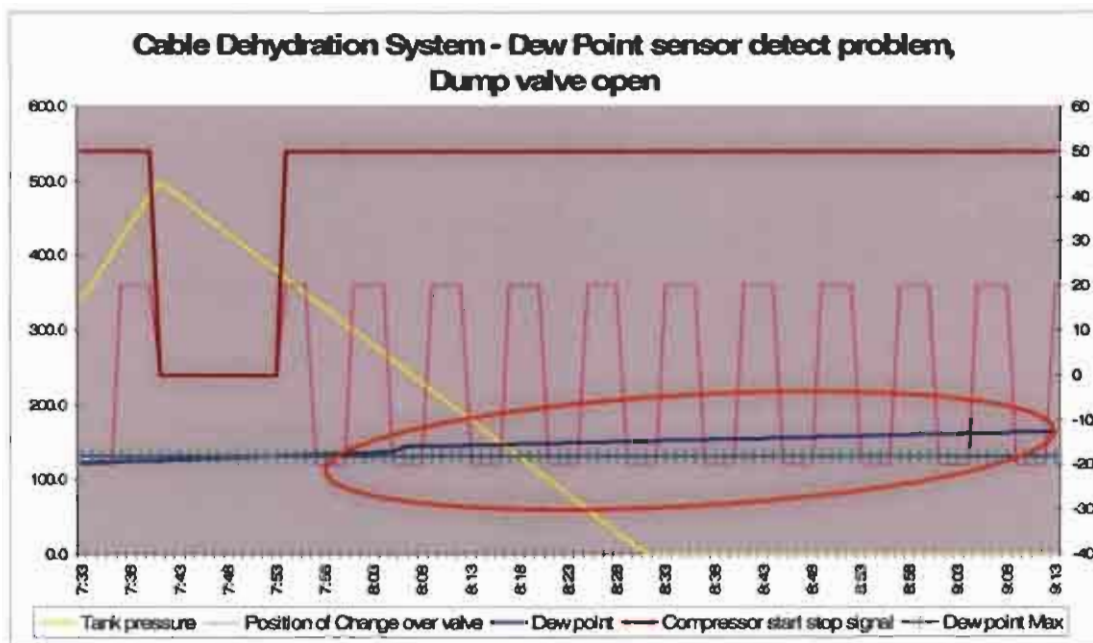


Figure 22: Both Desiccators Fault Condition

- The compressor is stopped (time=7:38) by the compressor stop/start switch when the pressure reaches the maximum pressure set point. At time=7:53 the compressor is again started by the stop/start switch, when the low pressure set point is reached.

- The Dew point reaches the alarm value (time=7:54) and the dump valve opens to ensure that no "wet" air reaches the cables. The CDH cannot dry the desiccator chemicals as the hole in the "top shuttle valve" is blocked.
- The tank pressure values drop as air is supplied to the cables and no air is added resulting from the open dump valve.
- The compressor will keep on running (trying to increase the tank pressure) with no effect as dump valve is open.

Scenario 3b: Simulating of an Expected Equipment Fault Condition

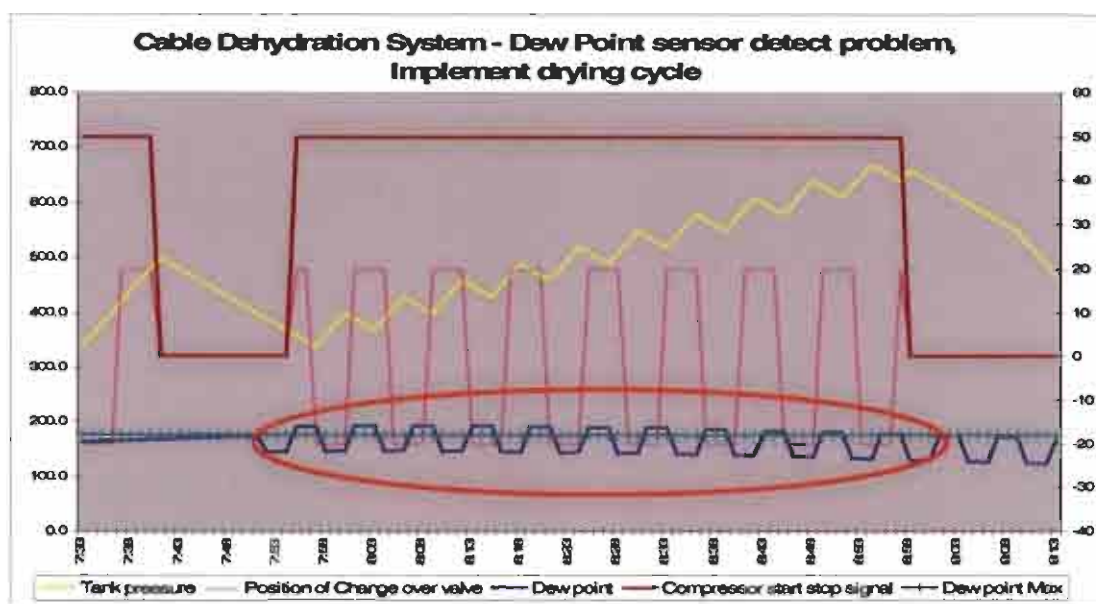


Figure 23: Single Desiccator Fault Condition

- The compressor is stopped (time=7:40) by the compressor stop/start switch when the pressure reaches the maximum pressure set point at time=7:55, the compressor is again started by the stop/start switch when the low pressure set point is reached.
- The Dew point reaching the alarm value on one of the desiccators (time=7:50) and the dump valve opens when wet air is sensed by the dew point sensor. If one desiccator is still dry, dry air from this desiccator will bleed back through the top shuttle valve bleeding hole to the wet desiccator chemicals to dry it.
- The tank pressure values fluctuate as only dry air from the one dry desiccator will reach the air receiver tank.

- The compressor is started by the compressor “stop/start switch”, when reaching the low pressure set point and will keep on running until its high pressure set point is reached.

5.6 Decision Support

This module receives data from the health assessment module and the prognostic module. Its primary focus is to generate recommended actions and alternatives. The actions can be related to maintenance or how to run the asset until the current mission is completed without the occurrence of a breakdown.

For the current phase of the study the BCC monitoring operators and the regional maintenance engineering specialist will perform the decision support function. They will be provided with support documentation and training to perform this task. Refer to Table 15 for typical Decision Support.

5.7 Presentation

The presentation module should present data from all the previous modules. The most important layers to present would be the data from the health assessment, prognostic and decision support modules as well as alerts generated from the condition monitors. The ability to look even further down in the layers should be a possibility. The presentation module could be built into a regular machine interface.

Refer to Figure 25 to Figure 31 for typical presentation to the user interface.

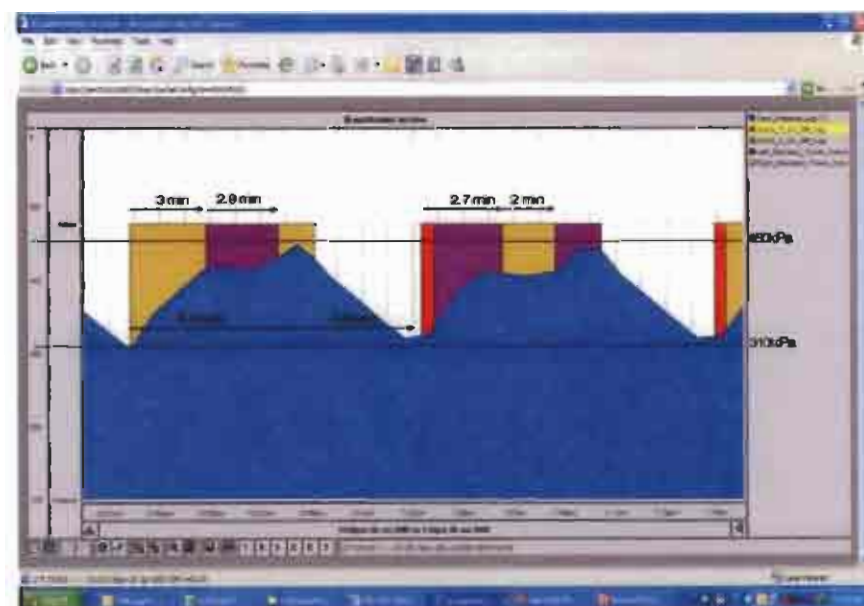


Figure 24: Typical User Analysis Interface

Real-time Condition data	Set point	Display value	Alarm Low	Alarm High	Units	Low Alarm	High Alarm
Line pressure		Real-time value	65	80	kPa	Cables not protected, adjust to minimum value, warns Telkom of cable leaks.	Pressure to cables too high, adjust back to 75kPa.
Airflow	52	Real-time value	90%	110%	l/min	Cables not protected, check flow panels and valves.	Airflow too high, check line pressure, also check if both compressors are running.
Dew point	-40	Real-time value	-23	-65	°C	Dew point too low, will result in dumping of air, investigate to find problem. Suspected wet desiccant chemicals or faulty dew point sensor.	Dew point too high, indicating faulty dew point sensor, investigate.
Tank Pressure		Real-time value	250	800	kPa	Refer to minimum tank pressure value.	Refer to maximum tank pressure value.
Tank pressure maximum Value	530		90%	110%	kPa	Investigate and adjust / change stop/start pressure switch. Check dump valve and dew point sensor.	Investigate and adjust / change stop/start pressure switch.
Tank pressure minimum Value	320		90%	110%	kPa	Investigate and adjust / change stop/start pressure switch. Check dump valve and dew point sensor.	Investigate and adjust / change stop/start pressure switch.
Pump-cycle time	6.7	Real-time value	90%	110%	Min	Check if line pressure and airflow have reduced, Determine if set point needs to be changed, resulting from lower need from client, check air filter.	Check if line pressure and airflow is within limits, possible problem dirty filter or damage to compressor.
Pump Off Cycle Set point	4.5	Real-time value	90%	110%	Min	Check if line pressure and airflow are within limits, possible problem both compressors running.	Check if line pressure and airflow is within limits, possible problem with compressors or cable demand valve partially closed.
Duty Cycle	50%	Real-time value	10%	80%		Check if line pressure and airflow have reduced, Determine if set point needs to be changed, resulting from lower need from client, check air filter.	Compressor will overheat with potential damage to compressor.
Compressor cycle change	2	Real-time value	90%	110%	Hours	Check for manual override or if both compressors are working.	Check for manual override or if both compressors are working.
Desiccators cycle change	3	Real-time value	90%	110%	Min	Check if microcontroller functioning normally, check settings.	Check if microcontroller functioning normally, check settings.
Temperature Compressor 1		Real-time value		85	°C	Not applicable.	Compressor too hot, potential damage to compressor, check if system is cycling between the two compressors, check duty cycle.
Temperature Compressor 2		Real-time value		85	°C	Not applicable.	

Table 15: Decision Support

5.8 Detail Design Conclusions

The design of the CBFM strategy on the CDH (FM equipment) was structured according to OSA-CBM standard.

The specific CDH equipment conditions parameters were developed in Chapter 4, and summarised in Table 7.

In the detail design, the complete OSA-CBM process and functionality were applied on the CDH, starting at the condition monitoring sensors, Signal processing, Condition Monitoring, Health assessment, Prognostics, Decision Support and eventually presentation of the Condition data and Maintenance tasks.

CHAPTER 6. RESULTS: THE EFFECT OF CONDITION BASED FACILITY MANAGEMENT ON THE CABLE DEHYDRATOR SYSTEM

6.1 Introduction

Six of the strategic Telkom sites within the Gauteng region were selected as prototype sites, where the Conditioned Based Facility Management system was implemented on CDH. The six sites contain eight CDH machines.

Sites	Number of Units	Manufacturer
Rosebank	1	Polar Air CCD 700
Benmore Gardens	2	Polar Air CCD 700 / 840
Jeppe Street	1	Polar Air CCD 700
New Doornfontein	1	Polar Air CCD 700
Braamfontein	1	Polar Air CCD 700
	1	Modified Nicotra DSA161
Germiston	1	Polar Air CCD 700

Table 16: Prototype CDH on which the RCMS System was Installed

The standard interface was implemented on eight CDH machines. On the Benmore Gardens machines additional temperature sensors and a power meter were installed on the compressors.

The CDH performance and condition were relayed back to the control room via the RCMS.

Within a few seconds the remote control room operator can determine if each CDH is performing its intended function and if it is operating optimally. Without the RCMS, only very limited “snapshot” information is available which is obtained during the scheduled visits once every few months.

The CDH Web page forms part of the normal TFMC RCMS Web pages.

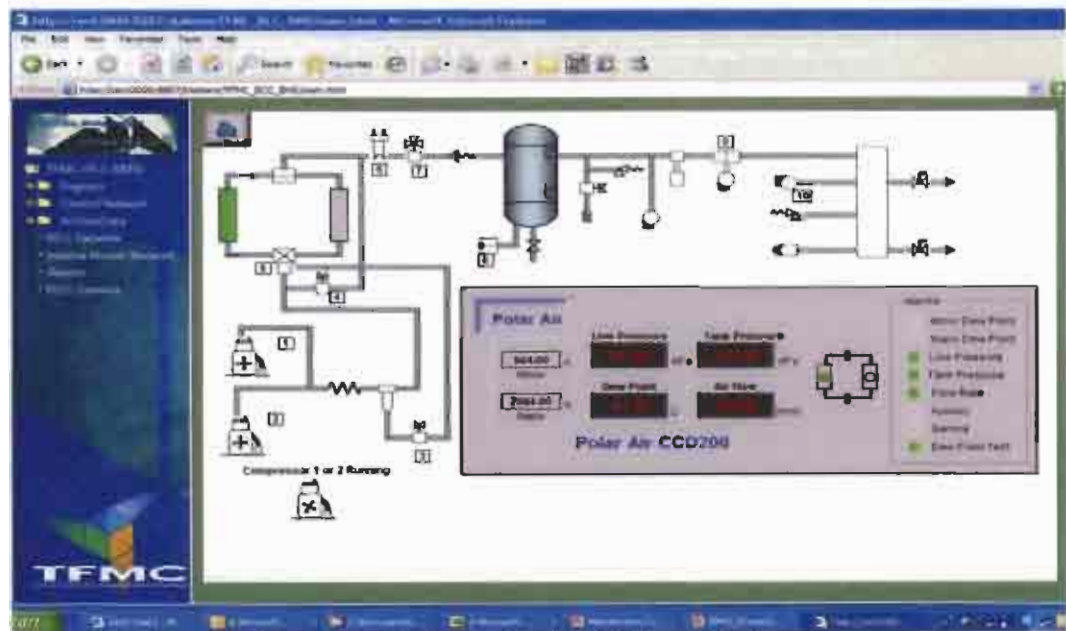


Figure 25: Cable Dehydrator Web User Interface

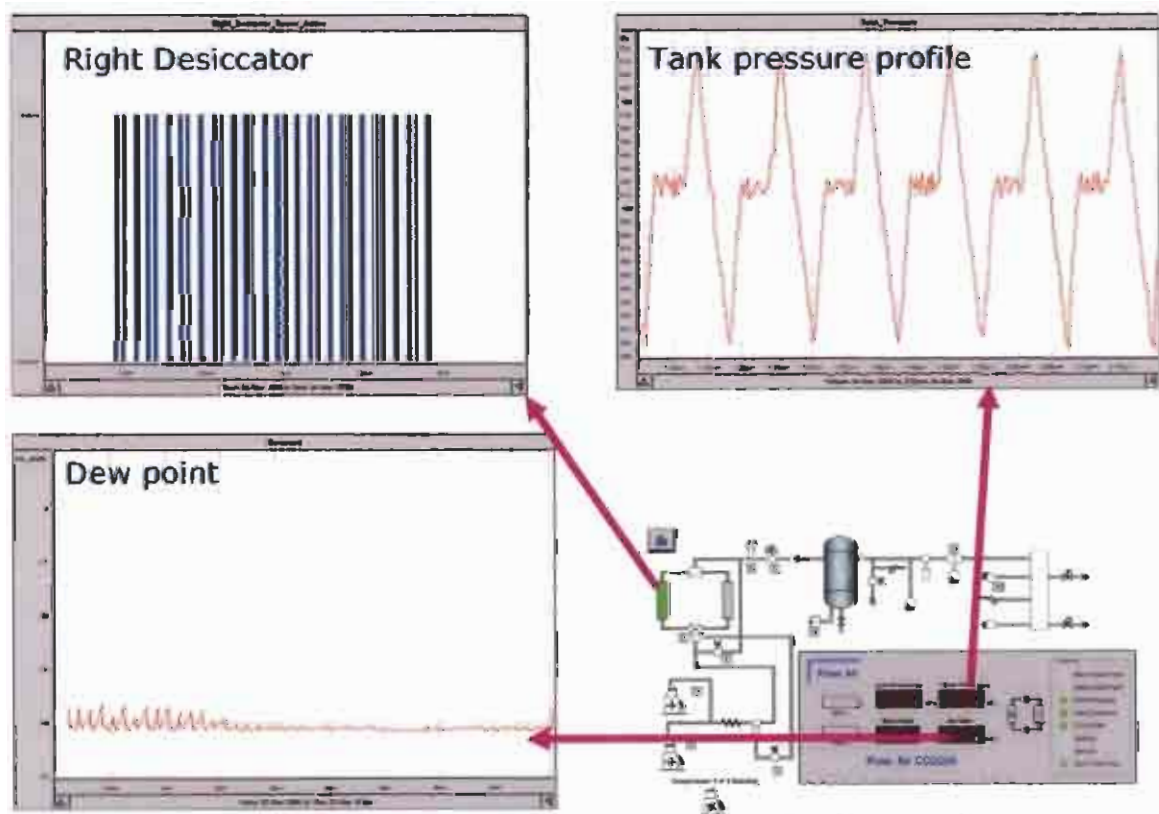


Figure 26: Typical CDH Logs Available for First Line Information

6.2 Results from the Condition Based Facility Management System

6.2.1 Monitor the System Operation

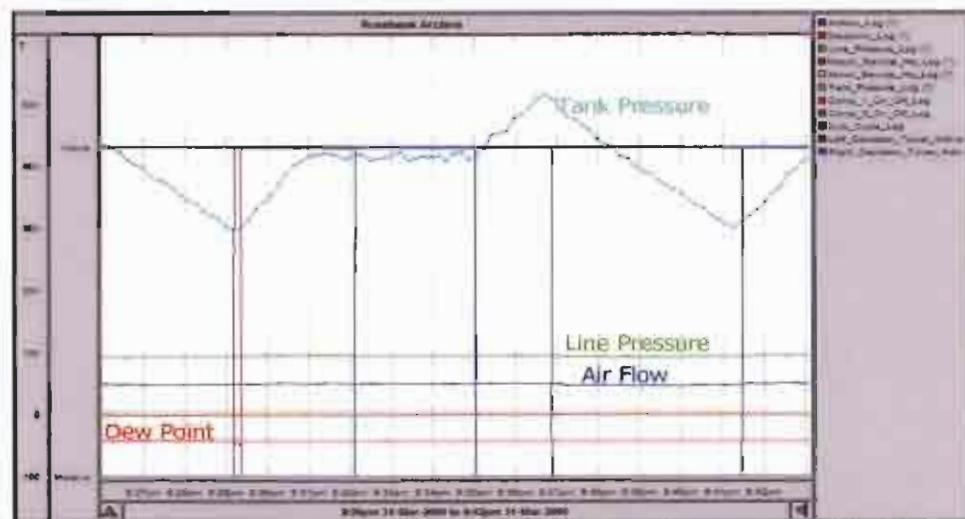


Figure 27: CDH Tank pressure and other vital performance indicators

The following typical user interface Web pages are available for analysing purposes.

