

Development of a supervisory system for maintaining the performance of remote energy management systems

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ABSTRACT

Title: Development of a supervisory system for maintaining the performance of remote energy management systems

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Energy services companies (ESCOs) typically implement energy management systems (EMSs) as part of Demand-Side Management (DSM) projects on South African mines. After DSM project completion, the mine becomes responsible for maintaining the performance of the EMS. Due to a lack of experience in using specialised EMSs, mines typically contract ESCOs for EMS maintenance. However, maintaining a large number of EMSs remotely is a resource-intensive task because of time wasted on daily monitoring and travelling to perform on-site maintenance.

For the same reason, remote maintenance technologies have become widely used to maintain cellular devices, vehicles and industrial equipment. Mine EMSs typically control production-critical systems that in turn ensure safe working conditions underground. EMSs execute highly specialised control philosophies to achieve electrical energy management, while ensuring safe and productive system operation. None of the work done on remote maintenance, however, provides an integrated solution to maintain the performance of a growing number of these specialised EMSs.

As part of this study, a supervisory system was developed to optimise remote maintenance of different EMS technologies. The supervisory system builds on the fundamentals of existing remote maintenance technologies, complemented by comprehensive diagnostics of specialised EMS technologies. This is possible through automated diagnostics of EMS components, the control philosophy and overall EMS performance. Maintenance management forms part of the supervisory system to ensure that maintenance is performed with optimal efficiency.

A system implementation was executed to prove the feasibility of the supervisory system. The functional operation of the system was verified with pre-set scenarios that simulated day-to-day operation and common fault diagnostic events. As part of the case studies conducted for this thesis, the supervisory system was integrated with three distinct EMS technologies implemented on South African mines. To support the results of these case studies, the system validation was extended through integrations with seven additional EMSs.

For the first time, a supervisory assessed the condition of the EMS components, the control philosophy and DSM performance comprehensively. The results (obtained over a period of more than six months) indicated that the average operational availability of EMS components improved from 90% to 97%. The average EMS performance improved from 1.8 MW to 2.5 MW, an improvement of 39%. The resulting electricity cost reduction achieved on the case studies accumulated to approximately R6 million during the respective assessment periods.

The supervisory system facilitated efficient EMS maintenance, thus reducing the risk of unsafe working conditions and production interruptions. The system also allowed maintenance personnel to improve the diagnostic process continually, thus aligning with the standards documented in ISO 50001:2011 (ISO, 2011) regarding continual improvement of electrical energy management initiatives.

The new supervisory system is scalable, thus an ESCO can maintain the performance of a growing number of EMSs remotely. Results of this study support further supervisory system integration with compatible EMS technologies, and expansion to new EMS technologies. The modular design of the supervisory system provides a basis for the development of a cross-industry platform for maintaining EMS performance.

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ABBREVIATIONS

APN	Access Point Name
BAC	Bulk Air Cooler
BEMS	Building Energy Management System
COP	Coefficient of Performance
CSV	Comma Separated Values
DC	Direct Current
DMA	Diagnostic and Maintenance Agent
DMC	Diagnostic and Maintenance Centre
DSM	Demand-Side Management
EDGE	Enhanced Data Rates for GSM Evolution
EMS	Energy Management System
ESCO	Energy Services Company
GPRS	General Packet Radio Service
GSM	Global System for Mobile communications
GUI	Graphical User Interface
HMI	Human Machine Interface
HVAC	Heating Ventilation and Air-Conditioning
IDM	Integrated Demand Management
IMMS	Intelligent Maintenance Management System
IP	Internet Protocol
LAN	Local Area Network
NASA	National Aeronautics and Space Administration
NERSA	National Energy Regulator of South Africa
OPC	Open Platform Communication
PC	Personal Computer
PDA	Personal Digital Assistant
PLC	Programmable Logic Controller
RAS	Remote Access Server
RDMS	Remote Diagnostic and Maintenance System
SCADA	Supervisory Control and Data Acquisition
sCC	Special Connection Component
SIM	Subscriber Identity Module
SMS	Short Message Service
SMTP	Simple Mail Transfer Protocol
TCP	Transmission Control Protocol
TOU	Time-of-Use
UPS	Uninterrupted Power Supply
VSD	Variable Speed Drives
VNC	Virtual Network Computing
VPN	Virtual Private Network

UNITS OF MEASURE

GW	Gigawatt
GWh	Gigawatt-hour
Hz	Hertz
kW	Kilowatt
kWh	Kilowatt-hour
MW	Megawatt
MWh	Megawatt-hour
W	Watt
Wh	Watt-hour

CHAPTER 1. INTRODUCTION

1.1 Demand-Side Management in the mining sector

It has become a global concern to sustain energy resources (Zografakis et al., 2012). Electricity utilities have a responsibility to maintain a reliable electricity supply with sufficient reserve capacity for emergencies. Power consumption peaks during the day require electricity utilities to maintain overcapacity that is only temporarily used during the peak consumption periods (Zhu, 2009; Briggs & Kleit, 2013). Utilities actively predict future peak demand in order to balance available resources amongst projects to increase supply capacity and to maintain existing capacity (Wilkerson et al., 2014).

South Africa relies on Eskom as the primary electricity utility. Eskom has been experiencing an imbalance in supply capacity and maximum demand since early 2008 (Eskom, 2012c). The electricity utility has since been operating power plants on constrained schedules while long-term capacity-increasing projects are underway (Eskom, 2012a). However, these projects do not provide immediate relief for an electricity utility with an insufficient reserve margin. It is challenging to finance large capital cost projects without increasing electricity tariffs. This is a concern for Eskom who has for decades maintained electricity tariffs amongst the lowest in the world (Tshikalanke, 2006).

Demand-Side Management (DSM) presents an opportunity to increase reserve capacity at a low cost, low risk, and with a short payback period (Perfumo et al., 2012), while having a lesser impact on the environment (Sun & Li, 2014). DSM has the potential to reduce maximum demand (W) to the benefit of the electricity utility. Furthermore, DSM minimises electricity usage (Wh) to the benefit of the client. Eskom initiated large scale DSM initiatives in 2004, making use of energy services companies (ESCOs) to facilitate rapid countrywide implementation (Eskom, 2012a). In South Africa, DSM projects have produced a verified demand reduction of 2.99 GW from 2005 to 2012 (Eskom, 2012b).

Figure 1 shows the distribution of Eskom's local electricity sales during 2012. The mining and industrial sectors contributed 16% and 28% respectively to the total local electricity sales (Eskom, 2012b). These two sectors have the most electricity intensive customers with an average electricity usage of 21 GWh/customer in the industrial sector and 29 GWh/customer in the mining sector (Eskom, 2012a). According to a study done by Pelzer et al. (2008), the mining and industrial sectors hold the greatest potential for DSM savings.

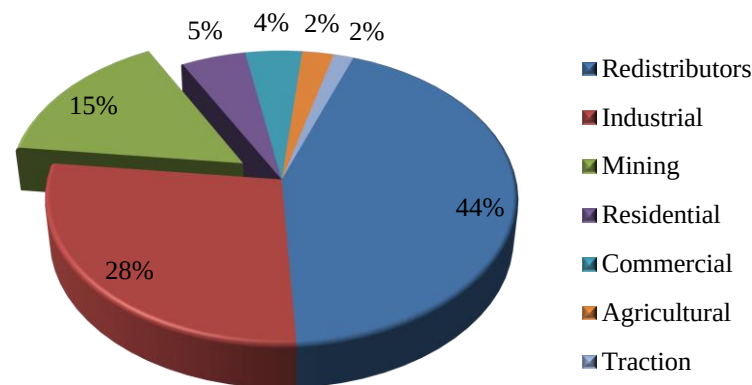


Figure 1: Local electricity sales in South Africa [created from (Eskom, 2012b)]

DSM projects typically use electrical energy efficiency, load-shifting and peak-clipping strategies (Dube et al., 2005). Electricity utilities prefer peak-clipping and load-shifting strategies because these strategies do not cause significant revenue loss when compared with electrical energy-efficiency strategies (Sebitosi, 2010). However, all of these DSM strategies reduce the peak demand and therefore relieves pressure on Eskom. Because the mining sector has the most electricity intensive users, Eskom actively incentivises different DSM projects in the mining sector to achieve DSM targets in excess of 1 MW.

As part of a DSM project an ESCO implements an energy management system (EMS) to ensure a sustainable reduction in peak electricity demand (Du Plessis, J.N. et al., 2012). Although the mine becomes responsible for maintaining the EMS, the mine will also benefit from subsidised DSM infrastructure and the resulting reduction in electricity cost (Pelzer et al., 2008). DSM allows mines to operate at a lower production cost by reducing electricity costs. According to Sebitosi (2010), financial consumer incentives are more effective than regulations. Accordingly, the future drive behind DSM might rather shift from the electricity utility to the mine.

1.2 Sustaining DSM performance

The cost of EMS maintenance is low when compared with the potential financial savings produced by a well-maintained EMS (Pelzer et al., 2008). Continuous monitoring is essential for sustaining EMS performance (Sebitosi, 2010). Daily monitoring gives an indication of whether an EMS meets its DSM target. If maintenance personnel are aware that an EMS is underperforming, corrective action is possible.

Before commencing with the EMS implementation, a power baseline is developed to represent the power profile before DSM intervention (Reichl & Kollmann, 2011). Baseline scaling takes the effect of changing production and seasons into account (Wannenburg et al., 2009). Baseline scaling is necessary to ensure that performance measurement stays accurate and relevant over many years. EMS performance calculations compare the baseline with the post-implementation power profile on a daily basis. Different DSM strategies require different calculations to obtain EMS performance.

As part of Eskom's Integrated Demand Management (IDM) process, a measurement and verification team issues monthly performance tracking reports to verify that an EMS meets a set target (Lengoasa & Potgieter, 2007). During a performance assessment period, the ESCO adjusts the EMS control philosophy to optimise DSM performance. If the EMS does not meet the target during the performance assessment period, Eskom may penalise the ESCO. Unless the mine has a maintenance agreement with the ESCO, the mine becomes responsible for maintaining the proven performance of the implemented EMS over several years (Lengoasa & Potgieter, 2007).

Rawlins (2006) developed an energy management framework to realise the long-term cost savings potential of well-maintained EMSs. According to Pelzer and Kleingeld (2011) and Merry (2013), the sustainability of EMS performance depends on the management structures that coordinate the maintenance effort. To illustrate this, Pelzer and Kleingeld (2011) compared the cumulative performance of two EMSs.

An EMS under maintenance agreement was initially underperforming. However, the cumulative cost saving produced by this EMS exceeded the proposed savings after a two-year period. Figure 2(a) shows the cumulative effect of continuous maintenance, ensuring sustained EMS performance. In contrast, Pelzer and Kleingeld (2011) also described an EMS that initially overperformed. Due to supervisory control and data acquisition (SCADA) system reconfiguration, this EMS malfunctioned and produced no further savings as shown in Figure 2(b). The mine was responsible for, but incapable of performing EMS maintenance.

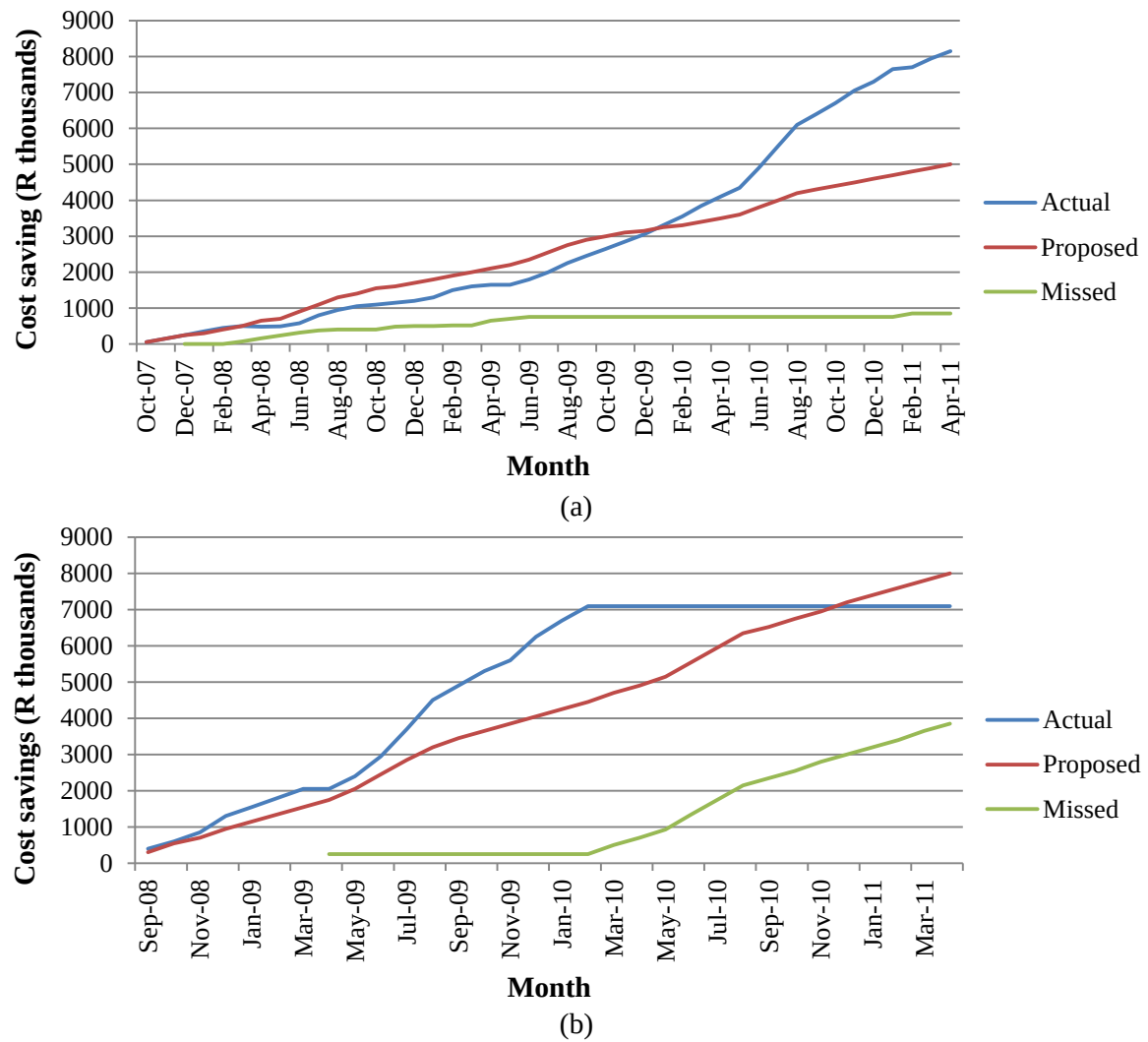


Figure 2: Cumulative effect of EMS maintenance [adapted from (Pelzer & Kleingeld, 2011)]

An ESCO's reputation is dependent on the performance of its completed DSM projects. If a maintenance contract is not in place, ESCOs maintain and service EMSs to a certain extent without compensation to increase their prospect of future DSM projects. The number of EMSs for which an ESCO takes responsibility increases over time, making it increasingly more difficult to maintain these EMSs on a daily basis. This is especially true for EMSs that require excessive travel to perform on-site maintenance.

1.3 Existing maintenance approaches

Research done by Schach (2007) shows that maintained software stays operational while software that is not actively maintained, becomes unusable. A typical EMS consists of an intricate combination of hardware, software and networks. Without periodic maintenance, the performance of an EMS degrades over time (Rawlins, 2006; Merry, 2013).

Maintenance approaches are either reactive or proactive (Locy, 2001; Biehl et al., 2004). Reactive maintenance involves corrective action in response to failure (Weppenaar et al., 2012). Proactive maintenance either makes an assumption of degradation over time, or predicts degradation based on feedback from the maintained system (Weppenaar et al., 2012). ESCOs typically employ reactive EMS maintenance based on daily performance assessment.

Many ESCOs have systems in place to monitor the performance of EMSs on a daily basis. ESCOs often report on the daily financial impact of an EMS to make performance measurement more relevant for the client. Financial savings earn client cooperation, but electricity cost inflation disguises reduced EMS performance over time. Reduced performance typically initiates diagnostics in order to identify the cause and perform corrective maintenance.

It is difficult to maintain EMSs remotely, especially when the EMS and maintenance centre are situated far apart (Zhou et al., 2009). Maintenance personnel are required to visit the EMS for detailed diagnostics and maintenance if telephonic support is not possible. The lack of remote support causes delays between the time that a maintenance-requiring event occurs and maintenance personnel reach the EMS to perform maintenance. According to Blumberg (1982), typical remote maintenance could involve:

- technical training;
- technical support via telephone;
- on-site delivery of replacement hardware; and
- on-site technical assistance.

Traditionally, telephonic support is preferred to on-site support mainly due to the unnecessary time and cost to travel to remote sites. Telephonic support is, however, only feasible when on-site personnel have taken ownership of the system that they maintain. Because telephonic support lacks visual interaction, maintenance personnel rely on the interpretations of on-site personnel to make suggestions for corrective

action. It is imperative that the ESCO trains client personnel adequately to use and maintain the implemented EMS (Ibrahim et al., 1993).

After analysing more than twenty electronics-, data processing- and telecommunication-based service organisations, Blumberg (1982) estimated that 35% to 50% of all service centre calls do not require on-site support. This could be true for situations where:

- Problems correct themselves.
- Replacement equipment is delivered to the site.
- The customer failed to follow procedures.
- Software errors can be corrected remotely.
- Maintenance-requiring events are miscommunicated.

Currently, telephonic support together with technical training is the most widely used mechanism to perform remote maintenance of EMSs in the mining industry. However, Zhang and Wu (2010) describe remote maintenance via industrial programmable logic controllers (PLCs). According to Merry (2013), some EMSs used in commercial buildings already incorporate remote maintenance systems to ease the maintenance process. Automating the diagnostic process and granting maintenance personnel remote access to EMSs can reduce the human resources required to perform remote EMS maintenance.

1.4 Remote maintenance system overview

According to Blumberg (1982), 10% to 40% of hardware-related issues and 80% to 90% of software-related issues can be resolved remotely. In addition to this, advances in communication technology have made remote maintenance more feasible. Remote monitoring and diagnostics have become widely used with increased bandwidth, availability and affordability of Internet connections. Remote maintenance is also expanding due to globalisation (Weppenaar et al., 2012).

Bhurtun et al. (2007) developed agent software to monitor and control computers on a local network. A central server delegates sleep commands to network computers, based on the requirement for access to these computers. Fu et al. (2010) tested a diagnostic system that facilitates remote customer service for specialised equipment. Future implementation could include automated diagnostic and repair suggestions. Existing diagnostic systems monitor the operation of aircraft (Janasak & Beshears, 2007; Stora & Kalgren, 2009) and motor vehicles (Janasak & Beshears, 2007; Kai & Fuwu, 2010) remotely.

Existing patents cover remote diagnostics of mobile devices (Neuenschwander et al., 2009) and robots that are used in industrial manufacturing plants (Blanc et al., 2012). According to Janasak and Beshears (2007), remote diagnostic technology is also used to monitor computer server farms and medical diagnostic equipment remotely. Industrial plants use remote diagnostics to monitor equipment and predict failure (Bixler, 2008). ABB Ltd. provides a remote diagnostic service as part of a maintenance agreement on selected ABB equipment (Reinikkala et al., 2006; ABB, 2008b).

According to Du Plessis, J.N. et al. (2012), the purpose of these remote diagnostic and maintenance systems (RDMSs) is automating the monitoring and diagnostics of equipment, vehicles, aircraft or other devices for early signs of malfunction or failure. Automating these repetitive monitoring tasks increases the efficiency of the maintenance team and reduces the cost associated with maintaining specialised equipment remotely. Figure 3 is a schematic of a basic RDMS implemented on a single remote system. This schematic was developed based on existing implementations of this technology.

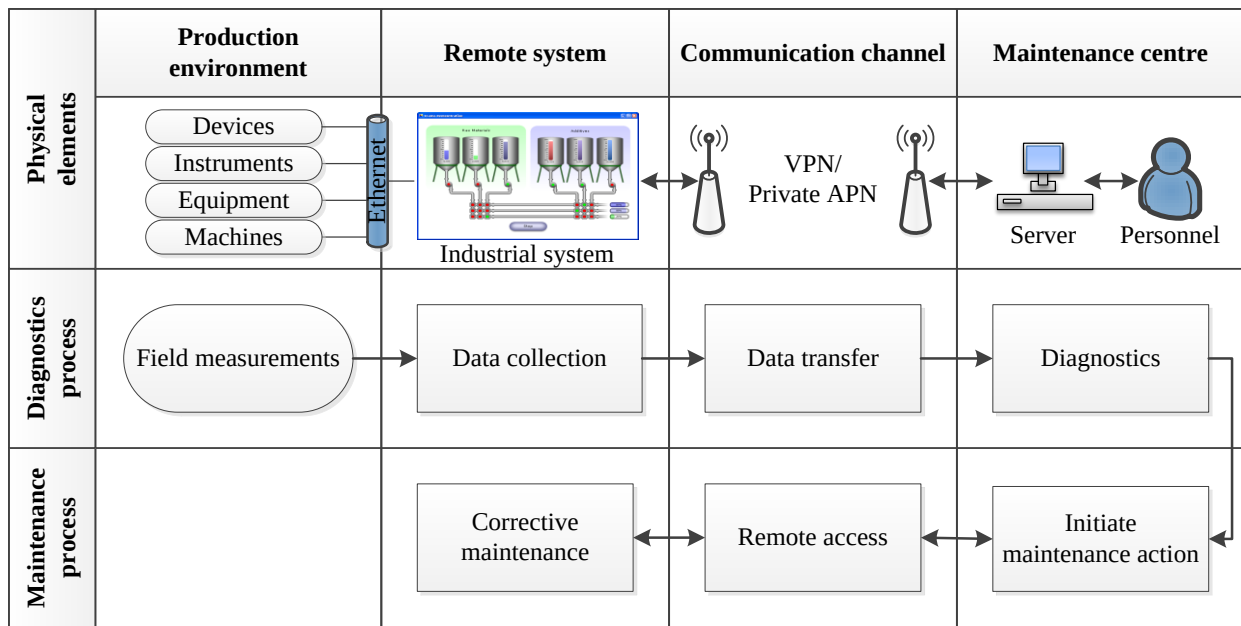


Figure 3: Basic RDMS layout

A computer network connects a remote system with a maintenance centre. The computer network is typically an Internet connection with additional security measures, a virtual private network (VPN) or a private access point name (APN) (Du Plessis, J.N. et al., 2012). System devices and equipment connect to a local processing unit, which is typically a local computer. The processing unit gathers diagnostic information and maintains a communication channel between the remote system and the maintenance centre. The communication channel facilitates data transfer from the remote system to the maintenance centre for automated diagnostics.

The RDMS architecture is scalable and meant for integration with several remote systems, allowing the RDMS to diagnose issues remotely from a central point. The RDMS infrastructure makes remote diagnostics possible by allowing authorised personnel to access equipment and measure performance remotely (Yang et al., 2007). Some of these systems employ automatic predictive preventative maintenance to minimise equipment downtime due to failure or unscheduled maintenance. Despite initial security concerns, RDMSs are moving towards being generally accepted (Biehl et al., 2004).

Minakawa et al. (1995) state that an RDMS increases maintenance efficiency by reducing the time and cost of performing on-site maintenance. An RDMS can reduce after-sales costs by 20% to 30% and improve service efficiency and customer relations (Biehl et al., 2004). Additionally, Holzmüller (2011) notes that an RDMS reduces the cost of maintenance by giving freedom to both the client and maintenance personnel. RDMSs have the potential to reduce the workload of maintenance personnel and facilitate maintenance of a large number of remote EMSs (Holzmüller, 2011).

1.5 Need for this study

DSM provides short-term relief for the critically low reserve capacity under which Eskom is operating (Eskom, 2012b). In addition to this, DSM is a relatively inexpensive energy resource because of the short payback periods of DSM projects. The National Energy Regulator of South Africa (NERSA) approved an average Eskom tariff increase of 8% for 2013/2014 (NERSA, 2013a; NERSA, 2013b). This increase is significantly lower than that of the previous three years but still exceeded the average annual inflation rate of 5.7% during 2013 (StatsSA, 2014). Steep tariff increases further reduce payback periods, making implementation of EMSs more feasible and more attractive to electricity consumers, especially in the mining sector.

However, studies show that EMS performance degrades over time. Even with a small number of EMSs to maintain, daily performance assessment is fundamental to ensure sustainable EMS performance. A successful ESCO implements a growing number of EMSs over time. The ESCO might take responsibility for sustaining the performance of a large number of EMSs without compensation. Maintaining geographically separated EMSs is expensive and time-consuming, increasing proportionally with the distance travelled (Biehl et al., 2004).

Traditional preventative maintenance is inefficient and costly (Weppenaar et al., 2012) especially for EMSs. According to Deb et al. (2000), a system for the continuous real-time failure detection and isolation is essential for operating complex systems economically. The traditional maintenance approach involves maintenance personnel travelling to perform maintenance. Without the need for travel, a rapid maintenance response is possible. This is especially true for remote maintenance systems that improve on the limited interaction that telephonic support provides.

With few limitations on modern communication networks, vast amounts of data become available to maintenance centres. Remote maintenance and diagnostic technologies have become widely used to maintain cellular devices, vehicles and industrial equipment. RDMSs even monitor systems that perform energy management on the lighting and HVAC systems of large buildings. Analysis of the requirements, benefits and shortfalls of existing remote maintenance technologies showed that existing systems do not adhere to the maintenance requirements of specialised mine EMSs implemented as part of an Eskom DSM programme.

Figure 4 shows the high-level composition of an EMS consisting of physical components, a control philosophy and the resulting performance. Maintaining the physical EMS operation is the first step to maintaining EMS performance. Unhindered EMS operational availability is important, but does not

guarantee consistent EMS performance over time. The EMS executes a control philosophy that ultimately determines EMS performance. Maintaining the control philosophy in conjunction with the physical EMS components is a daunting task, but is critical to ensure sustained EMS performance.

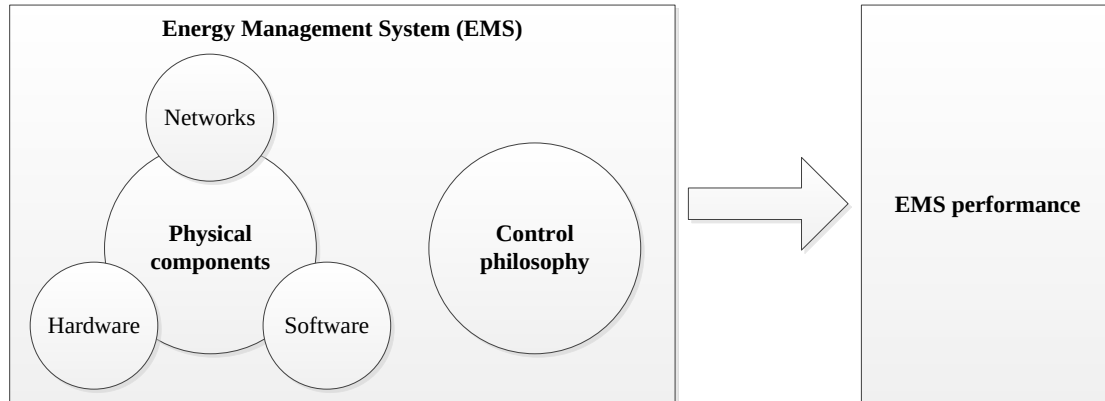


Figure 4: Composition of a typical EMS [adapted from (Du Plessis, J.N. et al., 2013)]

The observation of Marais et al. (2009) is that access to condensed information reduces the expenses required to achieve electricity savings. To go beyond isolated assessment of EMS performance, a supervisory system is required to assess the status of the physical EMS components in addition to control philosophy effectiveness.

According to Holzmüller (2011), remote maintenance has the advantage of employing virtual teams. These teams apply the collective knowledge of maintenance experts to ensure the most efficient maintenance. Maintaining a large number of EMS remotely also requires automated maintenance management to ensure that maintenance teams respond promptly to identified faults.

To summarise, the literature survey establishes the need to develop a supervisory system that performs integrated diagnostics of the physical EMS components, the control philosophy and the resulting DSM performance. This new system should incorporate automated maintenance management and enable remote maintenance to facilitate sustained DSM performance of a growing number of EMSs in the mining industry.

1.6 Contribution of this study

Analysis of the requirements, benefits and shortfalls of existing remote maintenance technologies led to the development of a novel EMS supervisory system. Various elements of the work presented in this thesis contribute to the field of remote diagnostics and maintenance of mine EMSs. The subsections that follow provide details on these contributions.

EMS supervisory system requirements and specifications

As part of this study, the unique requirements of a comprehensive mine EMS supervisory system were determined. This was done after analysing current ESCO diagnostic, ESCO maintenance procedures, and the benefits and shortfalls of existing remote maintenance technologies. A detailed process and component specification was then developed to adhere to the set requirements. The developed specifications support a scalable supervisory system for diagnostics and maintenance of mine EMSs distributed across South Africa.

Comprehensive remote diagnostics for mine EMSs

DSM performance assessment is widely used as an indication of the operational condition of an EMS. Reduced performance prompts corrective maintenance but does not provide maintenance personnel with any indication of the cause. The newly developed supervisory system addresses the need for an integrated solution for remote EMS diagnostics. For the first time, a supervisory system assesses the condition of an EMS in every respect by concurrently assessing the physical EMS components, the control philosophy and the DSM performance indicators.

Integrated EMS operation and DSM performance reporting

Traditional EMS reporting consists of a daily DSM performance overview. The newly developed supervisory system, however, offers a unique approach to mine EMS reporting that integrates both diagnoses of the EMS operation and the resulting DSM performance. This new approach shifts the perspective of maintenance personnel from disjointed EMS subsystem maintenance to integrated EMS maintenance, which leads to sustainable DSM performance.

Automated maintenance management for mine EMSs

Literature shows that the main factor that causes maintained EMS performance to decrease over time is a lack of active maintenance management. Research has shown that no existing system actively manages

the EMS maintenance process based on comprehensive mine EMS diagnostics. The new supervisory system initiates maintenance action by notifying maintenance personnel of diagnosed problems and providing suggestions for corrective action. Furthermore, the supervisory system facilitates remote access and control of EMSs, thus further increasing the efficiency of the maintenance process.

Generic maintenance solution for different mine EMS technologies

Control philosophies of various EMSs differ fundamentally irrespective of the underlying EMS technology. Mine EMSs perform energy management with the objective of achieving DSM load shifting, peak clipping or electrical energy efficiency. The supervisory system design is modular to adhere to the requirements of various EMS technologies with different DSM objectives. The newly developed system provides a generic solution for maintaining the performance of different EMS technologies integrated with complex mining systems.

Improved system operation and a safer working environment

Specialised EMSs control production-critical mining systems to achieve electrical DSM while ensuring safe system operation and uninterrupted production. The supervisory system is primarily concerned with sustaining EMS performance. Inherently, the supervisory system improves the operation of the controlled system through continuous EMS control optimisation. Specialised on-site diagnostics also include operational safety checks that trigger immediate notifications to maintenance personnel and operators. The new supervisory system thus ensures optimal energy management, improved system operation and promotes a safer working environment.

Diagnostic strategies for large energy intensive mine systems

The new supervisory system was integrated with operational mine EMSs. These EMSs were implemented on mine water reticulation systems, cooling systems and compressed air systems. Unique diagnostic strategies were developed for each of these electricity intensive systems. The diagnostic strategies encapsulate ESCO best practices to ensure relevant and efficient diagnostics of diverse EMS technologies.

1.7 Thesis overview

This work follows a path from studying existing RDMSs to leveraging the advantages of these systems to develop a supervisory system for remote EMS maintenance. The system integration with existing EMSs in the mining industry forms part of the work that is set forth in this document.

Chapter 1 provides background information on DSM and EMS maintenance. An overview of existing remote maintenance approaches serves to establish the need for the supervisory system that has been developed as part of this study. Literature proves that existing RDMSs are insufficient for specialised mine EMS maintenance. This chapter is concluded with a summary of the contribution made to this field of study.

Chapter 2 presents a detailed analysis and comparison of existing remote maintenance technologies as an extension to the overview provided in Chapter 1. Consideration is given to the contributions that diverse industries have made to remote maintenance technology. Benefits and shortfalls of these technologies are used to establish the critical requirements of a successful supervisory system for remote EMS maintenance in the mining industry.

Chapter 3 documents the development of the supervisory system based on the requirements established in Chapter 2. A detailed system design is presented, addressing the need for a supervisory system that facilitates maintenance of existing and new EMS technologies in the mining industry. This chapter also presents the system design for specialised EMS diagnostic and maintenance management.

Chapter 4 describes the implementation process to verify that the conceptual supervisory system discussed in Chapter 3 could be implemented successfully. An emulated EMS was incorporated as part of the implementation process to prove the feasibility of the developed supervisory system.

Chapter 5 documents the validation of the supervisory system by using real-world implementations. Validation of the system is presented in the form of three case studies, each on a different EMS technology implemented in the mining industry. Chapter 5 also presents results from seven additional implementations.

Chapter 6 serves as the conclusion of the presented study. Recommendations are made for future work, giving suggestions for improvements and further development. These recommendations are intended to reveal further opportunities for contribution to this field of study.

CHAPTER 2. EXISTING REMOTE MAINTENANCE SYSTEMS

2.1 Introduction

Typical maintenance efforts involve data observation and recording. Data is analysed to identify failures or trends, and to determine the appropriate course of corrective action. Yan and Lu (2007) describe this analysis as a time-consuming process giving system maintenance a reputation of continuous and repetitive tasks. They also imply that the maintenance service provided with a product is of equal importance to the quality, cost and performance of the product itself.

Maintaining any operational systems remotely is a labour-intensive task and becomes even more so over time due to system degradation. RDMS are examples of technologies that facilitate cost- and time-efficient maintenance by:

- ensuring reliable system operation to minimising unplanned system downtime;
- improving productivity, efficiency and effectiveness of maintenance personnel (Blumberg, 1982);
- reducing the duration of maintenance and mistakes by maintenance personnel (Guo et al., 2007);
- reducing time and cost of maintenance in general (Hofmann & Phares, 2003; Yan & Lu, 2007);
- reducing the time and cost of travel to remote sites (Jazdi, 2010); and
- efficiently identifying maintenance-requiring events and taking action (Yun et al., 2011).

This chapter presents an investigation into existing remote maintenance technologies that could present a solution for maintain the performance of remote EMSs. An overview of the typical EMS infrastructure considered for this study, led to the critical evaluation of existing remote maintenance technologies against the maintenance criteria of typical remote EMSs.

2.2 Typical application

Remote diagnostic and maintenance technology has diverse fields of application due to the abundant advantages it offers. RDMSs initially monitored spacecraft and aircraft, because of the extent of their remote operating environments. Further applications range from retail products to industrial systems as described in the subsections that follow.

Spacecraft

Remote maintenance becomes a valuable tool when the operating environment extends to outer space. In the United States of America, the National Aeronautics and Space Administration (NASA), the military and the Defence Advanced Research Projects Agency (DARPA) developed remote repair, diagnostics and maintenance for remote telemetry, space probes and satellites (Biehl et al., 2004). The sensor-rich international space station transmits all sensor data to the NASA base station in near real-time (Deb et al., 2000). NASA also uses this diagnostic technology on liquefying fuel hybrid rockets (Poll et al., 2003).

Aircraft

The value of RDMS technology used in spacecraft clearly illustrates that this technology is suitable for aircraft (Yang et al., 2007). Remote aircraft engine monitoring is a major application of this technology (Crapo et al., 2003; Janasak & Beshears, 2007). General Electric Aviation understands the physics behind typical aircraft engines failures (Janasak & Beshears, 2007). In order to evaluate the condition of aircraft engines, engine data is communicated to a customer service centre via satellite link or Internet (Hofmann & Phares, 2003; Janasak & Beshears, 2007). Similar RDMS technology is also used to monitor helicopter engines (Deb et al., 2000).

Land-based transport

Locomotives are monitored remotely to generate proactive service schedules (Crapo et al., 2003; Hofmann & Phares, 2003). Many vehicle manufacturers integrate remote diagnostic systems during vehicle manufacturing (Janasak & Beshears, 2007). GenRad, ACUNI and OnStar develop remote diagnostic systems for the automotive industry (Biehl et al., 2004). Vehicles periodically transmit diagnostic data to OnStar. OnStar sends owners monthly e-mail reports that describe the condition of key vehicle subsystems (Janasak & Beshears, 2007).

Remote diagnostic systems typically monitor the vehicle engine, and the oil-, fuel-, electrical- and control systems (Janasak & Beshears, 2007). More specialised applications of remote diagnostic systems monitor vehicle:

- battery systems (Liu et al., 2011; Zhang et al., 2009);
- global positioning systems (GPSs) (Al-Taei et al., 2007); and
- air-pollution levels (Lin et al., 2007).

According to Campos et al. (2002), the aim is to anticipate vehicle failure and improve the operational availability of different vehicle types. To facilitate this, Mahfoud et al. (2008) propose a remote diagnostic and maintenance framework that makes vehicle data available to vehicle manufacturers and service centres.

Medical

Physicians use telemedicine to reach rural areas (Biehl et al., 2004). The need for modern medical expertise in remote areas also prompted the development of a super-media interface for telediagnosics on breast pathology (Pomeroy et al., 2006). The super-media interface enhances telepresence in remote areas. This system enables manual remote medical diagnostics via the Internet.

Expensive computed axial tomography (CAT) scan machines employ automatic remote diagnostic systems (Hofmann & Phares, 2003). These machines periodically run local diagnostics comparing results to a predefined standard. Irregular results prompt the machine to notify a maintenance company. This technology is also used for remote diagnostics and maintenance of medical imaging and other equipment (Crapo et al., 2003; Janasak & Beshears, 2007).

Environmental

Krapivin and Mkrtchyan (2007) propose an expert system for operative environment diagnostics (ESOED). ESOED is a land- and remote observation system for environmental diagnostics. This diagnostics system collects data from satellites, flying laboratories and ground observation units. ESOED records suspicious elements when indicators correspond to those of natural anomalies. When ESOED verifies that the approach of a catastrophe is imminent, it transmits the relevant data to the affected environmental control services.

Buildings

High-rise buildings have large numbers of elevators, escalators, heating and ventilation systems. OTIS manufactures elevators that transmit sensor data to remote service centres (Deb et al., 2000). Building heating, ventilation and air-conditioning (HVAC) systems are also being serviced remotely (Biehl et al., 2004). Siemens Site Controls™ is an EMS that offers an integrated remote maintenance service to allow retail stores to sustain reduced electricity consumption (Siemens, 2012). This system allows maintenance personnel to diagnose and maintain lighting and HVAC problems remotely.

ecoCENTRE provides a diagnostic and maintenance service for building energy management systems (BEMSs) (ESG, 2013b). ecoCENTRE monitors BEMS performance to identify anomalies. ecoANALYTICS monitors BEMS via the ecoCENTRE to determine the effectiveness of the control strategy. ecoMONITOR collects energy consumption data from utilities to highlight abnormal energy usage that initiates remote maintenance (ESG, 2013a).

Computers and office equipment

Pitney-Bowes produces copy machines that transmit sensor data to remote service centres (Deb et al., 2000). The high-end range of Xerox copiers are capable of sending data to maintenance centres via the Internet (Biehl et al., 2004). Hewlett-Packard and Stratus remotely monitor personal computers and send notifications to technicians before computers become completely unusable (Biehl et al., 2004).

Phoenix Technologies developed technology that allows computer technicians to receive diagnostic information via telephone or modem before the computer starts up (Biehl et al., 2004). Server farms use remote diagnostic tools to monitor server health and optimise availability. Sun Microsystems uses electronic prognostics technology to remotely monitor the health of servers and proactively perform just-in-time preventative maintenance (Janasak & Beshears, 2007).

Distributed DSM

Kupzog (2006) describes distributed DSM as opposed to traditional DSM. Distributed DSM requires concurrent DSM of geographically separated facilities. A distributed communication infrastructure is required to enable flow of information. An integrated resource optimisation network uses a hierarchical network structure with the Internet facilitating distributed data acquisition. With this level of communication required between remote DSM implementations, the role of remote diagnostics and maintenance is unmistakable.

Industrial

In the industrial sector, remote monitoring systems are implemented on power plants (Crapo et al., 2003), chemical plants (Biehl et al., 2004), pulp- and paper plants (ABB, 2008b), and industrial motors (Hou & Bergmann, 2012). According to Biehl et al. (2004), manufacturing was the main driver of the development of remote repair, diagnostic and maintenance technology in the United States of America.

TELstaff uses different communication channels to notify maintenance personnel of identified problems and facilitates remote access for corrective maintenance (Biehl et al., 2004). Products such as SCADAonWeb make remote access to any industrial plant possible (Yang et al., 2007). Prvulović et al. (2013) access and maintain remote heating plants via the SCADA system.

Many industries use RDMS technology to increase the efficiency of maintaining devices, equipment, machines or complete systems. Industrial systems correlate with systems used in the mining sector. Because this study focusses on EMSs implemented in the mining sector, a detailed discussion of the industrial application of RDMS technology follows in the next section.

2.3 Industrial application

Dolezilek and McDermott (2006) propose the industrial application of RDMS technology to collect data from data historians and with real-time communication. The potential benefit of implementing RDMS technology to support the maintenance of industrial integrated systems is unmistakable. A description of existing industrial applications of RDMS technology follows on this section. These applications progress from systems that purely offer remote access, to systems that facilitate scalable remote diagnostics and maintenance of distributed equipment or systems.

