Benefits of improved performance monitoring of mine cooling systems

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ABSTRACT

Mine cooling system components are an integral part of a mine's ventilation system. A mine's reliance on these capital intensive components are set to increase as mines deepen. Mine cooling systems consume up to a quarter of the electricity used on mines. Component efficiency should be monitored to ensure optimum utilisation. Downtime should be minimised so that production is not negatively influenced. Replacing expensive components in an age of severe economic pressure should be avoided altogether.

In this study, the performance of mine cooling system components was monitored. The effects of various operational and maintenance interventions on component performance have been quantified. Quantifying the effects of management decisions led to the refining of operational procedures, the optimisation of future maintenance, and the subsequent identification of electrical energy savings potential without the need for expensive modifications.

Investigations show that a mine could realise a saving of up to nine hundred thousand rand annually by optimising the maintenance schedule of chillers. Extrapolated results estimate an electrical energy saving of 52 127 MWh per year if the strategy were implemented on twenty of South Africa's biggest mines. In addition, a monetary saving in excess of five hundred thousand rand could be saved through refining operational procedures. These strategies will be possible without the need for expensive installations or complicated modifications.

Monitoring cooling system performance allows management to identify trends in performance, to understand component inter-dependence, and to allow for informed decision-making. In addition, performance monitoring allows for the identification of component and instrumentation faults. Statistical control charts and simulation modelling are some of the tools that have been employed in this study. These tools assist management formulate strategies and decisions with a higher degree of confidence.

Key words: mine cooling systems, performance monitoring, simulation modelling, maintenance

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

A	area	(m^2)
approach	approach of direct contact heat exchanger	(°C)
COP	coefficient of performance	(-)
c_p	specific heat capacity	(J/kg.°C)
D	diameter	(m)
h	convection heat transfer coefficient	($W/m^2.K$)
k	number of measurements	(-)
L	length	(m)
MR	moving range	(-)
$\dot{m}$	mass flow rate	(kg/s)
P	power	(kW)
R	moving range	(-)
$\overline{R}$	process moving range average	(-)
range	range of direct contact heat exchanger	(°C)
RH	relative humidity	(%)
t	temperature	(°C)
x	process measurement	(-)
$\overline{x}$	process average	(-)

ABBREVIATIONS

BAC	Bulk air cooler
DMP	Demand market participation
DSM	Demand side management
IDM	Integrated demand management
KPI	Key performance indicator
LCL	Lower control limit
PCA	Principle component analysis
MR	Moving range
SCADA	Supervisory control and data acquisition
UCL	Upper control limit
VSD	Variable speed drive

GREEK SYMBOLS

η	efficiency	(-)
$\sum$	summation	(-)

SUBSCRIPTS

a	air
f	fouling
i	inner wall
in	inflow
o	outer wall
out	outflow
t	thermal
w	water

1. INTRODUCTION

1.1 BACKGROUND

Electricity usage in South Africa

Eskom is South Africa’s main electricity supply utility and is purportedly one of the top twenty utilities in the world in terms of generation capacity. Eskom generates approximately 95% of the electricity used in South Africa and 45% of the electricity used in Africa. Figure 1 illustrates Eskom’s percentage sales of electricity according to industry type (Eskom, 2011).

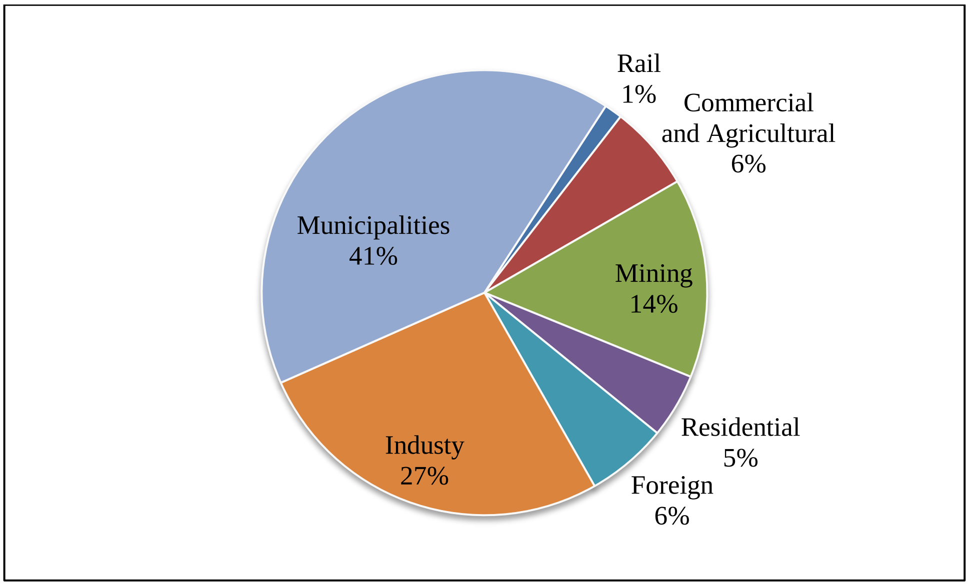

Figure 1: Electricity sales (Eskom, 2011)

Brian Dames, the Chief Executive Officer of Eskom, recently appealed to businesses and residential users in South Africa to help ‘beat the peak’. This comes on the back of what he calls a “tight” system balance caused by ongoing maintenance and unplanned outages[1]. For an economy that looks to continue growing, it is crucial that the state has a reliable and cost-effective electricity supply.

The South African economy

The South African economy has seen a 3% growth, on average, per year since 2009. Government expects this growth to increase to 3.6% and 4.2% in 2013 and 2014 respectively (Gordhan, 2012). This growth in the economy will result in a subsequent increase in electricity demand. An increase in demand will put further strain on what is already an overburdened national grid.

Companies have now realised that, in order to remain competitive in an increasingly demanding economy, they must trim their energy budgets and utilise higher efficiencies. Large companies with high energy consumptions have retrofitted process plants and facilities; others have resorted to investments with the shortest possible payback times (Hepbasli & Ozlap, 2003; Petrecca, 1992; du Plessis, et al., 2013). These measures not only allow companies to become more competitive financially, but have also helped them realise the importance of protecting the environment (Abdelaziz, et al., 2011).

International trends

A proactive, integrated energy management system is essential for controlling costs (Carbon Trust, 2011). Energy management is now considered one of the main functions of industrial management. It has been suggested that large companies should include details of their energy conservation activities and achievements in their annual reports (Abdelaziz, et al., 2011). This is as a result of rising energy prices and reports about the approaching exhaustion of world energy resources (Petrecca, 1992).

The industrial sector, which includes the mining industry, currently consumes approximately 37% of the world’s total delivered energy (Abdelaziz, et al., 2011). Industrial development across the world will result in increased energy use. This will lead to higher concentrations of

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[1] http://www.polity.org.za/article/eskom-outlines-plan-to-trim-unplanned-outages-to-10-2013-04-22 (Accessed 24/04/2013).

greenhouse gases such as carbon dioxide (CO_2), sulphur dioxide (SO_2) and other emissions. These emissions have devastating consequences for the earth's climate and contribute to rising temperatures, drought, famine and economic chaos (Mahalia, 2002).

The Department of Energy in the United States of America has highlighted the fact that global carbon emissions are rising by more than 2% per year. This will result in carbon emissions being 50% higher in 2015 than they were in 1997. This increase is a direct result of ever-increasing energy demands and inefficient methods of energy use (Mahmoud, et al., 2009).

Demand Side Management

Demand Side Management (DSM) measures allow customers to use electricity less intensively or at times that do not coincide with unavoidable peak demand. This results in a reduction in demand and therefore delays the need for new generation capacity. The existing demand, together with the lead time needed to develop new generating plants, means that it will become more difficult to meet electricity demand in the future (Hughes, et al., 2006).

Eskom has implemented a number of DSM initiatives in recent years to encourage companies to reduce their electricity usage. These include Integrated Demand Management (IDM) and Demand Market Participation (DMP). Eskom plans to continue with a range of DSM measures. Some of these measures are likely to be curtailed, however, in the near future. This is due to reductions in planned tariff increases by the National Energy Regulator of South Africa (NERSA)[2].

Mining in South Africa

Mining profits are being eroded year-on-year by the increasing costs associated with extracting minerals from ever-deepening mines. A large component of these costs is the energy cost associated with ensuring that working conditions underground comply with regulatory requirements. For mining companies to remain globally competitive, they have to embark on improving energy efficiency. The viability of energy efficient intervention is dependent on whether the measure would lead to a benefit that would exceed its cost (Lee & Yik, 2002).

Mining is a capital intensive business requiring large and expensive equipment. To sustain the financial well-being of a mine, all aspects of their operations must be managed in an optimal

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[2] http://www.polity.org.za/article/eskom-outlines-plan-to-trim-unplanned-outages-to-10-2013-04-22 (Accessed 24/04/2013).

manner. Mining projects are often associated with high operating costs. An increase in equipment productivity will result in significant cost savings (Topal & Ramazan, 2010). Eliminating inefficiencies is essential to getting the job done efficiently (Abdelaziz, et al., 2011).

1.2 MOTIVATION FOR THE STUDY

Electricity usage on mines

Within the mining industry, gold mines use approximately 47% of the industry's electricity (Eskom, 2010). The extreme depths to which gold mines stretch to reach the precious metal result in increased operational costs. Platinum mines are the next highest consumers (33%), with the remaining 20% being used by other mines – for example, coal, copper and iron mines. The main consumers of electricity on mines in South Africa and their respective usages can be seen in Figure 2 (Eskom, 2010).

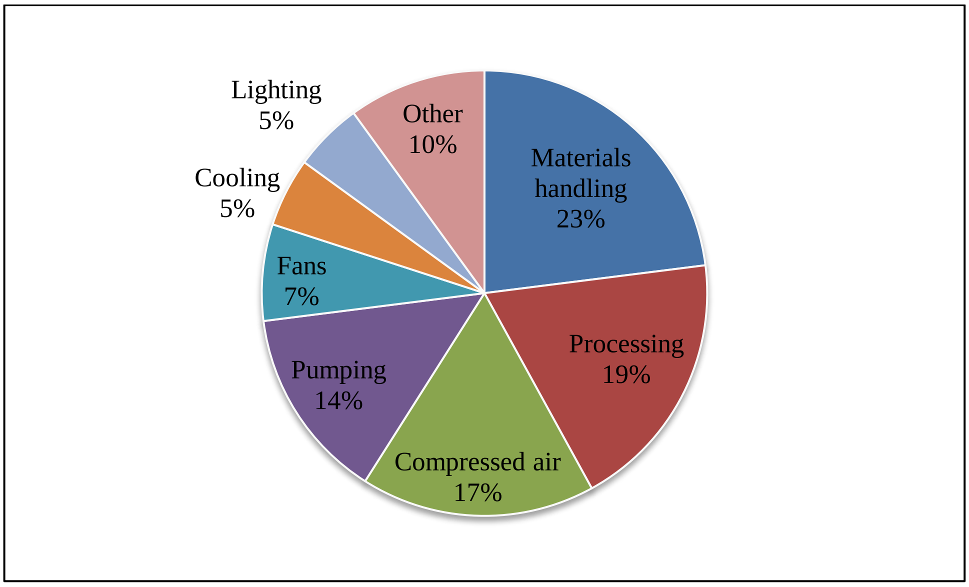

Figure 2: Main consumers of electricity on mines and their respective usages (Eskom, 2010)

Mines are often located in remote areas with very little infrastructure. This means that operations must have a clear incentive to become less energy- and water-intensive. The current mining environment is associated with high energy costs and growing concerns regarding sustainability. Reducing energy and water consumption is now becoming an important goal for the mining industry (Gunson, et al., 2010).

Energy audits are commonly used to identify areas for potential electricity usage improvement. An energy audit entails an inspection, survey and analysis of energy flows for energy conservation. The aim is to reduce the amount of energy input into the system without negatively affecting the output. Results of projects that come about due to energy audits include a reduction in energy consumption, environmental pollution and operating costs, and an improvement in overall system efficiency (Saidur, 2010).

The percentage of energy used by cooling systems in particular is set to increase due to the rigorous cooling demands of deeper mining activities and increased surface temperatures (du Plessis, et al., 2013). The reliability of these capital intensive cooling system components is also likely to be put under greater pressure. Any downtime will have an adverse effect on production and should be minimised. Replacing expensive components in an age of severe economic pressure ought to be avoided altogether. Identifying ways to improve reliability and efficiency whilst reducing electrical energy usage should be a priority.

Applications of technologies and control strategies has tremendous potential to reduce energy use. These technologies include the use of energy management software (Pelzer, et al., 2008), variable speed drives (VSDs) (du Plessis, et al., 2013), and high efficiency motors (Abdelaziz, et al., 2011). Control strategies include peak-clips, load-shifts and energy efficiency. With the possibility of Eskom-funded DSM projects being reduced in future, it is crucial that the industry investigates other opportunities to conserve electrical energy – preferably with low capital outlays.

Water usage on mines

Civil society and governments are encouraging the global mining industry to move toward sustainable development (Gunson, et al., 2010). Some reports suggest that mining in South Africa only accounts for 2-3% of national water demand (Brown, 2003). Although this figure may seem relatively low, mine water consumption can have a significant impact on local supplies. In addition, acid rock drainage, leaks from tailings and waste rock impoundments into waterways can seriously contaminate water sources (MMSD, 2002; Nedved & Jansz, 2006; Akcil & Koldas, 2006; Cohen, 2006).

Mines typically use between 0.3 m^3 and 0.7 m^3 of water per tonne of ore processed. For a water source to meet consumers' pressure, temperature and quality requirements it may need to be pumped, cooled/heated, and treated. Generally, the greater the difference between the water consumer requirements and the water available, the higher the cost of meeting mining needs (Gunson, et al., 2010). Chilled water service delivery now has to be more reliable than ever before.

Water is used in many applications on mines. In most applications, the water must be chilled before use. Water is mostly used for dust suppression, washing, cooling and ventilation. As mines deepen, the amount of chilled water required to cool increasingly warmer working environments increases. Deep level mines have virgin rock temperatures of up to 60 °C (Stephenson, 1983) and require wet-bulb temperatures below 27.5 °C at underground working areas (Vosloo, et al., 2012).

Preliminary findings

Site visits were arranged and meetings conducted with experienced mine personnel to identify opportunities for electrical energy savings. The operating conditions and layouts of various mine cooling systems were also assessed. It was apparent that the demanding targets set by production departments leave mine personnel with little time for more time-consuming maintenance. Operational procedures also vary from mine to mine.

Maintenance procedures typically take the form of daily inspections to ensure operational continuity and compliance with regulatory requirements. Critical maintenance of cooling system equipment is carried out in the winter months or holiday periods when less cooling is needed. Other cooling system maintenance performed during the year is usually unscheduled, reactive maintenance due to breakdowns[3]. There is little awareness as to the other associated benefits of maintenance, particularly cost savings.

Operational procedures vary from mine to mine and, at times, from operator to operator. Most mines appear to operate cooling systems, each based on their own ‘rule of thumb’. Some operators are also more pro-active than others. In some instances, a controller may operate more chillers and pumps than is required, or switch off the pre-cooling tower fans. These actions can contribute to increased electrical energy usage or decreased performance and efficiencies.

It is evident that significant electrical energy and monetary savings can be realised by implementing effective maintenance and operational procedures for mine cooling systems. No

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[3] Meeting held with Andre Joubert, mine mechanical foreman, January 2013 (phone: 082 788 9390).

expensive, additional equipment or instrumentation is needed to realise these benefits – an important fact in an age of increased economic pressure.

1.3 GOALS OF THE STUDY

The goals of this study are as follows:

1. *Propose a performance monitoring system that will allow mine personnel to track the performance of cooling system components*. This will allow the mine to identify trends and inefficiencies, ascertain component interdependence and assist in the planning of maintenance and operational schedules.
2. *Quantify the effects of management decisions*. Understanding the effects of their actions will allow management to make decisions with a higher degree of confidence in future. This will also encourage a more proactive approach to system maintenance, thus increasing the operational lifespan of mining equipment.
3. *Identify energy savings opportunities*. Simulation models are a cost-effective means of identifying energy saving opportunities. The information gleaned from the performance monitoring tools can be included in simulation models for higher fidelity.

1.4 SCOPE

The emphasis of this study is on the associated benefits of improved performance monitoring – specifically of mine cooling systems. It is envisaged that the principles and findings in this dissertation could be applied elsewhere in the mining environment – for example compressors and hoists. These components will, however, not be considered.

This study will only focus on the effects of certain interventions as identified by the performance techniques developed, rather than the specific details of the interventions themselves. The details of these interventions, as well as possible improvements, will form part of future studies.

1.5 OVERVIEW OF THIS DISSERTATION

Chapter 1

The state of electricity supply and demand is analysed. Opportunities for energy savings and improvement in performance are identified in the mining environment, specifically cooling systems. Large mines have the ability to record vast amounts of real time and historical data. Most of this data is used for control purposes only. Processing this data and presenting it in a usable manner will yield a number of advantages. It is envisaged that one will be able to identify causes for changes in component performance at an early stage, recognise energy saving opportunities, and ensure prolonged, optimal operation.

Chapter 2

The various components of mine cooling systems are analysed. Particular attention is given to attributes of the components that are susceptible to performance deterioration.

Chapter 3

A strategy for monitoring cooling system performance is developed. The strategy includes the use of simple scatter charts and statistical control charts. Information gleaned from these tools can be used to test hypothetical scenarios and increase simulation model fidelity. In addition, the information can be used to gain a better understanding of component interdependence and to assist in planning future maintenance.

Chapter 4

A case study is used to test the strategy developed in this dissertation. Attributes of the respective components of the cooling system are analysed, and the effects of management decisions quantified. This allows mine personnel to optimise operational and maintenance procedures, thus increasing system efficiency.

Chapter 5

Results from the investigation in Chapter 4 are used to test scenarios that could potentially result in energy-saving opportunities. The findings are then extrapolated to understand what the effect would be if the strategies were implemented throughout the mining industry.

Chapter 6

Chapter 6 presents a summary of the findings and suggestions from this dissertation. Opportunities for further studies are also discussed.

2. MINE COOLING SYSTEMS

2.1 INTRODUCTION

In Chapter 1, mine cooling systems were identified as an area for possible electrical energy savings and performance improvement. It was established that mine cooling system maintenance is reserved for winter months or holiday periods. Operational procedures also vary widely.

Chapter 2 looks at the various components of mine cooling systems. Particular attention is given to components of the system that use large amounts of electricity, and their susceptibility to performance reduction.

2.2 OVERVIEW OF MINE COOLING SYSTEMS

Overview

Pumping and cooling constitute the bulk of the energy requirements of a mine’s water network. Pumping power is a product of the total dynamic head, the capacity of water to be pumped, and the water density (Perry & Green, 1997). Pump and motor efficiency can have a significant impact on the amount of energy consumed by the treatment system. This efficiency is a ratio of the power output and the power input (U.S. Department of Energy (DOE), 2009).

Energy consumption can be reduced by improving the water network design. This can be achieved by taking advantage of opportunities to re-use water where possible, and by analysing options to minimise pumping, cooling and water treatment requirements (Gunson, et al., 2010).

The energy required for cooling is dependent on the cooling methods used. Mines typically use a combination of pre-cooling towers and refrigeration machines (chillers) to meet the chilled water requirements of the mine. Cooler ambient air is used in pre-cooling towers to remove heat, whereas chillers use a refrigerant. Both methods make use of evaporative heat transfer to cool the water.

Reagent costs are incurred with the addition of anti-scalants to reduce scale formation, or corrosion inhibitors to reduce corrosion in pipelines and equipment. Other treatment methods that incur additional costs include filtration, clarification, cold- and hot-lime softening, evaporation, ion exchange and electrodialysis (Gunson, et al., 2010).

Operator and maintenance staff are required to control and maintain the water treatment system. Regular cleaning is required to prevent a build up of sediment within filters, tubes and pipes. Pumps must also undergo regular maintenance to ensure continued high operating efficiencies. In general, the poorer the water quality, the more frequently maintenance procedures will have to be carried out. This results in increased labour costs.

Design and operation

The components of the mine cooling system are now discussed in detail. Attention should be given to understanding not only the operating characteristics of all energy-consuming systems, but also situations that cause profile performance variation (Abdelaziz, et al., 2011). The discussion will include the technical aspects of the components, as well as the susceptibility of each component to factors that affect its performance.

A mine cooling system is an integral part of the mine water reticulation system. A typical mine cooling system consists of hot water storage dams, pre-cooling towers, pre-cooling dams, chillers and associated condenser cooling towers, Bulk Air Coolers (BACs), and cold water storage dams (McPherson, 1993). Figure 3 is a schematic drawing of a typical mine cooling system.

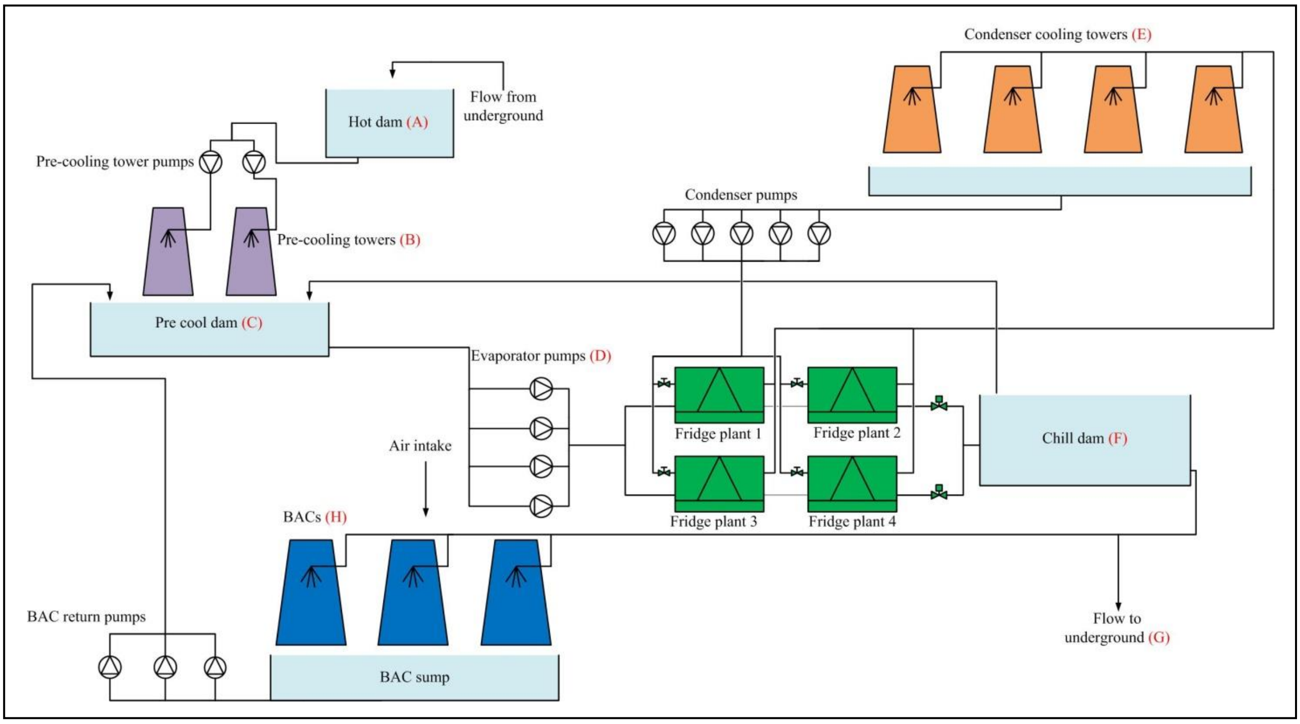

Figure 3: Typical mine cooling system surface layout

Hot water is pumped from underground into a hot water storage dam (A). This hot water is then sprayed through pre-cooling towers (B) and stored in a pre-cooling dam (C) before passing through the evaporator side of the chillers (D). The evaporator cools the water further, depending on the requirements of the mine. The condenser water is cycled around a condenser cooling tower for heat rejection to the atmosphere (E). The chilled water is stored in a cold water storage dam (F). The cold water is sent underground when required (G), or fed to a BAC (H). The BAC uses chilled water to cool ambient air.

Refrigeration plants

Overview

Refrigeration plants usually consist of one or more chillers arranged in series, parallel, or a combination of both. Chillers typically use shell and tube, or plate heat exchangers, and make use of centrifugal or screw compressors. The vapour compression refrigeration cycle (Figure 4) is typically used in conjunction with shell and tube heat exchangers. Plate heat exchangers make use of the ammonia absorption cycle (Figure 5). Refrigeration plants can be built with cooling capacities of up to 20 MW (du Plessis, 2013).

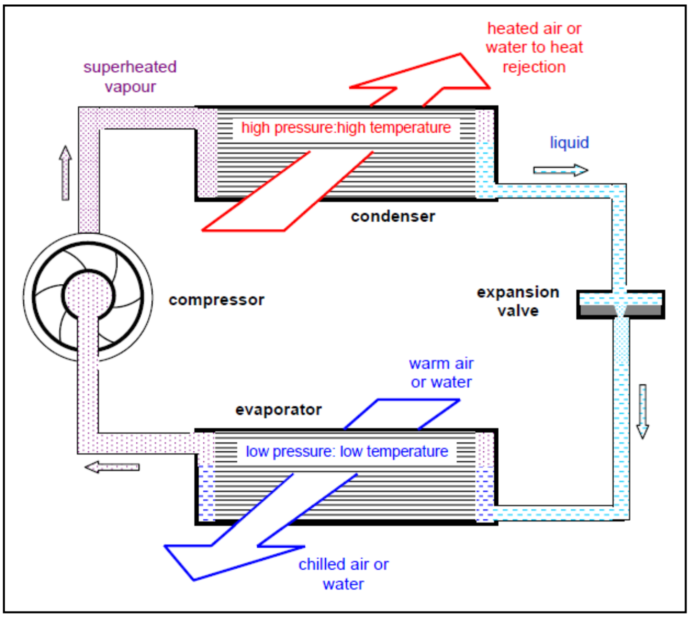

Figure 4: The main components and attributes of the vapour compression cycle (McPherson, 1993)

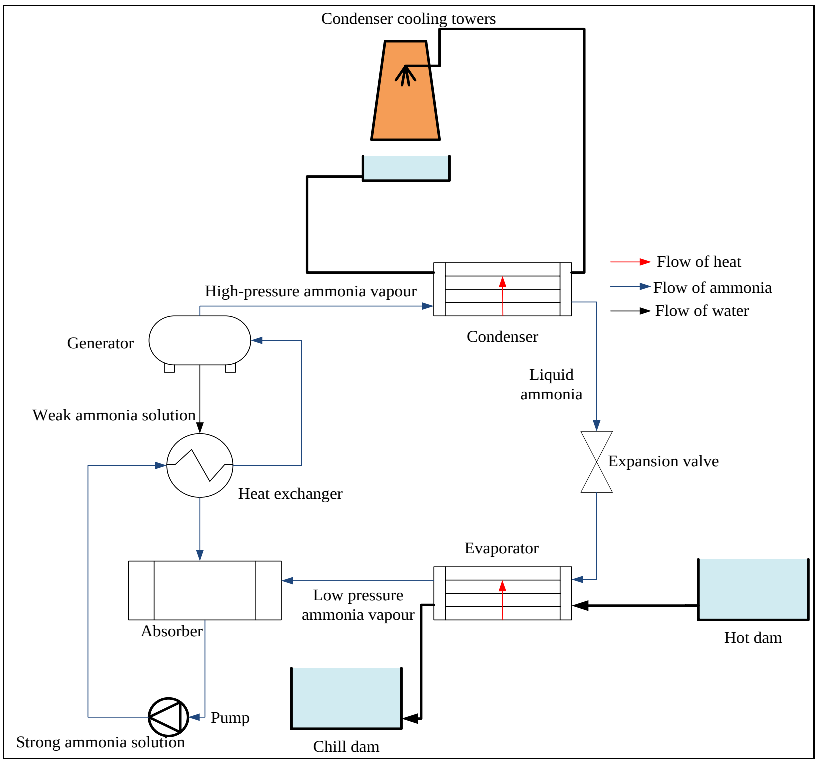

Figure 5: Ammonia absorption refrigeration cycle indicating critical components, as well as heat and fluid flows (Borgnakke & Sonntag, 2009)

The cooling loads are controlled using guide vanes in centrifugal compressors and slide valves in screw compressors (Widell & Eikevik, 2010). These control methods adjust the refrigerant flow, ensuring that a set outlet water temperature is maintained for variable inlet conditions (McQuay International, 2005). The greater the difference between the inlet and the pre-set outlet temperature, the higher the compressor power consumption. The refrigerants commonly used in refrigeration machines are R134a or ammonia (NH_3) (du Plessis, 2013). Major variations in cooling requirements due to seasonal changes are allowed for by varying the number of refrigeration machines in operation (Bailey-McEwan & Penman, 1987; Van der Walt & De Kock, 1984).

Figure 6 is an example of a chiller installed at a gold mine near Klerksdorp. These chillers utilise shell and tube heat exchangers within the condenser and evaporator chambers.

Figure 6: Shell and tube heat exchanger chillers typically used at a gold mine

Figure 7 is an ammonia refrigeration machine installed on a platinum mine near Northam. The figure shows the evaporator and condenser heat exchanger plates.

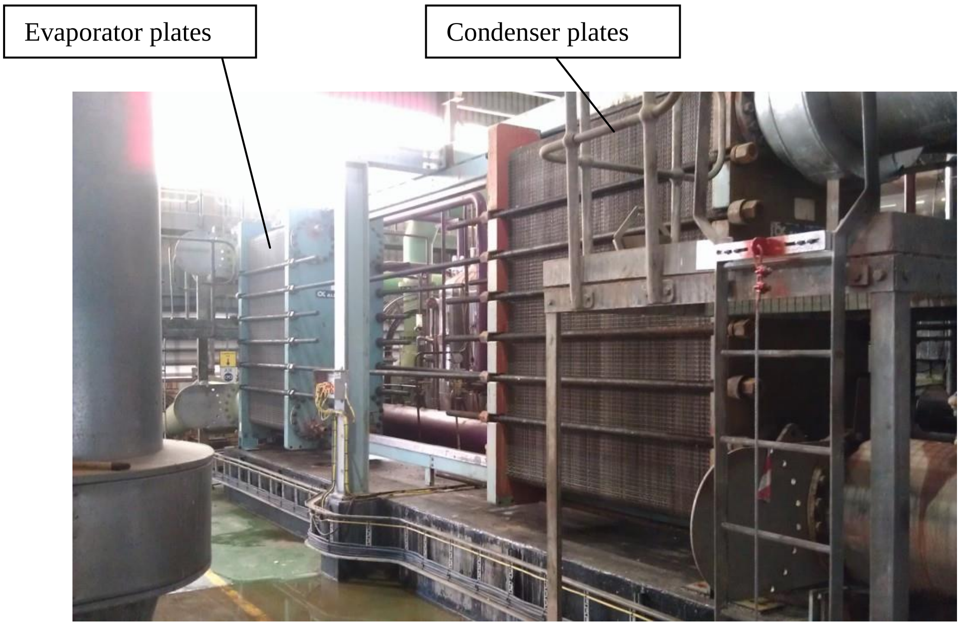

Figure 7: Evaporator and condenser heat exchanger plates of an ammonia refrigeration machine

Chillers work through evaporative heat transfer, using a refrigerant as the cooling agent. When the refrigerant evaporates, heat is removed from the water. After evaporation, the gas is compressed and condensed, which requires additional air or water cooling. Chillers usually have high energy consumptions, and require significant capital and operating costs as well as specialised maintenance. Chillers also use refrigerants that are often toxic and can have negative environmental impacts if the refrigerant leaks or if it is not properly controlled (Gunson, et al., 2010).

Surface refrigeration plants are typically used to chill water and cool bulk air. Underground plants do the same work as surface plants, but are located closer to the work areas. While surface plants use atmospheric air for heat rejection, underground plants use exhaust air. This raises natural ventilation pressure. The main disadvantages of underground plants are that heat rejection is limited by the amount of exhaust air available, and the high costs associated with excavations. Maintenance and a reliable power supply can be difficult due to shaft logistics and other mining disruptions (ASHRAE, 2011).

Factors affecting chiller performance

Plant performance will be maintained if the system is monitored and the appropriate corrective action is taken when necessary. Ensuring that controls and instrumentation are calibrated regularly will allow for the efficient operation of refrigeration systems. Instrumentation should be sufficient to enable the performance of the cooling system to be assessed and faults diagnosed. Variables to be monitored include pressures, temperatures, currents and power usages (The Energy Research Institute – University of Cape Town, n.d.).

The performance of a heat exchanger will usually decrease over time. This is due to the accumulation of sediment or deposits on the heat transfer surfaces (Figure 8). A layer of deposit increases the resistance to heat transfer and causes the rate of heat transfer in the heat exchanger to decrease. The effect of sediment build up on heat transfer is represented by a fouling factor (R_f) (1), which is a measure of the thermal resistance introduced by fouling (Çengel, 2006).

Figure 8: Sediment build up in heat exchanger tubes (CQM, n.d.)

The most common type of fouling is the precipitation of solid deposits in a fluid on the surfaces of the heat exchanger. These deposits can be cleaned by chemical treatment or mechanical scraping (Figure 9 and Figure 10). Deposits restrict the flow rate within the heat exchanger and reduce the rate of heat transfer. This results in an increase in pumping and compressor power usage. To reduce the amount or rate of sediment build up in the heat exchanger, the water should be treated before passing through the heat exchanger (Çengel, 2006).

Fouling should be considered during the design and selection of heat exchangers. In applications such as the mining industry where fouling is expected, it may be necessary to select a larger, more expensive heat exchanger. This will ensure that it continues to meet the service delivery requirements of the mine after fouling occurs. The periodic cleaning of heat exchangers and the resulting down time are additional penalties associated with fouling (Çengel, 2006).

Figure 9: Pressure washer used for cleaning chiller tubes

Figure 10: Pressure washer hose

The fouling factor depends on the operating temperature and velocity of the fluids, as well as the length of service. Fouling increases with increasing temperature and decreasing velocity. The total thermal resistance in a typical shell and tube heat exchanger can be calculated using (1) and (2) (Çengel, 2006):

$$R_t = R_i + R_{f,i} + R_{wall} + R_{f,o} + R_o \qquad (1)$$

$$R_t = \frac{1}{h_i A_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(D_o/D_i)}{2\pi k L} + \frac{R_{f,o}}{A_o} + \frac{1}{h_o A_o} \qquad (2)$$

where R_i, R_{wall} and R_o are the thermal resistance factors of the inner, tube and outer walls of the heat exchanger respectively. $R_{f,i}$ and $R_{f,o}$ are the fouling factors on the inside and outside of the heat exchanger surfaces. A_i and A_o are the areas of the inner and outer surfaces of the wall that separate the two fluids. h_i and h_o are the convection heat transfer coefficients inside and outside the tube. k is the thermal conductivity of the wall material, and L is the length of the tube. D_o and D_i are the inner and outer diameters of the tube wall. Representative values for R_f can be found in handbooks.

The thermal resistance of the inner and outer surfaces of the tubes, as well the tube wall itself, is constant. Thermal resistance due to fouling increases over time. Total thermal resistance is directly proportional to the inner and outer fouling factors. In addition, a decrease in the internal diameter of the heat exchanger tubes (A_i) due to sedimentation build up will increase the total thermal resistance R_t.