Of the eight CDHs which were equipped with the Remote Condition Monitoring System (RCMS), not one of the CDH was performing optimally. Table 17 summarises their initial performance when the RCMS was implemented, and the conditions that were detected.

Real-time Condition data	Set Point	Alarm Low	Alarm High	Units	Rosebank CCD840	Benmore Gardens CCD700	Benmore Gardens CCD840	Jeppe CCD700	NDF CCD700	Germiston CCD800	Braam-fontein CCD700	Braam-fontein CCD840
Line pressure		65	80	kPa	81	82	88	88	90	91	70	70
Airflow	52	90%	110%	l/min	47	140	47	72	70	88	45	102
Dew point	-40	-23	-50	°C	-40	-60	-47	-41	-42	-40	-45	-60
Tank pressure				kPa								
Tank pressure maximum value	530	90%	110%	kPa	527	440	445	408	438	450	454	429
Tank pressure minimum value	320	90%	110%	kPa	300	310	380	306	296	305	310	290
Pump-cycle time	6.7	90%	110%	Min	7.2	6		5.4	5.5	5.7	7	62
Pump off cycle set point	4.5	90%	110%	Min	5	2		2.7	2.8	2.5	3.35	2
Duty cycle	50%		80%		59%	75%	100%	88%	88%	70%	88%	87%
Compressor cycle change	2	90%	110%	Hours	720	720	720	720	720	720	720	720
Desiccators cycle change	3	90%	110%	Min	2.7	2.7	2.7	2.7	2.7	3	3	3
Compressor 1 working					Yes, full time	Yes, full time	No	Yes	Yes, full time	Yes, full time	Yes	Yes, full time
Compressor 2 working					No	Yes, full time	Yes, full time	Yes	Yes, full time	Yes, full time	Yes	Yes, full time

Table 17: Performance and failure prediction data from CDHs

Real-time Condition data	Alarm Low	Alarm High	Units	Benmore Gardens CCD700
Compressor 1 Temperature		80	°C	64
Compressor 2 Temperature		80	°C	64
Compressor 1 Bearing Frequency	TBD	TBD	Hz	TBD
Compressor 2 Bearing Frequency	TBD	TBD	Hz	TBD
Energy Consumption		TBD	kWh	1.4

Table 18: Failure prediction data from CDHs

6.2.2 “What Failures were Detected”?

Monitor Vital Signs for Early Warning to Avoid Failures

The performance of the system is clearly visible from the real-time - and archived data. Figure 28 typically displays the tank pressure profile in relation with the functioning of compressors 1 and 2 and dessicator towers 1 and 2.

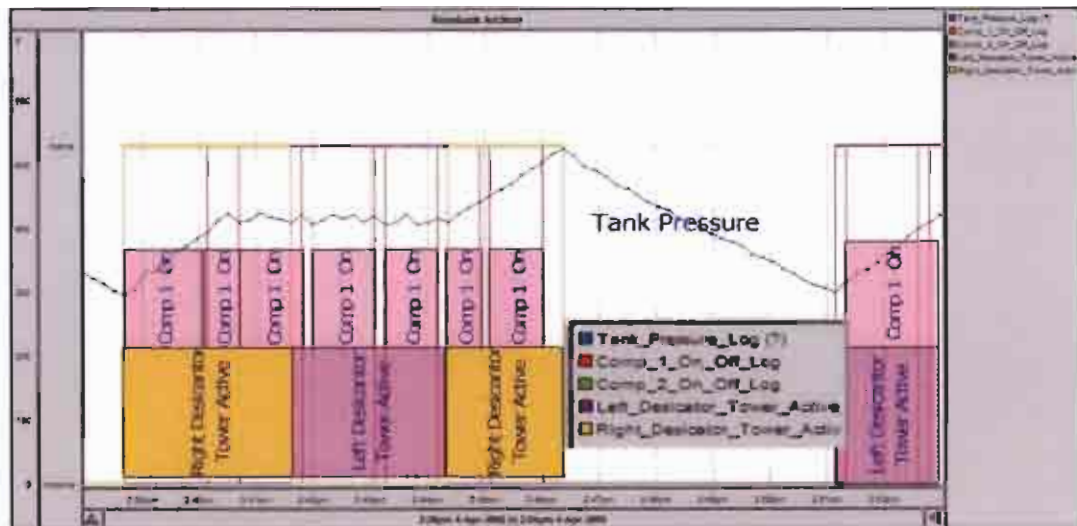


Figure 28: Rosebank CDH Tank Pressure Profiles

The CDH used oil-free compressors to ensure optimum air quality. The compressors were designed for a maximum duty cycle of 50% to ensure that the compressors do not overheat. High temperatures would considerably reduce the RUL. From Figure 29, it is clearly visible that the duty cycle of the Rosebank CDH was exceeding this maximum duty cycle. From Figure 30 it is visible that the Braamfontein CDH was running at a duty cycle close to 95%.

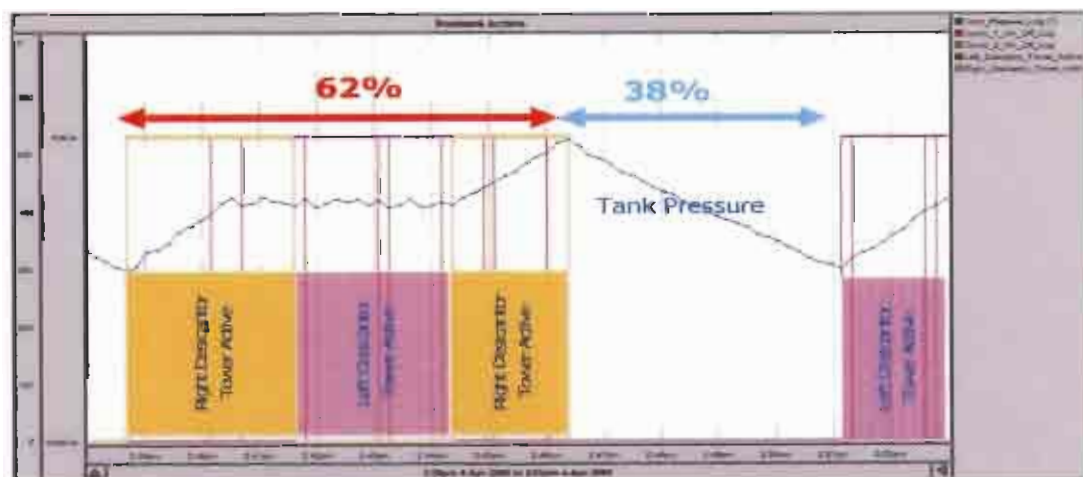


Figure 29: Rosebank CDH Duty Cycle Analysis

In 25% of prototype sites, one of the two compressors were not fully functional, resulting in the operational compressors running without a cooling cycle. This resulted in the shortening of the RUL of those compressors.

A faulty dew point sensor also resulted in the CDH running without producing any dry air to the air receiver pressure tank. The CDH was running at a duty cycle of more than 95% in order to try and heal itself. Again, the compressor RUL was significantly reduced and the cable's lifespan was possibly also reduced as a result of possible moisture ingress into the cable housings resulting from no pressure in the cable housing to prevent moisture and water ingress.

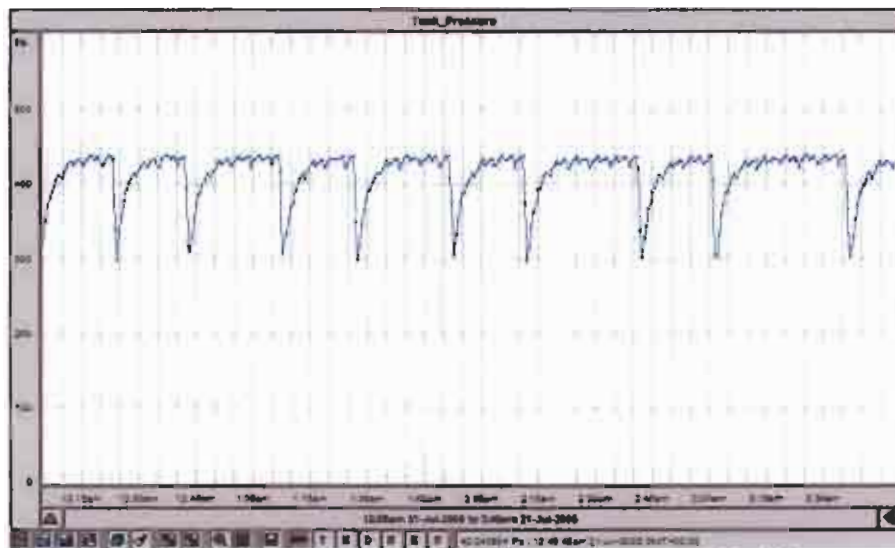


Figure 30: Braamfontein CDH Tank Pressure Profiles

From the Braamfontein tank pressure profile it is clearly visible that the compressor only switched off for a very short time. During this time the pressure rapidly dropped to the point where the compressor has to start again. In order to provide the required pressure, both compressors were running together with a duty cycle of 94%. This again, drastically, reduces the RUL of both compressors.

A list of faults and optimisation tasks was prepared in Table 19 for each of the CDH being managed via the Condition Based Facility Management System making use of RCMS.

Sites	Manufacturer	Comments
Rosebank	PA-CCD 840	The line is set at a too high pressure resulting in the machine working at a higher workload than contracted by Telkom. Only one compressor is operational which reduces this compressor's intended lifecycle.
Braamfontein	PA-CCD 700	The maximum tank pressure is set too low resulting in a very short duty cycle, which does not allow the compressor to cool down sufficiently. The duty cycle is also higher than recommended by the manufacturer and only one compressor is operational.
Braamfontein	N-DSA 161	The line is set at a too high pressure resulting in the machine working at a higher workload than contracted by Telkom. The maximum tank pressure is set too low, resulting in a too short duty cycle, which does not allow the compressor to cool down sufficiently. The duty cycle is too high and only one compressor is operational. The dew point sensor is suspect of giving a very low value of -60°C.
Benmore Gardens	PA-CCD 700	The line is set at a too high pressure and the airflow required is also too high, resulting in the machine working at a higher workload than contracted by Telkom. The maximum tank pressure is set too low, resulting in a too short duty cycle, which does not allow the compressor to cool down sufficiently. The duty cycle is too high and only one compressor is operational. The dew point sensor is suspect of giving a low value of -60°C.
Benmore Gardens	PA-CCD 840	The line is set at a too high pressure, resulting in the machine working at a higher workload than contracted by Telkom. Both stop/start pressure switches are faulty or incorrectly adjusted, resulting in the maximum tank pressure being too low and the minimum pressure being too high, the system is not cycling and only one compressor is operational.
Germiston	PA-CCD800	The line is set at a too high pressure and the airflow required is also too high, resulting in the machine working at a higher workload than contracted by Telkom. The maximum tank pressure is set too low and the duty cycling too high. In order to provide the required airflow both compressors are running simultaneously.
Jeppe Street	PA-CCD 700	System not yet commissioned.
New Doornfontein	PA-CCD 700	The line is set at a too high pressure and the airflow required is also too high, resulting in the machine working at a higher workload than contracted by Telkom. The maximum tank pressure is too low and the duty cycling too high. In order to provide the required airflow both compressors are running simultaneously.

Table 19: Faults Detected with RCMS

6.2.3 Redesign the CDH to Improve System Performance

When the CDH performance were analysed in detail, it was found that although the compressor is running and pumping air, for 50% of the pumping cycle the tank pressure was not rising.

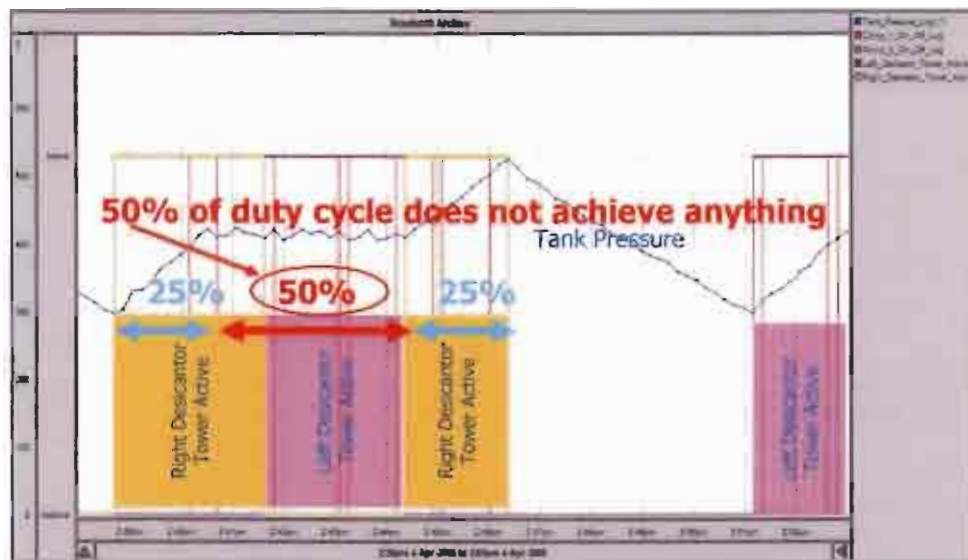


Figure 31: Rosebank CDH Effectiveness Analysis

During this period air was dumped through the dump valve to allow the first (right) dessicator tower to complete a full drying cycle (refer to Paragraph 4.2.2 CDH Basic Operation) and allow the system to start on the next pump cycle with the left dessicator tower. This philosophy has a resulted in 50% of the energy consumed by the CDH was used for drying. According to the manufacturer, the system only needs 10% of its energy to dry itself.

Resulting from the information and the failure data gathered in an analysis of the last year's repair cost data, the suggestion was made to the manufacture to change the CDH design to overcome the inefficiency without reducing the systems performance.

The current methodology applied by the manufacturer does affect both the lifecycle of the compressors and dump valve as well as uses twice the amount of electrical power.

Refer to Annexure B or energy usage calculations.

6.2.4 "What Failures were Predicted?"

From the information obtained via the remote real-time monitoring system, the following typical faults were predicted:

- All the CDH compressors, (of which 11 of the 16 were running) were running continuously with very limited cooling-down time. The compressor's RUL were significantly reduced. This is backed by the high replacement cost of compressors, refer to Paragraph 4.3.4 for more detail. As illustrated in Figure 16, the compressor replacement cost is recorded as the second highest component cost.

- In 5 of the 8 CDH, there line pressures and/or airflows are running close to, or higher than the maximum limit. As a result the complete system is operating on a high workload, with all the related higher maintenance costs on both the FM and the client side. This indicated that Telkom has serious leaks in their cable housings which need to be repaired, or alternatively they need to add additional CDH to assist with the supply of air.
- One incident occurred where the system was not supplying air to Telkom due to faulty dew point sensors, indicating that the air is wet and therefore the air was dumped.
- Two of the CDHs dew point sensors were picked up as being faulty or damaged indicating permanently that the air is not wet. This puts Telkom's cables at risk with potentially high replacement costs.

6.2.5 “What Costly Maintenance was Prevented?”

Not enough data is available to determine accurately what maintenance cost was prevented. From Table 18, it can be seen that all the compressors were operating outside their design parameters. This means that their RUL were reduced, but no data is available on how much the reduction could be. The replacement cost for these compressors is R120 000, in total.

Should these compressors fail, and the failure it is not detected quickly enough, Telkom has a potential physical risk in repair cost in the order of R6,4 million with a further potential loss of income, of more than R10 million. The repair cost from a single previous incident was R800 000 to replace a cable.

6.3 Prediction on the Effectiveness of Condition Based Maintenance on CDH

6.3.1 Are the RCMS and CBFM Working as it Should?

With the Condition Monitoring system the performance or non-performance of each CDH can be easily detected via the real-time information displayed on the Web pages.

The alarms, as programmed into the system, also assist to draw the control room operator's attention to the problem, with a pop-up alarm window on his monitoring workstation (PC). With the URL in the alarm window or alarm panel the operator can easily jump to the specific CDH webpage from where the alarm was raised.

It was however necessary to train the BCC operators in the CDH operations and to sensitise them on the importance of each parameter measured. They also needed some guidance to interpret the different alarms and CDH performance data in order to inform the technicians of the specific problem which required maintenance actions.

The RCMS was implemented during June 2005 and during July 2005 the system was used to record the current status of the current maintenance strategy. In August 2005 the CBFM system was activated with the CDH availability results as displayed in Figure 32. Refer to Annexure D for detail on Availability, MTBA and MTTR calculations.

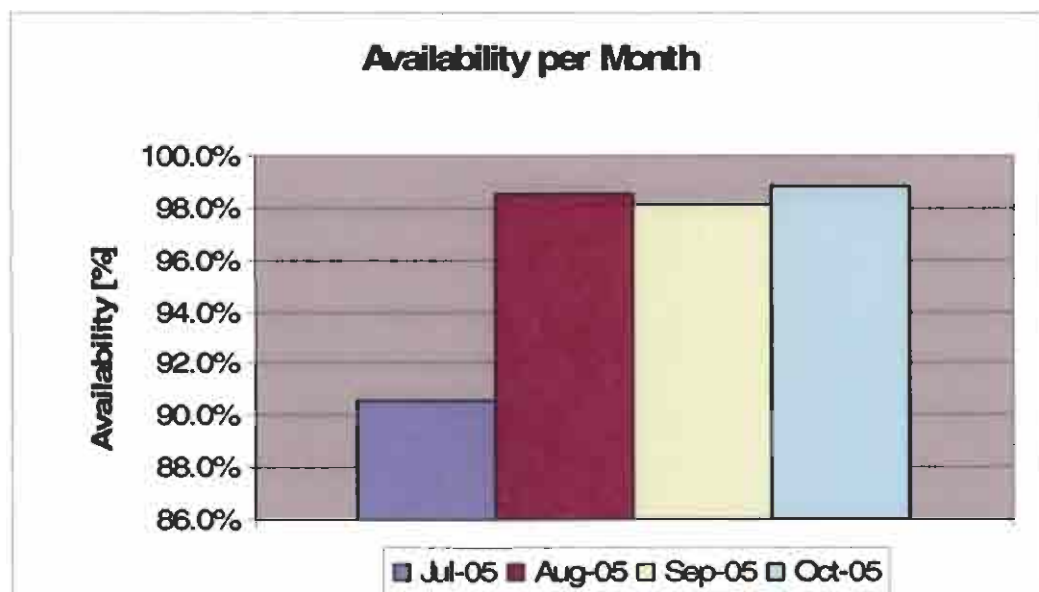


Figure 32: % Availability of CDH

The system also allows the operators to track maintenance progress, as they can see when the problem was repaired as displayed in Figure 33 where a faulty stop/start switch was replaced.