Remote access

Mouton et al. (2009) successfully tested a communication interface for protection relays used on three-phase induction motors. This interface allows technicians to remotely change settings or assess the circumstances that caused motors to trip. Mouton et al. (2009) used existing public communication infrastructure instead of installing private networks. Public communication infrastructure is more cost effective and facilitates secure data transfer between the relay and maintenance personnel via short message service (SMS). Figure 5 is a schematic of the system developed by Mouton et al. (2009).

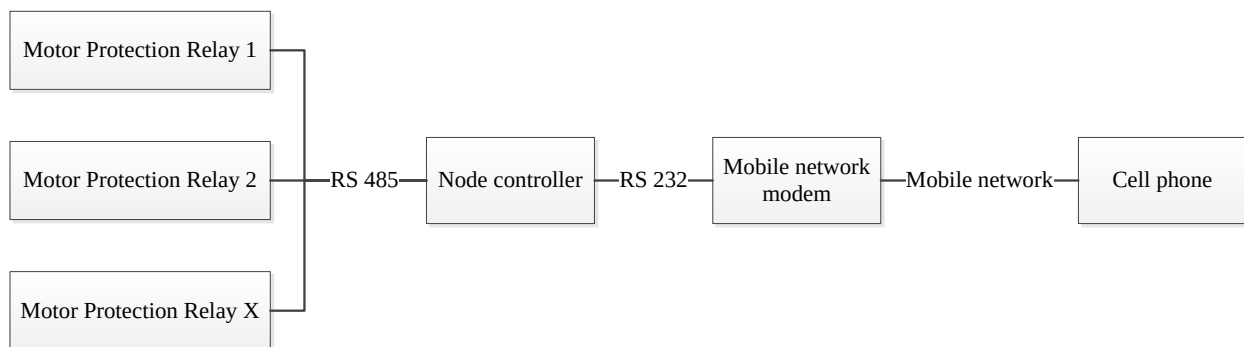


Figure 5: Protection relay communication interface [adapted from (Mouton et al., 2009)]

However, Malek-Zadeh and Dietsch (2006) propose web-based technology for remote maintenance. A prototype proved the feasibility of this concept for maintaining an electrical drive and its control environment. Figure 6 shows a schematic of the prototype developed by Malek-Zadeh and Dietsch (2006). An open platform communication (OPC) connection bridges the gap between the industrial network and the web-based system, allowing for centralised monitoring and control. This solution incorporates Internet access to facilitate remote measurement, supervision and control.

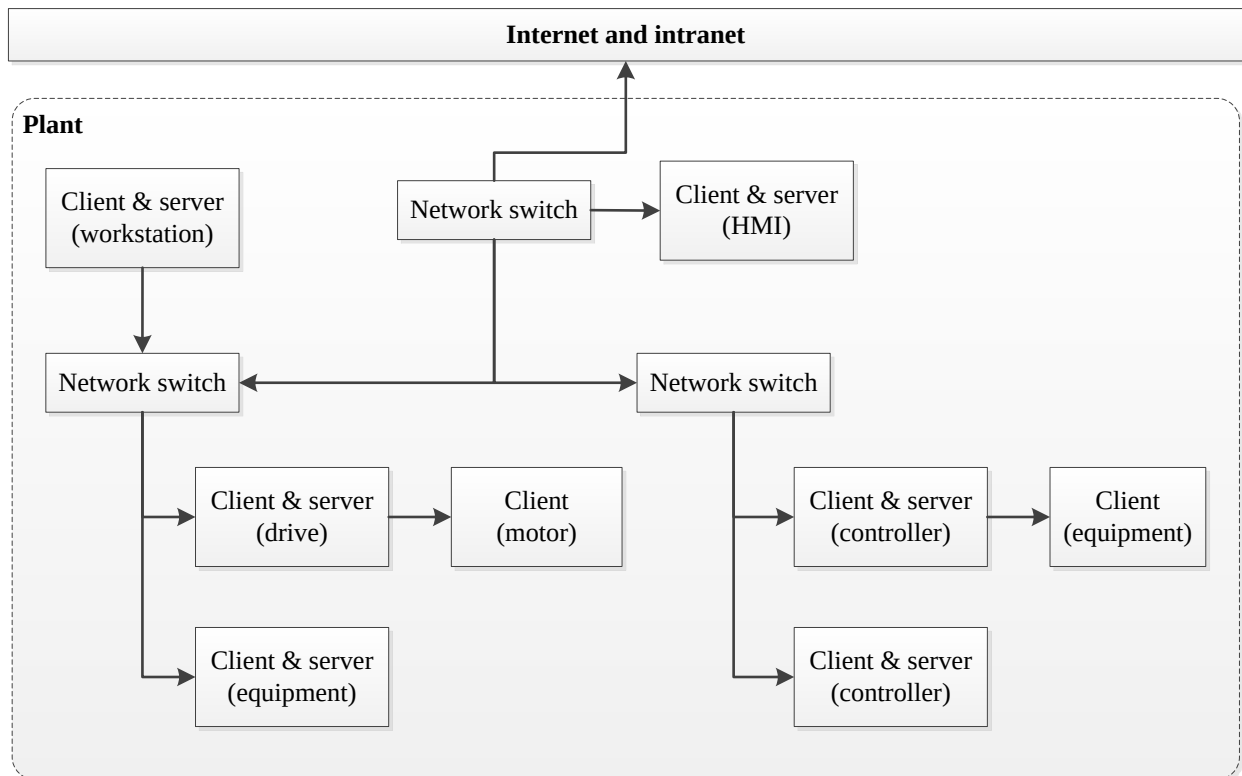


Figure 6: Web-based remote maintenance diagram [adapted from (Malek-Zadeh & Dietsch, 2006)]

Zhang and Wu (2010) propose a more generic solution – using RDMS technology to maintain PLCs over mobile networks. This system also facilitates remote controllability. Because remote access to the PLC exposes all connected equipment to remote control, Internet protocol security (IPSec) or a VPN connection secures the remote access session.

Automated diagnostics

Weppenaar et al. (2012) applied the concept of multi-agent systems to develop an intelligent maintenance management system (IMMS). This system was tested and simulated on a direct current (DC) induction motor system, using OPC for communication between the agent and the industrial platform. The IMMS provides maintenance personnel with the information they require to perform effective maintenance. Maintenance personnel receive diagnostic information in the form of degradation trends and automated prognoses.

Automated diagnostics with remote access

A comprehensive RDMS requires reliable remote access analogous to the work of Malek-Zadeh and Dietsch (2006), and Mouton et al. (2009). Furthermore, an RDMS benefits from automated diagnostics or prognostics in line with the work of Weppenaar et al. (2012).

Goosen and Vermaak (2006) developed a system for remote monitoring and control of a manufacturing process via the Internet. A PLC connects to control and instrumentation equipment, and the SCADA system in turn connects to the PLC via Ethernet. An Ethernet interface connects the SCADA system to the Internet to make remote data upload and download possible. The Internet connection allows access to a simple mail transfer protocol (SMTP) server to facilitate data transmission via e-mail. This system configuration is similar to the configuration described by Yan and Lu (2007), as shown in Figure 7.

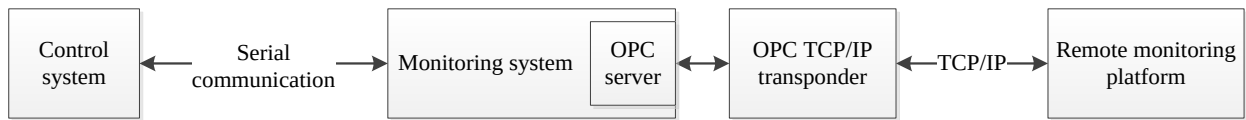


Figure 7: Remote monitoring system diagram [adapted from (Yan & Lu, 2007)]

According to Dolezilek and McDermott (2006), electronic devices and robust communication networks make large amounts of substation data available. Diagnostic systems are used to maintain and optimise the operation of power plants (Minakawa et al., 1995; Guo et al., 2007) and substations (Dolezilek & McDermott, 2006). Furthermore, diagnostic systems provide valuable information for future substation development. Figure 8 shows the architecture of the maintenance system described by Guo et al. (2007).

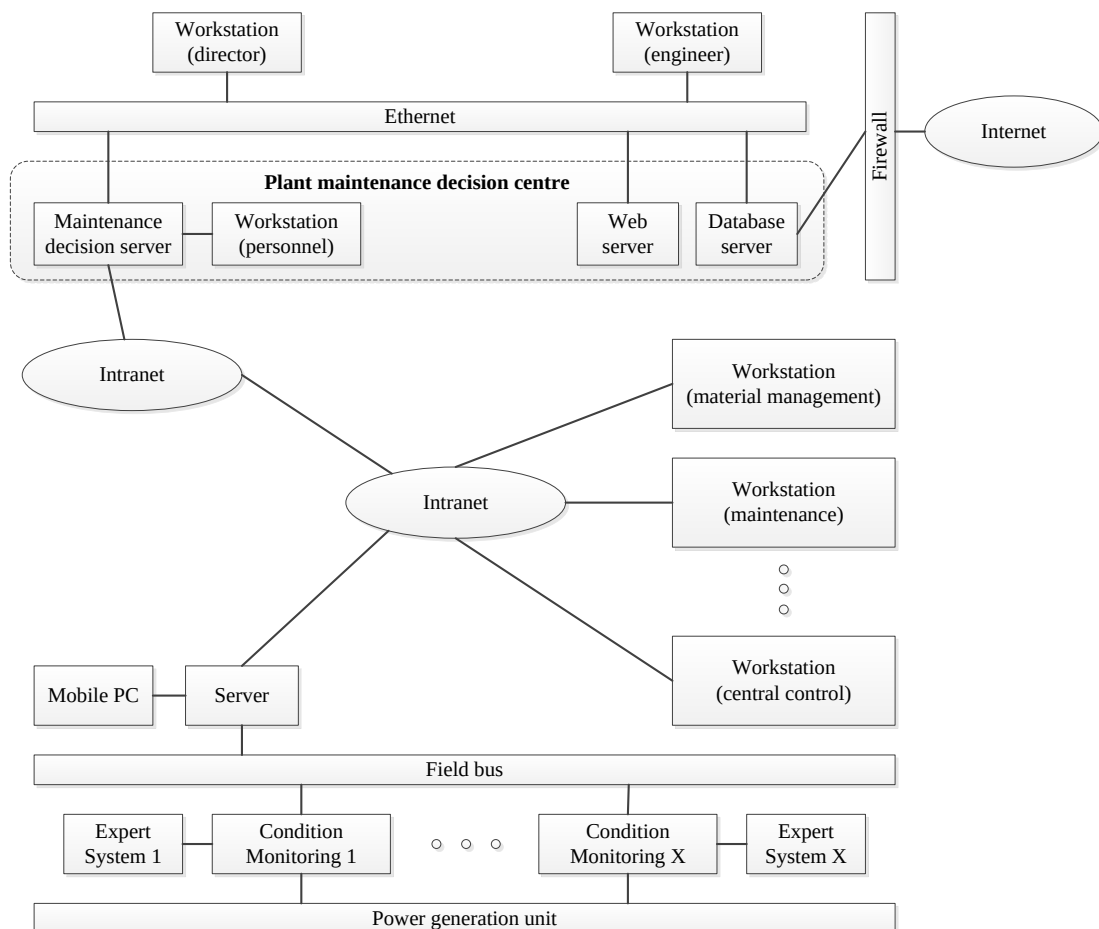


Figure 8: Remote maintenance system hardware diagram [adapted from (Guo et al., 2007)]

The maintenance system on the power plant in Figure 8 stores raw data and diagnostic data in a centralised database. Access to stored data is possible via network infrastructure. A remote support centre has access to the power plant via the Internet, allowing maintenance experts to diagnose and resolve identified faults remotely.

Figure 9 is a diagram showing the maintenance system from a software perspective. The service agent allows maintenance personnel decentralised access to the database and on-site systems using human machine interfaces (HMIs) or web browsers.

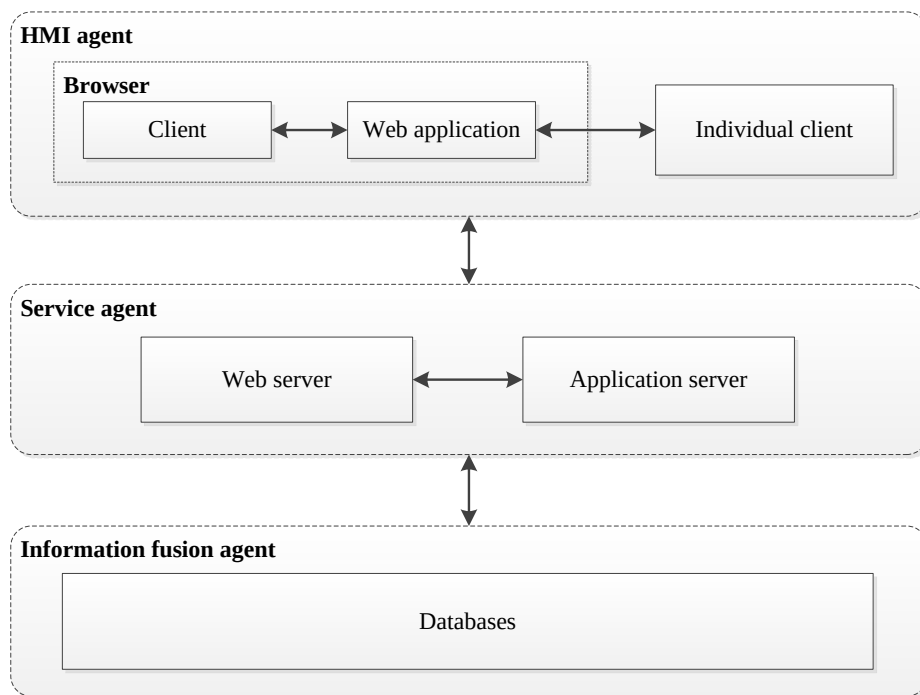


Figure 9: Remote maintenance system software diagram [adapted from (Guo et al., 2007)]

Similar RDMSs have been implemented to ease maintenance of advanced process control systems (Yang et al., 2007) and machines at paper mills (ABB, 2008a). These RDMSs include local monitoring and diagnostics of process and control systems. RDMSs enable companies to access, analyse and react to diagnostic data from remote sites quickly and efficiently.

Distributed remote diagnostics and maintenance

To ensure that an RDMS is scalable and easily maintainable, the bulk of diagnostic processing is centralised at a dedicated maintenance centre (Yan et al., 2010). This reduces the requirement for unnecessary software updates of on-site diagnostic applications. As an example of this, the work of Ghoshal and Deb (2001) aim to increase the functionality of the remote diagnosis server as the central point of the remote maintenance service.

The systems developed by Crapo et al. (2003) function on the concept of the human automatic nervous system to maintain and support a fleet of complex equipment. These systems use agent software to package and transfer information to a maintenance centre. The maintenance centre diagnoses equipment to identify anomalies and recommends a set of corrective actions. According to Crapo et al. (2003) data integrity is essential to ensure accurate system diagnostics.

According to Zhou et al. (2009), automated fault diagnostic systems consist of local computers connected to a remote diagnostic centre. When a malfunction occurs, the local computer contacts the maintenance centre for online support. The automated fault diagnostic system makes real-time monitoring of remote equipment possible. Zhou et al. (2009) describes this system as a scalable solution for remote diagnostics that provides equipment suppliers, maintainers and third parties with access to diagnostic information. Figure 10 shows a schematic of this system.

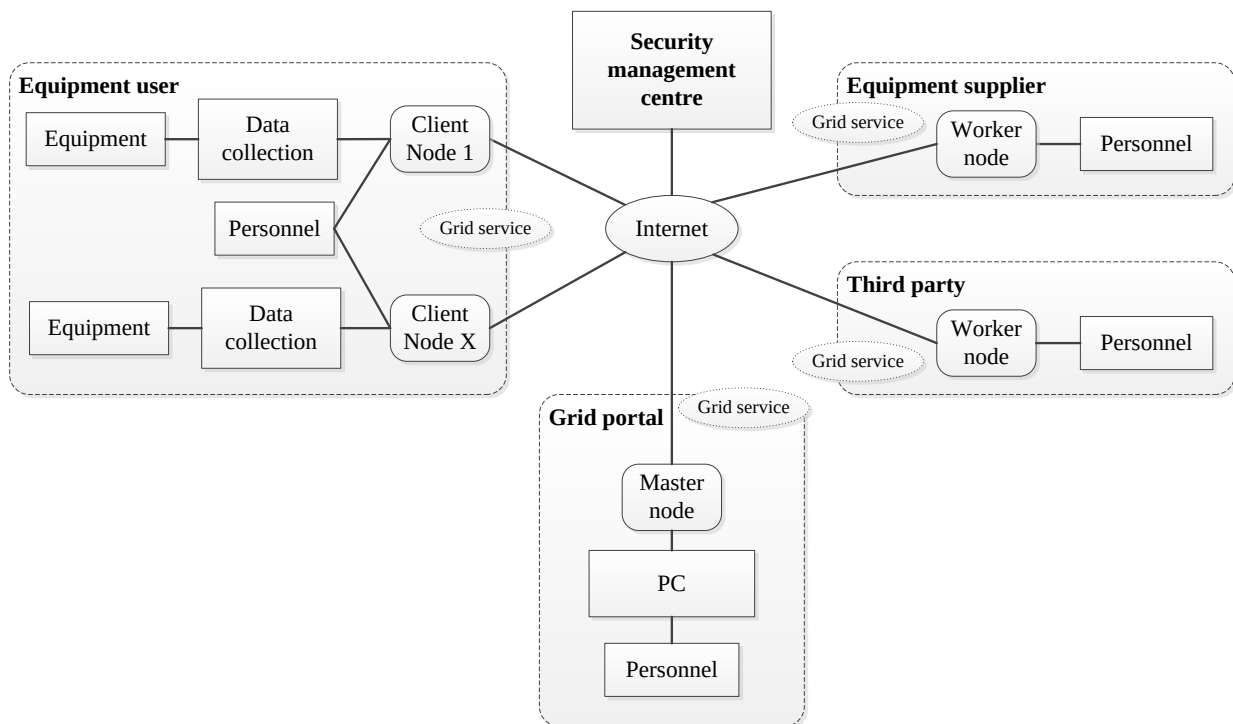


Figure 10: Grid based fault diagnostic system [adapted from (Zhou et al., 2009)]

Jazdi (2010) proposes the use of a remote access server (RAS) that has greater computing capability to process embedded systems data. The remote access server provides maintenance personnel with access to current and historical data, statistics and maintenance instructions. Remote access infrastructure facilitates visualisation to enable maintenance personnel to control embedded systems remotely. Figure 11 is a schematic of the remote access infrastructure for embedded systems.

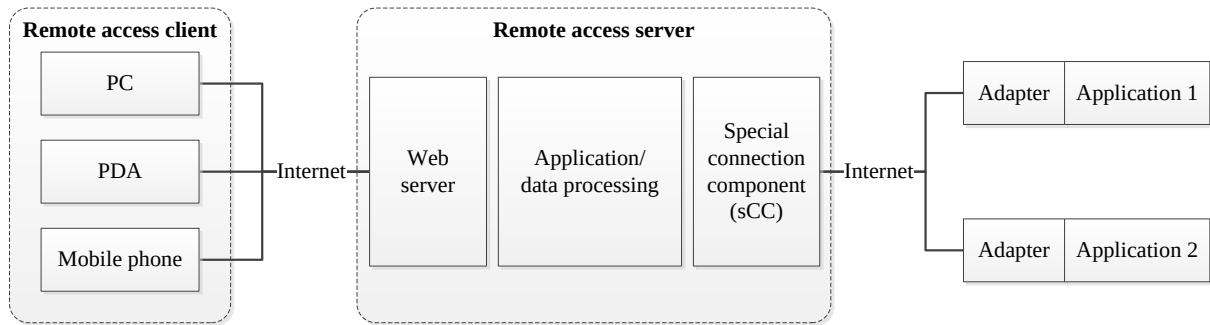


Figure 11: Remote access infrastructure for embedded systems [adapted from (Jazdi, 2010)]

The proposed system consists of modular components of which the special connection component (sCC) is adapted for each unique embedded system. This system offers a provider-independent interface for different embedded systems, with a user interface that is remotely accessible. The remote access server processes data differently for individual remote access user groups, creating a generic RDMS with specialised diagnostic capabilities.

None of these industrial applications accurately corresponds to the infrastructure and operating environment of EMSs implemented in the mining sector. However, before a comprehensive evaluation of existing solutions is possible, an overview of typical mine EMS infrastructure and operating environment is required.

2.4 Energy management system overview

This study ascertained the essence of a typical mine EMS, taking into consideration different EMS technologies. The typical EMS considered for this study employs an EMS platform application with control capability and extensive data, action and event logging. These EMSs rely on supporting software applications to ensure redundancy and reliable communication with the system controlled by the EMS.

All of these software applications typically run on a redundant EMS server pair shown schematically in Figure 12. The EMS server connects directly to a PLC, or indirectly through a SCADA system to obtain control of field equipment, machines and instruments. An OPC connection facilitates read and write access to the PLC (OPC Training Institute, 2012). Supporting EMS applications have no influence on the energy management process and, therefore, do not require direct interaction with PLCs.

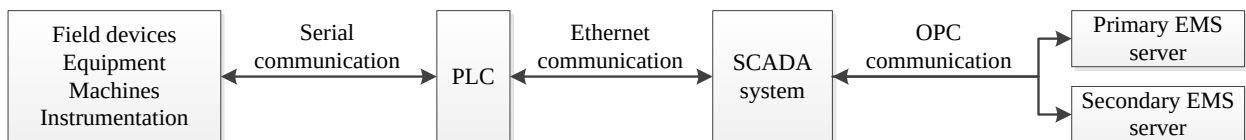


Figure 12: Basic composition of a typical EMS

The EMS platform application forms the core of on-site EMSs. For increased reliability and availability, the EMS server typically includes an operational secondary server as shown in Figure 12. Each EMS technology controls a specific operational system to achieve a DSM target. The EMS technologies considered in this study perform energy management on mine:

- compressed air systems;
- cooling systems; and
- water reticulation systems.

Each EMS technology uses a model to emulate the controlled mining system. The system model holds the relevant characteristics of equipment and machines that make up the controlled system. Figure 13 shows an example of the EMS graphical user interface (GUI) of an emulated mine cooling system. An OPC connection allows the EMS platform to perform real-time control according to a control philosophy. A specialised control philosophy is an integral part of each EMS model.

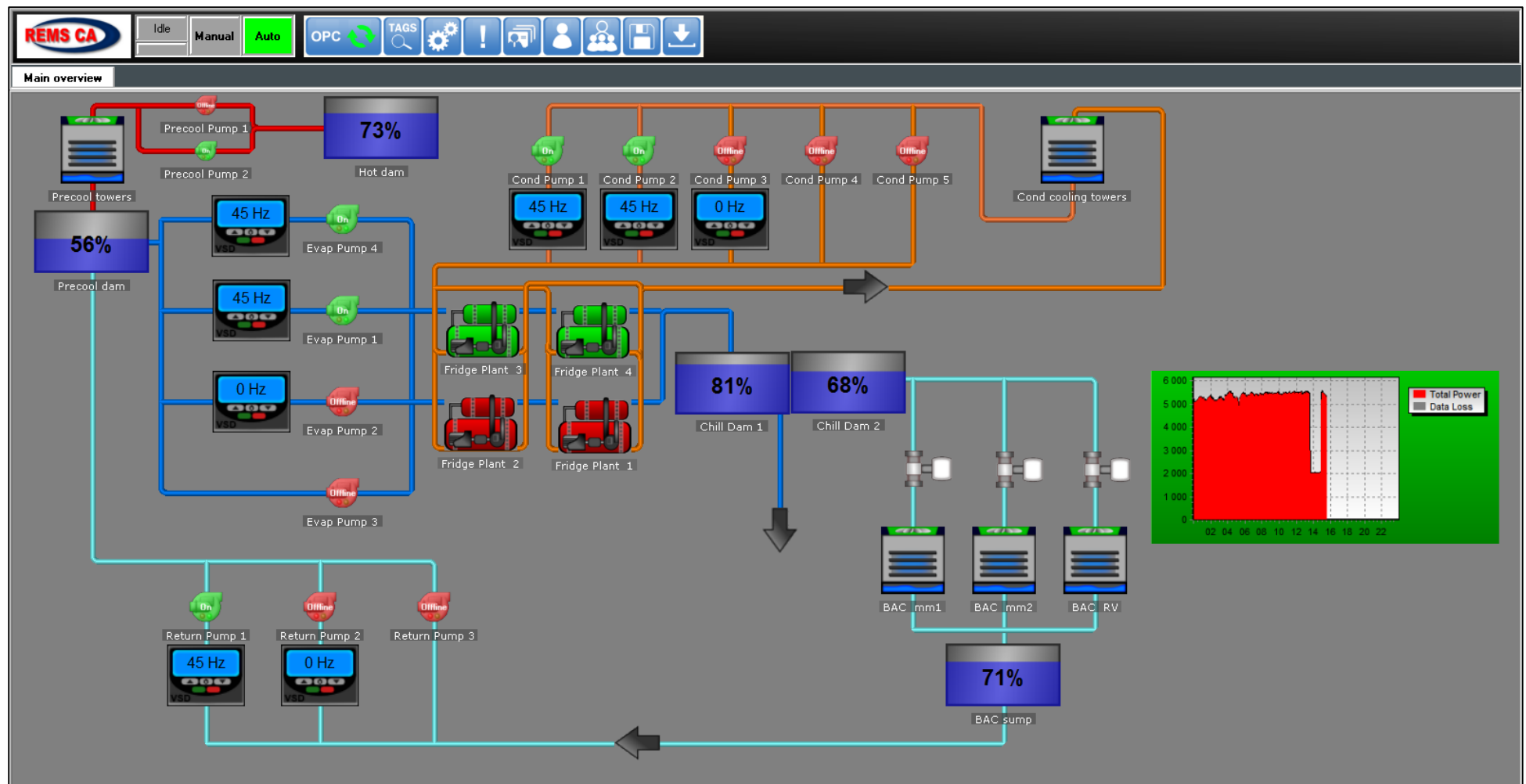


Figure 13: EMS modelled cooling system

Some EMS technologies have simulation capability to allow energy management personnel to optimise EMS operation. Optimisation involves updating the control philosophy according to results obtained from simulations. This study found that the basic EMS architecture shown in Figure 12 is consistent across more than fifty investigated EMS implementations in the mining sector.

Irrespective of this consistency, the control philosophies of individual EMSs differ fundamentally because these control philosophies pursue different DSM objective that could include electrical load shifting, peak clipping or energy efficiency. The control philosophy is thus unique to each EMS, irrespective of the underlying EMS technology.

Similarities exist between the operating environments of industrial RDMS applications and mine EMSs. Each EMS is, however, integrated with large and production-critical mining systems. EMSs optimise electrical energy consumption according to a specialised DSM control strategy. A supervisory system for mine EMSs is thus required to be adaptable to different EMS technologies with site-specific control philosophies.

2.5 Existing systems evaluation and limitations

The systems discussed in Section 2.2 and Section 2.3 provide insight into remote maintenance technology with different fields of application. Advantages of implementing this technology to support remote maintenance were discussed. Table 1 (Page 30) is a matrix that summarises the characteristics of several RDMSs based on available information. This evaluation does not serve to assess each RDMS individually, but provides a comprehensive survey of the characteristics and limitations of existing remote maintenance technologies. The subsections that follow correspond to the categories listed in Table 1.

On-site system

On-site systems perform interval logging (Weppenaar et al., 2012) and event logging (ESG, 2013b). These on-site systems log less critical data on a predefined interval for daily transmission to a maintenance centre. Critical event occurrences trigger immediate data transmission to alert maintenance personnel. EMS maintenance requires both interval and event logging to ensure prompt maintenance action. This will prevent extended production losses or EMS performance reduction due to malfunction.

Execution of on-site diagnostic algorithms improves the accurate identification of predefined maintenance-requiring events. This could be useful to diagnose issues with an EMS control philosophy. On-site diagnostics should be simplified and limited to identifying critical events to the analogy of systems presented by Ghoshal and Deb (2001) and Yan et al. (2010). This increases maintainability of on-site diagnostic algorithms, especially when maintaining a large number of systems remotely.

Section 2.4 provided an overview of typical EMSs implemented in the mining industry. Specialised on-site EMS diagnostics requires access to network devices and machines to ensure comprehensive diagnostics. Network diagnostic requirements include Ethernet and industrial OPC connectivity.

Communication

Communication networks facilitate data transfer to a remote maintenance centre for detailed diagnostics. Existing RDMSs incorporate either fixed medium (Goosen & Vermaak, 2006) or wireless network connections (Zhang & Wu, 2010) for data transfer and remote access. Due to the remote nature of some mining operations, wireless network access is preferential. Remote locations may, however, not offer a reliable mobile network signal thus requiring the use of fixed medium communication. Support for both wireless and fixed medium communication is thus required for remote EMS maintenance.

RDMS communication is sometimes limited to automated data transmission to the maintenance centre. Some RDMSs facilitate remote access to, and control of, on-site systems. This gives maintenance personnel an extended reach when in-depth, interactive diagnostics is necessary.

Maintaining complex EMSs requires bidirectional communication with remote access (Suhonen et al., 2011) and control (Jazdi, 2010) of the on-site system. EMS platform updates often address reduced performance due to software instability, thus revealing the need for software updates that are deployable remotely as proposed by Mahfoud et al. (2008).

Maintenance centre

To improve diagnostic accuracy, maintenance centres perform data integrity verification before proceeding with detailed diagnostics (ESG, 2013b). Maintenance teams typically perform remote maintenance from the maintenance centre. Opening the diagnostic process for input by maintenance personnel allows the system to take the effect that external factors has on system reliability or EMS performance into account (Weppenaar et al., 2012).

Only one of the evaluated systems perform remote backup of critical on-site configuration data (ESG, 2013b). This is also a requirement to ensure that mine EMSs produce reliable DSM performance. However, none of the evaluated systems provided performance assessment suited for DSM

Feedback to maintenance personnel

Some of the evaluated systems provide maintenance personnel with periodic reports or fault notifications (Weppenaar et al., 2012). Most of these RDMSs provide feedback to maintenance personnel in various forms, including reports and notifications via e-mail, SMS or onscreen notifications at the maintenance centre (Yun et al., 2011). Some RDMSs provide maintenance personnel with suggestions for corrective action based on diagnoses. Only one of the evaluated systems were found to drive the maintenance process through alarm escalation based on maintenance personnel feedback (ESG, 2013b).

Although all of these RDMSs are properly suited for their respective fields of application, a supervisory system that satisfies all of the criteria listed in Table 1 is required for comprehensive remote maintenance of a large number of mine EMSs. EMSs are specialised systems that employ diverse EMS technologies, with different DSM strategies. Mine EMSs thus require a robust supervisory system to ensure sustained DSM performance while maintaining uninterrupted production and ensuring a safe working environment.

Table 1: Existing RDMS evaluation overview

RDMS	On-site				Communication					Maintenance centre					Feedback				
	Interval logging	Event logging	Customisable diagnostics	Industrial networks	Different mediums	Data transmission	Remote access	Remote control	Remote software deployment	Data integrity checking	Diagnostics	DSM performance assessment	Maintenance teams	User input or approval	System backup	Scheduled reports	Maintenance suggestions	Maintenance management	Notifications
BEMS (ESG, 2013b)	x	x	x	x	x	x	x	x		x	x		x		x	x		x	x
Complex equipment (Crapo et al., 2003)	x		x		x	x				x	x		x	x			x		x
Embedded systems (Jazdi, 2010)					x	x	x	x			x		x						
Online vehicle monitoring (Mahfoud et al., 2008)	x	x	x			x	x	x	x		x		x						x
Manufacturing equipment (Lee, 1997)	x			x	x	x	x	x			x		x						
Motors at cement plants (Hofmann & Phares, 2003)	x			x	x	x	x	x		x	x		x			x	x		
Paper mills (ABB, 2008a; ABB, 2008b)	x			x	x	x	x	x	x		x		x			x			x
Vehicle air pollution (Lin et al., 2007)	x	x				x					x		x			x	x		
Vehicle battery health (Zhang et al., 2009)	x	x				x	x				x		x						x
Vehicle battery system (Liu et al., 2011)						x	x				x		x				x		x
Vehicle failure prediction (Campos et al., 2002)	x		x			x	x	x	x		x						x		x
Vehicle health (Yun et al., 2011)						x	x				x								x
Vehicle health and location (Al-Taee et al., 2007)	x	x	x			x					x								x
Wireless sensor networks (Suhonen et al., 2011)	x	x		x		x				x	x						x		x

2.6 Supervisory system requirements

A comprehensive supervisory system is required that integrates with existing and new EMSs. The previous section identified functionality common to existing RDMS technologies. This forms the starting point for the development of a supervisory system for specialised EMSs implemented on South African mines. By evaluating existing systems, the following seven areas of consideration for the new system development were identified:

- Communication security
- Data integrity
- Diagnostics
- Maintenance management
- Compatibility
- Simplicity
- Reliability

This subsections that follow present a detailed discussion of these areas of consideration.

Communication security

Data communication forms an integral part of any remote maintenance system. Communication infrastructure allows data to be transmitted to maintenance centres and facilitates remote access on demand (ABB, 2008a). Kotze and Visser (2012) regard reliable communication as an essential tool to ensure quality maintenance. EMSs implemented on operational mining systems often indirectly influence production and the safety of mineworkers, thus requiring solid communication security.

According to Holzmüller (2011) remote sites must harbour technology that allows remote data retrieval and control from a maintenance centre. In accordance with this, the work of Zhang and Wu (2010) promotes remote controllability and rapid responsiveness. The communication infrastructure should allow experts to provide prompt remote support (ABB, 2008b).

Liu et al. (2011) suggest that the communication infrastructure sends commands from the maintenance centre to the site. Al-Taee et al. (2007) recommend transmission control protocol (TCP) communication for concurrent data transfer between a maintenance centre and vehicles. TCP controls the flow of data and prevents network congestion.

Yan and Lu (2007) characterise weak data security as one of the limitations of traditional consumer services. The work of Yang et al. (2007) and Peng et al. (2011) also emphasise the importance of data security. Holzmüller (2011) states that compromised security could result in unauthorised access that poses the risk of data theft.

Furthermore, unnoticed access by maintenance personnel or an unauthorised person could compromise the safety of on-site personnel. The safety concern becomes apparent in the work of Zhang and Wu (2010) that allows remote access to PLCs that could control large machines. This configuration is analogous to the typical EMS configuration described in Section 2.4. Holzmüller (2011) predicts an increase in the use of this technology as customers become more trusting of the security measures that protect RDMSs.

Data integrity

Minakawa et al. (1995) stress the importance of choosing the correct data for fault diagnostics because diagnostic results are reliant on input data. Campos et al. (2002) agree that the integrity of data must be verified before proceeding with diagnostics. Krapivin and Mkrtchyan (2007) employ statistical analysis to make decisions about noise and integrity of environmental data before proceeding with diagnostics. Peng et al. (2011) refer to the impact that data authenticity has on equipment maintenance. This also applies to EMS maintenance.

Diagnostics

Fault detection before, or at an early stage of failure is important to minimise the extent of equipment damage or production loss (Yang et al., 2007). Guo et al. (2007) state that by accurately identifying faults, equipment life will be extended and risk of failure reduced. Diagnostic algorithms are typically employed for this purpose (Campos et al., 2002). These algorithms are executed either on-site or at the maintenance centre, or at a combination of both.

On-site and maintenance centre diagnostics are essential for mine EMSs that require immediate critical event diagnoses and daily degradation diagnoses. Execution of on-site diagnostic algorithms improves the accurate identification of predefined maintenance-requiring events. As recommended by Yan et al. (2010), on-site diagnostics is simplified and limited to identifying critical events to ensure optimal algorithm maintainability.

Maintenance centre diagnostics typically aims to monitor system performance (Biehl et al., 2004) to identify degradation (Yang et al., 2007). Tshikalanke (2006) believes that reporting on DSM systems is

essential to track performance against contractual or voluntary targets. EMS metering and reporting is a useful diagnostic tool and validate energy conservation measures. This forms the basis of the measurement and verification process. Kotze and Visser (2012) suggest that performance measurement is an essential part of the maintenance management process.

According to Kotze and Visser (2012), maintenance indicators are often categorised. Diagnostics involves monitoring these indicators to identify anomalies. Krapivin and Mkrtchyan (2007) describe how a knowledge base stores indicators for all possible fault occurrences. This provides a tool to assist maintenance personnel to reason as experts would. Crapo et al. (2003) describe a system that simulates expert reasoning by making use of a GUI with large amounts of information available to maintenance personnel.

Maintenance management

According to Locy (2001), diagnoses should be made available to maintenance personnel for prompt follow-up. Diagnostic feedback initiates maintenance action in response to failures (Campos et al., 2002; Biehl et al., 2004). Furthermore, Crapo et al. (2003) describe how diagnostic feedback narrows down the location of the problem to further assist maintenance personnel.

E-mail alerts can be used to provide real-time diagnostic feedback (ABB, 2008a). Minakawa et al. (1995) suggest that diagnostic results should be displayed in a maintenance centre using a GUI that is easy to understand. Real-time alerts such as these make quick remedial response possible to reduce or prevent downtime. Guntermann (1982) suggests custom-formatted reports, allowing problem areas to be located quicker. These reports summarise generic information and provide detailed information on identified faults to minimise troubleshooting time (Deb et al., 2000).

A large quantity of data is beneficial and allows for comprehensive diagnostics, but according to Crapo et al. (2003) it can overwhelm maintenance personnel. Janasak and Beshears (2007) state that by transmitting non-critical data unnoticeably, airplane pilots are protected against information overload. Crapo et al. (2003) realised that users have their own preferences when viewing information. This includes the type of information and the visual representation thereof.

Lengoasa and Potgieter (2007) emphasise the importance of client cooperation to ensure that the potential of an RDMS is optimally utilised. Equally important is the competency level of maintenance personnel who use the RDMS, which is only a tool that eases the process of maintaining remote systems. Kotze and Visser (2012) take this further to say that comprehensive maintenance management requires feedback to

all levels of management. The purpose of diagnostic feedback is to allow maintenance managers to coordinate the maintenance effort more efficiently.

Angeli and Chatzinikolaou (1995) share the idea of an RDMS assisting maintenance personnel to reason as experts would. More advanced RDMS technology establishes the best course for corrective action (Kotze & Visser, 2012) and alerts maintenance personnel when it is necessary to perform corrective maintenance. In an attempt to automate the maintenance process, some RDMSs manage the maintenance process by escalating issues to maintenance managers based on maintenance progression (ESG, 2013a).

Compatibility

All of the sensor data from the international space station is transmitted to the NASA base station in near real-time (Deb et al., 2000). Deb et al. (2000) illustrated the benefits of a real-time remote monitoring system without integrating any hardware or software with the space station, making use of the existing data stream. Gungor (2009) also proposes non-intrusive integration of monitoring systems on existing motor systems.

EMSs consist of different variations of hardware, software and communication infrastructure (Yan & Lu, 2007). Because of this, Crapo et al. (2003) and Jazdi (2010) propose the development of highly configurable RDMSs that are compatible with available communication infrastructure. Malek-Zadeh and Dietsch (2006) put standards in place to ensure backward compatibility and interoperability, while bridging the differences between hardware types. To support these views of a standardised and centralised design, Guo et al. (2007) suggest bridging of differences between hardware, software, databases and networks.

Krapivin and Mkrtchyan (2007) developed a system for the unique application of environmental diagnostics. This system emphasises the need to integrate the diagnostic system with existing and new subsystems because of the diverse nature of the equipment and their geographic locations. An EMS supervisory system is required to be compatible with existing and new EMS implementations. Seamless integration with existing EMSs will reduce downtime that could lead to reduced performance.

According to Lee (1997), each manufacturing process has its own process variables that are important for diagnostics. Campos et al. (2002) developed an RDMS with parallel infrastructure to distinguish between different vehicle types. For this multiplicity, Yan and Lu (2007) and Weppenaar et al. (2012) suggest using different diagnostic models for different systems, processes, equipment and manufacturers. This is also true for EMSs that all have distinct control philosophies, yet require a single supervisory system.

Dolezilek and McDermott (2006) made substation data available to the RDMS that was not traditionally available. This emphasised the importance of allowing future expandability of the RDMS to accommodate new data when it becomes available.

Simplicity

Diagnostics can easily become very complex (Hofmann & Phares, 2003). Krapivin and Mkrtchyan (2007) recommend a balance between complexity and practicality. Diagnostics should be complex enough to be beneficial, but should not be so complex that automated diagnostics is not viable. Adhering to this trade-off, Crapo et al. (2003) propose a diagnostic system that functions transparently and accepts input from maintenance personnel. System complexity is strategically reduced by allowing maintenance personnel to intervene when the diagnostic process staggers due to unusual circumstances.

Reliability

RDMSs assist with the maintenance of diverse operational systems. While the system owner is mainly concerned with product availability and cost of operation (Janasak & Beshears, 2007), maintenance improves system availability by reducing downtime (Hou & Bergmann, 2012). According to Kotze and Visser (2012), maintenance is an essential part of an organisation's long-term profitability. An RDMS has the capacity to improve:

- operational safety (Deb et al., 2000);
- reliability (Peng et al., 2011); and
- efficient operation (Hou & Bergmann, 2012).

Furthermore, an RDMS has the capacity to reduce:

- lifecycle and maintenance cost (Guo et al., 2007); and
- unexpected maintenance and catastrophic failures (Hou & Bergmann, 2012).

