

Investigating the effect of pump availability on load shift performance

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Abstract

Title: Investigating the effect of pump availability on load shift performance

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Due to the high electricity consumption trends of pumping operations in the mining sector, numerous load-shifting projects have been implemented to reduce peak TOU demand for electricity.

A lack of maintenance on pump dewatering systems has caused some deterioration in load shift performance. Many studies have been conducted, focusing on the maintenance of mining dewatering systems to improve the load shift performance during the performance tracking period. However, limited research has been published that evaluates the effect that pump availability has on load shift performance.

No method was found in existing literature that investigates the effect that pump availability has on load shift performance. The need to investigate such effect of pump availability on load shift performance is identified. A method is required that enables investigation and quantification of the effect that pump availability has on load shift performance. Furthermore, the method should enable one to schedule and prioritise maintenance on a dewatering system.

A step-by-step methodology is developed from the research to investigate the effect of pump availability on load shift performance. The methodology consists of four phases supported by eight individual steps. The methodology assists in the development of a simulation model to investigate the effect that pump availability has on load shift performance. Additionally, the methodology outlines how to use the simulation model to obtain quantifiable results.

The methodology is applied to the dewatering systems on three different mines. Each dewatering level of the mine is isolated from the adjacent dewatering levels. Eight case studies are described in the study. The results obtained from the case studies revealed

reduced pump availability. The reduced availability correlated to poor load shift performance. Specifically, hours of reduced availability preceded peak TOU. It is also found that reduced availability of pumps for more than one hour further decreases performance.

The results proved that if the availability of one pump is reduced for one hour, the operating cost can increase to a total of R1.4-million p.a. for the abovementioned three mines. If the availability of one pump is reduced for two hours, the operating cost can increase to a total of R 4.6-million p.a. for the three mines.

Lastly, it is found that maintenance should be conducted during the peak TOU periods. If maintenance is conducted during these times, then no effect will be seen on the load shift performance due to unavailable pumps. If maintenance cannot be conducted during these times, then maintenance should be conducted in the hours not preceding the four hours of peak TOU.

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All information portrayed in this dissertation was applied with the acknowledgment of sources and reference to published work. Please inform me if any oversights are noticed by the reader, so any omission can be rectified.

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Abbreviation

CL	Comeback Load
CR	Control Range
DE	Drive End
DL	Dam Level
DOE	Design of Experiment
DSM	Demand Side Management
ESCO	Energy Services Company
FMC	Flexible Manufacturing Cells
GWh	Gigawatt-Hour
HMI	Human Machine Interface
km	Kilometre
kPa	Kilopascal
kWh	Kilowatt-Hour
LB	Lower Bound
m	Metre
MW	Megawatt
MWh	Megawatt-Hour
NDE	Non-Drive End
NERSA	National Energy Regulator of South Africa
NL	Normal Load
OB	Offset Bottom
OBV	Offset Bottom Value
OPC	Object Linking and Embedding for Process Control
OT	Offset Top
OTV	Offset Top Value
PA	Performance Assessment
PL	Preparation Load
PLC	Programmable Logic Controller
PT	Performance Tracking
R	South African Rand
REMS-Pumps	Real-time Energy Management System for Pumps
SCADA	Supervisory Control and Data Acquisition
SME	Subject Matter Expert
TOU	Time-Of-Use
UB	Upper Bound
UPS	Uninterrupted Power Supply

Chapter 1:

Introduction



Wind and solar energy¹

Electrical science has revealed to us the true nature of light, has provided us with innumerable appliances and instruments of precision, and has thereby vastly added to the exactness of our knowledge

(Nikola Tesla)

¹ World energy council, 2015.[Online].
Available at: <https://www.worldenergy.org/news-and-media/local-news/usea-shares-knowledge-on-small-island-power/solar-panels-and-wind-turbines/>

1 INTRODUCTION

1.1 ELECTRICITY SUPPLY AND DEMAND

1.1.1 GLOBAL ENERGY DEMAND

Energy promotes social and economic development. Global energy supply has changed significantly over the past 20 years. The global population has increased by 27% from 1993 to 2011, whereas the electricity supply has increased by 76% for the same period [1]. As a result, the need for more generating capacity exists [1].

Fossil fuels, particularly coal and oil, are by far the most frequently used resources to generate electricity globally. Generation via coal-fired power stations provides approximately 40% of the global electricity. The reason coal is used as an energy source can be attributed to the fact that it is a widely spread resource, and less expensive to mine than other resources [1].

However, generation from alternative energy sources is being developed to replace fossil fuels, particularly with international pressure to create sustainable and cleaner / greener energy. As the technology develops in terms of electricity supply, so the need for more efficient and cleaner energy is imminent to reduce greenhouse gasses. Therefore, the need for clean energy, even if the World believes fossil fuel resources are in abundance, will be the future of electricity generation. However, clean energy is costly and can lead to an increase in electricity prices. [1]



Figure 1-1: Green energy awareness²

² Figure received from [77] a courtesy of justiceandenvironment.org

1.1.2 SOUTH AFRICAN ELECTRICITY SUPPLY

South Africa generates two thirds of Africa's electricity [2]. Coal-fired power stations contribute to approximately 90% of the total electricity generation. The remaining 10% of electricity is generated by alternative power stations such as nuclear- and hydro-power stations [2].

Eskom leads in electricity generation in South Africa. The utility accounts for 95% of electricity generated. Eskom controls high-voltage power lines and supplies electricity directly to the main consumers such as municipalities, mines and industries [3].

In 2008, South Africa faced a severe electricity supply shortage. Blackouts, or so-called load-shedding, affected the country. Domestic and industrial sectors were all affected by the blackouts. The reasons for blackouts are disputed in an article by Inglesi, published in 2010, to be caused by insufficient local information and a lack of generating capacity by Eskom [4].

In August 2008, the Mail & Guardian released an article that stated that the National Energy Regulator of South Africa (NERSA) calculated the estimated loss to the economy to be R50-billion, due to the blackouts [5]. This is the estimate only for 2008 and since then, load-shedding is still part of an ordinary day in South Africa [6].

The Mail & Guardian reported on 3 July 2015 that the cost of running emergency open gas cycle turbines is estimated at R2-billion a month. Eskom, however, estimates the loss of income to the country to be R80-billion per month – if the emergency generators do not operate [7].

In conclusion, Eskom struggles to meet the electricity demand of South Africa and is faced with extreme costs for upgrades and maintenance. Operating emergency turbines also led to electricity price increases. Initiatives such as time-of-use structures (TOU) and demand side management (DSM) were implemented to counter some of the emergency measures. The initiatives aim to reduce the electricity demand during peak periods of electricity usage. TOU structures and DSM will be discussed in the sections that follow

1.1.3 TIME-OF-USE STRUCTURES

Eskom introduced variable price structures, also known as TOU tariffs, in 1992. The TOU structures consist of three periods, i.e. peak, off-peak and standard times. The TOU structures focus on reducing the electricity usage of consumers during certain periods of the day. The usage is reduced by billing more per unit used during peak TOU periods [8].

From the average demand profile of Eskom illustrated in Figure 1-2, three distinct periods can be identified: periods of low, medium and high demand. [9]

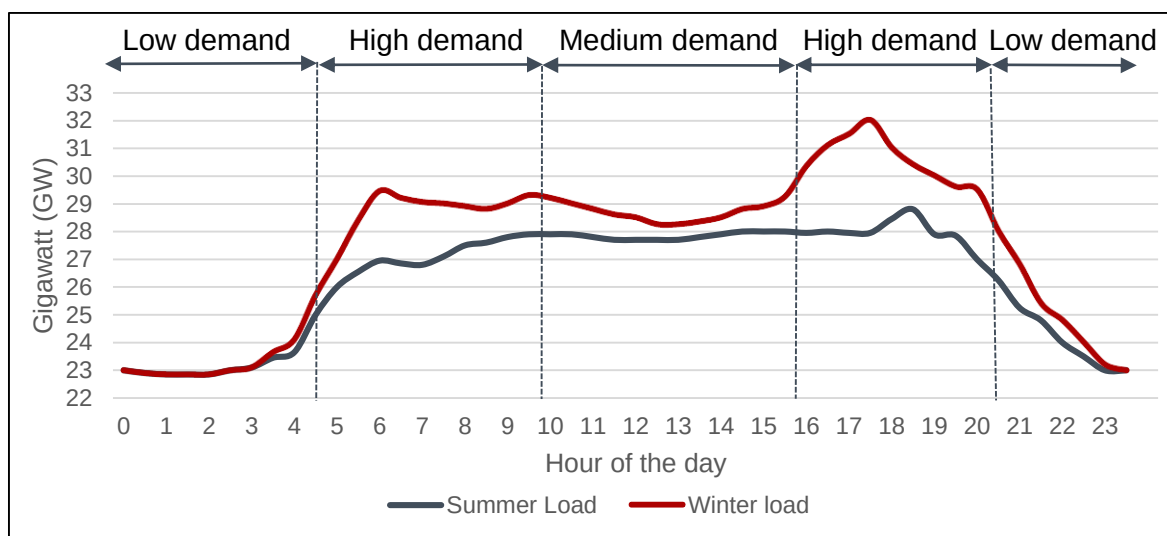


Figure 1-2: Average winter and summer load profiles

Peak TOU pricing is enforced at times of the day when the electricity demand is the highest, and thus the most expensive. Off-peak TOU structures apply during times of the day when the electricity demand is the lowest, making it the least expensive. Standard TOU structures apply to periods of the day when the demand is moderate [8]. More information on TOU structures and tariffs are available on the Eskom webpage [10].

In 2015, Eskom requested to move the TOU structures an hour earlier during high-demand winter months. NERSA approved the change in TOU periods on 26 February 2015. The request was uplifted because of the misalignment between the actual peak demand period and the peak TOU period [11]. Low demand season (summer months) and high demand season (winter months) TOU periods can be seen in Appendix A shown in Table 6-1.

1.1.4 DEMAND-SIDE MANAGEMENT

To reduce peak electricity demand in South Africa further, demand-side management (DSM) interventions were developed [12]. DSM can be defined as a set of interconnected and flexible programmes, which allow electricity consumers to shift their demand for electricity out of peak periods to standard and off-peak periods or to reduce the electricity usage overall [13], [14].

DSM can be divided into two major groups, i.e. demand response programmes and energy efficiency programmes [13]. Various methods exist to manage an electricity users' demand for electricity. The three most common DSM strategies implemented in industries are energy efficiency, load shifting and peak clipping [15].

Energy efficiency initiatives focus on the average reduction in electricity usage throughout a day, therefore reducing the amount of electricity usage without affecting production [13]. Figure 1-3 shows an energy efficiency initiative's power profile example.

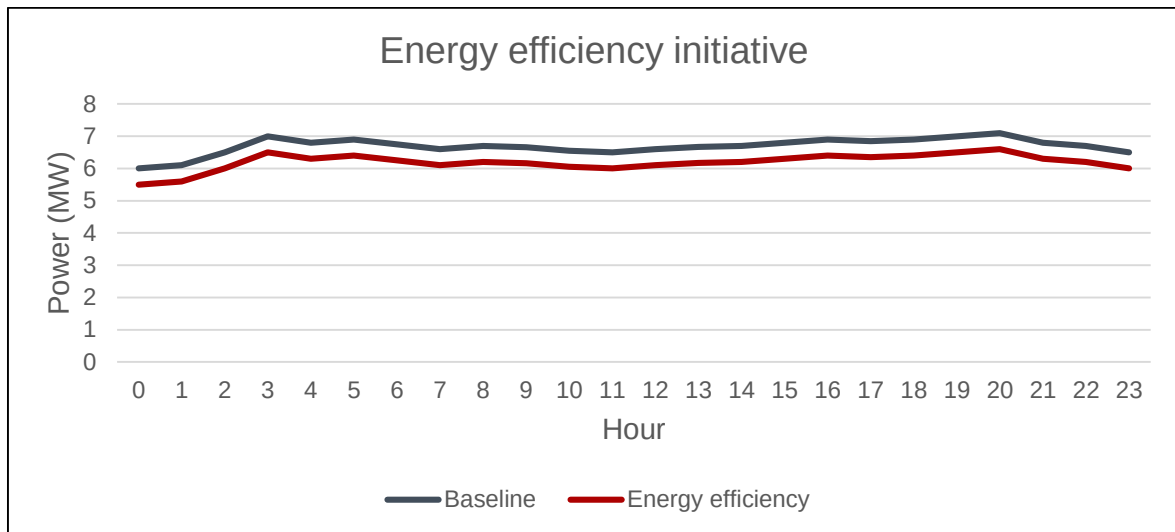


Figure 1-3: Energy efficiency initiatives

Peak clipping initiatives are similar to energy efficiency initiatives. However, peak clipping focuses on reducing the amount of electricity during peak TOU periods instead of reducing the electricity usage overall [15]. Peak clipping initiatives' power profile would typically look like the power profile illustrated in Figure 1-4.

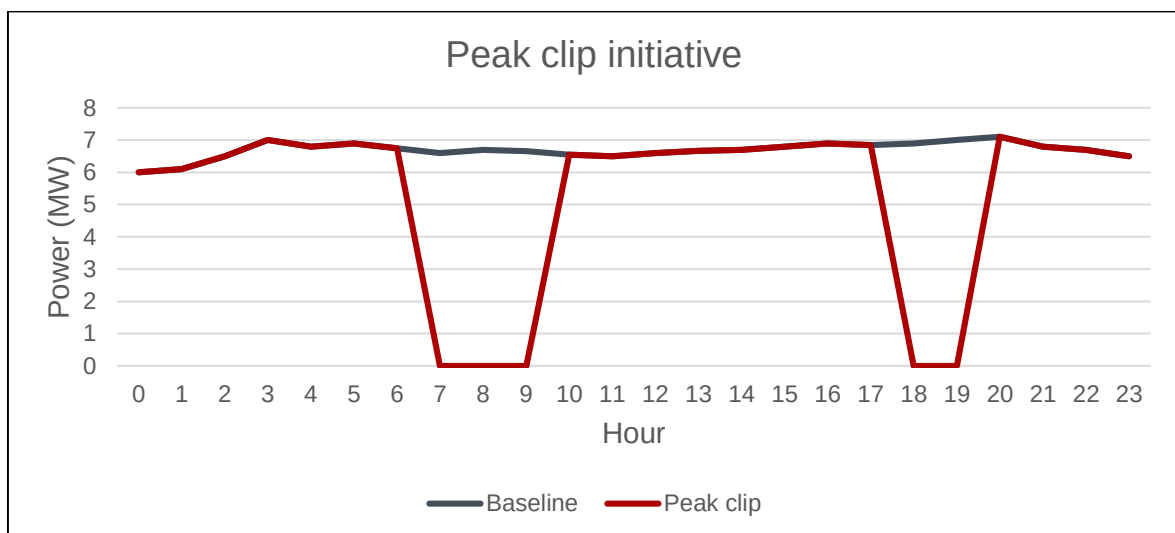


Figure 1-4: Peak clip initiatives

Load-shifting initiatives focus on moving the electricity demand out of peak TOU periods into off-peak and standard periods. Load shift initiatives are considered energy neutral because the same amount of energy is required [15]. The energy used is distributed to less expensive periods of the day as illustrated in Figure 1-5 [13], [15]. The areas (kWh) under both baseline and load-shift profile are equal [15].

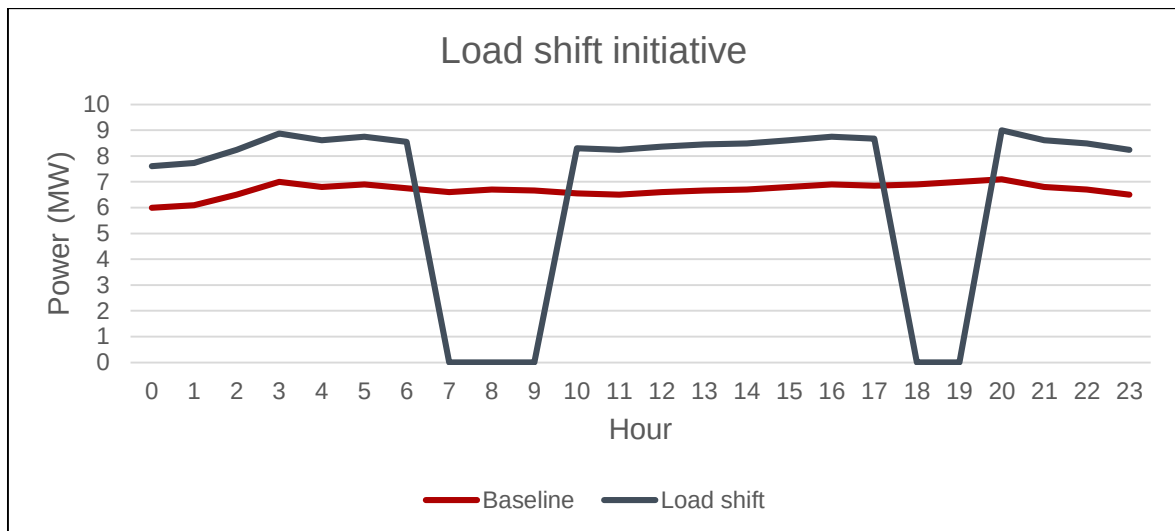


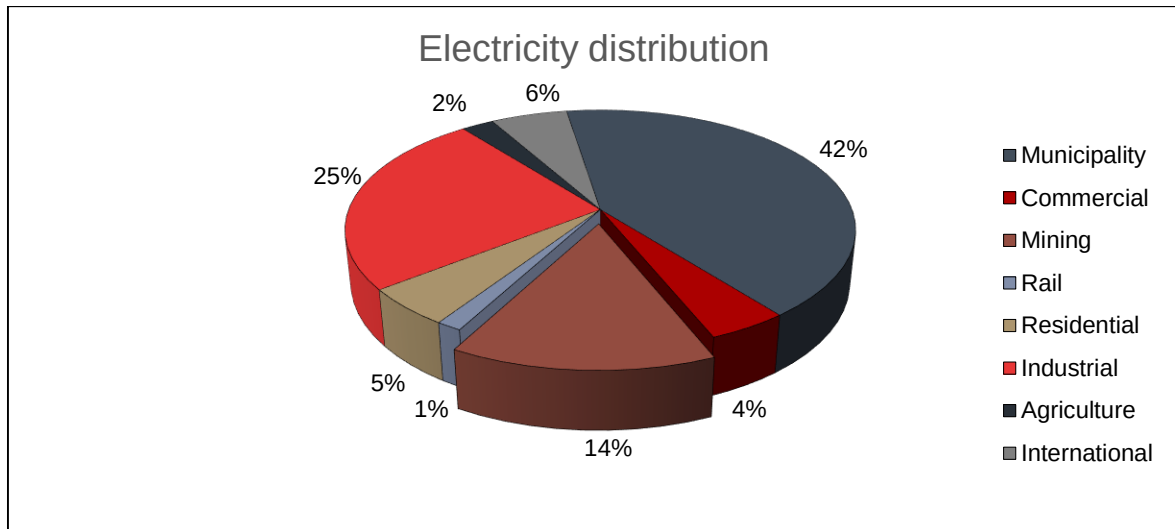
Figure 1-5: Load shift initiatives

Energy services companies (ESCOs) or major energy consumers conduct energy audits and determine if DSM initiatives are viable options to reduce the electricity demand during peak periods. If the ESCO or consumer finds a DSM initiative viable, then formal proposals are presented to Eskom. If the proposal is found to be cost-effective by Eskom, then funds can be provided theoretically to the ESCO or consumer. The funds provided will be used to implement the DSM initiative [14].