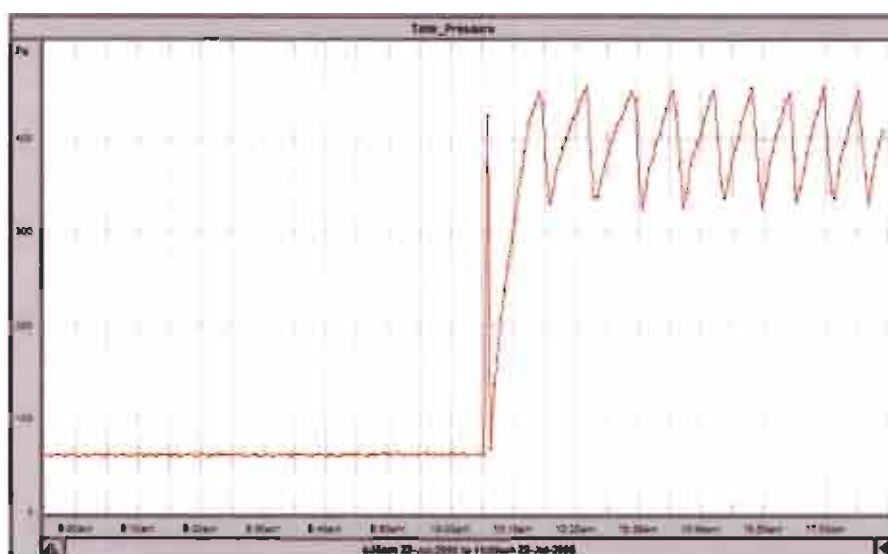


Figure 33: Tracking Repair Actions

6.3.2 The Cost Effectiveness of the RCMS and CBFM System

The cost to extend the current RCMS to include the CDH is R2 500 to upgrade the Polar Air CCD system, R1 800 in contractor labour to extend the monitoring network within the building and R400 for internal labour cost for programming, configuration and commissioning. This brings the total implementation cost to R4 700 per CDH.

By implementing CBFM the cost of travelling for Planned Maintenance could be significantly reduced with some conservative savings on replacement of spares. Table 20 and Figure 34 represent a prediction of the cost saving which is envisaged.

Inspection maintenance tasks (JPCAB0001) could be performed via RCMS at a fraction of the cost, by the functional specialist in the office.

Saving to the minor services (JPCAB0002) could also be reduced, as minor services are now only performed when a CDH performance requires it. Savings on major services (JPCAB0003) can also be reduced and coordinated with EMs and PCMs.

Refer to Annexure C for detail description of the assumptions and reasoning behind the assumptions.

Condition Based Maintenance cost					
Job Plan	Service type	PM ever X Month	Cost Remote monitoring	Cost for CBM per Annum	Cost for CBM per annum for all CDH
JPCAB001	Remote surveillance	1.0	105.00	105	99,435
JPCAB001	Remote surveillance	2.0	105.00	210	198,870
JPCAB002	Remote surveillance	2.8	105.00	315	298,305
JPCAB001	Remote surveillance	4.0	105.00	420	397,740
JPCAB002	Minor service	5.0	105.00	1,083	1,025,569
JPCAB002	Remote surveillance	5.6	105.00	1,188	1,125,004
JPCAB001	Remote surveillance	7.0	105.00	1,293	1,224,439
JPCAB003	Minor/Major service	8.3	105.00	2,084	1,973,365
JPCAB001	Remote surveillance	10.0	105.00	2,189	2,072,800
JPCAB002	Minor service	11.1	105.00	2,852	2,700,628
JPCAB001	Remote surveillance	12.0	105.00	2,957	2,800,063
JPCAB003	Major service	13.9	105.00	3,839	3,635,589
Planned Total PM cost per annum				3,317	R 3,141,149

Table 20: CBM Cost Prediction

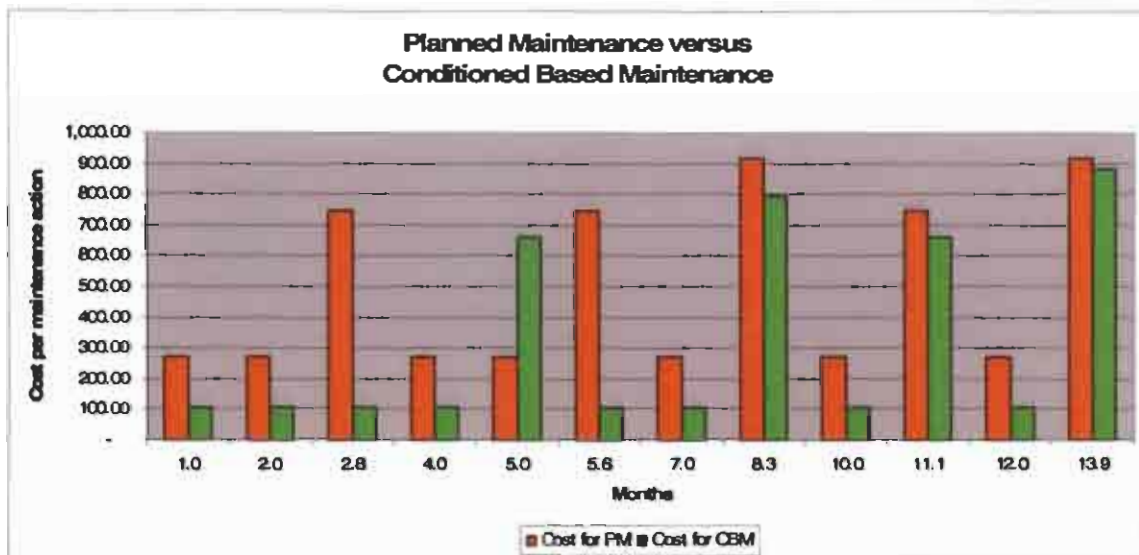


Figure 34: Scheduled Maintenance versus Condition Based Maintenance

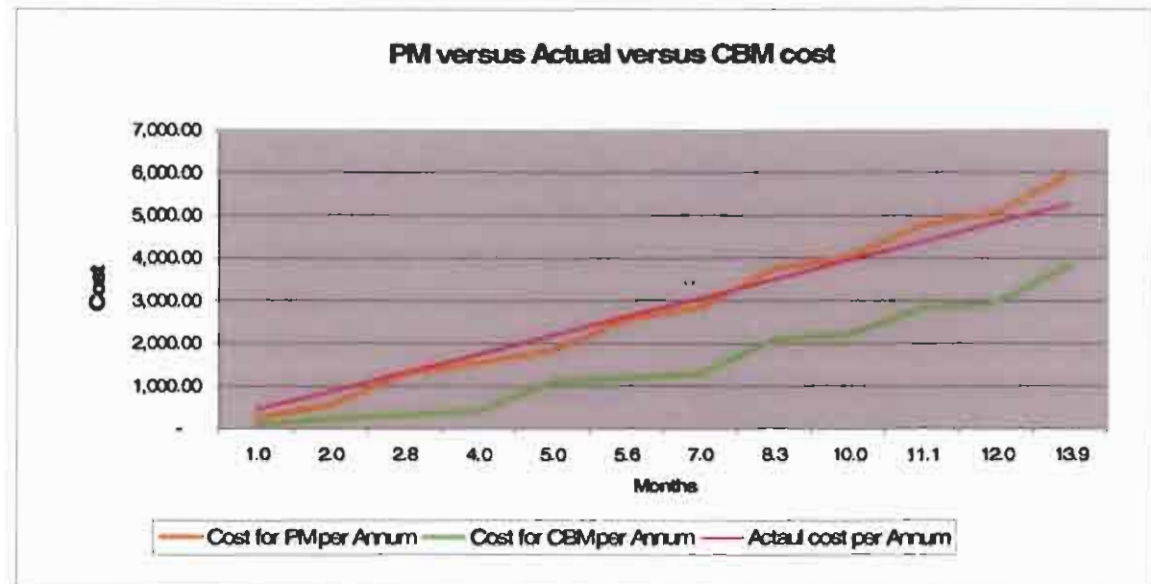


Figure 35: Annual Comparison between PM, Actual Cost and CBM

As discussed in Paragraph 4.3.6 and the recording of the actual cost for maintenance according to CMMS (Maximo), R 4.3 million was spent on CDH maintenance for the previous year. As indicated in Table 20 the CBFM only envisage a total maintenance cost of R3.1 million with an increase in availability of 8%, refer to Figure 32.

6.4 Conclusion

The implementation of the Condition Based Facility Management on the CDH is completed but the system has not been in operation long enough to gather substantial data on the real cost savings and availability improvement. The three months that the system has been implemented only gave us a glimpse of the potential advantages of the system.

The effectiveness of the additional condition monitoring sensors, like compressor temperatures and bearing vibration sensors, must still be further tested and measured over a period of at least a year.

CHAPTER 7. CONCLUSION AND RECOMMENDATIONS

7.1 Introduction

The problem statement for this project was to investigate and develop a new maintenance strategy which would drastically improve the availability of the environmental equipment in a cost-effective manner.

As the author was previously involved in the development and implementation of the Remote Alarm Monitoring System, the study focuses on the contribution of remote monitoring towards a new improved maintenance strategy. Resulting from the new emphasis and importance of cables within the telecommunication chain, the Cable Dehydration System was selected for the case study.

7.2 Were the Study Objectives Achieved?

The following sub objectives were successfully addressed:

- Evaluate the different maintenance strategies.

Several Maintenance Management strategies were investigated. A new Condition Based Facility Management (CBFM) strategy was developed for the modern Facility Management environment where remote management is particularly important.

This strategy overcomes most of the previous drawbacks of Condition Based Maintenance (e.g. immature technology, focus on all equipment and conditions, data capturing of the equipment condition in the plant room, etc.). The new strategy includes principles from the other important strategies.

- Evaluate the different condition monitoring techniques.

Before the Condition Monitoring technologies were selected, it was necessary to establish what condition data this maintenance strategy required. Different functional requirements were formulated and those contributing the most, were selected.

They were: holistic equipment performance, a sub-system performance to pinpoint problem areas, prediction of failures and reducing maintenance cost drivers. The different condition monitoring techniques were also investigated.

After the functional requirements were determined, the study focused on those traditional condition monitoring technologies that contribute towards achieving the functional requirements. (e.g. Vibration analysis, temperature analysis, motor current analysis, etc.). Refer to Table 7 for a summary.

- Develop a methodology to extract and pinpoint the critical equipment condition.

The study investigates several tools to determine what equipment condition information needs to be remotely gathered. Different tools were investigated and three were selected to be used with the implementation of Remote Condition Monitoring: Plant performance analysis, Failure Mode Effect and Criticality Analysis and Historical maintenance data analysis.

- Investigate the relevant standards.

Different Condition Monitoring and Condition Based Maintenance standards were investigated. The main aim of these standards was to promote Open System Architecture (OSA), ensuring that products from different suppliers can be used within any system.

The Open System Architecture for Condition Based Maintenance (OSA-CBM) standard was selected as the most appropriate for TFMC, this standard is promoted by MIMOSA.

Previously the maintenance technician had to regularly walk through the building to get a feeling of the condition of all the equipment. When it was attempted to optimise the building, the system very quickly returned to its previous unoptimised status. Even with modern BMS, which controls the complete building system, the true condition of all the equipment, is not measured and reflected in the PC-based front-end.

The concept of Condition Based Facility Management was formulated, focusing on remote monitoring to optimise the maintenance strategy within the Facility Management industry.

7.3 Is the New Strategy and Methodology on the Cable Dehydration System Effective and was the Problem Solved?

The new Condition Based Facility Management strategy was applied on the Cable Dehydration System. The system immediately highlighted several problem areas within the current maintenance strategy of the Cable Dehydration Systems. These problem areas could not be detected with the normal Planned Preventative Maintenance strategy.

The availability of the Cable dehydrators was improved from 90% to 98%. The cost savings achieved through the system was increased.

When comparing the original budgeted Planned Maintenance Costs of R4,8 million or the actual maintenance cost for the previous year of R 4.3 million with the envisaged R3,1 million of CBFM maintenance cost, a potential cost reduction of 36% to 27% can be achieved.

7.4 Recommendations: The Way Forward

The Condition Based Facility Management concept (CBFM) has proved to be very successful to improve the Cable Dehydration System service cost, effectively. The methodology spelled out in this study can now be applied to all the other environmental systems for which the Facility Manager is responsible.

As the system, to be maintained, becomes more complex (e.g. complete HVACR system for large buildings), the advantages and contribution of the CBFM system will become more and more evident. This results from the fact that the condition and level of optimisation of the complete system is visible in a single simplified manner, every day.

The way forward is thus to influence and convince all role players within TFMC, that the CBFM can be effectively applied on all of the environmental equipment as listed in paragraph 1.1.1.

Several key factors were identified which need to be success implemented in order to ensure that TFMC will adopt the new approach:

- Support form TFMC top management
- Selection of environmental equipment on which the biggest impact could be demonstrated. (Phased in approach)

- Selection of the correct condition data to be collected through the RCMS, using the methods as selected within this study, refer to paragraph 3.2.5.
- Research on the application of specific equipment which requires collecting of the appropriate condition data for the specific equipment, e.g. vibration analysis.
- Designing of the RCMS for the specific equipment.
- Training of the BCC surveillance agents to perform proper predictive surveillance.
- Providing the regional maintenance engineering departments with proper condition data (Health assessment data)
- Performance of proper diagnostics by the functional specialists from this data and recommending appropriate preventative maintenance.
- Tracking and recording of all these actions, preventative maintenance recommendations, execution of these actions and the outcome to highlight the success of the CBFM concept.
- Automation of the initial human assisted prognoses and preventative maintenance action activation via proper integration with CMMS.
- Development of the Management Information System as described in paragraph 3.5

7.5 Further work

The two big areas where additional work is required to complete the study, is:

- Proving the predicted cost savings over a longer time period.
- Applying traditional compressor and bearing vibration monitoring on the Cable Dehydration System and determine if it could further improve failure prediction cost effectively.

The author will address both of these outstanding issues over the next few months.

REFERENCES

- [1] Paskin, W; (2004), "**Facility Management with a Difference**", SAPOA News letter, April 2003.
- [2] Fourie, W A S; (2003), "**Designing a Novel Centralised Monitoring And Control Facility**", Dissertation submitted for the degree Magister Engineering at the Potchefstroomse Universiteit vir Christelike Hoër Onderwys.
- [3] Frieden R; (2005), "**Lessons from broadband development in Canada, Japan, Korea and the United States**", Article Telecommunications Policy, Volume 29, Issue 8, September 2005, Pages 595-613.
- [4] Ayres R U, Williams E; (2004), "**The digital economy: Where do we stand?**" Article Technological Forecasting and Social Change, Volume 71, Issue 4, May 2004, Pages 315-339.
- [5] Rausand M, (1998), "**Reliability centred maintenance**", Article Reliability Engineering & System Safety, Volume 60, Issue 2, May 1998, Pages 121-132.
- [6] Groenewald R; (1999), "**Maximising efficiency**", Published by Telkom <http://www.publicservice.co.uk/pdf/pfi/spring2001/p174.pdf>.
- [7] Laverack, R; (1987), "**Facilities management-a contract to boost the bottom line**", Source: Accountancy, v 100, n 1131, Nov. 1987, p 164.
- [8] DiLeo, M, Manker, C, Cadick, J; (1999), "**Condition Based Maintenance**", Cadick Corporation, Revised October 1999, Pages 7.
- [9] SIS (Swedish Standards Institute) Industriteknik, (2001) "**Maintenance terminology**" SS-EN 13306
- [10] Bengtsson M, (2004), "**Condition Based Maintenance System Technology – Where is Development Heading?**", Euromaintenance 2004 – Proceedings of the 17th European Maintenance Congress, 11th – 13th of May, 2004, AMS, Barcelona, Spain, B-19.580-2004.
- [11] Cadick J, (1999), "**Condition Based Maintenance - How to get started**", by Cadick Corporation.
- [12] Staller C, (1998), "**Condition Based Maintenance – What is the condition of Condition Based Maintenance?**", Article 1 for Condition Monitor News.
- [13] Mitchell, J. S; (1998), "**Five to ten year vision for CBM**", ATP Fall Meeting – Condition Based Maintenance Workshop, USA, Atlanta, GA, 1998 (PowerPoint Presentation), <http://www.atp.nist.gov/files/3>.
- [14] Deshpande V. S and Modak J. P, (2002), "**Application of RCM to a medium scale industry**", Article Reliability Engineering & System Safety, Volume 77, Issue 1, July 2002, Pages 31-43.

- [15] Kathleen E. McKone, Roger G. Schroeder and Kristy O. Cua, (1999), "**Total productive maintenance: a contextual view**", Article Journal of Operations Management, Volume 17, Issue 2, January 1999, Pages 123-144.
- [16] Kristy O. Cua, Kathleen E. McKone and Roger G. Schroeder, (2001), "**Relationships between implementation of TQM, JIT, and TPM and manufacturing performance**", ARTICLE Journal of Operations Management, Volume 19, Issue 6, November 2001, Pages 675-694.
- [17] Fujiyama K, Nagai S, (2004), "**Risk-based inspection and maintenance systems for steam turbines**", • Article International Journal of Pressure Vessels and Piping, Volume 81, Issues 10-11, October-November 2004, Pages 825-835.
- [18] Krishnasamy L, Khan F, Haddara M; (2005), "**Development of a risk-based maintenance (RBM) strategy for a power-generating plant**", • Article Journal of Loss Prevention in the Process Industries, Volume 18, Issue 2, March 2005, Pages 69-81.
- [19] Bond T H and. Mitchell J S, (1994), "**Profit Centred Maintenance, A Management Opportunity**", submitted to The Wall Street Journal for publication on 2/27/95 but was not accepted.
- [20] Mitchell J S, (1994), "**Profit Centred Maintenance – A new Vision**", Article in P/PM Technology.
- [21] Thielsch H, Cone FM, (1993), "**Increasing Plant reliability by Non-destructive Inspections**", Nitrogen No 205, September-October 1993.
- [22] Yanga, B Hwanga W, Kima D, Tanb A C; (2005) "**Condition classification of small reciprocating compressor for refrigerators using artificial neural networks and support vector machines**" ARTICLE Mechanical Systems and Signal Processing, Volume 19, Issue 2, March 2005, Pages 371-390.
- [23] Tapson, J; (2002), "**Canary in a Coal Mine: The Development of a Web-based Online Condition Monitoring System**", Electrical Engineering University of Cape Town or www.motornostix.com.
- [24] Petreski D,(2002), "**Infrared Thermography Survey for C.P. Foods**", Mahachai Plant, Shell.
- [25] Bengtsson M, (2004), "**Technical Design of Condition Based Maintenance System -A Case Study using Sound Analysis and Case-Based Reasoning**", Maintenance and Reliability Conference – Proceedings of the 8th Congress, May 2nd – 5th, 2004, University of Tennessee – Maintenance and Reliability Centre, Knoxville, USA.