It is the responsibility of the proposed supervisory system to maintain the operation of production-critical systems. For this reason, the reliable operation of the supervisory system itself is a non-negotiable requirement.

2.7 Conclusion

This chapter investigated the application of RDMS technology to maintain diverse operational devices, equipment or systems. RDMS technology is already utilised to maintain spacecraft, aircraft, medical equipment, mobile devices, buildings, vehicles and industrial equipment. Particular attention was given to the operation of RDMSs used in the industrial sector because the industrial operating environment resembles the mining environment.

Even industrial remote maintenance applications did not present a solution for comprehensive remote EMS maintenance. This is mainly because different EMS technologies implemented in the mining sector require a single supervisory system to facilitate efficient remote maintenance. In addition to these different technologies, the unique underlying control philosophy requires highly specialised diagnostics. This is because mine EMSs perform electrical energy management to achieve a specific DSM objective that could include load shifting, peak clipping or energy efficiency.

An evaluation of existing applications revealed the key characteristics of RDMSs. These characteristics were categorised under the RDMS subsystems that include the on-site, communication channel, maintenance centre and feedback subsystems. Furthermore, existing RDMS applications revealed seven fundamental areas to be considered when developing a supervisory system for remote EMS maintenance in the mining industry. These considerations include communication security, data integrity, diagnostics, maintenance management, compatibility, simplicity and reliability.

The elicited characteristics and fundamental requirements of existing RDMSs provide the basis for the development of a supervisory system, specifically designed to facilitate the maintenance of remote EMSs. This supervisory system builds on the work of existing RDMS developers with the goal of sustaining DSM performance of existing and new EMSs in the mining industry. Sustained DSM performance is possible through generic diagnostics of the EMS operation and specialised diagnostics of the EMS control philosophy.

CHAPTER 3. NEW SUPERVISORY SYSTEM DESIGN

3.1 Introduction

Chapter 2 established that mine EMSs require continuous maintenance to ensure optimal operation. The chapter also discussed the potential benefits of implementing RDMS technology for maintaining EMS performance. Research into existing RDMS technology forms the basis of developing a supervisory system that facilitates sustained DSM performance of existing and new EMSs. This chapter documents the development of the new supervisory system, incorporating the main RDMS characteristics identified in the previous chapter.

New diagnostic methods were developed for comprehensive EMS assessment. From the perspective of a supervisory system, the control philosophy is a maintainable component that directly influences the performance of an operational EMS. The supervisory system design includes generalised EMS diagnostics while accommodating specialised control philosophy diagnostics.

The development focusses on diagnostics of the physical EMS components, control philosophy operation and overall performance. The supervisory system further incorporates automated maintenance management capability as a requirement of daily DSM performance assessment and efficient EMS maintenance.

The supervisory system design allows integration with different EMS technologies based on the same energy management platform. This chapter presents the development of a comprehensive supervisory system that easily integrates with existing and new EMS technologies, infrastructure and supporting systems.

3.2 Functional design

An EMS monitors devices, machines, equipment and instrumentation in the production environment and generates control instructions according to a control philosophy. The supervisory system, the EMS, the systems controlled by the EMS and the maintenance centre consist of physical components that are grouped into distinct categories. These categories include the:

- production environment;
- remote system;
- communication channel;
- maintenance centre; and
- maintenance personnel.

Figure 14 is a high-level schematic of the data flow and interaction between these main categories. The supervisory system employs a diagnostic and maintenance agent (DMA) to gather on-site data for secure daily transmission to the diagnostic and maintenance centre (DMC).

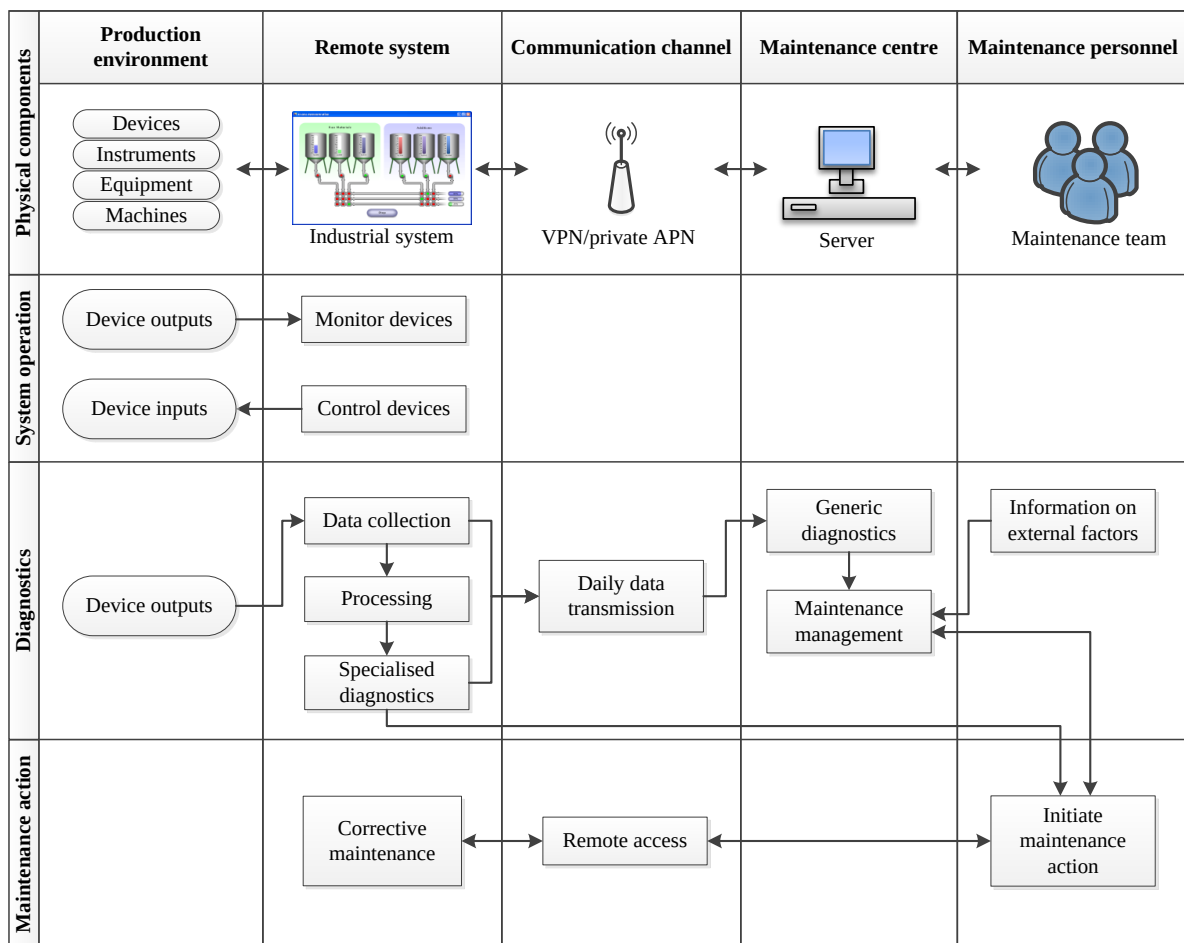


Figure 14: DMC data flow diagram

The DMC performs diagnostics that assess the on-site supervisory system and the EMS operation. Diagnostics further include DSM performance calculations and generic control philosophy assessment. The DMA executes specialised on-site EMS diagnostics. Specialised diagnostics assess elements critical to the correct operation of the control philosophy, which might warrant immediate corrective action. The DMA securely transmits non-critical data to the DMC on a daily basis.

The DMC enables maintenance personnel to input information about external factors that affect the correct operation of the EMS. To produce comprehensive diagnoses, the DMC processes general and specialised EMS diagnostics in conjunction with information about external factors.

A maintenance management unit prompts maintenance personnel to initiate corrective maintenance based on these comprehensive diagnoses. Maintenance personnel acquire secure access to the remote site via a VPN or a private APN, which also facilitates daily data transmission. The maintenance management unit then drives the resolution process by actively prompting corrective action and progress feedback. The supervisory system expects feedback from maintenance personnel on maintenance progress until the identified issue is resolved.

The supervisory system accepts user input during the on-site DMA diagnostics configuration, DMC diagnostic configuration and maintenance management stages. User input creates a complete feedback loop from the time of identifying a maintenance-requiring event, through corrective maintenance to issue resolution. The supervisory system thus retains information on the diagnostics and maintenance processes of each maintenance-requiring event and subsequent maintenance action.

The new supervisory system will assist maintenance personnel in complying with ISO 50001:2011 requirements (ISO, 2011) regarding measurement, review and continual improvement of EMS performance. ISO compliance is simplified by providing maintenance personnel with daily EMS assessment information, managing the maintenance process and facilitating remote maintenance.

3.3 Detailed design

As discussed in Section 2.4, understanding mine EMS architecture and operation is essential when developing a comprehensive EMS supervisory system. An EMS supervisory system is primarily required to ensure that the physical EMS stays operational. When an EMS malfunctions, even manual energy management could be ineffective due to unimplemented control commands. Sustaining EMS performance is the secondary objective in the overall maintenance effort.

Figure 15 is a schematic of the developed supervisory system, consisting of the DMC, secure communication and remote DMA installations. In line with the analogy of existing RDMSs, a dedicated DMC establishes a supervisory system with a centralised point of operation that offers decentralised access to diagnostic data. The DMA gathers on-site data for transmission to the DMC. The DMC performs diagnostics on the DMA and EMS data to identify anomalies that could cause reduced performance. The DMC notifies maintenance personnel of these maintenance-requiring events and drives the maintenance effort.

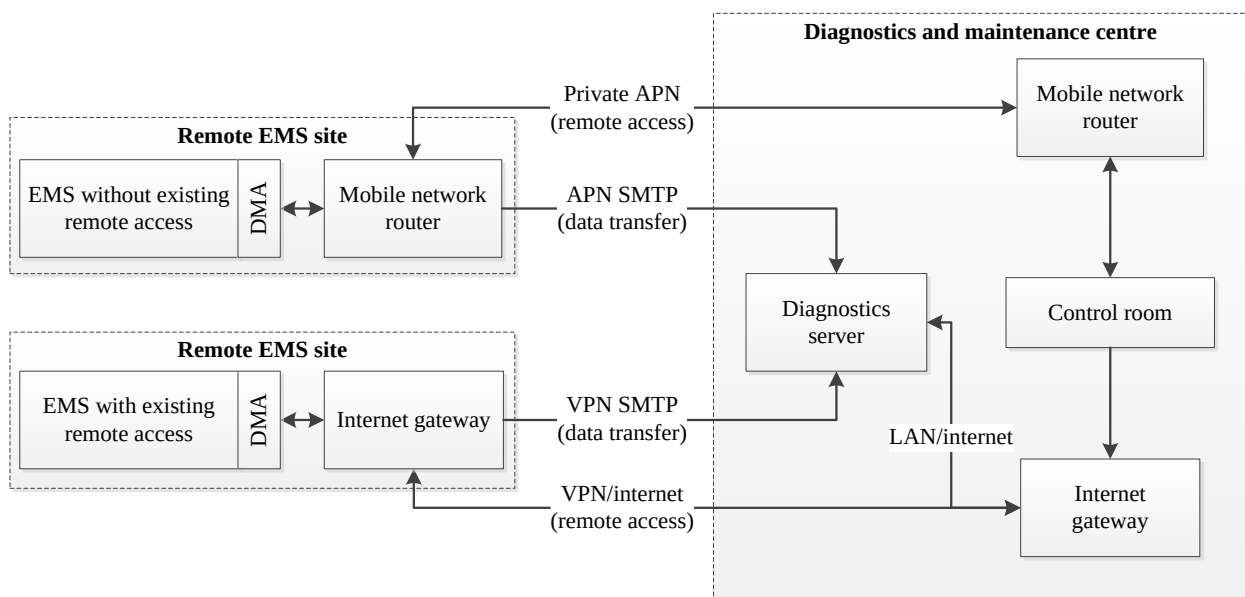


Figure 15: Supervisory system schematic

A secure communication channel facilitates data transmission and allows remote access and control of the EMS for maintenance purposes. The supervisory system is designed to primarily use a private APN connection established by a mobile network router for data transmission and remote access. On sites where corporate security policies or network coverage do not permit the use of these routers, existing VPN connections offer a viable alternative to a private APN.

The system design further allows the diagnostic server to be on the same local network as the control room computers, or a hosting company must reliably host it. The subsections that follow provide a detailed description of the DMA, DMC and the secure connection.

DMA

The DMA addresses the requirement to gather on-site EMS information for diagnostic and maintenance purposes. To access hardware in the production environment, the DMA runs on the EMS server. The DMA also monitors the operation of the EMS server, network connections, EMS platform and supporting applications. On-site data processing and diagnostics are limited to minimise the need for remote DMA updates resulting from continuously improved diagnostic algorithms. Figure 16 is a detailed schematic of the on-site components of the supervisory system, showing the operation of the DMA.

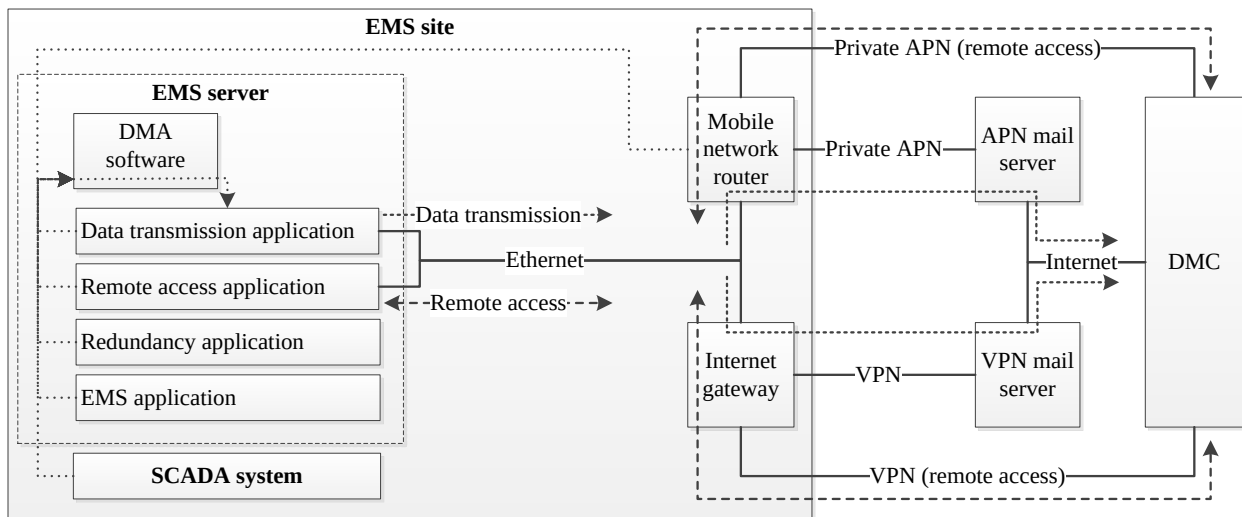


Figure 16: DMA operational schematic

As described by Du Plessis, J.N. et al. (2012), all applications running on the EMS server are monitored to assess their existence, version, running status, responsiveness and memory usage. The DMA obtains information such as mode of operation, OPC connectivity and control actions non-invasively through an existing EMS software interface. The router and the SCADA machine are considered as generic network components. The DMA assesses the accessibility of these network components from the EMS server.

Table 2 summarises the data that the DMA collects for generic diagnostics executed by the DMC. Each data item in this table has a corresponding diagnostic result. Data such as the server operating system version and username consist of a string that describes the latest state of each data item. The last status of data – such as the EMS server firewall and firewall exceptions – is expressed as a Boolean value that is either “true” or “false”. Software availability and network accessibility are expressed as a percentage of each day.

Table 2: DMA collection summary

Category	Data	Diagnostic type
EMS server	Operating system version	String
	Uptime	Time period
	Username	String
	Host name	String
	Firewall enabled	Boolean
	Remote desktop enabled	Boolean
Software	Installed	Boolean
	Version	String
	Firewall exception	Boolean
	Availability	Percentage
Network	Network router access	Percentage
	Private APN SMTP access	Percentage
	SCADA access	Percentage
	Secondary EMS server access	Percentage
EMS platform	Automatic operation	Percentage
	OPC connected	Percentage

The DMA packages collected data for transmission using the data transmission application. Data transmission software transmits the complete data set of the previous day on a daily basis. Data about emergency conditions are, however, transmitted in real-time to avoid extensive delays before initiating corrective action. In addition to this, the DMA periodically sends EMS configuration files to the DMC for backup purposes. The DMA also executes specialised EMS diagnostics, allowing for the robust assessment of the control philosophy. Section 3.4 discusses these specialised diagnostics in further detail.

In concept, the DMA is adaptable for data collection on any EMS server hardware configuration. Its generic design allows for basic data logging on any software application running on the EMS server, in addition to network devices connected to the EMS server. The DMA design ensures that the supervisory system easily integrates with existing and new EMS infrastructure.

Communication

The communication network forms an important part of an EMS supervisory system, because it allows data transfer and access to remote EMSs. With existing EMSs distributed across South Africa, mobile networks offer the best flexibility to facilitate standardised communication. A mobile network router provides a highly available connection to on-site systems. These routers incorporate hardware-based services that sustain the network connection with failover capability between two different service providers.

Network signal strength could, however, be insufficient at remote sites thus requiring the use of fixed medium networks to obtain a reliable connection. Alternatively, some sites have communication infrastructure in place to remotely access on-site servers. These sites typically impose strict security policies that do not allow installation of third-party communication hardware. A mobile router is the preferred device to standardise the communication interface of the supervisory system. However, it is unrealistic to assume that mobile network coverage and on-site security policies will allow the exclusive use of mobile routers.

Secure communication between the maintenance centre and on-site systems facilitates data transfer from, and remote access or control of remote EMSs. For security purposes a VPN or private APN connection is preferred. Fixed medium networks are the preferred alternative for areas without mobile network coverage because of their good reliability (Klink, 2003). The installation and service cost of these networks are, however, more expensive when compared to mobile networks.

The EMS remote access application allows maintenance personnel to view and control the EMS via the router or VPN connection. This secure connection facilitates virtual network computing (VNC) or remote desktop sessions, thus making remote control possible and allowing maintenance personnel to perform interactive diagnostics and maintenance remotely. To protect the privacy and to ensure the safety of the EMS accessed through this connection, on-site operators should be authorised to administrate remote access to the EMS server.

DMC

A reliable communication channel allows the DMC to receive secure data from the DMA automatically. The DMC processes and runs diagnostics on the data received from the DMA. The DMC is the central point of the supervisory system, connecting maintenance personnel to a growing number of remote EMSs. Figure 17 is a schematic representation of the DMC, showing the interconnectivity of all its relevant components. The DMC consists of coding modules to encapsulate functionalities that include:

- data integrity checking and processing;
- data diagnostics;
- report generation;
- maintenance management;
- e-mail handling;
- database communication; and
- user access management.

The DMC runs data integrity checks to identify data that is corrupt or incomplete. These checks ensure quality diagnostics based on complete and correct data sets. DMC diagnostics includes the on-site DMA, the physical EMS components, the EMS control philosophy and the resulting DSM performance. Furthermore, the DMC considers the result of specialised on-site diagnostics. Diagnostic results are stored in the DMC database, which is accessible via the Internet as shown in Figure 17.

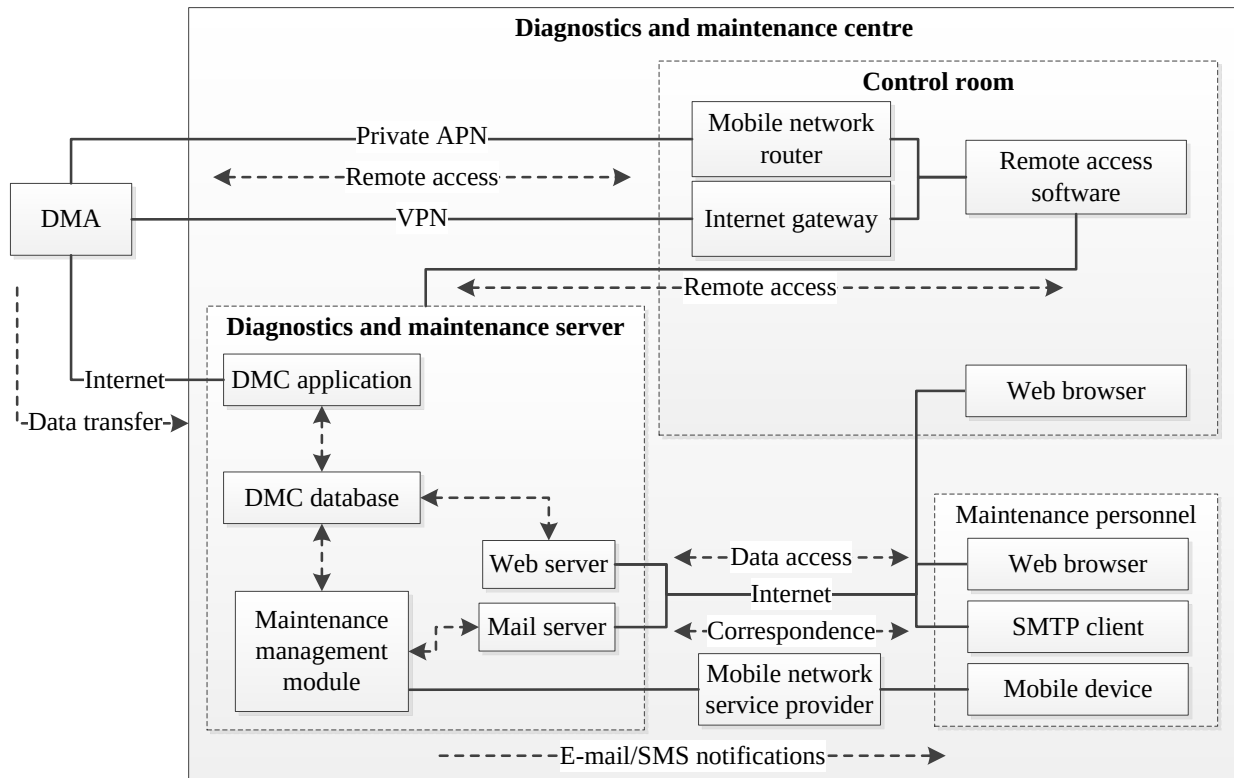


Figure 17: DMC operational schematic

The supervisory system automates the fault-detection process and provides maintenance personnel with diagnoses. An overview report provides maintenance personnel with high-level diagnostic information on all aspects that affect correct EMS operation. These reports highlight inconsistencies or malfunctions on all monitored applications, network connections, the EMS server and the control philosophy. The DMC also generates daily EMS performance reports providing maintenance personnel with detailed DSM performance figures.

In addition to the daily overview and reports, maintenance personnel receive e-mail notifications with the supervisory system's diagnoses of anomalies. Automated diagnoses typically initiate corrective maintenance. A web interface enables maintenance personnel to view detailed diagnostic information that is not present in reports. The DMC makes diagnostic information available online to assist authorised personnel to take the appropriate corrective action.

Finally, the DMC also drives the maintenance process to ensure prompt reaction to critical diagnoses. The maintenance management process starts by prompting maintenance personnel to initiate maintenance, but also ensures that the maintenance process receives the required attention. The DMC prompts maintenance personnel for progress feedback and conclusive details of the implemented solution. Section 3.5 discusses the maintenance management process in further detail.

A maintenance-focussed supervisory system optimises the efficiency of maintenance teams by automating repetitive tasks such as daily EMSs status and DSM performance assessments. Section 3.4 and Section 3.5 expand on the concepts of specialised diagnostic and maintenance management to ensure that the developed supervisory system offers a robust solution for the growing number of remote EMSs that employ a variety of EMS technologies with different DSM strategies.

3.4 Design for EMS diagnostics

Diagnostic algorithms are required to be adaptable to the differences between diverse EMS technologies with which the supervisory system integrates. Campos et al. (2002) highlight the importance of software components that are reusable regardless of the specific variation of the system that is being monitored or maintained. On-site diagnostics for specialised EMS hardware and control philosophies supplement generic EMS diagnostics. This accommodates diagnostics of diverse EMS technologies while maintaining a relatively simplistic design.

The main factors that cause an EMS to require maintenance include changes or failures to the EMS or the system controlled by the EMS. The EMS control philosophy could also become outdated, resulting in reduced performance despite actively maintaining the EMS components. Typical maintenance-requiring events that can be identified by monitoring the status of physical EMS components, performance and efficiency of the control philosophy execution include:

- network or OPC failure;
- EMS software failure or override;
- on-site communication software failure;
- on-site redundancy software failure;
- on-site remote access software failure;
- loss of communication with the site;
- data corruption;
- partial or complete data loss;
- control strategy inconsistencies; and
- human interference by control overrides.

EMS performance could, however, be influenced by external factors. These factors include emergencies, reduced production or unfavourable circumstances that make effective energy management unrealistic, even with manual intervention. Information on external factors allows the supervisory system to assess the efficiency of the control philosophy more accurately.

In overview, Table 3 categorises EMS diagnostics into four distinct categories. Each category has a list of indicators that are measured against predefined criteria to obtain fault diagnoses. The DMC checks data integrity before performing diagnostics. The main indicators for the on-site supervisory system include DMA availability, SMTP accessibility and remote accessibility. Diagnostic algorithms compare these indicators to acceptable thresholds to arrive at the corresponding diagnoses shown in Table 3.

Table 3: EMS diagnostics overview

Category	Indicator	Criteria	Diagnosis
Supervisory system	DMA availability	Below threshold	DMA availability low
	SMTP accessibility	Below threshold	SMTP availability low
	Remote accessibility	Below threshold	Access availability low
EMS	EMS platform availability	Below threshold	EMS availability low
	OPC availability	Below threshold	OPC availability low
	EMS operation mode	Below threshold	Control availability low
	EMS version	Occurrence	Updates required
	Supportive applications	Below threshold	Supportive availability low
Control philosophy	Performance	Out of range	Irregular performance
	Power profile	Out of range	Irregular power profile
	EMS specific	Occurrence	Custom message
Personnel input	External factors	Occurrence	Custom message

The EMS platform makes data available to the DMA regarding its version, mode of operation and OPC connectivity with the SCADA system. From the DMA log files, the DMC calculates the operational availability of the EMS platform and supportive applications. Table 2 listed the additional information collected by the DMA for both the EMS platform and supportive applications.

A diagnostic database increases the efficiency of the maintenance effort. The DMC diagnostic database holds diagnostic patterns for commonly occurring EMS anomalies. Diagnostic patterns link to suggested solutions for associated anomalies. This enables the supervisory system to provide maintenance personnel with a suggested corrective action to address identified anomalies. Because most issues are common issues, a simple tree diagnostic approach as described by Blumberg (1982), Minakawa et al. (1995) and Zhang et al. (2009) is sufficient for mine EMSs.

To mould the proposed supervisory system into a comprehensive remote diagnostic and maintenance solution, the supervisory system is designed to allow maintenance personnel to provide input on external factors that influence the performance of the EMS and its control philosophy indirectly.

EMS diagnostics

The supervisory system is required to identify data discontinuity because of complete EMS platform failure. It is critical to diagnose this data set with data loss instead of substituting these periods with zero values. In a situation where the OPC connection becomes faulty, the EMS could log zero or latched values until a connection reset. The supervisory system should automatically interpret periods of OPC failure as data discontinuity.

The graph in Figure 18 shows a power profile with an extended period of zero values from 07:00 to 14:00. Baseline scaling compensates for production variations before calculating EMS performance as discussed in Section 1.2. Suppose the production period for the system controlled by this EMS occurs between 8:00 and 12:00. A production indicator such as flow or pressure typically determines the scaling factor based on the data captured during the production period.

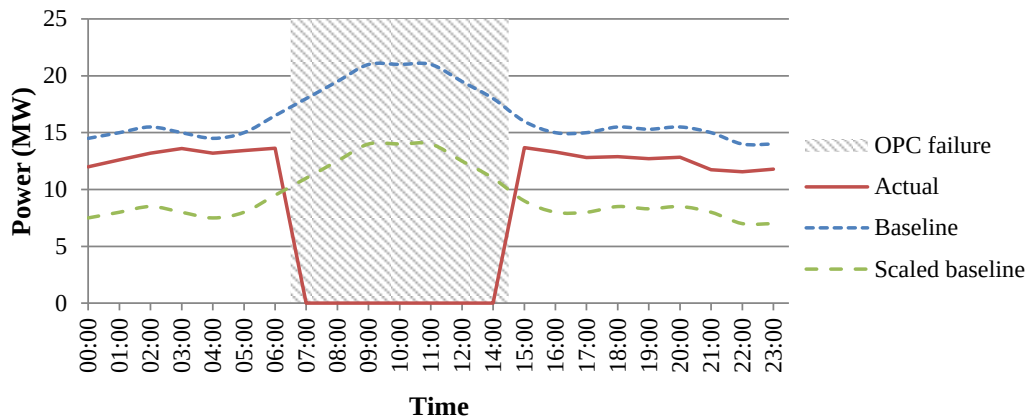


Figure 18: Effect of zero values on scaling (Du Plessis, J.N. et al., 2013)

The zero-value period will result in a low scaling factor, which influences DSM performance calculations. The electrical energy efficiency for this scenario will likely be negative, because the performance calculation compares the actual power usage to the unrealistically scaled baseline. This shows the importance of automatically identifying both data discontinuity and OPC suspension.

It is also possible that the OPC connection malfunctions and latches all values at the previous live values. This inherently qualifies as data discontinuity, but is more difficult to diagnose when there is no adverse effect on the calculated DSM performance, as was the case in the previous scenario. Figure 19 illustrates that latched values could remain within the expected range for an extended period. The supervisory system is also required to identify this situation as data discontinuity.

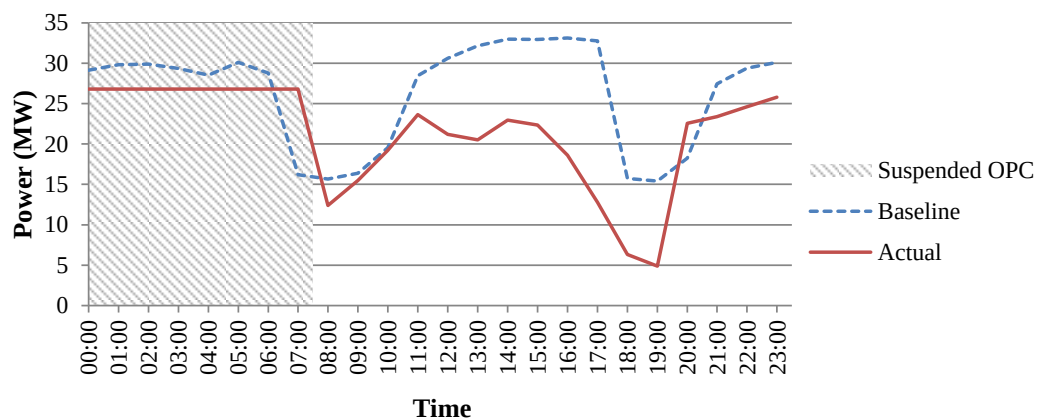


Figure 19: Unnoticed OPC malfunction (Du Plessis, J.N. et al., 2013)

Data logged by the DMA is analysed by the DMC to identify data discontinuity based on the number of data samples taken at constant intervals. The DMC uses the same method to calculate the operational availabilities of the EMS platform, its mode of operation and supportive applications, such as redundancy and backup applications.

To improve the diagnosis of zero-value or latched-value logging due to OPC malfunction, the DMC uses a SCADA system heartbeat value, which the DMA monitors via the standard EMS interface. The supervisory system adjusts the EMS performance calculations to exclude minor data discontinuity. Excessive data discontinuity does, however, warrant disregarding the whole day's data. This is unavoidable and the only option when excessive data loss affects DSM performance calculations. The supervisory system notifies maintenance personnel of excessive data discontinuity to initiate corrective maintenance.

In addition to data discontinuity, the DMC uses the EMS mode of operation to identify extended periods of overridden operation that impairs automated EMS operation. This also impairs the execution of the control philosophy and potentially reduces EMS performance. The supervisory system notifies maintenance personnel of extended override periods to initiate correspondence with on-site operators regarding the benefits of automated EMS control.

Control philosophy diagnostics

The first two indicators listed under control philosophy diagnostics in Table 3 provide a generic assessment of the control philosophy, based on the 24-hour power consumption profile and the calculated EMS performance. The DMC calculates the electrical and financial performance of the remote EMS. The electrical impact of the EMS provides an indication of the correct execution of the control philosophy, while the financial impact is the main concern of the client. The supervisory system compares the calculated electrical performance with predefined limits and automatically diagnoses irregular performance.

EMS technologies implemented in the mining sector focus mainly on time-based energy reduction or shifts as discussed in Section 2.4. A generic method of performing a high-level analysis on the power profile of a specific control philosophy is defining a minimum- and maximum power profile that encloses the acceptable power consumption area for a specific EMS. The DMC compares the actual power profile with predefined limit profiles to diagnose an irregular power profile automatically.

To illustrate this concept Figure 20 shows a power profile of an energy efficiency EMS that violates the maximum profile limit from 15:00 to 18:00. The total electricity usage does not exceed the set limit, but the deviating power profile could indicate a faulty control philosophy.

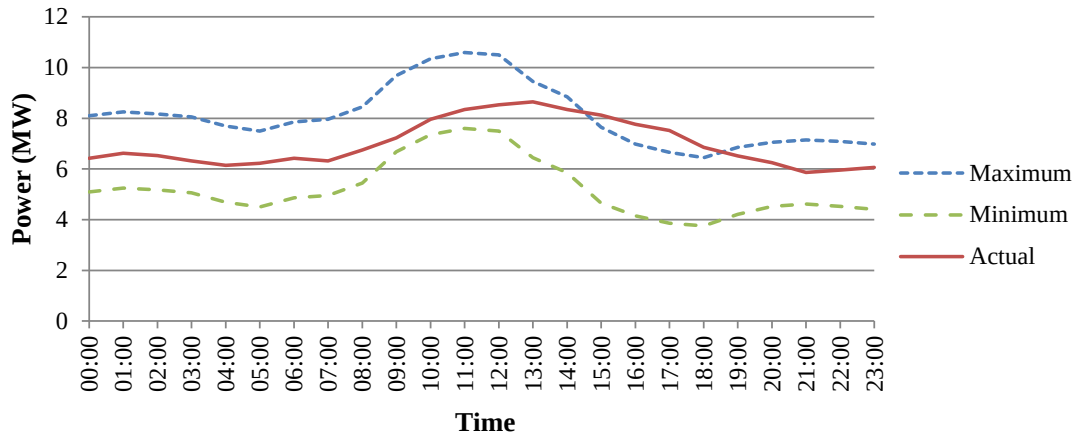


Figure 20: Limit profiles for power efficiency

To apply this illustration to a load-shifting EMS, Figure 21 shows a power profile with an insufficient evening load shift. In this scenario, the electrical EMS performance remains within limits. However, the fact that the profile does not conform to the required shape could once again indicate in ineffective control philosophy.

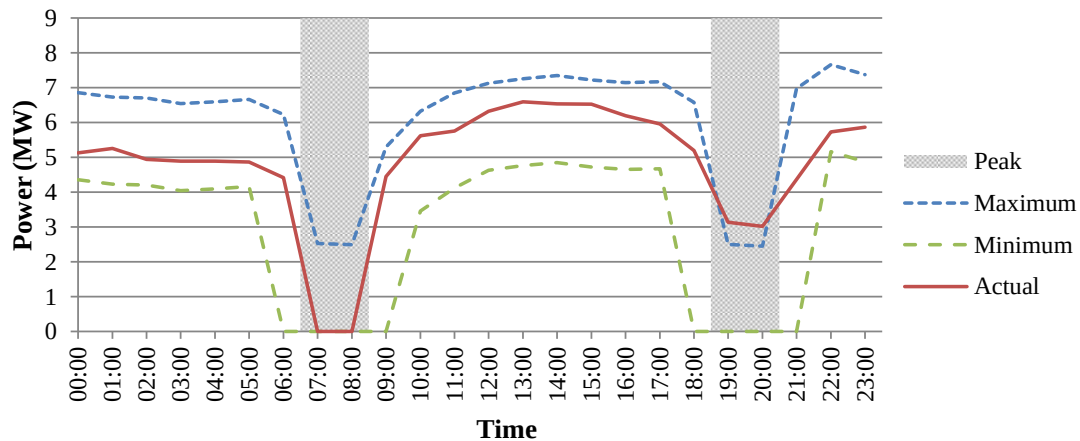


Figure 21: Limit profiles for load shifting

EMS performance and power profile limits provide a generic solution to assess the control philosophy on a high level, but the rate at which EMS technology develops makes it difficult to provide in-depth generic diagnostics. A supervisory system will not be able to replace the intuition that maintenance personnel develop over years of experience with EMS maintenance (Lee, 1997; Crapo et al., 2003).

Accordingly, the supervisory system processes customisable on-site algorithms for diagnostics that more accurately assesses the control philosophy of each EMS. Maintenance personnel use basic ‘if...else’

logic combined with condition-based monitoring to configure specialised on-site diagnostics. Table 4 summarises the configurable conditions used to assess measurements on-site, listing typical EMS diagnoses possible with each condition.

Table 4: Specialised EMS diagnostic conditions

Condition	Typical diagnosis
Change	OPC connection failure
	Faulty instrumentation
Equal	Control compromised
	Failed control actuation
Larger	Faulty measurement
	Safety risk
Smaller	Faulty instrumentation
	Safety risk
Between	Control compromised

The configuration of on-site diagnostics is customisable, allowing for endless combinations of ‘if...else’ and logic operators to diagnose events that require maintenance. Figure 22 shows a simplistic diagram that illustrates the configuration of on-site diagnostics. ‘If...else’ logic is applied to measurements that are represented as inputs in Figure 22.

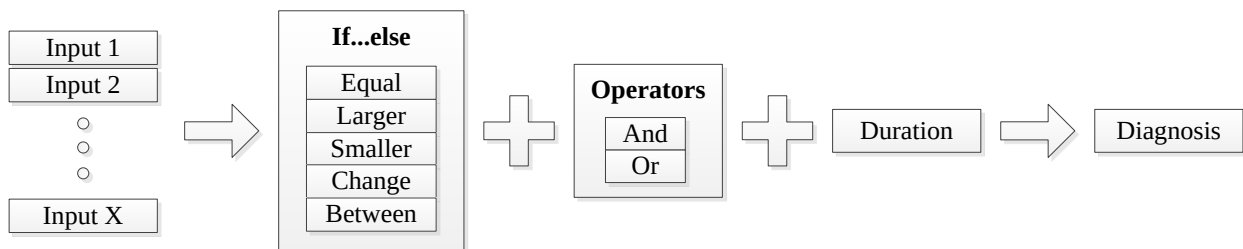


Figure 22: On-site diagnostic configuration

The conditions summarised in Table 4 are used together with ‘if...else’ logic. Mathematical operands allow for combinations or nested ‘if...else’ logic. Finally, a minimum duration is added to assess whether the condition or combination of conditions has been satisfied for a predefined minimum period.

Such configurable functionality enables maintenance personnel to set up customised on-site diagnostics that adhere to the diagnostic requirements of each EMS. This is the best solution to make the supervisory system truly efficient in diagnosing ineffective control philosophies of different EMS technologies that have different DSM objectives.

Diagnostic fingerprints

Based on the application of decision tree analysis by Blumberg (1982), Minakawa et al. (1995) and Zhang et al. (2009), diagnostic fingerprints are employed to represent known diagnostic patterns. A diagnostic fingerprint encapsulates a combination of diagnostic results or a single diagnostic pattern linked to a known diagnosis. This allows the supervisory system to link diagnostic results to a diagnosis, with corresponding suggestions for corrective maintenance.

Table 5 shows two examples of diagnostic fingerprints that link daily indicators to predefined diagnoses, with suggestions for corrective action. Both fingerprints consist of the status of EMS availability, mode of operation, performance and OPC connectivity. Each of these indicators has corresponding targets shown in Table 5. The fingerprints are constructed by comparing the indicator statuses with the corresponding targets.

Table 5: Example of diagnostic fingerprints

#	Indicator	Status	Target	Fingerprint	Diagnosis	Suggestion
1	EMS availability	100%	> 80%	1	Underperformance due to manual EMS operation	1. Assess reason for manual operation 2. Switch EMS to automatic operation
	OPC connectivity	90%	> 80%	1		
	Automatic operation	0%	> 80%	0		
	Performance	90%	> 80%	0		
2	EMS availability	100%	> 80%	1	Underperformance due to ineffective control philosophy	1. Check control philosophy 2. Check control permission
	OPC connectivity	90%	> 80%	1		
	Automatic operation	90%	> 80%	1		
	Performance	50%	> 80%	0		

The first fingerprint identifies an EMS that is underperforming due to manual operation. This diagnosis requires maintenance personnel to assess the reason for manual operation and encourage on-site operators to maintain optimal automatic EMS operation. The second example in Table 5 identifies an underperforming EMS despite complete automatic operation. The suggested corrective action is not as trivial as is the case with the first fingerprint, thus requiring maintenance personnel to perform manual diagnostics unless specialised on-site diagnostics provide a further diagnosis.

Diagnostic fingerprints provide an approach to analyse the physical EMS components and control philosophy concurrently. Additional fingerprints can diagnose issues with the on-site supervisory system. Incorporating diagnostic fingerprints ensures robust diagnostics through continuous addition of newly encountered diagnostic patterns. Section 4.4 provides further practical examples of typical EMS diagnostic fingerprints.