The amount of sediment build up in heat exchangers is dependent on the quality of the water passing through the chiller. One of the main reasons for high sediment build up in mine water is the inability of underground settling dams to cater for increased water volumes. This is typically associated with deepening mines. Figure 11 is a picture of a hot dam on a mine near Carletonville. This figure illustrates a typical example of the water that mine cooling systems have to chill.

Figure 11: Hot dam with high sediment concentration

Anticorrosion compounds are usually used to protect metal components of the chiller, particularly the condenser tubes. These anticorrosion compounds generally take the form of chromates, phosphates, or polyphosphonates of zinc, and promote the formation of a protective film on the metal surfaces. Biocides, for example chlorine, are added to control the growth of algae and other organic matter (McPherson, 1993).

Other aspects that can affect the performance of cooling systems include ensuring the repairing of refrigerant suction gas and liquid line insulation. This will reduce superheating of suction gas and loss of sub-cooling. The refrigerant lines will gain heat in areas that are not air-conditioned, thus increasing the system load without producing useful cooling (The Energy Research Institute – University of Cape Town, n.d.).

It is also important to maintain the specified refrigerant charge in the chiller. Insufficient refrigeration reduces system performance and capacity. A reduction in mass flow rate of refrigerant results in superheating of the refrigerant at the evaporator. This reduces the efficiency of the compressor and increases condensing temperatures (The Energy Research Institute – University of Cape Town, n.d.).

The performance of a chiller is typically defined by its coefficient of performance (COP) (3). The COP of a chiller is defined as the ratio of the chillers cooling output and the electrical input (Yu & Chan, 2012).

$$COP = \frac{thermal\ cooling\ \ (kW)}{electrical\ input\ \ (kW)} \tag{3}$$

$$COP = \frac{mass\ \ flow(\dot{m}) \times specfic\ heat\ capacity(c_p) \times change\ in\ temp(t_{in} - t_{out})}{electrical\ \ power} \tag{4}$$

Accumulation of sediment can cause a decrease in heat transfer. This results in an increase in electrical power usage to maintain the predetermined outlet temperature of the chiller. Furthermore, sediment build up can also restrict the flow of water through the chiller. All of these factors contribute to a decrease in chiller COP.

Cooling towers and spray chambers

Cooling towers and spray chambers are commonly referred to as direct heat exchangers. Cooling towers and spray chambers are used to pre-cool water before it enters the evaporator of a chiller or to cool water from the condensers. If the airflow into the heat exchanger has a lower wet-bulb temperature than that of the water, heat will be transferred from the air to the water. Heat is removed from the water through a combination of evaporation and convection (McPherson, 1993).

There are many different designs of cooling towers and spray chambers. Every design however, is subject to the same factors which influence their efficiency and heat exchange capacities. These factors include (McPherson, 1993):

- Water mass flowrate
- Supply temperature of water
- Air mass flowrate
- Psychrometric condition of the air at inlet
- Contact time between air and water

The contact time between the air and water will depend on the design of the heat exchanger. Factors that can have an effect on the contact time include the relative velocity between the air and water droplets, as well as the concentration and size of water droplets. The size and concentration of droplets are influenced by the pressure and flow of water supply, arrangement of spray nozzles, and presence of packing or fill in the heat exchanger (McPherson, 1993).

Figure 12 illustrates a schematic design for a cooling tower typically used on the surface of a mine. Warm water is sprayed into the tower and mixed with cooler air in the tower's fill area. The air moves in an upward, counterflow direction to that of the water. The fill is used to distribute the water and airflow, as well as increase the contact area and contact time between the water and the air. The fill usually takes the form of plastic mesh or splash bars. Air velocities through counterflow cooling towers are in the range of 1.5 to 3.6 m/s (McPherson, 1993).

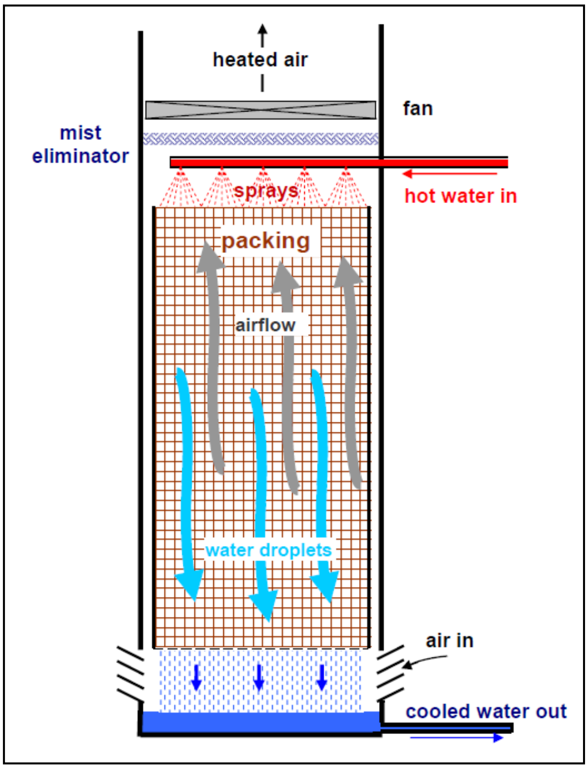

Figure 12: Schematic illustration of a counterflow cooling tower (McPherson, 1993)

Cooling towers used on mine surface cooling systems are usually between 10 and 20 m in height and 3 to 8 m in diameter. Heat loads may be as high as 30 MW. Cooling towers use considerably less electrical energy than chillers requiring energy for three primary functions: running fans to force air into or out of the cooling towers, pumping the re-circulating cooling water, and replacing the amount of evaporated water (Gunson, et al., 2010). The COP of an efficient cooling tower, defined as the ratio of cooling output to electrical input (Yu & Chan, 2012), can be as high as 30.

Figure 13 and Figure 14 are examples of pre-cooling and condenser cooling towers respectively. These cooling towers are in operation at a gold mine near Klerksdorp.

Figure 13: Example of pre-cooling towers typically used on mines

Figure 14: Condenser cooling towers installed on a mine near Klerksdorp

Open cooling towers are susceptible to losses in the form of evaporation and drift. Evaporation losses amount to approximately 1% per 7 °C of water cooling, while drift losses are in the region of 0.2% of the water circulation rate (ASHRAE, 1988). These losses mean that water must be replaced regularly. Evaporation can result in an escalation in concentration of dissolved solids and impurities. This leads to scaling, corrosion, and sedimentation within the system (McPherson, 1993). Cooling towers are also prone to fouling by dust or contamination build up

(Gunson, et al., 2010). The quality of the water should be constantly monitored to ensure continued effective heat transfer in the cooling towers and downstream cooling components.

Bulk air coolers

If water is supplied to a direct heat exchanger at a temperature lower than the wet-bulb temperature of the air, then cooling and dehumidification of the air takes place. This is the method typically used to cool air for underground ventilation of mines. BACs can be constructed vertically in the form of a tower, or horizontally in the form of a chamber. Large BACs are usually used on surface for cooling main airflows. In areas where space is limited, smaller BACs, usually portable in nature, can be used (McPherson, 1993).

A schematic diagram of a vertical BAC is shown in Figure 15. In this instance, chilled water is sprayed through the tower, cooling the ambient air. Such designs can be installed on surface or underground for bulk air cooling, and may have heat transfer duties of up to 20 MW (McPherson, 1993). Figure 16 shows a vertical BAC currently installed at a platinum mine near Thabazimbi.

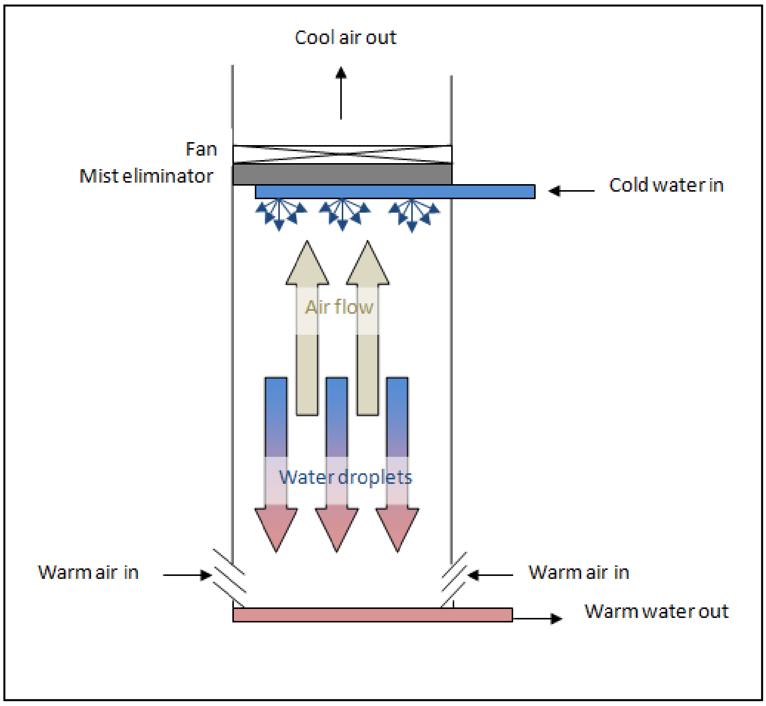

Figure 15: Schematic diagram of a vertical, counterflow BAC

Figure 16: An example of a vertical BAC typically used on mines

Horizontal spray chambers have more limited cooling capacities, typically in the region of 3.5 MW. They can however be more easily used underground without the need for extensive excavations. Figure 17 illustrates a single stage spray chamber. The sprays can be directed into or across the airflow. The nozzles can either be distributed over the cross-section, as shown in Figure 17, or along the sides near the base of the chamber. The positioning of the nozzles is critical to ensure that the spray and airflow are distributed uniformly across the chamber (McPherson, 1993).

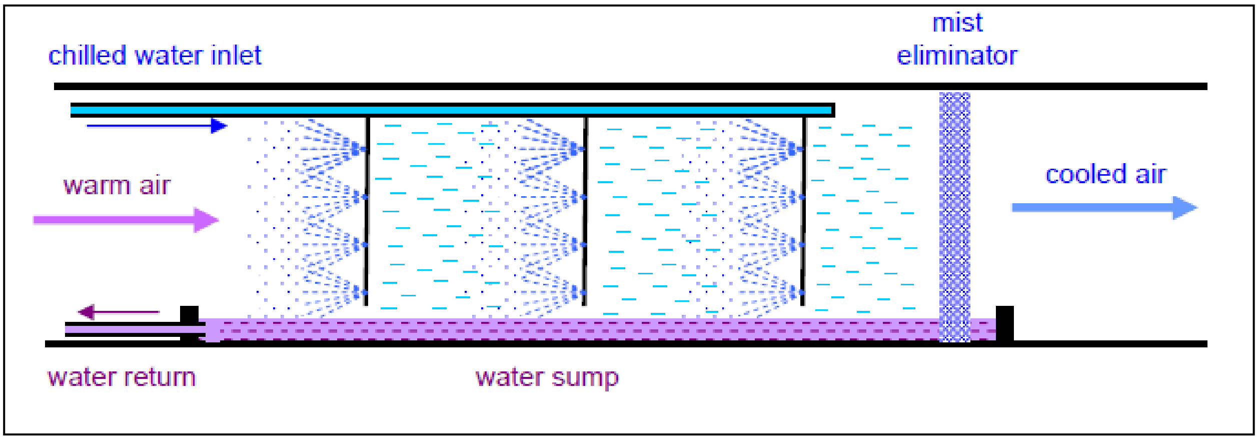

Figure 17: Schematic illustration of a single stage, horizontal spray chamber (McPherson, 1993)

Figure 18: A horizontal spray chamber BAC installed on a platinum mine near Thabazimbi

The efficiency of a heat exchanger increases with smaller water droplets. Small droplet sizes can however, result in excessive losses or require highly constrictive mist eliminators. In addition, finer spray will require higher water pressures and therefore higher pumping costs (McPherson, 1993). In practice, water droplet diameters of 0.5 mm and water pressures between 150 and 300 kPa give adequate results in horizontal spray chambers (Reuther, et al., 1988).

Relative air and water droplet directions can be counterflow or crossflow, depending on the nozzle orientation. Aerodynamic drag can convert small water droplet spray to parallel flow. Two- or three-stage spray chambers may be required to recoup losses in efficiency. Multiple spray chambers ensure that the air leaving the chamber comes into contact with the coldest sprays (McPherson, 1993).

Figure 19 illustrates a two-stage spray chamber. The cross sectional area of a spray chamber should be chosen to provide an air velocity of 4 to 6 m/s. Higher air velocities decrease the efficiency of heat transfer, and can result in unwanted pressure drops in the air flow (McPherson, 1993).

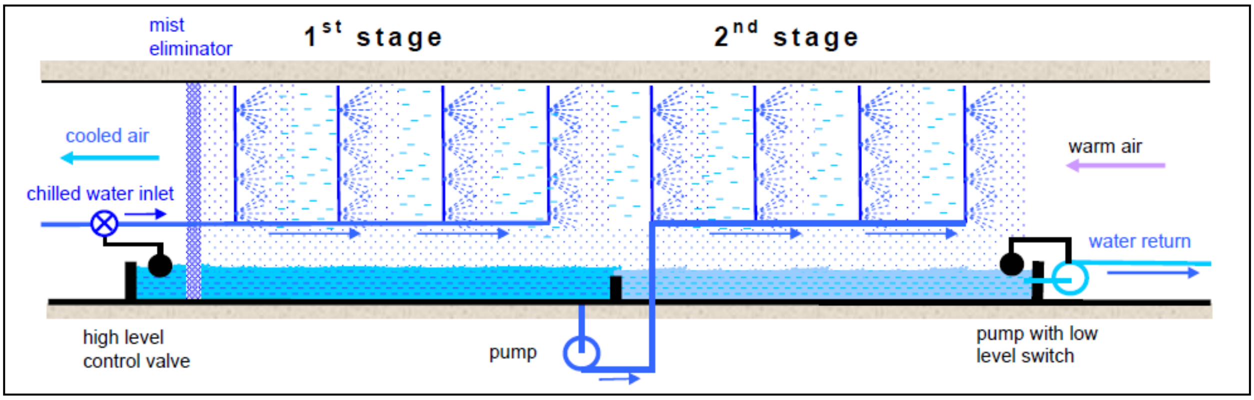

Figure 19: Schematic illustration of a two-stage horizontal spray chamber (McPherson, 1993)

In addition to cooling and dehumidifying the air, air coolers can also reduce dust concentrations. Figure 20 shows the accumulation of sediment in the sump of a vertical BAC. A build up of dust particles in the re-circulating water system can cause fouling of pipes and heat exchangers. This may necessitate the installation of filters or sedimentation zones (McPherson, 1993) that should be cleaned regularly.

Figure 20: A common problem experienced on mines is sediment build up in dams and sumps

Portable and enclosed air coolers have also been developed. These coolers are often mounted on sleds or wheels, and are often referred to as spray mesh coolers. Figure 21 is a schematic drawing illustrating the principle of operation of the portable mesh cooler. It is important that the area and time of contact between air and water is maximised. This requirement and the possibility of high water loading are critical considerations during the design of the cooler to ensure that it can be used for portable applications (McPherson, 1993).

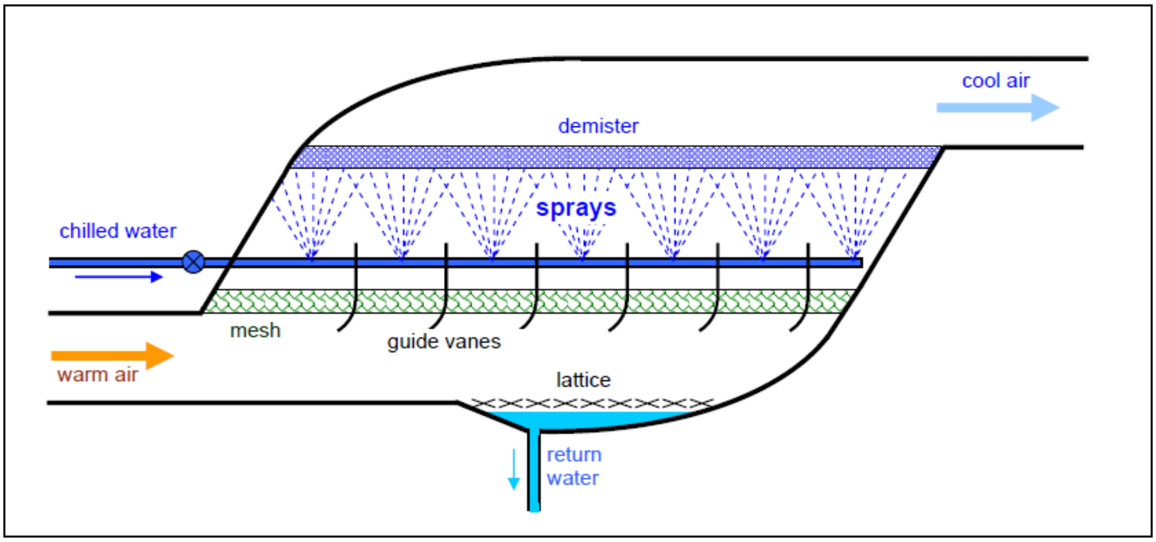

Figure 21: A section through a portable mesh cooler (McPherson, 1993)

Direct heat exchanger performance

The rate of heat rejection in the cooling tower depends on the heat load imposed on it. If the cooling tower is inefficient in transferring heat from the water to the air, the temperature of the water throughout the circuit will rise until a balance is obtained between heat loss and heat gain. This can result in a decrease in the COP of the refrigeration plants (McPherson, 1993).

The same theoretical analysis can be applied to both cooling towers and chilled water air coolers. Figure 22 illustrates the decrease in water temperature as it falls through a cooling tower and the subsequent increase in wet-bulb temperature of the air.

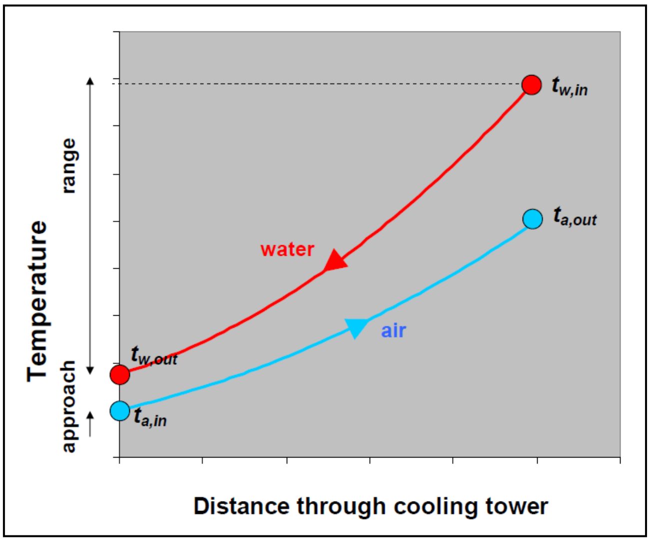

Figure 22: Variation of water temperature and air wet-bulb temperature through a cooling tower (McPherson, 1993)

The range is the change in the temperature of the water:

$$range = t_{w,in} - t_{w,out} \tag{5}$$

The approach is the difference between the temperatures of the water outflow and the wet-bulb temperature of the air inflow:

$$approach = t_{w,out} - t_{a,in} \tag{6}$$

A perfect cooling tower would result in a situation where the water leaves at the same air inlet wet-bulb temperature (7), while the air would leave at the temperature of the incoming water (8) (McPherson, 1993) – that is:

$$t_{w,out} = t_{a,in} \tag{7}$$

$$t_{a,out} = t_{w,in} \tag{8}$$

The performance of a cooling tower is actually usually measured by its efficiency (η_w) as opposed to COP. The efficiency of a cooling tower is calculated as follows (McPherson, 1993) (9):

$$\eta_w = \frac{actual\ heat\ loss\ \ from\ water}{theoretical\ maximum\ heat\ loss\ that\ could\ be\ lost\ \ from\ water} \tag{9}$$

$$\eta_w = \frac{t_{w,in} - t_{w,out}}{t_{w,in} - t_{a,in}} \tag{10}$$

$$\eta_w = \frac{range}{range + approach} \tag{11}$$

The difference between the outlet water temperature and the inlet air temperature will typically be very small in an efficient cooling tower.

Hot and cold water storage dams

Hot and chilled water storage dams are used to provide storage capacity in the system (McPherson, 1993). This additional storage capacity allows the mine to cope with fluctuations in demand. Mines will often make use of additional storage capacity to aid in implementing load shifting and peak clipping initiatives. The build up of sediment will reduce the dam’s capacity, which in turn limits opportunities to shift electrical load during peak times.

2.3 PROBLEM IDENTIFICATION

Introduction

The foremost priority of a mine cooling system is to enable the complete mine cooling and ventilation system to function properly and reliably (Van der Walt & De Kock, 1984). Literature contains a number of tools and techniques to improve the operational performance of the cooling system. The majority of these interventions are costly and/or implemented in less industrial applications than the mining environment. Furthermore, cooling systems operate in diverse combinations of load and weather conditions meaning there is no straightforward means to assess the potential electricity savings resulting from optimal control (Yu & Chan, 2012).

Chillers

Variable speed drives

Recent advances in design and semiconductor technology have meant that the use of VSDs has become more popular and financially viable (Teitel, et al., 2008; Beggs, 2002; Johansson, 2009) (Figure 23). Studies show that the use of variable speed electric motors is the most efficient means of realising energy savings whilst operating under a given load (Kaya & Canka Kilic, 2004; Mecrow & Jack, 2008). For example, pressure drop and frictional resistance can all but be eliminated by opening valves fully and controlling water flow using VSDs (du Plessis, et al., 2013). VSDs are typically installed between the electric motor and its power supply.

Figure 23: VSDs installed on a mine cooling system

One study pertaining to the use of VSDs involves the optimal control of thermal systems by the development and implementation variable flow strategies. These strategies entailed matching evaporator flow with demand for chilled water, and condenser flow with heat load (du Plessis, et al., 2013). The study was made possible by the installation of VSDs on the evaporator and condenser pump motors respectively. Results include improved chiller COPs and a reduction in overall power usage whilst maintaining chilled water service delivery requirements.

Research shows that the widespread implementation of this variable flow strategy on mines across South Africa will result in significant electrical energy savings and reduced carbon emissions (du Plessis, et al., 2013). Payback periods for VSD installations on pumps and cooling tower fans are typically in the region of eighteen months. The authors also investigated the possibility of installing VSD technology on chiller compressors. Results show that this strategy is not economically feasible at present for large chillers, but may be viable on smaller chillers with cooling capacities of less than 6 MW.

Saidur et al. (2011) present a similar study into the effects of installing VSDs on the chillers and cooling auxiliary equipment at the University of Malaya. Estimates show potential savings of 8 368 MWh and 23 532 MWh can be realised on the chillers and auxiliary equipment respectively. Motors can be operated at a 60% speed reduction and chiller load can be reduced up to 50%. Additional benefits include a significant reduction in carbon emissions. Payback periods for using VSDs on pump and fan motors was found to be a few months.

The cost of low voltage drives applicable to pumps and fans in South Africa ranges between US$ 155 /kW and US$ 105 /kW. The cost per kilowatt generally decreases with an increase in power rating. Medium voltage VSDs have a significantly higher cost per kilowatt, ranging from US$ 200 /kW for an 800 kW, 6 600 V drive, to US$ 279 /kW for an 800 kW, 11 000 V drive (du Plessis, et al., 2013). Medium voltage VSDs will typically be installed on large pumps and chiller compressors.

One of the main reasons for the non-feasibility when installing chiller VSDs is the associated installation costs. Most of the chillers currently in operation on mines were designed and installed in the 1980s and early 1990s. The original designs only allowed for small load ranges. This means that the chillers will often require modifications to the impeller and expansion valves to accommodate operations conducive to VSD control (du Plessis, et al., 2013).

Chiller maintenance

Another novel approach for improving the long-term efficiency of cooling systems has been developed by an Israeli company called CQM (Ltd). CQM developed a product called ATCS (automatic tube cleaning system), which is installed on the heat exchangers of cooling systems (Figure 24)[4]. The system keeps the tubes clean without the need for stoppages or human intervention. The system injects sponge balls, which are slightly larger than the diameter of the

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[4] http://www.cqm-tech.com/products_atcs.html (Accessed 2013/08/11).

tubes themselves, into the tubes. The sponge balls then rub the tubes clean before being trapped at the outlet and cleaned for the next run.

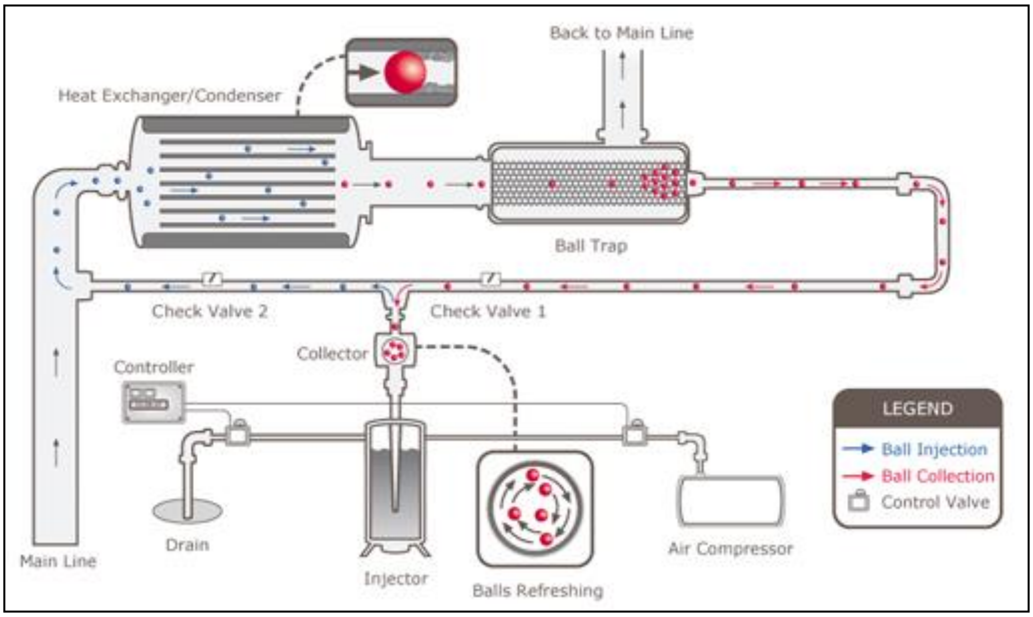

Figure 24: ATCS schematic layout

Studies show that this technology has been successfully implemented in the cooling system of a sulphide retrieval mono-ethanolamine treatment plant (Sugarmen, et al., 2007), a subway station in Guangzhou, China (Guangzhou Ailo Mechanical & Electrical Company Ltd., n.d.), and a bromine compounds facility (Yossi & Amir, 1997). All three cooling systems operate in unique environments with their own specific cooling requirements. Results after implementation include increased productivity and operational efficiency, minimal plant shutdown, reduced energy consumption and decreased managerial effort. One problem encountered was the damage to and loss of the sponge balls. This harms downstream equipment, raises environmental concerns, and results in increased cleaning costs.

Most of the mines visited have not implemented any sort of formal maintenance schedule. These studies have highlighted the benefits of regular maintenance and warrants further investigation.

Chiller control

Yu and Chan (2012) use cluster analysis to assess the operating performance of chiller systems. Cluster analysis is a statistical tool used to identify groups of individuals similar to each other but different from individuals in other groups. This study attempts to establish which operating conditions contribute to high or low system performance. The study uses a systematic method to rank operating variables according to their influence on the COP of any chiller. This in turn will allow for controllable variables to be managed thus yielding higher COPs.

Based on the sensitivity coefficients calculated in Yu and Chan's study, they suggest first examining the chilled water flow rate to improve system COP, and then the condenser inlet temperature. This allows for an optimum trade-off between compressor power and cooling tower fan power. The sensitivity coefficient is used to help judge which controllable variable should be rectified first to reduce electricity consumption without incurring additional costs (Yu & Chan, 2012).

Chan and Yu (2005) looked at operating data from air cooled chillers to analyse how chiller components react with each other. They then developed a model that uses a floating condenser temperature control to improve system performance. A floating condenser temperature is achieved by varying the number of condenser cooling tower fans in operation, and setting the condensing temperature set point of the chillers based on ambient conditions. The study predicts constant, yet at times inefficient, chiller efficiencies at varying part load conditions.

Load shifting has also proved a successful DSM strategy (Van der Bijl, 2007; Swart, 2003; Calitz, 2006). These studies utilise improved control and scheduling of existing infrastructure to shift electrical load away from high cost and demand periods. This strategy of achieving electrical savings using existing infrastructure raises the question whether there could be additional energy savings potential using similar principles.

Cooling towers

CQM (Ltd) has also developed an innovative electrolytic method for combating scale and sediment build up in water systems[5]. The technology has been successfully implemented in industrial cooling applications and water purification plants (CQM, 2007). A cathode creates a high pH solution, encouraging scale formation within the device. In addition, small quantities of chlorine are generated by the process which helps to eliminate algae and bacteria in the water. Suspended solids are also removed from the solution. This technology treats the water prior to its passing through the cooling towers and or chillers.

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[5] http://www.cqm-tech.com/products_srs.html (Accessed 2013/08/11).

Schutte et al. (2013) look at the benefits of efficient pre-cooling of water prior to refrigeration. In this study, the entire pre-cooling towers had to be replaced. Sediment build up in the tower fill, as well as broken fans, resulted in poor heat transfer. A lack of monitoring and the unavailability of data pertaining to tower performance can be blamed for this escalation and subsequent costly intervention. Upgrading of the pre-cooling towers resulted in a 4 °C decrease in outlet temperature, under comparable conditions, after the intervention.

Installation of VSDs on the fans of cooling towers has also proved to be beneficial (du Plessis, et al., 2013; Saidur, et al., 2011).

2.4 CONCLUSION

The various components of typical mine cooling systems are analysed in Chapter 2. Attention is also given to their susceptibility to performance deterioration. Methods to improve cooling system component utilisations and performance are studied. The majority of these interventions involve costly installations or modifications. It is envisaged that savings can be realised through implementing principles similar to those found in literature, particularly improved maintenance.

Chapter 3 will explore the various techniques that can be used to monitor component performance. Their implementation and interpretation will also be considered.

3. DEVELOPMENT OF MINE COOLING SYSTEM PERFORMANCE MONITORING TOOLS

3.1 INTRODUCTION

Methods and tools to monitor the performance of mine cooling system components will be investigated in Chapter 3. This will allow mine personnel to take a high-level, yet proactive, approach to maintenance and refine their operational procedures. Decreases in component performance can be addressed before adversely affecting electrical energy usage or chilled water service delivery.

3.2 PERFORMANCE MONITORING TOOLS

Background

Performance monitoring tools are used to measure the inputs, outputs, impacts and outcomes of a process. This allows a project team to assess its progress toward the objective and, in turn, its success. Performance monitoring tools utilise indicators that are organised in a way that clarifies the interdependence of inputs and outputs, and helps to identify problems that may impede the achievement of project objectives (Mosse & Sontheimer, 1996).

Mosse and Sontheimer (1996) identified a number of reasons that affect the impact of bank operations. Based on site visits, these findings can also be applied in the mining environment, particularly cooling systems. The first reason states that too much emphasis is placed on the mechanics of a project. It is clear from the majority of mines visited that the primary objective of foremen is to ensure the cooling systems are operational. Foremen often adopt a 'if it's not broken, don't touch it' approach. Little attempt is made to investigate and implement strategies to improve performance.

The second reason suggests that risks and factors that influence project or process outcome are poorly identified (Mosse & Sontheimer, 1996). Generally, cooling system component performance is not monitored consistently over time. Management have little idea as to which influences have the greatest impact on the cooling process. If management do not know which factors influence the cooling system the most, they cannot mitigate the risks associated with each factor.

The third reason identified by Mosse and Sontheimer (1996) states that objective criteria, transparency and consistency across units are lacking. Motivation, training and knowledge often vary significantly from operator to operator and from foreman to foreman. This results in varying methodologies based on individual judgement, and a blurring of targets and objectives. Most sites have developed best practice methodologies to keep plants running. Their implementation thereafter appears to be lacking.

The final reason states that ratings are often overly optimistic (Mosse & Sontheimer, 1996). The same can be said for management responsible for cooling system operations. Mine personnel expect to continue achieving the targets set out by the design specifications of cooling system components. However, performance trends are hardly monitored and regular maintenance is not implemented. If a change is not made to the system itself, one is not going to see the process meet its requirements.

Mosse and Sontheimer suggest that a supervisory reporting system should be adopted to include performance monitoring indicators. These indicators should be derived from the process objectives. Performance monitoring indicators must be based on the unique objectives of the process. At present, most performance monitoring of chiller systems focuses on individual variables that form part of a process. These include flow rates and temperatures, and not system efficiency.

Guidelines have been developed for chiller performance monitoring and troubleshooting (NMAC, 2002). This report focuses on cooling systems specifically in the nuclear environment. Information and principles in the report can be applied to any cooling system. The report describes which system variables should be monitored and the equipment that can be used. Equipment mentioned in the report includes the use of flow meters and pressure transmitters.

Mines are, however, recording all this information already. Problems arise because they do not monitor these system variables in a satisfactory manner. The report does not make mention of any performance monitoring of overall system efficiency. It provides information on how to calculate important system efficiencies that can be used for quick decision-making. Important trends in system performance do not appear to be considered.

There are performance monitoring tools on the market at present. The majority, however, do not consider chiller performance. ABB has developed a service that combines hardware and remote monitoring to identify abnormal conditions on mine winders (ABB, n.d.). The tool uses continuous monitoring with real-time alarms. Such a system provides a proactive approach to system monitoring, thus reducing maintenance costs and downtime.

Another unique tool has been developed by a South African firm known as TAS Online[6]. The tool is specifically designed to monitor and provide feedback on pump performance. TAS Online uses the fluid flow and pump power usage to calculate a pump’s efficiency. This allows a user to know how efficiently the pumps are operating. Operating pumps at higher efficiencies will reduce power consumption, maintenance costs and pump failure induced downtime.

It is envisaged that similar tools, designed for cooling system components, will prove just as beneficial.

Instrumentation

An important factor for the efficient operation of chillers is the sensitivity and accuracy of instrumentation. Water flow rates, inlet and outlet temperatures, and power usages are just some of the key measurements needed for proper chiller sequencing control. Measurement accuracy is easily influenced by system dynamics and general equipment deterioration (Sun, et al., 2010). Faults in chiller systems can result in excessive energy consumption and decreased operational lifespan (Xu, et al., 2008).

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[6] http://www.tasonline.co.za/ (Accessed 2013/04/10).

Sun et al. (2010) developed an online fault detection and diagnosis strategy based on data fusion technology for building cooling system load measurement. A data fusion algorithm generates a confidence interval that is used to indicate the existence of faults. Confidence intervals are based on expected values for various system variables – for example, water temperatures and water flow rates. The strategy was tested on a high-rise building in Hong Kong. Results indicate that this proposed method to detect faults is highly effective. Faults can be isolated easily, even in the event of faults occurring simultaneously.