- [26] Beebe, R. (1998), "**Condition monitoring by performance analysis to optimise time for overhaul of centrifugal pumps**", Proceedings of 52nd Meeting of Society for Machinery Failure Prevention Technology, Virginia Beach, VA.
- [27] Dunn, S (2005), "**Condition Monitoring in the 21st Century**", Article for the Plant Maintenance Resource Center, 14 April 2005, Assetivity Pty Ltd.
- [28] Lofall, D A, Mereckis, T A; "**Integrating CMMS with Predictive Maintenance Software**", DLI Engineering and Dreamteam.
- [29] Wilcoxon Research, (2005), "**The NEW IT Alarm from Wilcoxon**", Wilcoxon Research, Inc. Press Releases.
- [30] Staller C, (1998), "**Financial Justification for CBM – is EVAØ the right answer?**", Article 3 for Condition Monitor Newsletter.
- [31] Harbor Research's study; (2004), "**Connecting to Your Future: The Networking of Every Manufactured Thing**", Harbor Research, Inc.
- [32] A Harbor White Paper, (2003), "**Think Smart, Think Connected: Maintaining Competitive Advantage in an Open, Connected Landscape**", Spinnaker Venture Partners, LLC and Harbor Research, Inc.
- [33] BMSI, (2003), "**The New Generation Facility Surveillance System**", TFMC.
- [34] Stamatis, D.H., (1995), "**Failure Mode and Effect Analysis: FMEA from Theory to Execution**", American Society for Quality (ASQ), Milwaukee, Wisconsin.
- [35] Kócza G Bossche A, (1999), "**Application of the Integrated Reliability Analysis System (IRAS)**", Article Reliability Engineering & System Safety, Volume 64, Issue 1, April 1999, Pages 99-107.
- [36] Brink A, (1999), "**RAM Report: Cable Dehydration System For Bronberg ETE**" (Doc no Telkom M00-REP-0100), Infracom Facility Management.
- [37] Unknown; (2005), From the newsletter "**Process Plant and Equipment UP-TIME**" by www.feedforward.com.au – Leaders in Plant Maintenance Continuous Improvement.
- [38] Vaishali R. Choksi, Marn C, (2005), "**Illustrating the Root-Cause-Analysis Process: Creation of a Safety Net with a Semi-automated Process for the Notification of Critical Findings in Diagnostic Imaging**", Article Journal of the American College of Radiology, Volume 2, Issue 9, September 2005, Pages 768.
- [39] Kahn, J., D., (2003), "**Overview of MIMOSA and the Open System Architecture for Enterprise Application Integration**", COMADEM 2003 Proceedings of the 16th International Congress, August 27-29, 2003, Växjö University, Sweden, Edited by Shrivastav, O. and Al-Najjar, B., Växjö University Press, ISBN 91-7636-376-7, pp. 661-670.

- [40] Müller, G, (2003), **"Fifth generation facilities maintenance management"**, Article for the African Cleaning Review, Jul / Aug 2003.
- [41] Msimango T, (2005), **"Strategic Direction Document for the Management of Outside Plant (OSP) and Wire-line Transport Media (WTM) Network Elements"** (Doc No SR-BJ0006), Telkom E-Dox System (CTO-006079).
- [42] Van Schalkwyk P, (2005), **"New Service Level Agreement between Telkom SA and TFMC – Fire and Infrastructure"**, Doc No: TFMC-CT-0415.
- [43] Reimer G, (2002), **"Operation & Instruction Manual - Polar Air Dehydrator, Model CCD 800"**, PolarAir.
- [44] Nicotra Sistemi , (2001), **"Operation & Instruction Manual - Nicotra Sistemi Spa DSA 160"**, Nicotra.
- [45] Sievert R, (1998), **"Total Productive Facilities Management (TPFM)"** Publisher:: RS Means Company.
- [46] Sun M, Ali N, Barrett P, (2003), **"An integrated management system for reactive building maintenance projects"**, Proceedings of the 10th ISPE International Conference on Concurrent Engineering, Research and Applications, Advanced Design, Production and Management Systems, 2003, p 225-232.
- [47] Bond T H and. Mitchell J S, (1996), **"Beyond Reliability and profitability"**, Proceedings of EPRI Fossil Plant Maintenance Conference July 1996.
- [48] Saleh J.H and Marais K, (2004), **"Highlights from the early (and pre-) history of reliability engineering"** Short Communication - Reliability Engineering & System Safety, Volume 91, Issue 2, February 2005, Pages 249-256
- [49] Staller C, (1998), **"Integration - are we going in the right direction?"**, Article 2 for Condition Monitor Newsletter.
- [50] Smit F, (2005), **"Maintenance Strategy Evolution"**

ANNEXURE

ANNEXURE A. DETAILED FMECA PERFORMED ON THE CABLE DEHYDRATION SYSTEM

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
Intake Air Filter	Totally Blocked	No airflow to flow panel, increased wear on compressor, energy waste	9	5	45	1	45	
	Partially blocked	Reduced airflow to flow panel, increased wear on compressor, energy waste	7	9	63	3	189	Compare to base cycle time
	Removed	Rapid increased wear on compressor rings and sleeves, contamination and blocking of desiccators chemical	9	8	72	9	648	Compare to base cycle time
Compressor complete								
Piston ring	Overheat - lost tension	Loss of compression, low pressure and airflow, energy waste	9	3	27	5	135	
	Dusty Air	Piston cease - no compression - no pressure and airflow	9	3	27	4	108	
Expander ring	Dirty - partially working	Leak - reduced compression - reduced pressure and airflow	6	4	24	5	120	
	Stuck - excessive	No compression, no pressure and airflow	9	4	36	1	36	Compare to base cycle time
Valve plate	Dirty - partially working	Leak - reduced compression - reduced pressure and airflow	6	4	24	5	120	
	Stuck - excessive	No compression, no pressure and airflow	9	4	36	1	36	Compare to base cycle time
Cylinder sleeve	Cease with piston	No compression, No pressure and airflow	9	3	27	1	27	
	Overheat - scratch marks - loss compression	Reduced compression, reduced pressure and airflow	4	6	24	3	72	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when It Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
Piston rod assembly	Overheating - cease	No compression, no pressure and airflow	9	4	36	1	36	Compressor temperature and vibration
	Bearings overheat - Cease	No compression, no pressure and airflow	9	4	36	1	36	Compressor temperature and vibration
	Break	No compression, no pressure and airflow	9	3	27	1	27	
Compressor body	Internal damage due to component breakage	No compression, no pressure and airflow	9	2	18	1	18	
	Dirty outside - reduced heat dissipating - Overheating - cease eventually	Too high air temperature, reduced airflow, reduced pressure and airflow	6	3	18	8	144	
Compressor bearings	Overheating - cease eventually	Eventually no compression, no pressure and airflow	5	5	25	6	150	
	Bearings cease	No compression, no pressure and airflow	7	4	28	2	56	
	Break	High cost to repair, no compression, no pressure and airflow	9	4	36	2	72	Tank pressure rise below
Motor	Power failure	No compression, no pressure and airflow	6	7	42	1	42	AC fail
Wires (power)	Damage of wires	No compression, no pressure and airflow	6	5	30	2	60	
	Wires damage / cracked - vibration	No compression, no pressure and airflow	6	5	30	2	60	
Motor bearings	Overheating - cease eventually	Eventually no compression, no pressure and airflow	6	4	24	7	168	
	Bearings cease	No compression, no pressure and airflow	7	3	21	1	21	
Piping	Leakages - damage	Loss of compression / reduce airflow	4	5	20	3	60	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when It Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
	Leakages - old age	Loss of compression / reduce airflow	4	5	20	3	60	
Mountings	Mounting broken or fasteners loose - vibration	Damage to compressor, can lead to loss of airflow and pressure	6	3	18	7	126	
See compressor 1	See compressor 1	See compressor 1			0		0	
					0		0	
					0		0	
See compressor 1	Resulting from hard work if one fails the wear on the other one is increased with several factors, this one cannot cool down properly	Eventually no compression, no pressure and airflow			0		0	
Cooling coil	Damage due to component breakage	Loss in compression and airflow	4	3	12	2	24	
	Damage / cracks due to vibration	Loss in compression and airflow	4	3	12	2	24	
	Dirty outside - reduced heat dissipating - Overheating - cease eventually	Too high air temperature, reduced airflow, reduced pressure and airflow	3	5	15	3	45	
Fan+ housing	Damage due to component breakage or cracks from vibration	Reduced airflow over cooling coil - reduced heat dissipating - lower air volume - energy waste	3	3	9	7	63	
	Severe damage due to component breakage or cracks from vibration	No airflow over cooling coil - reduced heat dissipating - energy waste - damage to chemicals	3	3	9	7	63	
Motor	Overheating - cease eventually	Reduced airflow over cooling coil - reduced heat dissipating - energy waste - damage to chemicals	5	4	20	2	40	
	Power failure	Reduced airflow over cooling coil - reduced heat dissipating - energy waste - damage to chemicals	6	7	42	1	42	Compare to base cycle time

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
Piping / fittings	Leakages - damage	Loss of compression / reduce airflow	3	5	15	2	30	
	Leakages - old ages	Loss of compression / reduce airflow	3	5	15	2	30	
Mounting	Mounting broken or fasteners loose - vibration	Reduced of compression / reduce airflow	4	4	16	5	80	
Moisture separator	Leakages - damage	Reduced of compression / reduce airflow	2	2	4	2	8	
	No moisture separation	More moisture to desiccators - more drying time to dry desiccators - less airflow to tank	4	4	16	5	80	
	Cannot bleed off moisture - no moisture separation	Eventually no moisture separation - more moisture to desiccators - more drying time to dry desiccators - less airflow to tank	4	4	16	5	80	
Unloading valve	Fail in open position	Loss of compression / reduce airflow	3	4	12	5	60	
	Fail in close position	More time required to do specific maintenance tasks	3	4	12	5	60	
Exhaust	Blocked exhaust	Cannot bleed off moisture or bleed air to dry dessicator - eventually leads to "wet" air - no airflow and air pressure in tank	2	3	6	3	18	
Bypass valve	Fail in closed mode	Cannot test dew point sensor - cannot guarantee proper working of dew point sensor could lead to either "wet" air to tank or no airflow and air pressure in tank	3	2	6	5	30	
	Fail in open mode	System will bypass desiccators, results in end "wet air" to dew point sensor - open dump valve - no airflow and air pressure in tank	6	2	12	1	12	
Change over valve	Dirty - no proper switching from one desiccators to another	Do not switch regular to new desiccators - desiccators will become "wet"- cannot dry air, no air to tank - no supply of dry air	4	4	16	1	16	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
	Stuck	Do not switch to new desiccators - desiccators will become "wet"- cannot dry air, no air to tank - no supply of dry air	4	4	16	1	16	
Cylinder	Damage - no dry air to tank	Damage - no dry air to tank	6	2	12	2	24	
Desiccators charge	Wet	Wet - cannot dry air, no air to tank - no supply of dry air	6	5	30	1	30	Wet alarm or change in dew point value
	Chemical to densely packed	Cannot dry air, reduced air to tank - reduced supply of dry air	5	5	25	3	75	
	Chemical to lightly packed	Cannot dry air enough, - if air too wet, reduced air to tank - reduced supply of dry air	4	4	16	1	16	
Fittings	Leakages - damage	Loss of compression / reduce airflow	4	4	16	1	16	
	Leakages - old ages	Loss of compression / reduce airflow	4	4	16	1	16	
Cylinder	See Desiccator 1	See Desiccator 2			0		0	
Desiccator charge					0		0	
Fittings					0		0	
Top Shuttle valve	Dirty - Stuck - Failed in position to one dessicator	Cannot switch to be in sync with bottom Shuttle valve, will only supply air to tank for 50% of the time	4	3	12	2	24	
	Stuck halfway between to desiccators	Cannot switch to dry desiccator, no air to tank - no supply of dry air	4	2	8	1	8	
	Bleeding hole dirty	Does not dry non working desiccator - dump valve will no airflow	4	6	24	1	24	
Bottom Shuttle valve	Dirty - Stuck - Failed in position to one desiccator	Cannot switch to dry desiccator, Air will become wet and dump valve will dump air - no air to tank - no supply of dry air	4	3	12	1	12	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
	Dirty - Stuck halfway between to desiccators	Cannot switch to dry desiccator, no air to tank - no supply of dry air	4	3	12	1	12	
Dew point Sensor	Dew point sensor failure to below minus 23°C	System will still continue to supply air, but no guarantee that system supplies dry air to Telkom	7	6	42	2	84	Dew point sensor in acceptable range Low -50 High -23
	Dew point sensor failure to above minus 18°C	Dump valve opens, no supply of dry air to tank	6	6	36	1	36	
Dumping valve	Dump valve fail to dump	No dry air to tank	6	4	24	1	24	
	Dump valve fail to close	System still supply air to tank - no guarantee that system supplies dry air to Telkom	6	3	18	1	18	
Non-return valve	Fail to open	No airflow to tank	6	2	12	4	48	
	Fail to close	Lose air in tank when compressor stop through desiccator or when dump valve opens	6	2	12	1	12	
Air receiver / Air tank	Catastrophic failure	No air to Telkom	8	1	8	1	8	
	Pipe leak or fitting leak	Losing air and pressure - compressor will start to provide additional air- can result in compressor damage	5	2	10	1	10	
Compressor start-stop pressure switch	Fail in compressor run position	Compressor will not stop - tank safety valve will open to release pressure - can result in compressor damage	7	4	28	1	28	Line pressure
	Fail in compressor stop position	Compressor will not start - supply to cables will stop	5	4	20	1	20	Change in duty cycle
Draining cock	Fail in open position	This will only occur when physically open by hand - system will drain - supply to cables will stop	2	2	4	1	4	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
	Fail in close position	This valve is only manually opened to drain	1	2	2	1	2	
Air release valve	Fail in open position or leaks	This will only occur when physically opened by hand - system will drain - supply to cables will stop - compressor will start and can result in compressor damage if fault is not detected.	2	2	4	1	4	
	Fail in close position	This valve is only manually opened to drain, no immediate effect, when maintenance must be performed more time will be needed to replace valve	3	2	6	1	6	
	Fail in open position	Losing air and pressure - compressor will start to provide additional air- can result in compressor damage	6	1	6	1	6	
Tank pressure safety valve	Fail in close position	Could be a safety risk when Compressor start-stop pressure switch fail in compressor run position	9	2	18	7	126	
Tank pressure sensor	Providing false reading	No immediate consequence, but remote monitoring will be seriously hampered	2	3	6	3	18	
Pressure gauge	Providing false reading	No immediate consequence, but remote monitoring will be seriously hampered	2	3	6	3	18	
Motorise pressure regulator	Fail in high pressure mode	Could result into damage to cable or cable housing joints	7	4	28	1	28	
	Failure in to low pressure mode	Could result into damage to cable resulting from moisture ingress into system	5	4	20	1	20	
Flow meter	Providing false reading	No immediate consequence, but monitoring of cable leaks will be seriously hampered	3	4	12	2	24	
Line pressure sensor	Providing false reading	No immediate consequence, but monitoring of cable leaks will be seriously hampered	3	3	9	2	18	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when It Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
Line pressure safety valve	Fail in open position	Losing air and pressure - compressor will start to provide additional air- can result in compressor damage	5	3	15	1	15	
	Fail in close position	Could be a safety risk when Compressor start-stop pressure switch fail in compressor run position	7	3	21	7	147	
Test valve					0		0	
Manifold	Pipe leak or fitting leak	Losing air and pressure - compressor will start to provide additional air - can result in compressor damage, low air pressure to cables	5	3	15	1	15	
Air outlet valve	Pipe leak or fitting leak	Losing air and pressure - compressor will start to provide additional air- can result in compressor damage, low air pressure to cables	5	4	20	1	20	
Dry air outlet valve					0		0	
Telephone cable connection	Modem or telephone line failure	No remote monitoring via old Polar Air system	1	5	5	1	5	
Connectors for alarm from flow panel	Connection line failure	No remote monitoring via old Polar Air system	1	5	5	2	10	
Power cable connections	No power	No air to Telkom	6	5	30	1	30	
Distribution manifold	Pipe leak or fitting leak	Losing air and pressure - compressor will start to provide additional air- can result in compressor damage, low air pressure to cables	5	3	15	1	15	
Dry air outlet					0		0	
Main circuit breaker	No power	No air to Telkom, can go on manual	6	4	24	1	24	
System check button					0		0	

Parts Hardware Failure	Failure Mode (Cause of Failure)	Failure Effect (What Happens when it Fails)	Severity	Occurrence	Monitor Importance	Detection	RPN	Alarm Comments
Terminal block					0		0	
Analogue Interface PCB	Losing controls logics	No air to Telkom, can go on manual	6	4	24	1	24	
Micro - processor PCB	Losing controls logics	No air to Telkom, can go on manual	6	4	24	1	24	
Dew point sensor PCB	Losing controls logics	No air to Telkom, can go on manual	6	4	24	1	24	

ANNEXURE B. CDH SIMULATION AND ENERGY USAGE CALCULATIONS

B.1 Simulation of CDH

A Simple spreadsheet model was developed to simulate different failure scenarios and how the RCMS can help to predict or warn against these failure conditions. The model describe the relations between, air volume delivered by the compressor, the position of the change over valve, the pressure in the air receiver tank, the dew point reading and the dump valve status.