3.5 Design for maintenance management

Maintenance personnel are responsible for maintaining remote EMSs based on diagnoses from the supervisory system. After the detailed diagnostic process discussed in the previous section, the DMC generates a maintenance item for each identified anomaly. Each maintenance item holds information about specific anomalies including information such as the date, time, diagnostic information and suggested maintenance action. Figure 23 is a flow diagram that shows the first part of the maintenance management process that starts with the creation of the maintenance item.

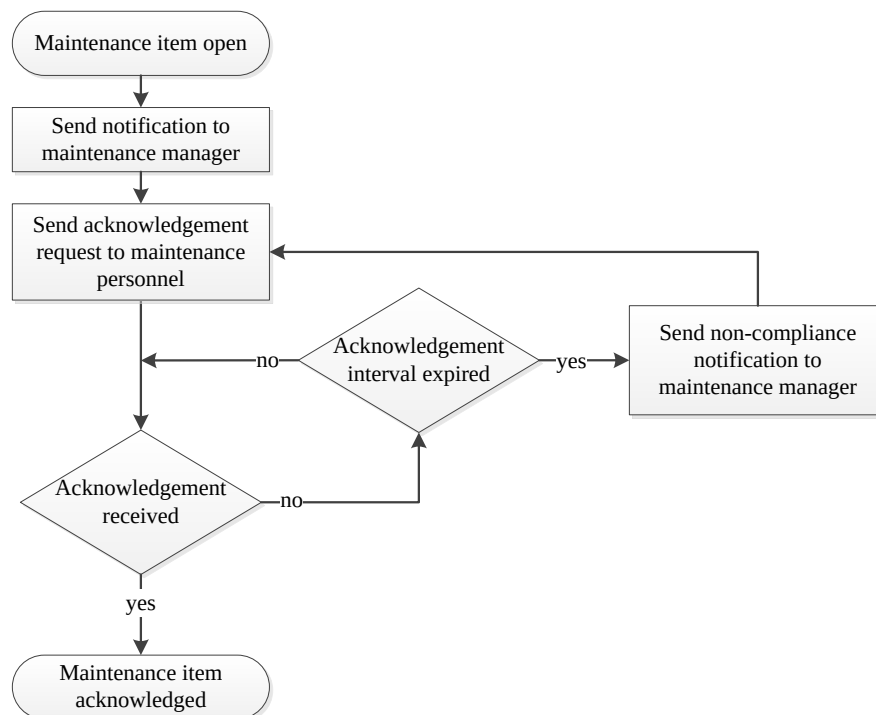


Figure 23: Maintenance item acknowledgement process

The DMC notifies relevant maintenance personnel of identified anomalies via e-mail and requests acknowledgement of receipt. The notification e-mail contains high-level diagnostic information to initiate corrective maintenance based on the results of automated diagnostics. To enforce prompt initiation and conclusion of corrective action, the DMC involves maintenance managers in the maintenance process by notifying them of created maintenance items. These notifications allow maintenance managers to remain informed about maintenance progress.

The DMC web interface allows maintenance personnel and managers to access maintenance items and to provide feedback. Maintenance personnel are allowed a predefined period to respond to this acknowledgement request. Failure to comply will result in the supervisory system prompting for

acknowledgement again, notifying the maintenance manager of the overdue response. The responsibility to initiate maintenance thus transfers to the maintenance manager.

Figure 24 is a flow diagram that shows the maintenance management process sustained by the DMC until the maintenance item is resolved. To ensure a closed feedback loop, the DMC requires maintenance personnel to provide periodic feedback on maintenance progress.

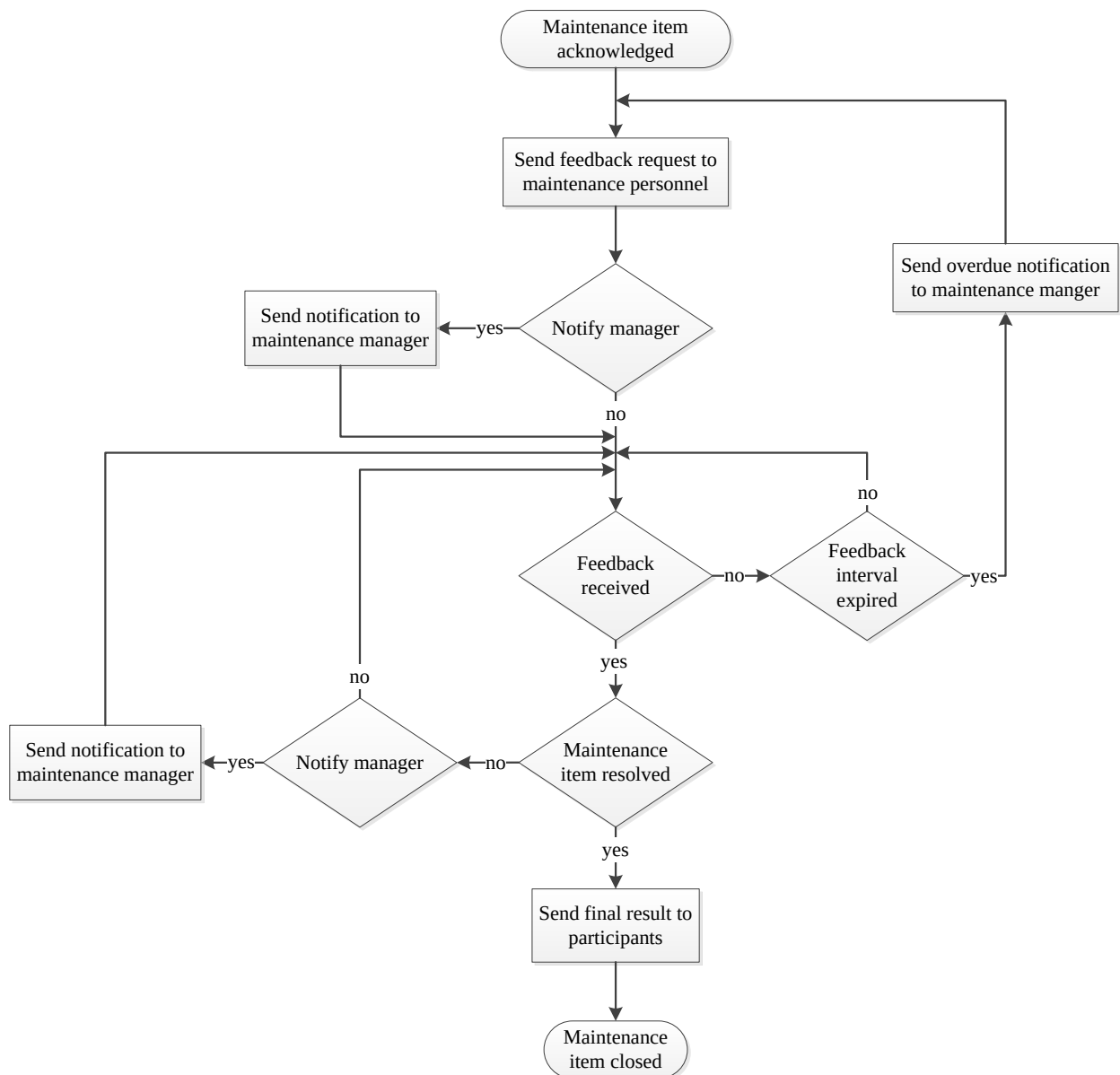


Figure 24: Maintenance management process

Maintenance managers have access to active maintenance items, making it possible for them to provide instructions to direct the maintenance effort. If the supervisory system does not receive correspondence from maintenance personnel, the maintenance manager is notified. When the maintenance item is resolved, the DMC sends relevant personnel a full summary of the maintenance process.

Depending on the size of the maintenance team and the number of maintained EMSs, the number of notifications could become overwhelming. To address this issue, the resolution of management notifications can be limited to notification of a diagnosed anomaly, overdue maintenance personnel feedback and maintenance completion.

Closed maintenance items remain in the DMC database, therefore providing a full history of anomalies and corresponding corrective action on each EMS monitored by the supervisory system. The detailed maintenance history enables maintenance personnel to identify new diagnostic fingerprints, and eases training of new maintenance personnel.

The supervisory system aims to provide diagnostic details and anomaly notifications to maintenance personnel to initiate prompt corrective maintenance. The responsibility for taking corrective action remains with maintenance personnel. If maintenance personnel take no action, the supervisory system involves the maintenance manager. The supervisory system optimises the management of the maintenance process by facilitating an active dialog from the time the issue is identified until it is resolved.

3.6 Conclusion

Designing a new supervisory system requires a broadened mind-set to ensure that the solution adheres to the requirements of existing EMS technologies and infrastructure. The EMS technologies that are compatible with the supervisory system have the same basic structure. This chapter described the development of a comprehensive supervisory system for mine EMSs, based on the requirements ascertained in Chapter 2.

The supervisory system consists of multiple on-site DMAs, a communication interface and a centralised DMC. The supervisory system design adheres to the restrictions and requirements of the DMA, the communication interface and the DMC. The DMA logs data for generic applications, network devices and the EMS server itself. In addition to this, the DMA logs OPC connection information directly from the EMS platform application. The interface with the EMS platform is standardised because all the considered EMS technologies are based on the same platform.

Mobile network routers facilitate communication between the DMA and the DMC, except on sites with fixed communication infrastructure in place, or unreliable mobile network coverage. A private APN connection is used with mobile network routers whereas a VPN connection is chosen for secure communication via fixed mediums. The communication interface is standardised using SMTP to facilitate reliable data transfer irrespective of communication medium.

Diagnostics algorithms are standardised for physical EMS components and DSM performance evaluation. The DMC remains adaptable to basic diagnostic requirements while allowing for specialised diagnostics through generic logic processing. Specialised EMS diagnostics is configurable on-site to cater for diagnostics of each unique control philosophy.

The modular design of the supervisory system ensures that it is adaptable enough to accommodate future change without redesign. This also ensures that the solution is scalable enough to accommodate an increasing number of remote EMSs.

CHAPTER 4. SUPERVISORY SYSTEM IMPLEMENTATION

4.1 Introduction

The previous chapters presented the transition from existing RDMS technologies research to the conceptual design of a new supervisory system capable of specialised EMS diagnostics. This system design ensures comprehensive diagnostics of the EMS components and the executed control philosophy to facilitate efficient maintenance that support sustained DSM performance.

As part of the initial system implementation, an emulated EMS was configured to assess the ease of integration with the developed supervisory system. This EMS consisted of a redundant server pair with an OPC simulator. In Chapter 3, the main variation in on-site DMA components was described to include the communication hardware – depending on mobile network coverage and on-site security policies. This system implementation used a mobile network router for data transmission and remote access.

Implementing the supervisory system on an emulated EMS provides an indication of whether the implementation process requires interruption in normal EMS operation. A simulated system implementation thus allows a safer viability assessment than implementing the developed system on an operational EMS.

4.2 Supervisory system implementation

The supervisory system implementation involved establishing a fully functional DMC. A local server emulated an on-site EMS with an OPC simulator representing a controllable mining system. The integration assessment involved installing a DMA on the emulated EMS server. Two mobile network routers – one at the emulated EMS and the other at the DMC – ensured secure communication between the DMA and the DMC via a private APN. The following subsections describe the DMC and DMA implementations.

DMC implementation

The DMC implementation started with the configuration of a local DMC server to host the DMC software and database. The server connected to the Internet through a gateway device, allowing it to receive incoming data and to send reports, notifications and maintenance management e-mails. This configuration also allowed access to the supervisory system web interface hosted on the DMC server.

If the DMC server goes offline due to a power interruption, no generic EMS diagnostics runs while the server is offline. However, specialised on-site EMS diagnostics and notifications will be unaffected in this event. An uninterrupted power supply (UPS) increased the reliability and availability of the DMC server. The DMC server, UPS and network switch installation is shown in Figure 25.

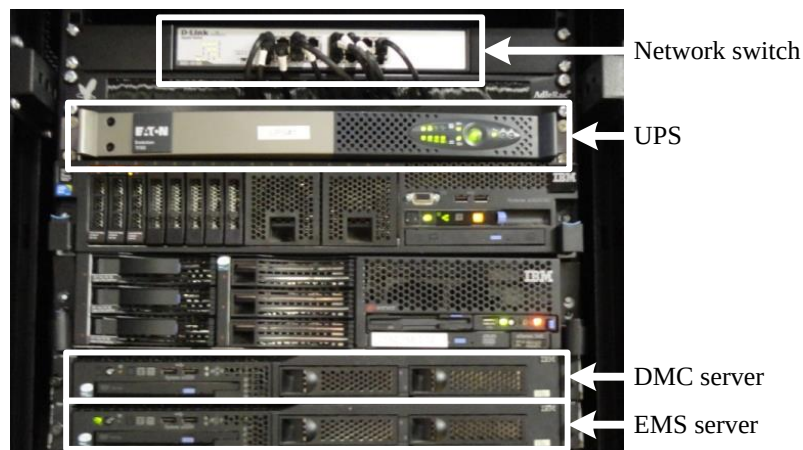


Figure 25: Supervisory system server and UPS installation

Not only does the DMC server receive EMS data to perform diagnostics, but it also handles all reporting and maintenance management via e-mail or web interface. Because of concerns about reliability and availability due to possible theft or long-lasting power interruptions, the server was migrated to a dedicated hosted environment after the initial implementation. The hosted solution also presented the added benefit of catering for system redundancy through an automated backup system.

A mobile network router established a secure communication channel between the DMC and the DMA installed on the emulated EMS. The router gains access to the mobile network through a registered SIM (subscriber identity module) card. This SIM card also has registered access to the Truteq private APN. Figure 26 shows the router installed at the DMC, which allows remote access and control of any connected EMS.



Figure 26: Emulated EMS mobile network router installation

Figure 27 shows the existing control room used to operate the DMC via a web interface. The control room computers have dedicated access to the private APN through the installed mobile network router. This router grants up to eight connected computers access to the private APN. As a security measure, control room computers connect to the local network hosted by the router exclusively.

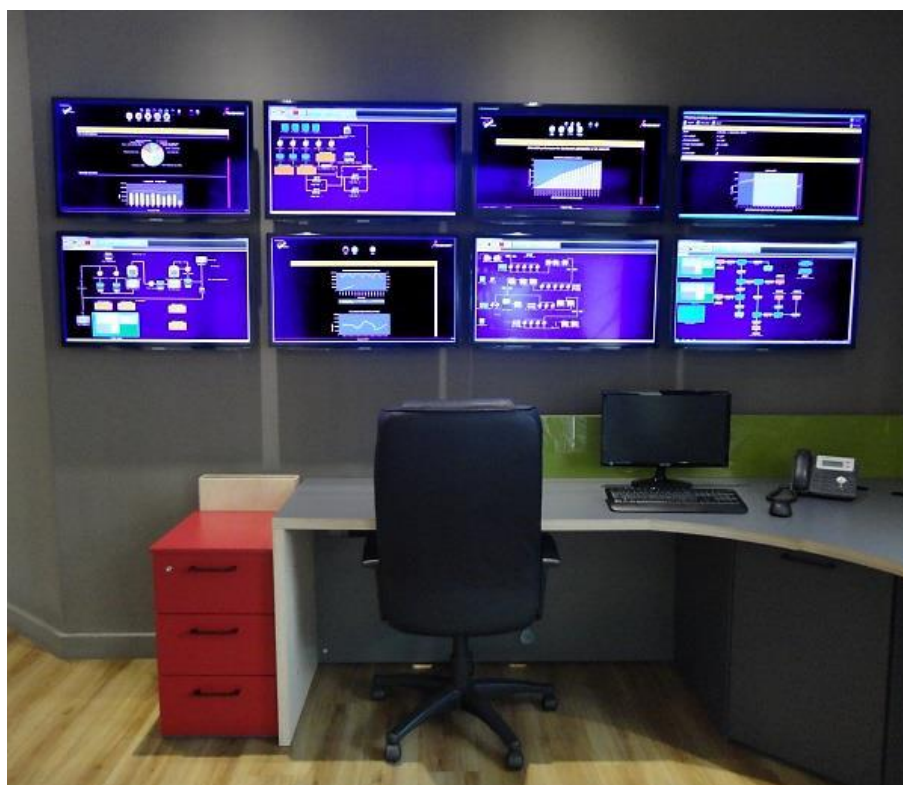


Figure 27: DMC control room

Incorporation of both a local Ethernet network and a private APN produces a geographically decentralised DMC that forms a conceptually centralised maintenance centre. The DMC server hosts the supervisory system database and web interface. The DMC employs MySQL database, HTML, CSS and JavaScript to produce a rich user interface. PHP classes encapsulate functionality that includes:

- database communication;
- user access management;
- e-mail handling;
- data processing and diagnostics;
- graph generation;
- report generation; and
- maintenance management.

The DMC provides a web interface that allows maintenance personnel decentralised access to diagnostic information on the EMS operational availability, control philosophy effectiveness and DSM performance.

The web-based GUI in Figure 28 shows the monthly overview screen of the emulated EMS. The grid shows a visual summary of the effective operational availability and performance of the emulated EMS. Each block in the grid is coloured green, red or grey. Grey blocks indicate that no data is available. Green blocks show sufficient EMS availability with acceptable DSM performance. Red blocks indicate unacceptable EMS availability, reduced performance, or a combination thereof.

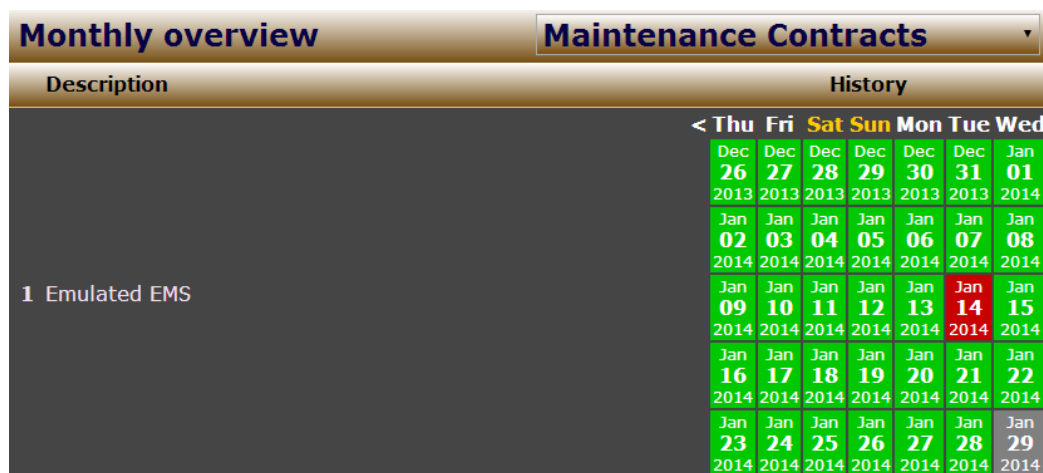


Figure 28: Weekly EMS overview screen

Figure 29 shows the daily overview of the emulated EMS in the form of availability percentages. The diagnostic overview screen provides the daily operational availability of all the EMSs and supportive applications integrated with the supervisory system. Daily percentages also provide an indication of the availability of OPC connectivity and automatic EMS operation.

Daily overview		Maintenance Contracts							
Date 2013-01-28		Performance	REMS	Auto	OPC	DMA	Access	Trans	Redund
Maintenance agreement									
1	Emulated EMS	138%	100%	98%	98%	100%	100%	100%	100%
2	Demonstration EMS 1	102%	-	-	-	-	-	-	-
3	Demonstration EMS 2	-1%	100%	-	-	100%	1%	100%	100%

Figure 29: Diagnostic overview screen

This is a high-level overview of all EMS statuses typically used by a maintenance manager. Managers also receive daily e-mails containing the EMS summary grid as shown in Figure 29. Each percentage block is coloured in green, red or grey making it easier for the user to interpret the provided information. Grey blocks indicate that no data is available. Green blocks show sufficient operational availability while red blocks indicate unacceptable operational availability.

DMA implementation

The configured DMA application monitored the Microsoft® Server operating system, applications running on it and network components. This application was developed in C# programming language to leverage the advantages of the object-oriented Microsoft® .NET Framework. As part of the initial implementation, the DMA was configured on the emulated EMS server with a unique site ID for identification purposes. The DMA monitored the emulated EMS platform and applications that enable redundancy, data transmission and remote access.

A mobile network router was installed on the emulated EMS server to facilitate secure data communication and remote access from the DMC via the Truteq private APN. The primary Ethernet port of the EMS server connected to a simulated OPC server. The secondary Ethernet port connected directly to one of the eight available Ethernet ports on the router. Operational EMSs use the same configuration, with the primary Ethernet port connected to the SCADA system as described in Section 2.4.

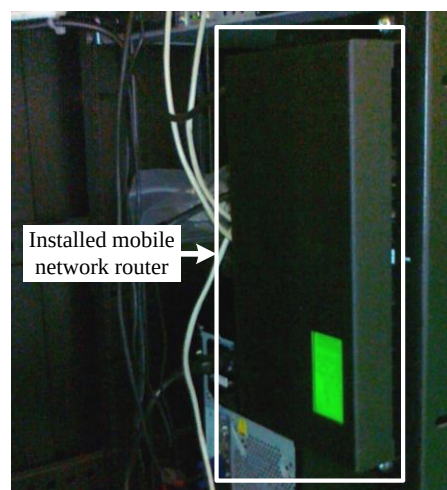


Figure 30: EMS mobile network router installation

The configured DMA monitored these network connections by running ping tests on the Internet protocol (IP) addresses of the OPC server, mobile network router and private APN SMTP server. Figure 31 shows a screenshot of the configured DMA, monitoring the operation of the EMS server, network connections, emulated EMS and supportive applications.

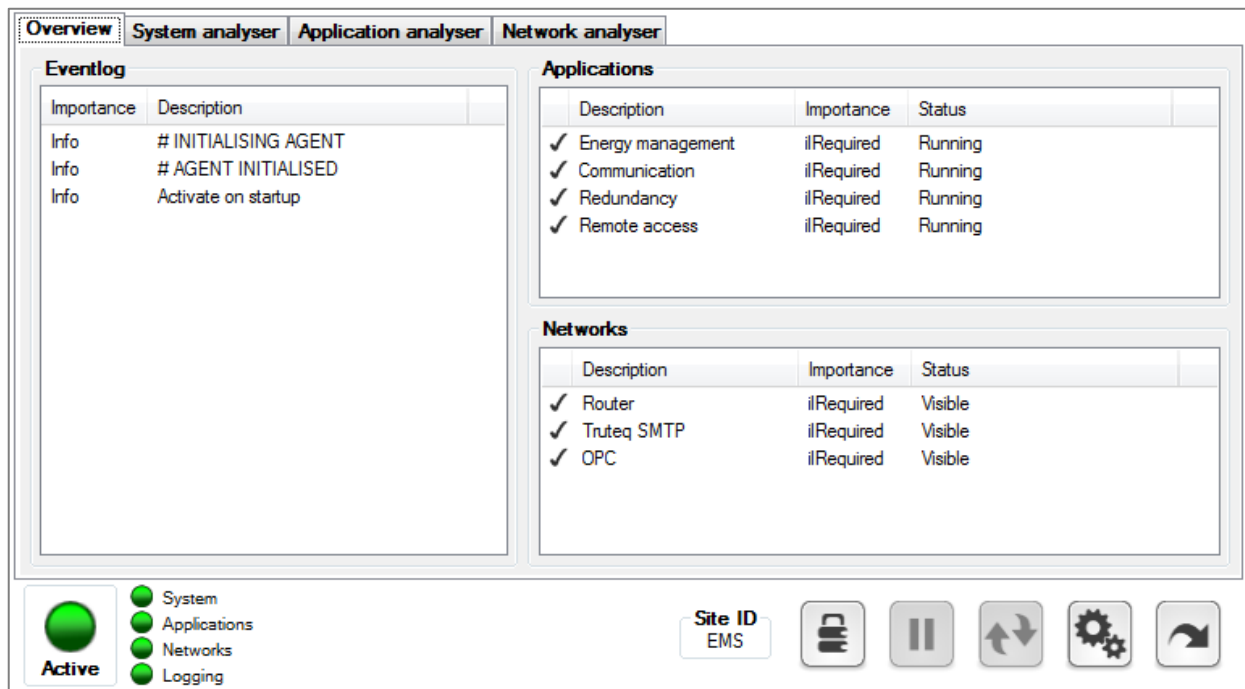


Figure 31: Screenshot of configured DMA application

The Overview tab shows the statuses of all monitored applications and network connections. The System Analyser, Application Analyser and Network Analyser tabs allow configuration of these respective analysers. After a specified period of user inactivity, the DMA automatically minimises to the Microsoft® Windows® system tray to run unnoticed.

The DMA stores the displayed data and additional data in comma separated values (CSV) format to minimise the size of data transmissions. The communication application transmits these CSV files as a compressed attachment in an e-mail. The private APN SMTP server relays the e-mail outside the private network to the DMC. Because of the variation in possible communication hardware, SMTP provides the most flexible solution for data transfer. SMTP is compatible with both private APN and VPN connections irrespective of the communication medium.

4.3 Functional verification

As part of the initial implementation, the developed system was verified against the development objectives set forth in Chapter 3. According to the International Organization for Standardization (ISO, 2005), the verification process aims to prove that the needs, requirements and specifications set forth are fulfilled before the developed system is accepted. The system verification involved measurement against critical criteria.

The list of critical criteria was adapted from the characteristics of existing RDMS technologies discussed in Section 2.4, taking into consideration EMS integration requirements. Table 6 summarises the results of the formal verification assessment. This table groups criteria according to categories that represent the four main elements of the supervisory system.

Table 6: System evaluation against verification criteria

Category	Criteria	Implementation
On-site system (DMA)	Interval logging	Ten-minute interval logging
	Event logging	Real-time event tracking
	Diagnostics	Specialised EMS diagnostics
Connection	Reliable mobile network	Two service providers with failover
	Security	Private APN access
	Safety	On-site authorisation for remote access
	Remote access and control	Remote desktop protocol or VNC
	Software update	Manual updates
Maintenance centre (DMC)	Data quality	Automated data integrity checking
	Maintenances team	DMC control room
	User input	Input on external factors affecting EMS performance
	EMS diagnostics	Performance calculation and generic diagnostics
	Knowledge base	Diagnostic fingerprints for known issues
	EMS model backup	Automated backup to DMC
Feedback	Periodic reports	Daily and monthly reports
	Maintenance suggestions	Daily overview of all EMSs
	Notifications	E-mail and SMS-based notifications
	Maintenance management	Automated notification and feedback requests

In Table 6 the Implementation column describes the real-world functionality that conforms to the corresponding criteria. Test cases verified all functionalities listed in Table 6. The outcome of the verification process showed that the supervisory system complied with the design requirements set forth in the Chapter 3 by conforming to all the criteria in Table 6. Section 4.4 and Section 4.5 discuss the verification of the diagnostics and maintenance management functionality in detail.

4.4 EMS diagnostics

The hardware configuration described in Section 4.2 initially excluded an EMS platform installation on the emulated EMS server. Originally, the supervisory system implementation only consisted of the DMA configuration without private APN access. The DMA started to log information on itself, the EMS server and network components. Table 7 is an extension of Table 2, showing the DMC diagnostic results of all the monitored components. The pre-implementation results showed no EMS platform or supporting applications installed, thus no further information was available on these applications.

Table 7: Results for generic EMS diagnostics

Diagnostic category	Diagnostic checks	Pre-implementation	Post-implementation
DMA	Version	1.1.6	
	Firewall exception	True	
	Availability	100%	
EMS server	Operating system	Microsoft® Windows® NT 6.1.7600.0	
	Uptime	1 day, 14 hours	4 days, 11 hours
	Username	Emulated EMS	
	Hostname	Emulated EMS	
	Firewall enabled	True	
	Remote desktop enabled	False	True
EMS platform	Installed	False	True
	Version	-	6.0.9
	Availability	-	100%
	Automatic operation	-	100%
	OPC connected	-	100%
Supporting software	Redundancy		
	Installed	False	True
	Version	-	3.0.0
	Availability	-	100%
	Data transfer		
	Installed	False	True
	Version	-	1.5.0
	Firewall exception	-	True
	Availability	-	100%
	Remote access		
	Installed	False	True
	Version	-	1.1.8
	Availability	-	100%
Networks	Network router access	0%	100%
	Private APN SMTP access	0%	100%
	OPC connectivity	100%	

After the EMS platform configuration and installation of the mobile network router, the DMC produced the post-implementation diagnostic results shown in Table 7. The DMA captured detailed information on all the EMS-related software and network connections. The post-implementation results in Table 7 cover the first full day of DMA operation after the complete EMS and DMA implementation.

Figure 32 shows a simulated power profile for a complete day. Simulated EMS platform and OPC connection failures induced data loss. The supervisory system correctly marked the data at 02:00 as data loss for both simulations, thus ignoring the expected minimum limit profile violation.

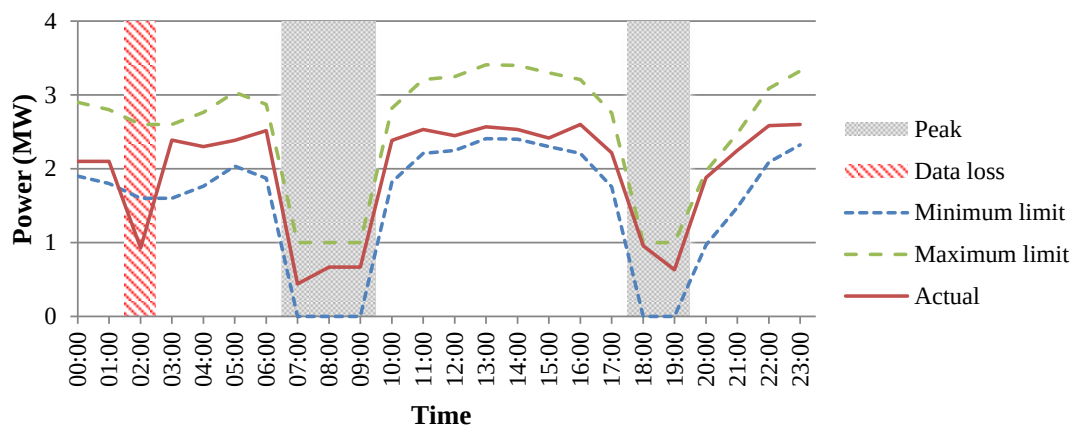


Figure 32: Example of data loss

The supervisory system excluded minor data loss from performance calculations. In situations of excessive data loss, however, the supervisory system deems the whole data set as corrupt and discards performance calculations for the specific day. If the DMC does not receive data for a specific day, the system creates a maintenance item that diagnoses complete data loss. The DMC then notifies maintenance personnel of this maintenance-requiring event.

Specialised diagnostics

Specialised control philosophy diagnostics described in Section 3.4 provide a customisable approach to allow on-site diagnostic configuration. The correct execution of these customisable diagnostics was verified by incrementally simulating circumstances that satisfied the conditions listed in Table 8.

Table 8 shows the five configurable diagnostic conditions. Each condition shows examples of a variable compared to a defined control value. These examples show that on-site diagnostics can produce a diagnosis based on a customised condition that is satisfied either instantaneously or for a predefined interval.

Table 8: Results for diagnostic condition verification

Condition	Variable	Compared to	Status	Occurrence	Diagnosis
Change	OPC heartbeat	Not applicable	False	Extended	OPC connection lost
	Measurement	Not applicable	False	Extended	Faulty instrumentation
Equal	EMS mode	Automatic	False	Extended	Control compromised
	Start/stop command	Machine status	False	Extended	Failed control actuation
Larger	Measurement	Defined value	True	Instantaneous	Faulty measurement
	Measurement	Defined value	True	Extended	Faulty instrumentation
	Measurement	Defined value	True	Extended	Safety risk
Smaller	Measurement	Defined value	True	Instantaneous	Faulty measurement
	Measurement	Defined value	True	Extended	Faulty instrumentation
	Measurement	Defined value	True	Extended	Safety risk
Between	Measurement	Set point	False	Extended	Control compromised

As mentioned in Section 3.4, ‘if...else’ logic forms part of the customisable on-site diagnostics. In combination with the conditions in Table 8, ‘if...else’ logic presents the opportunity for endless diagnostic permutations. Verification of the ‘if...else’ logic was limited to unit testing to ensure correct execution with any combination of conditions.

The emulated EMS simulation capability made it possible to generate power profiles expected from a load-shifting EMS. These profiles verified the correct execution of profile and total consumption maximum and minimum limits. Figure 33 shows the simulated power profile violating the maximum limits between 06:00 and 08:00. The supervisory system correctly identified this violation of the maximum limit profile resulting from delayed onset of the morning loaf shift.

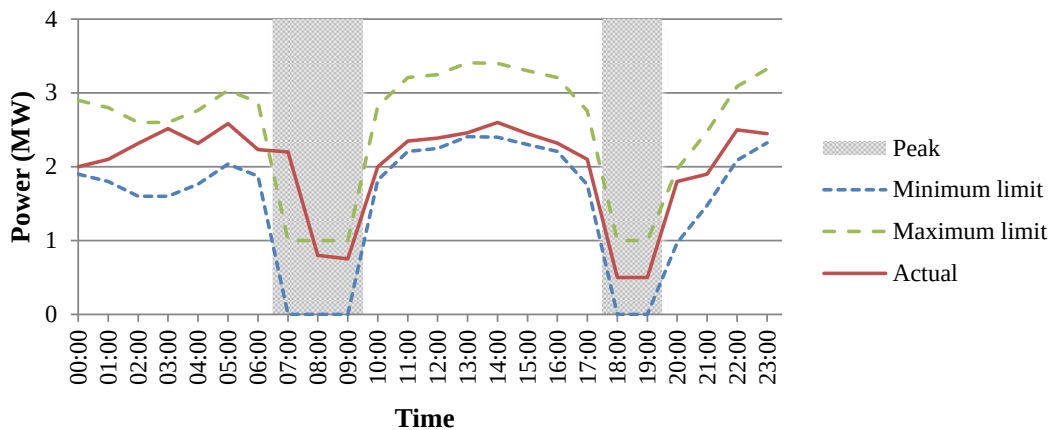


Figure 33: Example of maximum limit profile violation

The simulated power profile in Figure 34 shows a violation of the minimum power profile between 05:00 and 07:00. The supervisory system correctly identified this violation of the minimum limit profile.

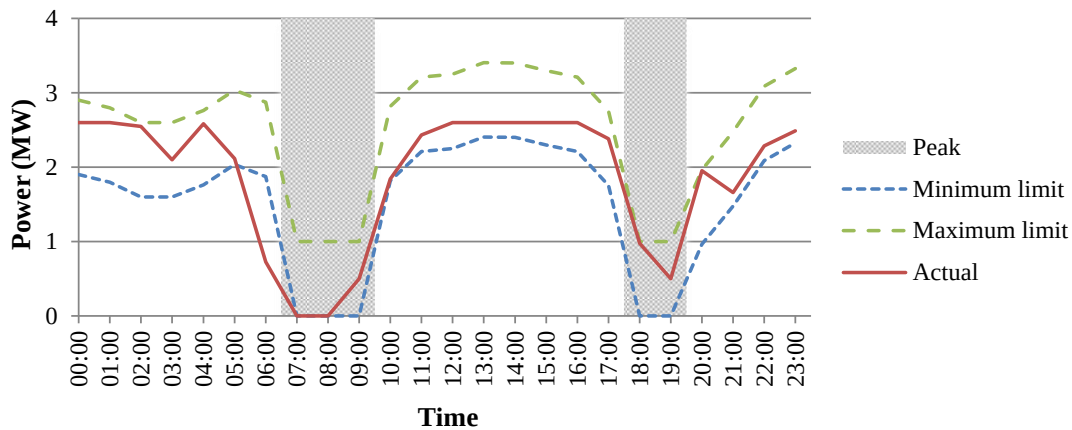


Figure 34: Example of minimum limit profile violation

The supervisory system also monitors the calculated EMS performance for excessive deviation from proposed performance figures. This deviation informs maintenance personnel of situations where the EMS performance is unrealistically high or low without just cause.

Diagnostic fingerprints

Diagnostic fingerprint examples were configured as part of this initial implementation. Table 9 lists these fingerprints and shows the suggested maintenance action linked to each fingerprint. A simulation of different scenarios verified the correct derivation of each fingerprint in Table 9, linking to the corresponding diagnosis and maintenance suggestion.

The first fingerprint template in Table 9 represents all combinations of fingerprints that start with one (1), indicating data loss of greater than 80%. Similarly, the second template includes all fingerprints that start with two zero values (00); not indicating data loss but rather reduced EMS operational availability. Maintenance suggestions for this diagnosis consist of ensuring that the EMS platform is running and that the server did not experience power interruptions.

The remaining fingerprint examples are all combinations that start with a zero and a one (01). All of these fingerprints automatically indicated an operational EMS and a complete data set. Additional diagnoses include low OPC connectivity, manual operation, irregular power profile and irregular performance calculation. All of these diagnoses have corresponding suggestions for corrective action as shown in Table 9.

Diagnostic fingerprints are customisable and can include additional diagnostic variables for highly customised diagnostics. The set of chosen variables cover the most common EMS issues and is sufficient to verify the correct function of fingerprint diagnostics execution.

Table 9: Results for maintenance suggestion verification

#	Fingerprint							Diagnosis	Maintenance suggestion(s)
	Data loss	EMS	OPC	Automatic	Performance		Profile violation		
	> 80 %	> 80 %	> 80 %	> 80 %	> 80 % < 150 %	< 0 % > 150 %			
1	1	?	?	?	?	?	?	Excessive data loss	Ensure EMS platform is running
2	0	0	?	?	?	?	?	Low EMS availability	Ensure EMS platform is running
									Check server uptime for power interruptions
3	0	1	0	?	?	?	?	Low OPC availability	Reinstate OPC connection
4	0	1	1	0	?	?	?	Manual operation	Switch EMS to automatic operation
5	0	1	1	1	1	0	0	None	None
6	0	1	1	1	1	0	1	Irregular power profile	Reassess control philosophy
7	0	1	1	1	?	1	0	Irregular performance	Reassess control philosophy
8	0	1	1	1	?	1	1		

4.5 Maintenance management

The DMA configuration ensures that all on-site diagnoses discussed in Section 4.4 are immediately relayed to the designated maintenance personnel via e-mail or SMS. These notifications initiate critical maintenance action immediately. Furthermore, the DMC uses generic and on-site diagnostic results to generate daily maintenance items as discussed in Section 3.5. These items initiate low priority maintenance action on a daily basis.

To verify the correct operation of the maintenance management module, all maintenance items generated during the verification process were configured for relay to designated maintenance personnel and managers. This configuration served to verify the relay mechanism and actuation of e-mail and SMS notifications using the mobile network router.

Each maintenance item has a generic structure with different diagnosis information, date, time and maintenance personnel feedback message. Maintenance items generated by the DMC during the diagnostics verification process mainly included these diagnoses:

- Low DMA availability (x%)
- Low SMTP availability (x%)
- Low remote access availability (x%)
- Low DMA availability (x%)
- Low EMS availability (x%)
- Low OPC availability (x%)
- Excessive manual operation (x%)
- Data loss (x%)
- No data received
- Minimum performance limit exceeded. Consumption: x MWh; Limit: y MW
- Maximum performance limit exceeded. Consumption: x MWh; Limit: y MW
- The minimum limit profile violated during hour(s): x, y, z...
- The maximum limit profile violated during hour(s): x, y, z...
- Software version with known issues identified: x

The web interface hosted by the DMC provides maintenance personnel access to automatically created maintenance items. This interface also allows maintenance personnel to create maintenance items based on manual diagnostics or external factors that are unknown to the supervisory system.

Figure 35 shows the basic maintenance management web-based GUI. The item selector at the top of this figure allows navigation between all maintenance items for the chosen EMS on a specific day. The GUI shows a diagnosis and suggested course of corrective action. User accounts restrict access to the GUI. Accounts held by maintenance personnel and managers are authorised to create new maintenance items and provide feedback relating to an existing item, until the item is closed.

Emulated EMS Back

Add Edit

Select item: 1. Reduced OPC availability (60 %) ▼

Suggestion: Reset OPC connection. Verify connection watchdog functionality. 2013-01-18 12:50 (DMC diagnostics)

Maintainer: A mine network failure occurred. The connection watchdog was enabled and tested. 2013-01-18 13:21 (Johan du Plessis)

Manager: This is an acceptable long-term solution. 2013-01-20 08:20 (John Smith)

Status: Closed

Figure 35: Issue resolution GUI

The supervisory system uses maintenance items to manage the efforts of maintenance personnel. The web-based GUI shown in Figure 36 provides detailed diagnostic information. This GUI provides a summary of the performance and operational availability of the selected EMS on a specific date.

Emulated EMS			
Performance			
Date:	18 January 2013		
Cost saving:	R 29,788		
Target:	2.50 MW		
Impact:	2.70 MW		
Electricity consumption:	125.35 MWh		
EMS diagnostics			
Component name	Detail	Importance	Operational
 DMA	1.1.11.0	Required	100%
Supporting applications			
 Data transmission	2.0.11.0	Required	100%
 Redundancy	2.0.1.0	Required	100%
 Remote access	1.1.8.1	Required	100%
EMS			
 Platform	6.3.0.1	Required	100%
 Control mode	Automatic	Required	53%
 OPC	ArchestrA.FSGateway	Required	98%
Remote access			
 Router	192.168.217.1	Required	100%
 Private APN SIM	10.123.1.162	Required	100%
 Private APN SMTP	10.124.0.3	Required	100%

Figure 36: Detailed diagnostic GUI

Further improving the capability of maintenance personnel to perform comprehensive maintenance, the DMC also provides information on all EMS and DMA software running on-site. Figure 37 shows the web-based GUI that gives maintenance personnel an overview of the installed software versions of all monitored EMSs. This GUI also shows the previously installed version and the last date the version information was updated.