Principal component analysis (PCA) has been used to model and correlate compressor power and the temperature and pressure of evaporators and condensers (Xu, et al., 2008). PCA is a method used to identify patterns in data, and to express the data in a way that highlights their similarities and differences (Smith, 2006). A number of sensors concerned with the control and monitoring of chiller systems are used in a PCA model to capture systematic variations of chiller performance. The authors used wavelet analysis to detect and diagnose faulty sensors and recover measurements to enhance the reliability and accuracy of the PCA model. Wavelet analysis is a tool that can be used to analyse changes in variance or time series with different timescales (Torrence & Compo, 1997).

The wavelet-PCA strategy was validated using operational data from an existing chiller plant. Sensor faults of varying magnitudes were systematically introduced to test the sensitivity of the strategy. Results show improved performance of sensor fault detection and diagnosis ratios compared with conventional PCA-based fault detection without wavelet analysis (Xu, et al., 2008).

Similarly, Wang and Cui (2005) developed a fault detection method whereby a number of critical chiller sensors are assigned to two models based on PCA. The models group a set of correlated variables and capture trends of the chillers. Statistical tools such as Q-statistic and Q-contribution plots are used to detect and diagnose faults respectively.

The extent of performance monitoring in the cooling environment appears to be limited to individual variables and fault detection. In addition, the implementation of recommendations from literature and their interpretation thereof may be difficult, considering the resources of mines. There is an opportunity for a high-level system performance monitoring tool that is effective, yet simple to interpret.

Statistical control charts

Overview

Any defined and documented process can be stabilised and then improved. Without valid measurements, process improvements are difficult, if not impossible. Statistical control charts are one of the most effective ways to measure process performance. Control charts are used to identify, and differentiate between, special and common causes of variation. When a process no longer exhibits special causes of variation (and only exhibits common variation) the process is said to be stable (Gitlow, et al., 2005).

Common causes of variation are inherent in any process. Common variation is composed of many sources that are present in a process and that affect all elements of the process. The process capability is determined by common causes of variation. Employees and operators cannot control common causes of variation. To improve the process capability, changes must be made to the process (Gitlow, et al., 2005). Mine cooling system performance is susceptible to a number of variables that can result in common variation. These include ambient conditions, as well as water and refrigerant temperatures and flow rates.

Special causes of variation are due to events external to the usual functioning of the system. Detection, possible avoidance, and rectification are the responsibility of the people directly involved in the process. Once a special cause of variation that has a negative impact on the process has been identified, measures should be put in place to ensure it does not recur (Gitlow, et al., 2005).

Statistical control charts use control limits to help identify and separate common and special causes of variation. Typically, values above the upper control limits or below the lower control limits signify special causes of variation.

Management must be aware of the different causes of special and common variation within the cooling system. For example, when monitoring the performance of a chiller, a possible cause of common variation could be the gradual build up of sediment within the heat exchanger. This will result in a gradual decrease in COP of a chiller. Identifying this common cause of variation and rectifying it – i.e., making a change to the process itself – will result in an increase in COP. If not identified, the excessive build up of sediment may result in the malfunction of the chiller or supply pumps, resulting in a special cause of variation.

Management might not be able to control all sources of common variation, but they should be able to put measures in place that mitigate their possible negative effects. Special causes of variation might occur due to operator error or mechanical failures. Being aware of the different causes of variation within the system will allow management to make informed decisions and allow for the prioritising of work schedules.

There are two types of statistical control charts: attribute and variable control charts. The type of chart used will depend on the application and the data that is available. Attribute control charts classify a process output as good or bad, or conforming or non-conforming. Variable control charts often contain more information than attribute control charts, and use measurements – for example, lengths, flow rates, or efficiencies (Gitlow, et al., 2005).

Statistical control charts have been used before in conjunction with chiller applications (Zhao, et al., 2013). This study's primary focus, however, is on fault detection and diagnosis, as opposed to chiller performance monitoring. It is felt that statistical control charts can be used to do both – that is, fault detection and performance monitoring. The primary advantage of statistical control charts is that only basic programming is required in Microsoft Excel. Their interpretation is also simpler than previously mentioned fault detection techniques.

Attribute control charts

There are two types of attribute control charts: classification charts and count charts. Each chart has its own conditions for use. Classification charts can take the form of either a *p* chart or an *np* chart. The *p* chart deals with the fraction of items in a series of subgroups that have a particular characteristic. The *np* chart is used to control the number, rather than the fraction, of items with a certain characteristic, and is only used with constant subgroup sizes.

Count charts deal with the number of times a characteristic appears in a given area of opportunity. There are two different count charts: *c* charts and *u* charts (Gitlow, et al., 2005). In general, attribute control charts classify outputs as either conforming or non-conforming, pass or fail.

A manager may be comfortable with categorising the performance of a component into two categories, such as good and bad. One might argue that if the COP of a chiller were above 3.5, for example, the performance was good. A manager could then plot the number of days in each month that the system COP was unsatisfactory, thus identifying which periods of the year the system performs better. Attribute control charts can be used for performance monitoring purposes, but may mask crucial information due to their simplicity (Gitlow, et al., 2005).

Variables control charts

Variables control charts will not mask crucial information as can be the case with attribute control charts. There are three types of variables control charts: $\bar{x}$ and R charts, $\bar{x}$ and s charts, and the individuals and moving range chart. All these charts are used when striving for continuous process improvement (Gitlow, et al., 2005).

The variables control charts are most suited to the cooling system application where a number of variables are used to calculate COPs and efficiencies. A good starting point is to monitor the average performance of each component daily. In looking for continuous improvement, a manager might consider monitoring the performance of the components more regularly – for example, hourly.

Individuals and moving range charts are typically used when only one variables measurement is available – for example, hours per week worked or, in this instance, daily average COP of an individual chiller. $\bar{x}$ and R charts and $\bar{x}$ and s charts are generally used when sampling two or more subgroups – for example, the daily average COP of a refrigeration plant comprised of two or more chillers (Gitlow, et al., 2005).

Applications

The performance of cooling systems, and of chillers in particular, is typically measured based on their respective COP. The COP of a chiller can be calculated as follows:

$$COP = \frac{thermal\ cooling\ (kW)}{electrical\ input\ (kW)} \tag{12}$$

$$COP = \frac{mass\ \ flow \times specfic\ heat\ capacity \times change\ in\ temperature}{current \times voltage \times \sqrt{3} \times power\ \ factor} \tag{13}$$

$$COP = \frac{\dot{m} \times C_p \times (t_{in} - t_{out})}{I \times V \times \sqrt{3} \times power\ \ factor} \tag{14}$$

Monitoring the performance of cooling system components using variables control charts yields a number of benefits. Management personnel will be able to identify trends in performance and ascertain the process average and variability. In addition, control charts form useful problem-solving and decision-making tools.

A sudden spike or dip in the process performance should be reason for further investigation. The change could have been caused by any number of factors. A change in performance could have been caused by a faulty flow meter, an incorrect reading at a temperature sensor, or a faulty power meter. If the performance of the component is not monitored, the likelihood of this fault being noticed timeously is minimal.

Control charts also allow management to track performance averages and performance deviation. A wide variation in performance results in a widening of control limits.

Process variation

Data is usually retrieved via a mine's Supervisory Control And Data Acquisition (SCADA) system and stored in a database. The SCADA (see the example in Figure 25) is typically used for real time control purposes only.

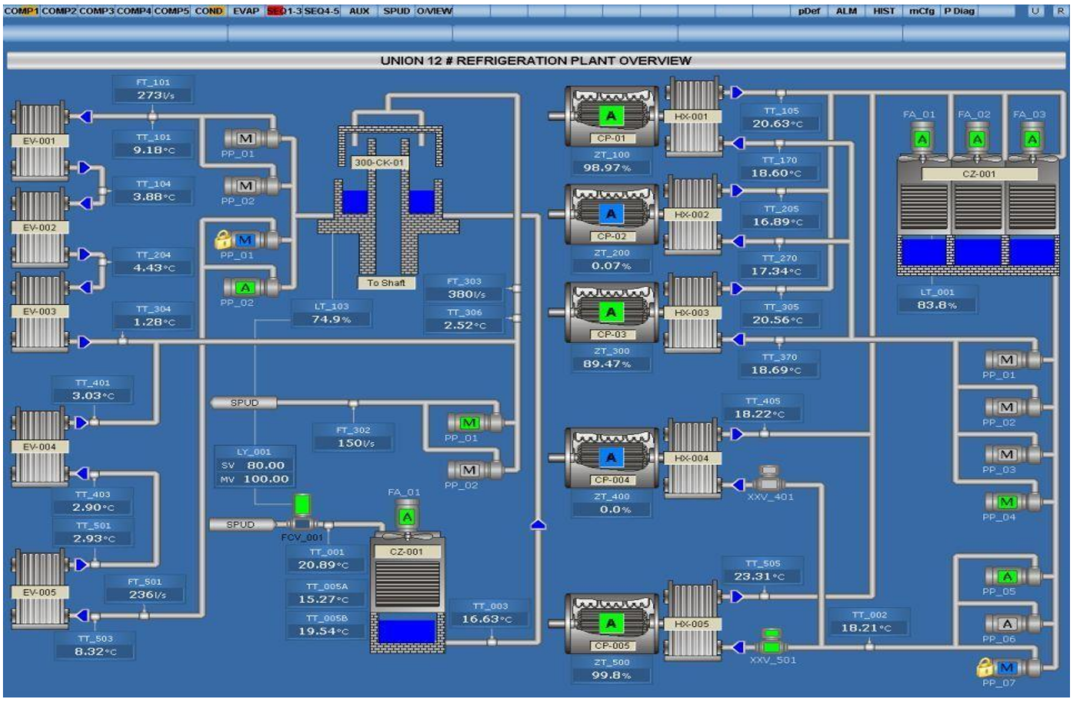

Figure 25: Example of a mine SCADA

As mentioned previously, mines generally have vast amounts of data and information available to them. Whether or not this information is used will often determine the long term effectiveness of their systems.

In general, managers and engineers do not often have time to process and analyse data. Key Performance Indicators (KPIs) can be used to monitor the performance of cooling system components and to provide managers with high level indicators on which decisions can be based. These KPIs must take into account all system variations. If managers are not aware of process and system variations, they will, at times, over-react.

3.3 METHODOLOGY

Introduction

Regular measurement of indicators allows one to track and monitor trends over time. Indicators provide valuable information that aid decision-makers formulate informed decisions and allow for continuous improvement (Department of Minerals and Energy: Republic of South Africa, n.d.).

To utilise statistical control charts effectively, one should have a thorough understanding of the process being monitored as well as the ‘rules’ associated with control charts. Gitlow et al. (2005) refer to the seven rules for identifying ‘out-of-control’ points. These rules have been developed to help identify whether or not a process exhibits a lack of statistical control.

The first of these rules states that a process exhibits a lack of control if a point lies outside the control limits. Other rules include three consecutive points lying within one or more standard deviations on the same side of the centreline, or an unusually high number of consecutive points lying above or below the centreline in a saw tooth pattern. These trends indicate that a process exhibits a lack of control (Gitlow, et al., 2005). If one is not aware of these rules, a situation may arise where management may become over- or un-reactive. Over-reactive managers will make changes to the system where change was not necessary. Un-reactive managers will ignore signs of lack of control, often leading to a significant malfunction of the process.

From site visits and meetings with mine personnel, it was evident that the performance of the various components of the cooling system were not graphically represented or monitored. Operators simply monitor real time readings on the SCADA, and base all their decisions on these values (Figure 26). This evidence, together with the knowledge that the majority of managers do not have an understanding of statistical control charts, led to the development of what shall be referred to as Principle 1.

M1_TT1	- Compressor DE Bearing Temp	51.33	°C
M1_TT2	- Compressor NDE Bearing Temp	41.98	°C
M1_TT3	- Compressor Trust Bearing Temp	54.95	°C
M1_TT4	- Compressor Trust Relay Disk Temp	53.50	°C
M1_TT5	- Compressor Discharge Refrig. Temp	38.19	°C
M1_TT6	- Compressor Sump Oil Temp	49.97	°C
M1_TT7	- Compressor Lube Oil. Temp	44.68	°C
M1_TT8	- Compressor Suction Refrig. Temp	5.48	°C
M1_PT7	- Compressor Oil Diff Pressure	294.27	°C

Evaporator

M1_TT13	- Evaporator Inlet Water Temp	11.99	°C
M1_TT14	- Evaporator Outlet Water Temp	5.87	°C
M1_TT15	- Evaporator Liquid Refrig. Temp	4.18	°C
M1_TT16	- Evaporator Evaporating Refrig Temp	5.38	°C
M1_PT2	- Evapotaror Pressure	261.57	kPa
M1_PT5	- Evaporator Inlet Water Pressure	106.77	kPa
M1_PT6	- Evaporator Outlet Water Pressure	0.00	kPa

Main Motor

M1_TT23	- Main Motor NDE Bearing Temperature	68.92	°C
M1_TT24	- Main Motor DE Bearing Temperature	58.48	°C
M1_X16	- Main Motor Current	130.82	A

Condenser

M1_TT9	- Condenser Inlet Temp	22.57	°C
M1_TT10	- Condencer Outplet Temp	26.43	°C
M1_TT11	- Condenser Liquid Refrig. Temp	28.94	°C
M1_TT12	- Condenser Condensing Refrig Temp	30.40	°C
M1_PT1	- Condenser Pressure	745.95	kPa
M1_PT3	- Condenser Inlet Water Pressure	133.10	kPa
M1_PT4	- Condenser Outlet Water Pressure	116.32	kPa
M1_VT1	- Compressor Vibration	0.66	mm/s

Gearbox

M1_TT17	- GearBox High Speed DE Bearing Temp	51.22	°C
M1_TT18	- GearBox High Speed NDE Bearing Temp	48.06	°C
M1_TT19	- GearBox Low Speed DE Bearing Temp	40.08	°C
M1_TT20	- GearBox Low Speed NDE Bearing Temp	38.37	°C
M1_TT21	- GearBox Oil Sump Temperature	40.77	°C
M1_TT22	- GearBox Lub Oil Sump Temperature	34.69	°C
M1_PT8	- GearBox Oil Pressure	167.53	kPa

COMMS MASTER 0

Figure 26: Mine SCADA - Critical indicators

Principle 1

Principle 1 simply states: *Plot and monitor the performance of the components graphically*. The performance of the components can be measured based on their respective KPIs – for example, COP or efficiency, depending on the application. The data that one has available will determine which KPI is used to monitor each component.

Benchmarks for each component can be set, from which component performance can be compared. This benchmark may be the design specification of the component or the performance level after recalibration and servicing. The manager will then have a better understanding of how the performance changes over time, and how the components of the cooling system interact and influence each other.

Figure 27 represents the COP of a typical chiller on a typical mine. This simple graph will allow the manager to gain a better understanding of the system, and how the performance of the system varies over time. The figure shows that the system COP has a downward trend. Trends assist management forecast the performance of the cooling system and to plan scheduled maintenance.

The scatter can be attributed to variations in air and water temperatures and flow rates, which in turn affect the load and efficiency of the cooling system. Chillers will typically only operate at maximum efficiency when operating conditions match design specifications.

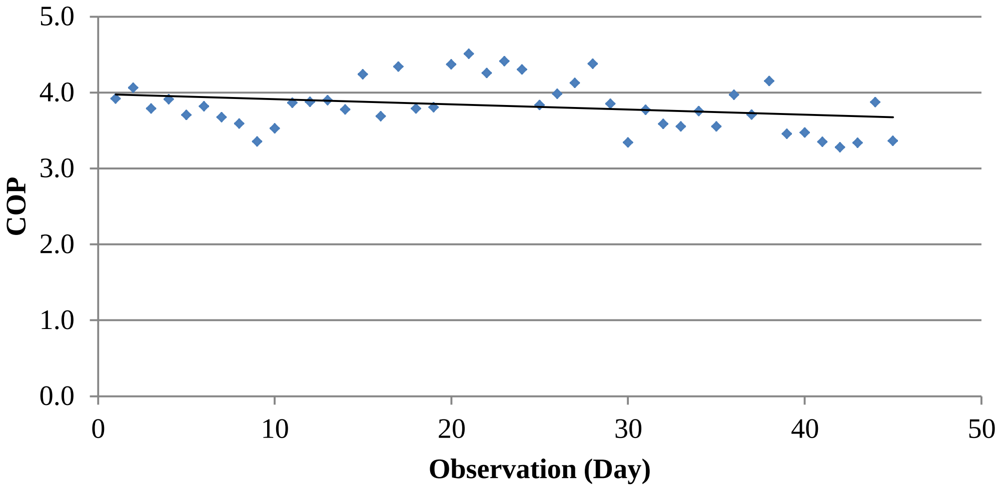

Figure 27: Graph depicting the average daily COP of a chiller

To obtain a more detailed understanding of the cooling system, KPIs can be depicted on the same graphs as other KPIs. For example, the COP can be plotted on the same graph as the corresponding power usage. Figure 28 shows, as expected, that as the power usage increases, the COP of the system decreases. One can also still see that there is a downward trend in the COP. Reasons for this trend should be investigated. Measures should be put in place to ensure that this trend does not adversely affect the performance and power usage of the system in the long term.

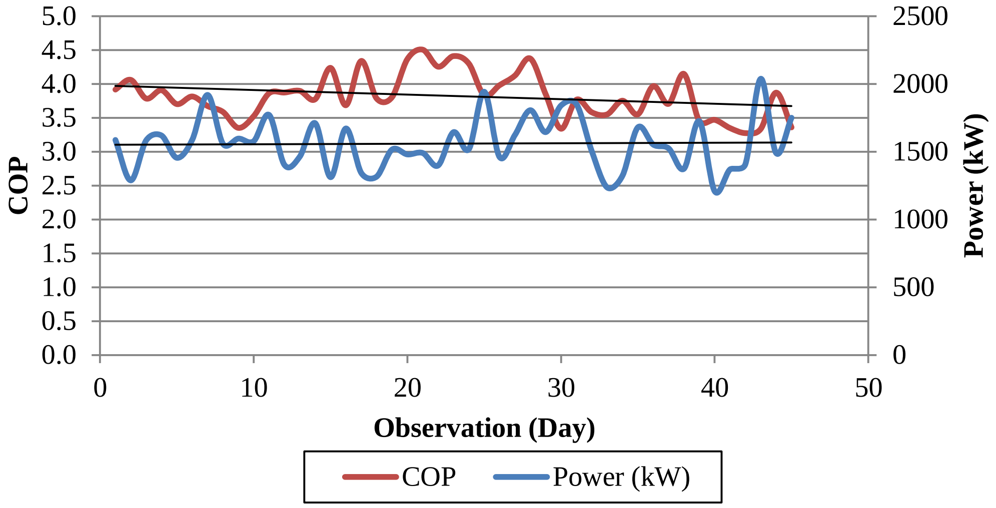

Figure 28: Cooling system COP and the corresponding power usage

It is recommended that this functionality be programmed into the mine's SCADA system. This will allow for ease of access and up-to-date performance tracking. As mentioned previously, this data is usually readily available. Simple tools like this provide a good starting point to monitor performance and detect faults.

Principle 2

With a better understanding of the system components and their influences on one another, statistical control charts should be used. This next step in performance monitoring will be referred to as principle 2: *Develop and plot the performance of the components using statistical control charts*.

Statistical control charts will allow a manager to make better informed decisions, and allow for continued process improvement and finer control. Trends and faults can still be identified. Trends will show how a process improves or degrades over time. Sudden spikes or dips in performance may point to a fault or a breakdown in the system. Control charts make use of limits and rules to identify instability in a process. The type of control chart used, the performance monitoring period, and frequency will depend on the application.

Figure 29 and Figure 30 contain the same information as Figure 27. In this instance the data is plotted on an individuals and moving range statistical control chart. The data used in the construction of this example can be found in Appendix I. The moving range portion of the figure is constructed first.

Stability must first be obtained in the chart illustrating the variability in the process (moving range chart) before the individual values can be plotted. This is because the data obtained in the moving range chart is used to calculate the limits in the individuals chart. A lack of control in the moving range portion will yield unreliable estimates of the process variation. This may lead to a failure in the control chart's ability to identify and separate special and common variation (Gitlow, et al., 2005).

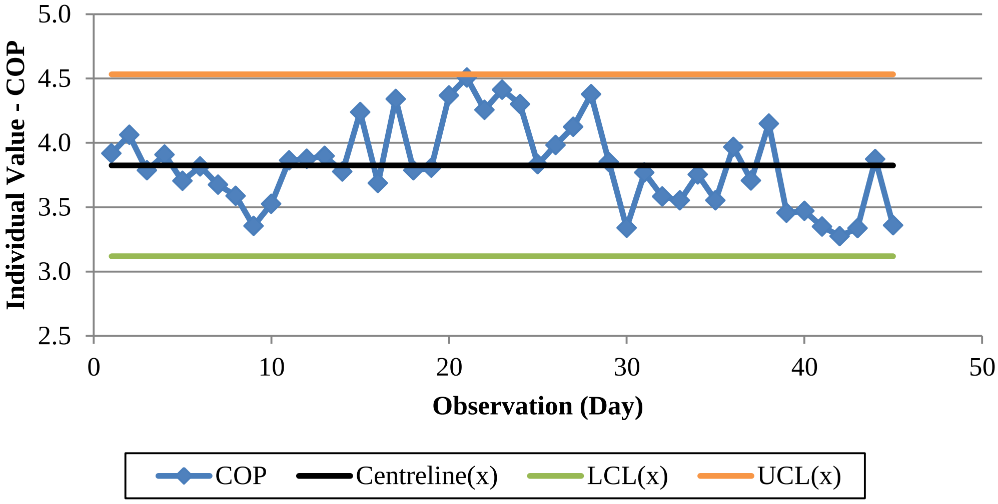

Figure 29: Individuals chart used to plot the COP of a chiller

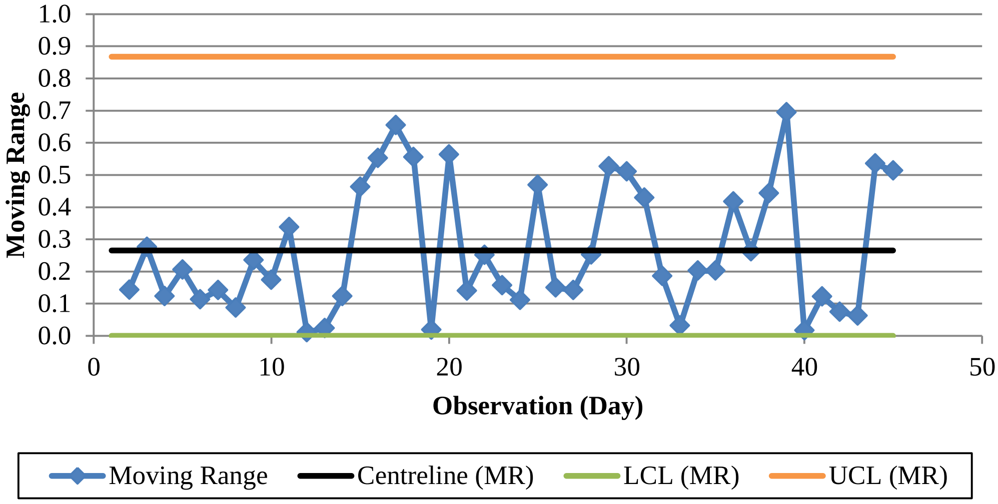

Figure 30: Moving range chart illustrating the variation in performance of a chiller

The individuals chart depicts the process performance. The moving range chart is used to determine the limits of the individuals chart. The centreline of the individuals chart (*Centreline* (*x*)) plots the process average (19). The limits and centrelines for the individuals and moving range chart are calculated as follows (Gitlow, et al., 2005):

Moving range

The moving range is an estimate of the variability based on the point-to-point variation in the sequence of values (15).

$$Moving\ range\ (R) = |x_i - x_{i-1}| \tag{15}$$

The centreline of the moving ranges chart portion is the moving range average. This is also an estimate of the overall process variation (16). The upper and lower control limits are dependent on the subgroup size and the moving range average (17) (18).

$$Centreline\ (moving\ range) = (\bar{R}) = \frac{\sum R}{k-1} \tag{16}$$

$$UCL\ (moving\ range) = D_4 \bar{R} \tag{17}$$

$$LCL\ (moving\ range) = D_3 \bar{R} \tag{18}$$

D_3 and D_4 depend on the subgroup sizes. In this case the subgroup size is two; therefore the values for D_3 and D_4 are 0.000 and 3.267 respectively. These values can be found in most statistical control chart handbooks.

Individuals

$$Centreline\ (x) = (\bar{x}) = \frac{\sum x}{k} \tag{19}$$

$$UCL\ (x) = \bar{x} + E_2 \bar{R} \tag{20}$$

$$LCL\ (x) = \bar{x} - E_2 \bar{R} \tag{21}$$

E_2 is dependent on subgroup size and can be found in most statistical handbooks. In this instance E_2 = 2.66.

Users must be cautious when applying rules for dealing with control charts that seemingly indicate a lack of control. Each type of control chart has its own unique characteristics of which the user should be aware to get the full benefit of control charts. For this reason, one should be conservative when applying the rules concerning patterns that indicate a lack of control in a process (Gitlow, et al., 2005). In this example (Figure 30), the moving range chart, which was constructed first, does not appear to exhibit a lack of control. This then allows for the construction of the individuals chart.

In the case of individuals and moving range charts, Gitlow et al. (2005) refer to two characteristics in particular of which one should always be aware. The first relates to the moving range correlation, where one large moving range value tends to be followed by another large moving range value, and small moving range values tend to be followed by other small moving range values. They urge caution when applying the rules of identifying instability in a process because of this phenomenon.

The second characteristic of which one should be aware is the presence of 'inflated limits' as a result of the way that the limits are calculated. This results in especially high upper control limits – limits that the process is unlikely to reach. If this is suspected, they suggest calculating the control limits based on the median of the moving range.

Again, to emphasise the point, the user must be aware of the intricacies associated with using statistical control charts. If used effectively, statistical control charts can be powerful tools to monitor system performance, and can add real value to operations.

Forecasting, fault-finding, and decision-making

The benefits of performance monitoring are numerous. Each component being monitored has its own particular characteristics, KPIs, and variables that are used to monitor performance. Each variable plays an important role in the overall control philosophy of the component. Monitoring system performance allows for a number of important variables to be monitored simultaneously, thus improving the long term effectiveness of each component.

Over time, management will identify trends in component performance. Identifying trends will allow for the planning of scheduled maintenance, thus minimising downtime and improving system performance. Planning of maintenance includes ensuring that the right personnel are available on a particular day, adequate stock of critical spares are readily accessible, and the possibility of ‘clashes’ with production schedules is reduced.

Performance monitoring also forms an effective fault-finding tool. Previously, mine personnel would have to monitor multiple values and components at any one time. The likelihood of detecting faulty instrumentation timeously is low. High level monitoring of KPIs indirectly allows mine personnel to monitor multiple instruments and components simultaneously, thus increasing the possibility of early fault detection.

Monitoring multiple components at any one time also permits management to make decisions with confidence. Management will be able to prioritise operations – for example operating only the most efficient components should maximum cooling not be required.

3.4 SIMULATION MODELS FOR DECISION MAKING

Simulation models are a cost-effective means to investigate the effects of system changes and to identify electricity savings potential. In industry, simulation models are used to calculate the savings potential and model the performance characteristics of multiple components. Accurate simulation models allow decision-making personnel to formulate decisions with a high degree of confidence.

Studies have been carried out to simulate the performance of mine cooling systems and chiller plants. Grollius et al. (1987) modelled the performance of centrifugal water chillers in mine refrigeration installations. Their findings allow designers to gain a better understanding of the influence of chiller parameters during the specification phase of design. In addition, operators are able to improve the operations of existing installations.

Bailey-McEwan and Penman (1987) developed an interactive computer program to simulate the performance of water chilling installations on mines. Arndt (2000) developed add-ons to existing software known as ‘QUICKcontrol’, making it suitable for use in many applications, including the mining industry.

A component-based simulation package known as 'Process Toolbox'[7] (Figure 31) has been identified as a possible simulation tool for this study. The software allows a user to model the entire cooling system and to make changes to multiple components without the need for extensive remodelling.

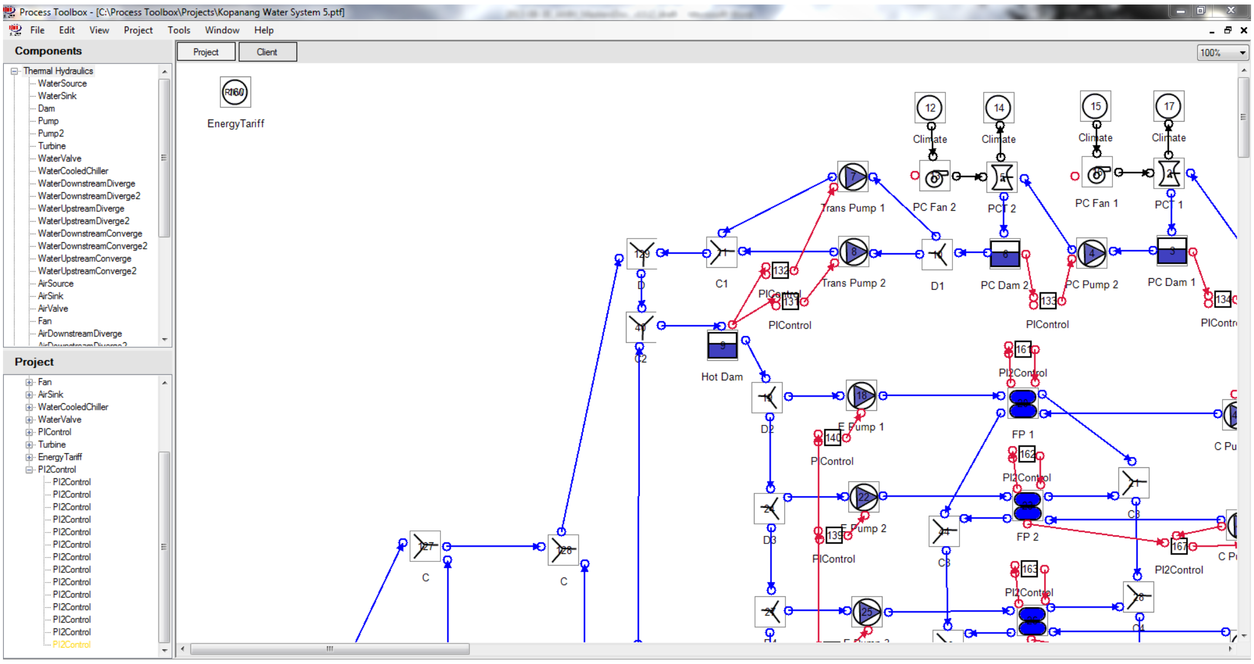

Figure 31: Process Toolbox

Monitoring cooling system performance allows mine personnel to gain a better understanding of the cooling system, trends over time, and component interdependence. Management will also gain more insight into the effects of their actions and quantify their effects on component performance. Once the effects of their decisions have been quantified, the results can be entered into a simulation model for higher fidelity. In addition, the user will be able to assess the possible impact of decisions prior to implementation.

Information gleaned from monitoring system performance can subsequently be included in simulation models. Simulation models are often used for forecasting future projects, maintenance schedules and performance. In addition, simulation models can be used to identify possible electrical energy savings potential.

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[7] Developed by TEMM International Pvt. (Ltd.). Contact Jan Vosloo: jvosloo@rems2.com; 087 980 3620.

The simulation model developed for this study will be validated before hypotheses testing. Existing system data such as flow rates and temperatures, as well as pump sizes and chiller capacities, will be verified before use. The model will allow various scenarios to be simulated.

3.5 CONCLUSION

Performance monitoring tools were identified in Chapter 3. These tools include the use of scatter charts, statistical control charts and simulation modelling. Performance monitoring tools allow management to quantify the effects of their decisions and identify trends in performance. Once the effects of these decisions have been quantified, management can use this additional information in simulation models for higher fidelity.

In Chapter 4, the tools identified in Chapter 3 will be applied to a specific mine cooling system at a gold mine near Carletonville.

4. APPLICATION OF PERFORMANCE MONITORING TOOLS

4.1 INTRODUCTION

By implementing performance monitoring tools, mine personnel will gain a better understanding of the cooling system. In addition, information gleaned from these tools will be used to identify and test scenarios relating to potential energy savings strategies in Chapter 5.

4.2 CASE STUDY

Design and operation

A schematic layout of the mine cooling system under study at a gold mine near Carletonville is shown in Figure 32. Typical operating conditions are as follows: hot water at a temperature of 28 °C is pumped from underground to the hot dam. This hot water is pumped to, and sprayed through, the pre-cooling towers where it is stored in a pre-cool dam. The average temperature of the water in the pre-cool dam is 18 °C. A total of 26 Ml/day is pumped from underground during an average day, and a total of 24 Ml/day during winter months.

The pre-cooled water is pumped through two parallel sets of chillers. Each set consists of two chillers configured in series to provide chilled water at 5 °C in the chill dam. The combined cooling capacity of the surface refrigeration plant is 42 MW. The combined COP of the surface refrigeration plant is 5.25 at design conditions.

From the chill dam, 180 l/s of water flows though the BACs. The water collects in the BAC sump before being pumped back to the pre-cool dam. The remaining chilled water is sent underground.

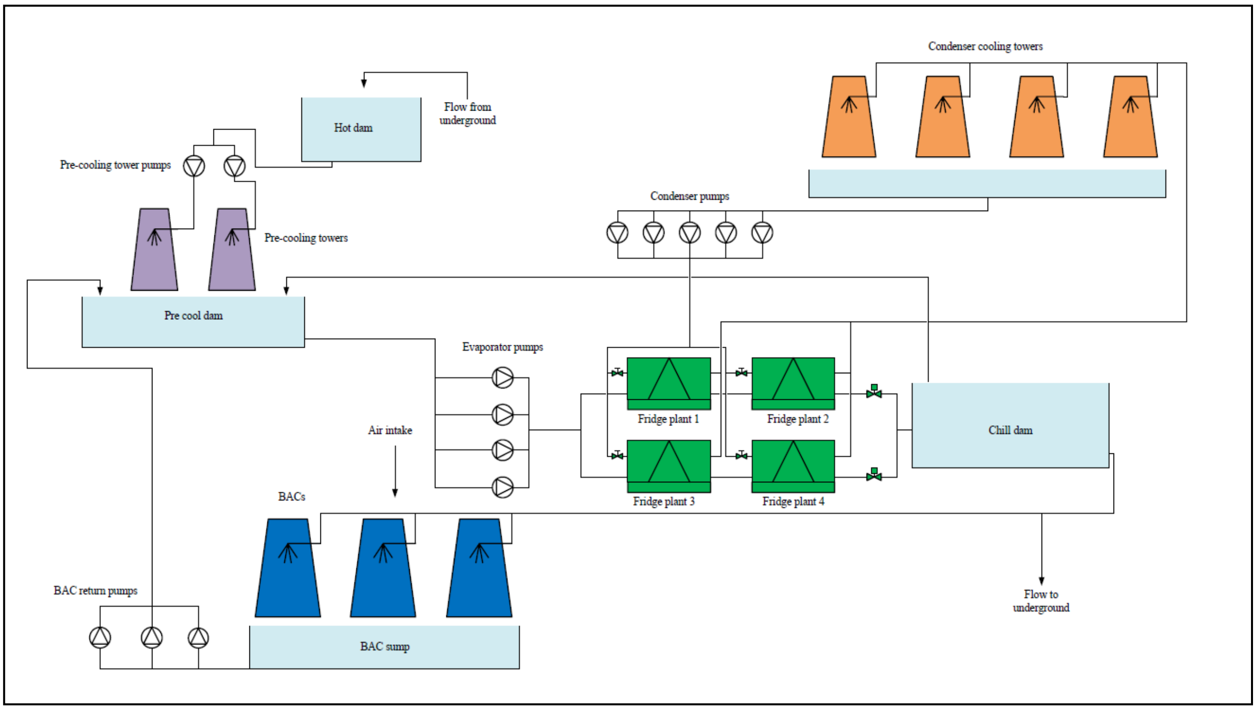

Figure 32: Schematic layout of mine cooling system under investigation

The surface refrigeration plant specifications are displayed in Table 1. An image of one of the chillers can be seen in Figure 33.