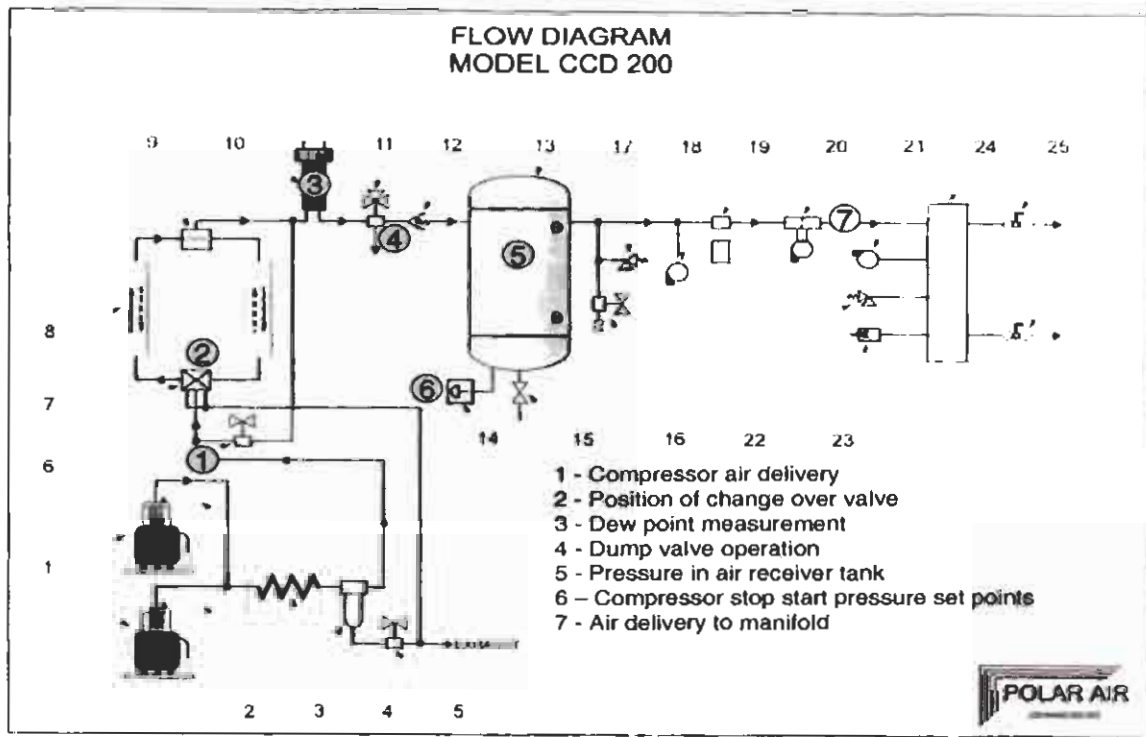


Figure B1: CDH subsystems

The module assume the compressor deliver air to the desiccators at the same pressure as the pressure in the air receiver tank, the pressure drop due to the resistance in the desiccator, valves and pipes was ignored. The tank pressure rise at a constant rate (the compressibility of the air was assumed to be constant between 250kPa and 600kPa).

When the dew point reading exceeded the allowable value, -18 deg C, the dump valve opened and the air from the compressor was dumped before it reached the air receiver tank. The air flow from the air receiver tank to the cable housing was considered to be constant.

The simple relationship between the compressor stop-start status, the change over valve position (indicating through which desiccator the air flow) and the pressure in the tank can be depicted in Figure B2.

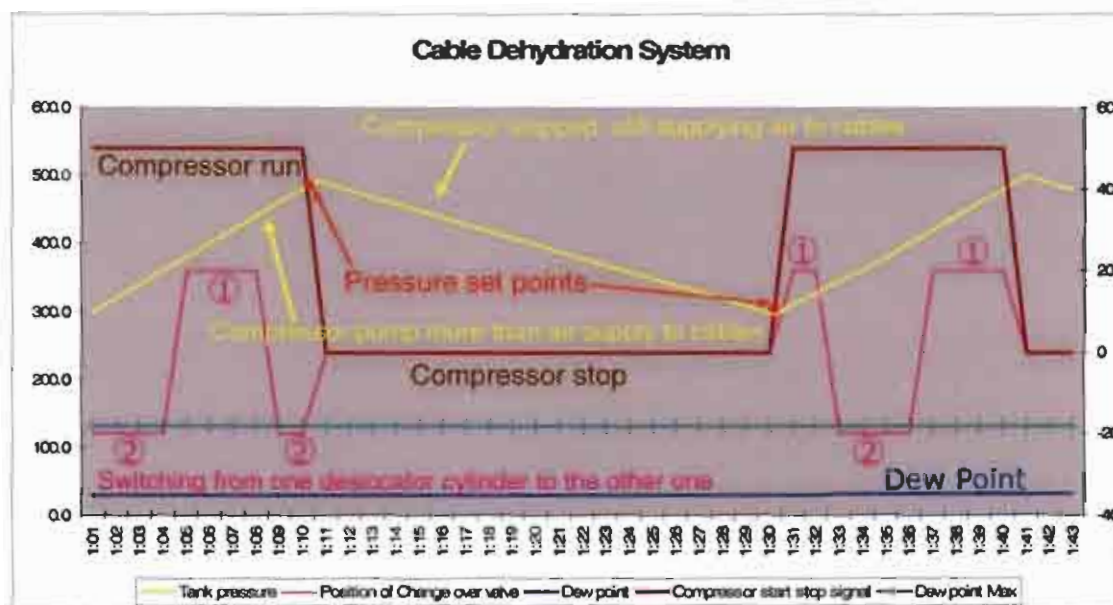


Figure B2: Cable Dehydrator Real-time Process

When an “-18 deg C” dew point reading was provided, as an input, simulating that one of the desiccator cylinder’s chemical was saturated, the relationships between the reading from the dew point sensor, the compressor run or stop status, the change over valve position and the pressure profile in the tank can be depicted in Figure B3

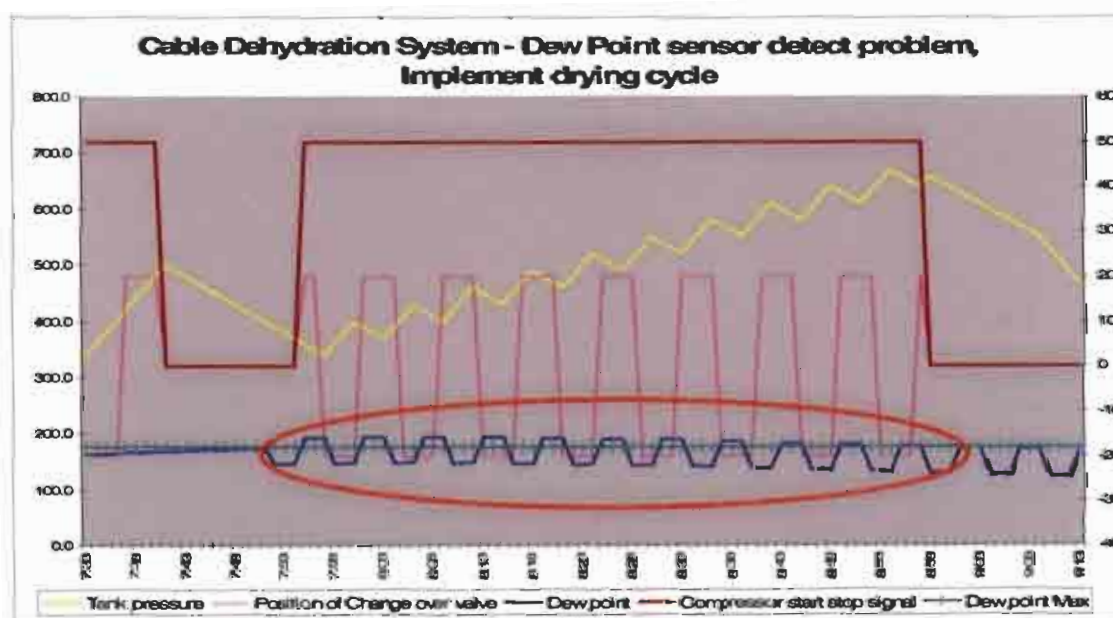


Figure B3: Single Desiccator Fault Condition

The same model can be used to depict various fault conditions. The results from this model could be compared to actual readings from the RCMS after it was implemented, refer to Figure B4

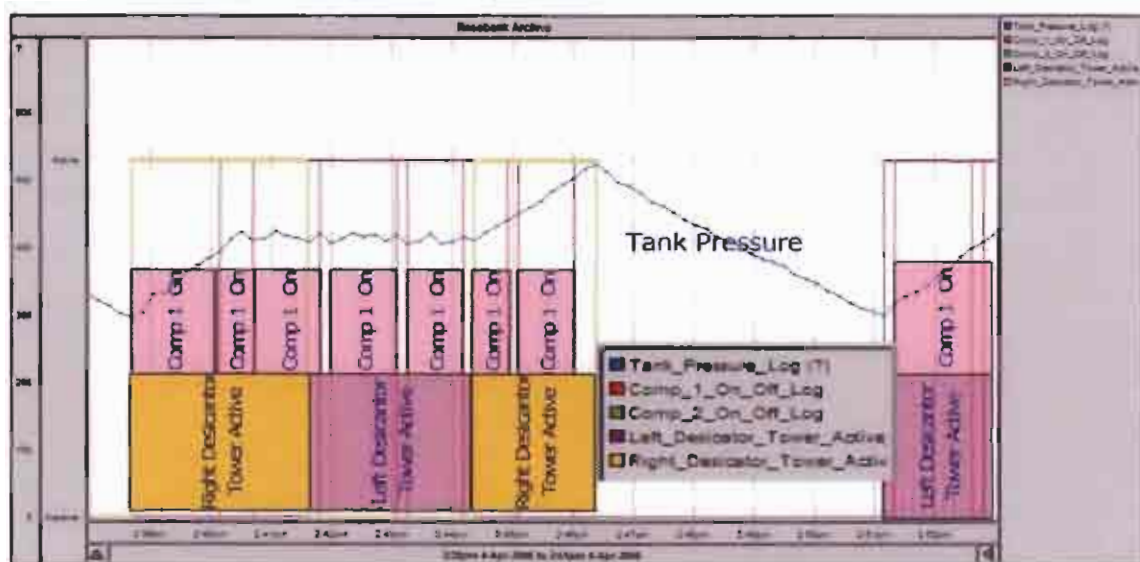


Figure B4: Rosebank CDH Tank Pressure Profiles

B.2 CDH Energy usage calculations

When the CDH performance was analysed it was found that although the compressor was running and pumping air, for 50% of the pumping cycle the tank pressure was not rising.

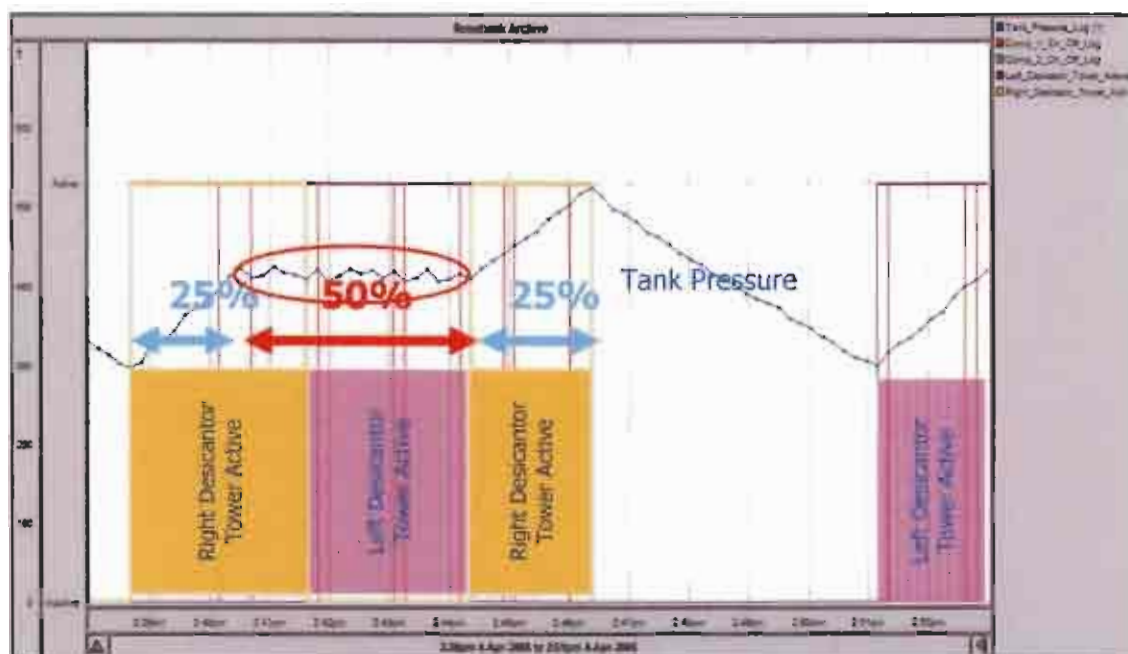


Figure B5: Rosebank CDH Effectiveness Analysis

During this period air was dumped through the dump valve to allow the first (right) dessicator tower to complete a full drying cycle and allow the system to start on the next pump cycle with the left dessicator tower.

To investigate the effect, which the dumping of air, during the compressor cycle have on the energy efficiency of the Cable Dehydration system, a simplified energy usage simulation was performed.

The pressure profile was used to calculate the energy usage for a complete compressor cycle. To simplify the calculations an ideal scenario was used ignoring the effect of friction, heat loss, electric motor efficiency, etc)

The following formulas were used:

$$E=PQ$$

where

P = pressure (kPa)

Q = displacement of compressor (liter/h)

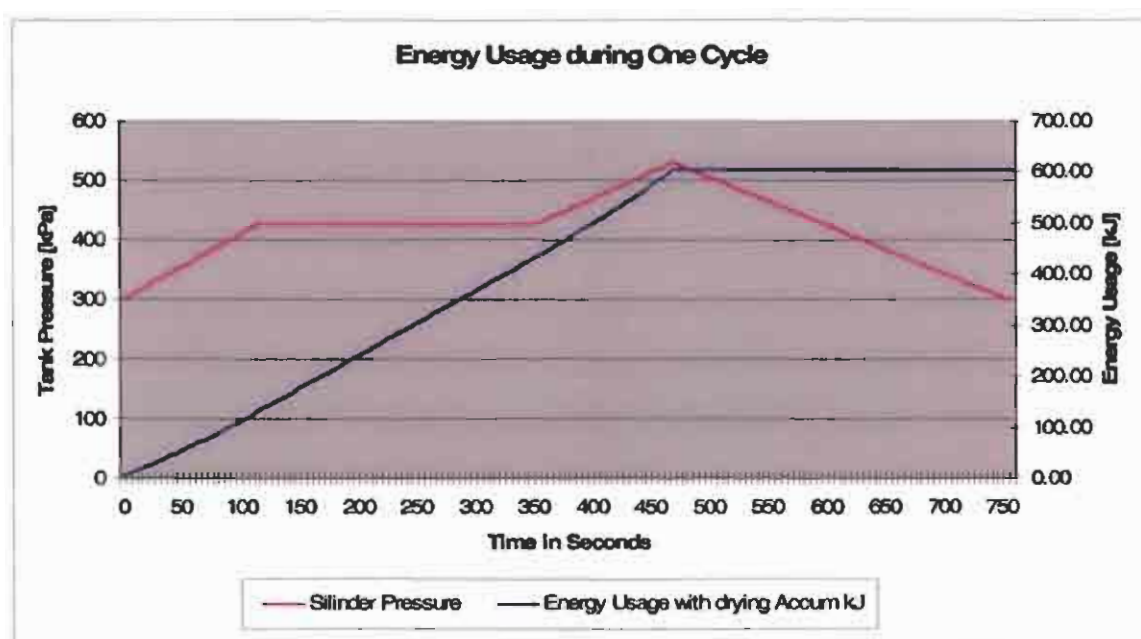


Figure B6: Energy Usage per Pump Cycle

In the new simulation, the energy usage for a system with a modified pressure profile (without drying cycle) has been calculated.

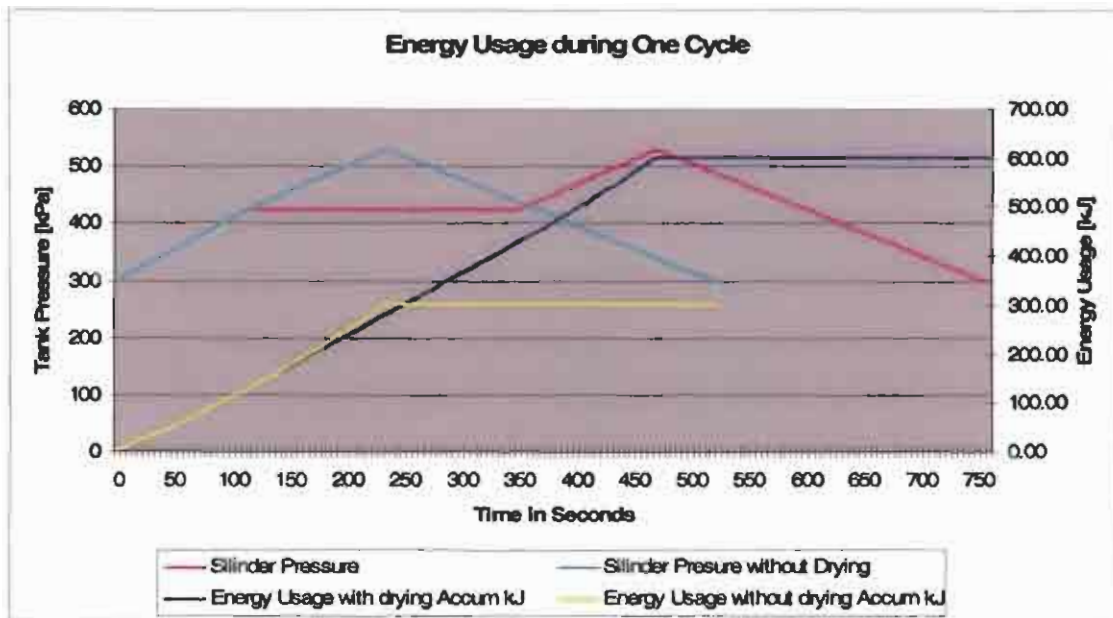


Figure B7: Energy Usage Comparison

The result of the current philosophy was that 50% of the energy used by the CDH was used for drying, while in theory, the system only needed 10% of the energy to dry itself.

The system's effectiveness and reliability could be further improved if the desiccators could be dried during the non-pumping cycle, allowing longer drying time for the desiccator. For this, the system must be modified to allow air from the pressure tank, to flow back to the desiccator during the full non-air drying cycle. Through this, the "Top shuttle valve" bleeding hole problems could be completely eliminated. Refer to Figure B8.