1.1.5 INDUSTRIAL DSM APPLICATIONS

Eskom, in their integrated report for 2015, published a distribution chart for electricity demand by client type. The distribution chart is illustrated in Figure 1-6. Evaluating the distribution according to client type, it is obvious that the mining industry makes use of approximately 14% of the total electricity generated by Eskom. [9]

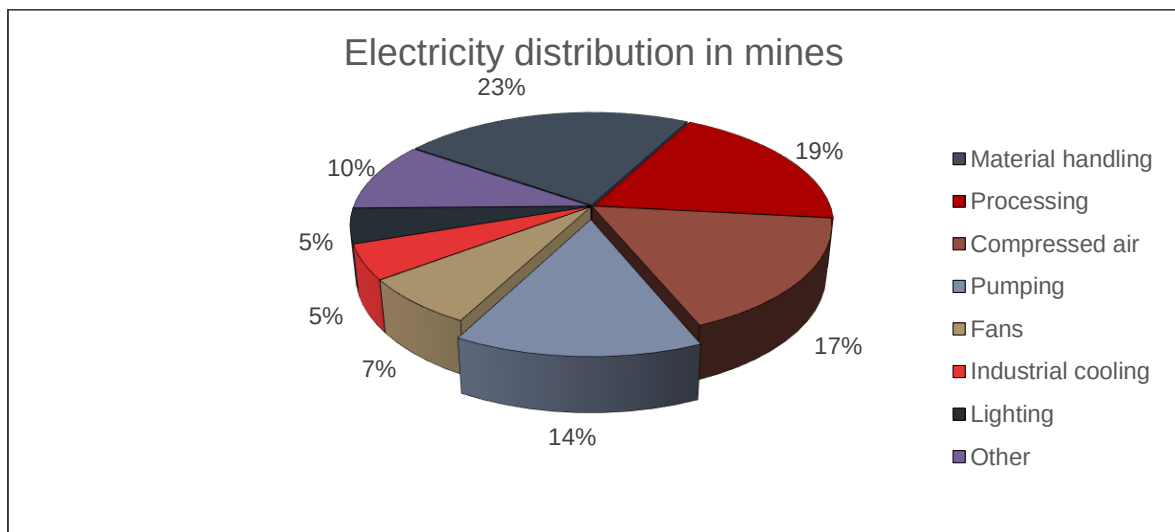
The mining industry is the third largest energy consumer in the country [9]. Therefore, ESCOs focus on mining for DSM interventions. These are found to be more viable in the mining industry, as energy intensive equipment is used in their operations. [9]

Figure 1-6: Electricity distribution between Eskom client types^[9]

During the 2014/2015 financial year, Eskom supplied 30 667 GWh to the mining sector. The main consumers of electricity in the mining sector can be divided into [9]:

1. Material handling;
2. Processing;
3. Compressed air;
4. Pumping;
5. Fans;
6. Industrial cooling;
7. Lighting;
8. Other.

The electricity distribution between the main consumers in the mining sector is illustrated in Figure 1-7 [9].

Figure 1-7: Electricity distribution in mines^[9]

Electricity consumption by pumping systems is the fourth largest in the mining industry. The total use of electricity for pumping in the mining industry is estimated to be 4 293 GWh [9]

The significant amount of electricity used by pumping systems in the mining industry creates ample opportunity for industrial DSM interventions such as load-shifting projects. A significant impact on the electricity demand during peak periods can be achieved if DSM projects are implemented on pumping systems within the mining industry. [15]–[17]

In the sections to follow, the performance of DSM projects will be discussed, particularly load-shift projects on pumping systems. Focus is placed on pumping systems due to the notable electricity demand percentage.

1.2 POST DSM IMPLEMENTATION PERFORMANCE

When ESCOs implement DSM initiatives, then a performance assessment (PA) period is mandatory. The PA period is used to establish if the contracted savings target is achievable by the client after the DSM initiative has been implemented. The client, or consumer, is then responsible to maintain the target achieved during the PA period. [18]

The target must be maintained for a minimum of five years after the PA. This period is known as the performance tracking (PT) period. ESCOs implemented a total of 261 (combined target of 676 MW) industrial DSM projects with the support of Eskom, from 2003 to 2014. The average performance of the 261 DSM projects during the PA period was 98% of the contracted target. [18]

Projects generally tend to deteriorate once the project is handed over to the client. As a result, the DSM projects underperform in some cases during the PT period. Underperformance can be seen when the cumulative savings achieved are compared to the cumulative target for a pumping load shift project as illustrated in Figure 1-8 on the next page.

The performance achieved, cumulated for each month of the PT period, is indicated by the bars. The cumulative contracted target for the project is indicated by the linear line. The X-axis indicates the month of PT and the Y-axis indicates the cumulative megawatts. It shows that the cumulative performance achieved is below the cumulative target. This indicates that the project underperforms during the PT period.

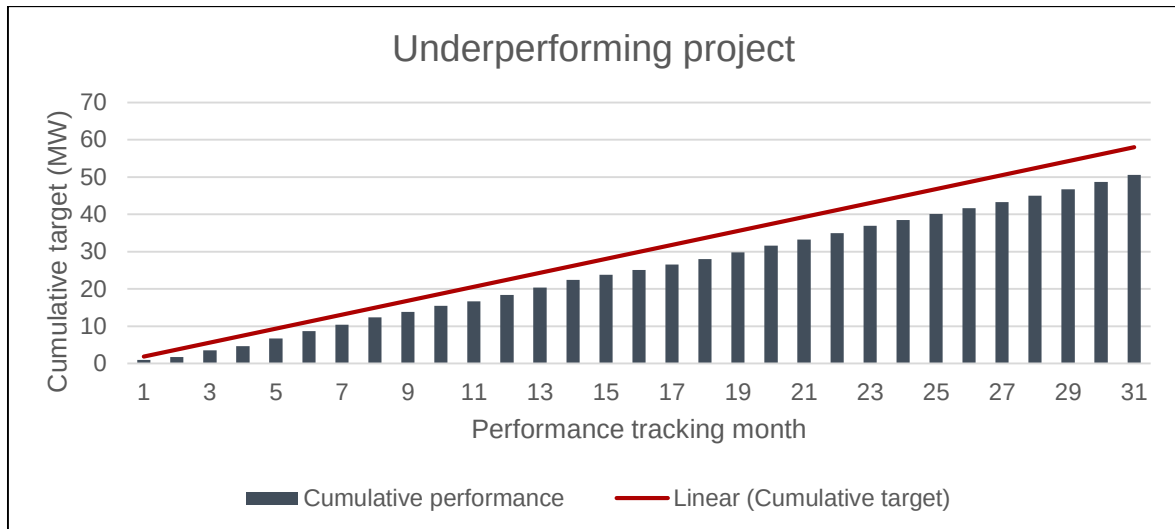


Figure 1-8: Underperforming project's cumulative target vs. cumulative performance

DSM project underperformance can be attributed to [18]:

1. Interference with automatic control;
2. Lack of buffer capacity;
3. High demand or unfavourable conditions that prevent application of DSM initiative;
4. Infrastructure constraints and breakdowns;
5. Control system problems.

Four of the five reasons of underperformance, as previously mentioned, can be a result of little or no maintenance carried out on the system or DSM project. Figure 1-9 illustrates a load-shift DSM project implemented and maintained by an ESCO during the PT period.

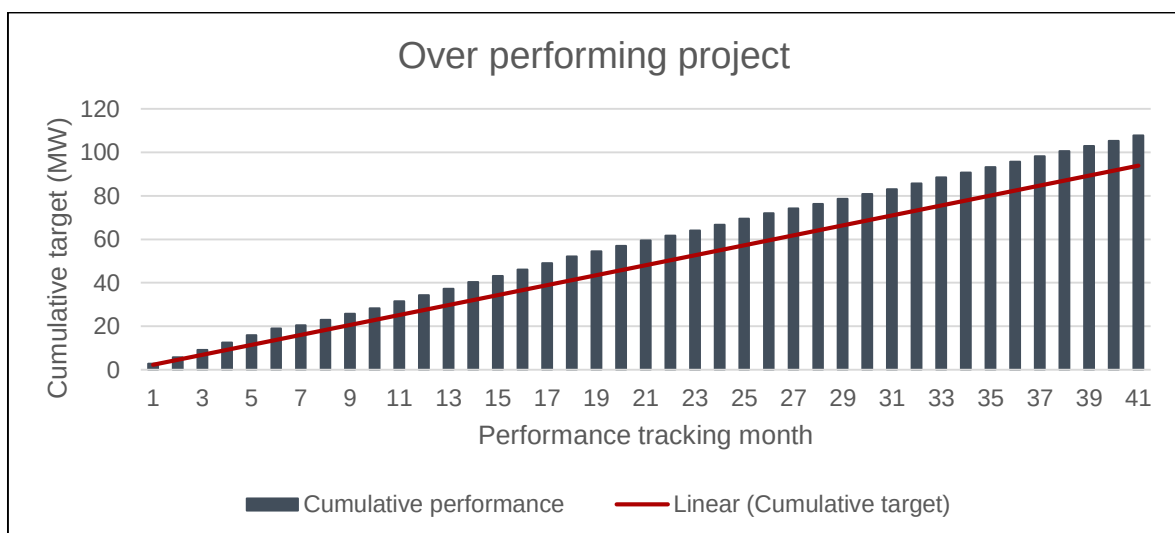


Figure 1-9: Over performing project's cumulative target vs. cumulative performance

The figure shows exactly the same trend as the previous figure, except that in Figure 1-9, the cumulative performance is higher than the cumulative target. This indicates that the project over performs on the contracted load shift.

Figure 1-9 indicates that maintenance on DSM projects is essential during and after the PT period. In the section to follow, maintenance on DSM projects will be discussed to provide further insight to the importance of maintenance.

1.3 PUMP PROJECTS MAINTENANCE

Various types of maintenance policies exist in the industry. Factors such as company policies, operating environment and criticality of the equipment all determine the maintenance type. Some of the most common maintenance types are discussed together with advantages and disadvantages [19]–[24].

1. Reactive maintenance

Reactive maintenance is maintenance done on equipment when the equipment fails. As a result, this maintenance policy can only be applied to equipment that is not essential for production or safety. In other words, no maintenance is done on equipment unless the equipment fails. Reactive maintenance is also known as run-to-failure maintenance or breakdown maintenance. Advantages and disadvantages are listed in Table 1-1 [25].

Table 1-1: Reactive maintenance advantages and disadvantages^[25]

Advantages	Disadvantages
Low policy cost	Increased equipment parts cost due to unplanned downtime of equipment
Staff reduction	Increased labour cost due to • Overtime possibly required • Special staff should be brought in
—	Cost involved with repair or replacement of equipment
—	Failure of secondary equipment as a result of the initial failure
—	Inefficient use of staff resources

2. Preventative maintenance

Preventative maintenance is the maintenance aimed at keeping equipment in a good operational state. Preventative maintenance is time-based and not condition-based. Therefore, this maintenance is done at predetermined time intervals of operation. The time intervals are based normally on the amount of hours of operation or the amount of start and stop cycles. Advantages and disadvantages of preventative maintenance are listed in Table 1-2 [25].

Table 1-2: Preventative maintenance advantages and disadvantages [25]

Advantages	Disadvantages
Cost-effective in capital-intensive processes	Catastrophic failure still likely to occur
Flexibility allows for the adjustment of maintenance periodicity	Labour-intensive
Energy savings	Includes performance of unrequired maintenance
Reduced equipment process failure	Potential for incidental damage to components in conducting unrequired maintenance
Estimated 12%-18% cost savings over reactive maintenance programs	—

3. Predictive maintenance

Predictive maintenance is similar to preventative maintenance. Predictive maintenance makes use of measurements of the equipment to determine degradation. Based on this information, maintenance is carried out. Predictive maintenance is, therefore, condition-based and not time-based such as preventative maintenance. Advantages and disadvantages are listed in Table 1-3 [25].

Table 1-3: Predictive maintenance advantages and disadvantages^[25]

Advantages	Disadvantages
Increased component operational life/availability.	Increased capital layout in diagnostic equipment
Allows for pre-emptive corrective actions	Increased expenses in staff training

Advantages	Disadvantages
Decrease in equipment or process downtime	—
Decrease in costs for parts and labour	—
Improved worker and environmental safety	—
Energy savings	—
Estimated 8%-12% cost savings over preventative maintenance program	—

4. Reliability-centred maintenance

Reliability-centred maintenance is focused on equipment that directly influences the system. Maintenance on equipment, that does not directly influence the system or process, is carried out on a reactive maintenance plan. Advantages and disadvantages are listed in Table 1-4 [25].

Table 1-4: Reliability-centered maintenance advantages and disadvantages^[25]

Advantages	Disadvantages
Can be the most efficient maintenance programme.	Can have significant start-up costs
Lower costs by eliminating unnecessary maintenance	Savings potential not readily seen by management
Reduced probability of sudden equipment failure	—
Able to focus maintenance activities on critical equipment	—
Increased equipment reliability	—
Incorporate root cause analysis	—

Many studies have been conducted on the effect that maintenance has on production [26]–[28]. Maintenance has a positive influence on manufacturing performance. High levels of quality, and strong delivery performance on the manufacturing process, are achieved when regular maintenance is carried out on the system [27].

In a study conducted by Savsar in 2004, five distinct maintenance policies were identified and tested on a Flexible Manufacturing Cells (FMC) system. The effects on production for each of the maintenance policies were determined. The author stated that the production

rate is a direct outcome of the availability of equipment. The increased availability can be attributed to regular maintenance done on the FMC system [26].

It is evident from the preceding information that maintenance on systems plays a primary role in sustainability of projects, equipment life and production. It is also clear that availability is increased when maintenance is carried out on equipment. In the section to follow, availability of equipment are defined and causes of pump unavailability discussed.

1.4 CAUSES OF PUMP UNAVAILABILITY

Availability can also be defined as “*The proportion of time for which the equipment can perform its function*” [29]. Therefore, the availability of dewatering pumps, in this context, can be defined as the portion of time for which the dewatering pumps can execute the commands given to them. In short, the pumps are available for control when the pump statuses and the number of pumps scheduled correlate for the period when the pumps should perform a function.

Availability of equipment can be calculated by determining the percentage of time for which the equipment was able to perform its function (uptime) for the total operating time (total time). The total time is equal to the uptime plus the time the equipment was not able to perform its function (downtime) [30].

Equation 1 illustrates the availability calculation.

$$Availability = \frac{Up\ time}{Total\ time} \quad \text{Equation 1}$$

Where:

Uptime = time period when equipment was able to perform its function

Total time = total time for operation

This calculation can be done for each time interval in a selected data pool [30].

To understand pump availability and to ensure proper load shifting is done on pumping projects, instrumentation and procedures should be set in place. A fully automated pumping system with remote control capability is necessary. Remote control capability means that pumps can be started and stopped from a remote location. Normally, the remote location is a control room on the surface where all operations of the mine are monitored [18].

A study conducted in 2011 stated that a decrease in electrical savings will occur if maintenance on the system is not conducted. The sustainability of projects is influenced by [31]:

1. Hardware failure of the control system;
2. Changes made to the communication system;
3. Changes made to the process being controlled;
4. Changes to the business and operational environment;
5. Conflicting priorities.

This section will discuss various issues that may arise with the automated system. Issues that could arise are divided into two major groups, i.e. network restrictions and hardware restrictions.

Network restrictions

Control mechanisms, such as the Real-time Energy Management System (REMS), make use of an Object Linking and Embedding for Process Control (OPC) connection. If the server is unable to make an OPC connection to the Supervisory Control and Data Acquisition control system (SCADA) or Programmable Logic Controller (PLC), the pumps are unavailable for control. [32], [33].

The reasons why the connection causes pump unavailability are:

1. No information is received from the pumps; and
2. No commands can be sent to the pumps.

This could lead to the dewatering system not being controlled according to the control philosophy and, in turn, being an unsafe operation.

Network and instrumentation cables

The network and instrumentation cables connect the control mechanisms with the dewatering pump system. Changes made, or damage caused to the network and instrumentation cables can result in loss of communication and lead to problems [31].

Most mines make use of fibre-optic cables as communication media between PLCs and the SCADA system. These network cables are fragile, and can easily be damaged. If the communication cables are damaged, no commands can be sent to or received from pumping stations [34].

Manual operation of the dewatering pumps must be conducted when communication cables are damaged [34]. Automatic control of the dewatering pumps is not possible, making the pumps unavailable for control through the control mechanism.