Table 1: Refrigeration plant specifications

Description	Value
Number of chillers	4
Make	Hitachi
Compressor type	Centrifugal
Refrigerant	R134a
Voltage (V)	6600
Cooling capacity (kW)	13300
COP	6.65
Evaporator outlet temperature (˚C)	5.9
Condenser inlet temperature (˚C)	18.5
Evaporator water flow (kg/s)	300
Condenser water flow (kg/s)	600
Evaporator pump motor rating (kW)	90
Number of evaporator pumps	4
Condenser pump motor rating (kW)	185
Number of condenser pumps	5

Figure 33: Example of a chiller currently being used on the mine

The surface pre-cooling tower specifications are displayed in Table 2. An image of the pre-cooling towers currently in use can be seen in Figure 34.

Table 2: Pre-cooling tower specifications

Description	**Value**
Number of cooling towers	8
Water inlet temperature (˚C)	28
Water outlet temperature (˚C)	24
Water flow (kg/s)	300
Air inlet wet-bulb temperature (˚C)	22

Figure 34: Pre-cooling towers currently in use at the mine

The condenser cooling towers currently in use can be seen in Figure 35. The surface condenser cooling tower specifications are displayed in Table 3.

Table 3: Condenser cooling tower specifications

Description	**Value**
Number of cooling towers	4
Water inlet temperature (˚C)	32
Water outlet temperature (˚C)	27.5
Water flow (kg/s)	670
Air inlet wet-bulb temperature (˚C)	22

Figure 35: Condenser cooling towers

The surface BAC specifications are displayed in Table 4, and an image of the BAC can be seen in Figure 36. The mine currently has three operational BACs.

Table 4: BAC specifications

Description	**Surface BAC 1 & 2**	**Surface BAC 3**
Number of BACs	2	1
Water inlet temperature (˚C)	3	3
Water outlet temperature (˚C)	14	14
Water flow (kg/s)	150	150
Air flow (kg/s)	225	230
Air inlet wet-bulb temperature (˚C)	18	18
Air outlet wet-bulb temperature (˚C)	7	7
Pump motor rating (kW)	75	75
Number of pumps	2	1

Figure 36: Three BACs currently in operation at the mine

Electrical energy usage of cooling system

An independent third party is currently monitoring the performance of the mine's cooling system. This is as a result of an Eskom-funded energy efficiency project. It was therefore assumed that all the data obtained from the mine have been verified and are accurate.

The average monthly power usage of the cooling system in this case study can be seen in Figure 37. The drop in power usage in the winter months can be attributed to a reduction in the number of chillers in operation. This is due to the fact that the BACs are not in operation during the cool, dry months. This reduces the amount of water that needs to be chilled.

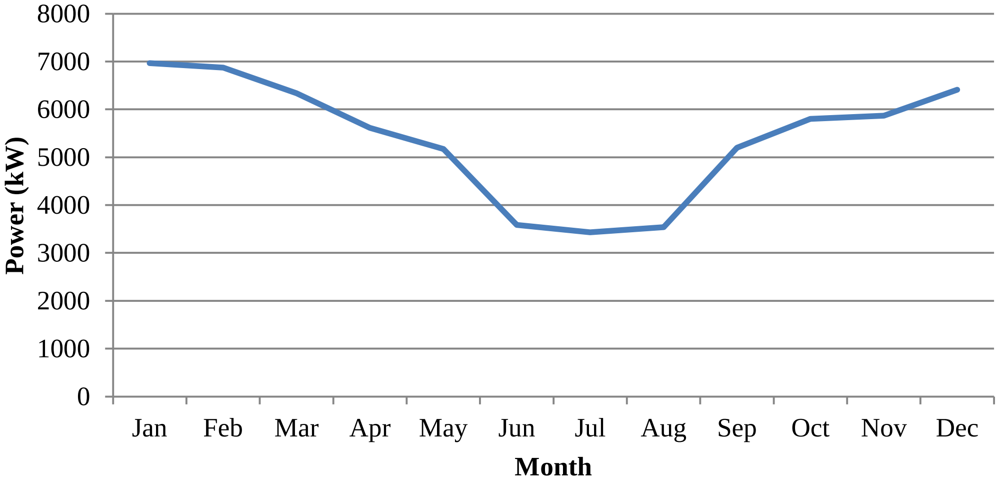

Figure 37: Overview of the mine's monthly power demand

Operational procedures

Normal operating procedures for the cooling system under study are as follows:

- During the hotter summer months, all chillers, BACs and pre-cooling towers are in operation. The hotter ambient conditions necessitate additional air and water cooling to satisfy the mine's underground service delivery requirements.
- During the cooler winter months, the amount of air cooling is reduced to the extent that the flow of water to the BACs can be stopped altogether. This reduces the amount of water that has to be chilled, allowing the mine to switch off one or more chillers.

Maintenance procedures

Maintenance procedures typically take the form of daily inspections to ensure operational continuity and compliance with regulatory requirements. Major maintenance of the mine cooling systems is reserved for the cooler periods or public holidays. During cooler periods, the mine does not have to do as much cooling as normal. During the holiday periods, usually towards the end of December, underground operations are halted, and only skeleton staff are on duty for critical maintenance. This contributes to a reduction in the amount of cooling required, allowing one or more cooling components to be serviced.

Chillers

Chiller maintenance typically involves opening up the shell-and-tube heat exchanger to allow for the tubes to be cleaned (Figure 38). While the chiller is decommissioned for servicing, other components of the chiller are also serviced.

Figure 38: Heat exchanger tubes within the evaporator chamber of the chiller

Cooling towers and BAC

Cooling tower and BAC maintenance usually entails cleaning and/or replacing the fill within the tower. The fill can be cleaned by using high pressure washers. Figure 39 shows the fill in the existing pre-cooling tower being replaced due to excessive sediment build up.

Figure 39: Fill replacement in pre-cooling tower due to excessive sedimentation build up

The sumps of the BACs and cooling towers are also cleaned periodically to prevent the sediment build up from entering the tubes of the chillers. In some instances, sediment build up can be excessive (as seen in Figure 20). For completeness, the figure is shown again in Figure 40.

Figure 40: Sediment build up in BAC sump

4.3 PERFORMANCE OF COOLING SYSTEMS

Overview

The performance of the mine's cooling system components were monitored and the principles mentioned in Chapter 3 applied. The full results can be found in Appendix II and Appendix III.

For the purposes of this study, certain periods have been highlighted and are discussed below, to emphasise the benefits of monitoring system performance. The study focuses on two core procedures that are both within management control, namely operational and maintenance procedures. This is as opposed to the effects of other conditions that are not within management control – for example, climatic conditions.

Operational procedures

Principle 1

The COPs of the chillers were calculated and monitored. The results and graphs depicting the daily average COPs of each chiller, as well as the average COP of all the chillers combined, can be seen in Appendix II and in the figures below.

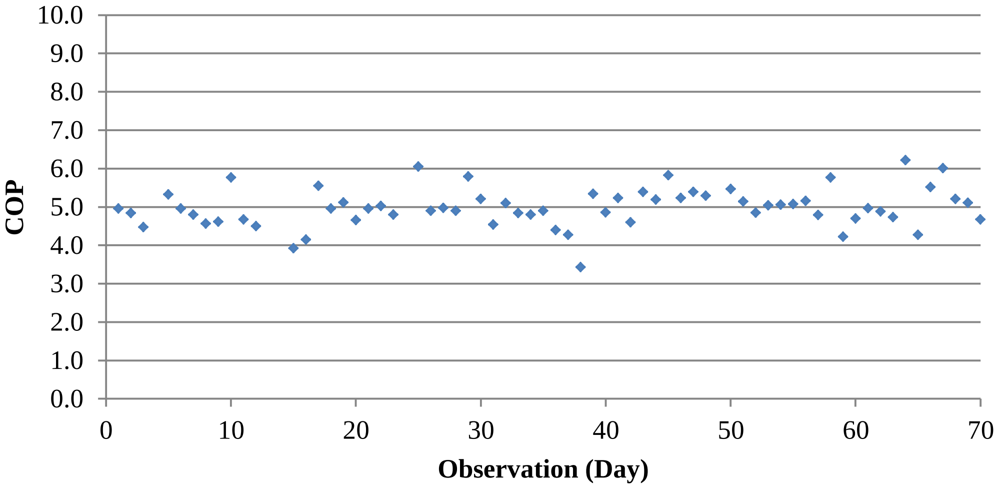

Figure 41: Daily average COP of the refrigeration plant under investigation

The combined COP of all the chillers is calculated based on the temperature difference across the entire plant, as well as on the total evaporator flow and power usage. The average COP of each chiller cannot be used to calculate the COP of the entire plant, because one or more chillers may be inoperative for a period of time. A chiller that is not operational will yield COP values close to zero. This in turn will reduce the combined COP.

Chillers 1 and 2 are operated in series with each other, and in parallel with chillers 3 and 4. Chillers 1 and 2 were taken out of operation for a period of time during the study. The daily average COPs of the respective chillers can be seen in the figures below.

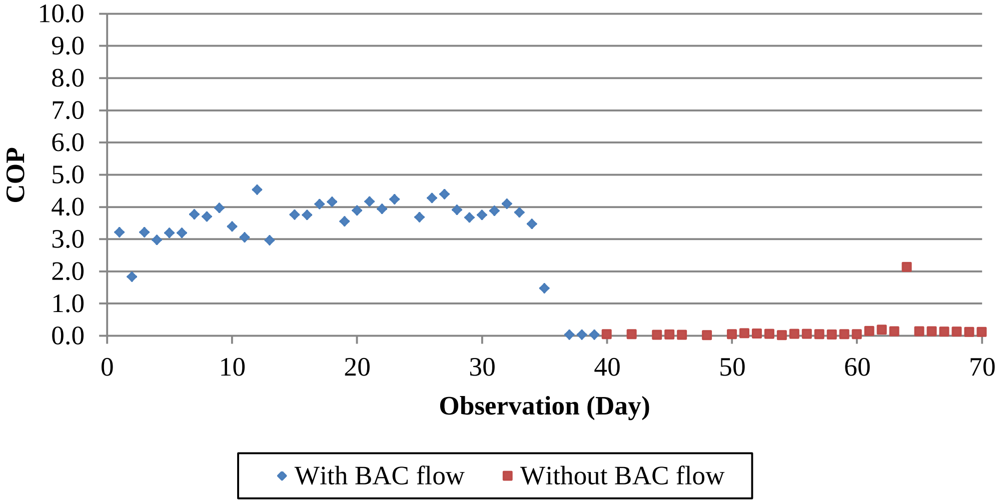

Figure 42: Daily average COP of chiller 1

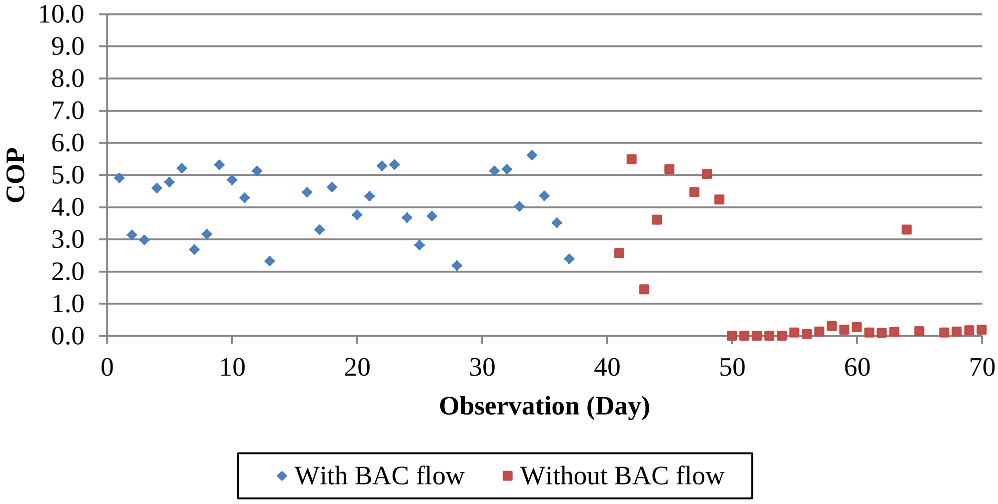

Figure 43: Daily average COP of chiller 2

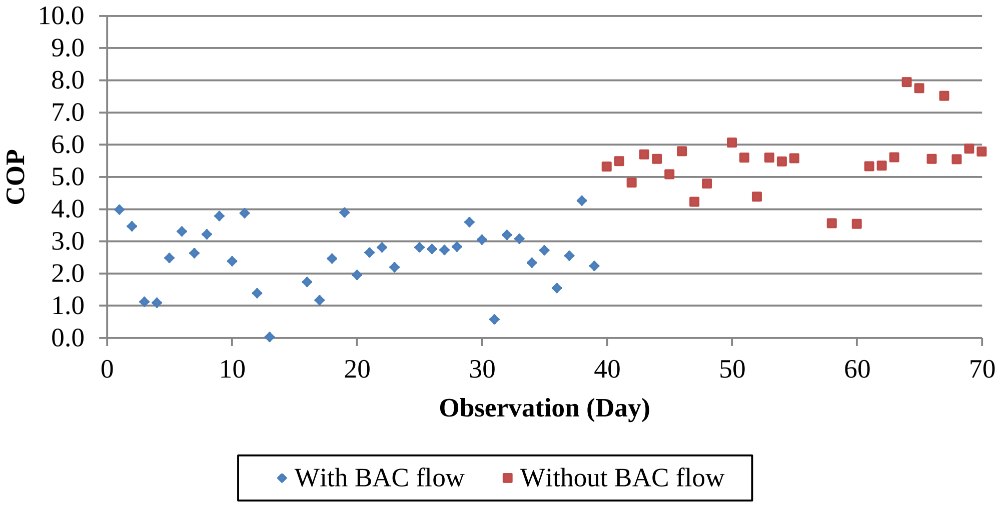

Figure 44: Daily average COP of chiller 3

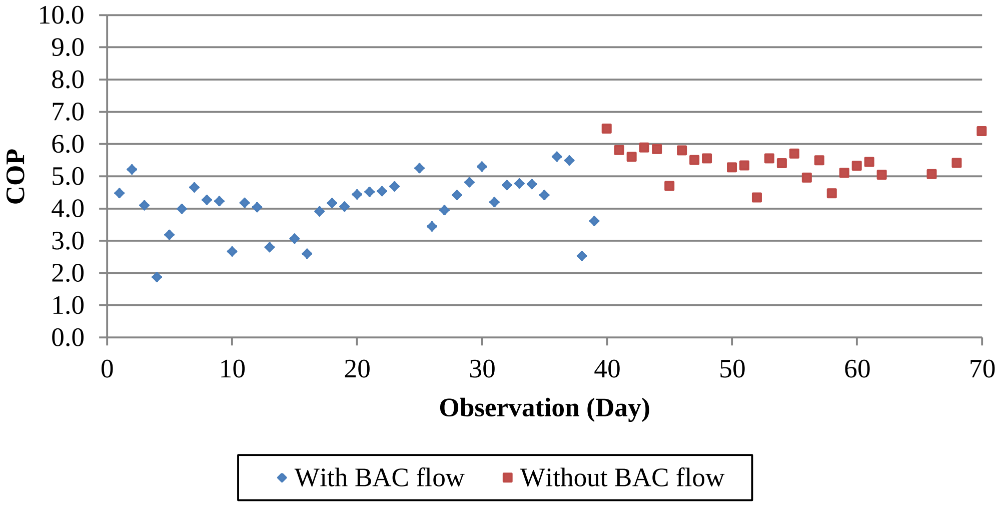

Figure 45: Daily average COP of chiller 4

Attention is given to Figure 44 and Figure 45. These figures show the COPs of chillers 3 and 4 which were in operation for the duration of the study. In both cases, particularly in the case of chiller 3 (Figure 44) there is a marked increase in COP at observation 40. Note that if one had only been monitoring the COP of the all the chillers combined (Figure 41), one might not have noticed this anomaly.

It must be noted that an increase in COP is not necessarily a positive outcome. The increase could be the result of a faulty temperature probe reading a higher than normal temperature value.

The fault could lead to an abnormally high COP value. Efforts should be made to establish the cause of any significant change in COP. This is with a view to identifying faults before any major damage results. If the increase in COP is due to a positive intervention, establishing the cause of this increase is important with a view to incorporating any changes into future operations.

Investigations were carried out to establish the causes of this increase in COP. On further analysis of system data and conversations with mine personnel, it was established that the operators had stopped the flow of water to the BACs (observation 40). This was because the ambient air was sufficiently cool, and no longer required additional cooling. Figure 46 shows the daily average ambient dry-bulb, hot dam, and pre-cooling dam temperatures over the period in which the investigation took place.

The efficiency of the pre-cooling towers could not be calculated as the wet-bulb air inlet temperature was not available. A decision was made to monitor the hot and pre-cooling dam temperatures in conjunction with the dry-bulb ambient temperature for any significant changes.

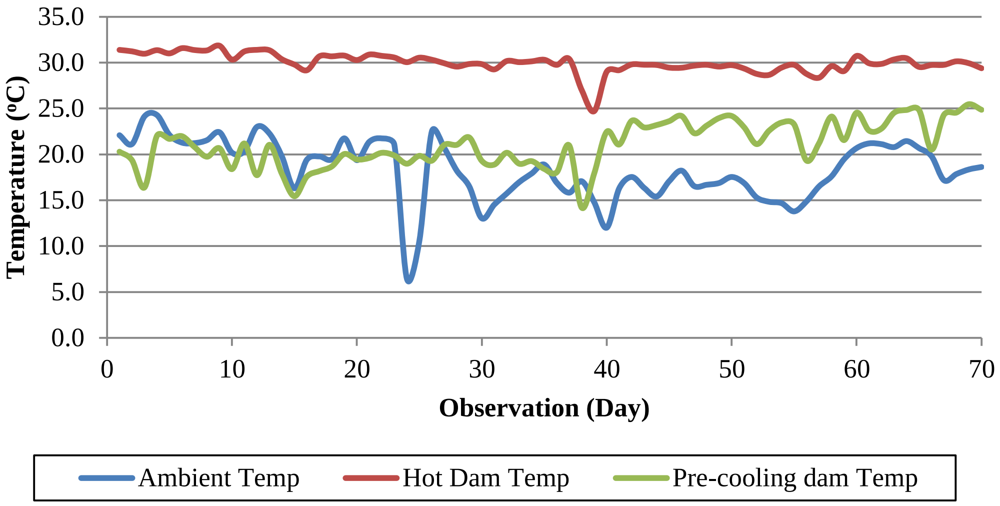

Figure 46: Change in average daily ambient, hot dam and pre-cooling dam temperatures

Figure 46 shows the effects of this action on the pre-cooling dam temperature. Previously, water sent back to the pre-cooling dam from the BACs helped cool the pre-cooling dam water further. Once the flow to the BACs was stopped, the supply of cool water from the BAC sumps ceased. The result was an increase in pre-cooling dam temperature.

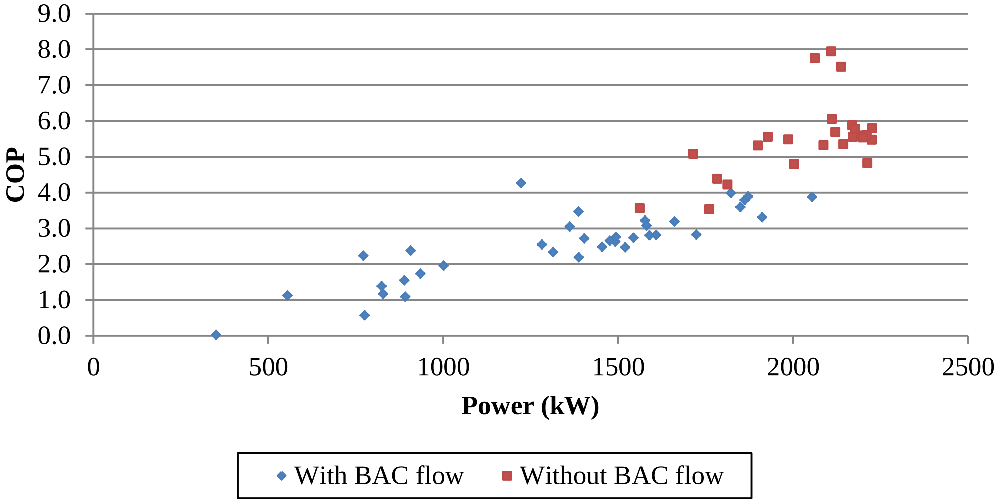

Figure 47: Graph depicting the change in power consumption of chiller 3 after the BAC was switched off

Figure 47 shows the subsequent change in the power consumption of chiller 3 before and after the flow to the BACs was stopped. Chillers are typically designed to provide a set outlet temperature using variable refrigerant flow and compressor control. The increase in inlet temperature resulted in an increase in compressor power to maintain the pre-set outlet temperature.

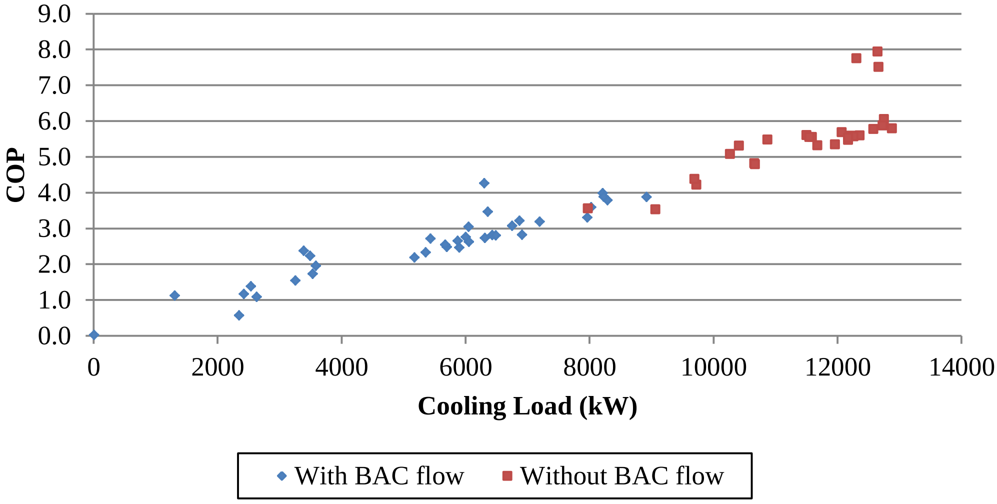

Figure 48: Change in chiller 3 cooling load after the BAC was switched off

The cooling load on the chillers can be seen in Figure 48. The increase in cooling load after the flow of water to the BAC was stopped can be attributed to the increased inlet water temperature.

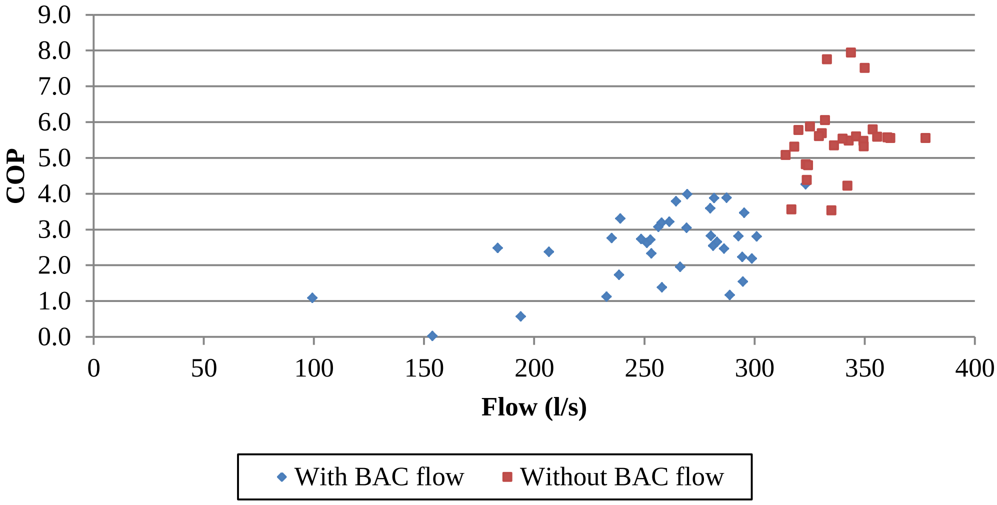

Figure 49: Change in evaporator water flow rate through chiller 3 after BAC was switched off

Figure 49 shows the change in the evaporator flow rate. Before the BACs were switched off, both sets of chillers were in operation. After the BACs were switched off, the demand for chilled water decreased to the extent that two chillers could be switched off. Despite this, there was an increase in flow rate through the remaining operational chillers.

Table 5 shows the average power usage, cooling load, evaporator flow, and COP of the chiller before and after the BACs were switched off.

Table 5: Average Chiller 3 key performance indicators

Scenario	Power (kW)	Cooling Load (kW)	Evaporator Flow (l/s)	COP
Before BAC switched off	1300	5416	257	2.55
After BAC switched off	1900	11021	336	5.15

The increased flow and power usage of the chiller meant that the chiller operating conditions were closer to those of the design specification. This resulted in an overall increase in average COP.

The major advantage of switching off the BAC was a reduction in chilled water service demand and in turn a decrease in power usage. The combined power usage of the refrigeration plant can be seen in Figure 50.

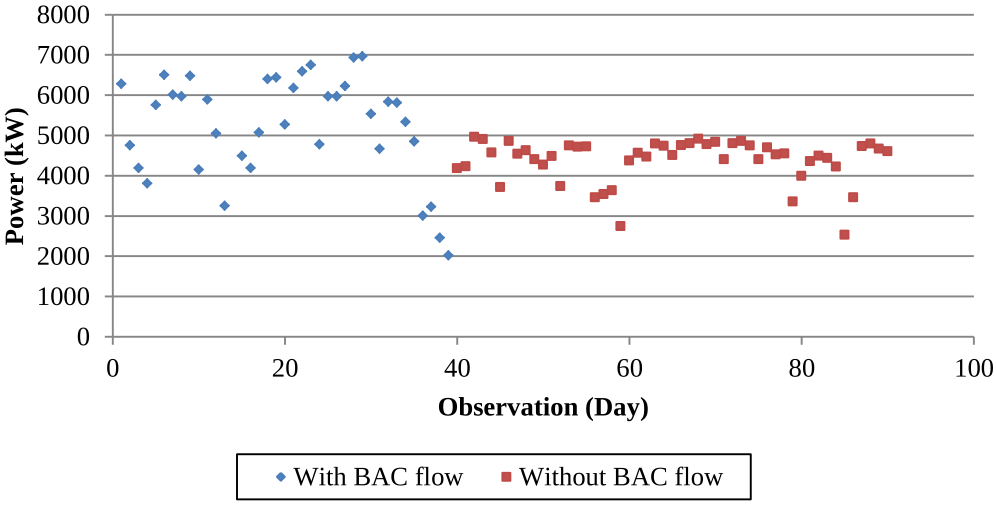

Figure 50: Refrigeration plant total power usage

Table 6: Average refrigeration plant power consumption

Scenario	Power (kW)
Before BAC switched off	5242
After BAC switched off	4261

The BAC was turned off as the ambient temperatures decreased with the onset of winter. The decrease in ambient conditions resulted in colder pre-cooling dam temperatures. Reduced inlet temperatures led to one or more chillers ‘tripping’ due to excessively cold water temperatures. This is the reason for the high dispersion in power usage before the change in operations.

After two chillers were turned off permanently, the mine was able to operate the two remaining chillers consistently. The two chillers in operation were able to satisfy the mine's chilled water service requirements.

This study illustrates the effects of operational procedures on the performance of the mine cooling system. Monitoring the cooling system performance allowed the effect of operational procedures to be identified and quantified.

In future, the mine's BAC control philosophy could be implemented throughout the year, not just during the winter months.

Principle 2

Principle 2 states that statistical control charts should be used to develop and plot the performance of components. For this study, individuals and moving range charts are the control charts of choice. This is because only a single variable is available for charting, and this variable is only calculated periodically – in this case, daily.

Individuals and moving range charts have two parts. The first part charts the process variability; the second part charts the process average. The first part of the graph illustrating the process variability, the moving range chart, should be stabilised before the individuals chart is constructed. The individuals and moving range charts for each of the chillers in operation can be seen in Appendix III. The principles and findings can be applied to all the chillers and the plant as a whole.

The charts for chiller 3 have been highlighted in this section for particular attention. Figure 51 and Figure 52 show the individuals and moving range charts for the performance chiller 3. $\overline{R}$ (R bar (MR)) and $\overline{x}$ (X bar (x)) are the individuals and moving range averages respectively.

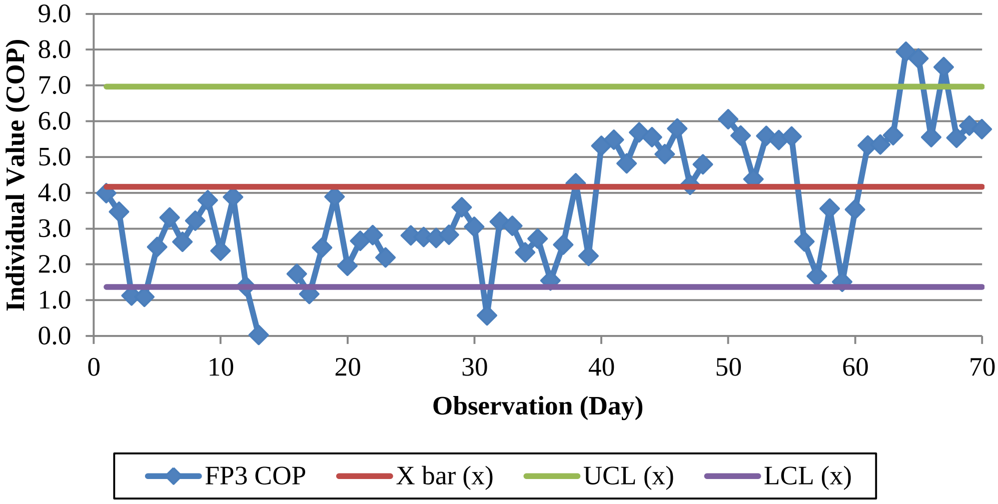

Figure 51: Individuals chart for chiller 3 indicating process performance, average, and control limits

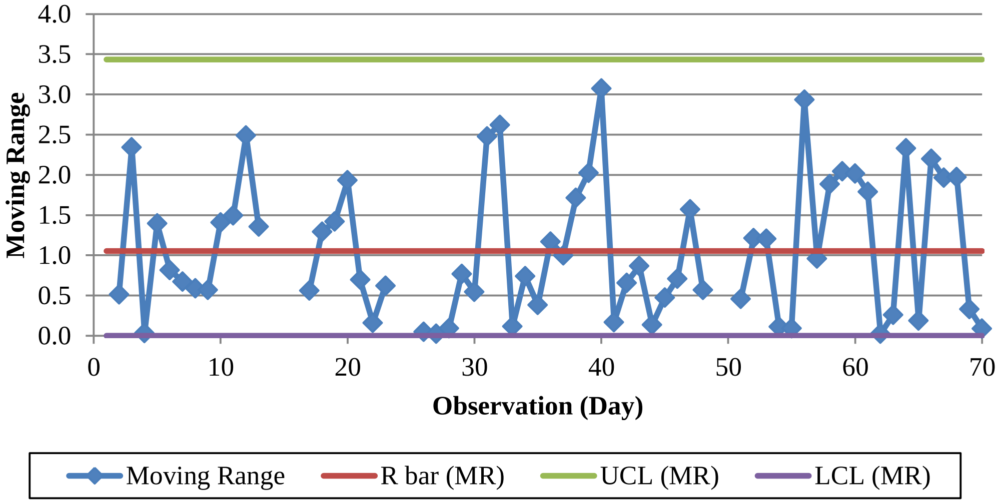

Figure 52: Moving range chart for chiller 3 indicating process variation and control limits

The moving range chart (Figure 52) was constructed first. The control limits do not appear to be inflated as there is an even spread of data points above and below the centreline. This means that there is no need to calculate the control limits using the median of the moving range values. All data points fall within the control limits. Instances where chillers were out of operation for a day were excluded from the control charts. If a chiller is inoperative, the COP will be zero. This will lower the control limits and overall process average, causing management to become over-reactive.

Once it was established that the moving range chart displayed a state of statistical control, the individuals control chart was constructed. The individuals chart (Figure 51) allows a manager to see the process average (X bar (x)) and establish typical operational performance. The increase in performance identified earlier is still noticeable using the control charts. The control limits allow management to monitor the performance of the components, taking into account natural process variation. Statistical control charts will assist management to achieve continuous process improvement.

Discussion

It is advisable that management use caution when applying the seven rules for identifying out-of-control points. Without a thorough grasp of statistics, only the first rule for identifying out-of-control points should be used. Employing the remaining six rules will certainly be beneficial if executed correctly. If their implementation is not carried out systematically and consistently, the result could be detrimental to overall process performance. Deflated control limits will affect the ability to make decisions with a high degree of confidence. Inflated control limits will negate the quest for ever-improving process performance.

No instrumentation faults were detected over the duration of this investigation.

Maintenance procedures

Principle 1

Investigations were carried out to assess the impact that maintenance procedures have on the performance of mine cooling systems. Data were obtained from the mine for the maintenance period during which the chillers were cleaned. The average daily COP of the chillers was calculated before and after the scheduled maintenance (Appendix II).

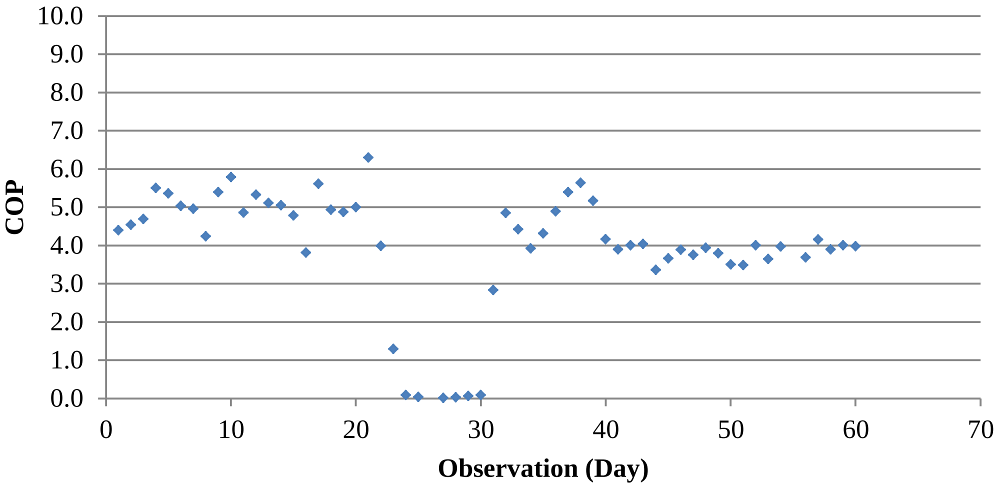

Figure 53: Daily average COP of the refrigeration plant under investigation

Figure 53 depicts the COP of the refrigeration plant over time. The plant was shut down for period of time for scheduled maintenance (observation 24 to observation 30). Over the course of scheduled maintenance, labour embarked on unforeseen strike action. During this time, only critical personnel were on duty. Chilled water service delivery requirements were reduced to the extent that only one chiller (chiller 1) was required full time. Chiller 2 was used intermittently.