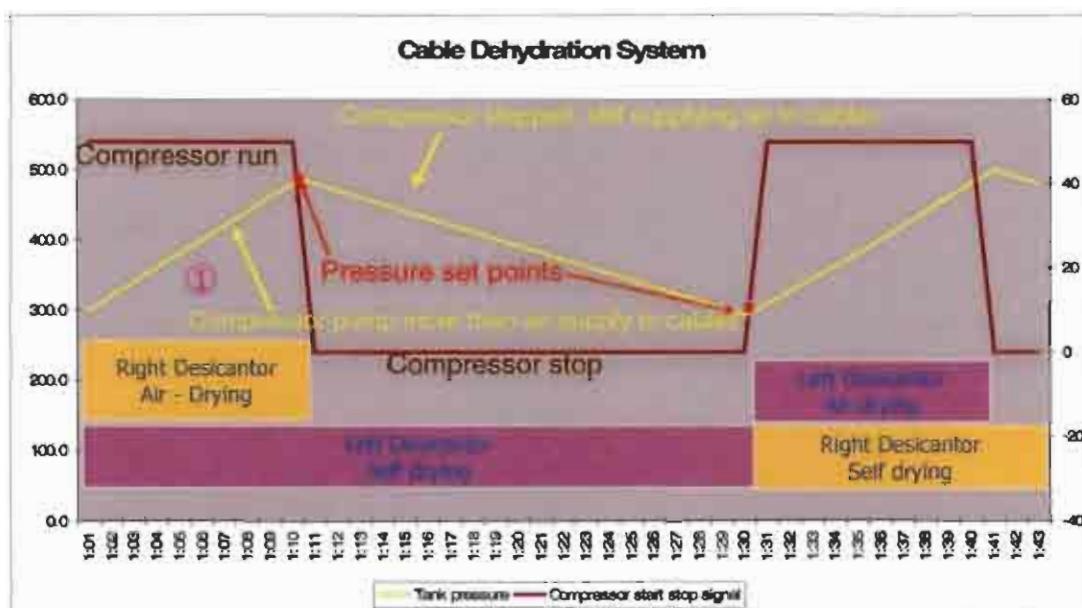


Figure B8: Improved Self-drying Cycle

Resulting from the information and the failure data gathered in analysis of the last year's repair cost data, the suggestion was made to the manufacturer to change its CDH design to overcome this inefficiency, without reducing the system's performance.

ANNEXURE C. CURRENT COST DRIVERS

C.1 Maintenance Type and Task Analysis

Maintenance Type and Maintenance Cost Driver Analysis

Through analysis of the CMMS data the importance of maintenance types within the current maintenance concept is obtained:

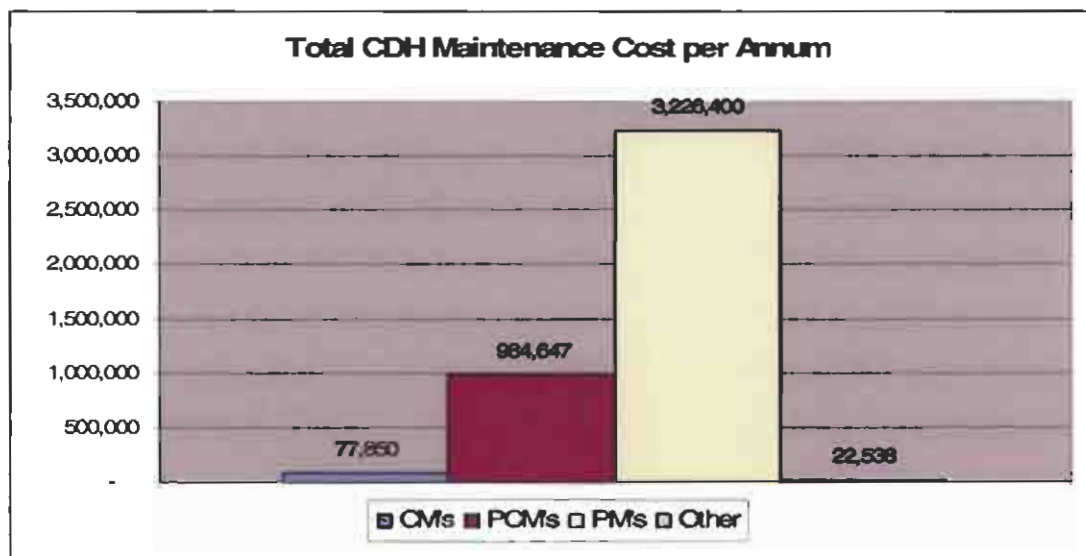


Figure C9: CDH Maintenance Cost per Annum per type of maintenance

This means that, 75% of all cost on CDH maintenance was for Planned Maintenance (PMs), while 22% was used for Planned Corrective Maintenance (PCMs) and only 3% was used for Emergency Maintenance (EMs).

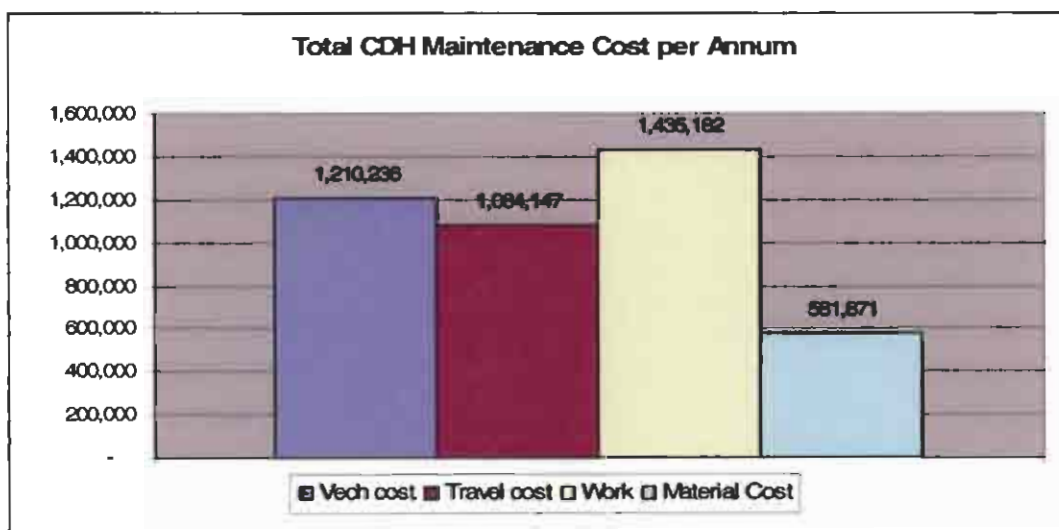


Figure C10: CDH Maintenance Cost Component Breakdown

When analysing the cost within these maintenance tasks it was found that 53% of all maintenance cost was travel-related (vehicle and manpower in vehicle) and 33% was for performing actual work (labour), while 14% was material cost. Refer to Figure C10.

Planned Maintenance Task Analysis

From the Planned Maintenance task analysis the following cost breakdown was revealed, as 62.5% of costs being travel-related cost (vehicle and travel) and only 37% cost was for the actual performance of physical PM work (labour) while 0.5% was for material cost, refer to Figure C11.

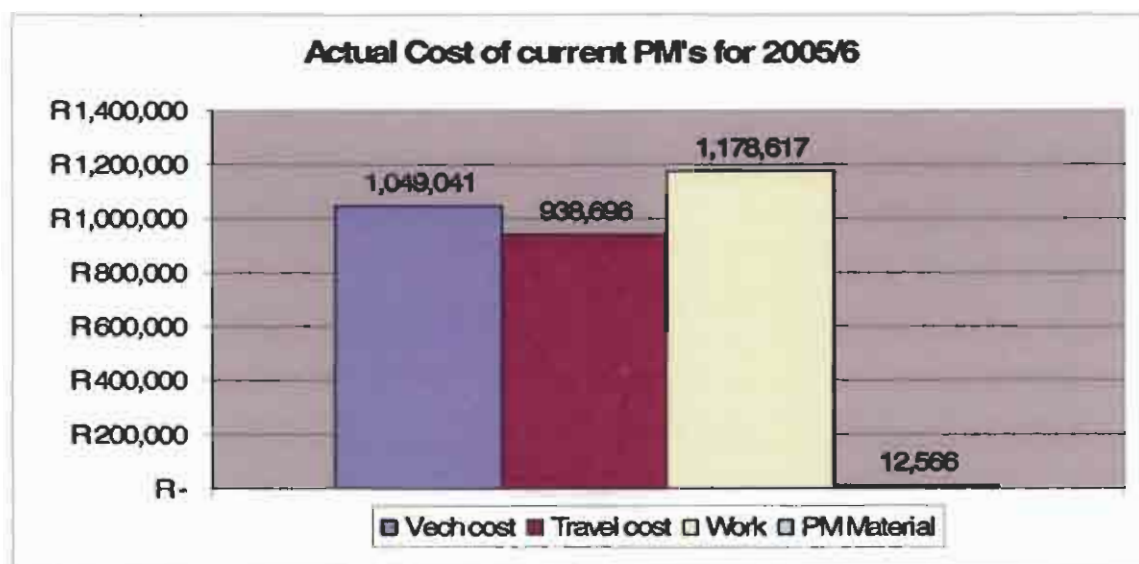


Figure C11: Actual PM Cost Breakdown

Non-PM Related Cost Analysis

The following non-planned maintenance tasks were recorded within CMMS: corrective or emergency maintenance (EM), PCM, vehicle stock (spares in vehicles used during EMs and PCMs), events, quality assurance, rework and observation.

Vehicle stock (V-STK) was used during both EMs and PCMs. All non-PM tasks can thus be summarised in CMs (8%) and PCM (91%) cost.

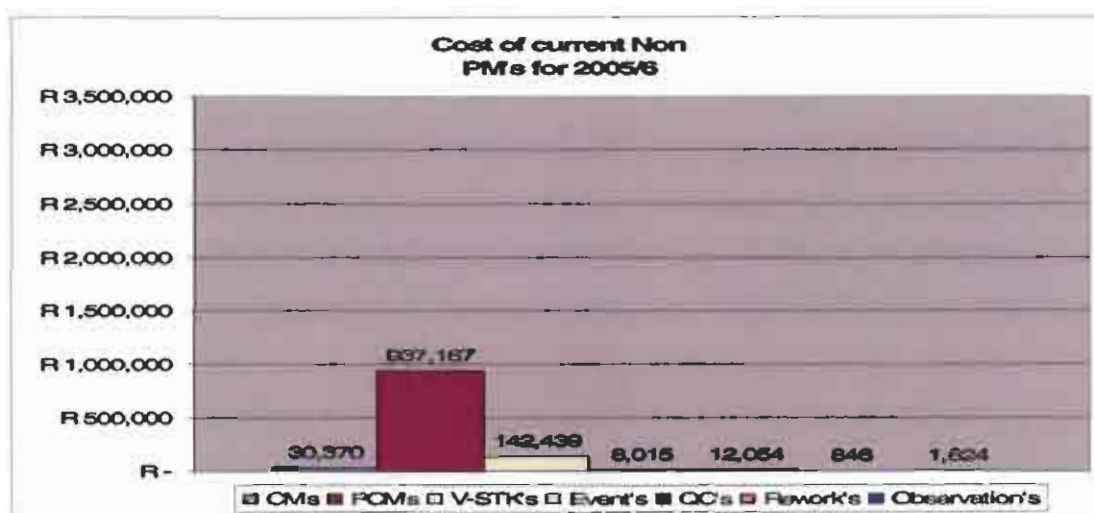


Figure C12: Actual CM and PCM Costs

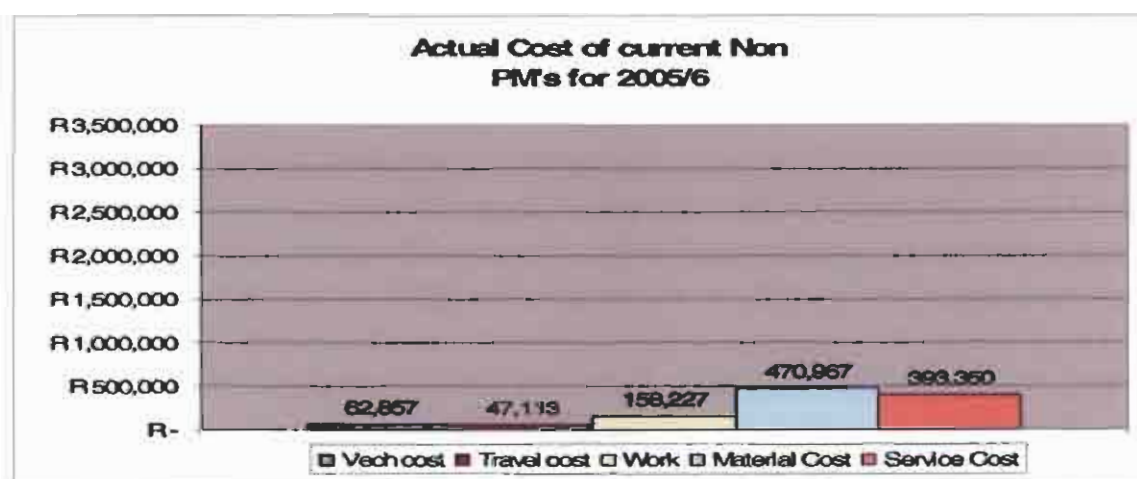


Figure C13: Actual Non-PM Cost Breakdown

From Figure C13 for Non-PM activities, it could be seen that the % of travelling related cost in relation with the total cost for non-PM cost is almost half (27%) of the % Travel related cost for PM's (62.5%).

The results from the above analysis can be summarised as follows:

Cost breakdown	Preventative Maintenance (PM activities 75%)	Corrective Maintenance (Non-PM activities 22%+3%)	Total
Travelling cost	62.5%	27%	53%
Material cost	0.5%	50%	14%
Work (labour) cost	37%	23%	33%

Table C1: Summary of Maintenance Task Cost Analysis

C.2 Material and Components Used, Analysis

The following results were obtained through analysing the material or components, used during the maintenance process.

Figure C14 indicates that the desiccant agent and the compressor contributed towards 40% of the total material cost used. According to the manufacturer, if proper maintenance was performed, these two components should last much longer, in fact it should normally last at least 10 years.

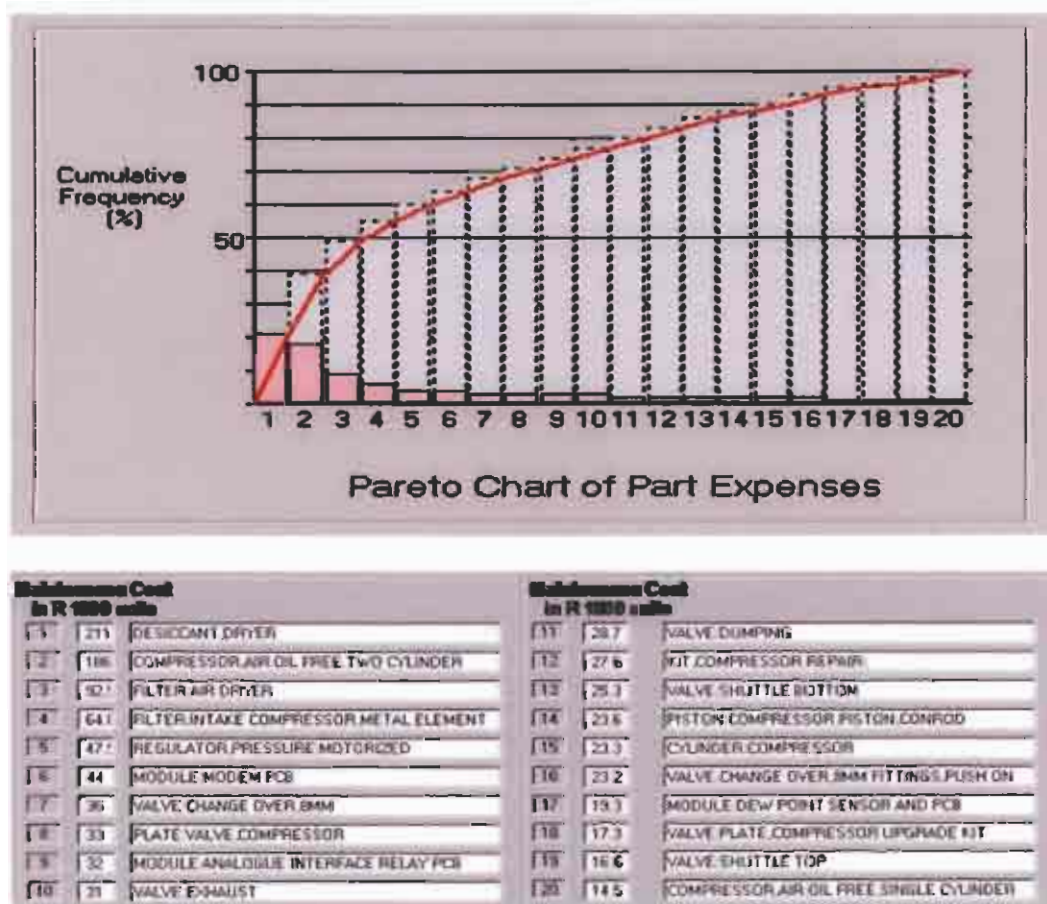


Figure C14: Pareto Chart of CDH Parts Being Used During Maintenance

The desiccant chemical needs to be replaced when the desiccant becomes total saturated (wet). This only occurs when the "top shuttle valve" bleeding hole is blocked or partially blocked. The CDH kept on running while the desiccant did not dry itself. Long before the desiccant chemical was totally wet, the dew point sensor should detect that the air was not dry enough and the dump valve should have opened. This failure leads to the next failure where the compressor was running continuously, as the compressor "stop/start switch" never reached the maximum pressure set point. This scenario continues and it is not noticed, as the CDH is only visited for maintenance once every 1 000 hours.

The main reason for Compressor replacement is due to high duty cycles or dirty air through the air intake filters (refer to detail FMECA or RCA). Higher wear occurs resulting in unnecessary reduction in compressor, Remaining Useful Life (RUL).

These failures can only be prevented with regular inspections (e.g. once a week) or through RCMS. When a minor fault occurs and these problem are not detected the system will keep on running. If these minor failures are not corrected in time, they will escalate until the specific equipment or other components are damaged to the extent that they have to be replaced. The normal control system of the CDH only protects the equipment when a major failure occurs.