Power failures or load shedding

In South Africa, power failures (or load-shedding) are frequent occurrences as was mentioned previously. All control mechanisms make use of electricity. If a power failure or load-shedding takes place, no communication between the pumping system and control mechanism is possible.

The only way communication can take place between the dewatering pumping station and the control mechanism is when all the control mechanisms have uninterrupted power supplies (UPS) or a backup power generator. In such a case, the network is restricted and the dewatering pumps are also unavailable for control.

Hardware restrictions

Hardware devices that form part of a dewatering system operating underground are subjected to extreme conditions such as high temperatures, dust and water. These devices are more likely to fail if unattended or not maintained [31].

Due to the lack of maintenance on automated dewatering systems, mechanical failures can occur, which make pumps unavailable for control. Mechanical failures can occur on clear-water dam level sensors, water columns, dewatering pumps, instrumentation and control mechanisms [18], [35], [36].

Water column failures

Leakages occur on water columns as the dewatering system ages and when no maintenance is done on the water columns. If leaks are present in the dewatering columns, pumps should be stopped until the leaks are repaired. Replacing water columns is a timeous process, and no pump control is possible [37].

Faulty instrumentation

Temperature probes, if not calibrated or maintained, can result in incorrect readings. High temperature readings on pump and motor Drive End (DE) as well as Non-Drive End (NDE) bearings, or motor winding temperatures, will trip the pump. Pumps are unavailable to start until the temperature readings are within desired ranges [35].

Low temperature readings, due to incorrect calibration or damaged temperature probes, could lead to damage to the pump or motor. The low temperature readings could also lead to inefficient pumps or a catastrophic failure. If a pump fails, the pump will be unavailable for control [35].

The same principle applies to damaged or non-calibrated vibration sensors. Incorrect high vibration readings could trip the pump, which prevents effective pump control. Incorrect low vibration readings can lead to inefficient pumps or catastrophic failures. This will result in pumps that are unavailable for control [35], [38], [39].

Faulty control mechanism

Automated dewatering systems depend on control mechanisms to operate effectively. Any disturbances in the control mechanism may lead to commands not being sent to the dewatering system or information received from the dewatering system. Faulty control mechanisms restrict the control of the dewatering pumps which, in turn, make the pumps unavailable for control [18], [36].

1.5 PROBLEM STATEMENT

Load shift performance deteriorates during the PT period. The deterioration is shown to be due to a lack of maintenance on the dewatering systems. As a result, many studies focused on the effect that maintenance has on dewatering systems. The studies showed that improved maintenance on equipment increases the availability of the equipment.

No information could be found that focuses on quantifying the effect that pump availability has on load shift performance. A need to quantify the effect of pump availability on load shift performance exists, and stresses the importance of maintenance on pumping systems. There is thus a need to *investigate the effect of pump availability on load-shift performance*. The method should enable one to investigate the effect of pump availability on load-shift performance. This method should also enable one to determine when maintenance should be conducted on the pumping systems

1.6 OUTLINE OF STUDY

The remaining chapters to follow in this thesis will be discussed in short, to give the reader an overview of the study.

1.6.1 CHAPTER 2

In Chapter 2, dewatering systems and simulation models will be discussed. The objective of the chapter is to give insight on:

1. Dewatering system operation;
2. The components of a dewatering system;
3. How the dewatering system is controlled;
4. Previous studies conducted in the field;
5. How to develop a simulation model;
6. Execution of experiments using the simulation model.

1.6.2 CHAPTER 3

In Chapter 3, a step-by-step methodology will be developed, which will empower the reader to investigate the effect of pump availability on load shift performance.

1.6.3 CHAPTER 4

Application of the methodology on case studies will be discussed in Chapter 4.

1.6.4 CHAPTER 5

Chapter 5 will conclude the study by stating how the problem statement was addressed, the benefits of the study, recommendations for future studies and the presentation of a closing argument.

Chapter 2:

Dewatering systems and simulation model development



Gold mine³

The computer is not, in our opinion, a good model of the mind, but it is as the trumpet is to the orchestra – you really need it. And so, we have very massive simulations in computers because the problem is, of course, very complex. (Gerald Edelman).

³ AngloGold Ashanti, "AngloGold restarts operations at South Africa gold mines following earthquake." "Mining-technology.com, 2015. [Online]. Available at :<http://www.mining-technology.com/news/newsanglogold-resumes-operations-at-south-african-gold-mines-following-earthquake-4342600>

2 DEWATERING SYSTEMS AND SIMULATION MODEL DEVELOPEMENT

2.1 INTRODUCTION

Numerous studies were conducted on dewatering systems for deep level mines together with maintenance on these systems [35], [37], [40], [41]. However, certain aspects of the maintenance and dewatering systems have not yet been investigated, only highlighted in previous studies. The first objective of this chapter is to provide more detail regarding pump dewatering systems and to gain an understanding of the functions of these systems.

Previous studies conducted on dewatering systems will be investigated. These studies focus on mine dewatering operation, automation, optimisation and maintenance thereof. The presented results give an overview of the industry norm, but also highlight aspects that need to be addressed by the methodology.

With enough background gained on all the aspects of a dewatering system, the next part of the research can commence. The second part of the research will investigate the effect of pump availability on load-shift performance. This will lead to the development of a methodology that will be discussed in Chapter 3.

The methods include how to develop a simulation model that will enable any mine to investigate the effect of pump availability on load shift performance. The verification process of a simulation model will then be discussed to determine how to test the correctness of a simulation model. The last part of the simulation model development will focus on how to evaluate the results obtained from the simulation model so that the effect on the load shift performance can be quantified.

Lastly, the research will discuss a technique that can be used to determine how the simulation model should be utilised. This technique will enable the user to develop an experimental model using the simulation model, to investigate the effect of pump availability on load shift performance.

2.2 PUMP DEWATERING SYSTEMS

2.2.1 OVERVIEW

To fully understand pump dewatering systems, several aspects of a pump dewatering system should be discussed. Thus, to understand pump dewatering systems, an overview

of a typical deep level mine water reticulation system will be given. The dewatering system within the water reticulation system will then be discussed along with all the components forming part of the dewatering system. Lastly, the control of the dewatering system will be discussed. This includes the parameters and limitations of the dewatering system.

Figure 2-1 illustrates a deep level mine's water reticulation system. Deep level mines make use of cold water for rock drilling, sweeping, cooling, dust suppression and other operations. Water is cooled on the surface using refrigeration plants or ice plants. Some of this cold water is sent down the mine for the above-mentioned operations. Due to the extensive depths that the water has to travel, a pressure increase occurs that has to be reduced [41], [42].

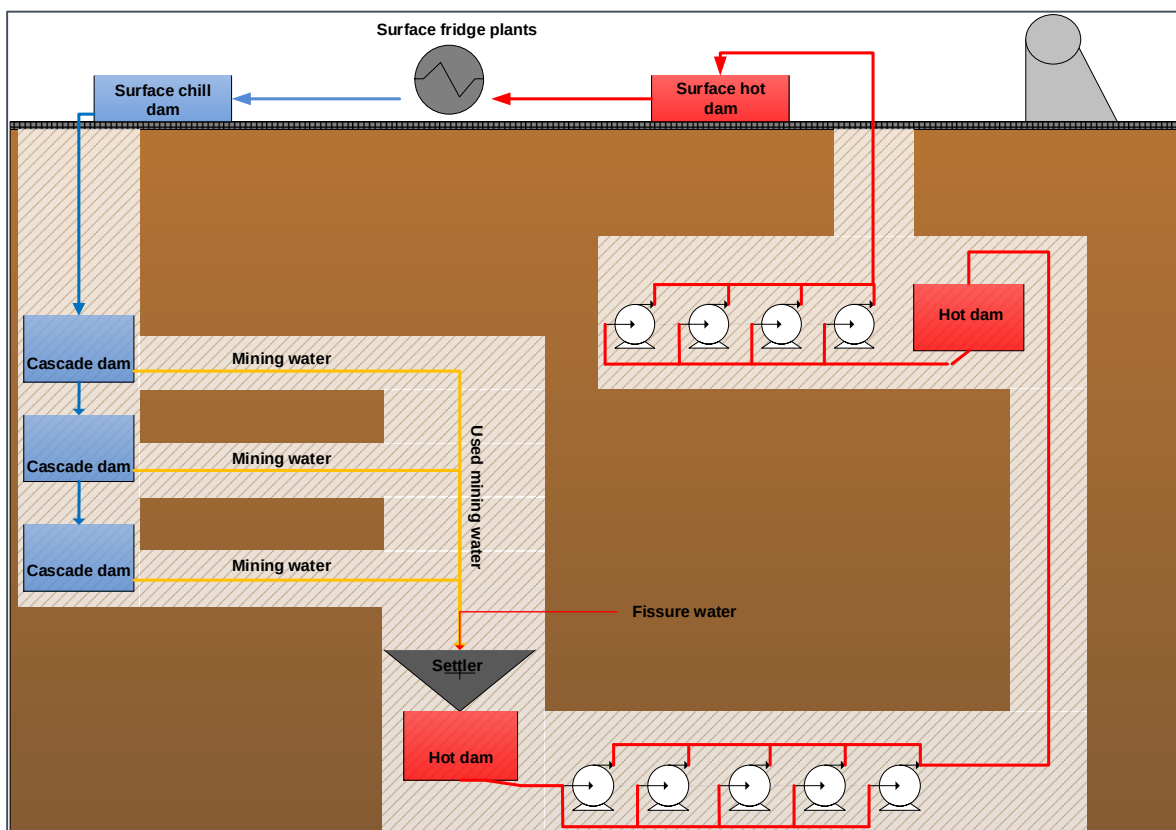


Figure 2-1: Deep level mine water reticulation system

The water pressure can be reduced using several systems. Cascading dam systems are the most common. Cascading dams are utilised on various levels throughout the system. Water is gravity fed from the cascading dam on the highest level to the cascading dams on the lower levels. The water utilised for mining operations is supplied from the dams to the working areas [40], [42].

Virgin rock temperatures at the mining sections have been known to exceed 65°C [43], [44]. Service water is used to cool the rock and machinery. The cold water is no longer cold when

used. The hot water goes down the shaft through trenches and plugholes to settlers at the shaft bottom. Fissure water seeping into the mine from surrounding areas also flows into the settlers [37], [40], [42].

The settlers are used to separate debris from the hot water before being pumped back to surface. Flocculent is added to the settlers to aid separation of debris in the hot water dams. The flocculent binds with debris, making it heavier, which allows it to settle at the bottom, where it can be removed. Lime is also added to the settlers to ensure the pH balance of the water stays within range of specifications. The clear water flows to hot water dams at the shaft bottom, where it is pumped back to the surface to restart the cycle [40], [42].

2.2.2 DEWATERING SYSTEM COMPONENTS

For the purpose of this study, only the components directly influencing the dewatering system will be discussed. These components include clear water dams, dewatering pumps, water columns, instrumentation and control mechanisms. Figure 2-2 shows a basic layout of a dewatering system with all the components that will be discussed.

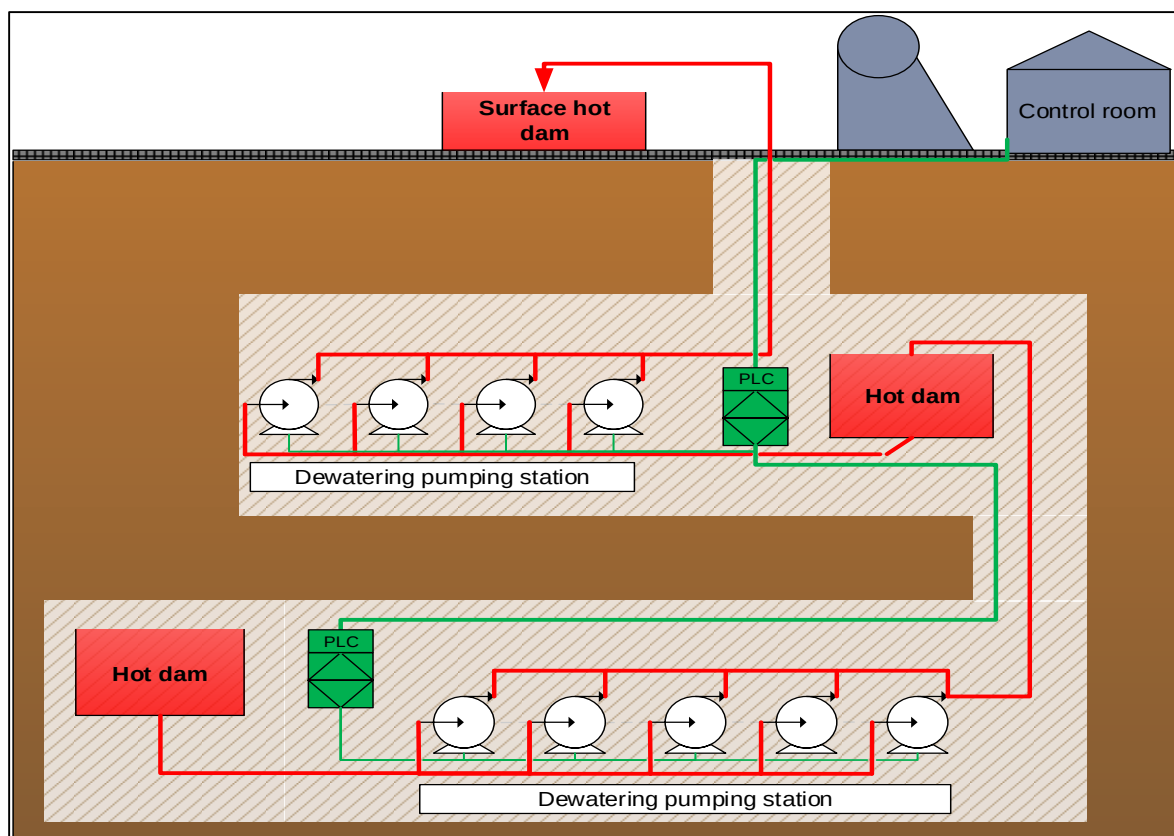


Figure 2-2: Dewatering system

Hot water dams

Water flows into the hot water dams after the settlers. The hot water dams store water that needs to be returned to surface. The hot water dams' capacity normally ranges from 0.75 ML to 5 ML, depending on the mine depth and size of mining operations [41], [45]. More than one hot water dam is usually located on a level [45].

The settlers remove the bulk of the debris, although some debris remains in the water. The remaining debris results in mud build-up over time [35]. Hot water dams have to be cleaned and washed out to ensure that no mud gets into the dewatering pumps that can lead to cavitation, and thus in turn, pump failure [35].

Dewatering pumps

Dewatering pumps are used to pump water from the clear water dams to pumping stations on various levels until the water reaches the surface dam. Each pump station consists of two to twelve pumps, depending on the size of the mine and the amount of water that has to be pumped [15], [35], [36].

Pumps are divided into two major categories, namely dynamic- and displacement pumps. Categorisation is based on the way the pump adds energy to the fluid. Dynamic pumps can be sub-divided into two categories, i.e. centrifugal and special effect pumps. Displacement pumps are subdivided into reciprocating and rotary pumps. A structured breakdown of the pump classification is illustrated in Figure 2-3 [46].

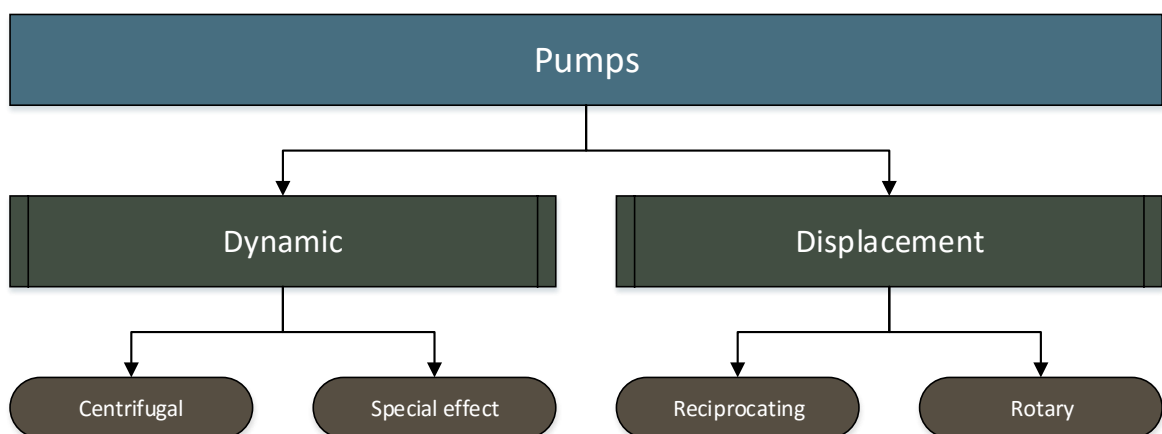


Figure 2-3: Pump classification

Multistage centrifugal pumps are used for high heads that water needs to be pumped against [47]. The head against which dewatering pumps in a mine have to pump water is known to exceed 1km [48], [49]. Multistage centrifugal pumps thus are used extensively in the mining sector as dewatering pumps [16], [50]–[52].

The setup for a dewatering pump configuration consists of a pump, electric motor and a cooling system as shown in Figure 2-4.