On-site software overview				Maintenance Contracts	
Name	Site version	Previous version	Updated	Information	EMS platform
1 Emulated EMS	6.3.0.1	6.2.9.0	2013-01-18	Latest version	DMA Communication
4 Demonstration EMS 1	6.3.0.0	6.1.3.0	2013-01-18	Outdated	EMS platform Redundancy
3 Demonstration EMS 2	5.17.0.2	-	2013-01-18	Pump scheduling error	Remote access
2 Demonstration EMS 3				No data	

Figure 37: Detailed software version control GUI

Information on software versions and update history provide maintenance personnel with an indication of EMSs with outdated software, or more importantly identifies EMSs that run software with known coding errors. The expanded drop-down list in Figure 37 allows maintenance personnel to switch the overview between different applications installed on-site.

Coloured versions promote readability of this potentially large list of EMSs. Software versions are coloured green to indicate that the latest version is installed. Orange indicates outdated versions with known errors. Red indicates versions with known errors that require prompt upgrading. Grey is used to indicate that no version data is available.

The maintenance management module was verified to prompt corrective action, provide maintenance suggestions, direct maintenance personnel to detailed information and prompt periodic feedback with non-compliance notification to managers. This functionality effectively automates the maintenance management process.

4.6 Conclusion

This chapter presented the first implementation of the supervisory system as part of the system verification process. The implementation involved the commissioning of a local DMC server, later converted to a dedicated hosting environment for increased reliability and availability. Although the supervisory system web interface is available over the Internet, the established control room provided dedicated access to the web-based maintenance GUI. The DMC control room allowed maintenance personnel remote access to an emulated EMS using a mobile network router.

The emulated EMS was commissioned on a local server with a mobile network router to establish a secure private APN connection with the DMC. An OPC simulator effectively represented a SCADA machine controlling a virtual mining system. The configured DMA performed on-site monitoring and data collection on the emulated EMS platform, supporting software, network devices and the EMS server itself.

After implementation, the supervisory system was verified against critical criteria to prove that the implemented system conformed to the requirements for a comprehensive EMS supervisory system. This implementation proved the feasibility of implementing the designed supervisory system. The implementation not only served to validate the conceptual design, but it also created an incubation environment in which the supervisory system underwent scrutiny to accelerate the refinement process.

The developed supervisory system delivered the expected results, adhering to the design put forth in Chapter 3. Successful system verification led to the system validation through integration with operational mine EMSs, presented in Chapter 5.

CHAPTER 5. VALIDATION OF DEVELOPED SUPERVISORY SYSTEM

5.1 Introduction

Results obtained during the initial implementation in Chapter 4 provided an assessment of the capability of the developed supervisory system. Verification of the supervisory system showed conformance with the design set forth in Chapter 3. This inherently means that the supervisory system should be capable of addressing the need identified in Section 1.5.

In this chapter, three integration cases studies prove that the newly developed supervisory system is capable of sustaining the DSM performance of remote EMSs. The three EMSs chosen for the case studies perform energy management on water reticulation systems, cooling systems and compressed air systems respectively. The three EMSs execute control philosophies that achieve DSM electrical load shifting, energy efficiency and peak clipping respectively.

The validation process is intended to prove that the supervisory system fulfils the requirements that apply to operational EMSs (ISO, 2005). This chapter assesses the impact that the supervisory system has on the operational availability, control philosophy effectiveness and finally the performance of the EMSs chosen for the case studies. Seven additional EMS integrations extended the validation presented as part of the case studies.

Increased EMS performance results in reduced electricity cost that translates to reduced production cost. In addition to this, the developed system increases the efficiency of maintenance personnel, effectively reducing the cost of maintenance. The case studies served to verify that the supervisory system is capable of supporting sustained EMS performance and effective maintenance over time. This justifies financial investment for further implementation.

5.2 Case Study 1 – Water reticulation EMS

Introduction

Water reticulation systems are used in South African mines for processes that include cooling and powering hydraulic equipment such as drills, water cannons and spot coolers (Van Rensburg et al., 2011). Service water depends on gravity to supply underground levels with water from surface chilled water dams. Underground water typically gathers in settlers from where pumps transport it to clear water dams. The dewatering system pumps hot water out of the mine through dams on different underground levels.

Electrical energy efficiency on these large pumping systems is mostly not feasible without increasing the efficiency of the pumps itself, or by reducing the amount of water pumped out of the mine. The water reticulation system does, however, provide the opportunity to optimise dam levels before the Eskom evening peak period commences to minimise pumping during this time. This will result in a DSM load shift, which does not reduce the amount of electricity used by the dewatering system, but shifts the electricity consumption from the evening peak period to off-peak and standard periods of the day.

Potential cost savings are significant because mines are large electricity consumers and are typically billed according to the Eskom Megaflex Time-of-Use (TOU) tariff structure. The Megaflex tariff structure set forth in Eskom's Tariff & Charges booklet (Eskom, 2013) increases the average electricity costs from off-peak periods to standard periods and peak periods. Electricity tariffs increase by 228% from off-peak periods to peak periods during summer months, and by 608% during winter months.

Integration

As part of this case study, the supervisory system was integrated with an EMS that controlled the dewatering pumps at a gold mine. At this mine, underground water is pumped to the surface from four sets of dams on different levels, making use of three pumping stations. These underground pumping stations have a total installed electrical capacity of 7.6 MW. Annexure B provides additional information including a schematic of the EMS and water reticulation system.

A SCADA system allows the EMS to execute a control philosophy by starting and stopping pumps based on measured dam levels, while adhering to predefined constraints on the pumps. Optimised dam levels allow the EMS to reduce the number of pumps that run during the evening peak period. The EMS aims to reduce the electricity demand by 1.8 MW during the Eskom evening peak period.

Figure 38 shows the industrial EMS workstation pair mounted in a server cabinet located in the central control room. This EMS has been operational for a period of more than eight years, during which time the UPS became faulty. The mine was responsible for EMS maintenance for several years, during which time the DSM performance become erratic.

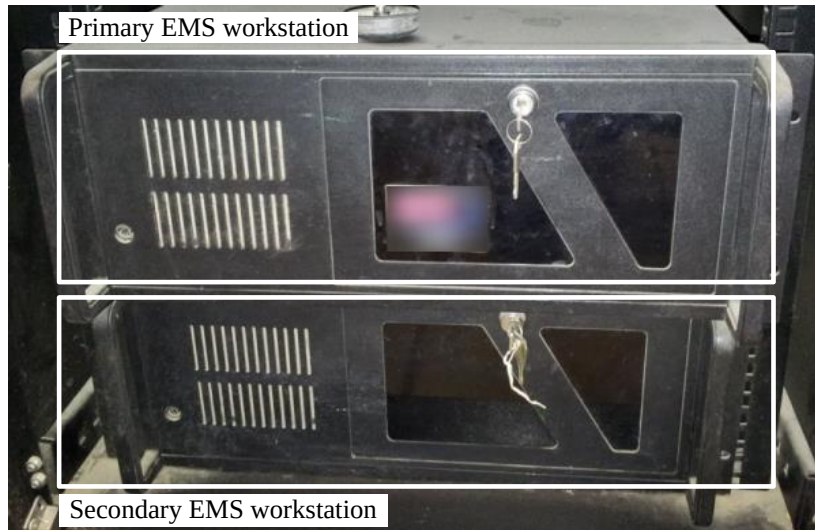


Figure 38: Case Study 1 – Industrial EMS workstations

Figure 39 shows the disorderly cabling inside the server cabinet, with the GPRS (general packet radio service) modem, and the network switch clearly marked. The GPRS modem connected to the primary workstation through a serial interface, with no plug-and-play capability. After a modem power failure, the workstation required a manual reboot before the connection with the modem could be re-established. This disruption impaired reliable automated data transmission without on-site human intervention.

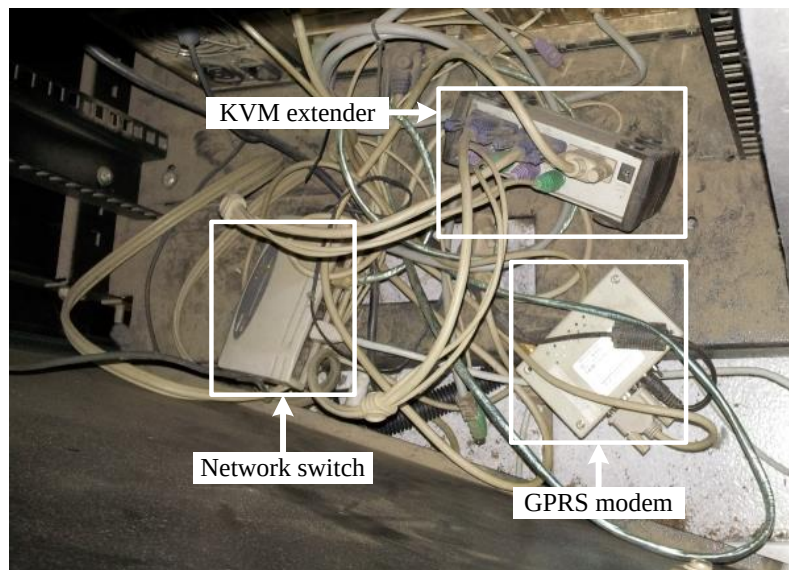


Figure 39: Case Study 1 – EMS cabling and communication hardware

Integration with this EMS involved the installation of a UPS, a DMA and a mobile network. A router replaced the unreliable GPRS modem. An EMS software upgrade made additional information available to the DMA as described in Section 3.2.

Operational availability

Before the supervisory system integration, the OPC connection was available 79% of the time. Without an OPC connection, the EMS is unable to control the pumps. During periods of OPC availability, however, intermittent incidents of manual EMS operation occurred. In manual operation mode, the EMS does not actuate the control schedule, but only makes control suggestions.

Interruptions in OPC connection and automatic operation resulted in an effective EMS availability of less than 75%. Figure 40 shows the operational availability of the main EMS components that are required to allow unimpaired execution of the control philosophy. These components include the EMS platform, OPC connection and automatic operation.

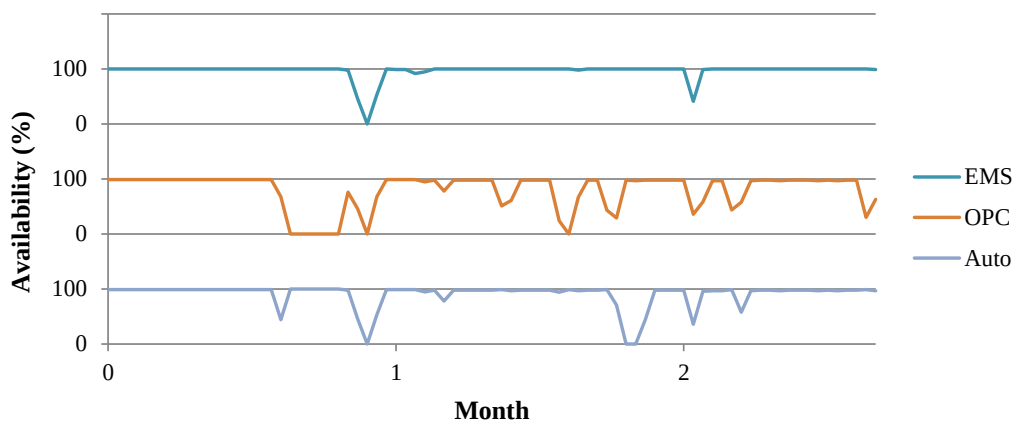


Figure 40: Case Study 1 – Pre-integration operational availability

Corrective maintenance during the integration stage reduced intermittent OPC failures. In addition to the EMS components shown in Figure 40, Figure 41 also shows the post-integration availability of the DMA application, remote access and access to the SMTP server. When compared with Figure 40, Figure 41 shows improved and reliable EMS operation over a period of six months.

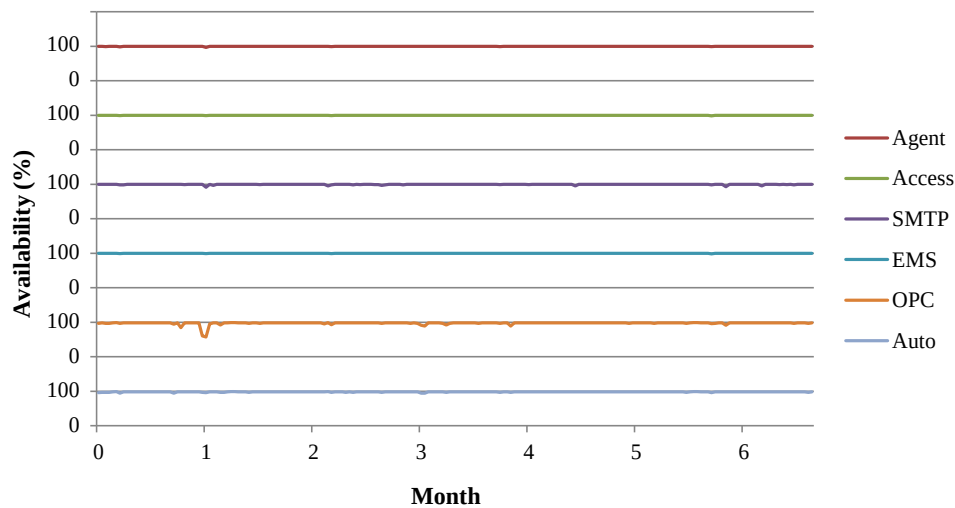


Figure 41: Case Study 1 – Post-integration operational availability

The supervisory system allowed maintenance personnel to reduce OPC connection problems on this long-running EMS. Availability of the OPC connection increased from 79% to 97%, maintained over a period of six months. Table 10 compares the average operational availability before and after the supervisory system integration.

Table 10: Case Study 1 – Operational availability summary

System	Item	Pre-integration availability (%)	Post-integration availability (%)
EMS	EMS	97	100
	OPC	79	97
	Automatic	90	98
Supervisory system	DMA	-	100
Access	Access	-	100
	SMTP	-	100
Overall EMS		75	97

The effective operational availability of the EMS increased from 75% before the supervisory system integration to 97% during the six-month period after integration.

Control philosophy

The main constraints on the pumping system are the availability of pumps, and minimum and maximum allowable dam levels. To maintain water balance, the pumping system must supply a sufficient quantity of water to the surface hot dam and cooling system. Specialised on-site diagnostics was configured to assess factors that impair the capability of the EMS to execute the control philosophy correctly. These conditions include that the:

- communication to the SCADA system is maintained;
- communication to each pumping station is maintained;
- pumps are stopped and started according to the EMS schedule;
- pumps that are not in maintenance mode are available to be started or stopped;
- pumps are scheduled according to dam levels; and
- dam levels remain within safe limits.

The flow diagram in Figure 42 is a visual representation of the on-site diagnostic process, showing the events that trigger notification to maintenance personnel. The critical events identified during on-site diagnostics generate alarms that the data transmission application sends immediately, via e-mail or SMS. The DMA logs the occurrence of low priority diagnostic events for transmission with daily EMS data.

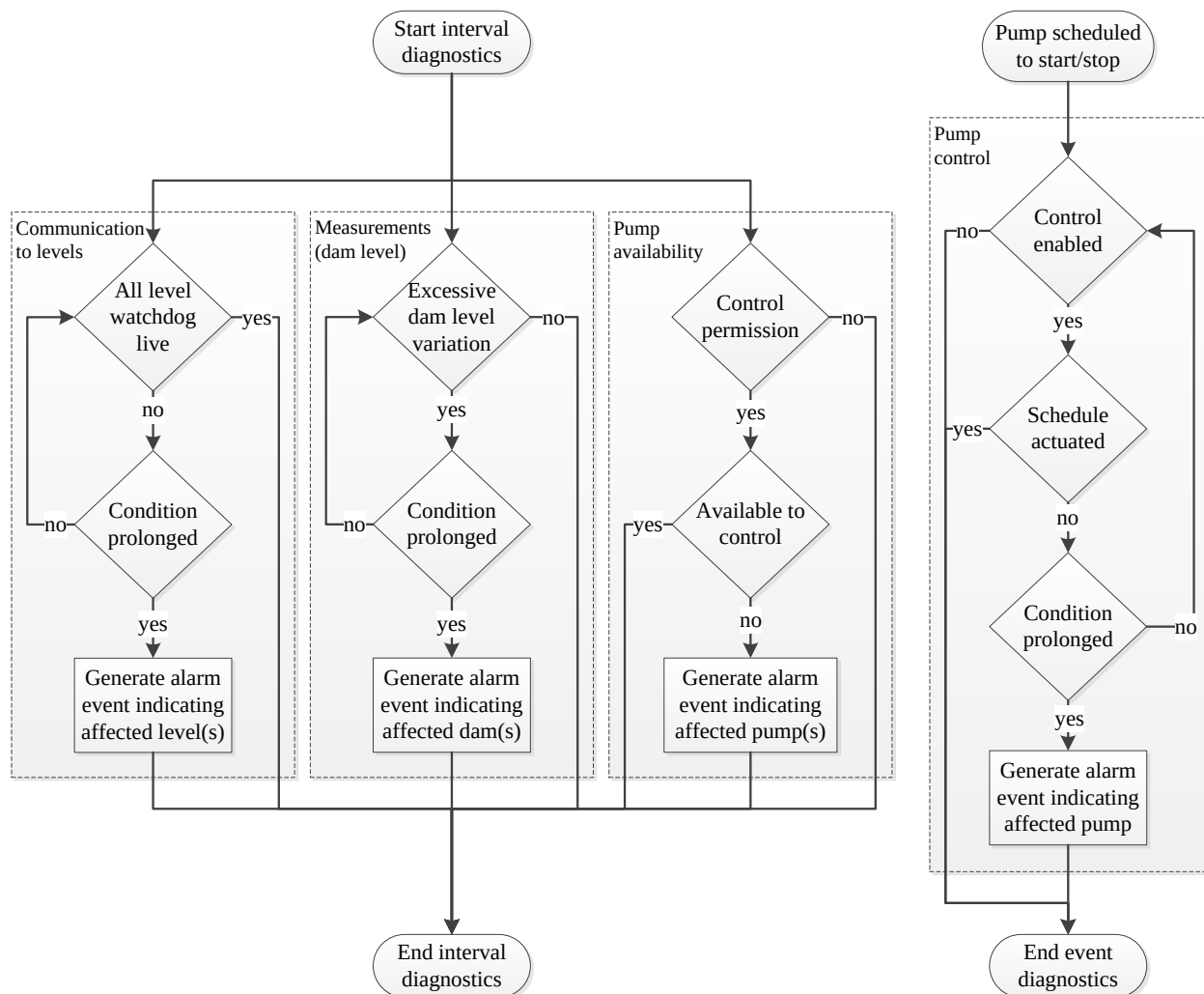


Figure 42: Case Study 1 – Specialised diagnostics flow diagram

Kilometres of fibre optic cable facilitate communication to underground levels. Interval diagnostics assesses the state of communication to each underground level. Diagnostics further evaluate dam level,

flow and pressure measurements for long-lasting violation of preset constraints. Interval diagnostics also verifies that all pumps are available for control according to the control philosophy. Event diagnostics generates a notification to instruct maintenance personnel to inspect a pump that does not react to an EMS control command within a reasonable time.

The supervisory system facilitated a decrease in the occurrence of mismatches between the number of running pumps and the number of pump scheduled by the EMS. Daily mismatch occurrences reduced by 25% after the supervisory system integration. This is due the specialised diagnostics in Figure 42 notifying maintenance personnel of prolonged mismatches, leading to prompt corrective action.

Many of these events resulted from the EMS providing an unrealistic schedule that prompted control philosophy optimisation. Figure 43 shows a comparison of the average occurrence of pump schedule violations between the three-month pre-integration and six-month post-integration periods.

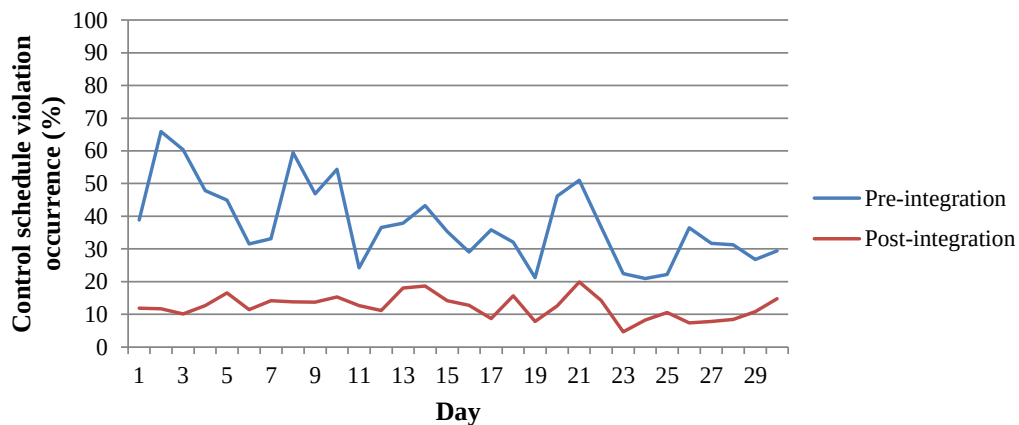


Figure 43: Case Study 1 – Daily average pumping schedule violation

The control philosophy of this EMS aims to increase pumping during the Eskom off-peak and standard periods by reducing pumping during peak periods. This load shifting is possible by defining less constrictive dam level constraints during peak periods. Table 17 in Annexure B summarises the dam level constraints and corresponding EMS control strategy.

To monitor the correct execution of the control philosophy on a high level, specialised diagnostics is configured to assess whether dam levels remain within preset constraints. These diagnostics compare measured dam levels to applicable dam level constraints. Figure 44 is a flow diagram of the diagnostic process that assesses the effectiveness of dam level control.

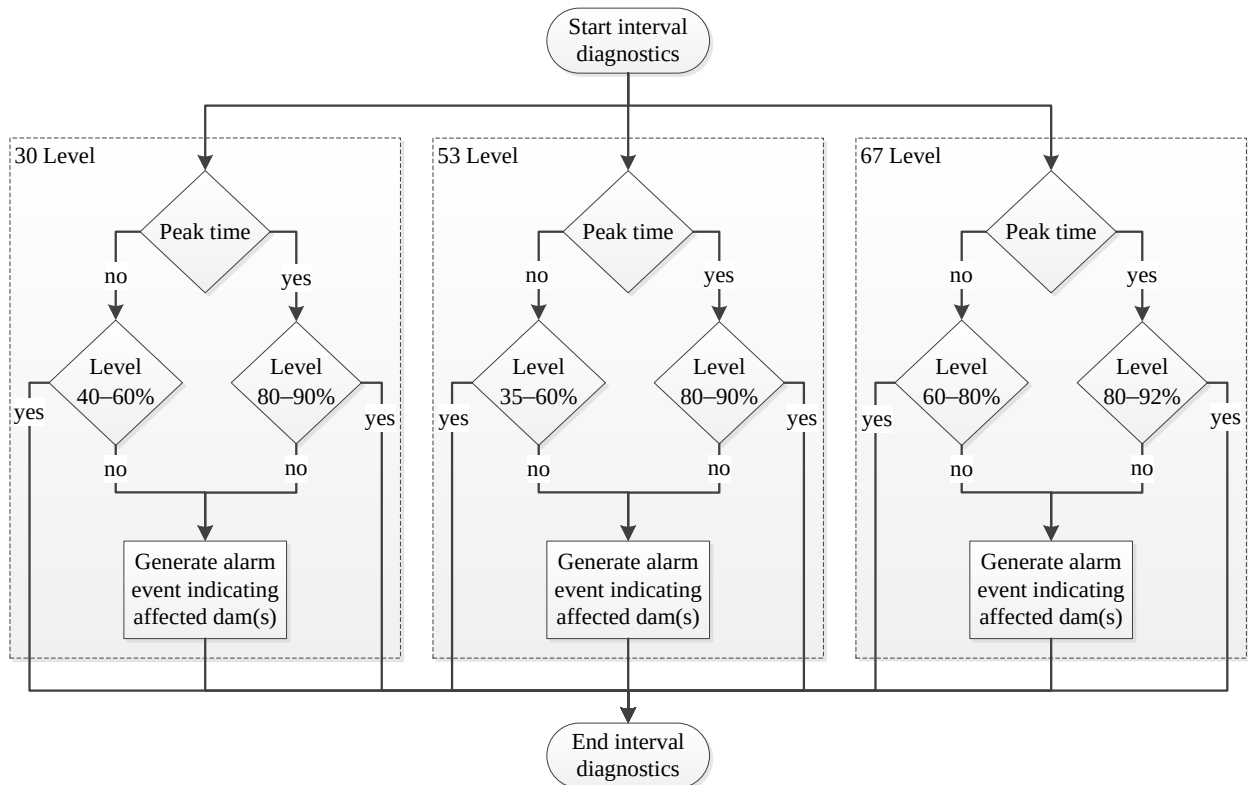


Figure 44: Case Study 1 – Dam level diagnostics flow diagram

Dam level diagnostics also ensures that mine personnel working underground are safe by identifying situations where dam levels violate safety constraints. When the supervisory system diagnoses these occurrences, it automatically notifies maintenance personnel and mine operators to override automatic EMS operation.

As a residual effect of increased operational availability and an optimised control philosophy, the EMS consistently produced a lower incidence of dam level violations over the six months after the supervisory system integration. Figure 45 shows a comparison of the average occurrence of dam level violations during the pre- and post-integration periods. Daily mismatch occurrence reduced by 9% after the supervisory system integration, reducing the risk of dams overflowing.

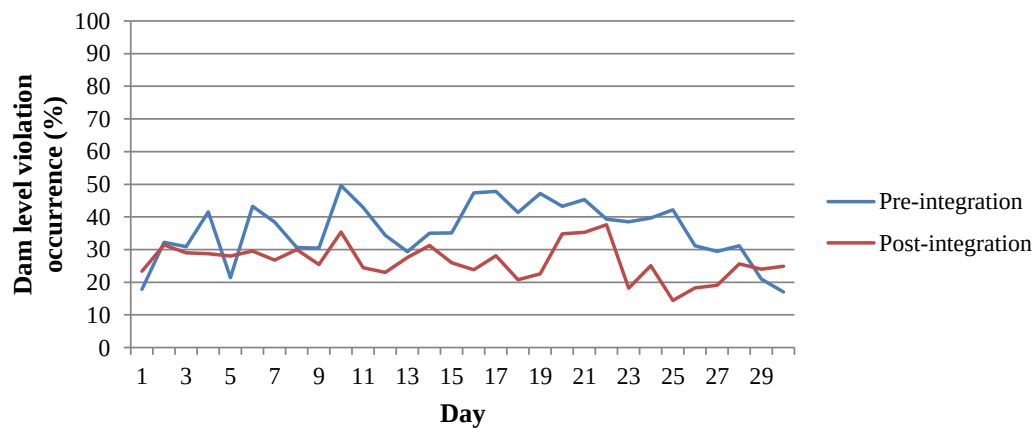


Figure 45: Case Study 1 – Average pre- and post-integration dam level violation

Although the supervisory system facilitated an overall EMS availability of 97%, on-site diagnostics identified circumstances that prevented the EMS from operating correctly. Technical errors made by operators that mistrusted the schedule of the EMS caused the majority of situations in which the EMS did not correctly execute the control philosophy. Annexure B provides two examples of this as illustrated in Figure 82 and Figure 83.

Situations like these inhibited EMS operation and resulted in unnecessary electricity cost. Control room operators were briefed on the control philosophy to allow them to understand the operation of the EMS. This increased their confidence in the EMS and reduced unnecessary overrides, allowing the EMS to execute the control philosophy more accurately.

Electrical performance

Prior to the supervisory system integration, the EMS performance was erratic due to unreliable OPC connectivity. The EMS produced an average load shift of 1.0 MW compared to the target of 1.8 MW. Figure 46 shows the EMS performance against the DSM target over the three-month period before supervisory system integration. These performance profiles exclude weekends because this EMS reduces electricity consumption during the Eskom evening peak period, which is not applicable over weekends.

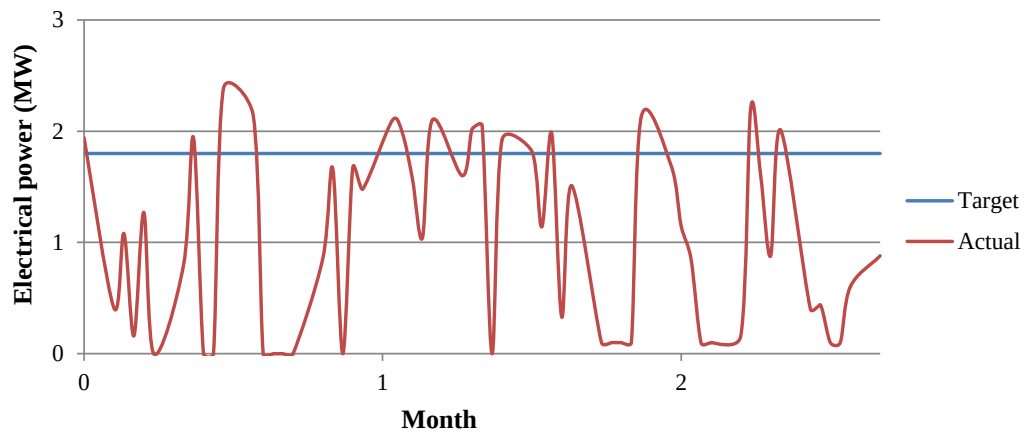


Figure 46: Case Study 1 – Pre-integration EMS performance

The supervisory system monitored the EMS performance over a six-month period. Figure 47 shows the post-integration performance profile. An additional adjusted profile shows the performance, taking into consideration data corruption and other condonable events automatically identified by the supervisory system, or manually logged by maintenance personnel.

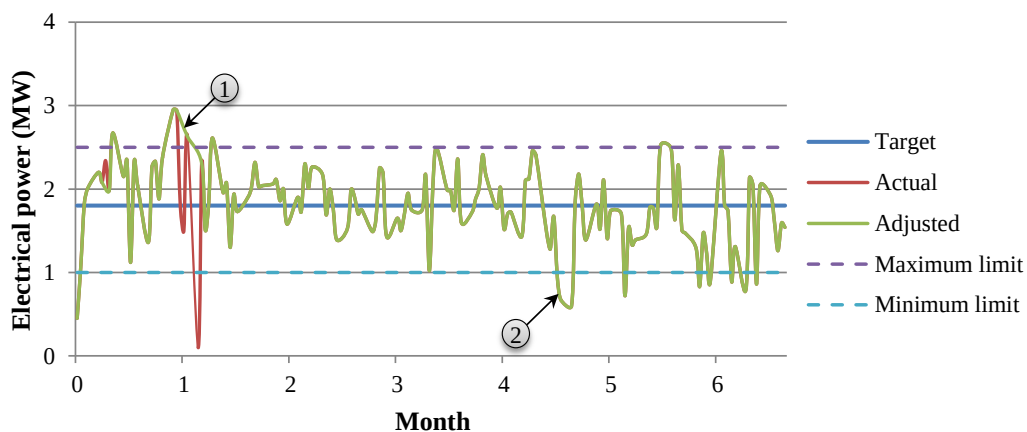


Figure 47: Case Study 1 – Post-integration EMS performance

The performance profile shows a fluctuating performance because the dams on different levels act as capacitors, each having an effect on the water reticulation system as a whole. Underground fissure water further destabilises the operation of the pumping system, because of unmeasured quantities of water flowing directly into underground dams. Maximum and minimum performance limits were used to identify unrealistic performance as discussed in Section 3.4. These limits remained unchanged throughout the six-month period as shown in Figure 47.

The OPC connection experienced intermittent connectivity interruptions resulting in reduced performance at Indicator 1 in Figure 47. These interruptions involved periods where all data from the SCADA system latched at the previous live values. This caused incorrect performance calculations that the supervisory

system marked as condonable, and adjusted the performance calculation accordingly as shown by the adjusted profile in Figure 47.

Attempts were made to optimise the control philosophy further by shifting pumping from standard periods to off-peak periods. Unfortunately, this caused erratic results during the evening peak period, as indicated by Indicator 2 in Figure 47.

The supervisory system assisted maintenance personnel to sustain the performance of this EMS over a period of six months, obtaining an average performance of 1.8 MW, thus meeting the 1.8 MW target. The post-integration EMS performance increased by 44% compared to the pre-integration performance of 1.0 MW, which resulted in an electricity cost reduction of approximately R392 000 after a six-month period.

5.3 Case Study 2 – Cooling EMS

Introduction

The cooling system of a deep level mine integrates with the water reticulation system. Cooling systems produce chilled process water to cool the underground working environment. According to Schutte (2007) cooling systems consume up to 25% of the total electricity used at deep level mines. The cooling system typically consists of auxiliaries such as:

- precooling pumps, fans and motors;
- evaporator pumps and motors;
- condenser pumps, fans and motors; and
- bulk air coolers (BAC) pumps, fans and motors.

Du Plessis, Liebenberg and Mathews (2013) used a case study to prove that a typical mine cooling system presents an opportunity for electrical energy efficiency. Optimised control of cooling auxiliaries reduced wasted cooling energy, while maintaining adequate service delivery.

Integration

The supervisory system was integrated with an EMS that regulates the temperature and flow of water through the cooling system, as presented by Du Plessis, Liebenberg, Mathews and Du Plessis (2013). An electrical energy reduction strategy developed by Du Plessis, Liebenberg and Mathews (2013) includes water flow control on the evaporators, condensers and BACs. Variable speed drives (VSDs) on the condenser pumps control the flow of water according to upstream dam levels.

An EMS server controls the cooling auxiliaries via the SCADA system and PLC. Annexure C discusses the EMS and cooling system layout in more detail. The process of integrating the supervisory system with the EMS was similar to the process described in Case Study 1. Figure 48 shows the on-site server cabinet that houses the redundant EMS server pair and UPS to ensure reliable and uninterrupted EMS operation.

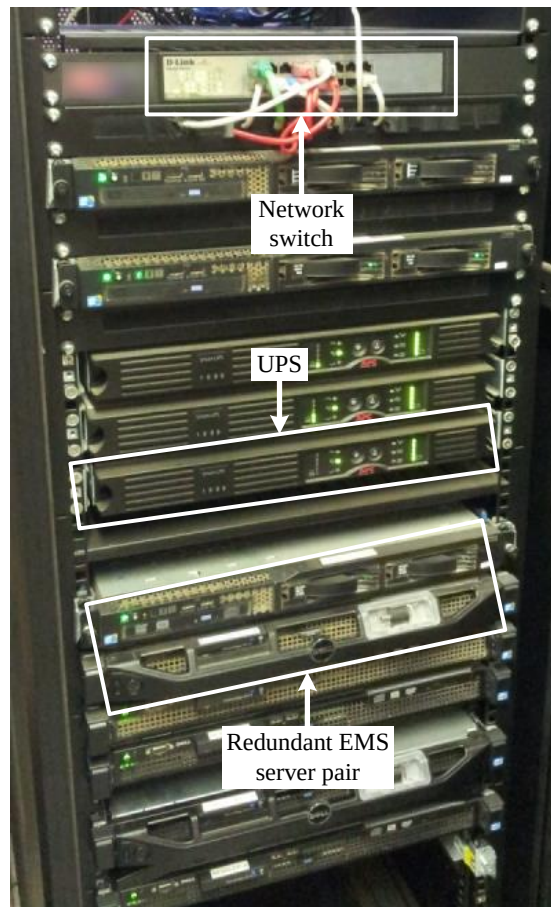


Figure 48: Case Study 2 – EMS server and UPS installation

The integration process involved installing and configuring the DMA application on the EMS servers. Figure 49 shows the DMA Overview tab after configuration. The Overview tab shows the statuses of the EMS application, supportive applications, router connectivity and SMTP accessibility. All applications were running responsively with full router and SMTP access, as shown in Figure 49.

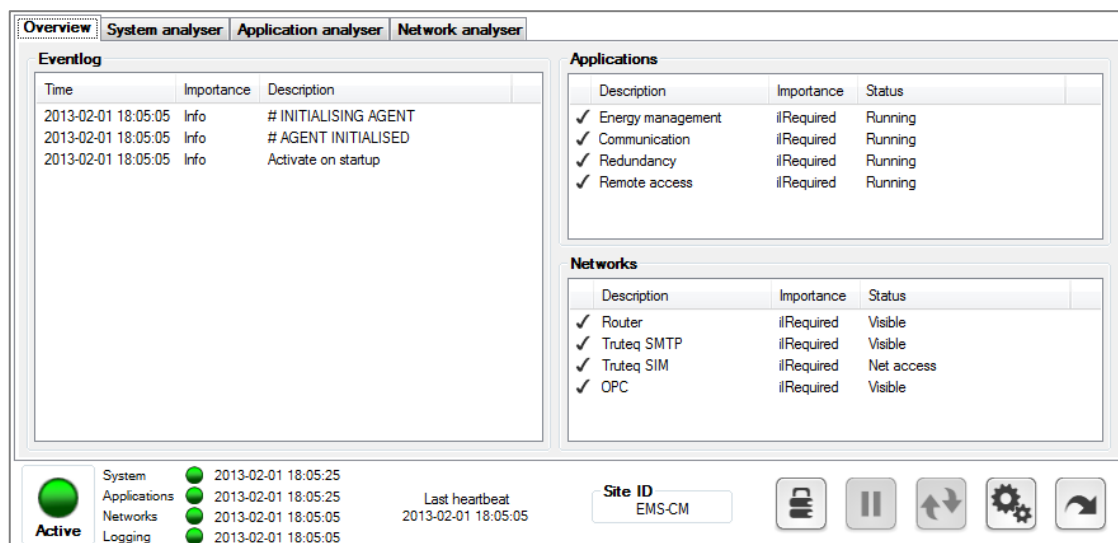


Figure 49: Case Study 2 – DMA Overview tab

The EMS was, however, implemented on the same mine as the EMS discussed in Case Study 1. The mobile network router installed as part of Case Study 1 has eight Ethernet ports, allowing the cooling system EMS access to the private APN, without installing an additional router.

Operational availability

Key EMS components such as the OPC connection, EMS software and automated operation showed high levels of availability due to active maintenance before the supervisory system integration. Figure 50 shows the operational availability of these components over a four-month period, before the supervisory system integration. The effective operational availability of the EMS was 98% during this period.

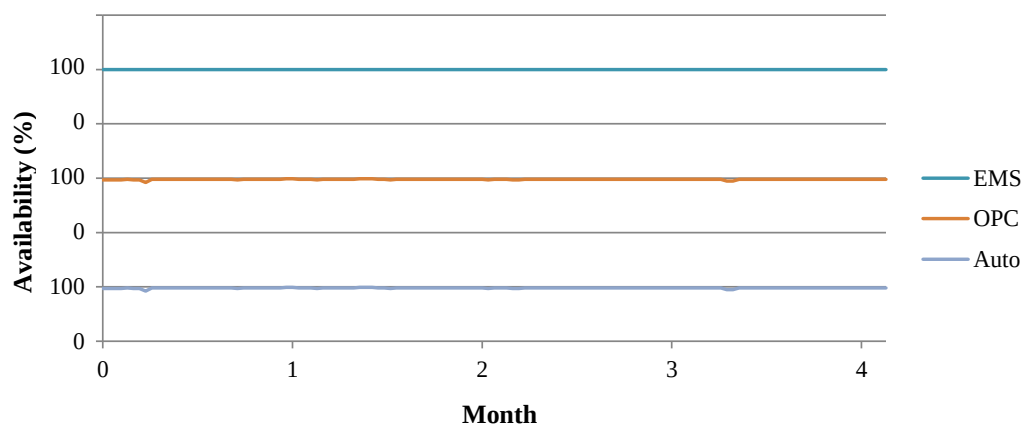


Figure 50: Case Study 2 – Pre-integration operational availability

Figure 51 shows the operational availability of key EMS and supervisory system components over a four-month post-integration period. The operational availability includes the availability of the DMA application, SMTP server connectivity and remote accessibility of the EMS.

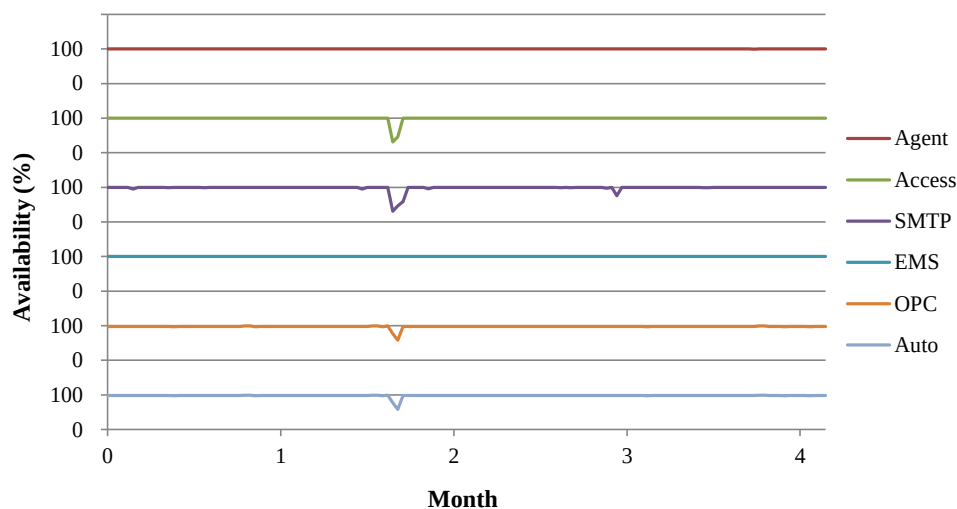


Figure 51: Case Study 2 – Post-integration operational availability

Towards the end of the second month, a localised network failure isolated the EMS server from the mine network. At 15:00 this network failure disrupted the OPC connection, SMTP connectivity and remote accessibility. On-site maintenance corrected this problem and restored EMS operation by 09:00 the following morning. On the following day, coincidental service provider maintenance caused the prolonged SMTP interruption. This interruption was unavoidable and delayed data transmission but did not disrupt the EMS or supervisory system operation.