C.3 Maintenance Concept Cost Analysis

Through analysing the current maintenance database as captured within Maximo (CMMS) the following results were obtained:

Actual Maintenance Cost						
Job Plan	Service type	PM every X Running hours	PM ever X Month	Actual cost	Actual cost per Annum	Cost for CBM per annum for all CDH
CJPCAB001	Composite PM	undefined	1.0	439.11	439.11	415,840.58
CJPCAB001	Composite PM	undefined	2.0	439.11	878.23	831,681.15
CJPCAB001	Composite PM	undefined	2.8	439.11	1,317.34	1,247,521.73
CJPCAB001	Composite PM	undefined	4.0	439.11	1,756.45	1,663,362.31
CJPCAB001	Composite PM	undefined	5.0	439.11	2,195.57	2,079,202.88
CJPCAB001	Composite PM	undefined	5.6	439.11	2,634.68	2,495,043.46
CJPCAB001	Composite PM	undefined	7.0	439.11	3,073.80	2,910,884.03
CJPCAB001	Composite PM	undefined	8.3	439.11	3,512.91	3,326,724.61
CJPCAB001	Composite PM	undefined	10.0	439.11	3,952.02	3,742,565.19
CJPCAB001	Composite PM	undefined	11.1	439.11	4,391.14	4,158,405.76
CJPCAB001	Composite PM	undefined	12.0	439.11	4,830.25	4,574,246.34
CJPCAB001	Composite PM	undefined	13.9	439.11	5,269.36	4,990,086.92
Actual PM cost per annum						R 4,311,435

Table C2: Actual Maintenance Cost

The theoretical Planned Maintenance Cost was determined from the detailed Job cards for each type of maintenance.

Planned Maintenance Cost						
Job Plan	Service type	PM every X Running hours	PM ever X Month	Cost for PM	Cost for PM per Annum	Total Cost per annum for all CDH
JPCAB001	Inspection	every month	1.0	273.06	273.06	258,585.02
JPCAB001	Inspection	every month	2.0	273.06	546.11	517,170.04
JPCAB002	Minor service	1000	2.8	743.95	1,290.07	1,221,694.86
JPCAB001	Inspection	every month	4.0	273.06	1,563.13	1,480,279.88
JPCAB001	Inspection	every month	5.0	273.06	1,836.18	1,738,864.90
JPCAB002	Minor service	2000	5.6	743.95	2,580.14	2,443,389.73
JPCAB001	Inspection	every month	7.0	273.06	2,853.19	2,701,974.75
JPCAB003	Major service	3000	8.3	914.45	3,767.65	3,567,963.07
JPCAB001	Inspection	every month	10.0	273.06	4,040.71	3,826,548.09
JPCAB002	Minor service	4000	11.1	743.95	4,784.66	4,531,072.92
JPCAB001	Inspection	every month	12.0	273.06	5,057.72	4,789,657.94
JPCAB003	Major service	5000	13.9	914.45	5,972.17	5,655,646.27
Planned Total PM cost per annum					5,159.96	R 4,886,478

Table C3: Theoretical Planned Maintenance Cost

A cost comparison between the Actual and the theoretical Planned Maintenance (PM) cost provides the following results:

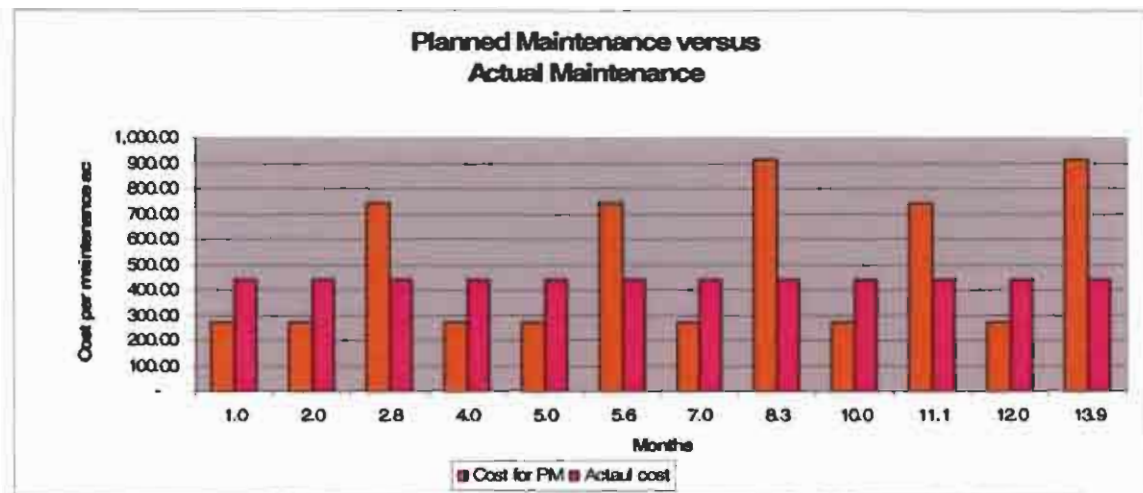


Figure C15: Theoretical Planned Maintenance versus Actual Maintenance

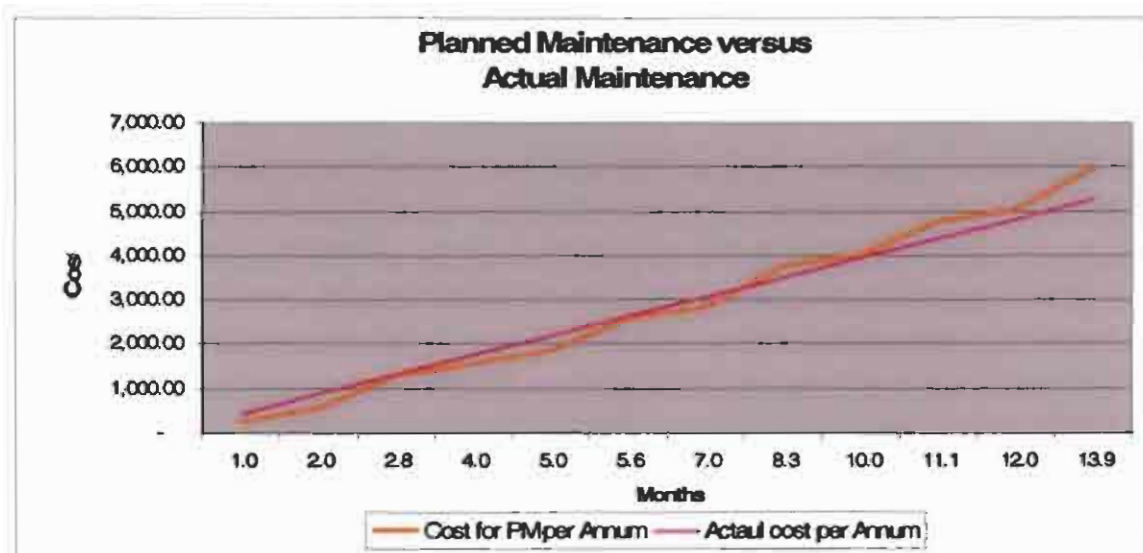


Figure C16: Actual versus Theoretical Accumulative Maintenance cost comparison

The poor availability performance of the Cable Dehydration system can be directly linked to the poor maintenance practice.

When the new Condition Base Facility Management concept is applied to the CDH, all inspection PM tasks (JPCAB001) can be performed via the RCMS. Minor and major services can be scheduled as and when really required, when the CDH conditions have deteriorated to the extent that such a service is required. This will translate into the following costs:

Condition Based Maintenance cost					
Job Plan	Service type	PM ever X Month	Cost for CBM	Cost for CBM per Annum	Cost for CBM per annum for all CDH
JPCAB001	Remote surveillance	1.0	105	105	99,435
JPCAB001	Remote surveillance	2.0	105	210	198,870
JPCAB002	Remote surveillance	2.8	105	315	298,305
JPCAB001	Remote surveillance	4.0	105	420	397,740
JPCAB002	Minor service	5.0	663	1,083	1,025,569
JPCAB002	Remote surveillance	5.6	105	1,188	1,125,004
JPCAB001	Remote surveillance	7.0	105	1,293	1,224,439
JPCAB003	Minor/Major service	8.3	791	2,084	1,973,365
JPCAB001	Remote surveillance	10.0	105	2,189	2,072,800
JPCAB002	Minor service	11.1	663	2,852	2,700,628
JPCAB001	Remote surveillance	12.0	105	2,957	2,800,063
JPCAB003	Major service	13.9	882	3,839	3,635,589
Planned Total PM cost per annum			3,317	3,317	R 3,141,149

Table C4: CBM cost prediction

Figure C17 visually portrays the typical maintenance task intervals with associated costs for the Scheduled (Planned) maintenance and the Condition Based Maintenance.

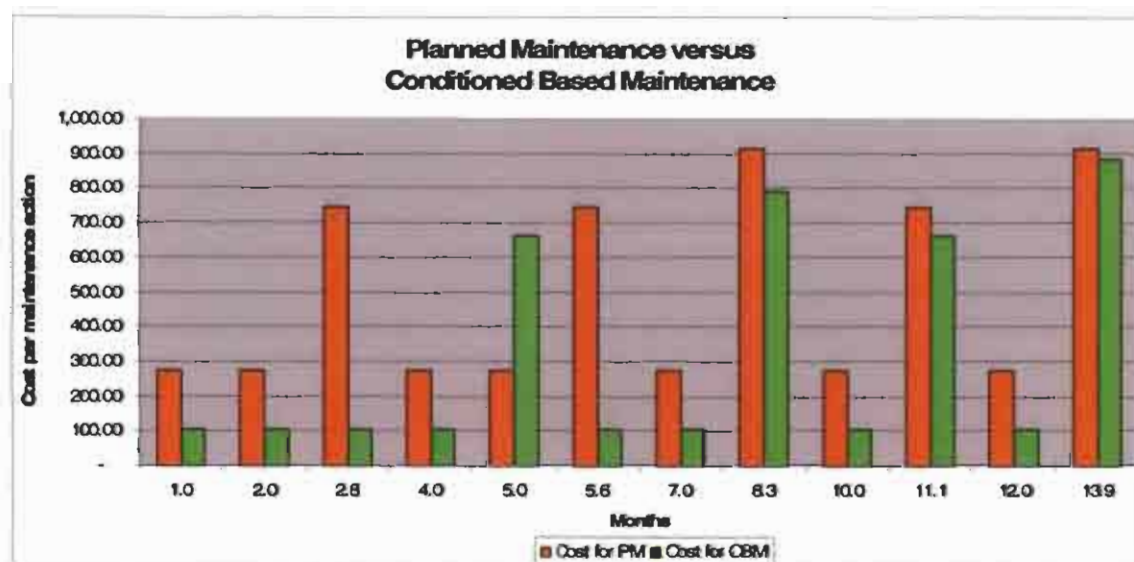


Figure C17: Scheduled Maintenance versus Condition Based Maintenance

Figure C18 visually portrays the same graph for Figure C17, together with the current actual maintenance cost as per Figure C15.

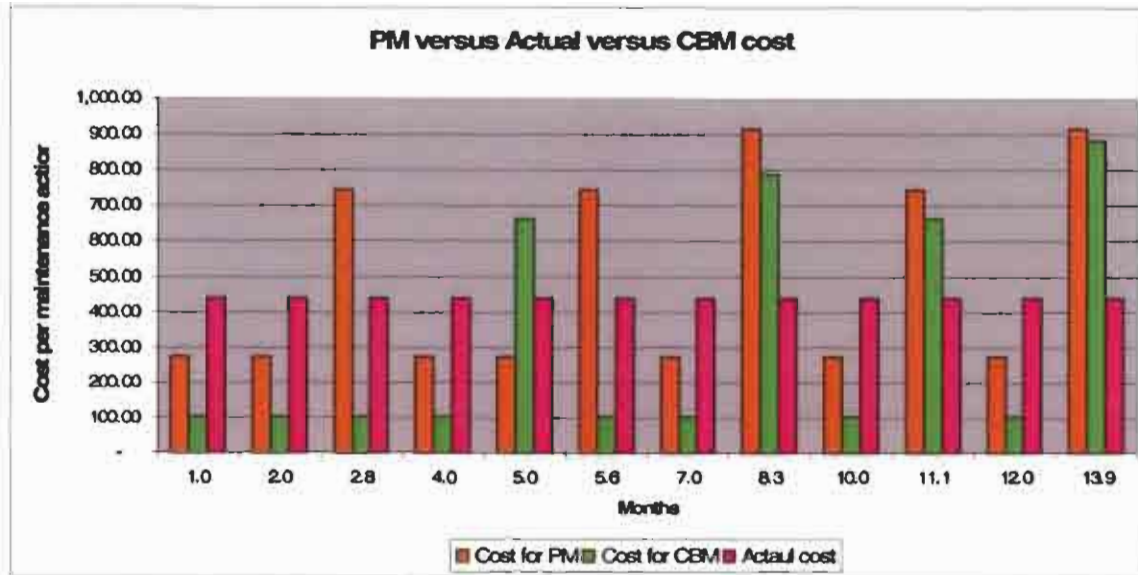


Figure C18: Comparison between PM, CBM and AM

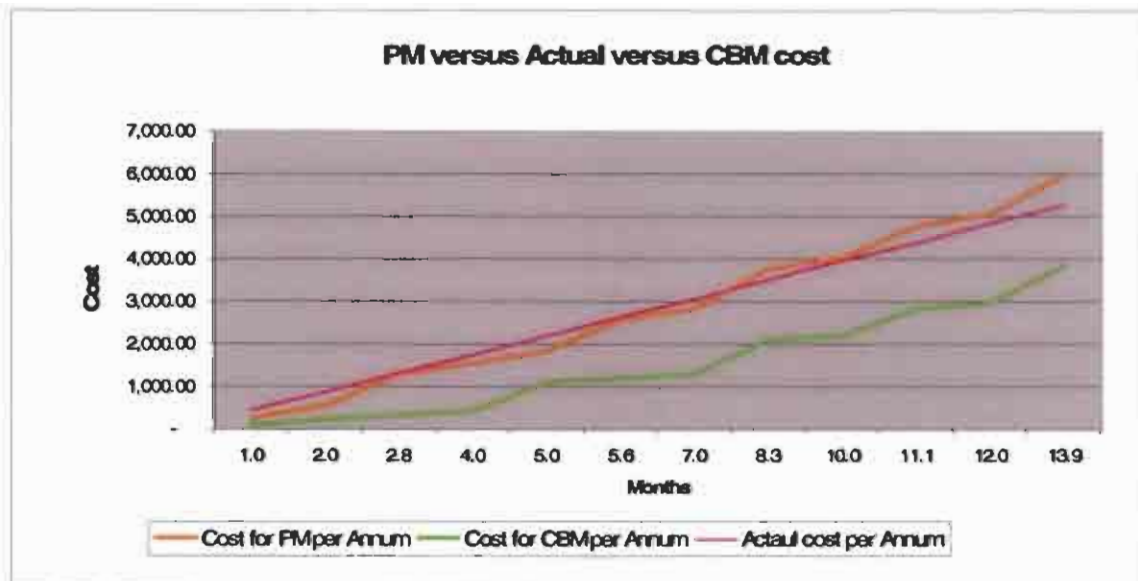


Figure C19: Annual comparison between PM, CBM and AM

By implementing CBFM the cost of travelling for Planned Maintenance could be significantly reduced, with some conservative savings on replacement of spares. Table C1 and Figure C18 represent a prediction of cost saving which is envisaged.

Inspection maintenance task (JPCAB0001) could be performed (via RCMS), at a fraction of the cost, by the functional specialist, from his office.

Saving to the minor services (JPCAB0002) and major services (JPCAB0003) could also be reduced as they would only be performed when CDH performance requires it.

ANNEXURE D. AVAILABILITY, MTBA AND MTTR CALCULATIONS

The RCMS was activated at the end of June 2005 and for the entire July 2005, the RCMS was used to collect alarms and condition data for the pre implementation of CBFM, refer to Table D5. No maintenance actions were activated during this month and the data was used as a reference to calculate the effectiveness or improvement obtained with the RCMS.

From August 2005 the CBFM was activated and used to initiate corrective and preventative maintenance actions, refer to Table D6.

In Table D7 the Time between Alarms (TBA) were calculated and in Table D8 the number of Alarms received during each month were calculated, from where the MTBA and MTTR were calculated.

Only the "Demand cable pressure Min" and "Dew point Max" alarms were classified as functional failures while the other alarms were classified as condition alarms. In Table D9 the % Availability and Number of days during which the system had Functional Failures, were calculated.

BEFORE REMOTE CONDITION MONITORING IMPLEMENTED					
Site	Alarm	Alarm Received	Time to Acknowledge	Fault Repaired	Time To Repair
New Doornfontein CCD 700	Major service	7/1/05 1:57	0:02:00	7/4/05 4:21	3.1
Braamfontein DSA 161	Compressor 1 running hours	7/1/05 6:00	0:02:48	7/5/05 3:36	3.9
Benmore Gardens CCD 840	Compressor 2	7/1/05 7:21	0:01:12	7/8/05 2:33	6.8
Benmore Gardens CCD 840	Compressor 1 temperatures	7/1/05 8:16	0:01:12	7/7/05 1:04	5.7
Rosebank CCD 700	Demand cable pressure Max	7/1/05 14:02	0:00:24	7/2/05 4:26	0.6
Jeppe st. CCD 700	Demand Air Flow Max	7/1/05 15:33	0:01:36	7/8/05 10:45	6.8
Benmore Gardens CCD 700	Major service	7/2/05 3:40	0:00:48	7/7/05 8:28	5.2
Rosebank CCD 700	Demand cable pressure Min	7/6/05 1:09	0:00:24	7/7/05 17:57	1.7
Jeppe st. CCD 700	Energy consumption (Compressor)	7/6/05 1:45	0:01:36	7/9/05 1:45	3.0
Braamfontein CCD 700	Dew point Max	7/6/05 3:12	0:02:24	7/6/05 12:48	0.4
Braamfontein DSA 161	Major service	7/6/05 6:14	0:02:48	7/12/05 11:02	6.2
New Doornfontein CCD 700	Dew point Min	7/6/05 7:57	0:02:00	7/11/05 10:21	5.1
Benmore Gardens CCD 840	Tank pressure Min	7/6/05 10:38	0:01:12	7/12/05 17:50	6.3
Benmore Gardens CCD 840	Dew point Max	7/6/05 11:45	0:01:12	7/8/05 9:21	1.9
Jeppe st. CCD 700	Compressor 1 running hours	7/6/05 15:07	0:01:36	7/13/05 10:19	6.8
New Doornfontein CCD 700	Change over valve position	7/6/05 19:02	0:02:00	7/12/05 11:50	5.7
New Doornfontein CCD 700	Compressor 1 temperatures	7/7/05 0:19	0:02:00	7/12/05 5:07	5.2
Germistion CCD 700	Dew point Min	7/27/05 0:48	0:03:12	7/28/05 5:36	1.2
New Doornfontein CCD 700	Compressor 1 running hours	7/27/05 5:16	0:02:00	7/31/05 0:28	3.8
Braamfontein CCD 700	Dew point Min	7/29/05 6:43	0:02:24	7/31/05 4:19	1.9
Braamfontein DSA 161	Compressor 2 temperatures	7/29/05 11:24	0:02:48	8/1/05 13:48	3.1
Benmore Gardens CCD 840	Dew point Min	7/29/05 16:43	0:01:12	8/2/05 23:55	4.3
Braamfontein CCD 700	Demand Air Flow Max	7/30/05 4:12	0:02:24	8/1/05 11:24	2.3
Benmore Gardens CCD 840	Demand Air Flow Min	7/30/05 15:33	0:01:12	8/5/05 13:09	5.9
New Doornfontein CCD 700	Dew point Min	7/30/05 19:16	0:02:00	8/2/05 9:40	2.6
Benmore Gardens CCD 700	Minor service	7/31/05 2:36	0:00:48	7/31/05 12:12	0.4
Braamfontein CCD 700	Energy consumption (Compressor)	7/31/05 14:33	0:02:24	8/5/05 21:45	5.3
Jeppe st. CCD 700	Pump Off Cycle 10% Change	7/31/05 23:07	0:01:36	8/3/05 20:43	2.9
Rosebank CCD 700	Demand Air Flow Max	7/31/05 23:33	0:00:24	8/4/05 6:45	3.3