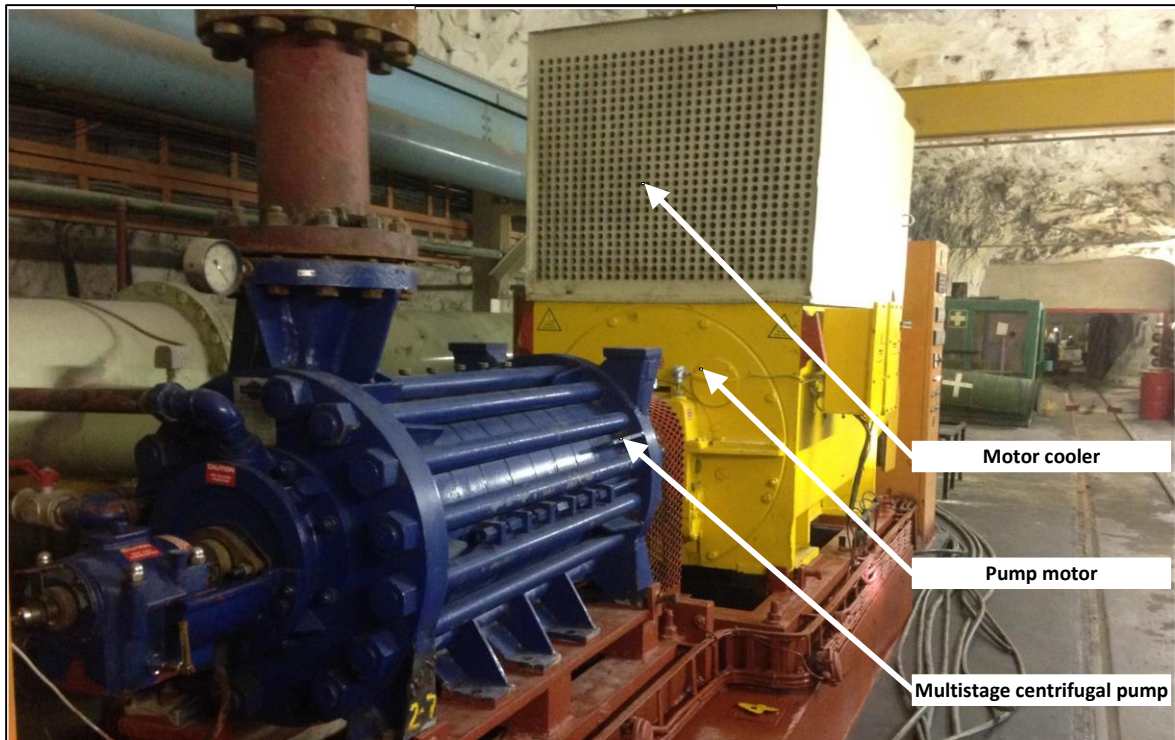


Figure 2-4: Dewatering pump setup

Multistage centrifugal pumps have more than one impeller or stage. When water enters the suction end of the pump, it enters the first stage with one impeller. The head is added to the water and enters the second stage with its impeller. The water continues through all the stages until enough head is added to the water to overcome the static and dynamic head of the pumping column [16].

To overcome dynamic and static head, the size of the pump and motor has to be sufficient. As the size of the pump increases, so the number of stages of the pump will increase. The more stages a pump has, the bigger the motor requirements will be to drive the pump [53]. However, pump and motor sizing does not form part of the scope of this study and will not be discussed further.

Instrumentation:

To automatically and remotely control the dewatering system, certain instrumentation is required. This instrumentation not only ensures the safe operation of the system, but also provides real-time information regarding the dewatering system. Instrumentation failures were already discussed in Chapter 1. Typical instrumentation installed on a dewatering pump is illustrated in Figure 2-5 on the next page.

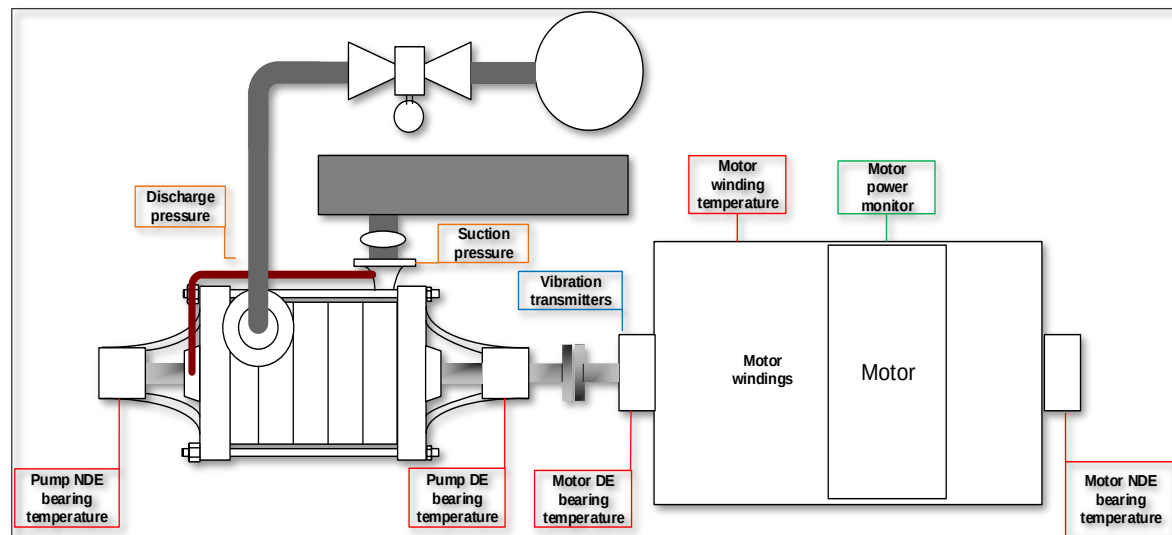


Figure 2-5: Instrumentation installed on dewatering pump setup^[15]

Hot water dam level transmitters

To determine when pumps should be started and stopped (controlled), level sensors should be installed on the clear water dams. The level sensor will ensure that pumps are started when dam levels (DL) are at the maximum threshold and the pumps stopped when dam levels are at the minimum threshold [35].

Various instruments can be used to determine the DL, one of which is a pressure transmitter that can be installed on the dam outlet. The pressure at the bottom of the dam is directly proportional to the amount of water that is in the dam [54], [55].

To ensure the pumps operate within manufacturer specifications, a few monitoring instruments are needed. Three of the most important instruments are temperature probes, vibration sensors and power meters [35].

Temperature probes

Temperature probes are installed in different locations on a pump and motor. The temperature probes measure the temperature of pump and motor DE and NDE bearings. Temperature probes are also installed on motor windings to ensure that the motor itself does not overheat because of excess amperage and friction [35].

Vibration sensors

Vibration is one of the main factors that leads to pump failures. Thus, vibration sensors are installed on pumps to monitor vibration levels. If excess vibration is measured, the pump has to be stopped in order to prevent catastrophic failure [56].

Condition monitoring of dewatering pumps can be done through the use of vibration sensors. When pumps are installed, vibration measurements are taken and used as a baseline. Vibration measurements are taken on a regular basis and compared to the baseline. Higher vibration measurements indicate pump inefficiency [35].

Power meters

It is important to install power meters on dewatering pump motors. High delivery pressures and pump motors that are incorrectly sized are known to cause excess motor ampère readings. Each pump motor has a maximum amperage that it is designed to draw, and if exceeded, the pump motor may overheat and become damaged. Ampère readings can be managed by opening or closing the delivery valve [35], [57].

If the automated pump system does not have a power meter on each pump, temporary power meters can be installed. The temporary power meters are installed on each of the pump's breakers to measure the ampère usage and the supplied volts. The power (kW) used by the pump motor can then be calculated [58].

Flow meters

Flow meters are not essential for the automation of a dewatering pumping system. However, flow meters are installed for condition monitoring purposes in certain mines. Collecting flow data of a pump when newly installed and comparing that data to real-time data after installation will give an indication of the pump's condition. If the flow decreases rapidly over a short period, the condition of the pump is deteriorating. Failure of the pump or inefficient performance can occur [59].

Ultimately, the total water volume can be measured. If no flow meters are installed on the dewatering system, the delivered flow of a dewatering pump can be determined using a pump flow chart or temporary flow meter. Manufacturers supply pump flow charts [59].

Control mechanism

Interpretation of and decision-making for a dewatering system have to be done by control mechanisms. The control mechanism can be pump attendants, a SCADA/Control Room Operator, PLC, a control program or a combination of the individual control mechanisms [60].

To control a dewatering system, certain steps should be followed. Firstly, data should be acquired and interpreted. Actions are then taken, based on the interpretations. A basic flow diagram for the control of a dewatering system is depicted in Figure 2-6 on the next page.

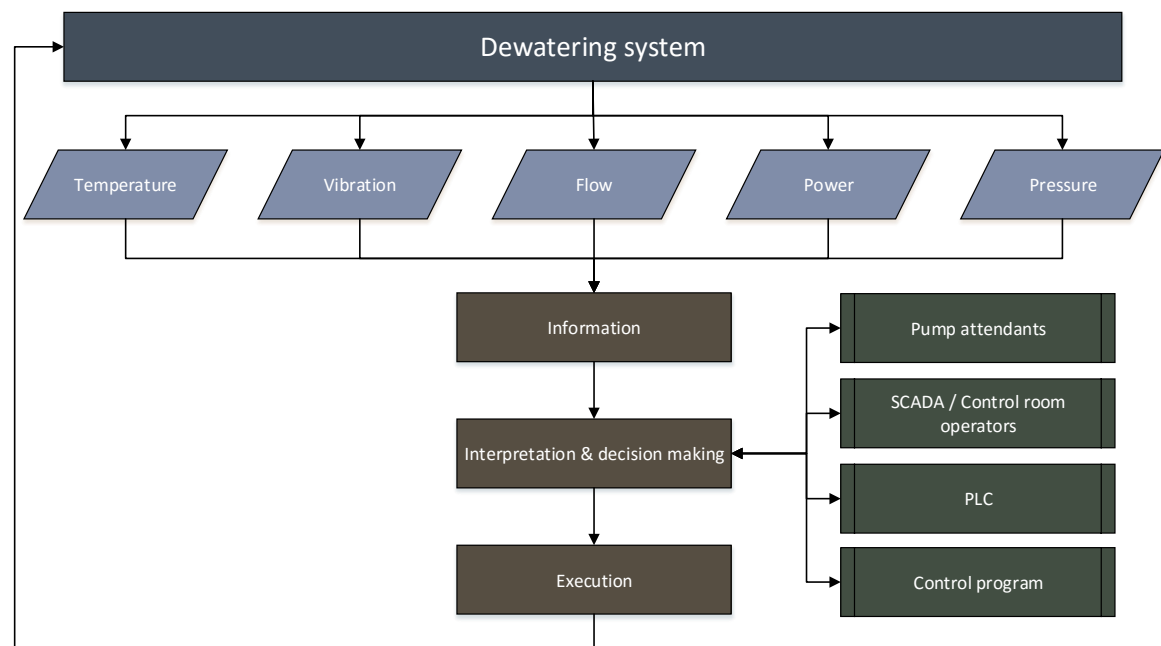


Figure 2-6: Dewatering system control

Illustrated in Figure 2-6, it can be seen that information from the dewatering systems such as temperature, vibration, flow, power and pressure need to be collected. Interpretation of the information and decision-making based on this information is done by a control mechanism. The decision is then executed by the PLC in conjunction with other control mechanisms. Upon completion of the execution step, information is gathered again and the cycle restarts.

Dewatering systems that have not been automated are controlled solely by pump attendants. The pump attendants make use of mechanical gauges and a pre-determined control philosophy to control the pumps manually. Pump attendants are also responsible for logging of instrumentation information in a logbook. Control mechanisms used for an automated dewatering system will now be discussed.

Programmable Logic Controller (PLC)

PLCs make use of input cards, where the information received from the instrumentation, normally in millivolts or milliamps, is converted to values that are usable by mine personnel. A control mechanism then interprets the information. Actions are then taken and executed by the PLC [34].

PLCs are used for different control processes. In some cases, a Human Machine Interface (HMI) is installed on the PLC. The user interface is used by pump attendants or mine personnel. PLCs are used in dewatering systems on mines for communication and control between the surface and underground pumping stations [61].

Supervisory Control and Data Acquisition (SCADA)

All operations and information from the PLCs are controlled from a centralised control room using a SCADA system. The control room operators use the information on the SCADA system to control the pump operations using a predetermined control philosophy [34].

Real-time energy management system for pumps (REMS-Pumps)

Different dewatering pump control programs for different applications are available on the market. One of these is referred to as REMS-Pumps. This program works in conjunction with a PLC or a combination of SCADA and PLC setup [15], [36].

The purpose of REMS-Pumps is to enable load shift on dewatering pumping projects. The program is used to prepare DL to shift load out of the peak periods to standard and off-peak periods [15], [36].

REMS-Pumps determine a schedule that is implemented by the control mechanism. The schedule is determined by the control philosophy of the dewatering pumping system that has been programmed into REMS-Pumps. The control of the dewatering system will be discussed in the following section [15], [36].

2.2.3 PUMP DEWATERING SYSTEM CONTROL

To maintain a safe and efficient system, a control philosophy for the dewatering system should be developed. A control philosophy consists of a predetermined set of inputs according to which pumps should be started and stopped [62].

The predetermined parameters normally consist of maximum and minimum dam levels, maximum and minimum number of pumps running simultaneously and a control range (CR). Each of these will be discussed [17], [35].

Maximum and minimum dam levels

To ensure that dam levels stay within safe operating limits, mine personnel or Subject Matter Experts (SMEs) should state the maximum and minimum allowable dam levels from which the pumps can be controlled. The maximum and minimum dam levels stay constant at all times unless changed by mine personnel or SMEs [17], [35].

The maximum dam levels are approximately 80% of the total capacity of the dam. Maximum dam levels not only ensure that the dam pressure stays within safe parameters, but also compensates for enough volume if a pump failure should occur. Additional time is thus available to repair the pump or start another in its place [17], [35].

The minimum dam levels are usually more than 20% of the total dam capacity. In some instances, the minimum dam level can be up to 50% of the total dam capacity [17]. The minimum dam level plays two major roles, i.e. supplying pumps with enough head and making sure excess debris that has not been filtered out by the settlers, does not enter the pumps [17], [35].

The maximum and minimum dam levels are illustrated in Figure 2-7. Although this is a simple concept, not enough emphasis can be placed on the maximum and minimum dam levels. Safe operation of the dewatering system is dependent on the maximum and minimum dam levels

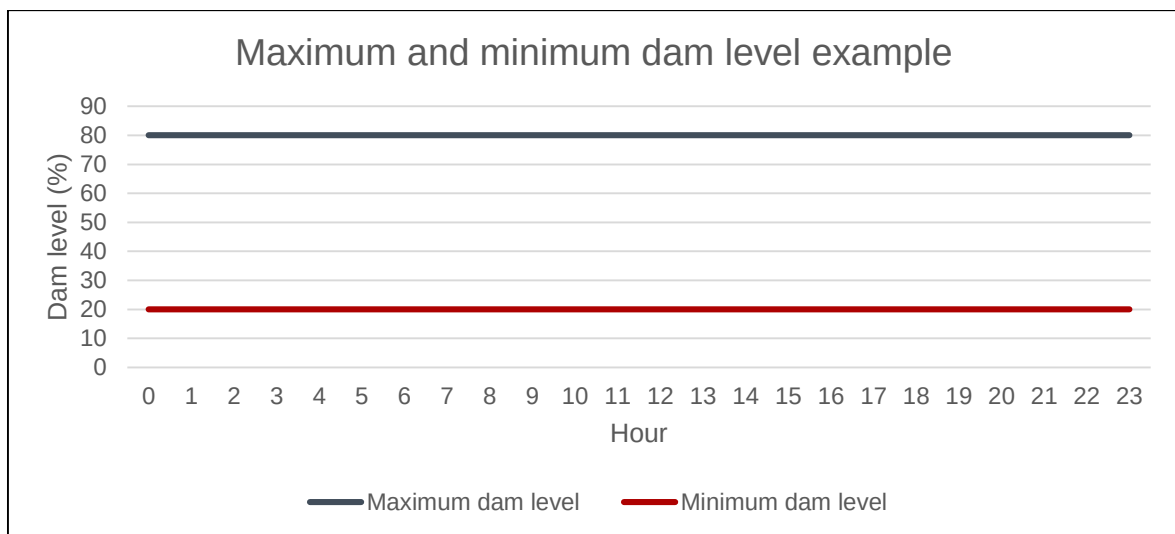


Figure 2-7: Maximum and minimum dam level

Maximum and minimum number of pumps

Each pumping station has a maximum and minimum amount of pumps that are allowed to operate simultaneously. The maximum and minimum number of pumps are determined by mine personnel and SMEs.

The maximum number of pumps to run on a pumping station is determined by the maximum allowable pressure the column can handle, and the efficiency of the pumps when pumping water into the same column. Furthermore, the dam level to which the pumping station pumps water (downstream dam) also determines the maximum number of pumps that are allowed to run at a time [34].

For instance, if the downstream dam is close to the maximum allowable dam level and the upstream dam is far from maximum allowable dam level, the maximum allowable pumps will be reduced. By reducing the maximum number of pumps, the downstream dam will decrease and stay within safe operating levels.

Control ranges

To ensure that enough capacity is available for a load shift, the dam levels should be prepared so that the pumps can be switched off during peak periods [15], [34]. REMS-Pumps make use of control ranges to ensure dam levels are low enough to allow a load shift.

Control ranges (CR) consist of an Upper Bound (UB) and a Lower Bound (LB). When a dam level reaches an UB, a pump has to be started – and when the dam level reaches an LB, a pump has to be stopped. UB and LB differ during the time of day [15], [34].

Mine personnel and SMEs determine the CR. The CR is determined in such a manner that pump cycling does not occur. Therefore, pumps are not started and stopped within short periods of time [17], [34]. Dam capacity and water inflow will influence the CR.

The UB is calculated according to the time of day. In peak periods, the UB is equal to the maximum dam level and in off-peak and standard periods, the UB can be determined using Equation 2 [15].

$$UB = \text{Minimum dam level} + CR \quad \text{Equation 2}$$

LB is also determined according to the time of day. The LB for off-peak and standard periods is equal to the minimum dam level.

In peak periods, the LB can be calculated using Equation 3 [15].

$$LB = \text{Maximum dam level} - CR \quad \text{Equation 3}$$

A line graph representing the UB and LB can be seen in Figure 2-8.