The supervisory system enabled maintenance personnel to achieve an effective EMS operational availability of 98% over a four-month period. Table 11 shows a comparison of the operational availability before and after the supervisory system integration.

Table 11: Case Study 2 – Operational availability summary

System	Item	Pre-integration availability (%)	Post-integration availability (%)
EMS	EMS	100	100
	OPC	98	98
	Automatic	98	98
Supervisory system	DMA	-	100
Access	Access	-	99
	SMTP	-	99
Overall EMS		98	98

Maintenance personnel were able to rectify the majority of EMS issues via remote access, which ensured an acceptable EMS operational availability. The overall operational availability of the EMS was maintained at 98%; an expected result because the EMS was maintained before the supervisory system integration.

Control philosophy

The EMS controls VSDs and valves to maintain a specified BAC dam level set point. EMS control further regulates BAC water inlet valves according to the ambient air enthalpy. A control philosophy encapsulates this strategy, allowing the EMS to reduce the daily average electricity demand by 1.6 MW, resulting in electrical energy efficiency.

The findings of Du Plessis, Liebenberg and Mathews (2013) indicate that the main concerns with the control of these cooling auxiliaries are service delivery and system efficiency. These concerns require the EMS to ensure optimal availability of chilled water at the correct temperature to maintain a safe underground working environment.

Additionally, the EMS prioritises efficient operation of the cooling system above electrical cost reduction because reduced system efficiency could result in increased cost of maintenance. Factors that the supervisory system typically needs to evaluate include:

- realistic ambient air enthalpy;
- realistic pressure and flow measurements;
- acceptable service water temperatures;
- coefficient of performance (COP) of refrigeration machines and the integrated system;
- VSDs adjust speed according to flow set points; and
- valves are actuated according to flow set points.

Figure 52 is a flow diagram of the specialised on-site diagnostic process. Interval diagnostics establishes whether all measurements are reliable to ensure correct control decisions. Diagnostics assess the control permission and availability of VSDs and control valves to identify impaired control philosophy execution. Furthermore, the diagnostic process assesses the correct actuation of control instructions according to the control philosophy.

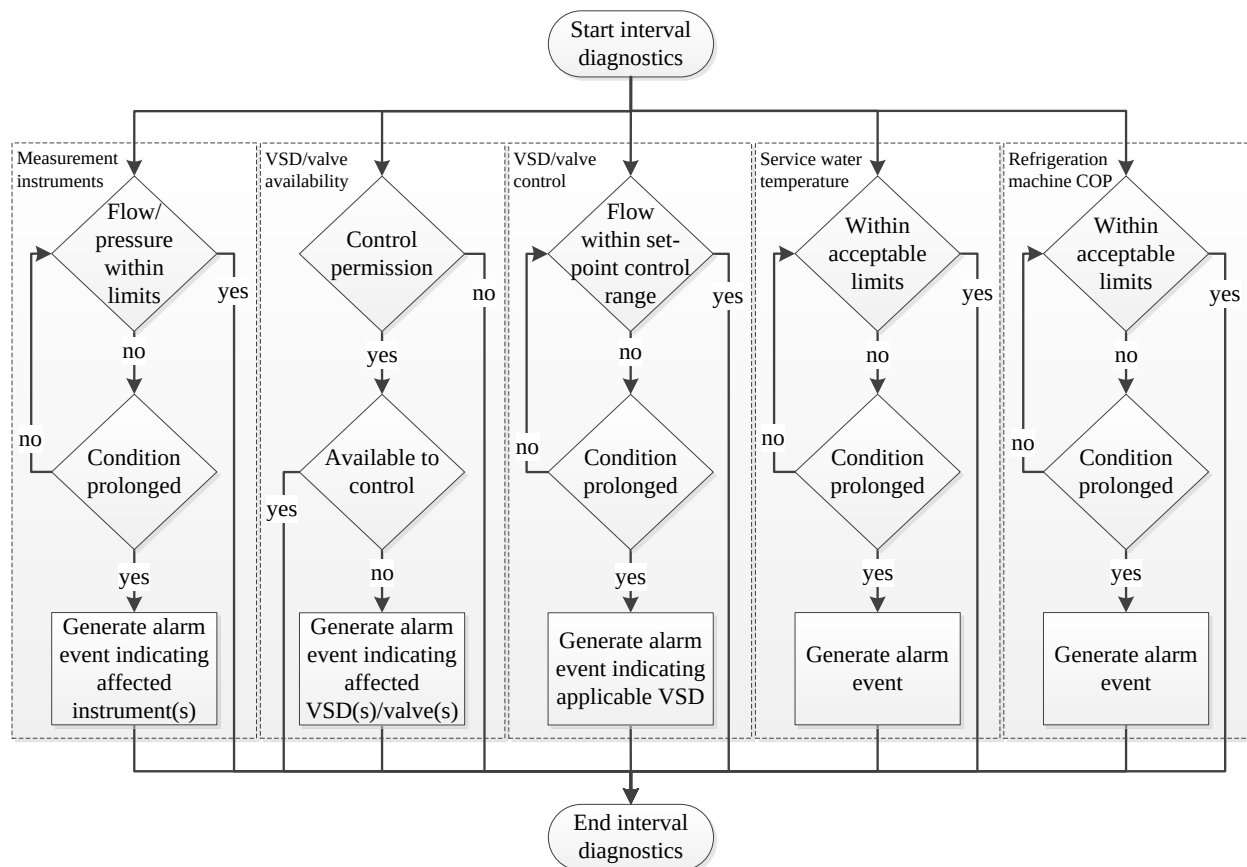


Figure 52: Case Study 2 – Specialised diagnostics flow diagram

To assess the global effectiveness of the control philosophy, diagnostics assess the service water temperature for prolonged non-conformity with safe limits. Automated notification of this event ensures that a safe working environment for underground workers is prioritised above control philosophy execution.

Specialised diagnostics also assesses the COP of all refrigeration machines to ensure that the EMS does not negatively affect the efficient operation of these machines. When diagnosed, the supervisory system notifies maintenance personnel to revise the control philosophy to ensure sustainable EMS operation. Specialised diagnostics ensures active optimisation of control parameters thus decreasing the extent to which controlled parameters deviate from set points.

Figure 53 shows a comparison of daily mismatch occurrences between the set point and actual differential temperatures of the refrigeration machines. The average profile for the four months after the supervisory system integration shows a 10% improvement in the correlation between set-point values and actual measurement.

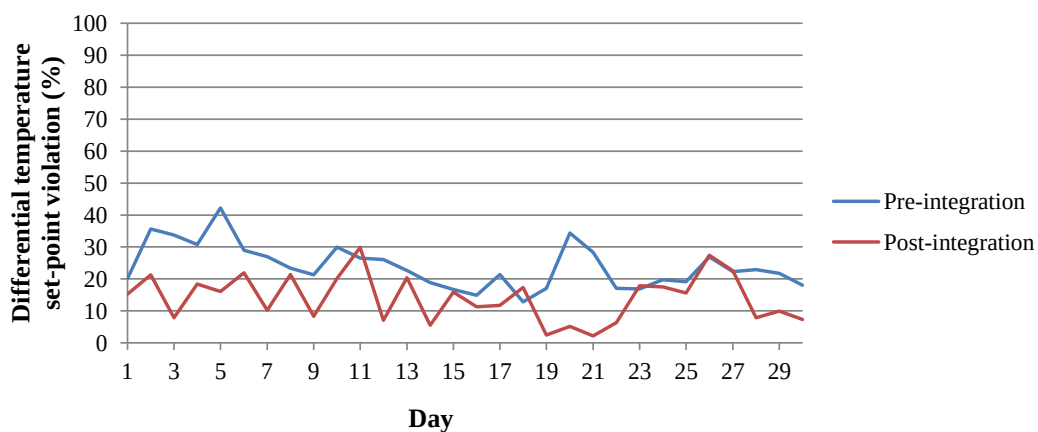


Figure 53: Case Study 2 –Pre- and post-integration differential temperature set-point violation

The average monthly occurrence of water temperature exceeding the maximum limit is a good indication of the EMS stability. The EMS is required to reduce electricity consumption without affecting production. This involves controlling the cooling system to produce water at the correct temperature to allow for safe and effective mine production. Figure 54 is a comparison of the temperature limit violations before and after the supervisory system integration.

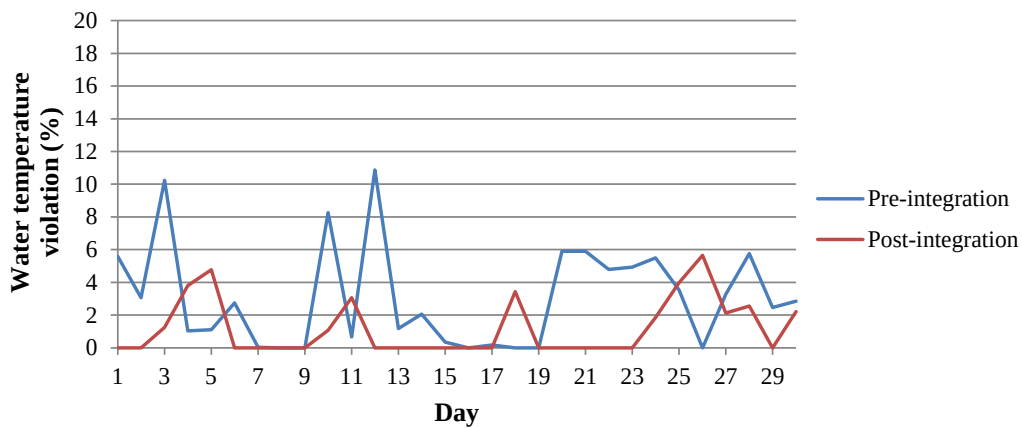


Figure 54: Case Study 2 – Water temperature limit violation

Figure 54 shows a 3% daily occurrence of water temperature violating safe limits. Violation occurrences reduced to 1% after the supervisory system integration. This improvement was the result of active control philosophy maintenance throughout the four-month period after supervisory system integration.

Electrical performance

The EMS performance consistently exceeded the DSM target before supervisory system integration because an ESCO actively maintained the EMS. Figure 55 shows the EMS performance achieving the set target of 1.6 MW over a four-month period. The performance profile shows excessive performance variation; it is expected because the EMS controls the cooling auxiliaries according to ambient temperatures that are influenced by the climate. Dam levels can also have a capacitive effect that inhibits optimal control.

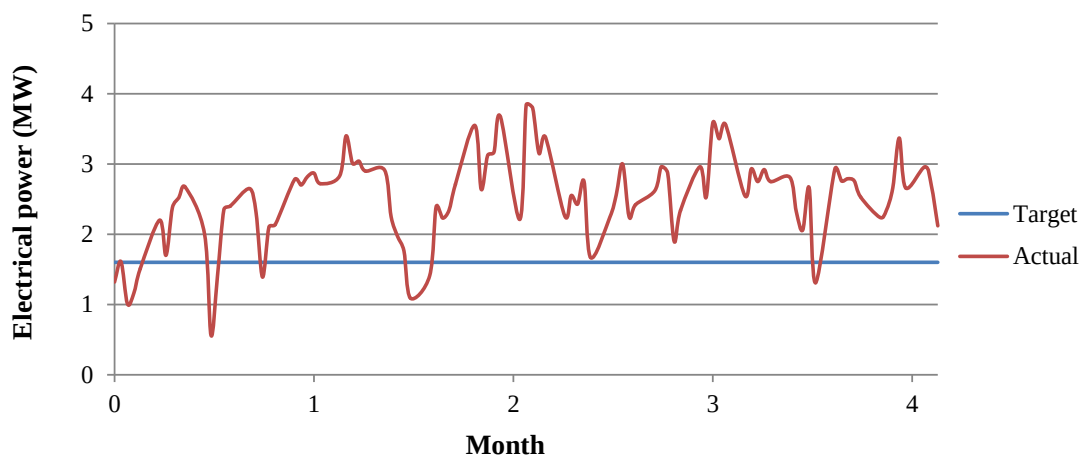


Figure 55: Case Study 2 – Pre-integration EMS performance

Figure 56 shows the performance of the EMS over the four-month period after supervisory system integration. Active control philosophy diagnostics enabled maintenance personnel to maintain the EMS performance significantly higher than the DSM target.

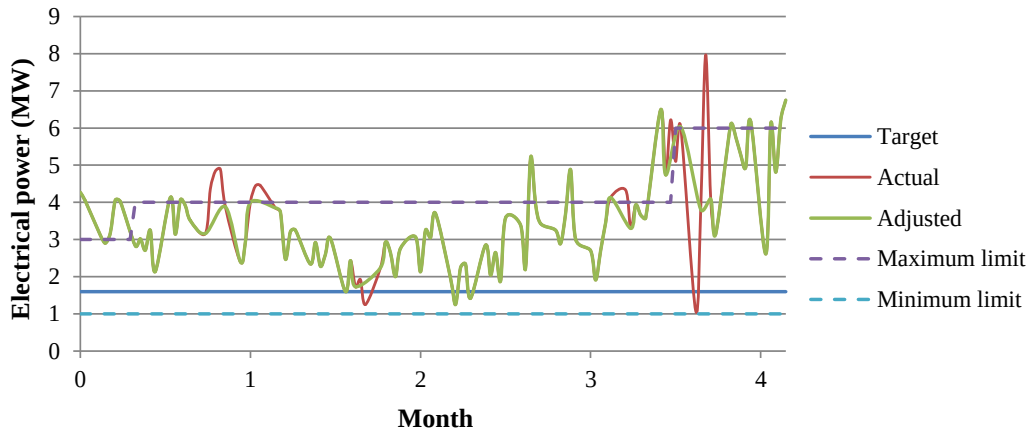


Figure 56: Case Study 2 – Post-integration EMS performance

Figure 56 shows the maximum and minimum performance limit adjustments over the course of the four-month period. These adjustments were necessary to assist with automated notifications of potentially unrealistic performance calculation. The supervisory system identified eight days that contained corrupted or incomplete data. To ensure data integrity, the supervisory system adjusted the calculated performance according to available data.

A clear performance increase is visible in Figure 56 when comparing the performance at the start and end of the four-month period. The supervisory system assisted maintenance personnel to sustain the performance of the EMS over this period. This resulted in an average energy efficiency performance of 3.4 MW compared to a pre-integration performance of 2.5 MW. The total electricity cost reduction amounted to approximately R5 088 000 over the four months post-integration period.

5.4 Case Study 3 – Compressed air EMS

Introduction

Compressed air is one of the most effective methods for providing ventilation in the South African mining environment. Mines also use compressed air networks to operate pneumatic equipment. Compressed air is typically used to power drills, loaders, loading boxes and pneumatic control valves. According to the findings of Howells (2006), compressed air generation requires a large amount of electricity, contributing up to 20% of the electricity requirement of an operational gold mine. Therefore, compressed air is crucial for ensuring optimal production and a safe working environment.

A typical mining cycle consists of drilling, blasting and tramming periods. Mines typically maintain a constant supply of compressed air throughout the mining cycle, although compressed air demand is at a maximum during drilling and tramming periods and at a minimum during the blasting period. When the blasting period correlates with the Eskom evening peak period from 18:00 to 20:00, the opportunity exists to optimise the supply of compressed air to meet the lower demand during the evening peak period. This in turn minimises the electricity cost to generate unnecessary compressed air.

The developed supervisory system was integrated with an operational EMS that controls the compressors at a gold mine. Five compressors at the same location supply compressed air to twenty-five underground levels, extending to 3.5 km below the surface. The EMS aims to optimise compressor control to reduce the electricity demand by 2.0 MW during the Eskom evening peak period.

Proven compressor management technology allows the EMS to achieve DSM peak clipping during the Eskom evening peak period. The EMS accurately matches the supply of compressed air to the demand by reducing the output of compressors as much as possible before unloading or stopping compressors in reaction to reduced demand.

Integration

The EMS consisted of a redundant server pair with a UPS that ensured reliable operation during brief electricity supply interruptions. Integration of the supervisory system entailed installing a DMA and a mobile network router to allow data transfer and remote access to the EMS via the Truteq APN.

Figure 57 shows the status screen of the mobile network router installed on-site in the server cabinet. This screen indicates that the router successfully connected to the Truteq APN and shows the registered

IP address blanked out in Figure 57 for security reasons. The status screen also shows that the EDGE (enhanced data rates for GSM evolution) signal strength is at 58%.



Figure 57: Case Study 3 – On-site mobile router status screen

Fluctuating signal strength was sufficient for data transfer because of persistent SMTP transfer attempts and the fact that sporadic network access remains sufficient for data transfer. A stable connection was, however, required for unrestricted remote access to the EMS. A high-gain directional antenna improved the signal strength and stability to facilitate reliable remote access.

Operational availability

An ESCO maintained the EMS to a certain extent before the supervisory system integration. Figure 58 shows the operational availability of the EMS, OPC connection and automatic operation. In combination, these three indicators give an indication of the effective operational availability of the EMS over the three-and-a-half month period prior to the supervisory system integration. Because of prior maintenance, the operational availability only experienced slight interruption throughout this period.

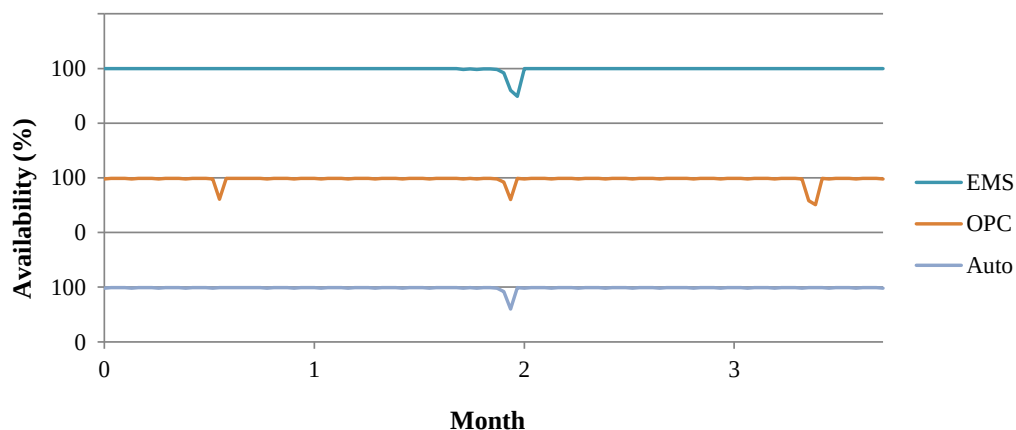


Figure 58: Case Study 3 – Pre-integration operational availability

The supervisory system evaluated the statuses of the EMS application, the DMA, and network connections that are critical to the operation of the EMS. Figure 59 shows the operational availability of the EMS components and the DMA after the supervisory system integration.

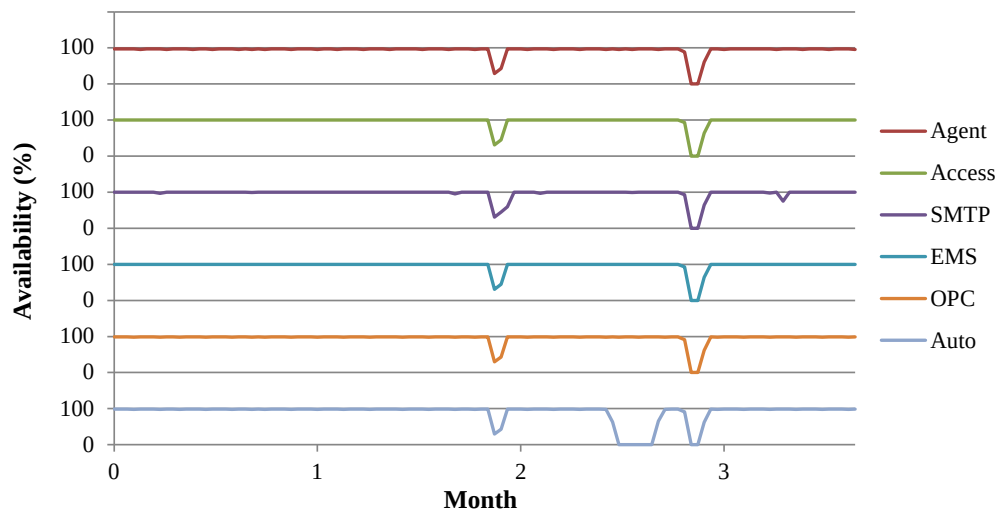


Figure 59: Case Study 3 – Post-integration operational availability

The supervisory system ensured that the EMS application stayed operational and in automatic mode with a sustained OPC connection. At the end of the second month, the EMS servers went offline due to a localised power failure. Maintenance personnel performed on-site maintenance the following day to get the servers back online, resulting in overnight EMS disruption. This event is visible in Figure 59, showing reduced operational availability for two days.

On request of the mine, maintenance personnel switched the EMS to manual operation for a week. This planned interruption of the automatic EMS operation is visible in Figure 59 during the second half of the third month. This period of manual operation proved that the DSM performance is reliant on automatic EMS operation.

At the end of the third month, the EMS servers underwent a routine reboot but failed to boot successfully due to non-bootable media left in the servers after previous maintenance. This boot failure occurred at 22:00 on a Friday night. Because of the flexible control over weekends with no Eskom peak periods, maintenance personnel performed on-site maintenance on Monday morning, resolving the issue before the production shift started. This event is visible in Figure 59, showing the effective EMS operational availability reduced to 0% for two days.

Table 12 shows the average pre- and post-integration operational availability calculated from the data displayed in Figure 58 and Figure 59. The table also includes the availability figures that exclude the week of planned manual operation. This increases the effective EMS availability from 90% to 95%.

Table 12: Case Study 3 – Operational availability summary

System	Item	Pre-integration availability (%)	Post-integration availability (%)	Availability excluding overrides (%)
EMS	EMS	99	97	-
	OPC	97	96	-
	Automatic	98	90	95
Supervisory system	DMA	-	94	-
Access	Access	-	97	-
	SMTP	-	96	-
Overall EMS		97	90	95

The effective EMS operational availability reduced from 97% to 95% after the supervisory system implementation. This was due to two incidents of complete EMS failure that required on-site maintenance. When compared with the duration of failures of the unmaintained EMS in Case Study 1, the reaction to these two maintenance-requiring events was a significant improvement.

Control philosophy

The core focus of compressor management technology is to reduce the supply of compressed air during the blasting period, when the demand for compressed air declines considerably. The EMS achieves this by running baseload compressors at maximum capacity while using trimming compressors to match the supply to the demand for compressed air. Local controllers on each compressor vary the flow through the compressor to match the supply to a specific pressure set point.

With the outputs of the trimming compressors reduced to a minimum and the supply still exceeding the demand, the EMS unloads a trimming compressor. If necessary, the remaining trimming compressors will increase their supply. Substantial reductions in electricity consumption are achieved when the EMS stops the unloaded trimming compressor. The EMS only stops an unloaded compressor once it has established that the supply of this compressor is not required to meet the demand.

Mine personnel typically prefer not to reduce the supply during this period to be prepared for the increased demand that follows the blasting period. Specialised on-site diagnostics was configured to ensure that the EMS executed the control philosophy correctly. These diagnostics assesses whether:

- pressure and flow measurements are realistic;
- compressors that are not in maintenance mode are available for control;
- compressor supply adjusts according to pressure set points;
- compressors follow the command to load/unload; or
- compressors follow the command to stop/start.

Figure 60 shows the diagnostic flow diagrams that represent the on-site diagnostic process. Interval diagnostics assesses pressure and flow measurements to ensure correct EMS control decisions. These diagnostics also assesses the compressor availability to identify a situation that could impair the execution of the control philosophy. As a high-level assessment of the control philosophy, interval diagnostics also compares the supply pressure to the pressure set point. The supervisory system notifies maintenance personnel immediately if any of these conditions occur for prolonged periods.

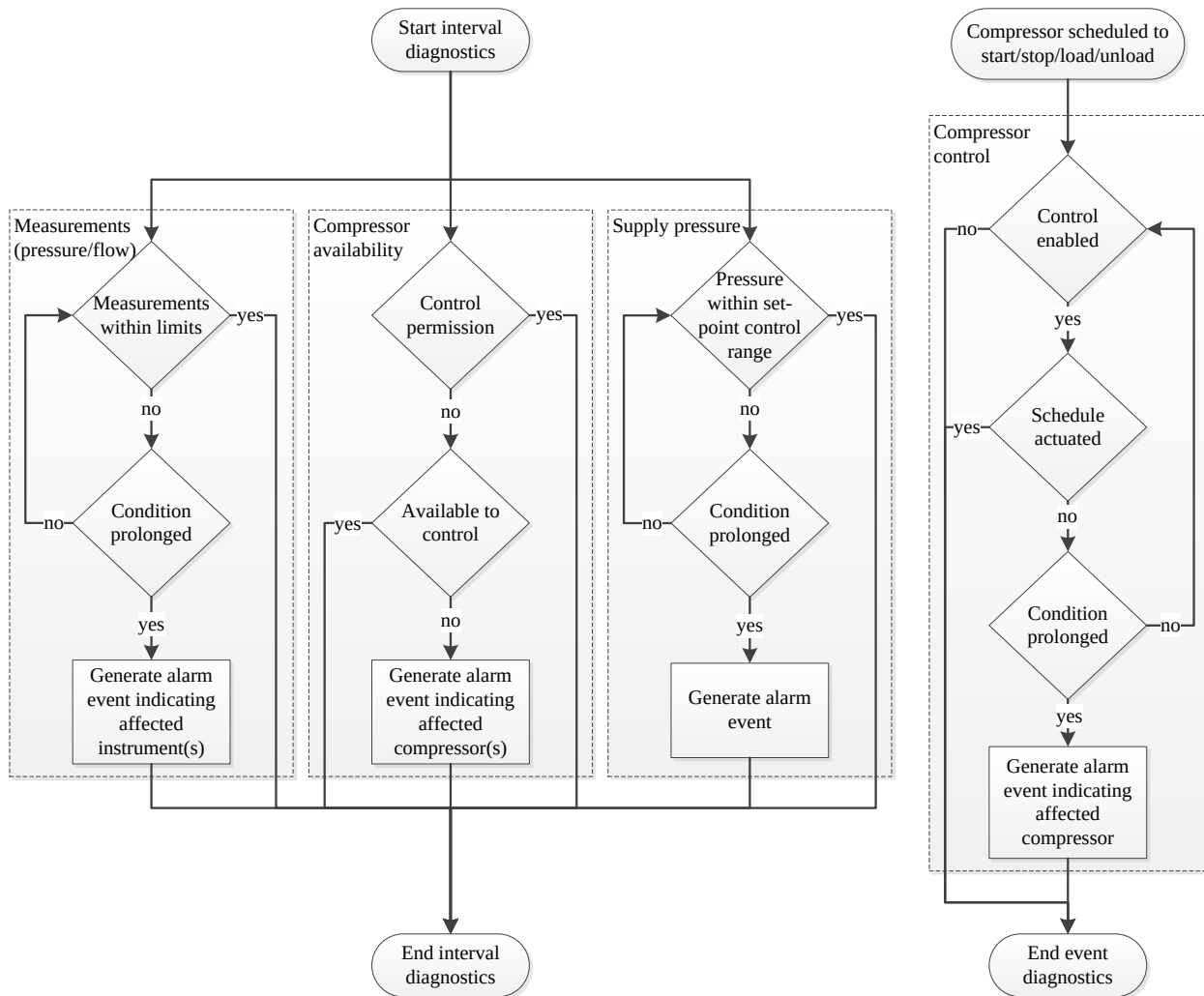


Figure 60: Case study 3 – Specialised diagnostics flow diagram

Event based diagnostics assesses the correct execution of control commands initiated according to the control philosophy. Configuration of these diagnostics is site-specific and extends the standardised EMS diagnostics executed by the DMC, as described in Chapter 3.

Electrical performance

Figure 61 shows the daily DSM target and actual EMS performance over the three-and-a-half month period before the supervisory system integration. Occasional EMS maintenance during this period ensured that the performance remained acceptable, but the linear trend in Figure 61 shows that the performance steadily declined over time.

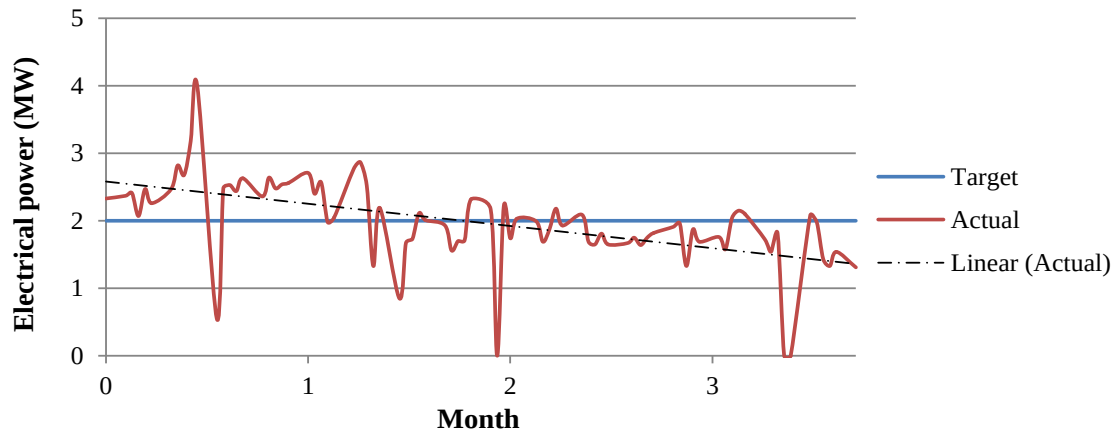


Figure 61: Case Study 3 – Pre-integration EMS performance

Figure 62 shows the EMS performance during the period after the supervisory system integration. During the supervisory system integration, one of the compressor motors required unplanned maintenance. This left the EMS with one less compressor to use for optimal scheduling, resulting in reduced performance during the first month and the first part of the second month. Maintenance personnel did not adjust the minimum performance limit because these circumstances were temporary.

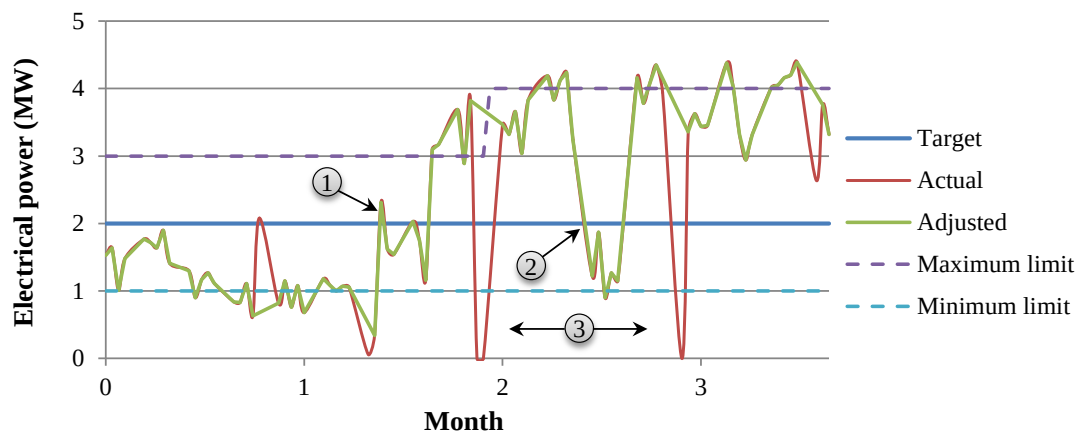


Figure 62: Case Study 3 – Post-integration EMS performance

After completion of the compressor motor refurbishment, maintenance personnel adjusted the control philosophy, resulting in increased performance as shown by Indicator 1 in Figure 62. After this

adjustment, the EMS performance increased significantly, exceeding the performance target. Maintenance personnel adjusted the maximum performance limit accordingly.

During the first part of the third month, the mine started doubting the significant performance increase. The mine requested that the EMS be reverted to manual operation for a week to establish whether the EMS was responsible for the large DSM performance figures. During this week, the performance decreased to below the target at Indicator 2 in Figure 62. Once maintenance personnel switched the EMS back to automatic operation, the performance once again exceeded the DSM target.

Indicator 3 shows the effect of two incidents where the EMS servers were offline for extended periods. The resulting data loss caused incorrect scaling that affected the performance calculation adversely. These days were marked as condonable. The supervisory system assisted maintenance personnel to increase the average peak-clip performance of this EMS from 2.0 MW to 2.4 MW. This resulted in an electricity cost reduction of approximately R570 000 after three and a half months.

Maintenance cost

This EMS was located 160 km away from the maintenance centre. It can take maintenance personnel more than one and a half hours in travelling and sign-in time to reach the EMS. Under ideal traffic conditions, it takes maintenance personnel approximately four hours to perform one hour of on-site maintenance. When considering the lost electricity cost savings of a malfunctioning EMS, travelling remains beneficial if no other means of maintenance are possible.

The cost of one hour of maintenance could thus amount to R1 120 (at R3.50 per kilometre) for reimbursed travel cost, and R1 600 (at a professional rate of R400 per hour) for maintenance specialist compensation. This amount might seem insignificant in the grand scheme of things, but when considering that the maintenance specialist could have performed four hours of effective maintenance remotely, the cost of time lost to travel has to be recovered by other maintenance personnel at R1 200 (at a professional rate of R400 per hour).

Every site visit that is avoided increases the efficiency of maintenance personnel thus reducing the cost and time wasted on ineffective maintenance. A single maintenance-related site visit to this EMS cost the ESCO approximately R3 920. The number of maintenance related site visits decreased from seven to four after the supervisory system integration. The supervisory system effectively reduced the average monthly site visits by one. This translates to an annual maintenance cost reduction of approximately R47 000 for this EMS.

5.5 Further EMS integration

To support the validation of the developed supervisory system, the results of the three case studies are considered in conjunction with seven additional supervisory system integrations. Table 13 provides information of the EMSs involved in the additional supervisory system integrations. This table shows the designation of the system controlled by each of the EMSs, the DSM type and DSM target of the EMS.

Table 13: Overview of further integration

EMS	Controlled system	DSM type	DSM target (MW)
A	Water reticulation	Load shift	3.1
B	Compressed air	Energy efficiency	2.5
C	Compressed air	Energy efficiency	1.5
D	Compressed air	Energy efficiency	3.0
E	Water reticulation	Load shift	2.3
F	Compressed air	Energy efficiency	1.7
G	Compressed air	Energy efficiency	1.4

These integrations serve to assess the impact that the supervisory system has on EMS operational availability and performance over several months after the respective supervisory system integrations. The subsections that follow present an overview of the results obtained on each of these EMSs.

EMS A

Figure 63(a) shows the operational availability of important EMS and DMA indicators over the nine-month period after supervisory system integration. The secondary server was non-operational during the first two months but was replaced during the third month. During the first month, the EMS was not operating fully automatically and experiences varying OPC connectivity. The duration of automatic operation and OPC connectivity increased during the first five months because of active maintenance.

Figure 63(a) shows that the supervisory system facilitated optimal operational availability during the last four months. Figure 63(b) shows the EMS performance for the nine-month period during which the EMS consistently met the DSM target, with the exception of the first two months and the eighth month.

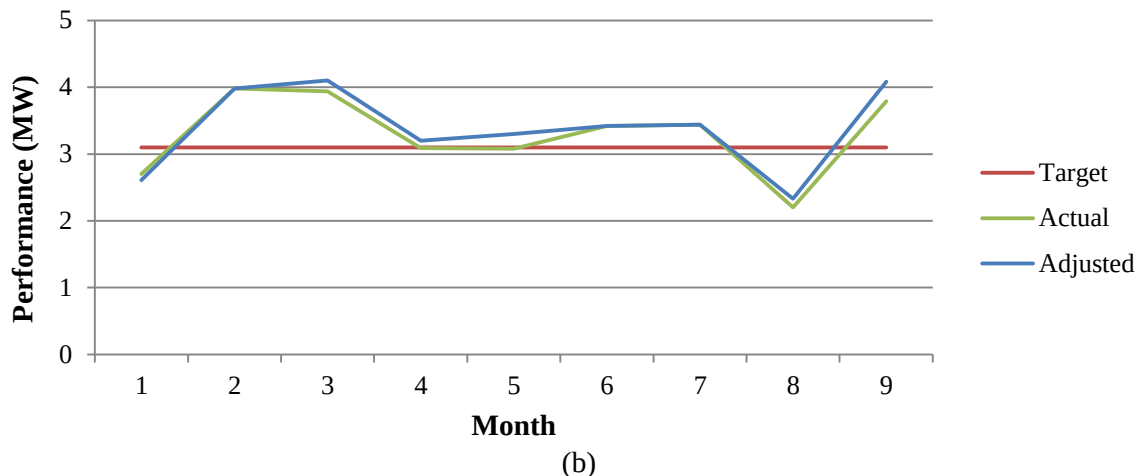
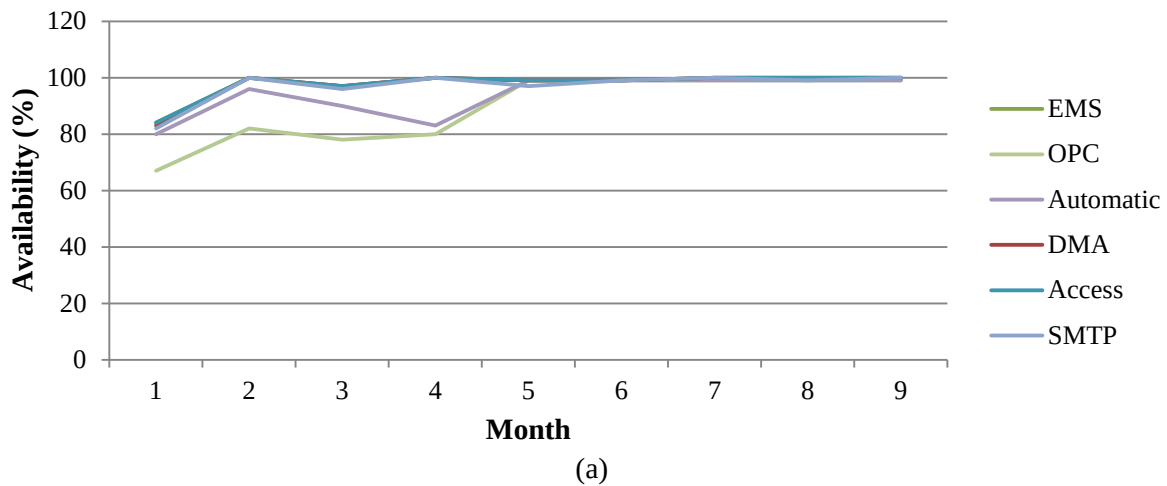


Figure 63: EMS A operational availability and performance results

EMS B

Figure 64 shows the results obtained on EMS B over a nine-month period. The effective operational availability of the EMS improved consistently as shown in Figure 64(a). Control room operators were reluctant to trust the EMS with full automatic operations, which resulted in a delayed improvement of automatic operation. However, this problem was resolved during the last two months of performance assessment. Figure 64(b) shows that the performance of EMS B exceeded the set DSM target throughout the nine-month period.