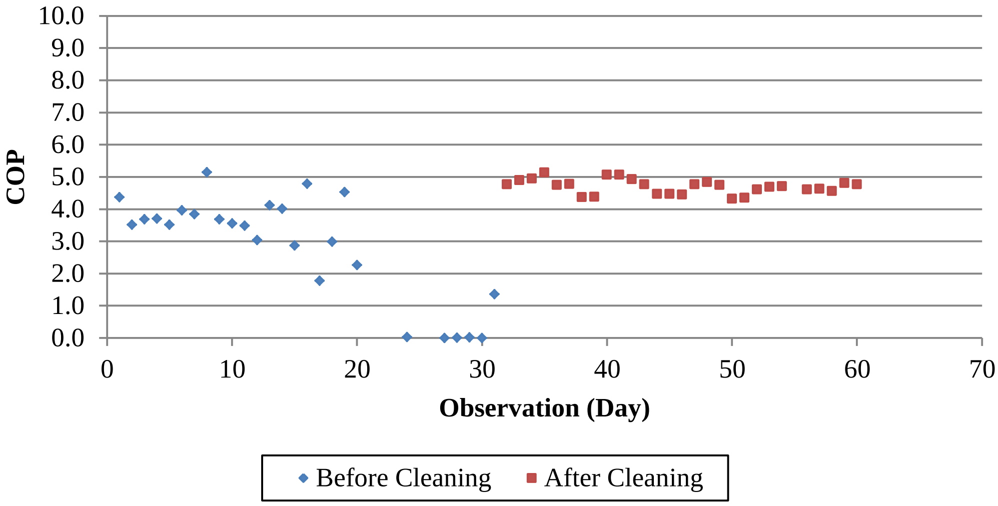

Figure 54: Change in COP of chiller 1 due to cleaning of evaporator tubes

Figure 54 shows the change in COP of chiller 1 before and after scheduled maintenance. The COP of chiller 1 increased from 3.64 before maintenance to 4.70. This is a 29% increase in chiller performance.

For consistency, the COP of chiller 3 was analysed further to compare the effects of maintenance with those of the earlier study that analysed operational changes. The chiller was taken out of operation for a period of approximately fifty days during the study due to the strike action by labourers. Figure 55 shows the change in COP for chiller 3 before and after maintenance.

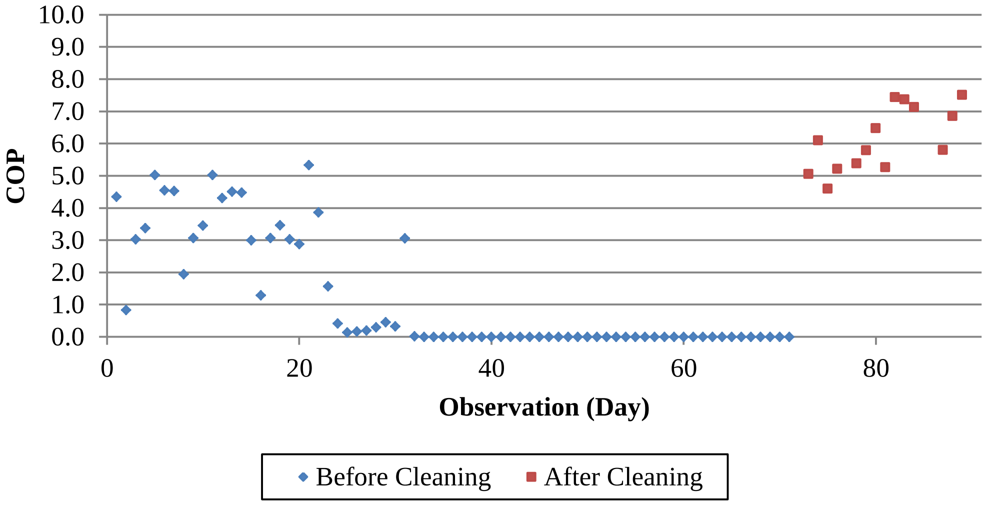

Figure 55: Change in COP of chiller 3 due to cleaning of evaporator tubes

The average COP of the chillers increased from 3.5 before cleaning, to 6.0 after cleaning. Further investigation showed that the mine only had the resources available to clean the evaporator tubes of the chillers. It is expected that additional improvements will be realised when the condenser tubes are also cleaned.

Figure 56 and Figure 57 illustrate the change in COP, together with the corresponding power consumption and water flow rate before and after cleaning.

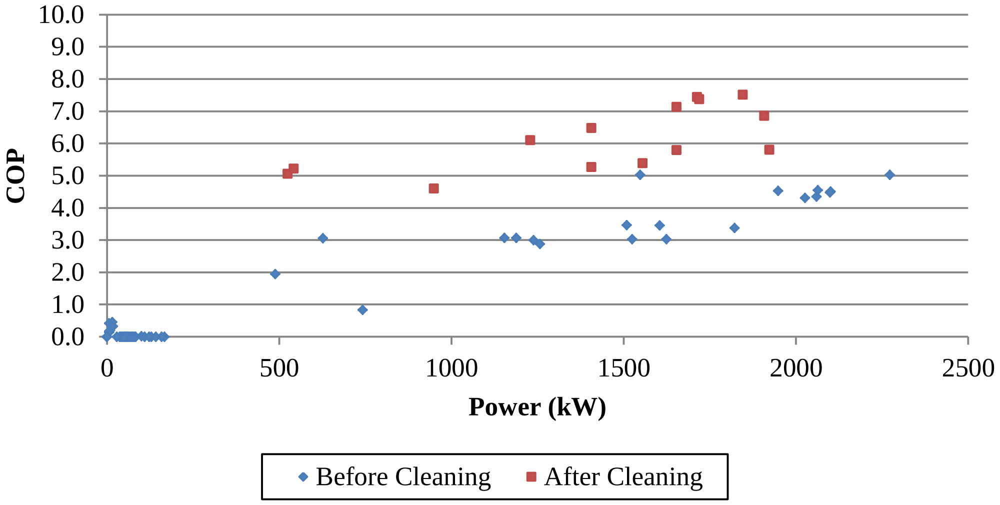

Figure 56: Graph depicting chiller 3 COP and corresponding power usage before and after maintenance

Figure 56 shows a consistently higher COP after cleaning, despite fluctuations in power consumption. Cleaning of the tubes allows for improved heat transfer between the water and the refrigerant. This results in improved cooling and decreased compressor power usage.

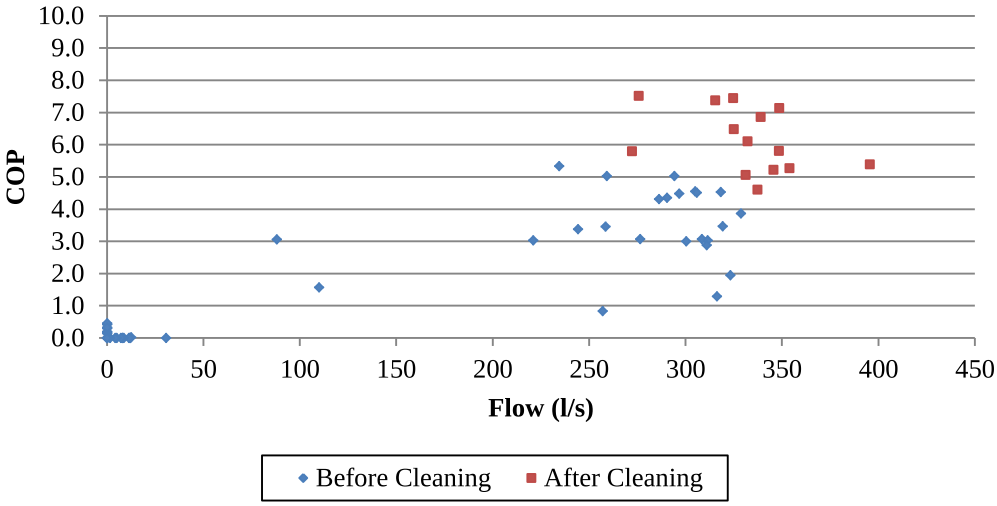

Figure 57: Graph depicting chiller 3 COP and corresponding water flow rate before and after maintenance

Figure 57 shows that a higher COP is achieved at comparable water flow rates. Cleaning the evaporator can contribute to a marginal increase in average water flow rate. This is due to less resistance in the chiller tubes, and an increase in internal pipe diameter.

Table 7 provides a summary of the key performance indicators for chiller 3, before and after scheduled maintenance.

Table 7: Chiller 3 performance before and after scheduled maintenance

Scenario	Power (kW)	Evaporator flow (l/s)	COP
Before scheduled maintenance	1593	281	3.5
After scheduled maintenance	1408	310	6.0

Principle 2

The data used to monitor the performance of the chillers was plotted and analysed using individuals and moving range statistical control charts. The individuals and moving range charts for each chiller, as well as for the plant as a whole, can be found in Appendix III. Again, individuals and moving range charts were chosen because only a single variable is available for charting. This variable is only calculated periodically – in this case, daily.

High variability in a process will make it difficult to establish the true performance of the process. The control limits, which denote the extent of variability within a process, should move closer to the centreline when striving for continued process improvement. Low process variability will benefit management when forecasting process performance and decision-making.

The individuals and moving range charts for chiller 1 before scheduled maintenance are shown in Figure 58 and Figure 59 respectively. The moving range chart illustrates the process variability. The individuals chart plots the process average.

Figure 58 shows high process variability before the chiller was cleaned. The high variability can be attributed to inconsistent heat transfer and flow as a result of sediment build up in the tubes of the heat exchanger. This also accounts for the low average COP (denoted X Bar (x)), seen in Figure 58 – the individuals chart of Figure 59. Before the scheduled maintenance period, the average COP of chiller 1 was 3.64 and the standard deviation was 0.80.

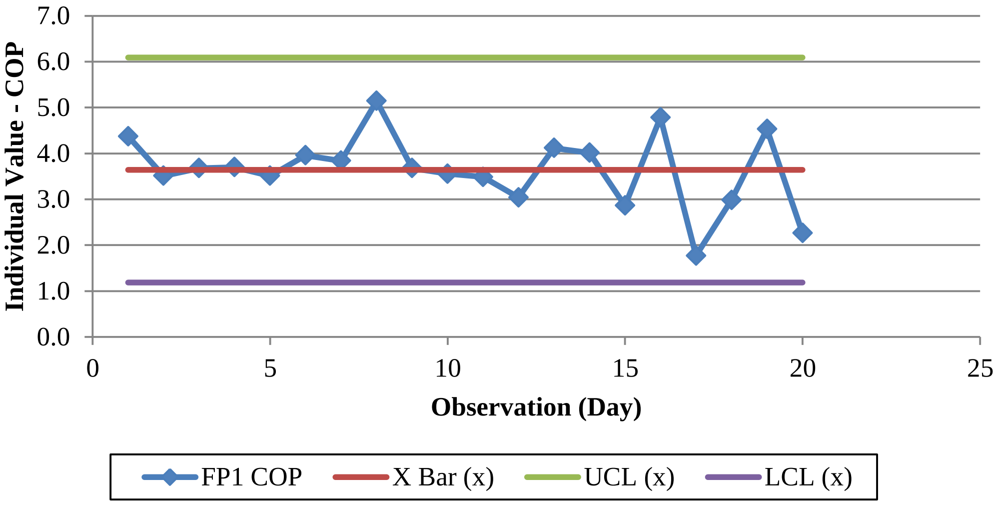

Figure 58: Individuals chart for chiller 1 indicating process performance, average, and control limits before maintenance

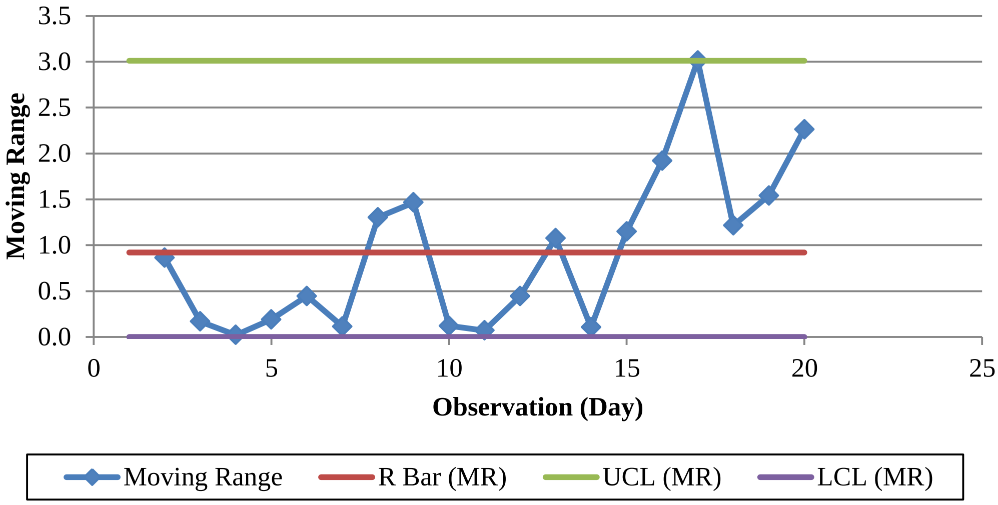

Figure 59: Moving range chart for chiller 1 indicating process variation and control limits before maintenance

The individuals and moving range charts for chiller 1 after the scheduled maintenance can be seen in Figure 60 and Figure 61 respectively. The post-maintenance period shows that the chiller was more consistent in terms of process performance, with very little process variability (Figure 61). Figure 60 also shows that the average COP of the chiller has increased to 4.70 with a standard deviation of 0.22 after maintenance. This is a 29% improvement in COP.

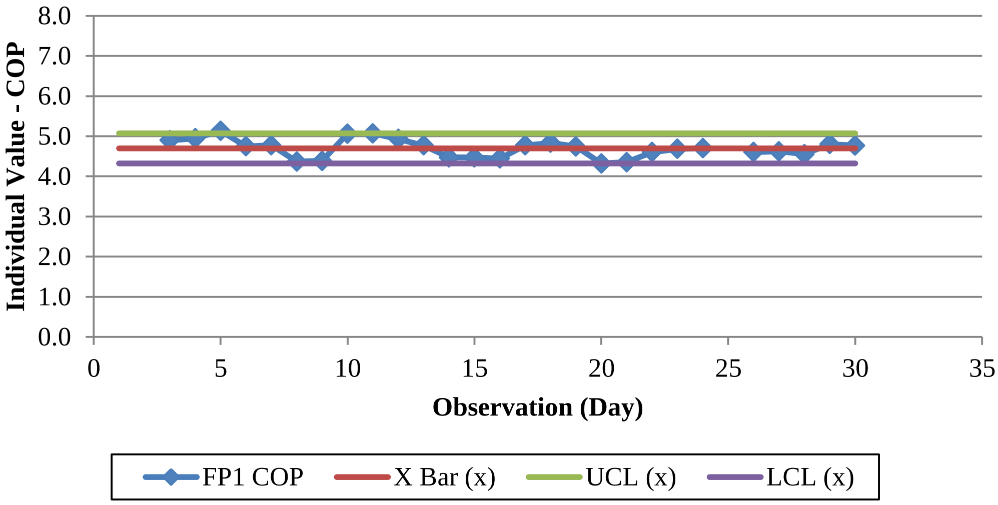

Figure 60: Individuals chart for chiller 1 indicating process performance, average, and control limits after maintenance

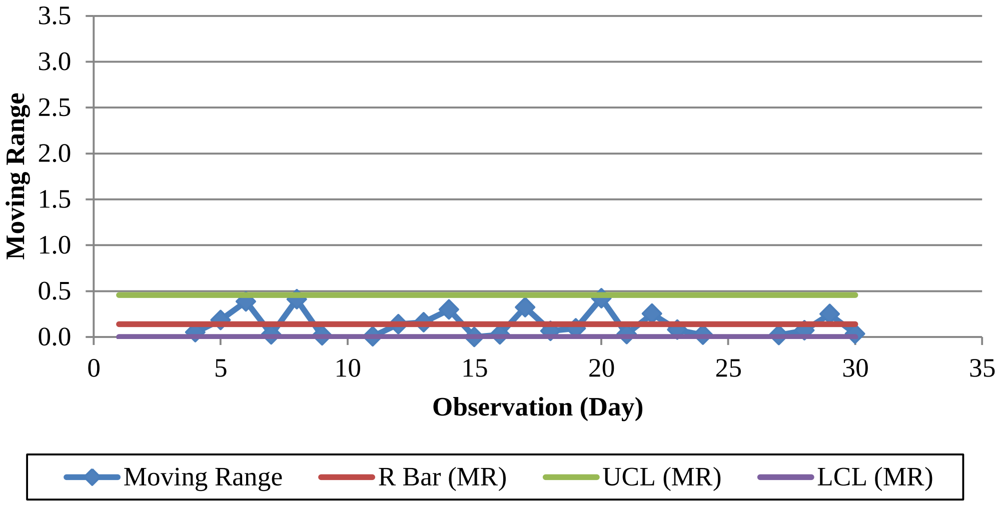

Figure 61: Moving range chart for chiller 1 indicating process variation and control limits after maintenance

Discussion

Control limits for the statistical control chart should be recalculated after a change has been made to the process. In this case the limits are recalculated after the scheduled maintenance. If the limits are not recalculated, the process will show a high degree of instability. This may lead to a manager becoming over reactive and instituting needless changes. In this instance, the pre-maintenance period data will lower the control limits and process average if included with the post-maintenance period data.

An added benefit of using control limits, in addition to monitoring average system performance, is the ability to track variation in process performance. An instance may arise where the process average is satisfactory, but system performance variation is high. The high variation will be a justifiable reason for further investigation. This anomaly is highlighted in the discussion above. No instrumentation faults were detected over the course of this investigation.

It is envisaged that regular maintenance could realise significant savings for the mine.

4.4 CONCLUSION

The tools identified in Chapter 3 were applied to a specific mine cooling system in Chapter 4. The effects of management decisions were quantified and component interdependence illustrated. The findings and suggestions will be used to test various energy saving strategies in Chapter 5.

5. IDENTIFICATION OF ENERGY SAVINGS OPPORTUNITIES

5.1 INTRODUCTION

This study has shown the effects of maintenance and operational procedures on the performance of cooling system components. The findings are now included, and various scenarios tested, using a simulation model. The simulation model was developed using a simulation package called ‘Process Toolbox’. The model is validated by comparing simulation results with actual mine data. Once a satisfactory degree of accuracy is reached, the model is then updated with the findings and suggestions presented in Chapter 4.

5.2 SIMULATION MODEL VALIDATION

A screen shot of the simulation model can be seen in Appendix IV. The power usage; flows and temperatures were compared with actual system data to compare the accuracy of the simulation. The validation results can be seen in Table 8.

Table 8: Simulation results

Hour	Actual Flow (l/s)	Simulated Flow UG (l/s)	Percentage Difference (%)	Actual Chill Dam Temp (^{o}C)	Simulated Chill Dam Temp (^{o}C)	Difference (^{o}C)	Actual Power (kW)	Simulated Power (kW)	Percentage Difference (%)
0	124.1	128.9	3.8	5.5	5.6	0.1	6632	7255	9.4
1	390.6	386.7	1.0	5.6	5.7	0.1	6026	7088	17.6
2	523.8	515.6	1.6	5.5	5.8	0.3	6770	7071	4.4
3	153.5	154.7	0.8	6.4	5.8	0.6	6802	7097	4.3
4	346.6	335.1	3.3	6.7	5.9	0.8	6649	6935	4.3
5	524.7	515.6	1.7	6.4	5.9	0.5	6626	6997	5.6
6	108.3	103.1	4.8	6.4	5.9	0.5	5834	7111	21.9
7	271.5	283.6	4.5	7.2	5.9	1.2	5311	6965	31.1
8	391.9	386.7	1.3	7.4	6.0	1.4	6548	7107	8.5
9	197.7	206.2	4.3	6.7	6.0	0.8	6474	7297	12.7
10	437.5	438.3	0.2	6.1	6.0	0.1	6950	7335	5.5
11	228.1	232.0	1.7	6.5	6.0	0.5	6976	7624	9.3
12	244.2	232.0	5.0	6.6	6.0	0.6	6570	7407	12.7
13	481.8	489.8	1.7	5.9	6.0	0.1	6821	7456	9.3
14	80.4	77.3	3.8	6.1	6.0	0.1	6985	7606	8.9
15	79.5	77.3	2.7	6.2	6.0	0.2	6489	7061	8.8
16	78.4	77.3	1.3	5.8	6.0	0.2	5338	5581	4.6
17	360.5	360.9	0.1	5.2	6.0	0.8	5306	5310	0.1
18	450.9	438.3	2.8	4.9	6.0	1.1	5432	7176	32.1
19	78.4	77.3	1.3	5.1	6.0	0.9	5882	7269	23.6
20	197.6	206.2	4.4	6.5	6.0	0.5	6333	6943	9.6
21	288.1	283.6	1.6	5.9	6.0	0.1	6755	6915	2.4
22	76.1	77.3	1.6	6.3	6.0	0.3	6664	6800	2.0
23	73.2	77.3	5.7	5.9	6.0	0.1	5594	4923	12.0
Average	**257.8**	**256.7**	**2.5**	**6.1**	**5.9**	**0.5**	**6323.7**	**6930.4**	**9.6**

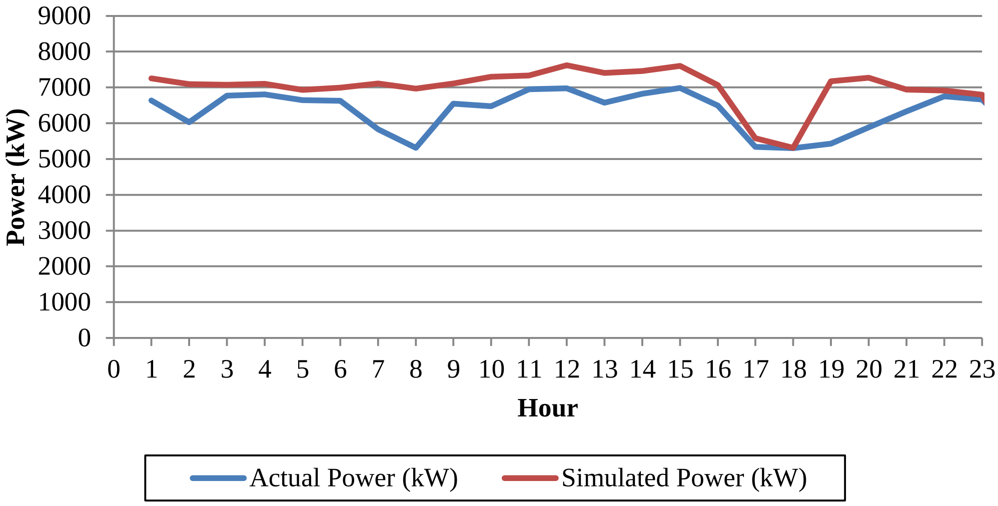

Figure 62: Actual and simulated 24 hour power profile

The simulated power usage shows a 9.6 % difference, on average, from the actual power usage (Figure 62). The comparative flow to underground and the chill dam temperature are shown graphically in Figure 63 and Figure 64 respectively.

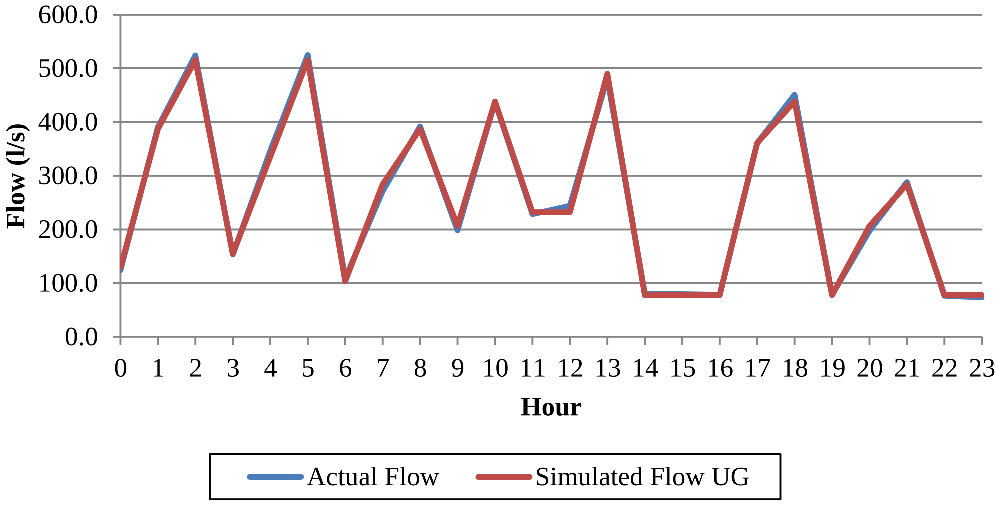

Figure 63: Actual and simulated 24 hour flow to underground profile

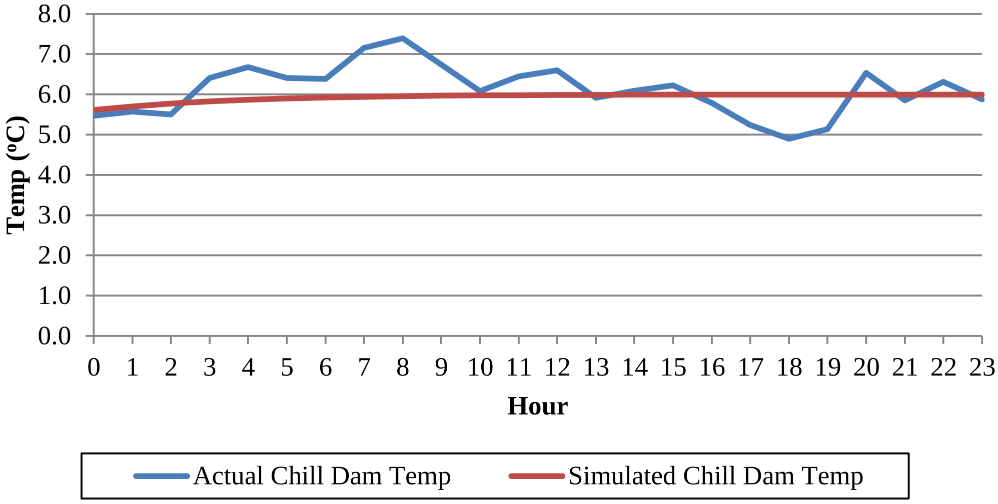

Figure 64: Actual and simulated 24 hour chill dam temperature profile

The simulated flow to underground shows a 2.5% difference from the actual data. The simulated chill dam temperature varies by 0.5 ˚C on average from the actual chill dam temperatures. Based on discussions with experienced personnel, the model was deemed sufficiently accurate for the purpose of this study.

5.3 REFINING OF OPERATIONAL PROCEDURES

Investigation

In Chapter 4, the benefits of stopping the flow of water to the BACs were highlighted. Benefits include improved chiller performance and the associated electrical savings by virtue of reduced service delivery demand. It was suggested that this control philosophy could be applied more regularly, throughout the course of the year.

Investigations were performed to establish the effects on the underground temperatures if the flow of water to the BAC was stopped on a typical summer day. The tests entailed stopping the flow of water for two hours from 18:00 to 20:00. This particular time period was chosen for the investigation as ambient conditions are typically cooler in the evening and the electricity tariffs are higher, thus maximising the potential cost savings.

Figure 65 shows the change in flow to the BAC and the corresponding dry-bulb air outlet temperature during the investigation. The flow of water to the BAC was stopped between 18:00 and 20:00. The tests were carried out over a period of two days.

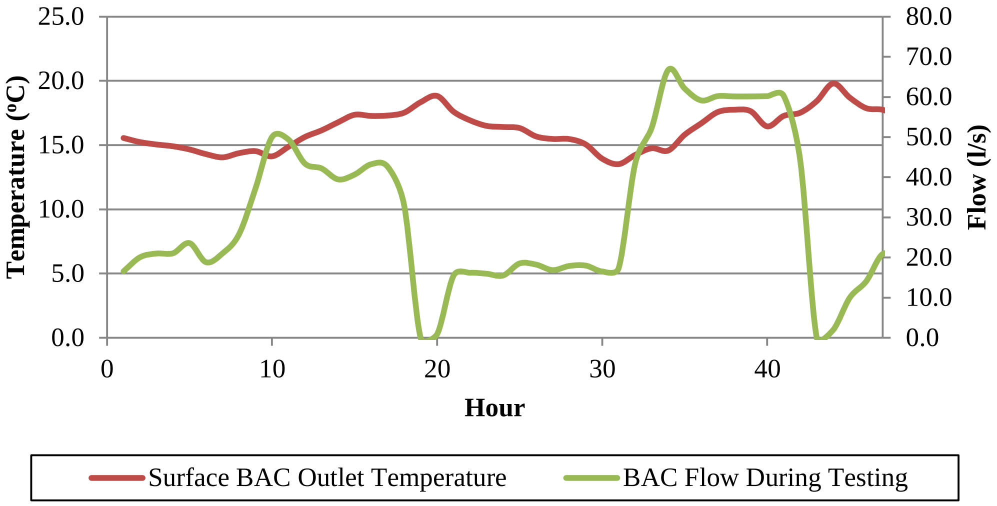

Figure 65: Flow to BAC and BAC outlet temperature profiles during investigation

The corresponding dry-bulb temperature and relative humidity of the air on Level 75, one of the underground mining levels, is shown in Figure 66.

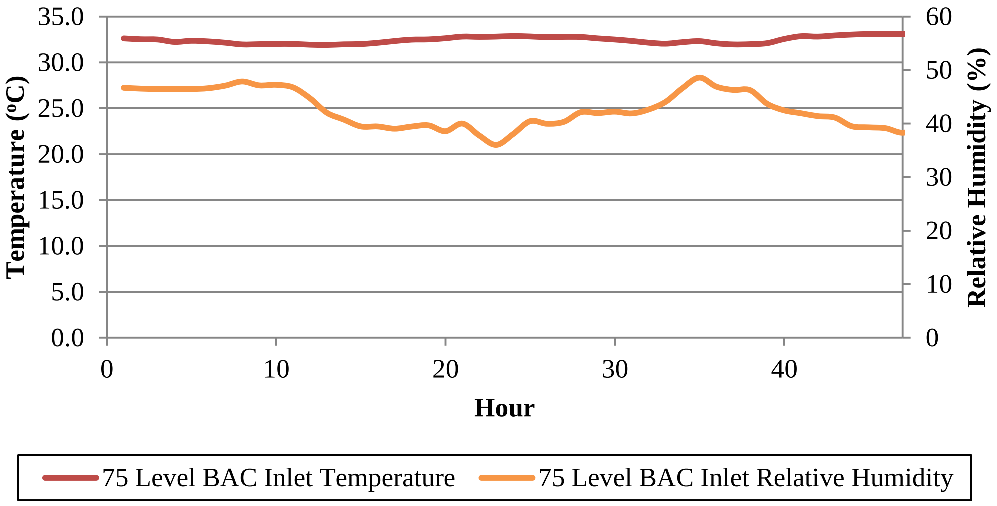

Figure 66: Level 75 temperature and relative humidity profiles during investigation

Figure 66 shows that the stoppage between 18:00 and 20:00 has no noticeable effects on the underground temperature and relative humidity. This investigation suggests that the proposed control philosophy can be implemented without adversely affecting underground working conditions.

Results

A simulation was performed to establish the potential electrical energy savings if the flow of water to the BAC and two chillers are stopped for two hours between 18:00 and 20:00 every day. This is in addition to the normal operating procedure of stopping two chillers and the flow of water to the BAC during the winter periods.

The average annual 24-hour profile can be seen in Figure 67. This figure depicts the current profile without BAC control, together with the new proposed profile with BAC control. Simulations show that a load shifting strategy is required to ensure that the chill dam level is restored to required levels after 20:00.

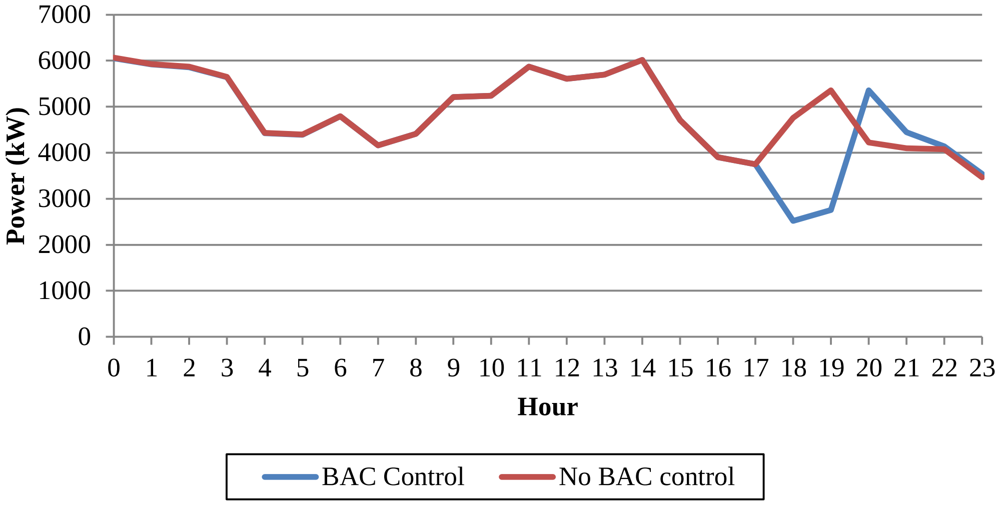

Figure 67: Average annual power profiles with and without additional BAC control

Table 9: Savings – summary of average annual savings due to additional BAC control

	Average Power (kW)	**Total Cost (R)**
Baseline	4 902	8 133 806
New Profile	4 766	7 586 341
Saving	136	547 465

The savings realised as a result of this intervention amount to R 547 465 annually, with an average daily electrical power saving of 136 kW. This additional saving is a direct result of stopping the flow of water to the BAC for two hours between 18:00 and 20:00 in the evening and turning two chillers off.

The initial investigation proves that the intervention will not adversely affect underground operating conditions. The associated electrical and monetary savings also prove that this control philosophy will result in significant savings without the need for expensive modifications and installations. The findings regarding the change in underground air temperatures, or lack thereof, prompted mine personnel to consider turning the BACs off for a longer period. This will result in additional savings, again highlighting the benefits of performance monitoring.

5.4 OPTIMISATION OF MAINTENANCE PROCEDURES

Investigation

In Chapter 4, the benefits of cleaning the tubes of the chiller machines were highlighted. Benefits include improved heat transfer, evaporator water flow, and chiller performance. An investigation was carried out to ascertain how regularly the mine should perform this maintenance to maximise electrical energy savings.