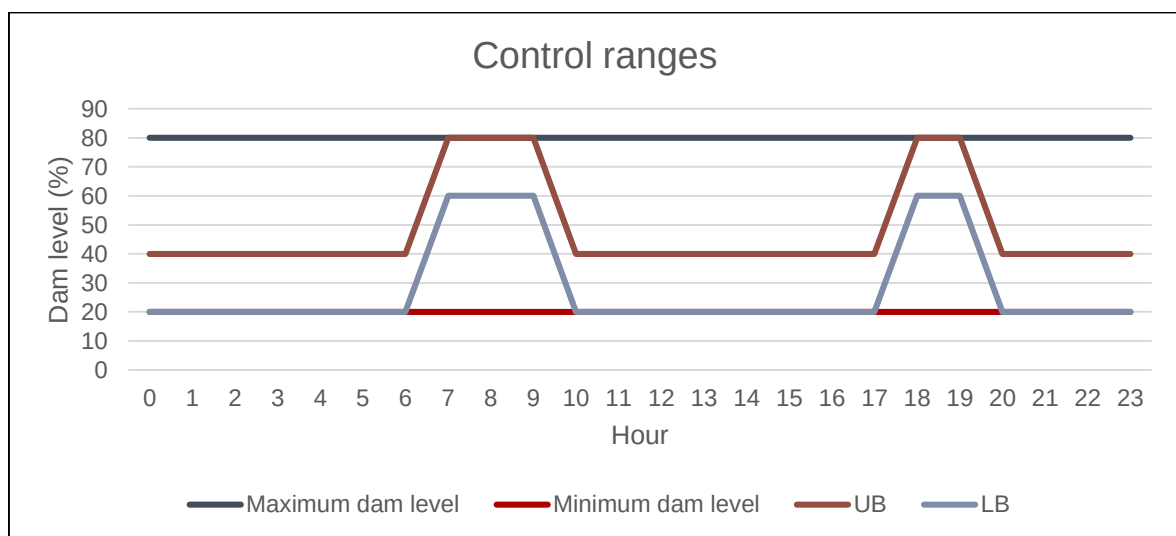


Figure 2-8: Control ranges

It is seen that the UB and LB change according to the time of day. During the peak periods, the UB and LB are higher than during the standard- and off-peak periods.

Control offsets

Control offsets are used when a pumping station utilises more than one pump at a time. Control offsets can be divided into two groups, i.e. Offset Top (OT) and Offset Bottom (OB). The control offsets are normally small percentages that are added or subtracted from the UB and LB [15]. Illustration of the Offset Top Value (OTV) and Offset Bottom Value (OBV) are depicted in Figure 2-9

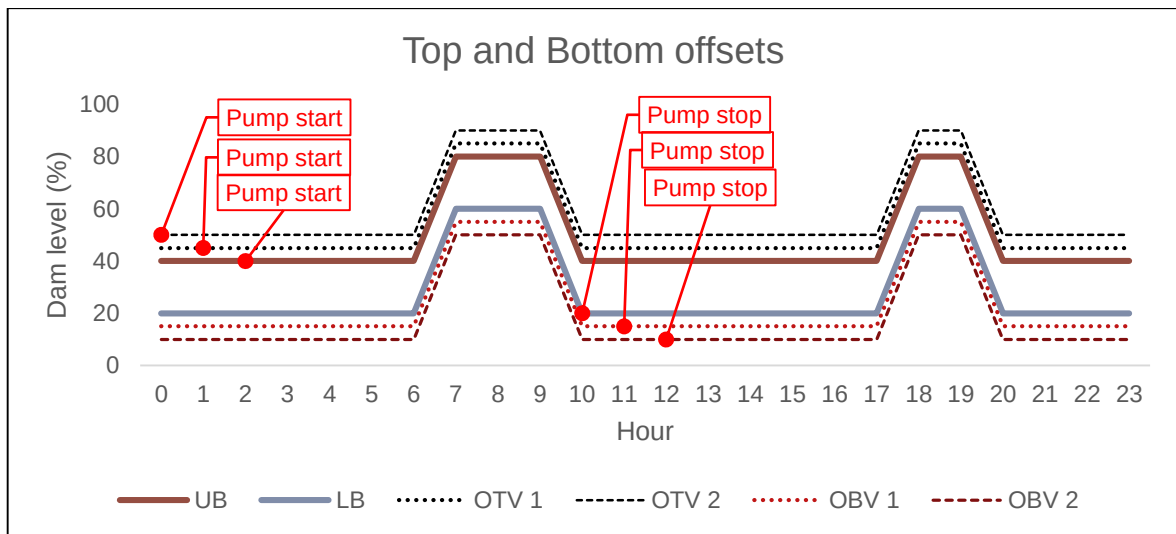


Figure 2-9: Control offsets

When the UB of a dam is reached, a pump has to start. If the pump is insufficient to lower the DL, the dam will keep on rising until the OTV is reached. If this occurs, and the maximum number of pumps are greater than one, another pump has to be started [15].

The inverse will happen if an OBV is reached. If more than one pump is running at a time, and the LB is reached, one pump will be stopped. If the dam level continues to decrease and the OBV is reached, the next pump will be stopped. This will continue until no pumps are running, or the minimum number of pumps are reached [15].

2.3 PREVIOUS STUDIES ON DEWATERING SYSTEMS

2.3.1 OVERVIEW

Now that a basic understanding of how a dewatering system functions is determined, previous studies on dewatering systems will be discussed. Three studies will be examined in the following sections. The first study focuses on automation of dewatering systems, the second discusses load shifting and cost savings and lastly, the maintenance of dewatering systems will be discussed.

2.3.2 AUTOMATION OF DEWATERING SYSTEMS

In 2014, a study was conducted by Oberholzer to establish new best practices and procedures for pump automation [35]. Previous practices were found to be inadequate as pump failures still occurred after implementation and automation [35].

The investigation into the root causes of pump failures and the installation of additional instrumentation led to the new best practice and procedures. The new best practice and procedure resulted in an automated dewatering pump system that yielded a R6-million electricity cost saving [35].

Through automating a dewatering system, using the new best practice and procedure, the pump reliability and availability was increased. Increased reliability and availability contributed to the electricity cost savings achieved in the case study [35].

The effect of pump availability, however, was not investigated or quantified. It was only mentioned that availability of dewatering pumps has an influence on project savings [35].

2.3.3 COST SAVINGS AND LOAD SHIFTING

Cilliers conducted a study in 2013, where the study objective was to enable cost savings on mine dewatering pumps by reducing preparation- and comeback-loads [15]. It was shown that reducing the preparation- and comeback-loads of the dewatering system resulted in substantial cost savings. Savings were achieved when the load was moved from standard TOU to off-peak TOU while still realising a full load shift out of peak TOU [15].

To enable the reduction of preparation- and comeback-loads, a step-by-step control technique was devised. The technique utilises dynamic control ranges instead of the traditional fixed control range [15].

Two case studies were conducted to validate the technique. By reducing the preparation- and comeback-loads using the step-by-step technique, the case studies resulted in a R1-million and R0.5-million additional saving per annum. Study A has shown that by managing the preparation- and comeback-loads, financial savings are achievable [15].

The study, however, did not mention the effect that pump availability has on the technique and the load-shift performance. If pumps are unavailable for control, the reduction of preparation- and comeback-loads will not necessarily be possible. [15]

2.3.4 MAINTENANCE ON DSM PROJECTS

Groenewald conducted a study in 2015, focusing on DSM project maintenance. A new performance-centred maintenance strategy for industrial DSM projects was developed [18]. The strategy was implemented on ten DSM projects. Results showed an average increase of 64.4% in performance when the new strategy was implemented [18].

The strategy also proved to be a cost-effective way to sustain project savings and improve the project performance. The total cost of implementing the strategy was 6% of the total savings achieved over a 60-month period [18].

Maintenance and maintenance strategies were discussed in the study. However, the study did not investigate the availability of pumps specifically. The study also did not discuss how the availability of pumps influences the load shift performance [18].

2.3.5 SUMMARY OF PREVIOUS STUDIES

The previous conducted studies focused on how to automate a dewatering system and then focus was placed on how to optimise the control of the automated system. Lastly, focus was placed on how to maintain the load-shift performance of the automated and optimised control of a dewatering system.

Previous studies focused on the three main parts of the project life cycle, i.e. implementation, optimisation and maintenance for sustainable performance. The previous studies conducted did not focus on the availability of pumps, nor was the effect of availability discussed. Furthermore, no studies could be found that focused on the availability of pumps and how this was investigated. As a result, the following sections will discuss how the effect of availability can be investigated.

2.4 SIMULATION MODEL DEVELOPMENT

2.4.1 OVERVIEW

Simulation and modelling have three purposes, i.e. performing experiments, providing experience and imitation pretence. Definitions of simulations can be classified into three groups as follows [63]:

- Group A – Experiment, training and gaming;
- Group B – Modelling, model implementation/ model execution and technique;
- Group C – Similarity/imitation, pretence/fake and other.

The focus is placed on Group A as experiments should be conducted to investigate the effect of pump availability. From the experimentation perspective, simulations are used for various outcomes. Outcomes include decision support, understanding and education.

Decision support simulations are used for the following [63]:

1. Evaluating performance;
2. Designs and alternative solutions;
3. Predicaments for performance and designs;
4. Proof of concepts.

This part will focus on simulation development, simulation verification and evaluation of simulation results.

2.4.2 SIMULATION DEVELOPMENT METHODOLOGY

To investigate and quantify the effect of pump availability on project performance, a simulation model has to be developed to predict the effect. Many studies have been conducted on simulation development [64], [65]. A methodology consisting of eight phases was developed to construct a simulation model. The eight phases are listed below [66]:

1. Define the problem;
2. Design the study;
3. Design the conceptual model;
4. Formulate inputs, assumptions and process definition;
5. Build, verify and validate the simulation model;
6. Experiment with the model and look for opportunities for design experiments;
7. Document and present results;
8. Define the model lifecycle.

In the paper *How to Build Valid and Credible Simulation Models*, a seven-step methodology was devised for building a simulation model. These seven steps are listed below [64]:

1. Formulate the problem;
2. Collect information/data and construct an assumptions document;
3. Determine the validity of the assumptions;
4. Program the model;
5. Determine the validity of the programmed model;
6. Design, conduct and analyse experiments;
7. Document and present simulation results.

From these two studies, similarities can be identified. Simulation methodology described in the eight phases of the first study, however, is suitable for more complex systems. Study one focuses on how to build a simulation for a client.

The scope of this study is not aimed at a specific client, but rather at an overall investigation of mine dewatering systems. Therefore, the steps described in the second study will be used to develop the simulation model that can satisfy the problem statement of this study. The seven steps will now be discussed in the context of the study.

Step 1: Formulate the problem.

To formulate the problem, meetings should be held with the client. Formulating the problem is an iterative process. When formulating the problem, the scope of the study should be defined. Identify specific questions the simulation should be able to answer. Discuss performance measures that will be used to validate the simulation and the overall objectives of the study [64].

Step 2: Collect information/data and construct an assumptions document

In step 2, all the information that is required for the simulation model should be gathered from SMEs. The data and information received from the SMEs include information on the structure, operating conditions and parameters of the system to be simulated [64].

Data should also be collected on the current performance of the system and the level of detail for the simulation model should be determined. All the information should be added to an assumptions document and presented to the SMEs for step 3 [64].

Step 3: Determine the validity of the assumptions

When the assumptions document is finalised, the document has to be presented to the SMEs and the person who requested the study. If any of the information is incorrect, adjustments have to be made to the assumptions and the simulation model [64].

Step 4: Program the model

Program the assumptions and data in a suitable programming software package and debug the software model. The software model used should be able to satisfy the needs of the study as well as a preferred programming language for the programmer [64].

Step 5: Determine the validity of the programmed model

To validate the correctness and credibility of the simulation model, the model should be verified using data collected in step 2. Compare the simulation values with actual operational values. Simulation verification will be discussed in detail later in this study [64].

Step 6: Design, conduct and analyse experiments.

Determine how the experiments will be conducted. Therefore, determine how many experiments should be conducted and the experimental procedure that should be followed. When results are obtained, discuss the results with SMEs and decide whether more simulations should be conducted or if the simulation model satisfies the needs of the study. Experimental design will be discussed in detail later in this study [64].

Step 7: Document and present simulation results.

All the simulation assumptions, inputs and results should be documented and presented to SMEs. A formal report should be written on the findings and design parameters should be listed. The report will be used for future reference [64].

2.4.3 SIMULATION MODEL VERIFICATION

To verify the correctness of the simulation, a verification process should take place to ensure the results obtained from the simulation can be used for predictions of the system. The verification of a simulation model can be done using different methods.

Balci et al. [67] divided verification, validation and testing of a simulation model into four groups, i.e. informal, static, dynamic and formal. A structured breakdown of the taxonomy of verification, validation and testing techniques are given in Figure 2-10.

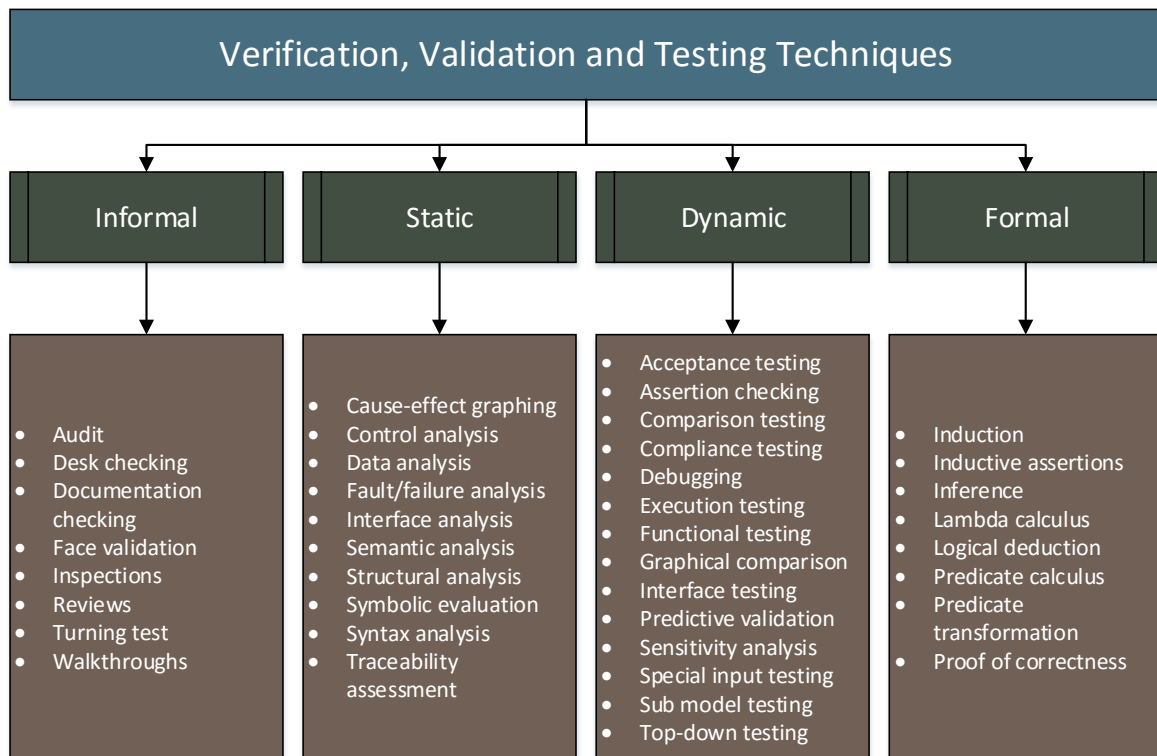


Figure 2-10: Taxonomy of verification, validation and testing techniques

Simulation model verification can also be done by testing the simulation program. Two different methods of tests, i.e. dynamic and static tests, can be done [68].

Static testing of a simulation model consists of a structured walk-through of each programmed line with other program developers. If all the program developers find the simulation program correct, the simulation model can be deemed as verified and valid [68].

Dynamic testing of a simulation program is done by changing the input variables of the simulation and then evaluating the results. Three different approaches can be used for dynamic testing, i.e. bottom-up, top-down and mixed [68].

In bottom-up dynamic testing, the sub-models are tested individually first and then the program as a whole. Top-up dynamic testing is done by testing the simulation program as a whole – and then the sub programs – and lastly mixed dynamic testing, done by a combination of bottom-up and top-down dynamic testing [68].

Verification of a simulation model used to determine the value of simulation models for mine DSM projects, however, was done differently. Verification was done by comparing the simulation results to actual measured values of the system [69].

The measured values of the actual system were acquired from a mine's SCADA system. Assumptions were made and because the simulation package could only simulate static

problems, three different simulations were done, i.e. low-, medium- and high-demand scenarios. [69]

Data acquired from the SCADA system of the mine includes [69]:

1. Power consumption for each compressor;
2. Delivery pressure setpoint of each compressor;
3. Compressed air delivery;
4. Compressed air flow at each shaft;
5. Compressed air pressure at each shaft.

Similar to the above-mentioned verification method, verification of a simulation model developed for another study was done through means of comparison. Comparing the simulation results with actual system data was used to verify the simulation model [70].

The simulation results were compared to actual values received from the mine's SCADA system. The simulation's electrical energy savings prediction was not a 100% match to the actual savings achieved, but, due to interacting and ever-changing input parameters, the simulation model results were deemed accurate enough, and the simulation model was verified [70].

In conclusion, three different verification methods were mentioned. Applying the verification method of comparing simulation results with actual results are found to be a good fit. The reason why the comparison method is a good fit can be attributed to the fact that two studies made use of this method and both of these studies developed simulation models for DSM projects.

2.4.4 EVALUATION OF SIMULATED RESULTS

After a simulation model has been developed and verified successfully, the simulation model will be used to execute experiments and, in turn, obtain results. The results obtained have to be evaluated to determine the effect of the changed input variables. Several methods exist to evaluate the performance of a DSM project. The methods can be grouped into four groups, i.e. [71]:

1. Retrofit isolation with key parameters;
2. Retrofit isolation with all parameters;
3. Utility data analysis;
4. Calibrated computer simulations.