Table D5: Alarms from RCMS before CBM activation

REMOTE CONDITION MONITORING IMPLEMENTED					
Site	Alarm	Alarm Received	Time to Acknowledge	Fault Repaired	Time To Repair
New Doornfontein CCD 700	Dew point Max	8/1/05 5:16	0:02:00	8/1/05 12:28	0.3
Benmore Gardens CCD 840	Demand cable pressure Min	8/1/05 6:12	0:01:12	8/2/05 3:48	0.9
Braamfontein DSA 161	Dew point Max	8/1/05 17:24	0:02:48	8/2/05 0:36	0.3
Braamfontein DSA 161	Compressor 2	8/1/05 21:14	0:02:48	8/2/05 4:26	0.3
Jeppe st. CCD 700	Demand Air Flow Max	8/2/05 1:19	0:01:36	8/2/05 15:43	0.6
Braamfontein DSA 161	Tank pressure Min	8/2/05 9:31	0:02:48	8/3/05 2:19	0.7
Jeppe st. CCD 700	Demand cable pressure Max	8/2/05 11:14	0:01:36	8/3/05 1:38	0.6
Jeppe st. CCD 700	Change over valve position	8/2/05 21:52	0:01:36	8/3/05 17:04	0.8
Benmore Gardens CCD 700	Minor service	8/3/05 8:50	0:00:48	8/3/05 16:02	0.3
Benmore Gardens CCD 700	Compressor 1	8/3/05 13:55	0:00:48	8/4/05 4:19	0.6
Braamfontein CCD 700	Compressor 1	8/3/05 17:55	0:02:24	8/4/05 8:19	0.6
Braamfontein CCD 700	Pump Off Cycle 10% Change	8/4/05 3:43	0:02:24	8/4/05 22:55	0.8
New Doornfontein CCD 700	Change over valve position	8/4/05 13:33	0:02:00	8/5/05 11:09	0.9
Benmore Gardens CCD 840	Dew point Max	8/4/05 20:12	0:01:12	8/5/05 8:12	0.5
Jeppe st. CCD 700	Pump Off Cycle 10% Change	8/5/05 7:04	0:01:36	8/6/05 7:04	1.0
Jeppe st. CCD 700	Dew point Min	8/5/05 16:04	0:01:36	8/6/05 1:40	0.4
Jeppe st. CCD 700	Minor service	8/5/05 18:48	0:01:36	8/6/05 16:24	0.9
Braamfontein DSA 161	Demand Air Flow Min	8/5/05 20:24	0:02:48	8/6/05 8:24	0.5
Jeppe st. CCD 700	Compressor 1 temperatures	8/5/05 22:00	0:01:36	8/6/05 17:12	0.8
Rosebank CCD 700	Change over valve position	8/5/05 22:40	0:00:24	8/6/05 20:16	0.9
Jeppe st. CCD 700	Compressor 1 running hours	8/6/05 7:04	0:01:36	8/7/05 4:40	0.9
Benmore Gardens CCD 840	Tank pressure Max	8/6/05 16:38	0:01:12	8/7/05 11:50	0.8
Germistion CCD 700	Tank pressure Max	8/7/05 0:50	0:03:12	8/7/05 5:38	0.2
Braamfontein DSA 161	Tank pressure Min	8/7/05 7:55	0:02:48	8/7/05 19:55	0.5
Braamfontein DSA 161	Dew point Min	8/7/05 8:31	0:02:48	8/7/05 18:07	0.4
Braamfontein CCD 700	Compressor 2 temperatures	8/7/05 16:12	0:02:24	8/8/05 9:00	0.7
Benmore Gardens CCD 840	Change over valve position	8/7/05 23:24	0:01:12	8/8/05 9:00	0.4
Rosebank CCD 700	Tank pressure Min	8/8/05 7:24	0:00:24	8/8/05 21:48	0.6
Benmore Gardens CCD 840	Demand Air Flow Min	8/8/05 8:28	0:01:12	8/8/05 15:40	0.3
Braamfontein DSA 161	Compressor 1 temperatures	8/8/05 15:52	0:02:48	8/8/05 23:04	0.3
Braamfontein CCD 700	Minor service	8/8/05 23:50	0:02:24	8/9/05 14:14	0.6

Table D6: Alarms from RCMS after CBM activation

Time Between Alarm and Time To Repair											
New Doornfontein CCD 700			Germiston CCD 700			Braamfontein DSA 161			Germiston CCD 700		
5	TBA	TTR	8	TBA	TTR	7	TBA	TTR	8	TBA	TTR
7/1/05 0:00			7/1/05 0:00			7/1/05 0:00			7/1/05 0:00		
7/1/05 1:57	0.1	3.1	7/3/05 23:38	3.0	5.2	7/1/05 6:00	0.3	3.9	7/3/05 23:38	3.0	5.2
7/4/05 19:36	3.7	1.0	7/8/05 22:28	5.0	0.4	7/4/05 10:12	3.2	0.4	7/8/05 22:28	5.0	0.4
7/5/05 2:19	0.3	2.8	7/10/05 14:14	1.7	5.4	7/5/05 10:36	1.0	5.1	7/10/05 14:14	1.7	5.4
7/5/05 22:12	0.8	1.3	7/12/05 2:24	1.5	4.1	7/6/05 6:14	0.8	6.2	7/12/05 2:24	1.5	4.1
7/6/05 7:57	0.4	5.1	7/13/05 13:07	1.4	3.1	7/7/05 21:48	1.6	1.4	7/13/05 13:07	1.4	3.1
7/6/05 19:02	0.5	5.7	7/16/05 15:38	3.1	1.8	7/8/05 4:09	0.3	5.9	7/16/05 15:38	3.1	1.8
7/7/05 0:19	0.2	5.2	7/17/05 19:33	1.2	2.0	7/8/05 10:09	0.3	4.2	7/17/05 19:33	1.2	2.0
7/7/05 2:57	0.1	0.9	7/17/05 23:19	0.2	3.1	7/9/05 11:36	1.1	3.7	7/17/05 23:19	0.2	3.1
7/7/05 9:38	0.3	4.7	7/25/05 5:50	7.3	1.7	7/12/05 13:52	3.1	5.3	7/25/05 5:50	7.3	1.7
7/7/05 15:00	0.2	2.5	7/27/05 0:48	1.8	1.2	7/13/05 18:57	1.2	0.4	7/27/05 0:48	1.8	1.2
7/9/05 4:26	1.6	6.7	7/28/05 18:12	1.7	3.2	7/15/05 0:12	1.2	1.8	7/28/05 18:12	1.7	3.2
7/9/05 14:52	0.4	2.4	7/30/05 21:48	2.2	5.0	7/16/05 14:38	1.6	3.2	7/30/05 21:48	2.2	5.0
7/9/05 17:21	0.1	5.4	8/7/05 0:50	7.1	0.2	7/18/05 17:16	2.1	1.7	8/7/05 0:50	7.1	0.2
7/10/05 12:57	0.8	3.6				7/19/05 23:26	1.3	1.9			
7/10/05 21:45	0.4	4.5				7/21/05 21:21	1.9	2.1			
7/14/05 13:33	3.7	0.4				7/22/05 5:04	0.3	2.4			
7/17/05 7:45	2.8	3.9				7/23/05 7:04	1.1	4.3			
7/19/05 20:04	2.5	4.8				7/23/05 18:55	0.1	6.0			
7/20/05 15:57	0.8	4.5				7/24/05 2:43	0.3	4.9			
7/21/05 1:21	0.4	0.5				7/24/05 13:00	0.4	2.9			
7/22/05 17:43	1.7	2.2				7/25/05 16:19	1.1	1.0			
7/22/05 21:14	0.1	4.1				7/26/05 2:04	0.4	2.2			
7/22/05 23:19	0.1	6.2				7/26/05 8:19	0.3	5.9			
7/23/05 22:45	1.0	6.8				7/29/05 11:24	3.1	3.1			
7/24/05 7:31	0.4	2.4				8/1/05 17:24	3.3	0.3			
7/25/05 10:19	1.1	3.8				8/1/05 21:14	0.2	0.3			
7/27/05 5:16	1.8	3.8				8/2/05 9:31	0.5	0.7			
7/27/05 7:38	0.1	1.9				8/5/05 20:24	3.5	0.5			
7/27/05 15:26	0.3	6.7				8/7/05 7:55	1.5	0.5			
7/30/05 19:16	3.2	2.6				8/7/05 8:31	0.0	0.4			
8/1/05 5:16	1.4	0.3									
8/4/05 13:33	3.3	0.9									

Table D7: Time between Alarm calculations

Time Between Alarm and Time To Repair											
New Doornfontein CCD 700			Germiston CCD 700			Braamfontein DSA 161			Garmistion CCD 700		
5	TBA	TTR	8	TBA	TTR	7	TBA	TTR	8	TBA	TTR

Jul-05												166 Alarms
Number of Alarms	30		Number of Alarms	12		Number of Alarms	25		Number of Alarms	12		20.8 Avg Alarms
Number of days	31.0		Number of days	31.0		Number of days	31.0		Number of days	31.0		
Number of days with Alarms	29.8	109.5	Number of days with Alarms	29.9	36.2	Number of days with Alarms	28.5	83.3	Number of days with Alarms	29.9	36.2	3.5 TTR
MTBA / TTR	1.0	3.7	MTBA / TTR	2.5	3.0	MTBA / TTR	1.1	3.3	MTBA / TTR	2.5	3.0	1.6 MTBA

Aug-05												105 Alarms
Number of Alarms	11		Number of Alarms	5		Number of Alarms	25		Number of Alarms	5		13.1 Avg Alarms
Number of days	31.0		Number of days	31.0		Number of days	31.0		Number of days	31.0		
Number of days with Alarms	28.1	5.5	Number of days with Alarms	30.9	3.4	Number of days with Alarms	32.4	13.5	Number of days with Alarms	30.9	3.4	0.6 TTR
MTBA / TTR	2.6	0.5	MTBA / TTR	6.2	0.7	MTBA / TTR	1.3	0.5	MTBA / TTR	6.2	0.7	3.2 MTBA

Sep-05												104 Alarms
Number of Alarms	20		Number of Alarms	6		Number of Alarms	15		Number of Alarms	6		13.0 Avg Alarms
Number of days	30.0		Number of days	30.0		Number of days	30.0		Number of days	30.0		
Number of days with Alarms	34.0	9.7	Number of days with Alarms	21.6	3.0	Number of days with Alarms	28.4	9.1	Number of days with Alarms	21.6	3.0	0.6 TTR
MTBA / TTR	1.7	0.5	MTBA / TTR	3.6	0.5	MTBA / TTR	1.9	0.6	MTBA / TTR	3.6	0.5	2.8 MTBA

Oct-05												100 Alarms
Number of Alarms	15		Number of Alarms	7		Number of Alarms	12		Number of Alarms	7		12.5 Avg Alarms
Number of days	31.0		Number of days	31.0		Number of days	31.0		Number of days	31.0		
Number of days with Alarms	23.6	9.4	Number of days with Alarms	39.3	4.1	Number of days with Alarms	33.2	8.5	Number of days with Alarms	39.3	4.1	0.6 TTR
MTBA / TTR	1.6	0.6	MTBA / TTR	5.6	0.6	MTBA / TTR	2.8	0.7	MTBA / TTR	5.6	0.6	3.2 MTBA

Table D8: Number of Alarms and MTBA calculations

2 = Demand cable pressure Min	New Doornfontein CCD 700		Germistion CCD 700		Braamfontein DSA 161		Germistion CCD 700	
	2	6	2	6	2	6	2	6
6 = Dew point Max	2	6	2	6	2	6	2	6
Jul-05								
Functional failure	0.0	2.8	4.8	2.8	6.2	7.1	0.0	0.4
Availability	100%	91%	85%	91%	80%	77%	100%	99%
Aug-05								
Functional failure	0.7	0.3	0.0	0.0	0.6	0.3	0.0	0.0
Availability	98%	99%	100%	100%	98%	99%	100%	100%
Sep-05								
Functional failure	0.6	1.2	2.3	0.0	0.0	0.7	0.4	0.0
Availability	98%	96%	92%	100%	100%	98%	99%	100%
Oct-05								
Functional failure	0.3	0.3	0.0	0.9	0.0	0.0	0.0	0.0
Availability	99%	99%	100%	97%	100%	100%	100%	100%
Aug-05 to Oct-05								
Functional failure	2.6	2.2	2.3	1.2	0.6	2.2	0.4	0.0
Availability	98%	98%	98%	99%	99%	98%	100%	100%
							98.4%	Availability after RCMS

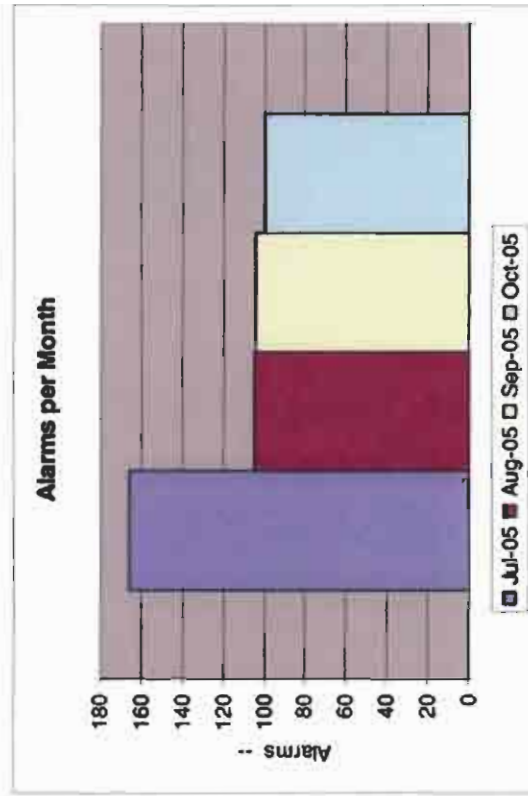
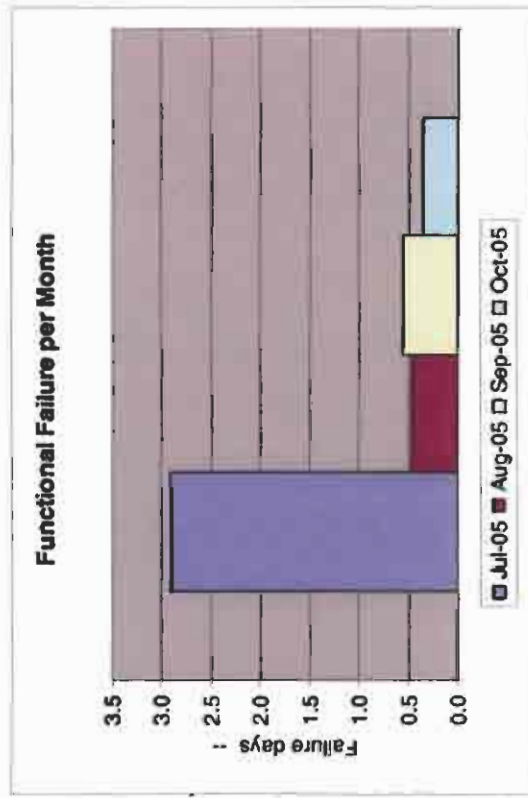
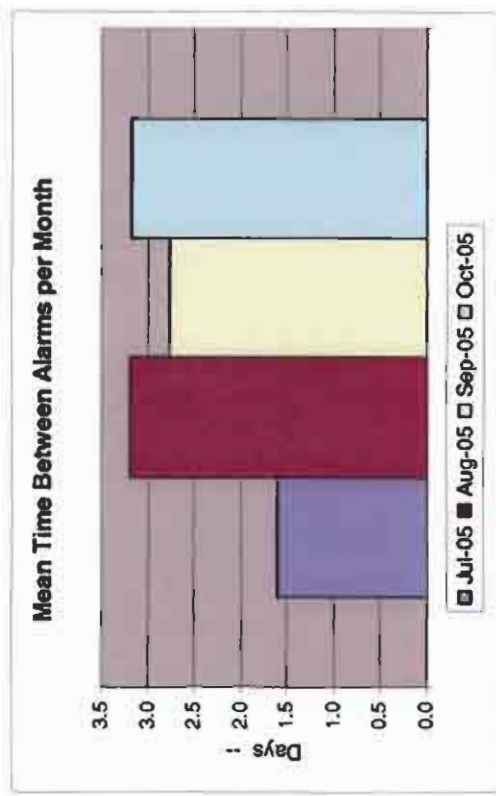
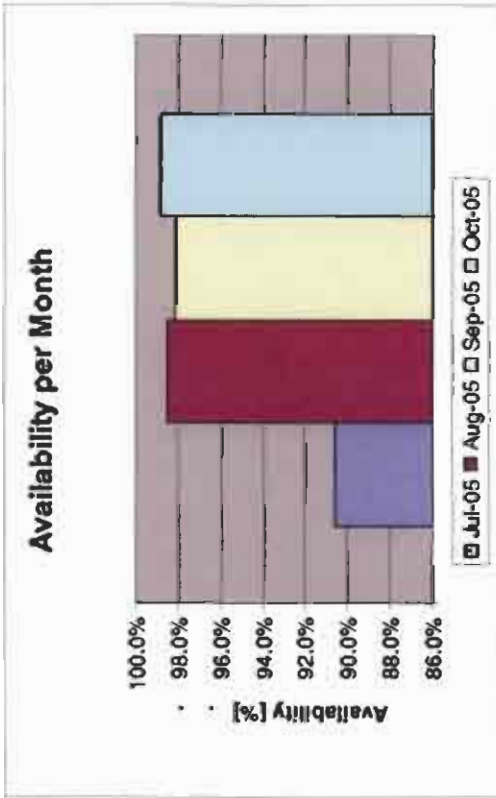


Figure D20: Availability, MTBF, Functional Failures and Alarms Graphs