The cost of carrying out this maintenance must be noted when determining the regularity with which the chillers should be cleaned. Replacing refrigerant, seals, and gaskets and labour costs are some of the factors that should be considered. According to Andre Joubert[8], the mechanical foreman responsible for maintaining the cooling system at the gold mine, the following costs and time frames are required to clean the chillers:

- Time frame – one day per chiller
- Spares and refrigerant – R 42 000 per machine
- Current cleaning schedule – Chillers cleaned once every four months

Simulations were performed whereby the average annual COP of the chillers are adjusted, thus simulating the overall effect of different cleaning schedules. A cost benefit analysis was carried

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[8] Meeting held with Andre Joubert, mine mechanical foreman, August 2013 (phone: 082 788 9390).

out to ascertain whether the monetary and electrical energy savings achieved as a result of improved efficiencies outweighed the costs associated with cleaning the chillers.

Results

Figure 68 shows the summer power profiles for the cooling system at different COPs caused by different cleaning schedules.

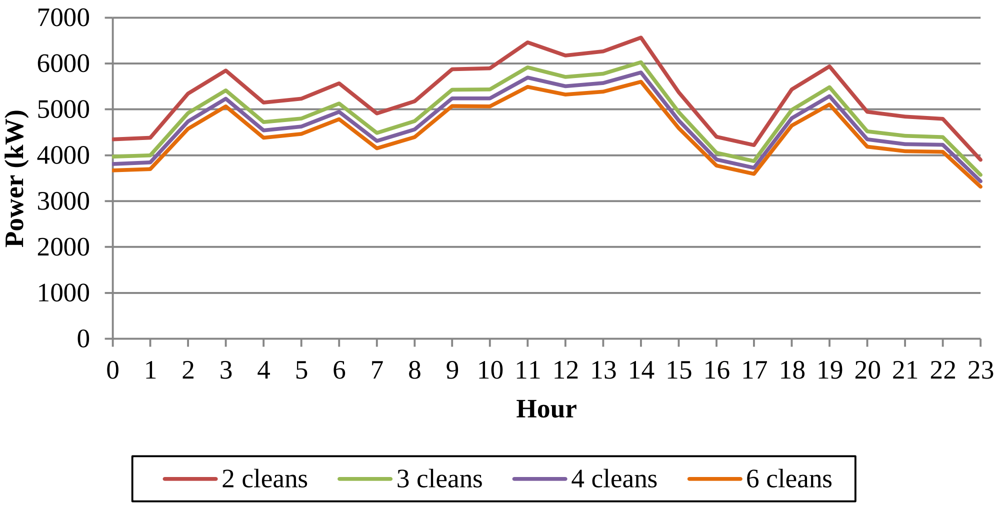

Figure 68: Annual average 24-hour power profile for different COPs as a result of differing maintenance schedules

The annual savings realised as a result of these interventions are shown in Table 10. The savings are calculated by comparing the benefits of improved chiller efficiency with those realised when cleaning the chillers once a year.

Table 10: Maintenance cost savings

Cleans Per Year	Average COP	Efficiency Savings (R)	Maintenance Costs (R)	Total Savings (R)	Energy Saving (kWh)	Average Power Saving (kW)
2	3.75	3 136 241	336 000	2 800 241	5 647 671	645
3	4.25	5 016 660	504 000	4 512 660	9 040 360	1 032
4	4.50	5 805 187	672 000	5 133 187	10 462 822	1 195
6	4.75	6 513 172	1 008 000	5 505 172	11 740 330	1 341

The existing maintenance schedule, where the chillers are cleaned three times a year, shows that the mine benefits by up to R 4 512 660 and saves up to 1 032 kW. The savings realised are a direct result of decreased chiller compressor power usage.

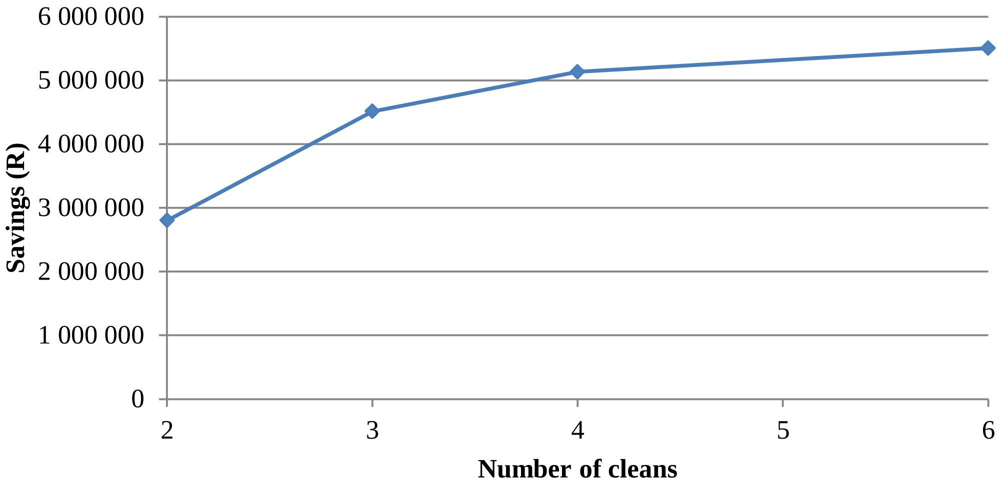

Figure 69: Cost savings per number of cleans

Figure 69 depicts the monetary savings graphically. The findings show that for the mine to realise the greatest electrical and monetary savings, the chillers should be cleaned six times per year. This will result in an additional annual monetary saving of R 992 512. Total energy consumption for the chillers is 46 719 MWh per year. This optimised strategy will yield an additional energy saving of 2 700 MWh per year – approximately 6% of total energy consumption.

Practical and time constraints may limit the mine’s ability to clean the chillers this regularly. Chillers may only be switched off for a limited period of time, usually only during ‘off’ Sundays when no production takes place. Production schedules change regularly, making it difficult for mine personnel to plan maintenance in advance. Additional critical maintenance is also scheduled for ‘off’ days – for example, cleaning dams. This limits the availability of staff to clean the chillers.

The more regularly the chillers are cleaned, the less the build up of sediment. This will make the chillers easier and quicker to clean. In addition, mine personnel are expected to become more proficient in the cleaning process, so the time taken to clean a chiller will be reduced. This may lead to the possibility of more than one chiller being cleaned in a day by a single maintenance team, thus making the optimised frequency of maintenance more attainable.

5.5 OPTIMISED MAINTENANCE – A THEORETICAL STUDY

Introduction

This study highlights some of the benefits of improved performance monitoring. Information gleaned from the study allows management to quantify the effects of their decisions. This leads to the development of an optimised maintenance schedule and improved operational procedure for the mine under study. Based on these findings, it is envisaged that significant electricity savings can be realised for a country should all mines implement similar strategies.

The benefits of maintaining important mining equipment, particularly chillers, are well understood in industry. It was apparent during multiple site visits and meetings, conducted at the outset of this study, that technical personnel do not fully comprehend the economic impact of maintenance. Management cite practical constraints such as time and personnel availability as common reasons for their reactive approach to maintenance.

Most of the mines visited are among the most technologically advanced mines in the world. Despite this, scheduling of chiller maintenance is still rudimentary. It is felt that increasing awareness as to the energy and subsequent monetary savings opportunities will change managements' priorities. The initiative will also prove to be an effective DSM strategy.

Investigation and results

The chillers on twenty deep mines in South Africa were analysed. None of the mines analysed had an optimised maintenance schedule. It can therefore be assumed that these mines will also benefit from an additional energy saving of up to 6% with the implementation of an optimised maintenance schedule. This saving assumes that each mine incurs the same relative costs as the initial study – in other words, that in-house labour is used rather than more costly contract labour.

Table 11 shows the number of chillers that are in operation at each mine, their cooling capacities, and subsequent energy consumptions (du Plessis, et al., 2013). The potential energy saving is also shown, based on an additional 6% energy saving.

Table 11: Annual chiller electrical energy consumption and potential savings of twenty South African mines (du Plessis, et al., 2013)

Site	**Chillers**			
	Quantity	**Cooling capacity (kW)**	**Total energy consumption (MWh/year)**	**Potential energy saving (MWh/year)**
1	4	13 300	46 719	2 803
2	6	6 500	41 099	2 466
3	4	5 000	19 320	1 159
	1	6 000	6 955	417
4	4	6 000	25 292	1 518
5	4	11 500	44 436	2 666
	1	5 500	8 855	531
6	3	5 000	15 807	948
	2	5 000	10 538	632
	1	14 000	12 679	761
7	3	7 500	20 700	1 242
	1	10 500	9 660	580
	1	16 400	16 974	1 018
8	2	10 000	18 400	1 104
	1	5 000	4 600	276
	1	12 000	11 040	662
9	3	11 000	31 878	1 913
	1	4 400	4 250	255
10	4	10 100	34 949	2 097
	6	3 700	33 861	2 032
11	4	6 600	27 821	1 669
12	4	4 150	25 319	1 519
	6	4 150	37 979	2 279
13	2	5 000	16 100	966
14	3	6 450	24 923	1 495
15	6	3 000	29 808	1 788
	3	6 000	29 808	1 788
16	5	5 340	26 914	1 615
17	2	10 000	21 955	1 317
18	8	6 000	84 562	5 074
19	12	4 000	86 940	5 216
20	4	10 000	38 640	2 318
Total	**112**		**868 781**	**52 127**

Discussion

Results show that an electrical energy saving of 52 127 MWh per year will be realised with the implementation of an optimised maintenance schedule for all chillers. This translates into a cost saving of R 28 669 850 per year based on Eskom’s 2012/2013 ‘Megaflex’ tariffs (Eskom, 2012). It is envisaged that the mines will also realise additional benefits of optimised maintenance schedules. This includes increased operator proficiency and a reduction in unplanned stoppages.

The findings resulting from the refined BAC operation were not extrapolated. This is due to the wide range of chilled water demands at the various mines. The periods over which BACs are switched off during the year also vary widely from mine to mine. Any assumptions are likely to introduce a high degree of inaccuracy into the study.

5.6 CONCLUSION

In Chapter 4, the effects of various operational and maintenance procedures were quantified. This information subsequently led to the identification of two energy savings strategies. Further investigations and simulation models were used in Chapter 5 to ascertain the viability of the interventions, and to determine the potential electrical energy savings.

The first strategy entailed stopping the flow of water to the BAC between 18:00 and 20:00 every day. Tests showed that there would be no adverse effects on underground operating conditions due to this stoppage. Stopping the flow of water to the BAC for two hours reduced the amount of water that had to be chilled, allowing for two chillers to be switched off for the duration of the stoppage. Tests showed that the mine could potentially realise a monetary saving in excess of five hundred thousand rand per year, based on Eskom’s 2012/2013 ‘Megaflex’ tariffs (Eskom, 2012).

The second strategy entailed optimising the cleaning of the chillers to realise additional electrical energy savings. Costs of maintenance were measured against the subsequent monetary savings resulting from more efficient chillers. Tests showed that the mine under study should clean the chillers at least six times per year. This is as opposed to the current strategy of cleaning three times per year. The new cleaning schedule would yield an additional monetary saving of approximately R 2.7-million per year. Other benefits that would result due to regular maintenance include increased proficiency of maintenance personnel, and shorter downtimes due to decreased sedimentation build up.

It was hypothesised that optimising the maintenance schedules of South Africa’s largest mines could result in significant electrical energy savings. Results showed that a potential saving of 52 127 MWh per year is possible. Optimising maintenance schedules could therefore form an effective DSM strategy.

6. CONCLUSION

6.1 MINE COOLING SYSTEMS

Mine cooling systems were identified as an area for improvement in performance as well as potential electrical energy savings. Any intervention had to be as cost effective as possible due to the financial constraints currently being faced by mines. Added to this, the pressure being placed on mine cooling systems is set to increase as the mines deepen. This means that the reliability and efficiency of the systems should be maximised.

Site visits were conducted at various mines to establish how the different cooling systems are operated and maintained. Investigations showed that operational procedures vary widely from site to site and, at times, from operator to operator. Each site has its own specific cooling requirements and demands. Maintenance typically takes the form of day-to-day inspections to ensure continued compliance with regulations. Major cooling system maintenance is usually reserved for holiday periods or the cool winter months when less cooling is required.

It became clear that there is the possibility of realising energy savings by optimising the maintenance and operational procedures of cooling system components. In addition, there is minimal, if any, performance monitoring of the cooling system, and the effects of managerial decisions have not been quantified. Furthermore, instrumentation faults may go unnoticed for long periods of time. This can have negative effects on the control philosophy of important cooling components.

A number of interventions were researched as possible solutions to these problems. The majority of these interventions entailed costly modifications to existing infrastructure, or the installation of expensive auxiliary equipment. The mine under study did not have the financial capital available to fund any additional projects. A decision was made to look at infrastructure already in place, the manner in which it is operated, and the condition of the equipment.

6.2 COOLING SYSTEM PERFORMANCE

Cooling system performance is typically measured based on a component's COP. The performance of the cooling system at a gold mine was monitored for a period of time. This allowed for trends to be established and the effects of managerial decisions to be quantified. It was felt that once management have established the effects of their decisions, they will be better qualified to plan maintenance and make decisions in future.

Simple 'Time vs COP' scatter charts were employed initially. These charts are simple to implement and interpret. Scatter charts allow component performance to be monitored, and can be used to highlight changes in system performance. It was suggested that once management had a better understanding of their systems, statistical control charts should be employed.

A number of statistical control charts are available. Based on the research findings and the application at hand, individuals and moving range charts were the control charts chosen for this study. The moving range chart plots the process variability, while the individuals chart plots the process average.

Statistical control charts allow for the performance of the cooling system to be monitored, tracking the process average and utilising control limits to understand natural process variation. Making use of control limits will prevent management from being over- or un-reactive when making decisions regarding operations. Over time, process variability increases; this, in turn decreases management's ability to make decisions with a high degree of confidence.

It is felt that statistical control charts will benefit management if implemented consistently by personnel with the appropriate statistical and system knowledge. There are a number of rules for identifying 'out of control' or instability in a process. Should these rules not be applied appropriately, any decision made based on the outcome of these charts could be detrimental to plant performance. Statistical control charts are also susceptible to faulty data. Incorrect data will cause the control limits and process average to be inflated or deflated.

From a practical point of view, it is unlikely that a mine engineer will have the time to process system data to obtain accurate control limits and identify and establish causes for instability. The required functionality can be programmed into a mine’s SCADA, for example, but a certain amount of human intuition is required to interpret the results. Mines should consider incorporating the monitoring of the cooling system performance into the portfolio of their asset optimisation departments, rather than leaving it to foremen. Asset optimisation teams should have the requisite knowledge to be able to use these tools effectively.

Information gleaned from performance analysis can be used in simulation models. A simulation package was identified as a potentially useful tool to identify energy savings strategies. This tool allows for the modelling of a complete cooling system, taking into account variable flows, ambient conditions and tariff structures.

6.3 CONSOLIDATION OF FINDINGS

Operational procedures

The COP of the entire system as well as the individual chillers was calculated and monitored for a period of time. Attention is given to a period in which there was a marked change in COP. It was noted that had one only been monitoring the COP of the system, this anomaly might not have been noticed.

Investigations were carried out to establish the causes of this increase in COP. On further analysis of system data and conversations with mine personnel, it was established that the operators had stopped the flow of water to the BACs. This is due to the fact that the ambient air was sufficiently cool and no longer required additional cooling. Stopping the flow of water to the BAC meant that the supply of cool water from the BAC sump also ceased. This resulted in an increase in the pre-cooling dam temperature. The COP increased due to the higher inlet temperature, causing an increase in cooling load placed on the chillers in operation. The machines subsequently operated under conditions closer to design specifications than those before the intervention.

Stopping the flow of water to the BAC also reduced the amount of water that had to be cooled. This meant that two chillers could be switched off for the winter period, resulting in additional electrical energy savings. It was proposed that this control philosophy be investigated further with a view to implementing it throughout the year.

It was mentioned that an increase in COP is not necessarily a positive outcome. The increase could be as a result of a faulty temperature probe reading a higher than normal temperature value. The fault could lead to an abnormally high COP value. Efforts should be made to establish the cause of any significant change in COP so that faults are identified before any major damage results. If the increase in COP is due to a positive intervention, it is important to establish the cause of this increase, and then to incorporate any changes into future operations. No instrumentation faults were detected during this investigation.

Maintenance procedures

Investigations were carried out to assess what impact maintenance procedures have on the performance of mine cooling systems. Data were obtained from the mine for the maintenance period during which the chillers were cleaned. Analysis of the data showed that the COP of the chiller machines increased between 29% and 42% after cleaning.

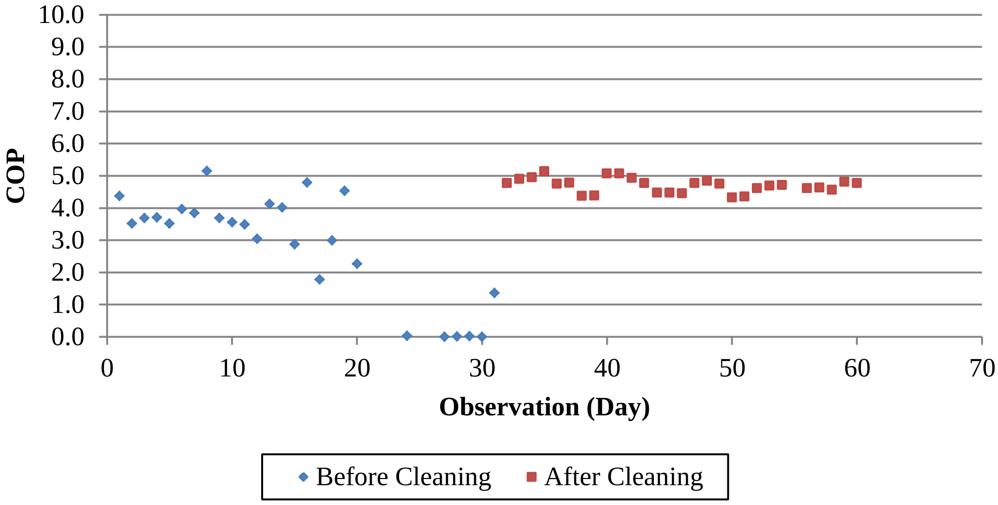

Figure 70: Change in COP of chiller 1 due to cleaning of evaporator tubes

Cleaning of the tubes improves heat transfer between the water and the refrigerant. Improved heat transfer results in enhanced cooling and decreased compressor power usage. In addition, cleaning the tubes of the chillers leads to a marginal increase in water flow rate. This is due to decreased resistance in the chiller tubes and an increase in internal pipe diameter. Consistency of performance also increased after scheduled maintenance. Process variability decreased from a standard deviation of 0.80 to 0.22. Low process variability allows management to make decisions regarding operations with a high degree of confidence.

An additional benefit of monitoring system performance is the ability to identify system faults. Monitoring the COP of a chiller also allows monitoring of multiple variables simultaneously – for example, water flow rates, inlet and outlet temperature, and power usage. Should any instrumentation become faulty, the subsequent COP value calculated using the reading from the faulty instrument will be abnormal. Management will very quickly be able to identify such a fault. If, for example, the COP of the chiller were not being monitored, the operator or manager would have to monitor all variables individually. This lowers the chances of being able to rectify any fault timeously. No faults were detected, however, over the course of this investigation.

6.4 ENERGY SAVINGS OPPORTUNITIES

Model constructional and validation

A simulation model was constructed to allow for various scenarios to be tested using software known as ‘Process Toolbox’. The model was validated before any testing commenced. When compared with actual system data, the results of the model were deemed adequate for the purposes of this study.

Refining of operational procedures

It was hypothesised that the existing policy of stopping the flow of water to the BAC could be incorporated throughout the course of the year. It was proposed that the flow of water to the BAC be stopped between 18:00 and 20:00 during the summer. This time period was chosen as ambient conditions are usually lower and the electricity tariffs are higher, thus maximising possible cost savings.

Tests were carried out to monitor the effects of stopping the flow of water to the BAC on the underground conditions. Analysing the data obtained from the sensors placed underground showed that there was no significant change in temperature or humidity that might make the proposal infeasible.

Simulations were performed whereby the flow of water to the BACs was stopped and two chillers were switched off every day between 18:00 and 20:00. This was in addition to the existing winter control philosophy. Results showed significant monetary and electrical savings potential. Monetary saving was in excess of five hundred thousand rand per year, with a power saving of approximately 136 kW per day. These significant savings can be realised without the need for expensive modifications or installations.

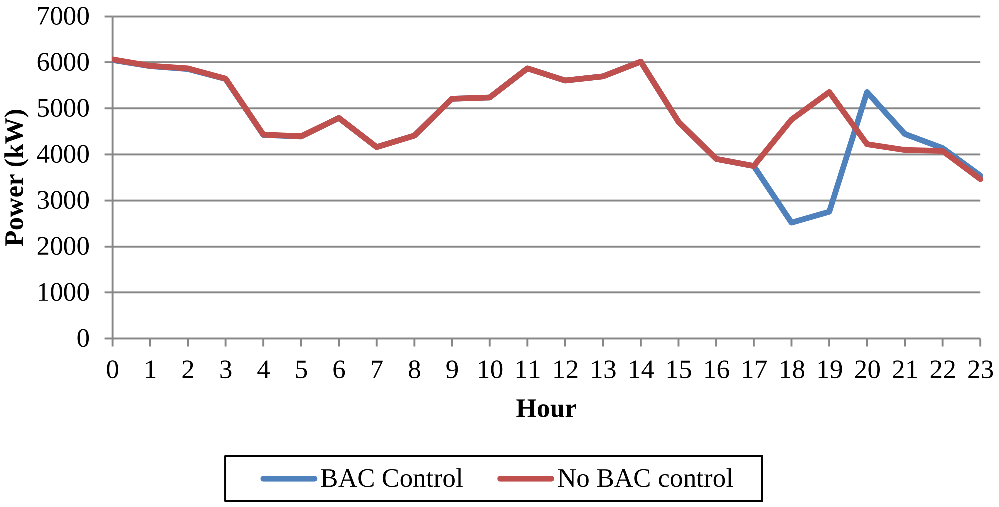

Figure 71: Average annual power profiles with and without additional BAC control

Optimisation of maintenance procedures

Having quantified the effects of maintenance procedures and realised the additional associated benefits, investigations were carried out to establish the frequency with which maintenance should be performed to maximise cost savings. The study took into account the costs of maintenance as well as the practical constraints. Optimising the maintenance schedule will allow the mine to realise electrical energy savings without the need for expensive installations or modifications.

Costs of maintenance were measured against the subsequent monetary savings resulting from more efficient chillers. It was established that mine personnel should schedule maintenance procedures six times a year to maximise cost savings. This results in an additional monetary saving of R 992 512 when compared with the existing cleaning schedule.

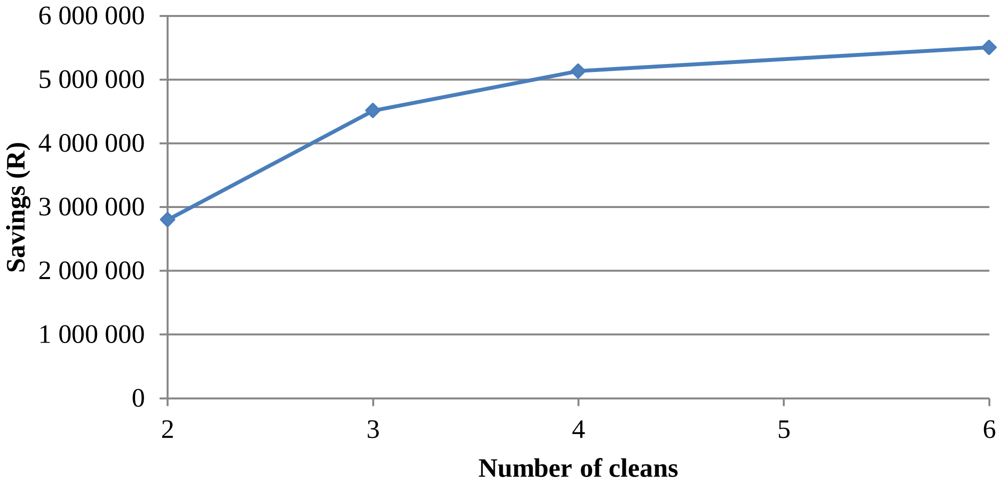

Figure 72: Cost savings per number of cleans

Practical constraints in terms of personnel and time availability may limit the frequency with which maintenance can be performed. Conversely, regular maintenance will result in less sediment build up, making cleaning easier and less time-consuming. In addition, personnel will become more proficient in carrying out maintenance. This could result in a situation where more than one chiller could be cleaned in a single shift, thus minimising downtime.

The findings were extrapolated to ascertain what the effect would be should South Africa's biggest mines implement an optimised maintenance strategy. An annual conservative electrical saving of 52 127 MWh is estimated – a cost saving of R 28 669 850.

6.5 FURTHER STUDIES

The principles and strategies identified in this study can also be applied to underground chillers and BACs. It remains to be seen what impact the strategies would have on the performance of underground cooling components. Improved efficiencies of underground cooling components would reduce the amount of water that has to pumped to surface for cooling, resulting in additional electrical energy savings.

The strategy can also be applied to other electricity-intensive components in the mining environment. These include compressors, extraction fans, and winders. Performance monitoring will assist in the optimisation of maintenance schedules and improve fault detection. The continued reliability and efficiency of these important components will be crucial to operations as mines strive to meet production targets.

The main reason for a reduction in cooling system component performance is the build up of sediment on the heat exchanger surfaces. This is primarily due to the poor quality of the water coming from underground mining operations. Settling dams become increasingly incapable of handling the additional flows resulting from increased production and ever-deepening mines. Treating the cause of poor water quality will reduce its subsequent effects. It is envisaged that improving the quality of water pumped from underground will markedly improve the performance of a cooling system.

The specific details pertaining to the cooling system maintenance procedures are not considered in this study. With further research, it is envisaged that the practical constraints associated with maintenance, particularly system downtime and costs, could be reduced.

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APPENDIX I

Control charts

Table 12: Data for individuals and moving range chart example

Observation	COP (x)	Moving Range (MR)	Centreline (MR)	LCL (MR)	UCL (MR)	Centreline (x)	LCL (x)	UCL (x)
1	3.92	-	0.27	0.00	0.87	3.82	3.12	4.53
2	4.06	0.14	0.27	0.00	0.87	3.82	3.12	4.53
3	3.78	0.28	0.27	0.00	0.87	3.82	3.12	4.53
4	3.91	0.12	0.27	0.00	0.87	3.82	3.12	4.53
5	3.70	0.21	0.27	0.00	0.87	3.82	3.12	4.53
6	3.82	0.11	0.27	0.00	0.87	3.82	3.12	4.53
7	3.67	0.14	0.27	0.00	0.87	3.82	3.12	4.53
8	3.59	0.09	0.27	0.00	0.87	3.82	3.12	4.53
9	3.35	0.24	0.27	0.00	0.87	3.82	3.12	4.53
10	3.53	0.17	0.27	0.00	0.87	3.82	3.12	4.53
11	3.86	0.34	0.27	0.00	0.87	3.82	3.12	4.53
12	3.87	0.01	0.27	0.00	0.87	3.82	3.12	4.53
13	3.90	0.02	0.27	0.00	0.87	3.82	3.12	4.53
14	3.78	0.12	0.27	0.00	0.87	3.82	3.12	4.53
15	4.24	0.46	0.27	0.00	0.87	3.82	3.12	4.53
16	3.69	0.55	0.27	0.00	0.87	3.82	3.12	4.53
17	4.34	0.65	0.27	0.00	0.87	3.82	3.12	4.53
18	3.79	0.55	0.27	0.00	0.87	3.82	3.12	4.53
19	3.80	0.02	0.27	0.00	0.87	3.82	3.12	4.53
20	4.37	0.56	0.27	0.00	0.87	3.82	3.12	4.53
21	4.51	0.14	0.27	0.00	0.87	3.82	3.12	4.53
22	4.26	0.25	0.27	0.00	0.87	3.82	3.12	4.53
23	4.41	0.16	0.27	0.00	0.87	3.82	3.12	4.53
24	4.30	0.11	0.27	0.00	0.87	3.82	3.12	4.53
25	3.83	0.47	0.27	0.00	0.87	3.82	3.12	4.53
26	3.98	0.15	0.27	0.00	0.87	3.82	3.12	4.53

Observation	**COP (x)**	**Moving Range (MR)**	**Centreline (MR)**	**LCL (MR)**	**UCL (MR)**	**Centreline (x)**	**LCL (x)**	**UCL (x)**
27	4.12	0.14	0.27	0.00	0.87	3.82	3.12	4.53
28	4.38	0.25	0.27	0.00	0.87	3.82	3.12	4.53
29	3.85	0.53	0.27	0.00	0.87	3.82	3.12	4.53
30	3.34	0.51	0.27	0.00	0.87	3.82	3.12	4.53
31	3.77	0.43	0.27	0.00	0.87	3.82	3.12	4.53
32	3.58	0.19	0.27	0.00	0.87	3.82	3.12	4.53
33	3.55	0.03	0.27	0.00	0.87	3.82	3.12	4.53
34	3.75	0.20	0.27	0.00	0.87	3.82	3.12	4.53
35	3.55	0.20	0.27	0.00	0.87	3.82	3.12	4.53
36	3.97	0.42	0.27	0.00	0.87	3.82	3.12	4.53
37	3.71	0.26	0.27	0.00	0.87	3.82	3.12	4.53
38	4.15	0.44	0.27	0.00	0.87	3.82	3.12	4.53
39	3.46	0.69	0.27	0.00	0.87	3.82	3.12	4.53
40	3.47	0.02	0.27	0.00	0.87	3.82	3.12	4.53
41	3.35	0.12	0.27	0.00	0.87	3.82	3.12	4.53
42	3.28	0.07	0.27	0.00	0.87	3.82	3.12	4.53
43	3.34	0.06	0.27	0.00	0.87	3.82	3.12	4.53
44	3.87	0.54	0.27	0.00	0.87	3.82	3.12	4.53
45	3.36	0.51	0.27	0.00	0.87	3.82	3.12	4.53
Total	172.09	11.69						

Moving range

$$Centreline\ (moving\ range) = (\bar{R}) = \frac{\sum R}{k-1} = \frac{11.69}{44} = 0.27 \tag{22}$$

$$UCL\ (moving\ range) = D_4\bar{R} = 3.267 \times 0.27 = 0.87 \tag{23}$$

$$LCL\ (moving\ range) = D_3\bar{R} = 0 \times 0.27 = 0 \tag{24}$$

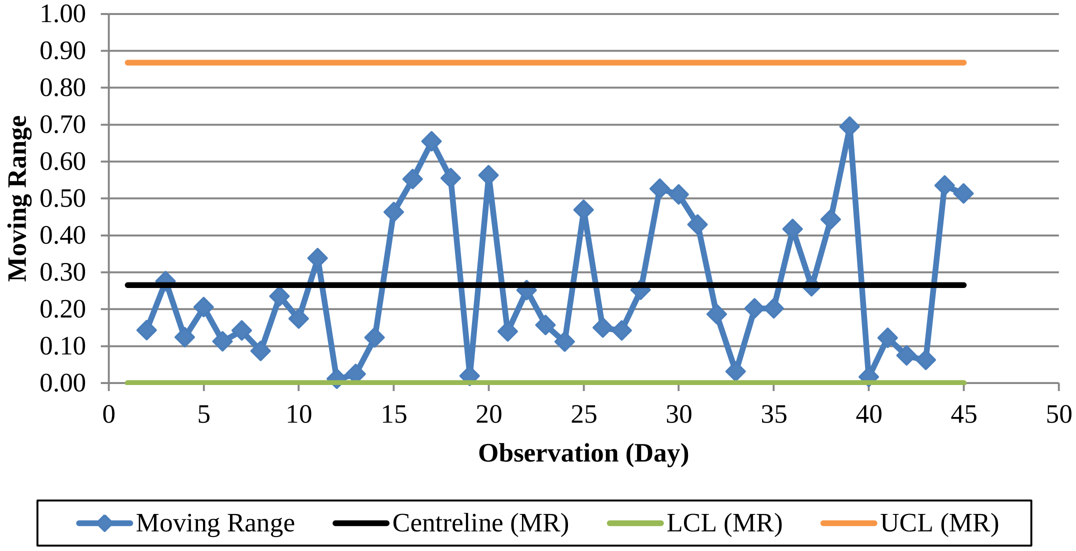

Figure 73: Example – moving range chart

Individual value

$$Centreline\ (x) = (\bar{x}) = \frac{\sum x}{k} = \frac{172.09}{45} = 3.82 \tag{25}$$

$$UCL\ (x) = \bar{x} + E_2\bar{R} = 3.82 + (2.66 \times 0.27) = 4.53 \tag{26}$$

$$LCL\ (x) = \bar{x} - E_2\bar{R} = 3.82 - (2.66 \times 0.27) = 3.12 \tag{27}$$

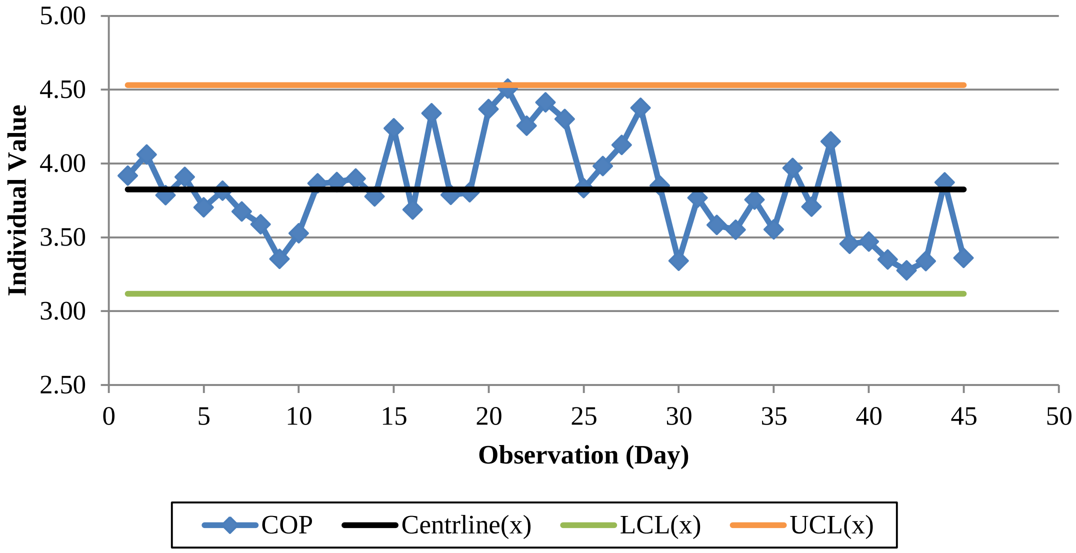

Figure 74: Example – individuals chart

APPENDIX II

Results – Principle 1

Operational procedures

Table 13 shows the daily average COPs of each chiller, as well as the combined average COP. The data is depicted graphically in the graphs below the table.