Evaluation of results is done by comparing the results obtained to the actual system. DSM interventions focus on the electrical energy that is used. Evaluation of the DSM projects' performance is done by comparing a set of data to a power baseline [72].

Power baseline

A baseline normally consists of a three-month period, in which the energy usage of the components in question are measured and averaged over a 24-hour power profile. The baseline is a representation of the normal power usage of the system. A typical power profile for a pumping project can be seen in Figure 2-11 [72].

Load-shift projects implemented on dewatering systems are energy-neutral. This means that the total amount of energy used to pump out water before the implementation of the project, and afterwards, should be equal to each other. To achieve this, the baseline has to be scaled to give an accurate measurement of performance [71], [72].

Scaled power baseline

The scaled baseline profile is obtained by adjusting the baseline by a factor according to the total amount of power used during a 24-hour period. The total power for the scaled baseline is equal to the total power actually used. A scaled baseline profile can be seen in Figure 2-11 below.

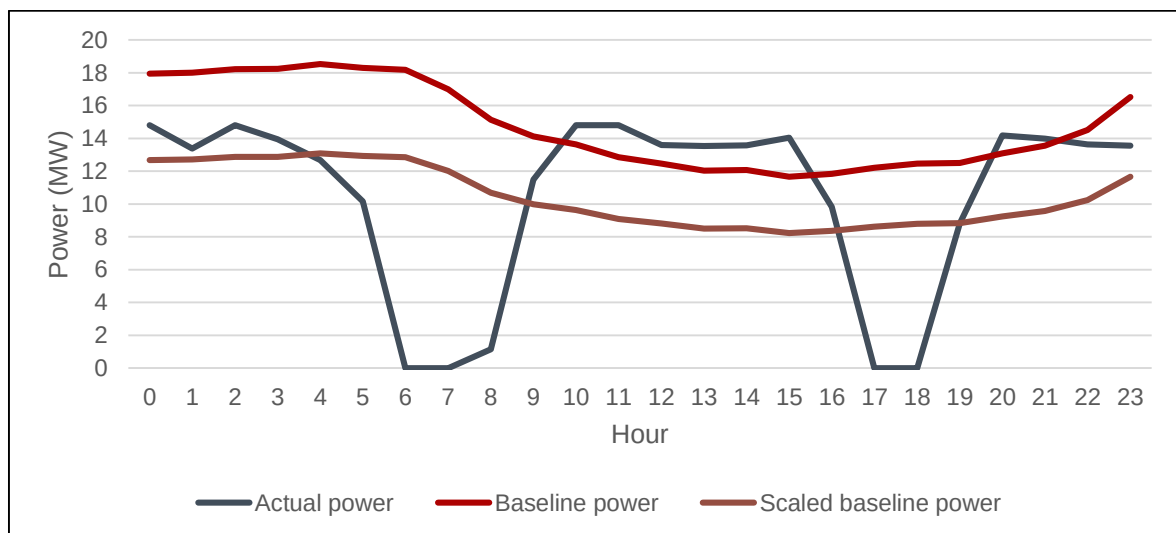


Figure 2-11: Example of a scaled baseline profile vs. actual power profile

The average energy load shift achieved for a pump project can be calculated for the morning and evening peak periods. This value is used to evaluate the project performance. The power that is shifted out of the peak periods to less expensive periods can be translated to an electricity cost saving. This is done by multiplying the megawatt-hour usage of each specific TOU with the TOU tariffs.

2.5 EXPERIMENTAL DESIGN

Designing a new product, or testing a hypothesis, can be a costly and time-consuming process for engineers. Design of experiments (DOE) is a technique for conducting experiments that is not only time-efficient, but also does not compromise on quality and reliability. The technique is used to design experiments to predict the outcomes of a system [73].

DOE principles state that an experiment is a system composed of independent input and dependant output variables. Thus, the design of an experiment can be described as the process of changing inputs to determine outputs for various scenarios [73].

DOE produces methods to determine which variables to change, how to determine the boundaries and how many runs or tests need to be done for a specific confidence interval [73].

Keystones of DOE are the identifiability of parameters, model distinguishability and the generation of optimal sampling schedules. No experiments are required to identify the parameters or to distinguish between models. However, optimal sampling schedules, or the amount of test runs required for a certain confidence level, may need some testing [74].

The DOE technique can be applied to many scenarios. Each of these scenarios will have a different approach to DOE. In one such scenario, the best way to microwave a bag of popcorn is determined using the DOE technique [75]. The DOE technique consists of seven steps that are shown in Table 2-1[75].

Table 2-1: DOE technique steps^[75]

Nr	Step	Description
1	Design the experiment	Define the responses – what is the outcome of the experiment? Define the factors – what factors influence the responses?
2	Define the factor constraints	Specify the constraints to which the factors should adhere
3	Add interaction terms	Specify what factors interact with each other
4	Determine the number of runs	Determine, with statistics, the minimum number of runs needed for the confidence interval.

Nr	Step	Description
5	Check the design	Review the design inputs and outputs to determine correctness.
6	Gather and enter data	Gather data for the factors and enter this in the simulation model
7	Analyse results	Analyse the data and draw a conclusion accordingly

A list of questions has been constructed by the Institute of Terrestrial Ecology to determine the correctness of the DOE technique when applied to a scenario. For the full question list, refer to the statistical checklist No.1: Design of Experiments [76].

Applying the DOE technique and verifying the technique using the list of questions, a valid and correct experiment can be conducted. The DOE technique has been proven to be a successful method when experiments are conducted [76].

From the literature, it can be seen that the DOE technique consists of different steps determined by the hypothesis. The key steps of the DOE technique are as follows:

1. Determine the outcomes of the study;
2. Determine inputs that affect the outcomes;
3. Determine how the inputs affect the outcomes;
4. Determine if there is any interrelation between the inputs;
5. Determine boundaries of inputs;
6. Determine the amount of runs needed for the determined confidence interval;
7. Conduct experiment and analyse results.

2.6 CHAPTER CONCLUSION

To investigate the effect of load-shift performance, extensive research is done. Before a method can be developed to investigate the effect of pump availability on load shift performance, a background on the operations of a dewatering system is needed.

The first two sections of Chapter 2 discuss the research conducted on pump dewatering systems. This research includes a background on the components of a dewatering system, the control of these components and previous studies conducted on dewatering systems. The previous studies focused on how to automate a dewatering system, optimise a dewatering system and maintain a dewatering system.

After dewatering systems are discussed, the research focuses on how to investigate the effect of pump availability on load shift performance. To determine this effect, a simulation model can be used. Therefore, focus is placed on how to develop a simulation model. The development methodology for a simulation model was discussed, to understand how the problem statement will be addressed.

After the simulation model development methodology was discussed, the verification process of the simulation model was discussed. This part ensures that the simulation model developed is accurate and can be used to simulate an actual dewatering system. Upon completion of the discussion of the verification process, a method was discussed to evaluate the results obtained from the simulation model. This method will enable the user to quantify the effect of pump availability on load shift performance.

The last part of literature research focused on a technique used to design an experimental procedure. This is known as the DOE technique and will enable the user to set up an experiment using the simulation model. The DOE technique determines which input values should be changed and how many simulations should be done.

All the research conducted in Chapter 2 will be used to develop a methodology to investigate the effect of pump availability on load-shift performance. The methodology that will be developed will be discussed in Chapter 3. The methodology uses all the research conducted and provides a method to identify all the information needed to develop a simulation model. Thereafter, the methodology will aid in the development of the simulation model and the experimental design. Lastly, the methodology will enable any mine to evaluate the results obtained from the simulation model.

Chapter 3:

Investigating the effect of pump availability



Underground pumping station⁴

We didn't set out to be educators or even scientists, and we don't purport that what we do is real science but we're demonstrating a methodology by which one can engage and satisfy your curiosity.

(Adam Savage)

⁴ Photo taken by Hannes de Jager (Author)

3 INVESTIGATING THE EFFECT OF PUMP AVAILABILITY

3.1 INTRODUCTION

In Chapter 1, it was determined that a need exists to investigate the effect of pump availability on load-shift performance. No viable research could be found on existing methods to address this problem statement. As a result, research was conducted in Chapter 2 to develop a method to investigate the effect of pump availability on load shift performance. The research in Chapter 2 includes information on:

1. Pump dewatering systems;
2. Previous studies on dewatering systems;
3. Simulation model development;
4. Experimental design.

The objective of this study is to investigate the effect of pump availability on dewatering pumping projects' load shift potential. Furthermore, it is to determine when maintenance should be done on pumps to ensure maximum load shift is achieved. This chapter will focus on how to achieve the objective of this study by developing a methodology that can be applied to any mine dewatering pumping project.

A detailed step-by-step methodology was developed using the research done in Chapter 2 as illustrated in Figure 3-1. The methodology developed consists of four main phases, i.e.

1. Develop a simulation model;
2. Verifying the simulation model;
3. Utilise simulation model to get results;
4. Analyse results obtained.

Each of the four phases consists of steps to be followed in order to complete the phase. Each of these steps is illustrated in Figure 3-1. A short description of each step will be provided as an introduction to the methodology. A detailed description of each phase, and the steps needed to complete that phase, will be discussed in the remainder of the chapter.

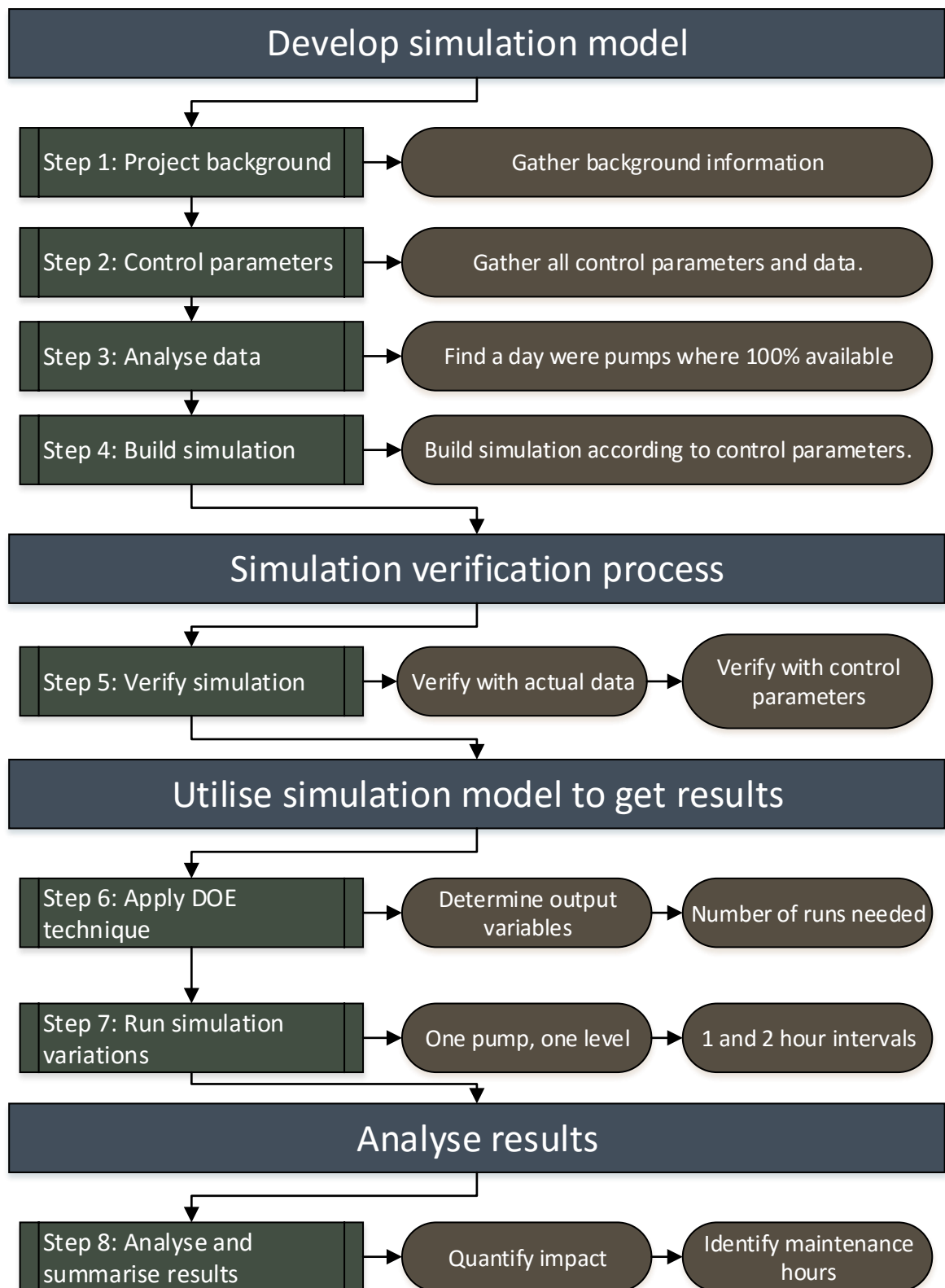


Figure 3-1: Step-by-step methodology

Develop simulation model

Step 1 consists of getting a basic overview of the load shift project; how the dewatering infrastructure works; the layout of the dewatering system; and understanding what could be the possible constraints of the project.

Control parameters are gathered during step 2. Control parameters include maximum and minimum dam levels; dam capacities; pump capacities; control philosophy; and logged data.

Step 3 is used to analyse data. From this data, two important aspects should emerge: firstly, if the control philosophy is followed and secondly, which day within the data pool results in a 100% pump availability. This day will be used to develop and verify the simulation model.

Step 4 includes the development of a project-specific simulation model. This is done while taking the constraints and control parameters into account.

Verify the simulation model

Step 5, the simulation, will be verified using the actual data; dam level and status correlation; and the control philosophy.

Utilise simulation model to get results

Step 6 applies the DOE method discussed in Chapter 2. The experiment should be designed to determine the needed parameters and the number of runs that should be conducted.

Step 7 is to execute the experiments to determine the effect of the pump availability on project performance.

Analyse results

In step 8, results will be analysed to quantify the effect of pump availability on load shift performance.

3.2 DEVELOP SIMULATION MODEL

3.2.1 STEP 1: PROJECT BACKGROUND

The first step towards developing a simulation model is to gather information on the dewatering system. Background information on the dewatering system will aid the simulation model developer, to get an understanding of the operations of the system. The background on the dewatering system can be retrieved from mine personnel or from the ESCO that implemented the load shift project.

Background information that needs to be gathered, as illustrated in Figure 3-2, includes:

1. The implementation date of the load shift project;
2. Whether project maintenance is done and by whom;
3. What control mechanisms are used to control the dewatering system;
4. A layout of the dewatering system.

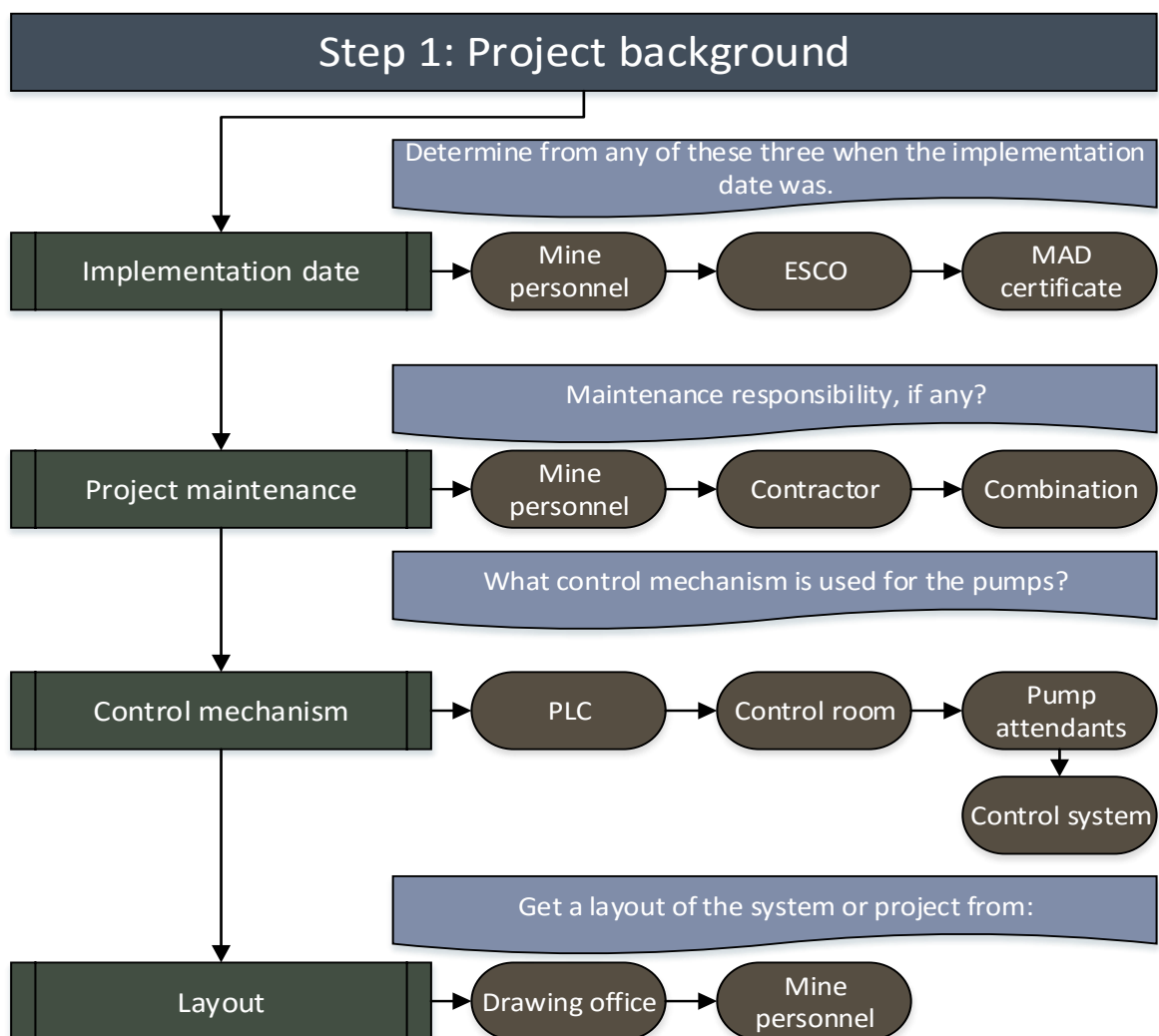


Figure 3-2: Methodology Step 1

Implementation date

The date when the load shift project was implemented should be received from mine personnel or the ESCO. This information can also be found on a Measurement Acceptance Date (MAD) certificate. The MAD certificate not only gives the implementation date, it also reflects the load shift target for the project. Furthermore, it gives the duration the project savings should be maintained for the mine to keep its contract commitments.