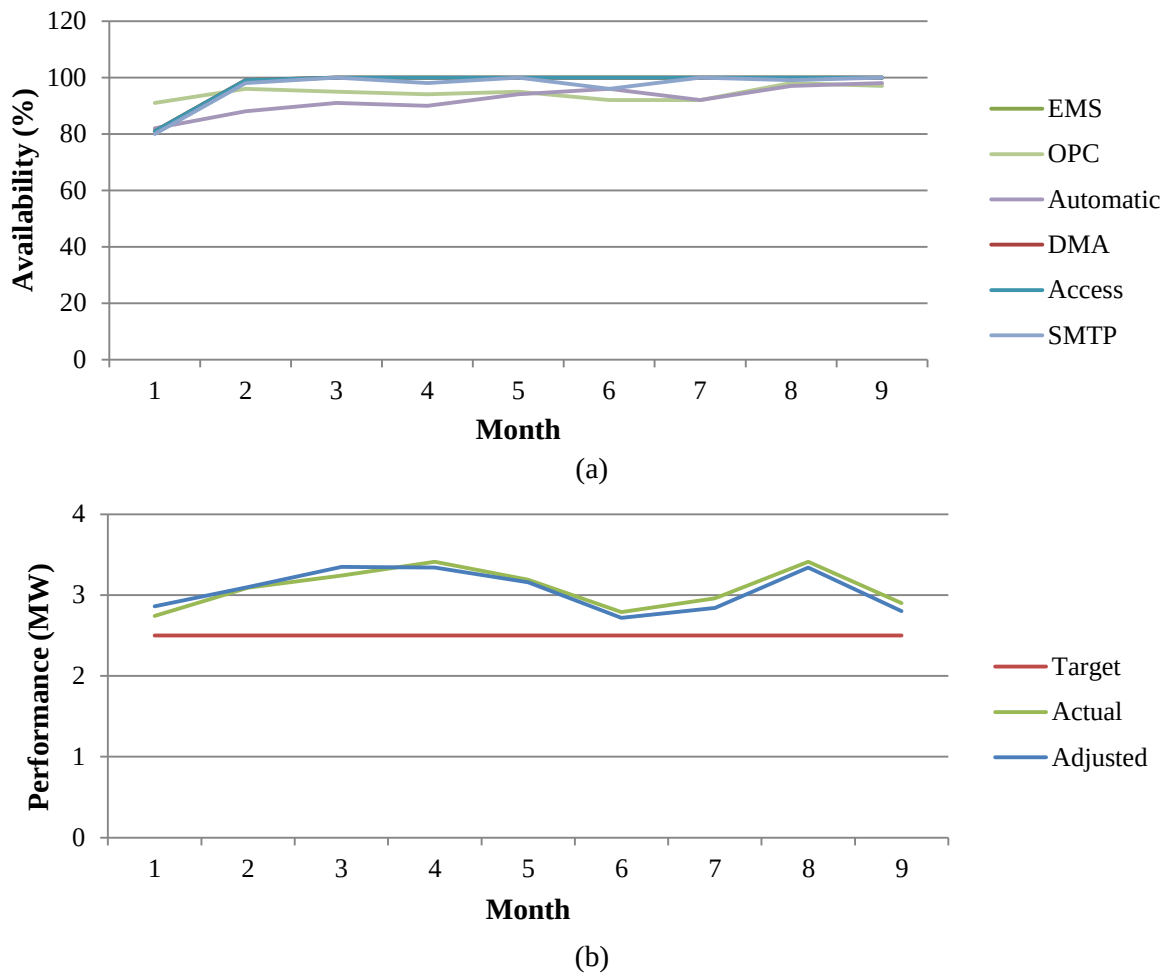


Figure 64: EMS B operational availability and performance results

EMS C

The supervisory system ensured that the operational availability of the EMS and DMA remained between 80% and 100% over an eight-month period, as shown in Figure 65(a). OPC connectivity once again proved to be one of the less reliable components of the EMS, reducing the effective operational availability of the EMS during the third and sixth month.

The EMS performance profile is shown in Figure 65(b). There is a notable difference between the performance calculation and supervisory system adjustment. This was due to reduced data integrity caused by the OPC connectivity problems during the third and sixth month. The supervisory system adjusted artificially high performance values caused by decreased production during the sixth month.

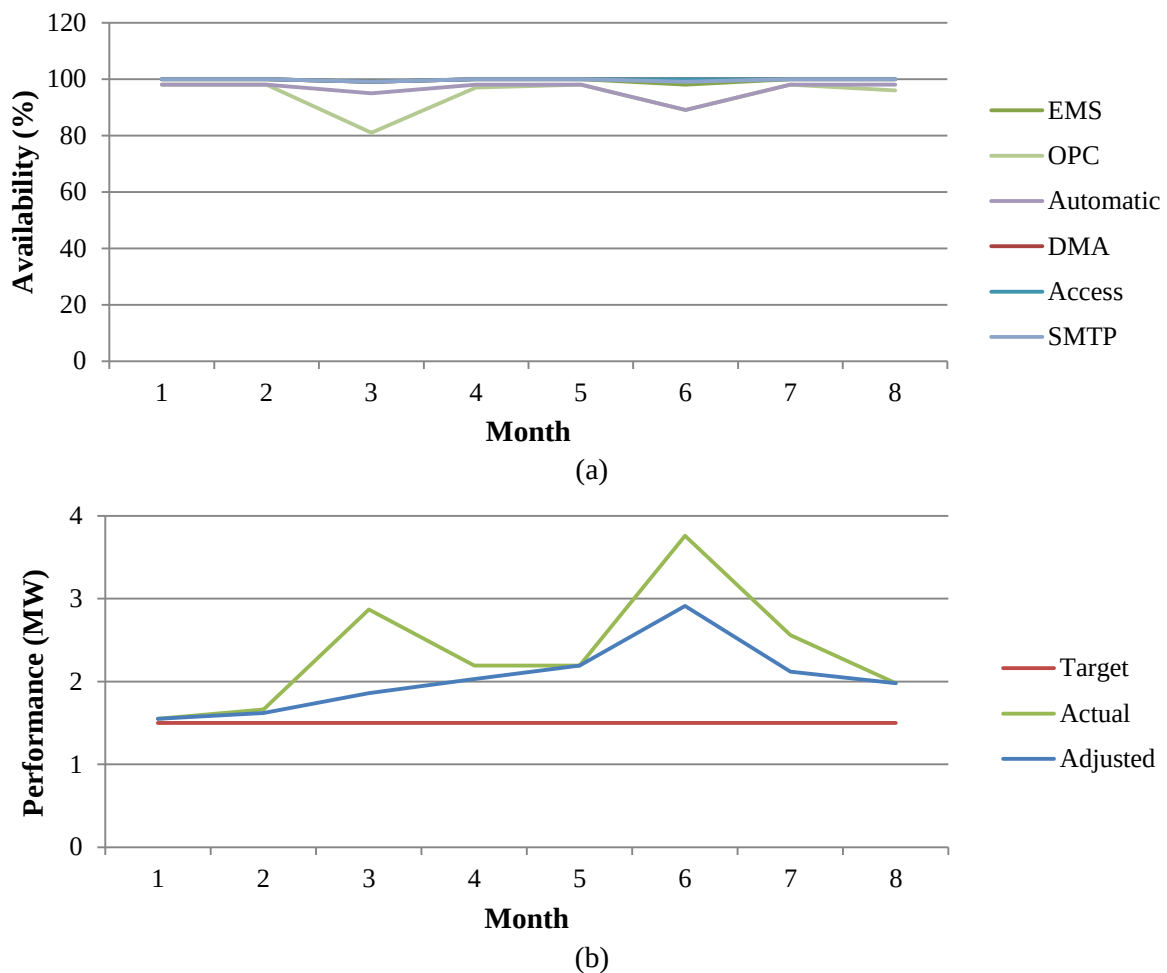


Figure 65: EMS C operational availability and performance results

EMS D

OPC connectivity and the operational availability of the EMS gradually improved after the supervisory system integration, as shown in Figure 66(a). The EMS did not receive approval for automatic operation but provided operators with control suggestions. Due to strict supervisory maintenance, the EMS performance exceeded the set DSM target over a seven-month period, as shown in Figure 66(b).

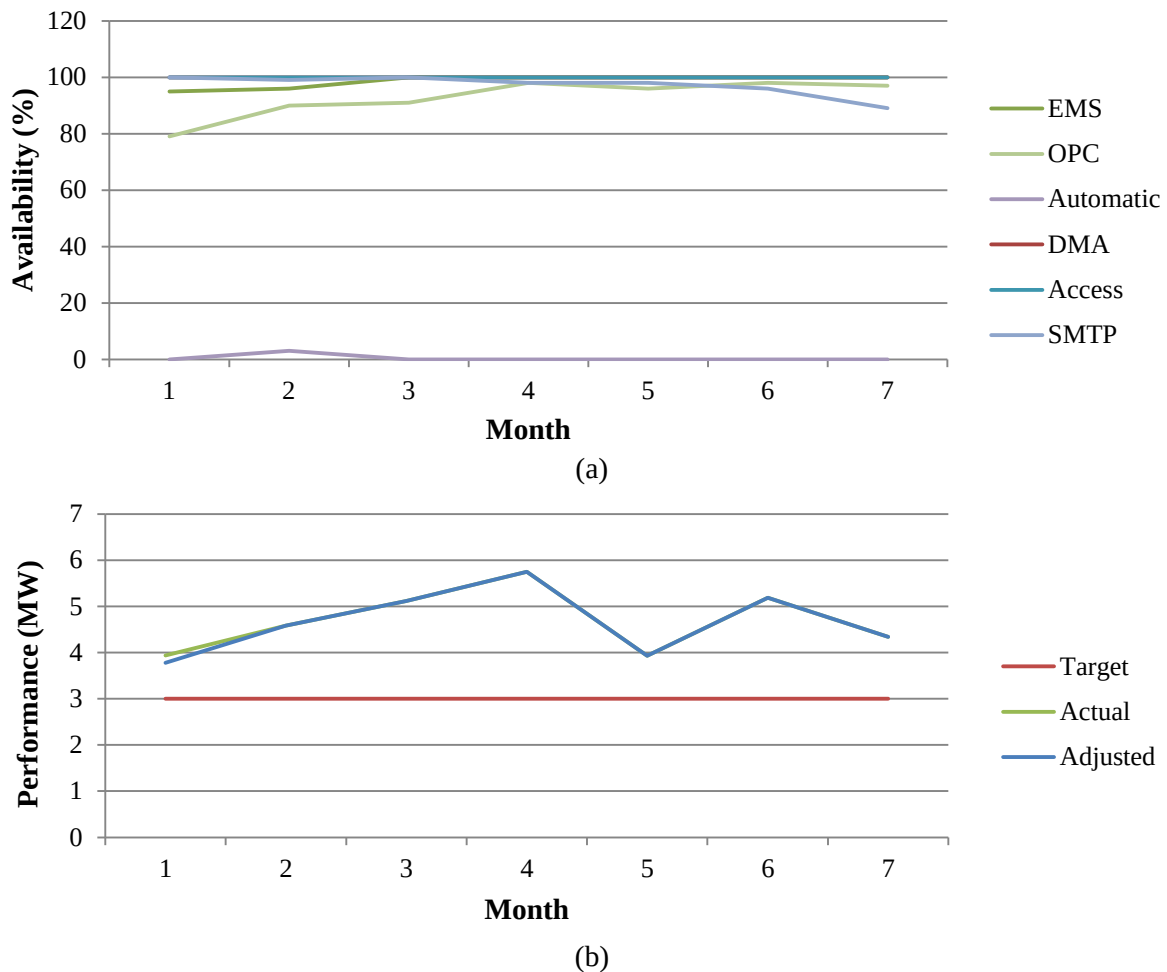


Figure 66: EMS D operational availability and performance results

EMS E

Initially, automatic operation was restricted on EMS E mainly because of mistrust in schedules proposed by the EMS. Maintenance personnel worked with operators to establish their trust in EMS schedules, leading to increased automatic operation over time, as shown in Figure 66(a). The supervisory system assisted maintenance personnel to ensure consistent EMS performance over a seven-month period as shown in Figure 66(b).

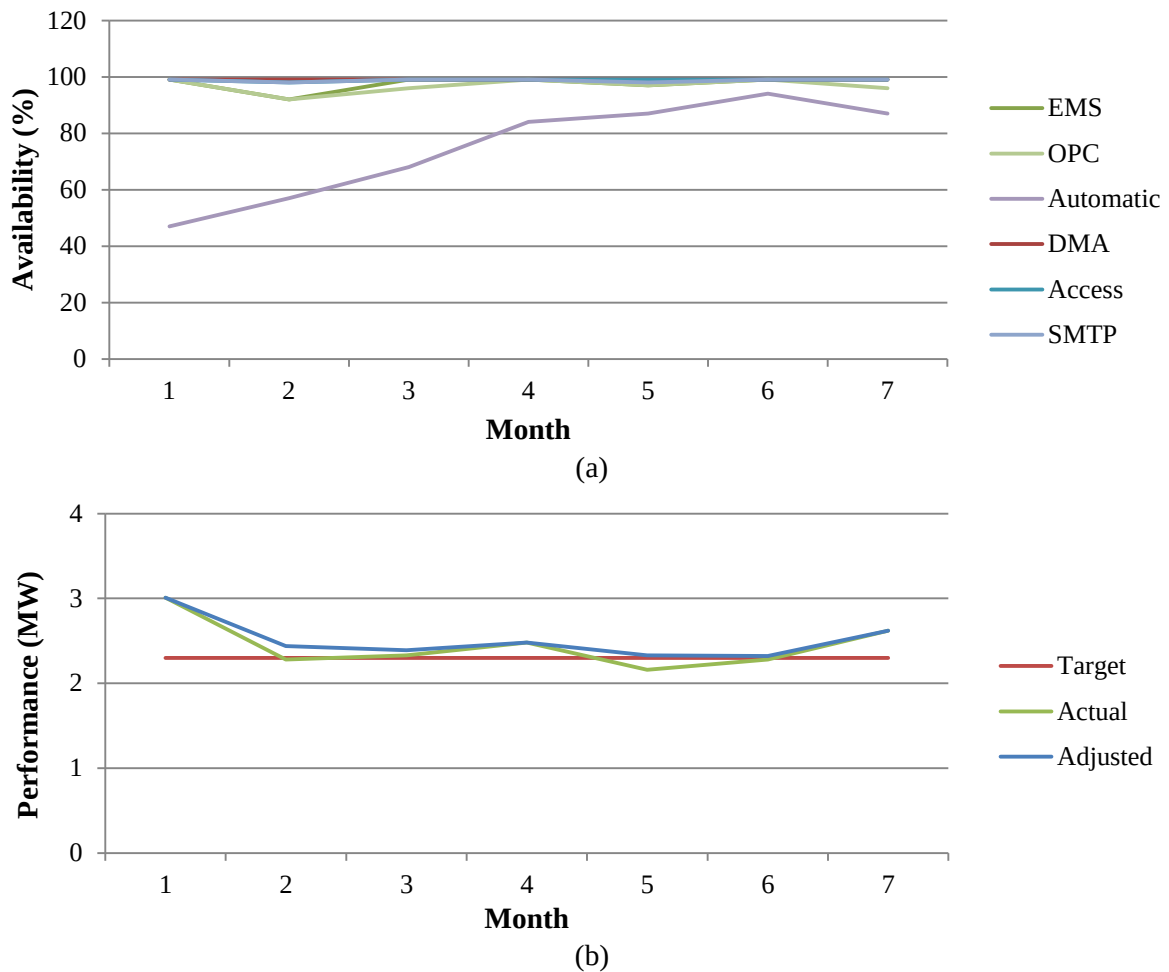


Figure 67: EMS E operational availability and performance results

EMS F

The operational availability of EMS F gradually increased during the first two months after the supervisory system integration. Figure 68(a) shows stable EMS operation after the initial rehabilitation that mainly included increased automatic operation. However, stable operation did not automatically ensure consistent performance throughout this period.

During the fifth and sixth months, a design fault in the EMS code caused failed execution of the control philosophy without affecting the EMS platform. This resulted in an artificially high EMS availability with no control commands issued; EMS performance decreased as shown in Figure 68(b). After conducting extensive diagnostics, a software update corrected the fault during the seventh month.

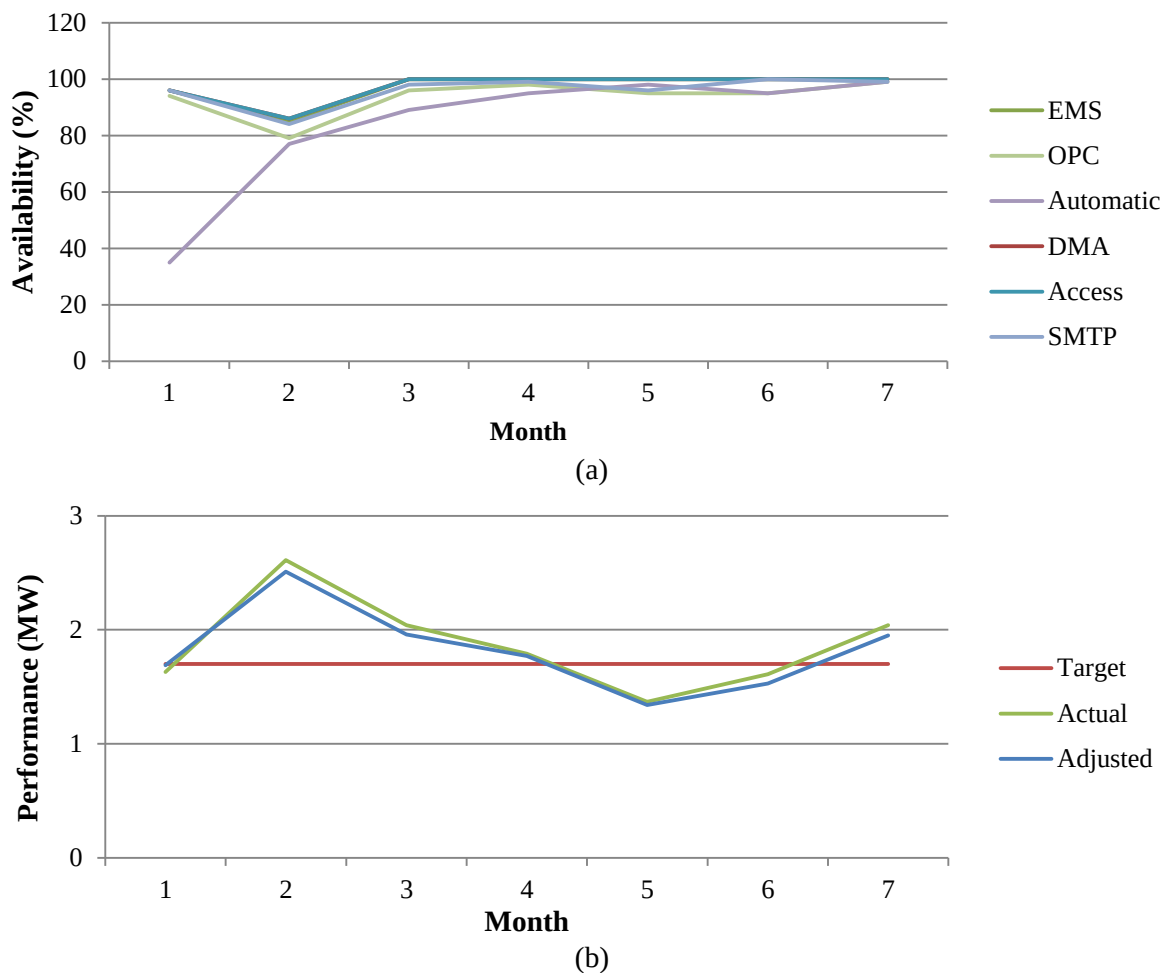


Figure 68: EMS F operational availability and performance results

EMS G

The OPC connectivity of EMS G degraded during the second and third month after supervisory system integration as shown in Figure 69(a). This required frequent OPC connection reset procedures. The supervisory system notified maintenance personnel of the connectivity failures, but an EMS platform upgrade provided a long-term solution. During the fourth month, the secondary server failed and was replaced. The EMS performance gradually degraded over the six-month period as shown in Figure 69(b). The performance did, however, still exceed the DSM target over the whole period.

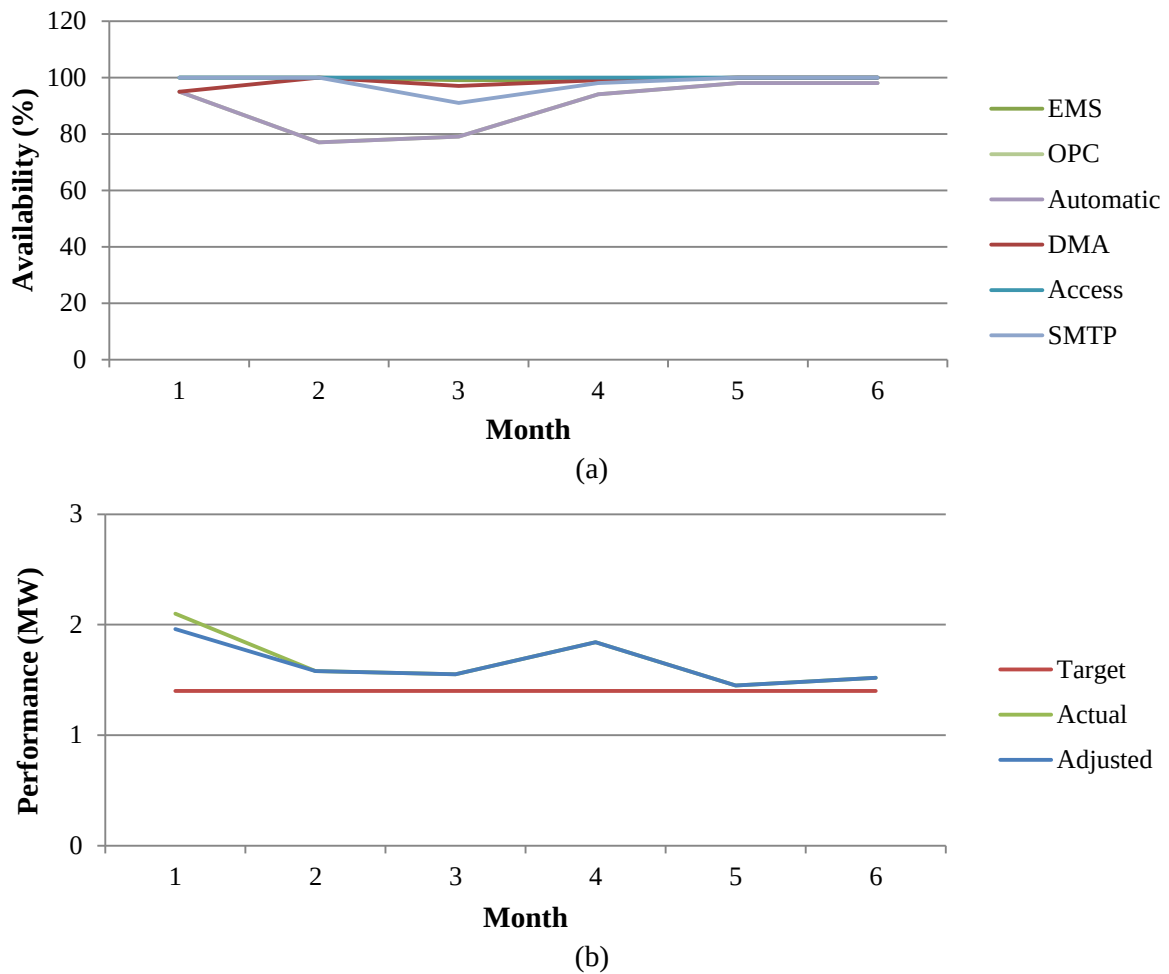


Figure 69: EMS G operational availability and performance results

Results interpretation

The DSM targets, average EMS performance and total electricity cost savings of the seven additional EMSs integrations are summarised in Table 14. The table also shows the assessment periods of the individual EMSs. Assessment periods that ranged from six to nine months showed satisfactory performance compared with the respective DSM targets, translating to a total electricity cost saving of approximately R35 469 000.

Table 14: Summary of average EMS performance

Name	Period (Months)	Effective EMS availability (%)	Average daily performance (MW)		Electricity cost saving (R)
			Target	Actual	
Mine A	9	89	3.1	3.4	2 260 000
Mine B	9	92	2.5	3.1	9 185 000
Mine C	8	94	1.5	2.0	5 728 000
Mine D	7	93	3.0	4.7	10 906 000
Mine E	7	75	2.3	2.5	877 000
Mine F	7	84	1.7	1.8	4 216 000
Mine G	6	90	1.4	1.7	2 297 000

Figure 70 shows the average operational availability of the EMS and on-site supervisory system components of all seven EMSs. This figure reiterates the results obtained during the case studies, indicating that the operation availability of EMS and on-site supervisory system components improved over time, reaching an average effective EMS availability bordering on 100%. The effective EMS operational availability improved from 73 % to 98 % after the nine-month period.

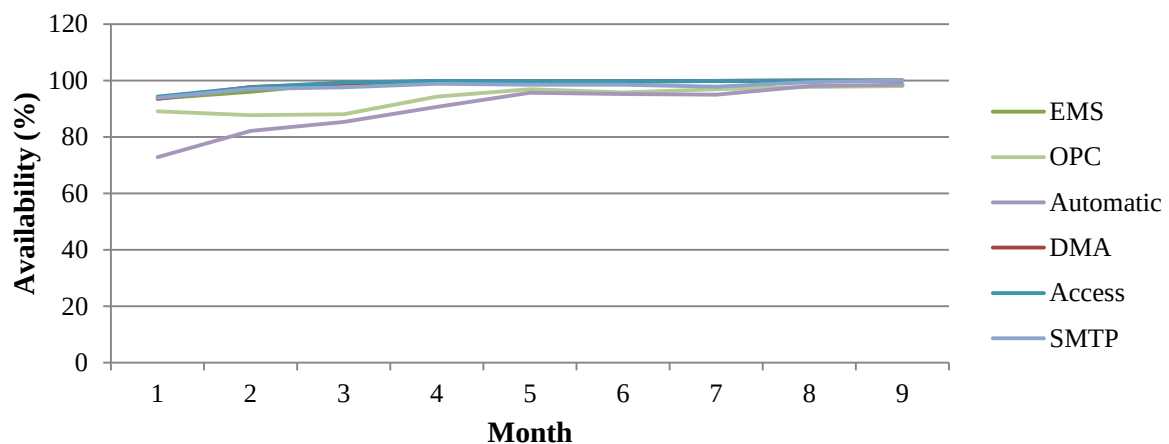


Figure 70: Average EMS and supervisory system availability

In addition to allowing maintenance personnel to provide information on external factors, the supervisory system also takes data loss and corruption into consideration. The effect of this is clearly visible when comparing the actual and adjusted performance profiles in Figure 71. These average profiles show sustained EMS performance in excess of the set DSM target over nine months of assessment.

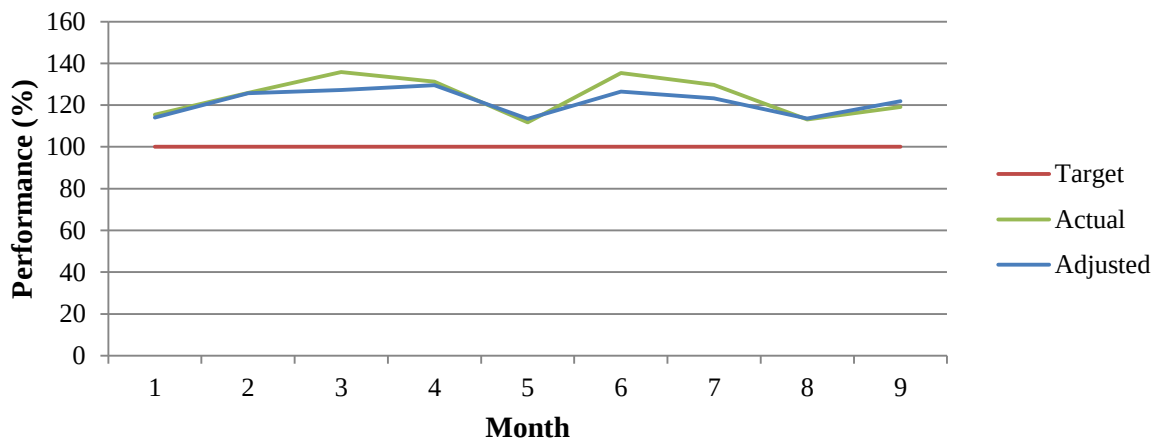


Figure 71: Average EMS performance

The cumulative electrical performance of all seven EMSs is shown in Figure 72. This figure shows a combined cumulative performance of 147 MW, which exceeded the target by 27 MW after a nine-month period. This translates to a 23 % overperformance compared to the cumulative DSM target of 120 MW.

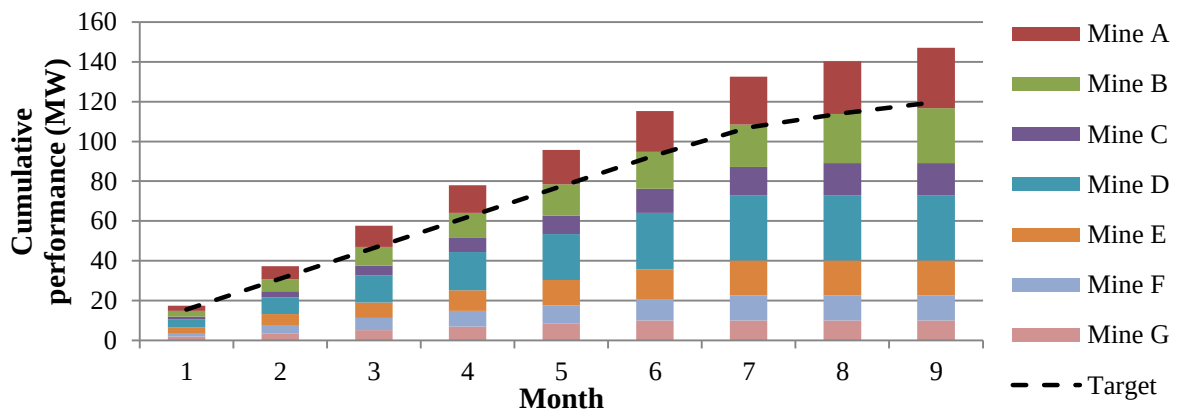


Figure 72: Cumulative EMS performance

The supervisory system successfully ensured increased operational availability of the EMSs. Some of the further integration results, however, revealed declining performance despite significant improvement in EMS component availability. The supervisory system notified maintenance personnel of reduced EMS performance and anomalies that required maintenance of the EMS control philosophy. Complex control philosophies do, however, require specialised maintenance and time to allow the effect of changes to the control philosophy to be verified.

The obtained results are consistent with the individual findings of the case studies, proving that the supervisory system facilitated improved operational availability and sustained EMS performance over several months after the system integration. Table 15 lists the EMSs with approximate distances from the maintenance centre. The table also lists the corresponding travel time to each EMS and the total cost to perform one hour of maintenance on-site.

Table 15: Estimated maintenance cost saving

EMS	Distance (km)	Time (hours)	Cost (R)	Annual saving (R)
A	340	3:40	7 000	84 600
B	340	3:40	8 600	103 800
C	340	3:40	8 600	103 800
D	135	1:30	3 700	44 900
E	340	3:40	8 600	103 800
F	330	3:40	8 600	102 900
G	340	3:40	7 000	84 600

If the supervisory system integration with these seven EMSs reduce site visits by one every month, the total reduction in maintenance cost can be reduced by approximately R628 000 per year. A successful ESCO can have more than twenty EMSs to maintain at any given time. This number of EMSs could increase the potential reduction in annual maintenance cost to R1.8 million.

The supervisory system thus decreased maintenance cost by facilitating effective EMS maintenance with a smaller maintenance team. To see this in a different light, this system allowed an ESCO to apply its existing human resources to maintain the performance of a larger number of EMSs.

5.6 Conclusion

Three case studies involved supervisory system integration with existing EMSs that control different mining systems, with different DSM objectives. After integration, the supervisory system ensured high levels of availability of the EMS and on-site supervisory system. Specialised diagnostics was configured to adapt to the specific infrastructure and control strategy of each EMS. These diagnostics assessed the ability of the EMS to execute the control philosophy successfully.

Case Study 1 presented the supervisory system integration with an EMS controlling the pumps of a water reticulation system. The control strategy of this EMS was to shift pumping energy from peak periods to standard and off-peak periods. The operational availability of the EMS improved from 75% pre-integration to 97% post-integration. The performance increased by 44% from 1.0 MW to 1.8 MW, translating to a total electricity cost saving of R392 000 over a six-month period.

Case Study 2 presented the supervisory system integration with an EMS controlling the pumps and valves installed on a mine cooling system. The control strategy was to reduce unnecessary flow and cooling of water. The operational availability of the EMS was maintained at 98% because the EMS was actively maintained before the supervisory system integration. The performance increased by 58% from 2.5 MW to 3.4 MW, translating to a total electricity cost saving of R5 088 000 over a four-month period.

Case Study 3 presented the supervisory system integration with an EMS controlling the compressors of a compressed air system. The control strategy of this EMS was to reduce the peak-time electricity consumption by matching the compressed air supply to the demand. The operational availability of the EMS decreased from 97% to 95%, which remained satisfactory. The performance increased by 21% from 2.0 MW to 2.4 MW, translating to a total electricity cost saving of R570 000 over three months.

To extend the supervisory system validation, further integrations included seven additional EMSs that controlled mine compressed air and water reticulation systems. The control strategies varied between load shifting and electrical energy efficiency. Combined results of all integrations proved an increase in effective EMS operational availability and sustained EMS performance. Results also proved that the supervisory system reduced the risk of production losses and accidents due to erratic system control.

The responsibility for maintaining the EMS control philosophy remains with maintenance personnel. Diagnostics, notifications and repair suggestions from the supervisory system allowed maintenance personnel to maintain the EMS operational availability and performance. The supervisory system thus facilitated sustained EMS performance by improving maintenance efficiency.

CHAPTER 6. CONCLUSION

6.1 Summary of work

As part of a DSM project in the mining sector, an ESCO typically implements an EMS on large energy-consuming systems to achieve a DSM target. Periodically, the EMS and the controlled system experience hardware failure, network reconfiguration, software upgrades, revised production schedules or other external factors. These events require corrective maintenance to ensure unimpaired EMS operation. The EMS thus requires continuous maintenance to produce sustained performance. Because of this, maintaining a growing number of EMSs remotely is a resource-intensive task.

Existing RDMSs remotely monitor and control vehicles, aircraft, mobile devices and industrial equipment. These systems do, however, not satisfy the need for a system that facilitates efficient maintenance of specialised EMS technologies implemented in the mining industry. Mine EMSs are required to achieve DSM targets while ensuring uninterrupted production and a safe underground working environment. An integrated solution is required to facilitate sustained performance of a growing number of EMSs implemented on mines.

The infrastructure and operation of existing mine EMSs were investigated to identify the requirements for a comprehensive EMS supervisory system. Simplistic supervisory system integration with both new and existing EMSs is required to ensure uninterrupted production. The EMS components and executed control philosophy were found to be separate maintenance-requiring entities. Mine EMSs require comprehensive diagnostics of the EMS components, the control philosophy it executes and the resulting DSM performance.

As part of this study, a supervisory system was developed to satisfy the need for an integrated solution to facilitate remote EMS maintenance. This system comprises a single decentralised DMC with remote DMA installations on maintained EMSs. The DMA forms the on-site component of the supervisory system that executes specialised diagnostics, collects EMS data and transmits collected data to the DMC. The DMC performs generalised diagnostics, reporting and maintenance management.

Generic diagnostic algorithms first assess the status of EMS components, to ensure that the EMS is able to execute the control philosophy without impairment. It was found that the DSM control philosophy is the main difference between EMS technologies developed on the same EMS platform. In addition to generic EMS diagnostics, the DMA allows maintenance personnel to configure customised diagnostics.

This allows the developed system to execute specialised diagnostics tailored to the needs of different EMS technologies and control philosophies, while retaining a simplistic design.

The DMC database stores known diagnostic fingerprints. Diagnostic fingerprints link a combination of diagnostic results to a known diagnosis or diagnoses. The supervisory system provides maintenance personnel with diagnostic information in the form of graphical and document-based reports. In addition to this, the supervisory system makes detailed diagnostic information available to authorised personnel via a web interface. The system further allows maintenance personnel secure remote access to EMSs for interactive diagnostics and maintenance.

The developed system incorporates maintenance management to ensure prompt corrective action based on each diagnosis. DMC sends notifications and suggestions for corrective action to maintenance personnel to initiate remote maintenance. The supervisory system requires periodic feedback on resolution progress, with non-compliance notifications being sent to maintenance managers. This ensures a complete feedback loop to optimise the efficiency of the maintenance process.

To verify correct operation of the newly developed supervisory system, the initial system implementation was completed. This involved the configuration of DMC and an emulated EMS with operational DMA hardware. The target EMS technology provided simulation of the control environment with automatically generated data values. This implementation allowed for verification of generic EMS and specialised control philosophy diagnostics. The function of the maintenance management module was also verified using the simulation environment.

Supervisory system validation consisted of three detailed case studies in addition to seven further integrations with operational EMSs, implemented in the mining sector. A set of diverse EMSs was chosen to prove that the supervisory system is robust enough for integration with different EMS technologies. Technology-specific diagnostics was configured for each of these EMSs, catering for the requirements of individual control philosophies.

The first case study involved an EMS that controlled the pumps of a water reticulation system with the aim of shifting pumping energy from peak periods to standard and off-peak periods. The second case study involved an EMS that controlled various pumps and valves installed on a mine cooling system. The control strategy was to reduce unnecessary flow and cooling of water. The final case study involved an EMS that controlled mine compressors in order to reduce the peak-time electricity consumption by matching the compressed air supply to the demand.

Results indicated improved EMS operational availability from 90% to 97% after the supervisory system integration. The diverse case studies also showed sustained performance after the supervisory system integration. The EMS performance increased by 39% from 1.8 MW to 2.5 MW. Although external factors caused performance impairment on some EMSs, case studies proved that the supervisory system enabled maintenance personnel to react promptly to diagnoses. The results obtained from seven additional integrations on compressed air and water reticulation EMSs supported these results.

The supervisory system enabled maintenance personnel to maintain EMSs, while reducing the time spent travelling to site and identifying faults. The estimated annual maintenance cost reduction achieved for the EMS in Case Study 3 amounted to R47 000. Based on the distances between the DMC and the EMS chosen for additional integrations, the estimated total annual cost reduction amounts to R628 000. The supervisory system allowed maintenance personnel more time to focus on specialised diagnostics of the EMS control philosophy that ultimately determines the performance of an EMS.

Results from Case Study 1 showed a reduction in discrepancies between the number of running pumps and the EMS control schedule. This also reduced incidences of dam levels exceeding safe limits. Case Study 2 presented comparable results, showing that the differential temperature over refrigeration machines more accurately matched the set point after the supervisory system integration. The temperature of underground service water thus less frequently exceeded the set maximum limit after the system integration.

Both the dam levels and water temperature are critical to ensure uninterrupted production and safe underground working conditions. The supervisory system improved EMS operational availability by automating diagnostics. This resulted in more stable EMS operation because of more reliable execution of the control philosophy. This in turn ensured optimal production and a safer working environment while optimising electrical energy consumption.

The supervisory system provides performance assessment, control philosophy assessment and notifies maintenance personnel to update the control philosophy based on specialised diagnostics. This forces maintenance personnel to comply with ISO 50001:2011 requirements (ISO, 2011) regarding result measurement, control philosophy review and continual improvement of the EMS performance.

The newly developed system is scalable and allows for non-intrusive integration with existing and new EMS. This allows for supervisory system integration with a large number of remote EMSs over time. Furthermore, the developed system ensures prompt identification of maintenance-requiring events based on both generic and specialised EMS diagnostics. This novel supervisory system uses comprehensive

EMS diagnostics to enable an ESCO to maintain the performance of a growing number of different EMS technologies implemented in the mining sector.

6.2 Recommendations for further work

The supervisory system validation was based on results obtained from EMSs that control water reticulation, cooling and compressed air systems in the South African mining sector. These EMSs implement electrical load-shifting, energy efficiency and peak-clipping control strategies. This study focussed on the development of a supervisory system for EMS technologies developed based on a specific EMS platform.

The recommendation is to implement the supervisory system as-is on additional EMS technologies developed on the same EMS platform. These existing EMS technologies control other complex mining systems and perform cement plant process optimisation to achieve DSM objectives. Cement plant process optimisation implements a distinctly different control philosophy than the water reticulation, cooling and compressed air EMSs presented in this study. This presents an opportunity for further contribution to the knowledge pool of remote EMS maintenance.

A further contribution to this field of study is also possible by building on this work to expand the compatibility of the developed system to include different EMS development platforms. This makes it possible to standardise the maintenance process for diverse EMSs using the comprehensive diagnostics and maintenance approach of the developed system. The potential outcome of the proposed work is a cross-industry diagnostic solution for remote EMS maintenance.

These recommendations for further research aim to prompt additional contributions to this field of study. It has been shown that RDMSs developed for vehicles, buildings and various other applications have made greater advances than systems applied for EMS maintenance, especially in the mining sector. Continuous development of diagnostic and maintenance technology is required to address the changing maintenance needs of industrial and mining EMSs.

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ANNEXURE A. UNMAINTAINED EMS PERFORMANCE

Annexure A provides the performance results of four EMSs implemented on a mine compressed air system, mine water reticulation system, water pumping scheme and cement manufacturing plant respectively.

Compressed air system

The historical and cumulative performance of an EMS implemented on a compressed air system at a gold mine is shown in Figure 73 and Figure 74 respectively. EMS performance exceeded the set target during the first three months but decreased during the next ten months because of a lack in maintenance.