Table 13: Chiller COPs - Operations

Observation	All Chillers COP	Chiller 1 COP	Chiller 2 COP	Chiller 3 COP	Chiller 4 COP
1	5.0	3.2	8.6	4.0	4.5
2	4.8	1.8	5.2	3.5	5.2
3	4.5	3.2	2.6	1.1	4.1
4	1.5	3.0	6.8	1.1	1.9
5	5.3	3.2	9.5	2.5	3.2
6	5.0	3.2	9.4	3.3	4.0
7	4.8	3.8	7.2	2.6	4.7
8	4.6	3.7	4.3	3.2	4.3
9	4.6	4.0	4.7	3.8	4.2
10	5.8	3.4	6.8	2.4	2.7
11	4.7	3.1	6.9	3.9	4.2
12	4.5	4.5	3.2	1.4	4.0
13	2.4	3.0		0.0	2.8
14					
15	3.9	3.8	1.5		3.1
16	4.1	3.8	2.0	1.7	2.6
17	5.6	4.1	2.6	1.2	3.9
18	5.0	4.2	9.8	2.5	4.2
19	5.1	3.6	9.8	3.9	4.1
20	4.7	3.9	7.2	2.0	4.4
21	5.0	4.2	9.9	2.7	4.5
22	5.0	3.9	9.6	2.8	4.5
23	4.8	4.2	11.6	2.2	4.7
24	8.1				
25	6.1	3.7	5.2	2.8	5.3
26	4.9	4.3	6.4	2.8	3.4
27	5.0	4.4	6.3	2.7	3.9

Observation	All Chillers COP	Chiller 1 COP	Chiller 2 COP	Chiller 3 COP	Chiller 4 COP
28	4.9	3.9	9.3	2.8	4.4
29	5.8	3.7	7.9	3.6	4.8
30	5.2	3.7	6.0	3.0	5.3
31	4.5	3.9	1.9	0.6	4.2
32	5.1	4.1	6.3	3.2	4.7
33	4.8	3.8	5.6	3.1	4.8
34	4.8	3.5	5.5	2.3	4.8
35	4.9	1.5	7.0	2.7	4.4
36	4.4		3.2	1.5	5.6
37	4.3	0.0	0.1	2.5	5.5
38	3.4	0.0		4.3	2.5
39	5.3	0.0	0.0	2.2	3.6
40	4.9	0.0	1.4	5.3	6.5
41	5.2		1.3	5.5	5.8
42	4.6	0.0	0.6	4.8	5.6
43	5.4		4.7	5.7	5.9
44	5.2	0.0	0.8	5.6	5.8
45	5.8	0.0	0.1	5.1	4.7
46	5.2	0.0	2.1	5.8	5.8
47	5.4		4.3	4.2	5.5
48	5.3	0.0	3.2	4.8	5.6
49					
50	5.5	0.1		6.1	5.3
51	5.1	0.1		5.6	5.3
52	4.8	0.1		4.4	4.3
53	5.0	0.1		5.6	5.5
54	5.1	0.0		5.5	5.4
55	5.1	0.1	0.1	5.6	5.7
56	5.2	0.1	0.0	2.6	5.0
57	4.8	0.0	0.1	1.7	5.5
58	5.8	0.0	0.3	3.6	4.5
59	4.2	0.0	0.2	1.5	5.1
60	4.7	0.0	0.3	3.5	5.3

Observation	All Chillers COP	Chiller 1 COP	Chiller 2 COP	Chiller 3 COP	Chiller 4 COP
61	5.0	0.1	0.1	5.3	5.4
62	4.9	0.2	0.1	5.3	5.0
63	4.7	0.1	0.1	5.6	9.2
64	6.2	2.1	3.3	7.9	9.8
65	4.3	0.1	0.1	7.7	
66	5.5	0.1	0.1	5.5	5.1
67	6.0	0.1	0.1	7.5	9.1
68	5.2	0.1	0.1	5.5	5.4
69	5.1	0.1	0.2	5.9	8.6
70	4.7	0.1	0.2	5.8	6.4

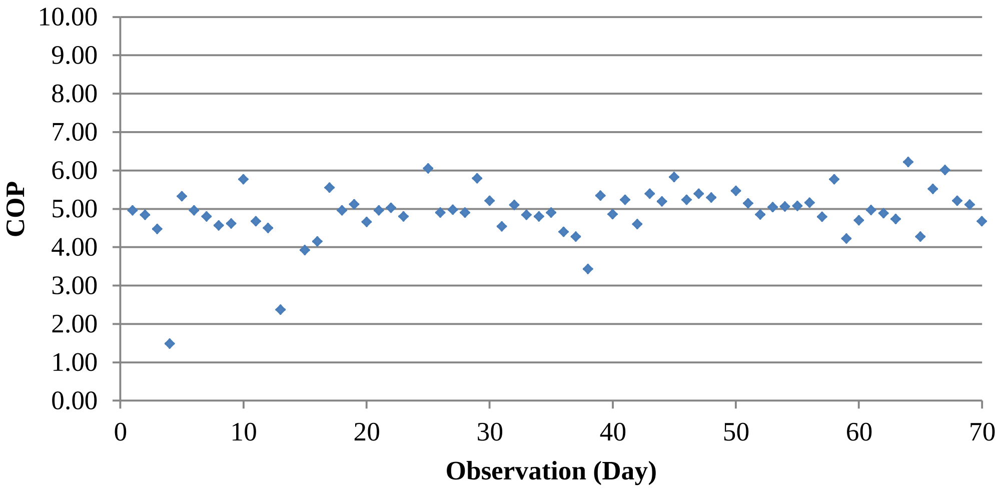

Figure 75: Refrigeration plant COP during investigation

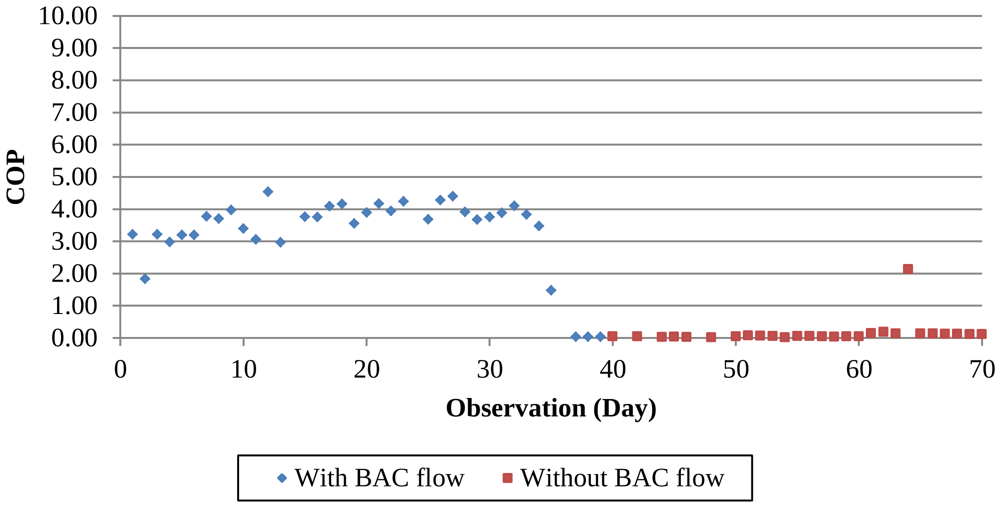

Figure 76: Change in COP of chiller 1 after BAC switched off

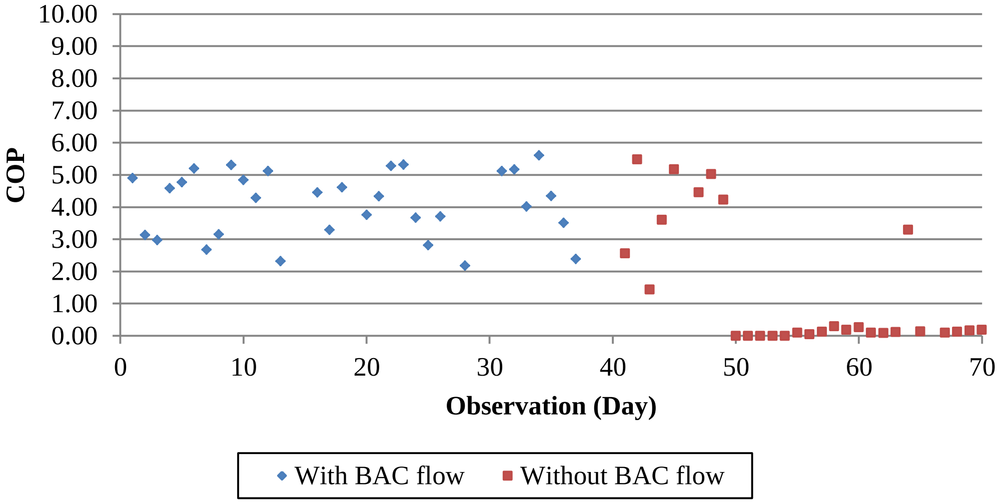

Figure 77: Change in COP of chiller 2 after BAC switched off

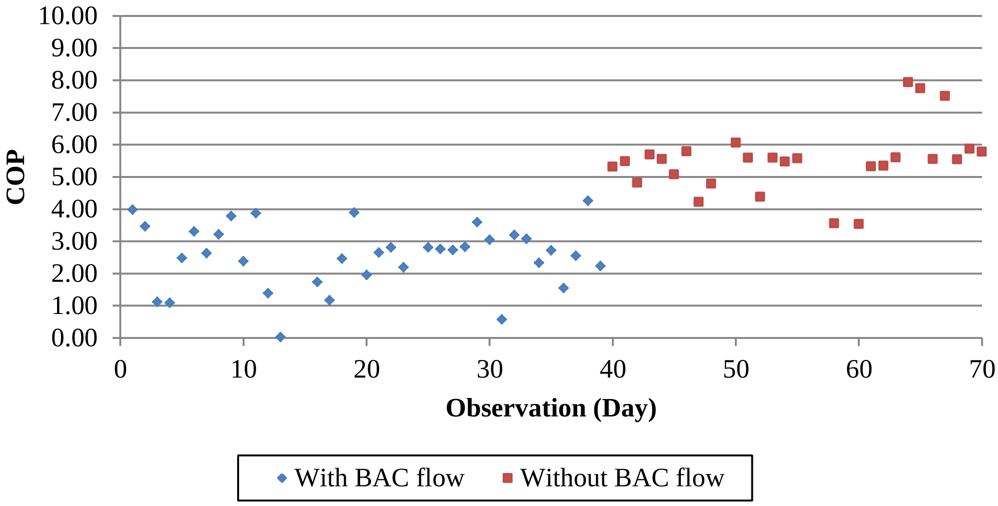

Figure 78: Change in COP of chiller 3 after BAC switched off

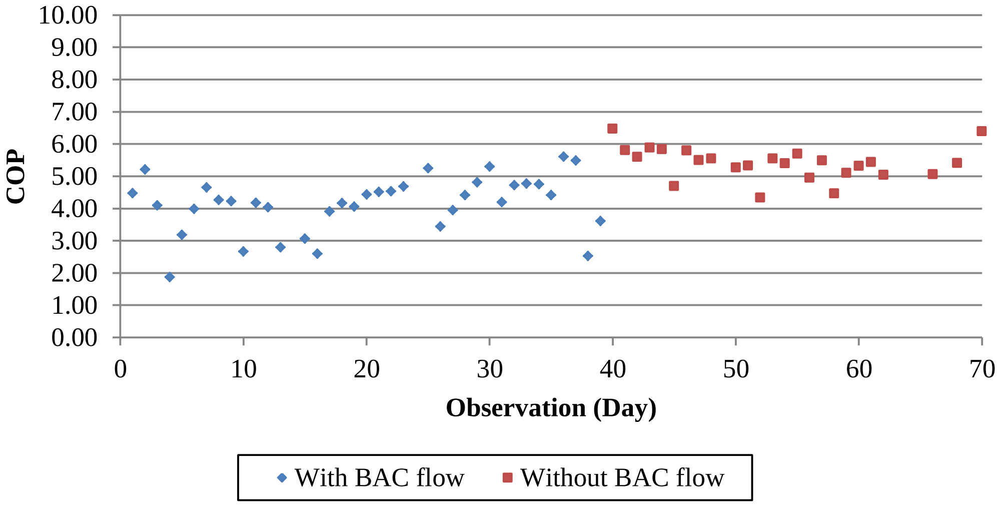

Figure 79: Change in COP of chiller 4 after BAC switched off

Maintenance procedures

Table 14 shows the COPs of the respective chillers as well as the COP of the entire refrigeration plant. The data was collected before and after the scheduled maintenance period. The data is depicted graphically below the table.

Table 14: Chiller COPs - Maintenance

Observation	All Chillers COP	Chiller 1 COP	Chiller 2 COP	Chiller 3 COP	Chiller 4 COP
1	4.39	4.37	3.04	4.35	4.64
2	4.54	3.51	2.76	0.83	5.20
3	4.69	3.68	3.61	3.03	3.75
4	5.50	3.70	4.22	3.37	4.03
5	5.35	3.51	6.82	5.03	2.72
6	5.03	3.96	4.17	4.55	3.61
7	4.95	3.84	5.86	4.53	3.68
8	4.24	5.15	1.99	1.94	0.44
9	5.39	3.68	3.55	3.07	2.61
10	5.78	3.56	4.07	3.45	3.64
11	4.85	3.49	4.60	5.02	4.08
12	5.32	3.04	4.91	4.30	3.63
13	5.10	4.12	4.73	4.51	3.66
14	5.05	4.01		4.47	3.35
15	4.78	2.86	5.40	3.00	3.80
16	3.80	4.79	2.16	1.29	4.14
17		1.77	2.73	3.06	2.37
18	4.93	2.99	3.87	3.46	4.57
19	4.87	4.53	3.90	3.03	4.69
20	4.99	2.26	2.22	2.88	4.95
21		0.00	4.70	5.33	3.18
22		0.00	1.72	3.86	5.02
23		0.00	1.76	1.57	1.75
24					
25					
26					
27					
28					
29					
30					
31		1.36	3.33		
32	4.85	4.76	4.58		
33	4.42	4.90	3.43		
34	3.92	4.95	2.79		
35	4.31	5.13	3.03		

Observation	All Chillers COP	Chiller 1 COP	Chiller 2 COP	Chiller 3 COP	Chiller 4 COP
36	4.89	4.75	1.63		
37	5.39	4.78	4.18		
38	5.63	4.37			
39	5.17	4.38	2.79		
40	4.16	5.06	3.31		
41	3.90	5.07	3.09		
42	4.00	4.93	1.85		
43	4.04	4.77	2.91		
44	3.36	4.47	3.25		
45	3.66	4.47	3.92		
46	3.88	4.45	2.49		
47	3.75	4.77	2.27		
48	3.94	4.84	3.41		
49	3.79	4.74	1.62		
50	3.50	4.32	2.35		
51	3.49	4.35	2.63		
52	4.00	4.60	2.54		
53	3.64	4.68	4.16		
54	3.96	4.70	3.51		
55			5.08		
56	3.69	4.60	3.44		
57	4.15	4.62	4.42		
58	3.90	4.55	4.43		
59	4.00	4.80	2.66		
60	3.98	4.77	3.87		

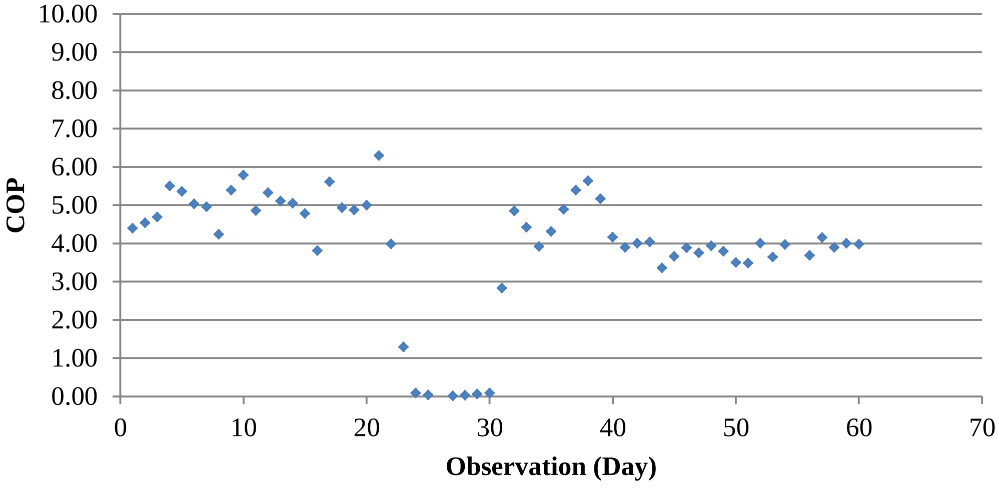

Figure 80: Refrigeration plant COP during investigation

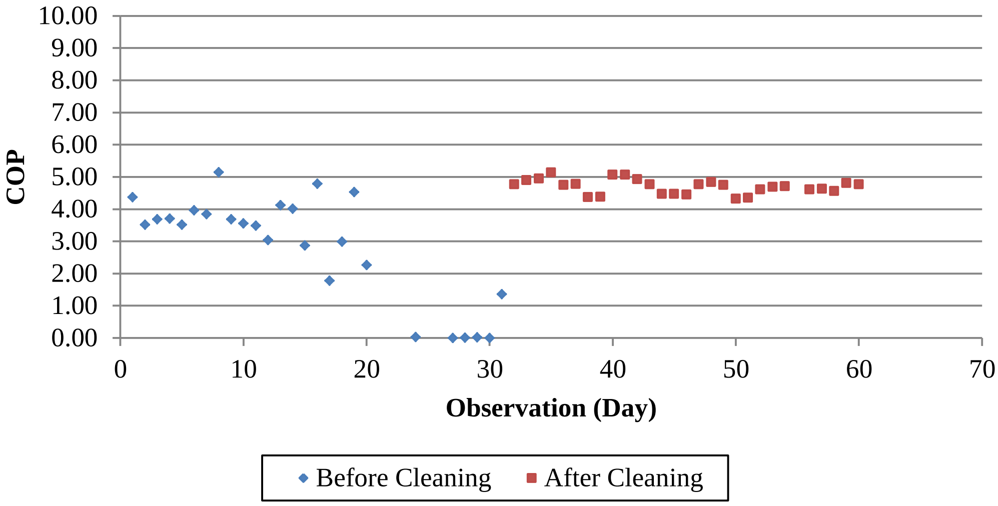

Figure 81: Change in COP of chiller 1 after scheduled maintenance

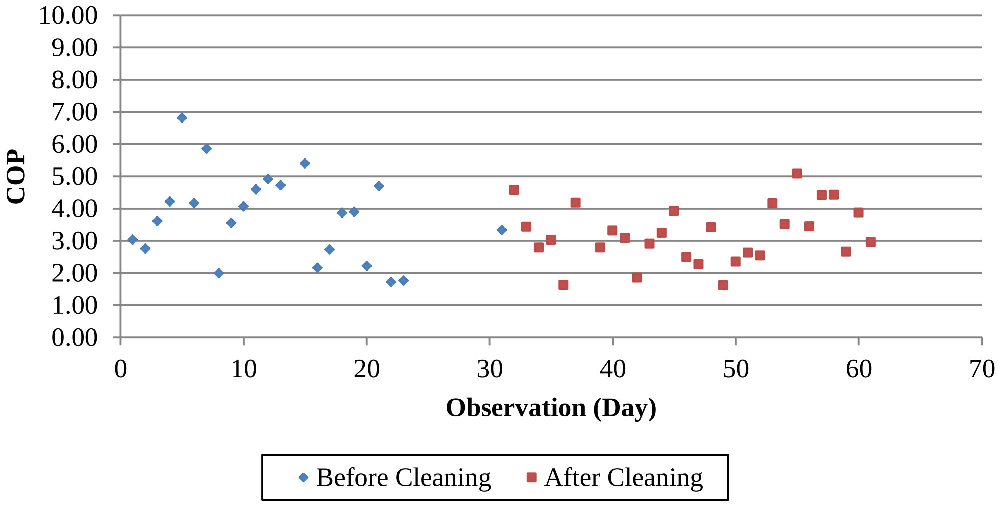

Figure 82: Change in COP of chiller 2 after scheduled maintenance

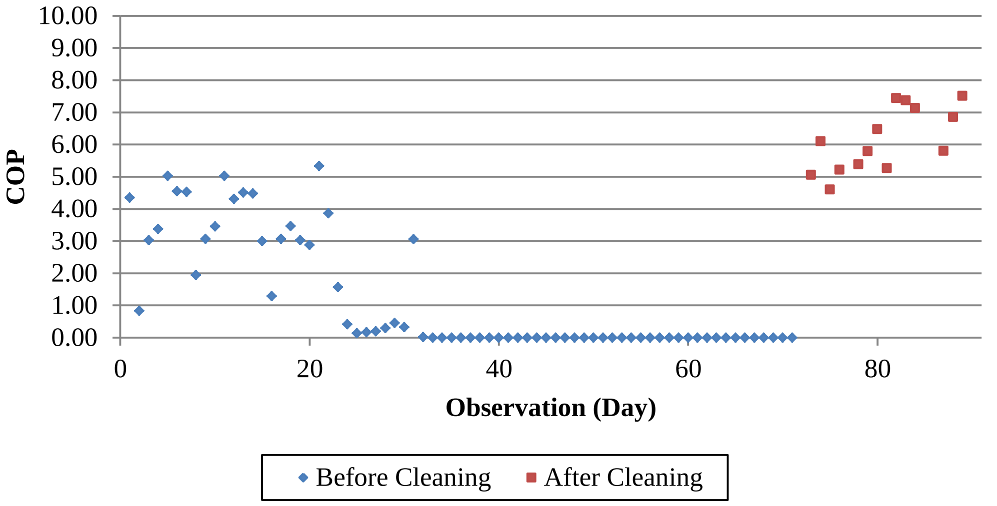

Figure 83: Change in COP of chiller 3 after scheduled maintenance

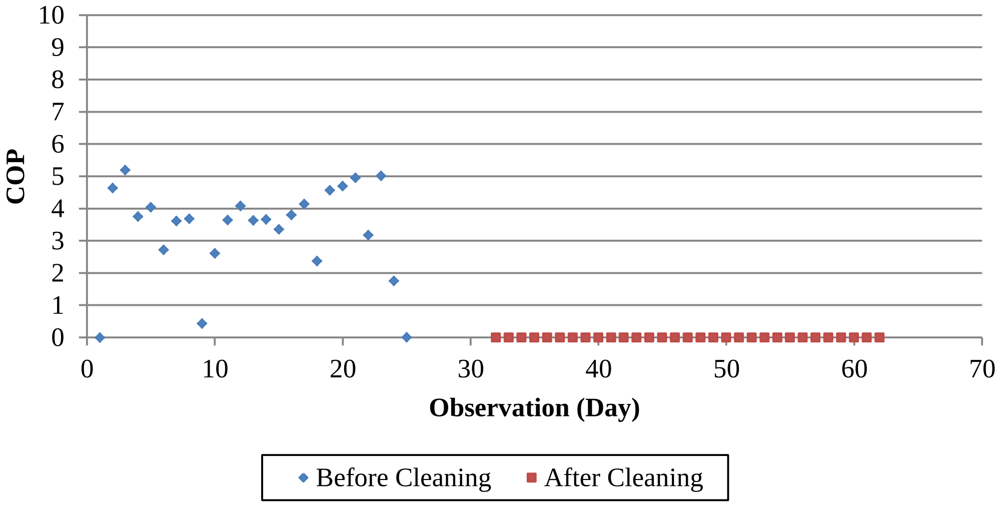

Figure 84: Change in COP of chiller 4 after scheduled maintenance

APPENDIX III

Results – Principle 2

Operational procedures

Observation (Day)	All Chillers COP	Moving Range (All)	Chiller 1 COP	Moving Range (1)	Chiller 2 COP	Moving Range (2)	Chiller 3 COP	Moving Range (3)	Chiller 4 COP	Moving Range (4)
1	4.96		3.22		4.90		3.98			4.96
2	4.85	0.11			3.14	1.76	3.47	0.51	0.73	4.85
3	4.48	0.37			2.98	0.16	1.12	2.35	1.11	4.48
4			2.97		4.59	1.61	1.09	0.04		
5			3.20	0.22	4.78	0.19	2.48	1.40	1.31	
6	4.96		3.20	0.00	5.20	0.42	3.30	0.82	0.80	4.96
7	4.80	0.17	3.78	0.58	2.68	2.52	2.63	0.68	0.67	4.80
8	4.56	0.23	3.70	0.07	3.16	0.48	3.22	0.59	0.39	4.56
9	4.62	0.06	3.97	0.27	5.31	2.15	3.79	0.57	0.04	4.62
10	5.77	1.15	3.39	0.58	4.84	0.47	2.38	1.41	1.56	5.77
11	4.68	1.10	3.06	0.34	4.29	0.55	3.87	1.50	1.51	4.68
12	4.50	0.18			5.12	0.83	1.38	2.49	0.14	4.50
13	2.37				2.32	2.80		1.38	1.24	2.37
14										
15	3.92		3.76							3.92
16	4.15	0.23	3.76	0.01	4.46		1.73		0.46	4.15
17			4.09	0.34	3.29	1.17	1.17	0.56	1.30	
18	4.96		4.16	0.07	4.62	1.33	2.46	1.29	0.26	4.96
19	5.12	0.15	3.56	0.60			3.89	1.42	0.11	5.12
20	4.66	0.46	3.89	0.34	3.76		1.95	1.93	0.38	4.66
21	4.96	0.31	4.17	0.28	4.34	0.58	2.65	0.70	0.08	4.96
22	5.02	0.06	3.94	0.23	5.28	0.94	2.81	0.16	0.02	5.02
23	4.80	0.23	4.24	0.29	5.32	0.04	2.19	0.62	0.15	4.80
24					3.67	1.65				
25	6.05		3.68		2.82	0.85	2.81			6.05
26	4.90	1.15	4.28	0.59	3.71	0.89	2.76	0.05	1.82	4.90
27	4.98	0.08	4.40	0.12	7.96	4.25	2.73	0.03	0.51	4.98
28	4.90	0.08	3.91	0.49	2.18		2.82	0.09	0.47	4.90
29	5.79	0.90	3.67	0.24			3.59	0.77	0.40	5.79
30	5.21	0.58	3.75	0.08	6.65		3.05	0.55	0.49	5.21
31	4.54	0.67	3.88	0.13	5.12	1.53			1.10	4.54

Observation (Day)	All Chillers COP	Moving Range (All)	Chiller 1 COP	Moving Range (1)	Chiller 2 COP	Moving Range (2)	Chiller 3 COP	Moving Range (3)	Chiller 4 COP	Moving Range (4)
32	5.10	0.56	4.10	0.22	5.17	0.05	3.19		0.53	5.10
33	4.84	0.27	3.83	0.26	4.02	1.15	3.08	0.12	0.05	4.84
34	4.80	0.04	3.48	0.35	5.61	1.59	2.33	0.74	0.02	4.80
35	4.90	0.10			4.35	1.26	2.72	0.38	0.33	4.90
36	4.40	0.50			3.51	0.84	1.54	1.17	1.20	4.40
37	4.28	0.12			2.39	1.12	2.55	1.00	0.12	4.28
38	3.43	0.85					4.26	1.71		3.43
39	5.34						2.23	2.03	1.08	5.34
40	4.86	0.48					5.31	3.07		4.86
41	5.23	0.37			2.56		5.48	0.17	0.66	5.23
42	4.60	0.63			5.48	2.92	4.82	0.66	0.21	4.60
43	5.39	0.79			1.44	4.04	5.69	0.87	0.28	5.39
44	5.19	0.20			3.60	2.16	5.55	0.14	0.05	5.19
45	5.83	0.63			5.17	1.57	5.08	0.47	1.13	5.83
46	5.23	0.60					5.79	0.71	1.09	5.23
47	5.39	0.16			4.46		4.22	1.57	0.30	5.39
48	5.30	0.10			5.02	0.56	4.79	0.57	0.06	5.30
49					4.23	0.79				
50	5.46						6.05			5.46
51	5.14	0.32					5.59	0.46	0.06	5.14
52	4.85	0.29					4.38	1.21	0.99	4.85
53	5.05	0.20					5.59	1.21	1.21	5.05
54	5.06	0.02					5.47	0.11	0.15	5.06
55	5.07	0.01					5.57	0.10	0.30	5.07
56	5.16	0.09					2.63	2.94	0.75	5.16
57	4.80	0.37					1.67	0.96	0.53	4.80
58	5.77	0.97					3.56	1.89	1.02	5.77
59							1.51	2.04	0.64	
60	4.70						3.53	2.02	0.22	4.70
61	4.97	0.27					5.32	1.79	0.11	4.97
62	4.89	0.08					5.34	0.03	0.39	4.89
63	4.74	0.15					5.60	0.26		4.74
64							7.94	2.33		
65	4.28						7.75	0.19		4.28

Observation (Day)	All Chillers COP	Moving Range (All)	Chiller 1 COP	Moving Range (1)	Chiller 2 COP	Moving Range (2)	Chiller 3 COP	Moving Range (3)	Chiller 4 COP	Moving Range (4)
66	5.52	1.24					5.55	2.20		5.52
67	6.01	0.49					7.51	1.96		6.01
68	5.21	0.80					5.54	1.98		5.21
69	5.10	0.10					5.87	0.33		5.10
70	4.68	0.43					5.78	0.09		4.68
Totals	**305.1**	**20.5**	**105.0**	**6.7**	**173.5**	**45.2**	**245.7**	**61.4**	**30.5**	**305.1**
Count	**62**	**52**	**28**	**24**	**41**	**34**	**64**	**60**	**52**	**62**
Moving Range										
$\bar{R}$		0.39		0.28		1.33		1.02	0.59	
UCL (MR)		1.29		0.91		4.35		3.34	1.92	
LCL (MR)		0.00		0.00		0.00		0.00	0.00	
Individuals										
$\bar{x}$	4.92		3.75		4.23		3.84			4.92
UCL (x)	5.97		4.49		7.77		6.56			5.97
LCL (x)	3.87		3.01		0.69		1.12			3.87

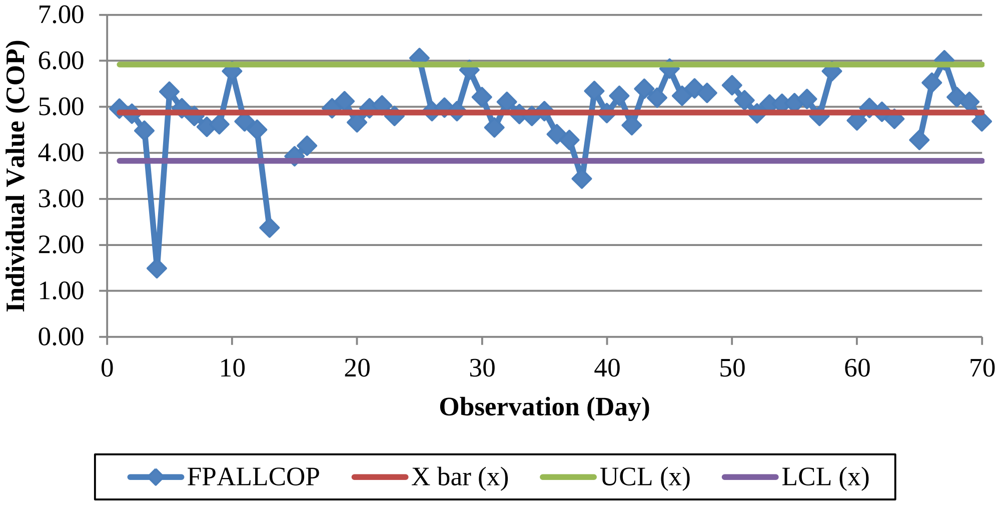

Figure 85: Individuals chart for all chillers indicating process performance, average, and control limits

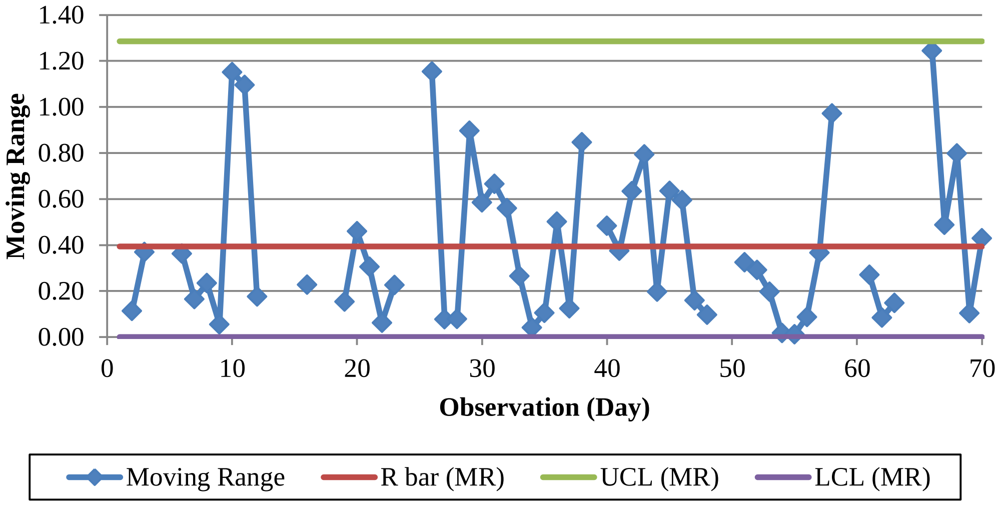

Figure 86: Moving range chart for all chillers indicating process variation and control limits

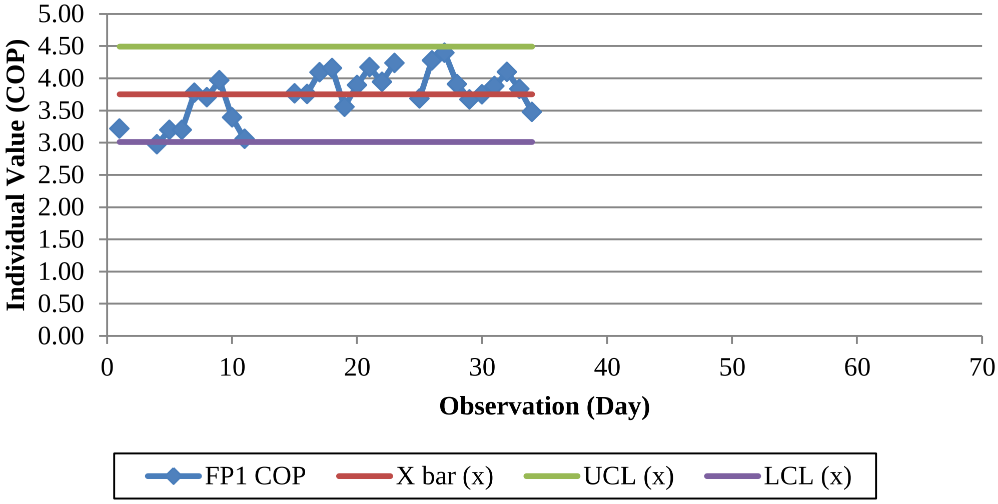

Figure 87: Individuals chart for chiller 1 indicating process performance, average, and control limits