By knowing this information, a quick assessment of the overall health of the project can be determined. If the project was implemented long ago, maintenance on the project may have been done poorly and thus the project performance could be influenced. This can also be an indication of pump availability and can play a major role in project performance.

Project maintenance

Information regarding the maintenance of the load shift project is required from mine personnel. The reason this information is essential, is to find out how important the project performance is to the mine personnel. If regular upkeep has been done, the mine would be interested in maintenance schedules and how the pump availability will influence the project performance.

Control mechanism

To be able to understand the control philosophy, it is important to understand how the load shift project is controlled. Are the pumps controlled by a PLC, through the SCADA by control room operators, by pump attendants, or using alternate control programs.

This information will be required to establish what the maintainability of savings will be. For instance, if pump attendants control the pumps, the chances are higher that savings will not be achieved, since preparation of dam levels are not necessarily done.

Layout

After the control mechanism has been established, a water reticulation layout has to be gathered from the mine personnel. The layout will be used to understand how the water is controlled and the path that the water has to go from the start to the end of the cycle. The layout will also aid in the isolation process of the dewatering levels. Isolation of dewatering levels will be discussed in step 4 of the methodology.

3.2.2 STEP 2: CONTROL PARAMETERS OF EXISTING PROJECT

To understand the control of the system, the remaining detail of the existing project should be gathered from the mine personnel, maintenance crew and SMEs. The information that needs to be gathered in step 2 is critical for the simulation model developer. The simulation model developer will use this information and program the simulation model to reflect the actual system parameters. Information needed to complete step 2, as illustrated in Figure 3-3, includes:

1. Hot water dam information;
2. Dewatering pump information;
3. Control parameters of the dewatering system;
4. Logged data of the actual system.

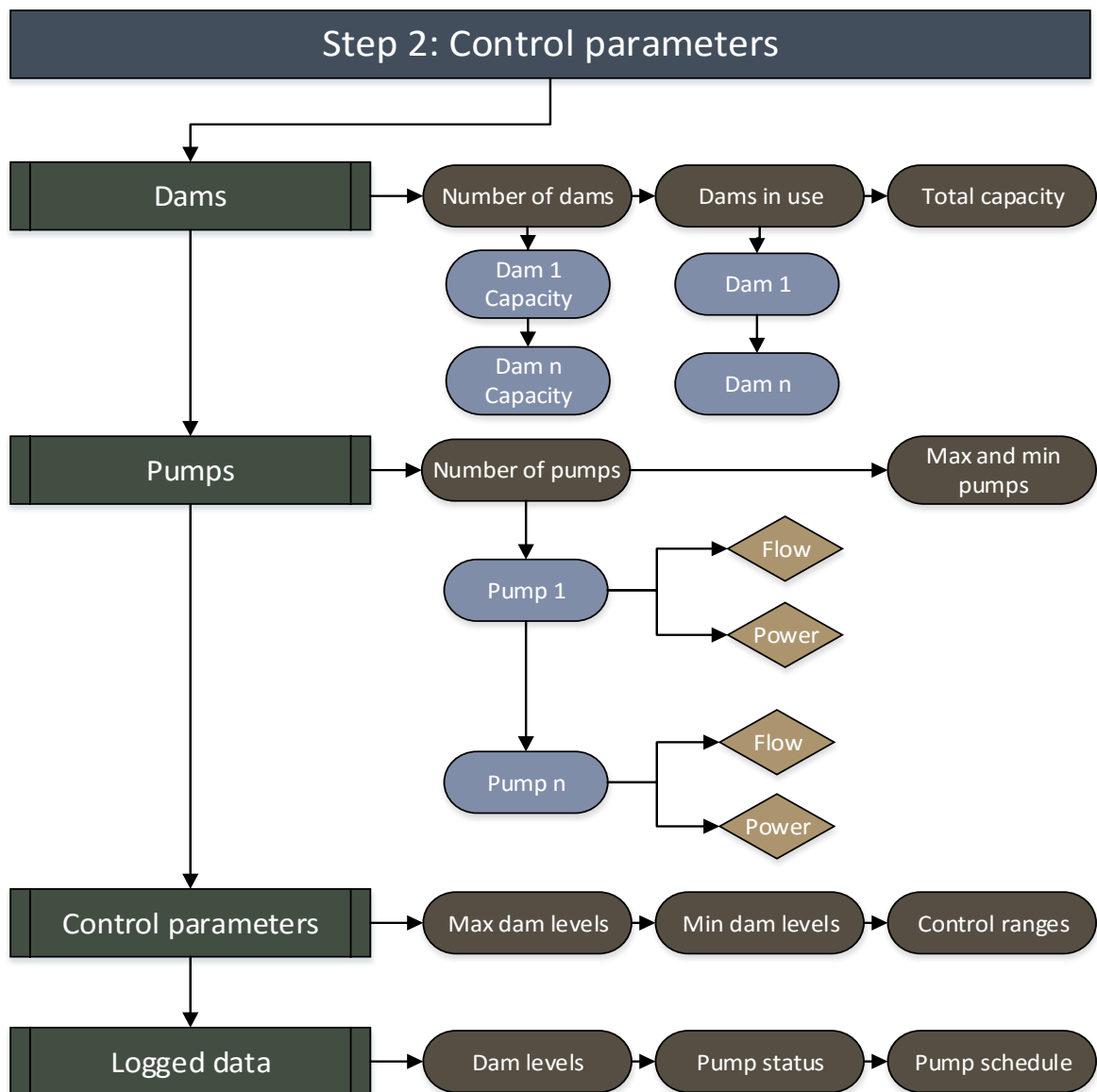


Figure 3-3: Methodology Step 2

The information that needs to be gathered in step 2 of the methodology will now be discussed below.

Hot water dams

Information regarding hot water dams at each pumping station has to be acquired. The information includes:

1. Number of dams;
2. Capacity of each dam;
3. Number of dams used at a time;
4. Which dams are in use.

Hot water dams are cleaned regularly to prevent debris from entering the pumps as this can lead to catastrophic failure. Therefore, the combination of dams used differs from time to time. By knowing which dams are in use, the total water capacity can be calculated. The total water or dam capacity is vital for simulation accuracy.

Dewatering pumps

Information regarding dewatering pumps at each pumping station has to be acquired. The information includes:

1. Number of pumps operational;
2. Operational power consumption;
3. Delivered flow;
4. Maximum number of pumps operating simultaneously;
5. Minimum number of pumps operating.

The information that needs to be gathered for the pumps will be discussed hereafter.

Number of pumps operational

This information serves one purpose – it will give the simulation model developer more background on the system and an idea of what the possibility is that no additional pumps are available for control.

Power consumption

If the actual power consumption is not available from power meters, temporary loggers can be installed on the pumps. The temporary loggers will then log the current, the voltage and

the power factor. If all of these parameters have been collected for a short period, then the power consumption can be calculated.

Delivered flow

Specifics are required for the delivered flow of the pump. This information can be supplied either by the mine personnel or the SME. Alternatively, the flow can be measured or calculated from flow diagrams. The delivered flow of each pump is necessary to develop an accurate simulation model.

Maximum number of pumps

Information on the maximum number of pumps allowed to operate simultaneously should be gathered from the mine personnel and SMEs. This information is needed to program accurately the simulation model for the system parameters.

Minimum number of pumps

Similar to the maximum number of pumps operating simultaneously, the minimum number of pumps operating simultaneously should be gathered. Accuracy of the simulation model depends on this information to replicate the actual system. The minimum number of pumps for certain system constraints is determined by the SMEs and is key input that has to be implemented in the control of the dewatering system.

Control parameters

The control parameters of each dewatering station should be gathered. The control parameters that should be gathered from mine personnel and SMEs include:

1. Maximum and minimum dam levels;
2. Control ranges;
3. Control offsets.

Each of these will be discussed shortly.

Maximum and minimum dam levels

Maximum and minimum allowable dam levels ensure safe operation of the dewatering system, leaving enough capacity in case a system failure should occur. This information is necessary to develop the simulation model accurately.

Control ranges

The control ranges are used to control the Preparation Load (PL) and Comeback Load (CL) of the project to ensure a full load shift is achieved. This information is necessary for the development of the simulation model.

Control offsets

Control offsets will ensure that the amount of pumps running at a time decreases the dam level and will ensure that pumps are not started and stopped simultaneously. Similar to the other control parameters, control offsets are necessary for an accurate simulation model if the actual system utilises more than one pump.

Logged data

Data from the dewatering system is required for the development of the simulation model. Data should be logged and gathered from the dewatering system. The data includes:

1. Dam levels;
2. Pump status;
3. Pump schedule.

The data should be logged in the smallest time increments possible. Smaller time increments will result in a more valid and accurate simulation model.

3.2.3 STEP 3: ANALYSE DATA

Logged data has to be analysed to determine a day with availability as close to 100% as possible. The day that results in 100% availability or the closest to 100% will be used to develop the simulation model. Availability can be determined when pump status and pump schedules are compared. Pump schedules are determined by the control mechanism mentioned in Chapter 2.

When a pump status and pump schedule are both equal to one another, it is an indication that the pump is available for control, thus making the pump 100% available. If the pump status and pump schedule do not correlate, an assumption can be made that the pump was not available for control.

Depending on the amount of pumps that are scheduled to run at a time, the availability is determined. The availability is determined by determining the factor of control. The factor of control is calculated by dividing the pump status by the schedule. This is done for instances

where the pump status is equal to or smaller than the pump schedule as illustrated in Equation 4.

$$Availability = (Pump\ status / Pump\ schedule) * 100 \quad \text{Equation 4}$$

The factor of control for instances where the pumps scheduled are smaller than the pump status, can be calculated by dividing the pumps scheduled with the pump status as illustrated in Equation 5.

$$Availability = (Pump\ schedule / Pump\ status) * 100 \quad \text{Equation 5}$$

The control factor is represented as a percentage that is equivalent to the availability. Figure 3-4 illustrates an example of the pump status and pump schedule for a dewatering system. The availability calculation for these time intervals is illustrated in Table 3-1.

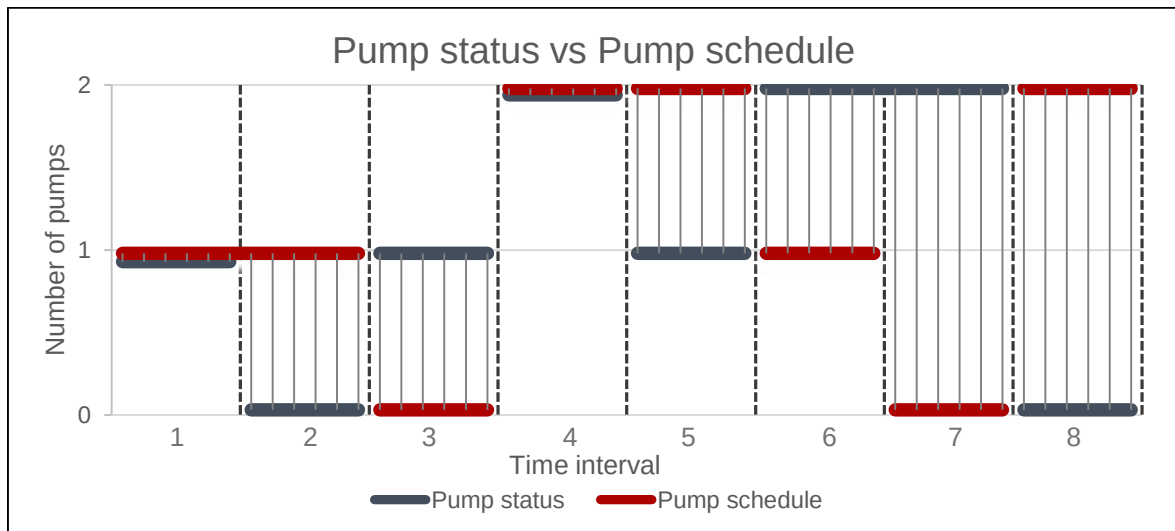


Figure 3-4: Example of pump status and pump schedule

It will be seen that for each time interval illustrated in Figure 3-4, an availability calculation is done in Table 3-1. The example given in Figure 3-4 is conducted in such manner so that the pump status and pump schedule differ for each time interval. Although the example represents a maximum number of two pumps, the concept can be applied to more pumps.

In instances where the pump status is equal to the pump schedule, the availability is 100% as illustrated in Table 3-1. In instances where the pump status and the pump schedule are not equal to each other, the availability is less than 100%.

Table 3-1: Availability calculation

Time interval	Pump Schedule	Pump Status	Equation	Pump Availability
1	1	1	Equation 4	100%
2	1	0	Equation 4	0%
3	0	1	Equation 5	0%
4	2	2	Equation 4	100%
5	2	1	Equation 4	50%
6	1	2	Equation 5	50%
7	2	0	Equation 4	0%
8	0	2	Equation 5	0%

Applying the formulas provided, the pump availability has to be calculated for each time interval of the logged data. Then the average availability has to be calculated for each day. The day that has a 100% availability, or close to 100%, can then be used to develop the simulation model.

Making use of Microsoft Excel's 'If' functions, the pump availability can be calculated. The 'If' functions in Microsoft Excel consist of three parts, i.e. a logical test; value if the logical test is satisfied; and value if the logical test is not satisfied. Logical tests are done by comparing the pump status with the corresponding pump schedule. A logical test consists of three parts, i.e:

1. When the pump statuses are equal to pump schedules;
2. When the pump status is more than the pumps scheduled;
3. When the pump status is less than the pump scheduled.

The three logical tests are depicted in Table 3-2 below

Table 3-2: Logical tests and results

Logical test number	Logical test	Availability if logical test is satisfied
1	Pump status = Pump schedule	$(\text{Pump status} / \text{Pump schedule}) * 100\%$
2	Pump status > Pump schedule	$(\text{Pump schedule} / \text{Pump status}) * 100\%$
3	Pump status < Pump schedule	$(\text{Pump status} / \text{Pump schedule}) * 100\%$

The logical test process is illustrated in Figure 3-5. If the first logical test is not satisfied, the next logical test is done. If the second logical test is not satisfied, the last logical test is done. When a logical test is satisfied, the corresponding availability is calculated.

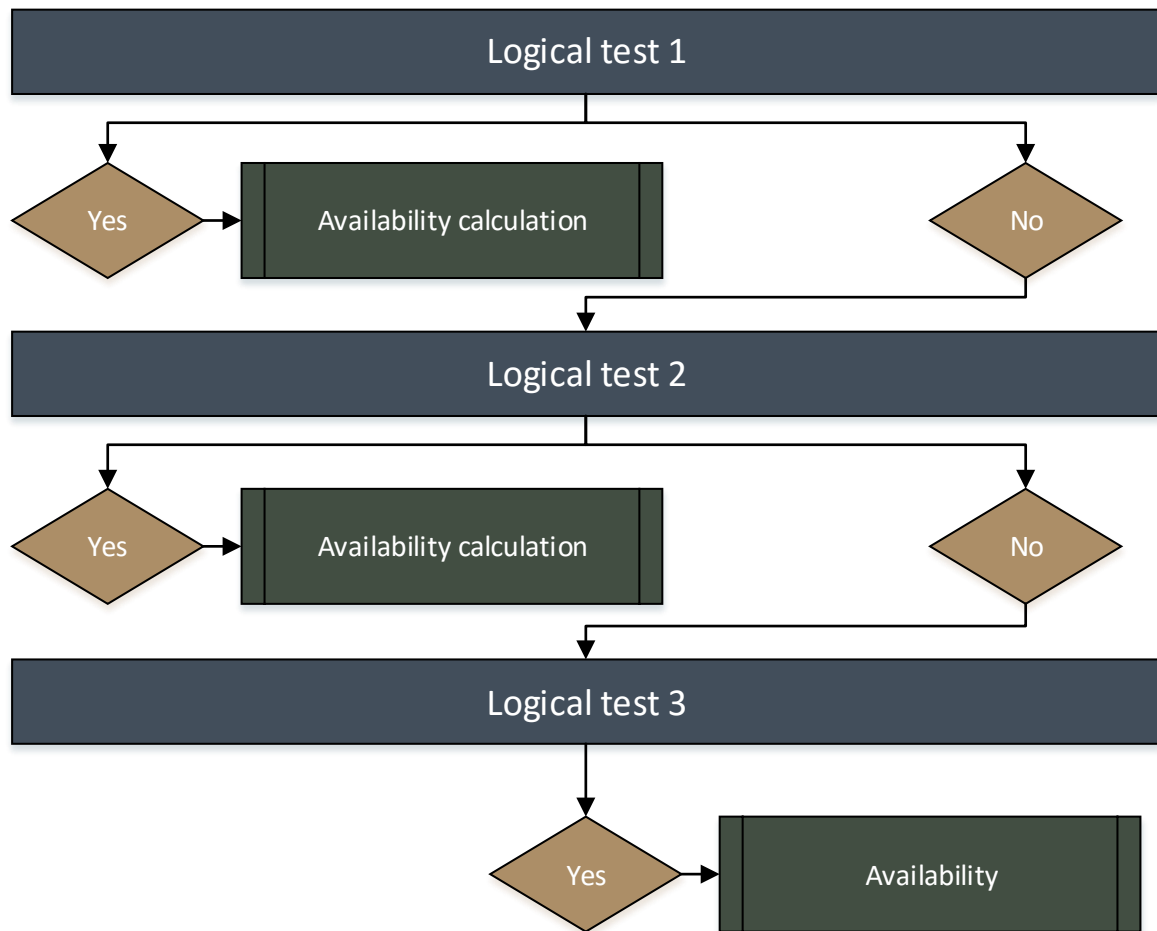


Figure 3-5: Logical test

3.2.4 STEP 4: DEVELOP SIMULATION MODEL

Upon the completion of steps 1 through to step 3 of the methodology, enough information is gathered to develop a simulation model. Any simulation package that is preferable for the programmer or simulator, can be used. The simulation package should, however, be able to satisfy the needs of the study.