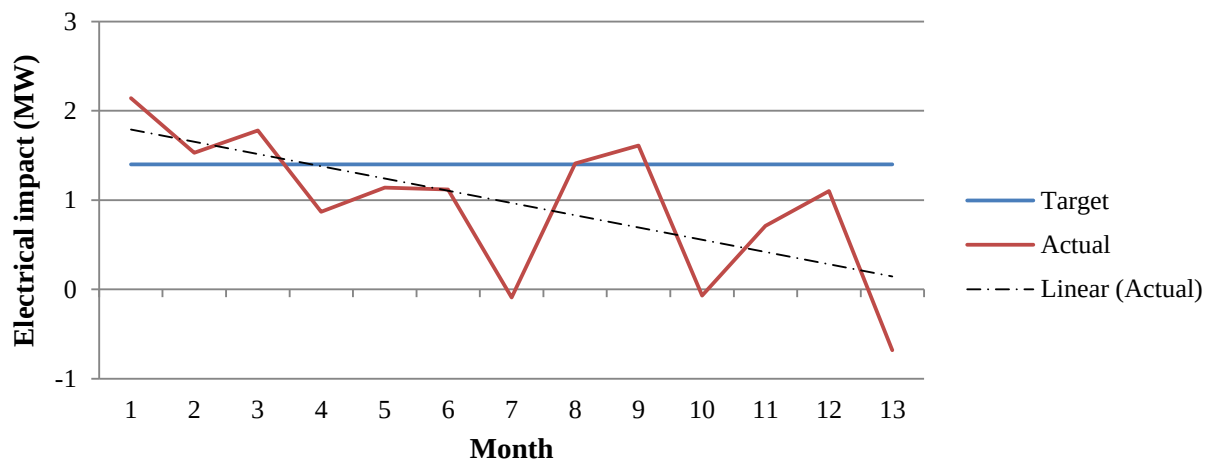


Figure 73: Unmaintained compressed air EMS performance history

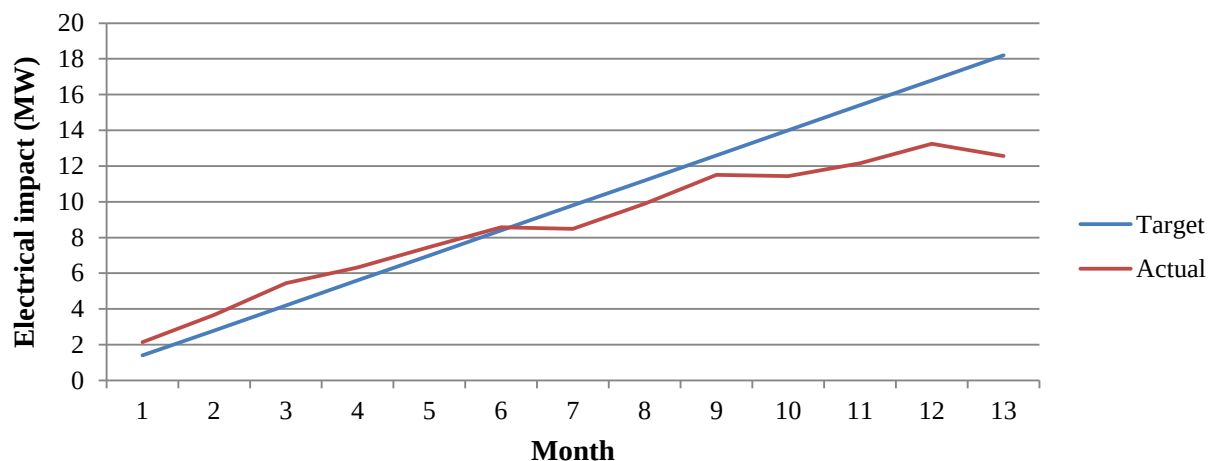


Figure 74: Unmaintained compressed air EMS cumulative performance

Water reticulation system

Figure 75 and Figure 76 show the performance of an EMS implemented on a water reticulation system at a gold mine. The EMS was operational before performance monitoring started. During a 22-month period, performance did not meet the set target and decreased until EMS operation ceased completely. This ultimately resulted in a cumulative missed opportunity of more than 30 MW as shown in Figure 76 after this 22-month assessment period.

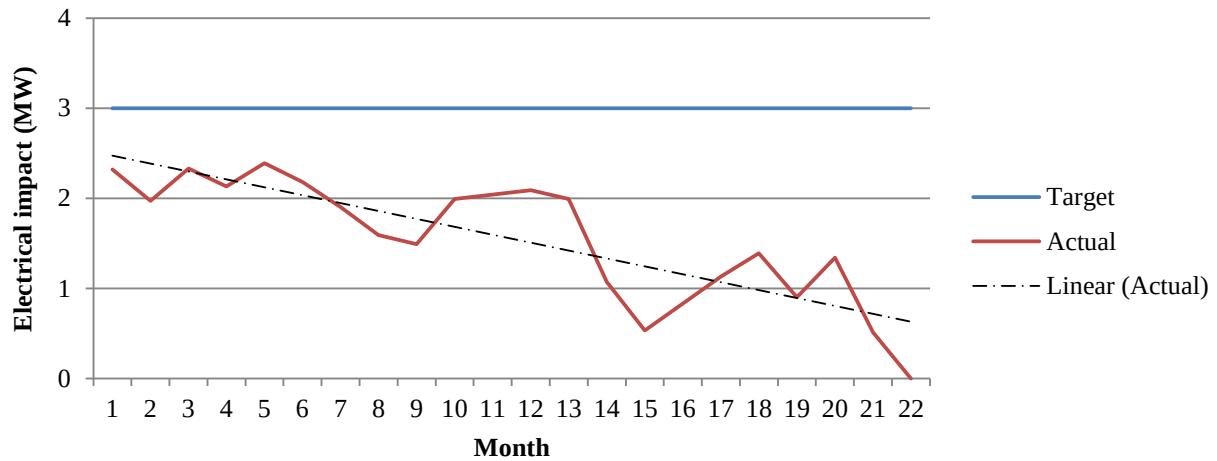


Figure 75: Unmaintained water reticulation EMS performance history

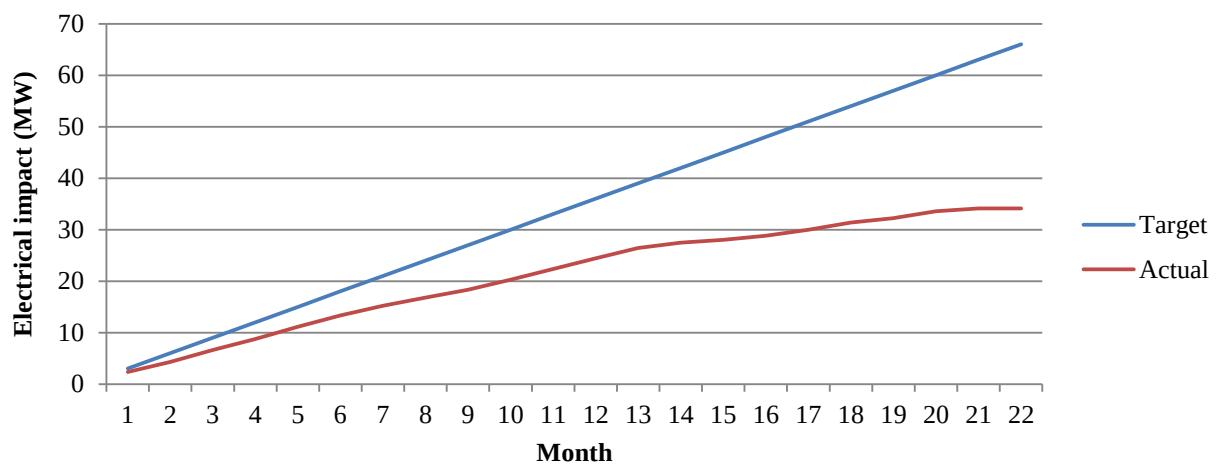


Figure 76: Unmaintained water reticulation EMS cumulative performance

Manufacturing process

After initially overperforming, the performance of an EMS implemented at a cement manufacturing plant decreased systematically over a nine-month period. The EMS performance history and cumulative performance are shown in Figure 77 and Figure 78 respectively. The constructive cumulative effect of initial overperformance was diminished after a ten-month period as shown in Figure 78.

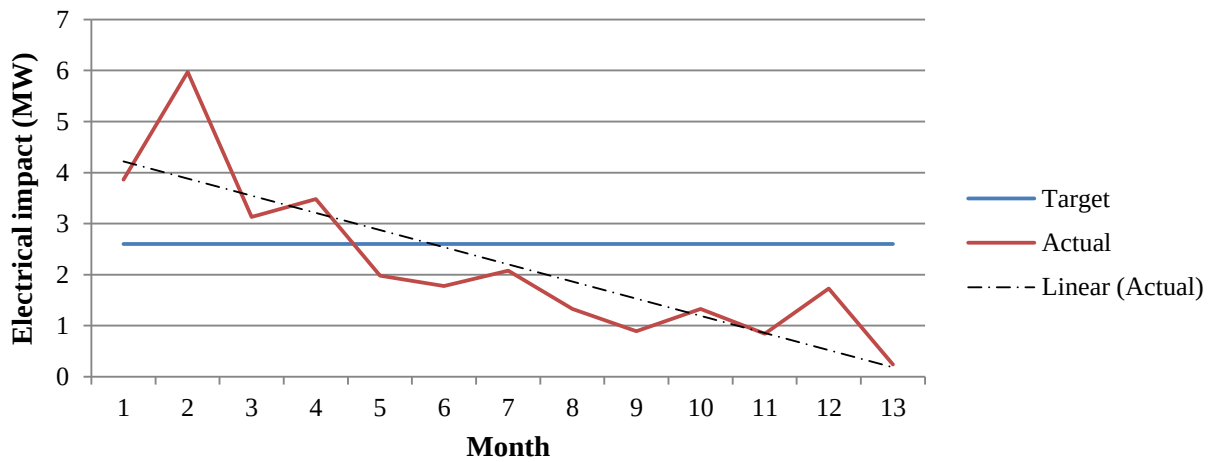


Figure 77: Unmaintained process EMS performance history

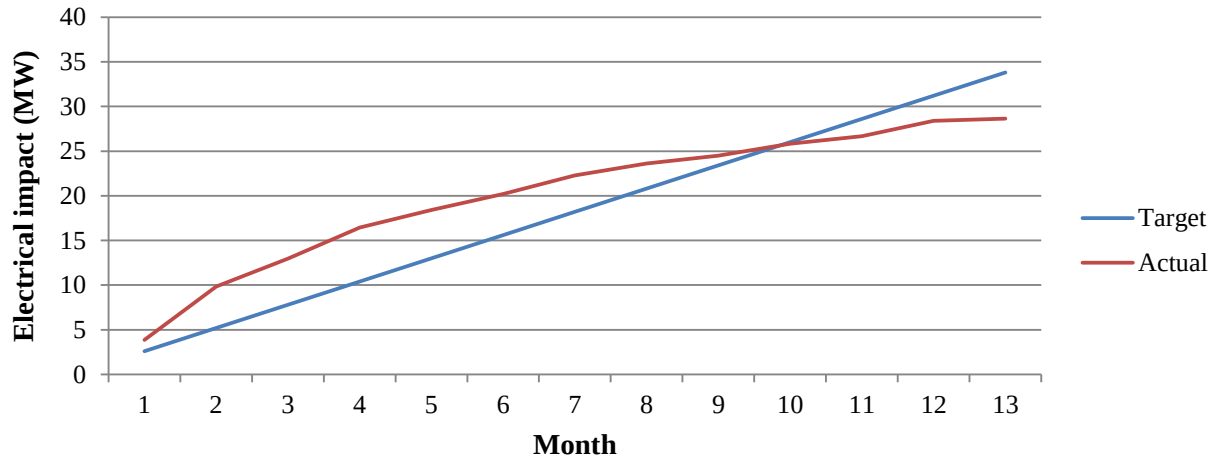


Figure 78: Unmaintained process EMS cumulative performance

Water pumping scheme

An EMS implemented on a national pumping scheme performed exceptionally well during the seven months following the system implementation. The performance met the set target for the first eleven months after implementation, but declined over the next nine months. Figure 79 shows that the performance decreased to around 33% compared with a maximum performance of approximately 240% achieved after the EMS implementation. As shown in Figure 80, the cumulative performance remains satisfactory due to the initial overperformance, but is expected to decline until the cumulative EMS performance becomes unacceptable.

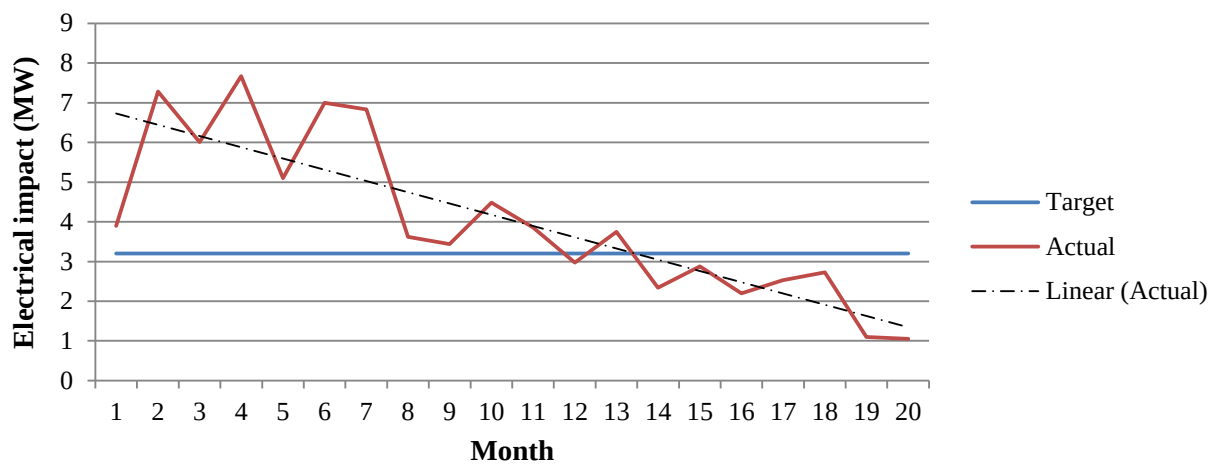


Figure 79: Unmaintained water pumping EMS performance history

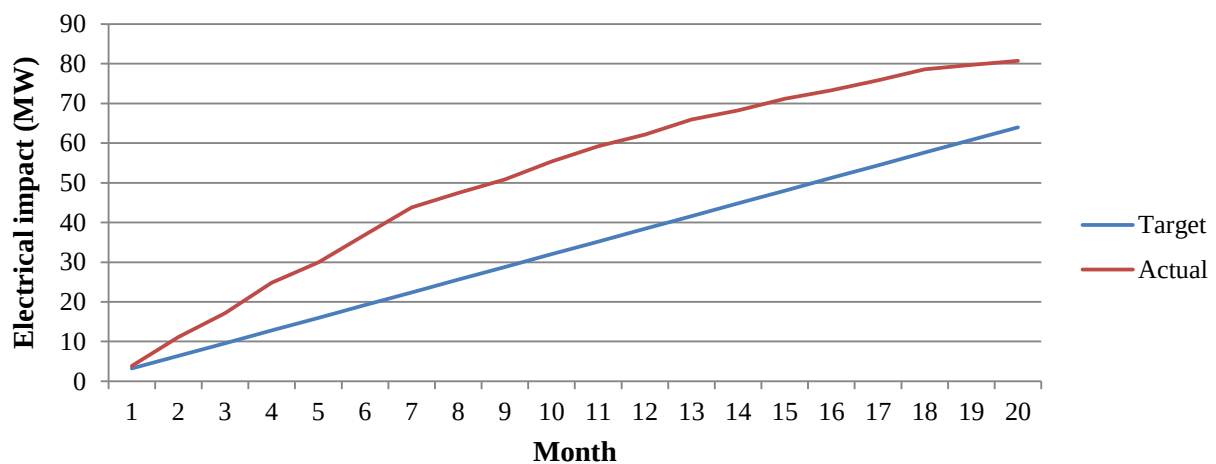


Figure 80: Unmaintained water pumping EMS cumulative performance

ANNEXURE B. ADDITIONAL INFORMATION ON CASE STUDY 1

EMS information

Figure 81 is a schematic of an underground water reticulation system. Water is pumped from the dams on 67 level to a dam on 53 level. From this pumping station, the water is pumped to a pumping station on 30 level, from where the water is pumped to the surface. This mine has three underground pumping stations with an installed electrical capacity of 7.6 MW.

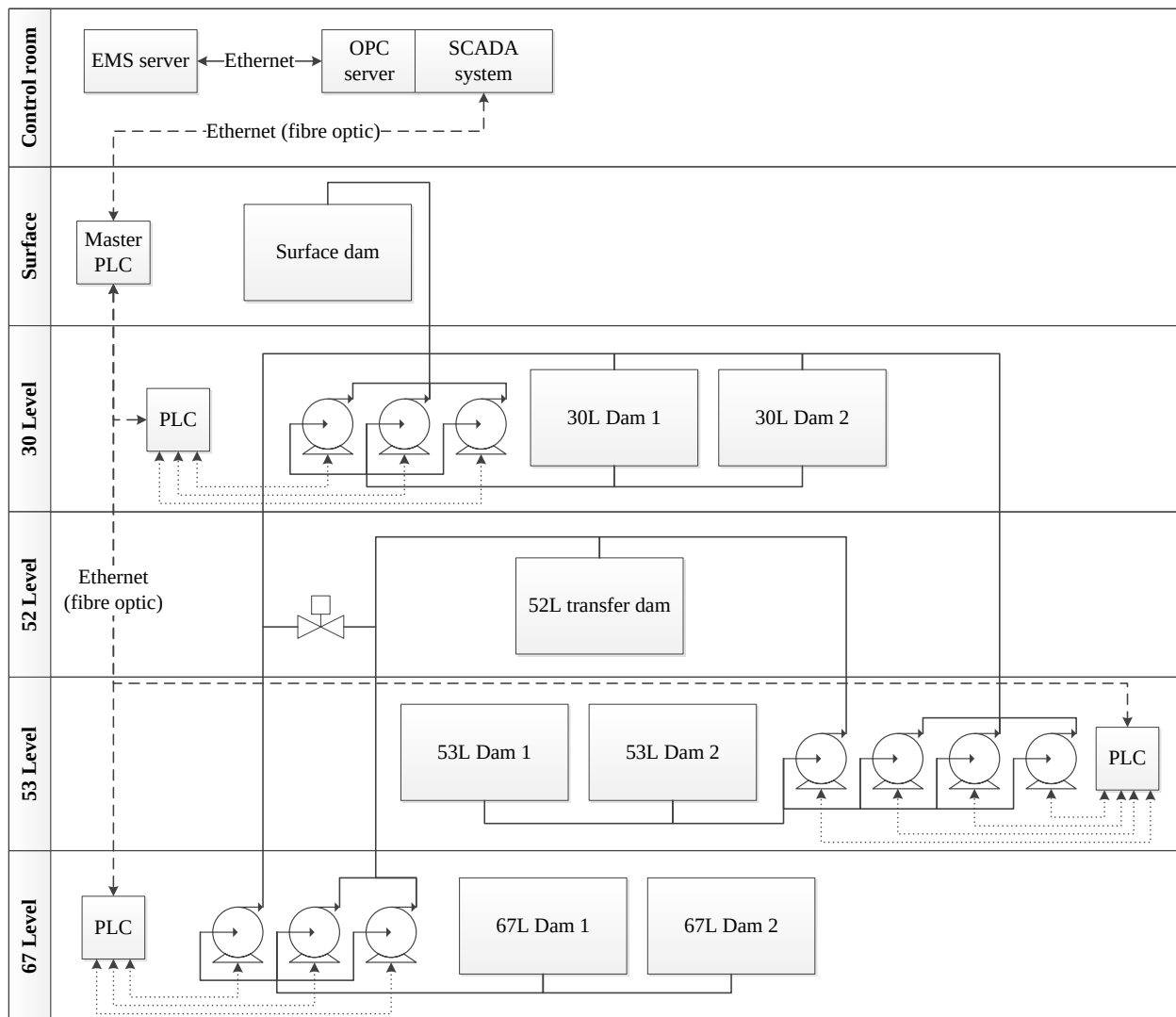


Figure 81: Case Study 1 – EMS layout

Table 16 provides a summary of the pumping installation.

Table 16: Case Study 1 – Pump information

Level	Pump Number	Manufacturer	Capacity (MW)
67	1	MRC	0.5
	2	MRC	0.5
	3	MRC	0.5
53	4	Sulzer	1.0
	5	Sulzer	1.0
	6	MRC	0.6
30	7	Sulzer	1.1
	8	Sulzer	1.1
	9	MRC	1.3

Dam level constraints are adjusted to be less constrictive during Eskom peak periods to achieve electrical load shifting. Table 17 summarises the dam level control executed by the EMS chosen for Case Study 1. Dam levels are allowed to increase above the control constraints set for non-peak periods. These levels are, however, maintained within safe level constraints.

Table 17: Case Study 1 – Dam level control strategy

Level	Level constraints		Control range	
	Minimum	Maximum	Non-peak periods	Peak periods
30	40%	90%	40% - 60%	No pumping until 90% Pumping until 80%
53	35%	90%	35% - 60%	No pumping until 90% Pumping until 80%
67	60%	92%	60% - 80%	No pumping until 92% Pumping until 80%

Examples of control philosophy overrides

Figure 82 and Figure 83 show two examples of operator overrides that negatively affected the performance of the EMS. These figures show the specific pump status in hourly averages for a specific day. In Figure 82, the EMS stopped the pump at 18:00 with an upstream dam level of 75%. The operator started the pump immediately even though the EMS would have scheduled the pump to start when the dam level reached 90%.

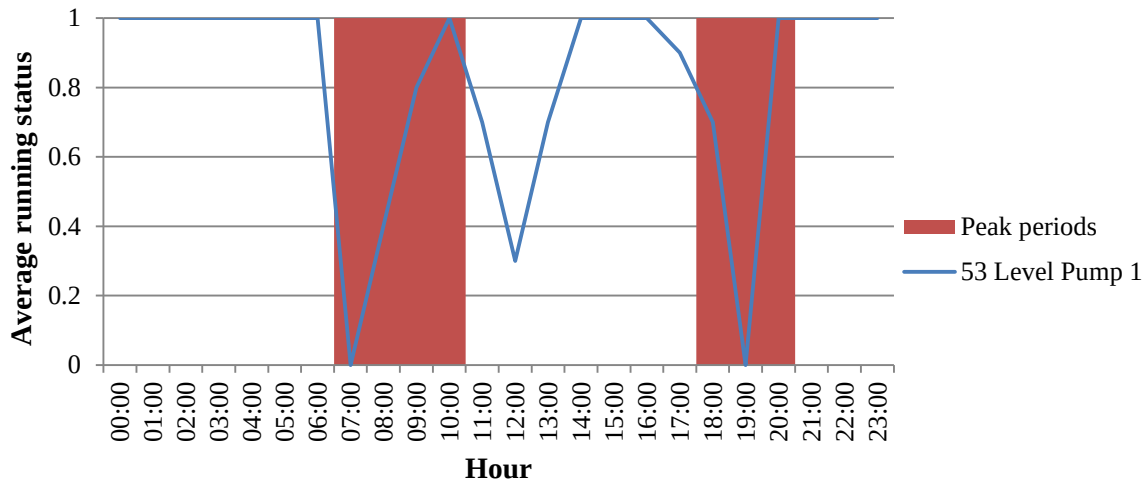


Figure 82: Case Study 1 – Effect of EMS Override 1

In Figure 83, the operator stopped the pump at 04:45 and kept it on override until the upstream dam level reached 83% at 07:00. The EMS would have kept the level below 60% before reaching the peak period at 06:00, allowing the pump to remain off until the end of the morning peak period.

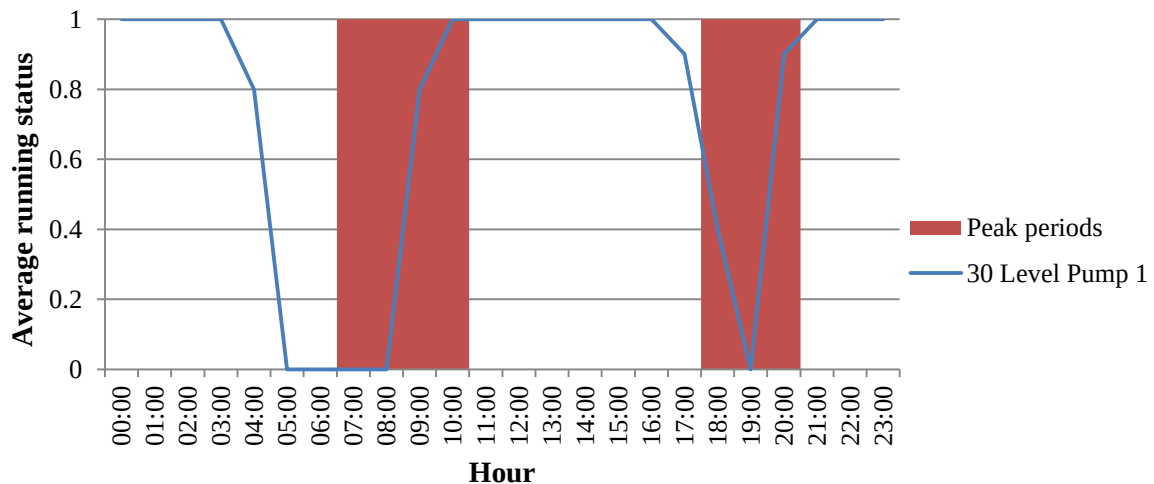


Figure 83: Case Study 1 – Effect of EMS Overrides 1

Additional results

Table 18 summarises the operational availability of the EMS and on-site supervisory systems components for Case Study 1 over a seven-month period.

Table 18: Case Study 1 – Average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	100	100	100	100	100	95	98	100
2	100	100	100	100	100	98	98	100
3	100	100	100	100	100	97	98	100
4	100	100	100	100	100	98	98	100
5	100	100	100	100	100	98	98	100
6	100	100	100	100	100	98	98	100
7	100	100	100	100	100	84	92	87

Table 19 summarises the electrical and financial performance of the presented in Case Study 1 over a seven-month period.

Table 19: Case Study 1 – Average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Cost saving (R)
1	1.9	2.1	2.2	42 819
2	1.9	2.0	2.0	251 052
3	1.9	1.8	1.8	281 620
4	1.9	2.0	2.0	286 841
5	1.9	1.5	1.5	40 222
6	1.9	1.6	1.6	50 944
7	1.9	1.1	1.2	32 488

ANNEXURE C. ADDITIONAL INFORMATION ON CASE STUDY 2

EMS information

Figure 84 presents a schematic of the surface cooling system. Warm water is pumped out of the mine and into a hot water storage dam. From there, water is pumped to a precooling tower and into a precooling dam. The precooling dam supplies water to two sets of fridge plants, which exports water to the chilled water storage dam. Water is gravity-fed underground according to demand. If the water demand is low, water is pumped back to the precooling dam and cycled through the cooling system.

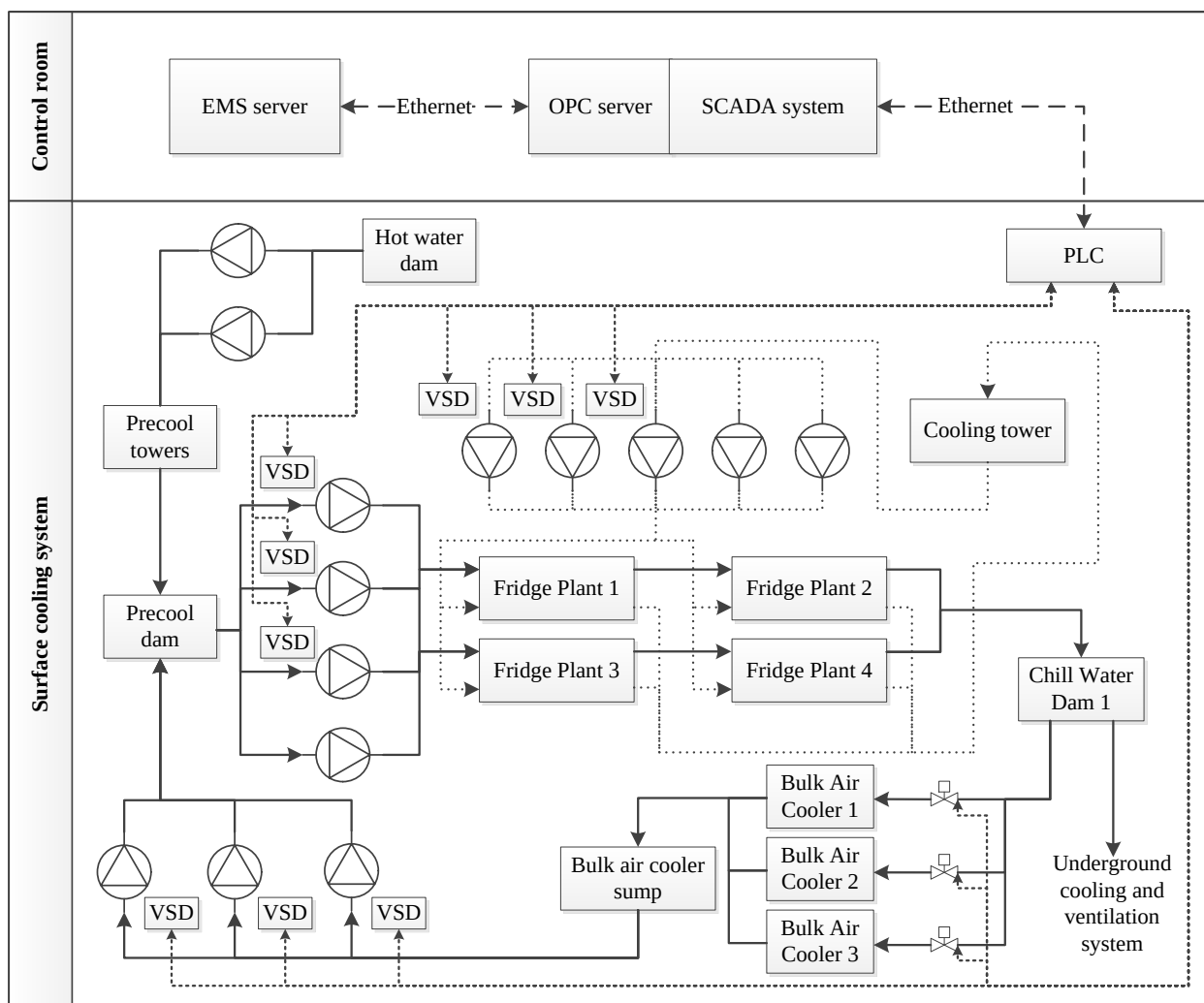


Figure 84: Case Study 2 – EMS layout [adapted from (Du Plessis, Liebenberg & Mathews, 2013)]

Additional results

Table 20 summarises the operational availability of the EMS and on-site supervisory systems components for Case Study 2 over a four-month period.

Table 20: Case Study 2 – Average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	100	100	100	100	100	98	98	100
2	100	100	96	94	98	96	96	100
3	100	100	100	100	100	98	98	100
4	100	100	100	99	100	98	98	100

Table 21 summarises the electrical and financial performance of the presented in Case Study 2 over a four-month period.

Table 21: Case Study 2 – Average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Cost saving (R)
1	1.5	3.5	3.5	889 818
2	1.5	2.8	2.9	738 820
3	1.5	2.8	2.8	713 143
4	1.5	3.9	3.6	841 886

ANNEXURE D. ADDITIONAL INFORMATION ON CASE STUDY 3

EMS information

At this gold mine five compressors supply compressed air to twenty-five underground levels, extending to 3.5 km below the surface. The compressors are all located at a central compressor house. The compressors are locally controlled using a PLC. Remote control is possible through an Ethernet network that connects the PLC to the SCADA system as shown in Figure 85.

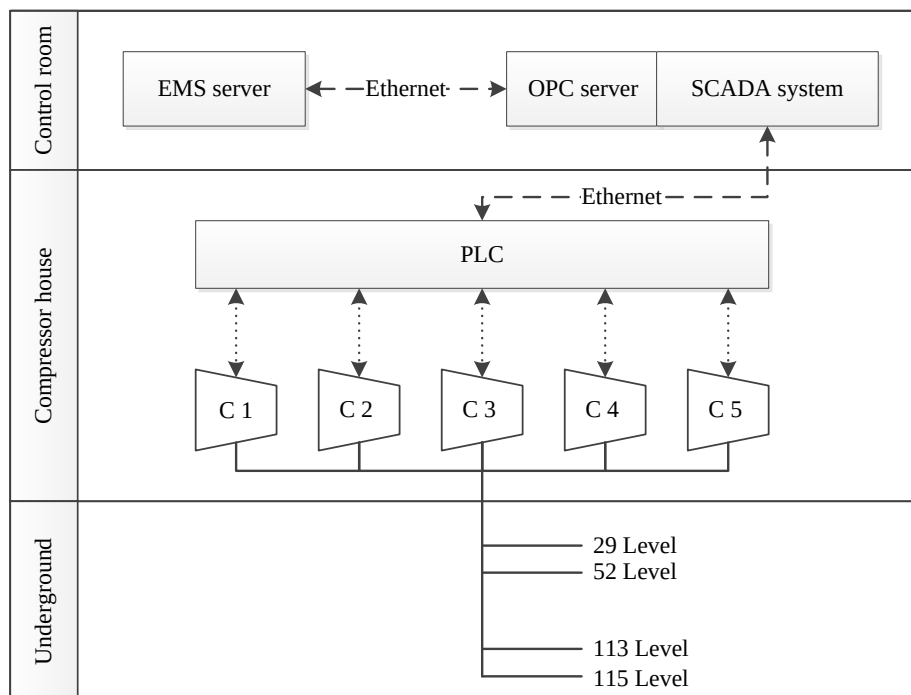


Figure 85: Case Study 3 – EMS layout

An EMS controls the compressors via an OPC server that runs on the SCADA system, using the infrastructure in Figure 85. Table 22 provides information on the compressors that have a total installed electrical capacity of 21.2 MW.

Table 22: Case Study 3 – Compressor information

Number	Manufacturer	Motor capacity (MW)
1	Sulzer	4.8
2	Sulzer	4.8
3	Sulzer	2.0
4	Sulzer	4.8
5	Sulzer	4.8

To control compressed air supply and demand, infrastructure was installed as part of the original EMS implementation. Details on the work that formed part of the EMS implementation is summarised in Table 23.

Table 23: Case Study 3 – EMS implementation

Area	Infrastructure
Supply	Compressor guide vane control for cutback
	Compressor automation
	Pressure and flow metering
Demand	Pipe work
Control	Optic fibre and tie-ins for patch panels
	PLC equipment and enclosure for each compressor
	SCADA system
	EMS server

Figure 85 shows the compressed air system with implemented EMS infrastructure. The SCADA system allows the EMS server control of the compressors and control valves, based on real-time flow and pressure measurements, as described in Section 2.4.

Additional results

Table 24 summarises the operational availability of the EMS and on-site supervisory systems components for Case Study 3 over a four-month period.

Table 24: Case Study 3 – Average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	97	100	100	100	100	99	99	100
2	93	97	97	95	97	95	95	97
3	95	99	99	99	99	97	74	99
4	92	96	96	95	96	94	94	96

Table 25 summarises the electrical and financial performance of the presented in Case Study 3 over a four-month period.

Table 25: Case Study 3 – Average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Cost saving (R)
1	2	1.2	1.2	32 842
2	2	1.6	2.3	142 369
3	2	3.0	3.2	191 205
4	2	2.5	3.8	151 568

ANNEXURE E. ADDITIONAL RESULTS ON FURTHER INTEGRATIONS

EMS A – Water reticulation system

Table 26 summarises the operational availability of EMS A and on-site supervisory systems components over a nine-month period.

Table 26: EMS A average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	83	84	84	82	84	67	80	1
2	100	100	100	100	100	82	96	19
3	97	97	97	96	97	78	90	97
4	100	100	100	100	100	80	83	100
5	99	99	99	97	99	99	99	99
6	99	99	99	99	99	99	99	99
7	100	100	100	100	100	99	99	100
8	100	100	100	99	100	99	99	100
9	100	100	100	100	100	99	99	100

Table 27 summarises the electrical and financial performance of EMS A over a nine-month period.

Table 27: EMS A average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	3.1	2.7	2.6	Summer	96 085
2	3.1	4.0	4.0	Winter	651 992
3	3.1	3.9	4.1	Winter	612 725
4	3.1	3.1	3.2	Winter	352 212
5	3.1	3.1	3.3	Summer	108 618
6	3.1	3.4	3.4	Summer	123 659
7	3.1	3.4	3.4	Summer	108 167
8	3.1	2.2	2.3	Summer	68 892
9	3.1	3.8	4.1	Summer	137 910

EMS B – Compressed air system

Table 28 summarises the operational availability of EMS B and on-site supervisory systems components over a nine-month period.

Table 28: EMS B average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	81	81	81	80	81	91	82	81
2	99	99	99	98	99	96	88	99
3	100	100	100	100	100	95	91	100
4	100	100	100	98	100	94	90	100
5	100	100	100	100	100	95	94	100
6	100	100	100	96	100	92	96	100
7	100	100	100	100	100	92	92	100
8	100	100	100	99	100	98	97	100
9	100	100	100	100	100	97	98	100

Table 29 summarises the electrical and financial performance of EMS B over a nine-month period.

Table 29: EMS B average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	2.5	2.7	2.9	Summer	750 661
2	2.5	3.1	3.1	Winter	1 358 082
3	2.5	3.2	3.4	Winter	1 598 421
4	2.5	3.4	3.3	Winter	1 580 036
5	2.5	3.2	3.2	Summer	792 197
6	2.5	2.8	2.7	Summer	763 967
7	2.5	3.0	2.8	Summer	722 714
8	2.5	3.4	3.3	Summer	870 804
9	2.5	2.9	2.8	Summer	748 207

EMS C - Compressed air system

Table 30 summarises the operational availability of EMS C and on-site supervisory systems components over an eight-month period.

Table 30: EMS C average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	100	100	100	100	100	98	98	100
2	100	100	100	100	100	98	98	100
3	99	99	99	99	99	81	95	99
4	100	100	100	100	100	97	98	100
5	100	100	100	100	100	98	98	100
6	100	100	100	99	98	89	89	81
7	100	100	100	100	100	98	98	100
8	100	100	100	100	100	96	98	100

Table 31 summarises the electrical and financial performance of EMS C over an eight-month period.

Table 31: EMS C average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	1.5	1.6	1.6	Winter	791 129
2	1.5	1.7	1.6	Winter	823 699
3	1.5	2.9	1.9	Summer	731 291
4	1.5	2.2	2.0	Summer	607 351
5	1.5	2.2	2.2	Summer	571 253
6	1.5	3.8	2.9	Summer	1 005 421
7	1.5	2.6	2.1	Summer	715 814
8	1.5	2.0	2.0	Summer	481 898

EMS D - Compressed air system

Table 32 summarises the operational availability of EMS D and on-site supervisory systems components over a seven-month period.

Table 32: EMS D average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	100	100	100	100	95	79	0	100
2	100	100	100	99	96	90	3	100
3	100	100	100	100	100	91	0	100
4	100	100	100	98	100	98	0	100
5	100	100	100	98	100	96	0	100
6	100	100	100	96	100	98	0	100
7	100	100	91	89	100	97	0	100

Table 33 summarises the electrical and financial performance of EMS D over a seven-month period.

Table 33: EMS D average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	3	3.9	3.8	Winter	2 232 512
2	3	4.6	4.6	Winter	2 309 414
3	3	5.1	5.1	Summer	1 320 809
4	3	5.8	5.8	Summer	1 567 593
5	3	3.9	3.9	Summer	959 371
6	3	5.2	5.2	Summer	1 355 598
7	3	4.3	4.3	Summer	1 160 429

EMS E – Water reticulation system

Table 34 summarises the operational availability of EMS E and on-site supervisory systems components over a seven-month period.

Table 34: EMS E average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	99	99	99	99	99	99	47	99
2	99	98	98	98	92	92	57	97
3	99	99	99	99	99	96	68	99
4	99	99	99	99	99	99	84	99
5	99	99	99	98	97	97	87	99
6	99	99	99	99	99	99	94	99
7	99	99	99	99	99	96	87	99

Table 35 summarises the electrical and financial performance of EMS E over a seven-month period.

Table 35: EMS E average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	2.3	3.0	3.0	Winter	449 114
2	2.3	2.3	2.4	Summer	54 657
3	2.3	2.3	2.4	Summer	72 416
4	2.3	2.5	2.5	Summer	72 409
5	2.3	2.2	2.3	Summer	70 421
6	2.3	2.3	2.3	Summer	80 159
7	2.3	2.6	2.6	Summer	78 322

EMS F - Compressed air system

Table 36 summarises the operational availability of EMS F and on-site supervisory systems components over a seven-month period.

Table 36: EMS F average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	96	96	96	96	96	94	35	51
2	86	86	84	84	85	79	77	85
3	100	100	100	98	100	96	89	100
4	100	100	100	99	100	98	95	100
5	100	100	100	96	100	95	98	100
6	100	100	100	100	100	95	95	100
7	100	100	100	99	100	99	99	100

Table 37 summarises the electrical and financial performance of EMS F over a seven-month period.

Table 37: EMS F average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	1.7	1.6	1.7	Winter	703 065
2	1.7	2.6	2.5	Winter	796 932
3	1.7	2.0	2.0	Winter	963 872
4	1.7	1.8	1.8	Summer	448 623
5	1.7	1.4	1.3	Summer	393 676
6	1.7	1.6	1.5	Summer	390 803
7	1.7	2.0	2.0	Summer	519 393

EMS G - Compressed air system

Table 38 summarises the operational availability of EMS G and on-site supervisory systems components over a six-month period.

Table 38: EMS G average daily operational availability

Month	DMA (%)	Access (%)	Router (%)	SMTTP (%)	EMS (%)	OPC (%)	Automatic (%)	Redundancy (%)
1	95	100	100	100	100	95	95	100
2	100	100	100	100	100	77	77	100
3	97	100	98	91	99	79	79	91
4	99	100	99	98	99	94	94	45
5	100	100	100	100	100	98	98	100
6	100	100	100	100	100	98	98	100

Table 39 summarises the electrical and financial performance of EMS G over a six-month period.

Table 39: EMS G average daily EMS performance

Month	Target (MW)	Actual (MW)	Adjusted (MW)	Tariff	Financial (R)
1	1.4	2.1	2.0	Summer	375 216
2	1.4	1.6	1.6	Summer	415 841
3	1.4	1.6	1.6	Summer	374 033
4	1.4	1.8	1.8	Summer	470 212
5	1.4	1.5	1.5	Summer	378 521
6	1.4	1.5	1.5	Summer	283 150