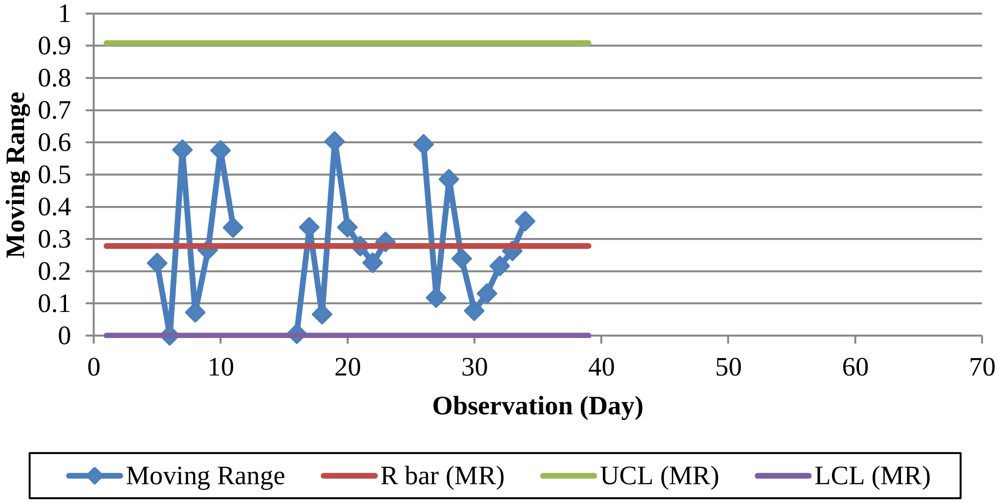

Figure 88: Moving range chart for chiller 1 indicating process variation and control limits

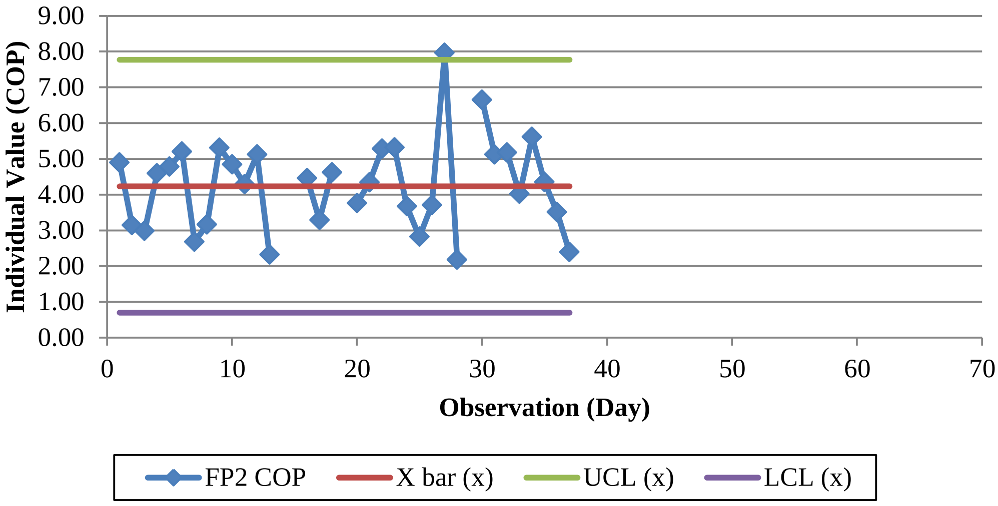

Figure 89: Individuals chart for chiller 2 indicating process performance, average, and control limits

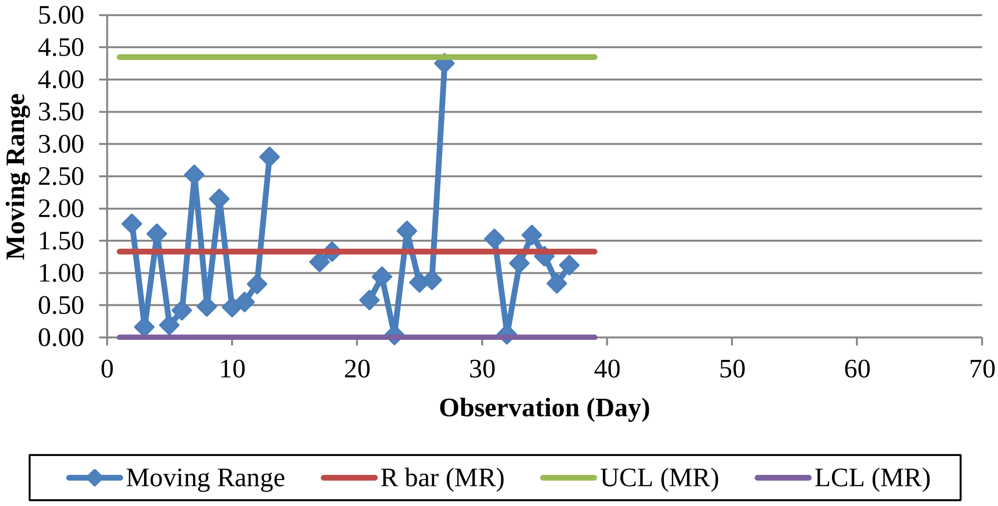

Figure 90: Moving range chart for chiller 2 indicating process variation and control limits

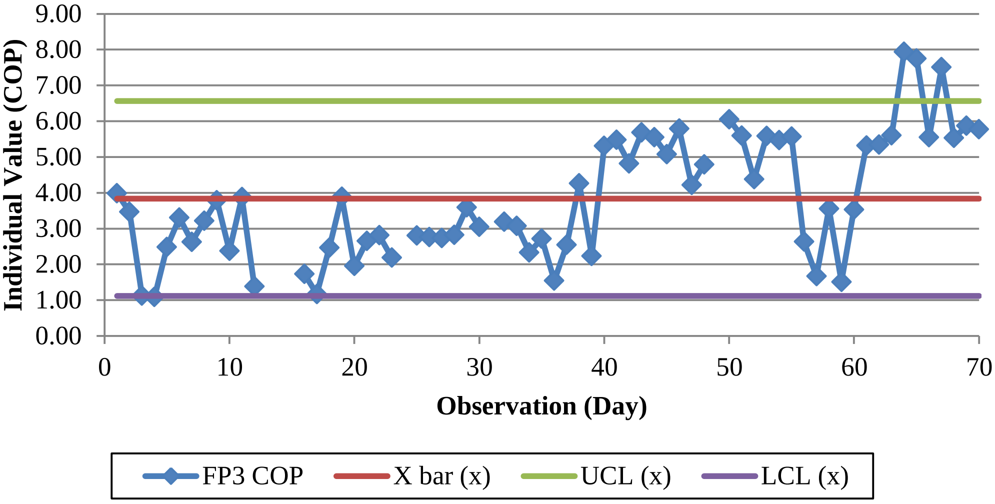

Figure 91: Individuals chart for chiller 3 indicating process performance, average, and control limits

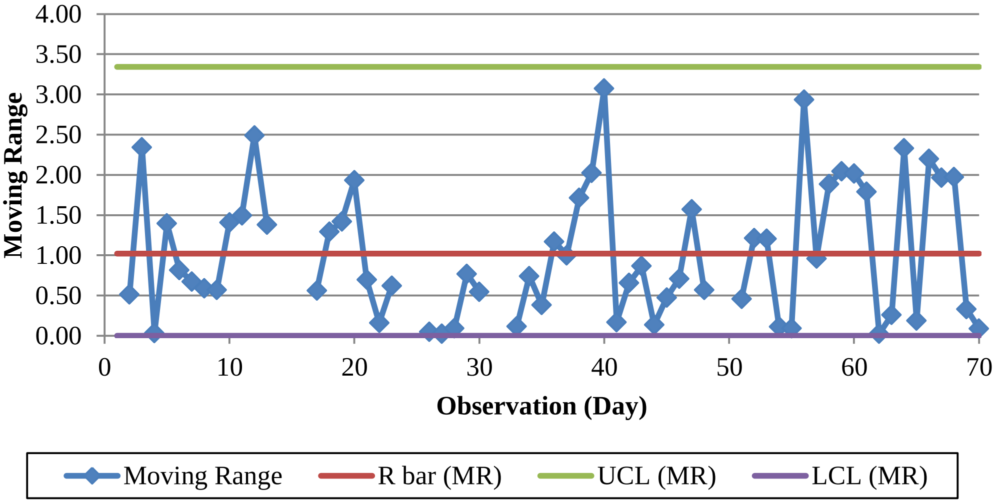

Figure 92: Moving range chart for chiller 3 indicating process variation and control limits

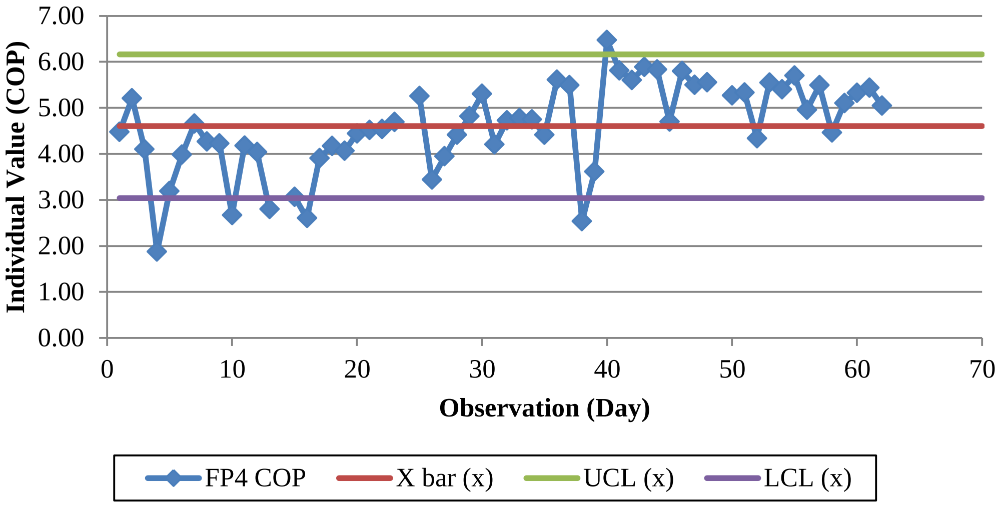

Figure 93: Individuals chart for chiller 4 indicating process performance, average, and control limits

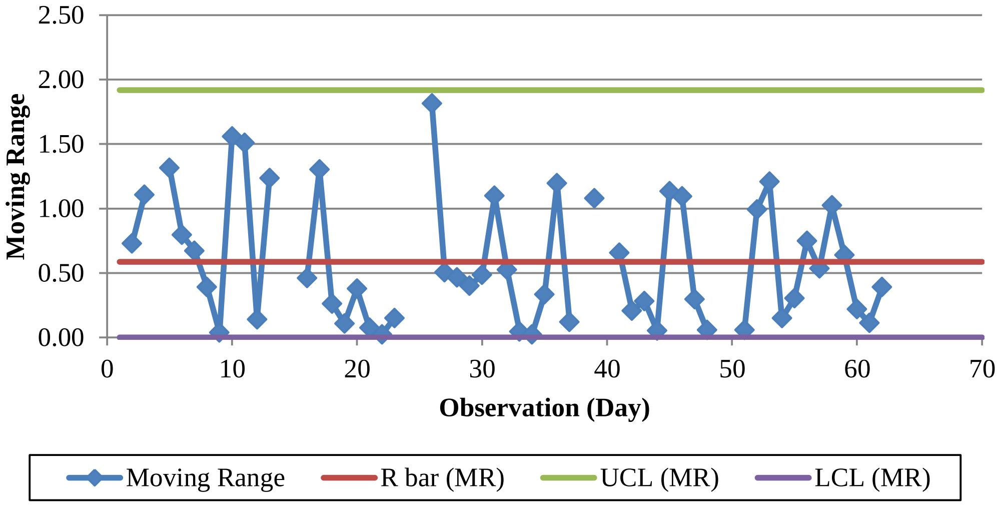

Figure 94: Moving range chart for chiller 4 indicating process variation and control limits

Maintenance procedures

Observation	All Chillers COP	Moving Range (All)	Chiller 1 COP	Moving Range (1)	Chiller 2 COP	Moving Range (2)	Chiller 3 COP	Moving Range (3)	Chiller 4 COP	Moving Range (4)
1	4.39		4.37		3.04		4.35		4.64	
2	4.54	0.15	3.51	0.86	2.76	0.28	0.83	3.52	5.20	0.56
3	4.69	0.15	3.68	0.17	3.61	0.85	3.03	2.20	3.75	1.44
4	5.50	0.81	3.70	0.02	4.22	0.61	3.37	0.34	4.03	0.28
5	5.35	0.14	3.51	0.19	6.82	2.60	5.03	1.65	2.72	1.32
6	5.03	0.32	3.96	0.45	4.17	2.65	4.55	0.47	3.61	0.89
7	4.95	0.08	3.84	0.12	5.86	1.69	4.53	0.02	3.68	0.07
8	4.24	0.71	5.15	1.30	1.99	3.87	1.94	2.59		
9	5.39	1.15	3.68	1.47	3.55	1.56	3.07	1.13	2.61	
10	5.78	0.39	3.56	0.12	4.07	0.52	3.45	0.38	3.64	1.03
11	4.85	0.93	3.49	0.07	4.60	0.53	5.02	1.57	4.08	0.44
12	5.32	0.47	3.04	0.44	4.91	0.31	4.30	0.72	3.63	0.44
13	5.10	0.22	4.12	1.08	4.73	0.18	4.51	0.21	3.66	0.03
14	5.05	0.05	4.01	0.11			4.47	0.03	3.35	0.31
15	4.78	0.27	2.86	1.15	5.40		3.00	1.47	3.80	0.45
16	3.80	0.97	4.79	1.92	2.16	3.24	1.29	1.71	4.14	0.34
17			1.77	3.01	2.73	0.57	3.06	1.77	2.37	1.77
18	4.93		2.99	1.21	3.87	1.14	3.46	0.40	4.57	2.20
19	4.87	0.06	4.53	1.54	3.90	0.03	3.03	0.43	4.69	0.12
20	4.99	0.13	2.26	2.26	2.22	1.68	2.88	0.15	4.95	0.26
Total	**93.57**	**7.00**	**72.81**	**17.50**	**74.61**	**22.31**	**69.17**	**20.78**	**73.14**	**11.95**
Count	19	17	20	19	19	17	20	19	19	17
Moving range										
$\overline{R}$		0.41		0.92		1.31		1.09		0.70
UCL (MR)		1.34		3.01		4.29		3.57		2.30
LCL (MR)		0.00		0.00		0.00		0.00		0.00
Individuals										
$\overline{x}$	4.92		3.64		3.93		3.46		3.85	
UCL (x)	6.02		6.09		7.42		6.37		5.72	
LCL (x)	3.83		1.19		0.00		0.55		1.98	

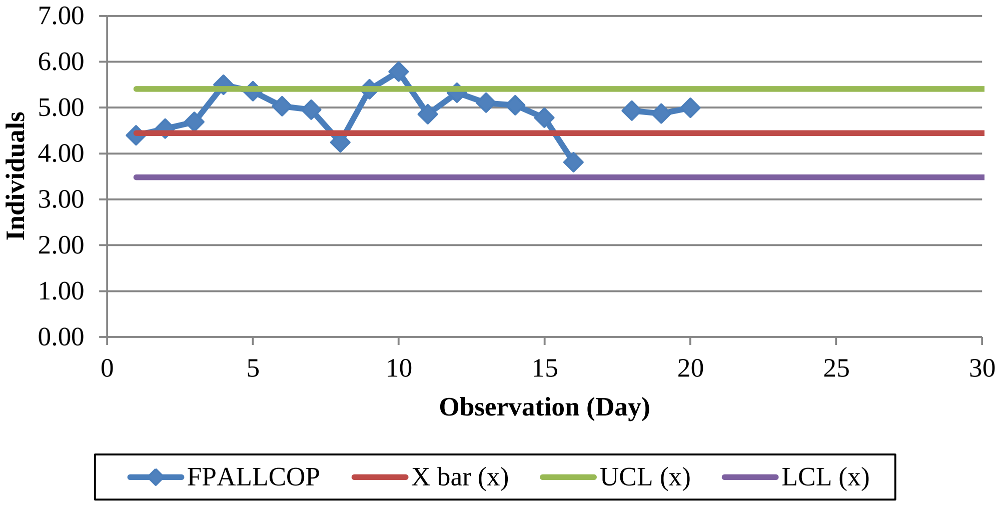

Figure 95: Individuals chart for all chillers indicating process performance, average, and control limits before maintenance

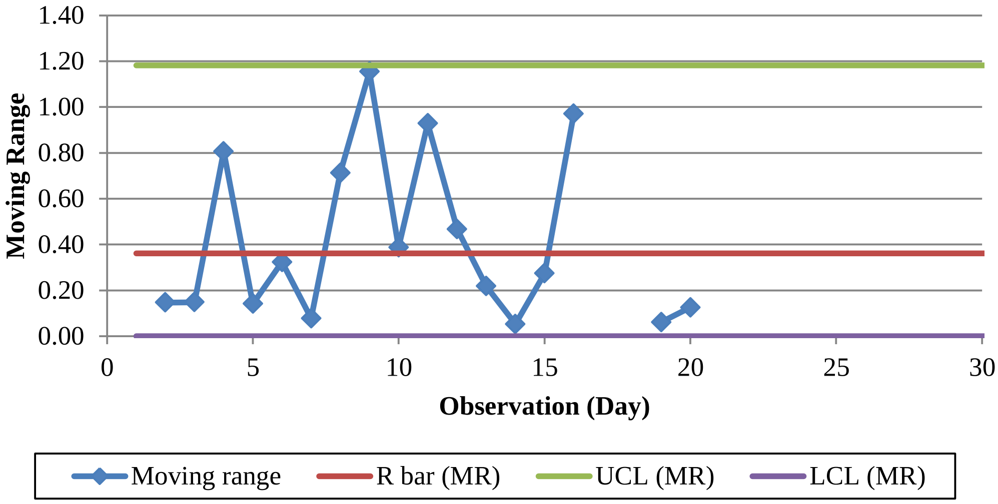

Figure 96: Moving range chart for all chillers indicating process variation and control limits before maintenance

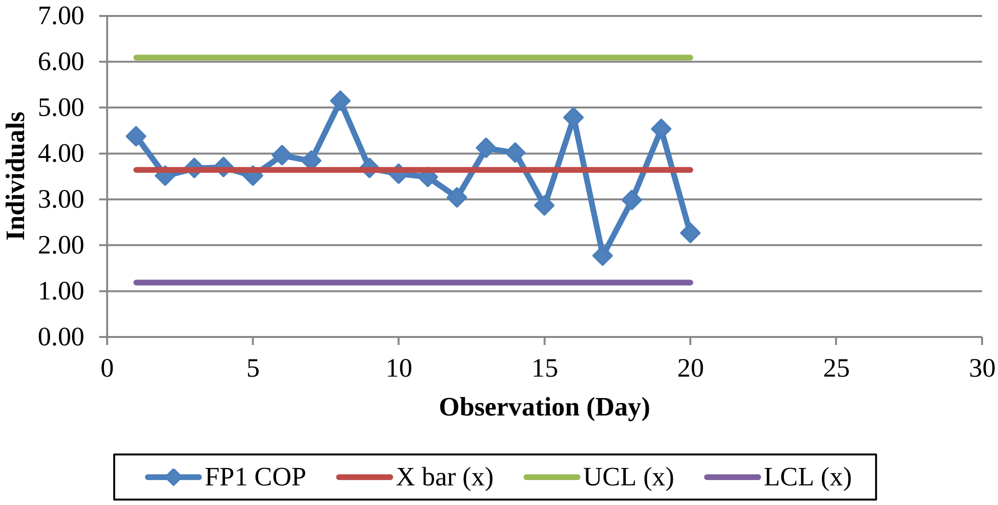

Figure 97: Individuals chart for chiller 1 indicating process performance, average, and control limits before maintenance

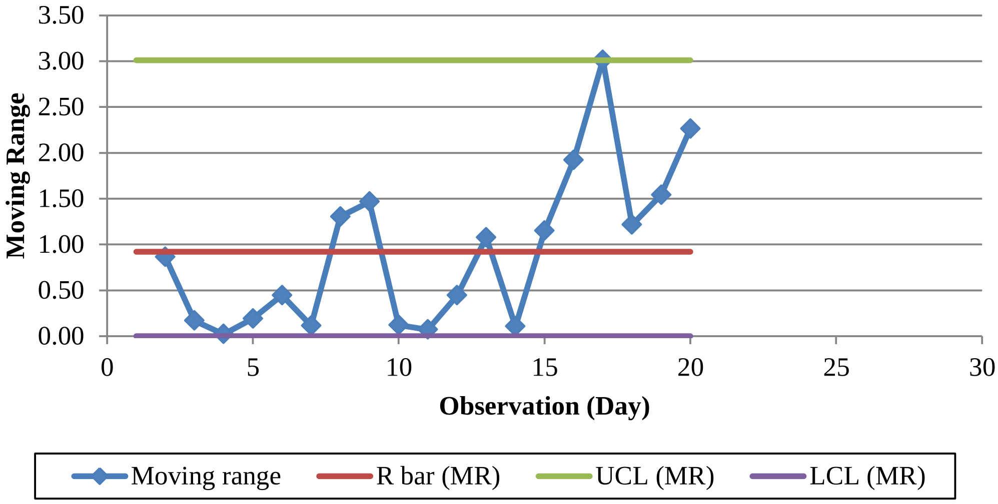

Figure 98: Moving range chart for chiller 1 indicating process variation and control limits before maintenance

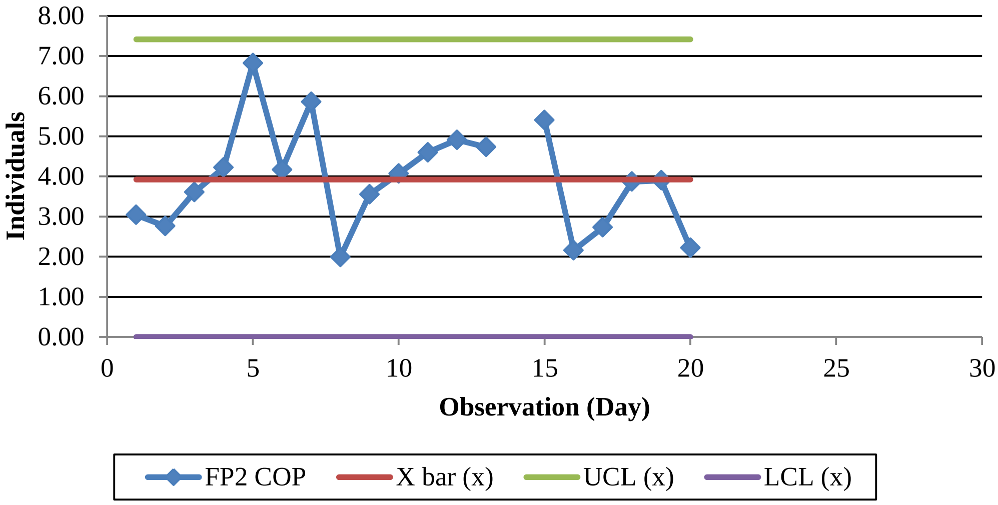

Figure 99: Individuals chart for chiller 2 indicating process performance, average, and control limits before maintenance

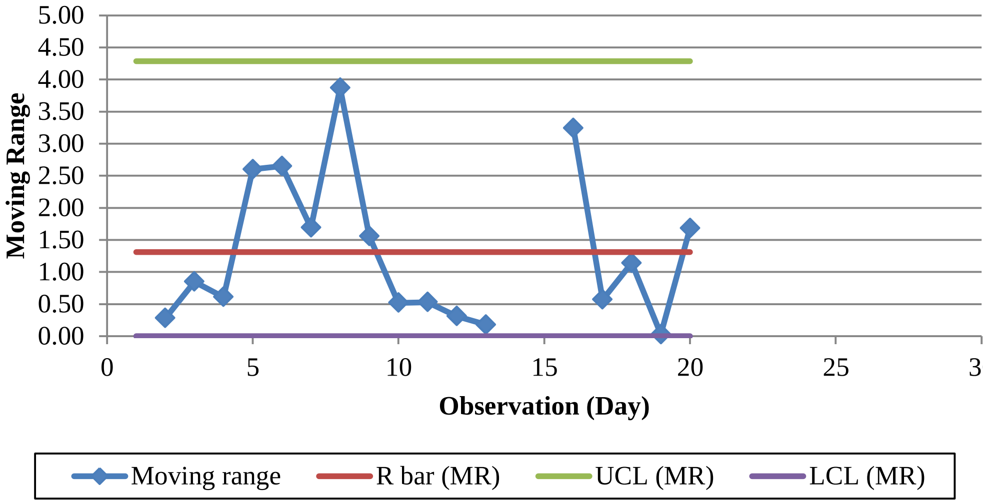

Figure 100: Moving range chart for chiller 2 indicating process variation and control limits before maintenance

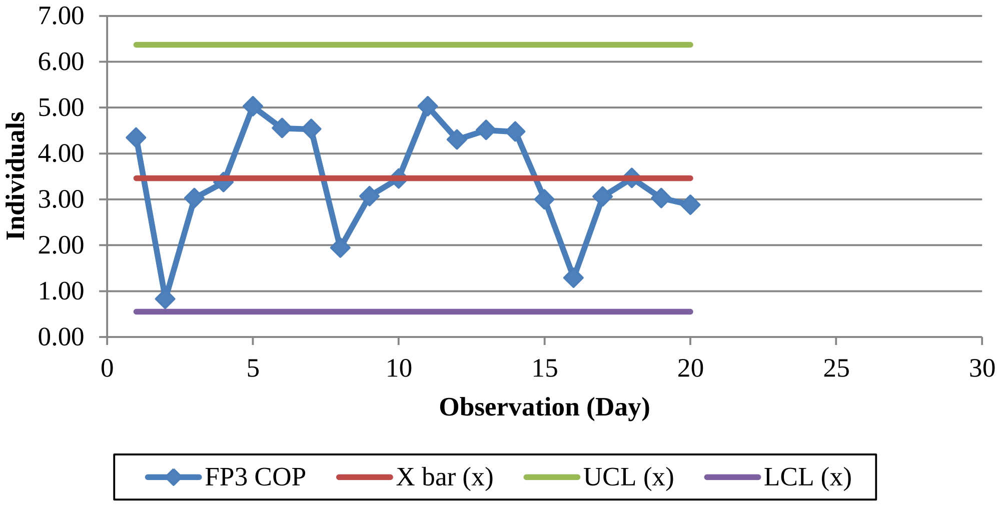

Figure 101: Individuals chart for chiller 3 indicating process performance, average, and control limits before maintenance

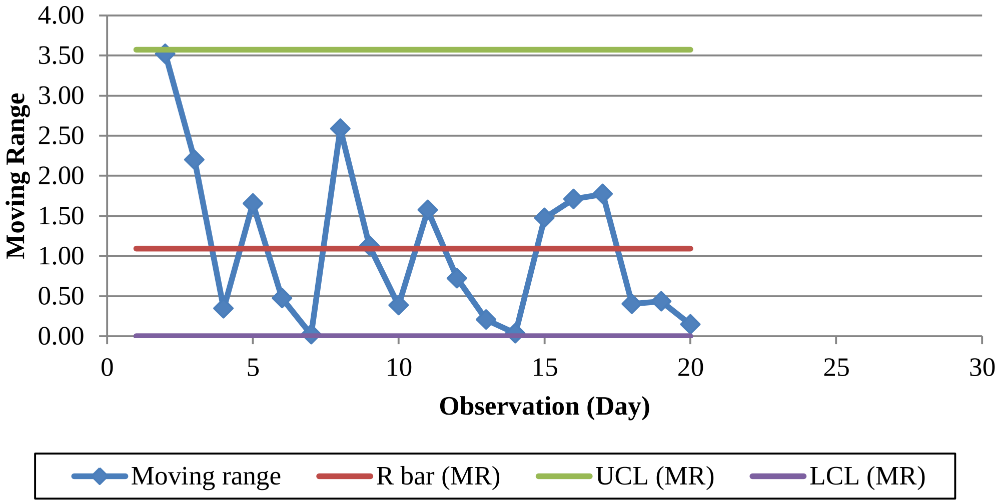

Figure 102: Moving range chart for chiller 3 indicating process variation and control limits before maintenance

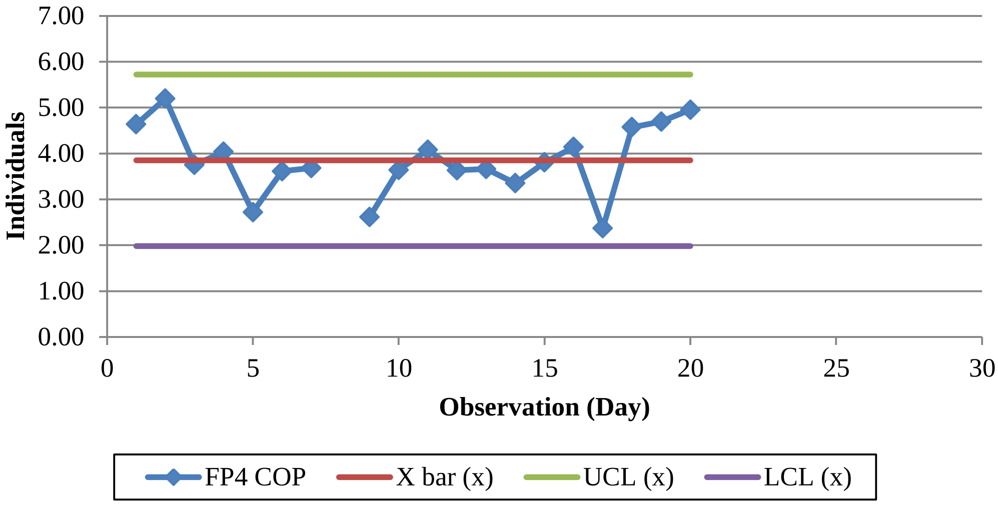

Figure 103: Individuals chart for chiller 4 indicating process performance, average, and control limits before maintenance

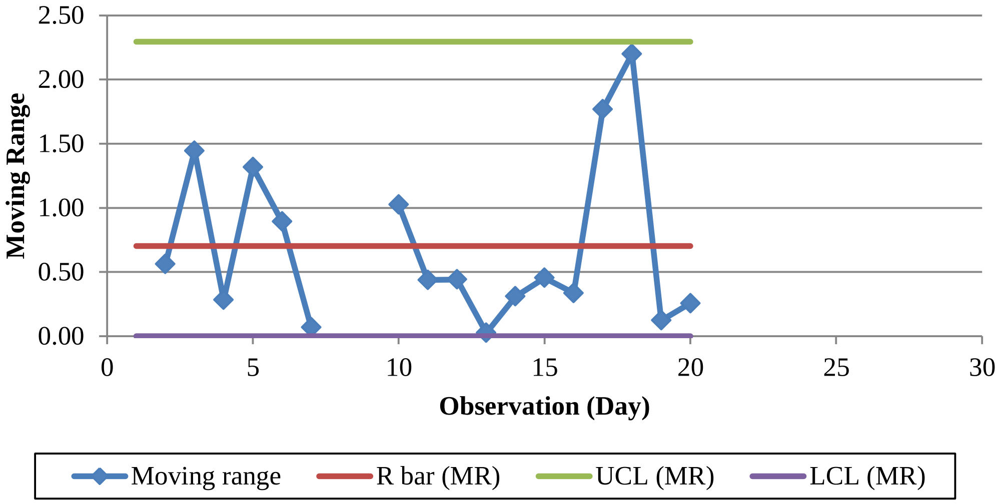

Figure 104: Moving range chart for chiller 4 indicating process variation and control limits before maintenance

APPENDIX IV

Simulation model

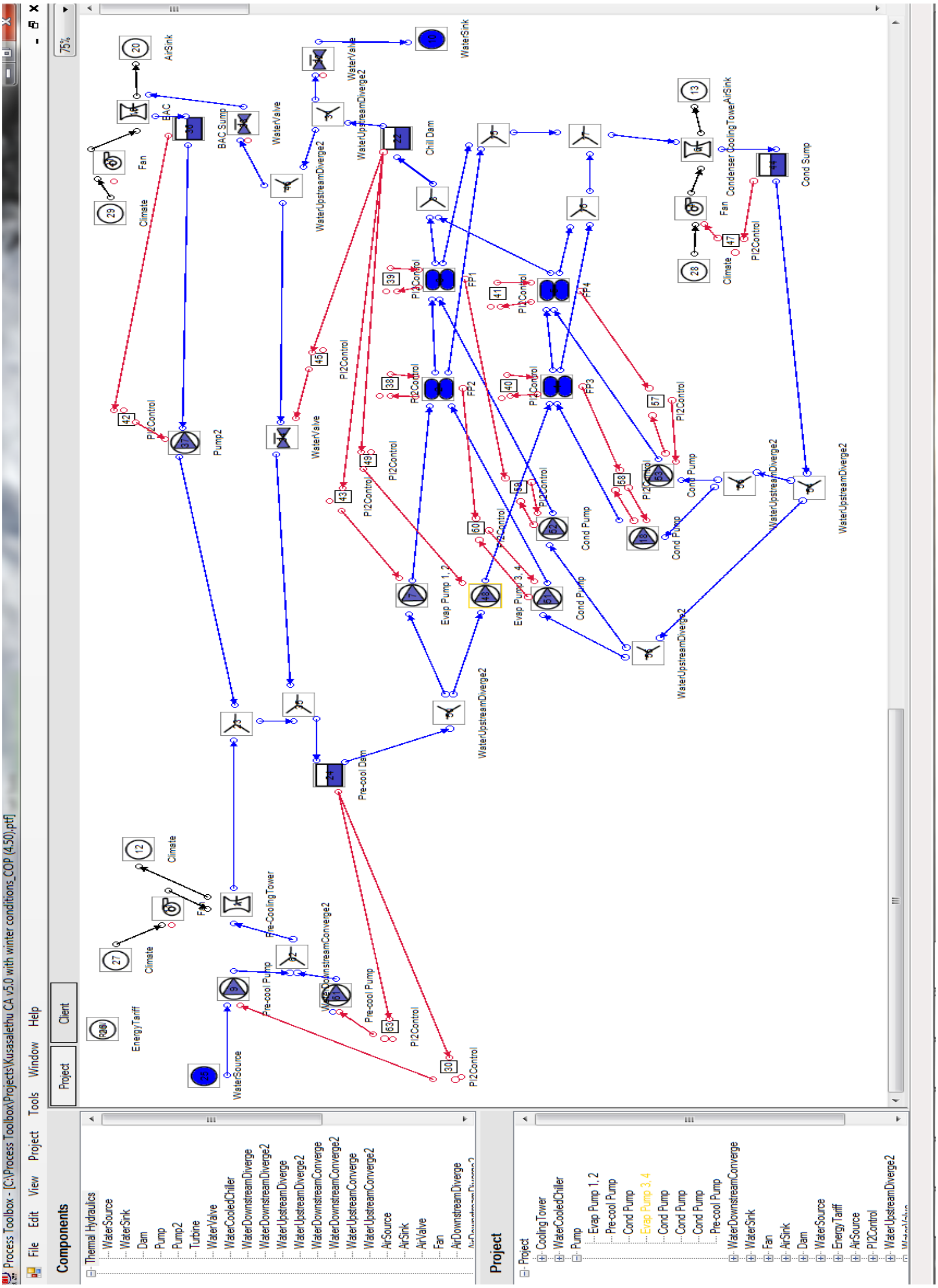

Figure 105: Simulation model