The final step of the first phase of the methodology consists of four main parts.

The main parts of step 4, as illustrated in Figure 3-6, are:

1. Isolate dewatering levels;
2. Classify information;
3. Complete assumptions document;
4. Develop simulation model.

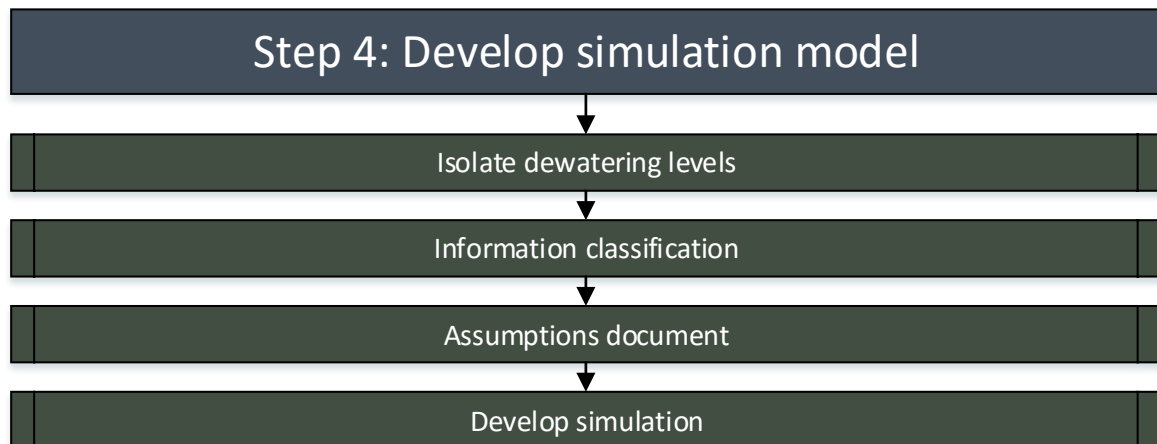


Figure 3-6: Methodology Step 4

Isolate dewatering levels

Due to the complexity of dewatering systems and the numerous interactions between the dewatering levels, it is difficult to determine the effect of availability on load shift performance. As a result, each dewatering level of a mine should be isolated to determine the effect that unavailable pumps have on each level. Isolating each dewatering level will result in a better understanding of the influence and will aid in the investigation.

Classify information

When developing the simulation model, the information received in the previous steps of the methodology should be grouped into two groups, i.e. inputs and outputs. Input data is required for the simulation model to be interpreted and modified in order to make predictions of the system. The predictions are the desired output information needed to address the problem statement.

Input variables can be classified into two groups, namely fixed inputs and variable inputs. Fixed inputs will be information that is unchangeable throughout the simulation variants. This is information such as dam capacities, water flow per pump, the number of pumps installed on each pumping station, etc.

Variable inputs are inputs that change throughout the duration of the simulation variants. This includes information such as the inflow of water into a dam, the number of pumps running, the control range and control offsets.

The output information can be classified as variable results. The outputs received from the simulation model will change for every iteration of the variable input. A document should be drafted to allocate all the information received into the different groups.

A list of input information should be compiled and divided into fixed inputs and variable inputs. A list of output variables should also be compiled. An example of the information classification can be seen in Table 3-3.

Table 3-3: Example of information classification

Information classification document		
Nr	Fixed inputs	Variable inputs
1	Dam capacity	Fissure water inflow
2	Number of pumps	Control ranges
3	Flow of pumps	Maximum number of pumps
Nr	Variable outputs	
1	Pump status	
2	Dam level	

Assumptions document

On completion of the classification of information, an assumptions document should be compiled. The assumptions document should include all the assumptions made when developing the simulation model. A reason for every assumption should be given for justification.

Further information required for the assumptions document include: simulation model name; date of the assumptions document; revision number of the document; and by whom the assumptions were accepted. A typical assumptions document can be seen in Table 3-4.

Table 3-4: Example of assumptions document

Assumptions document for simulation model A		
Revision number : XX		Date: YYYY/MM/DD
Nr	Assumption	Justification for assumption
1	Assumption A	Justification A Justification B Justification C
2	Assumption B	Justification D Justification E Justification F
3	Assumption C	Justification G Justification H Justification I
Accepted by:		Name:.....

Develop simulation

After all the information is categorised and assumptions are made for the simulation model, the simulation models should be developed. The assumptions and data should be programmed within a preferred and suitable programming software package and the simulation model should be debugged.

Many iterations of the simulation model can be completed until the simulation model and sub-systems are without bugs and the desired outputs are achieved.

3.3 VERIFY THE SIMULATION MODEL

3.3.1 STEP 5 VERIFY SIMULATION

The verification technique discussed in Chapter 2 will be utilised to verify the simulation model developed. The simulation model results will be compared to the actual system. If the simulation results and the actual system's data correlate, the simulation can be deemed valid and verified within a certain percentage of accuracy. The verification method used for the simulation models is illustrated in Figure 3-7.

Verification of the simulation model, as illustrated in Figure 3-7, consists of comparing the simulation results to the actual system by looking at three aspects listed on the next page.

1. System parameters;
2. Status correlation;
3. Dam level correlation.

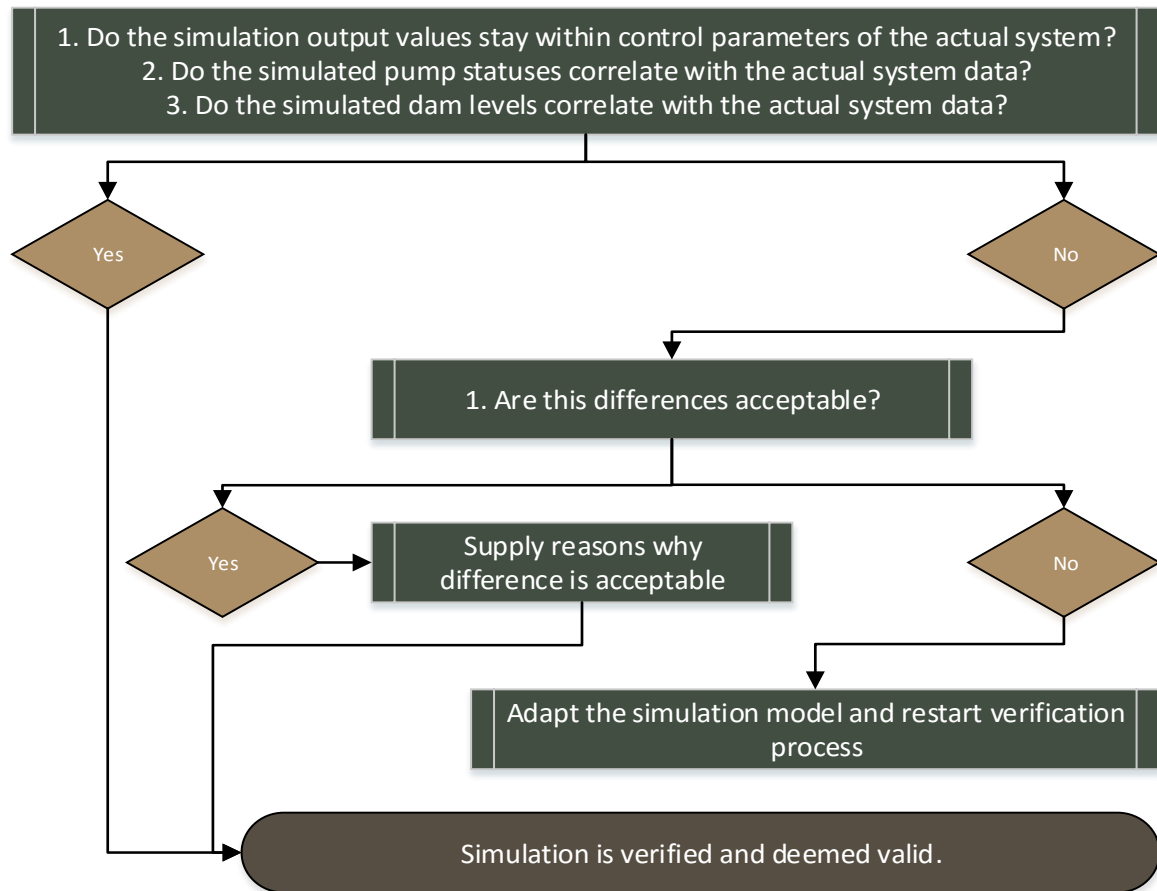


Figure 3-7: Simulation model verification process

A typical representation of the correlation between actual and simulated statuses is illustrated in Figure 3-8.

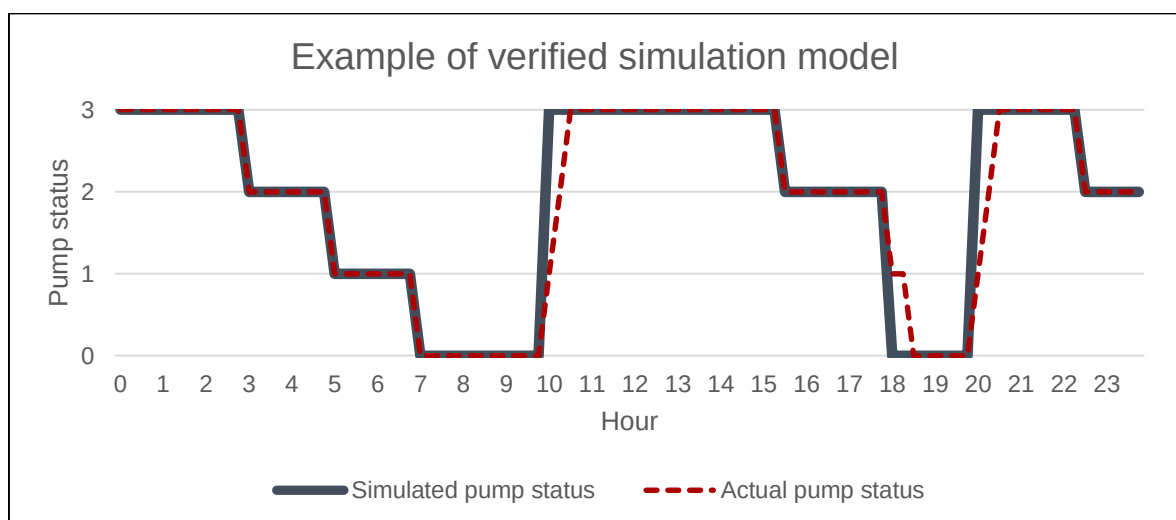


Figure 3-8: Example of verified simulation model

As seen from Figure 3-8, the simulated status and the actual system status do not correlate 100%. The difference in actual status and simulated status can be attributed to the fact that the pumps cannot always start simultaneously in the actual system.

A 5 to 10-minute delay is normally programmed into the PLC between start and stop of the pumps. The simulation does not have a delay on the start and stop. Nevertheless, the simulation model can be deemed verified for the example. The same principle will apply for the dam levels and the system parameters.

In the case where the simulation results and the actual system's data do not correlate 100%, reasons should be given as to why the data does not correlate. A decision based on the knowledge of the system's sensitivity should be made regarding the accuracy of the simulation results. If the results are found to be accurate enough, the simulation model can be deemed as valid and verified.

3.4 UTILISE SIMULATION MODEL FOR RESULTS

3.4.1 STEP 6: APPLY DOE TECHNIQUE

After the simulation model has been developed and verified, an experiment should be designed to investigate the effect of pump availability on load-shift performance. Application of the DOE technique will result in the experimental boundaries and the amount of runs needed. Illustrated in Figure 3-9, the DOE technique steps are listed.

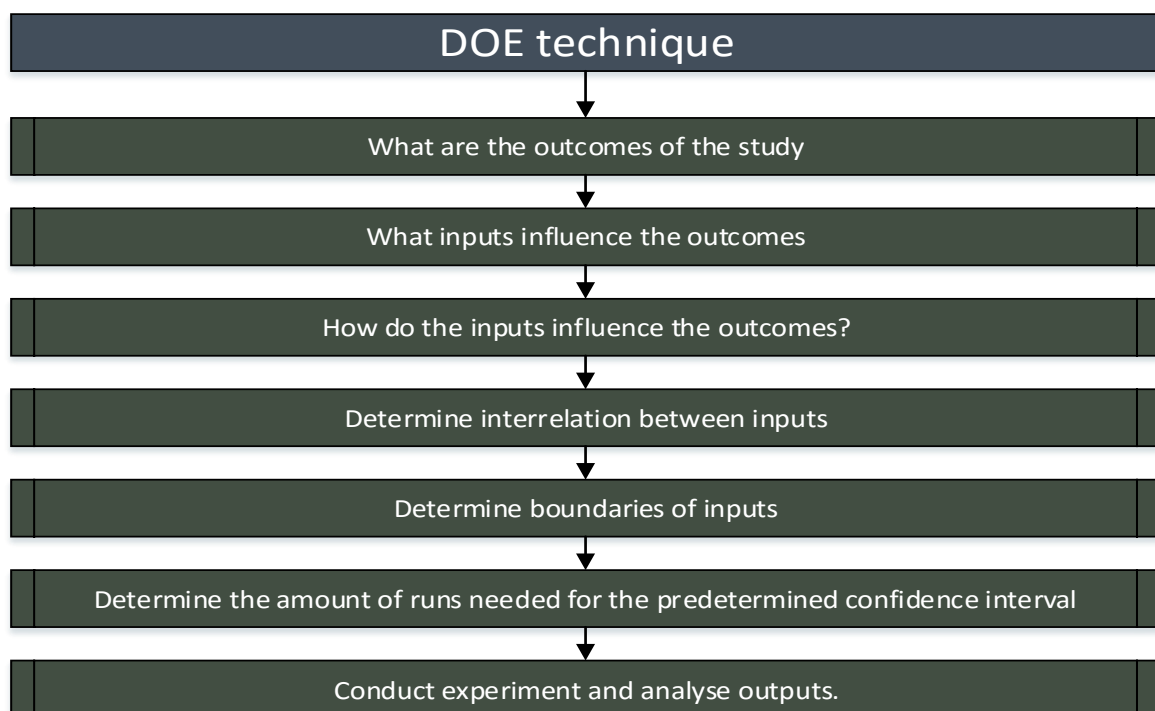


Figure 3-9: Methodology Step 6 – DOE technique

3.4.2 STEP 7: RUN SIMULATIONS

After the experiment has been designed for the specific case study, experiments should be conducted. The simulation model is used to conduct the experiments. Experiments should be conducted for each pumping station. Changing input values of the simulation model, as determined with the DOE technique, means the effect of pump availability on load shift performance can be determined.

The results obtained from the simulations conducted should be illustrated as an average power profile for the 24-hour period. A typical power profile for the simulations conducted is illustrated in Figure 3-10.

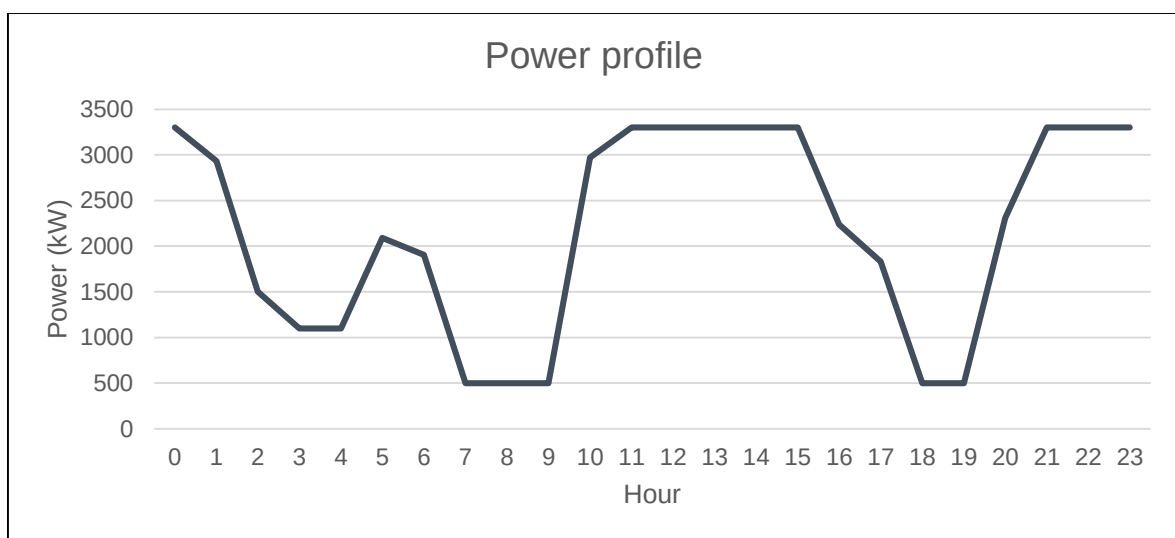


Figure 3-10: Example of a power profile

The results obtained will be evaluated in the final phase of the methodology. The power profile for each simulation model will differ depending on the amount of pumps that ran during the 24-hour period and the installed capacity of the pumps.

3.5 EVALUATING SIMULATION RESULTS

3.5.1 STEP 8: RESULT INTERPRETATION

Results obtained from the experimental procedure, using the simulation model, have to be interpreted and concluded. As discussed in previous chapters, DSM projects' performance is measured using a baseline.

The first step towards result interpretation is to develop a baseline. The baseline is a representation of what normal circumstances would have been. The baseline for result interpretation should thus be a baseline that is representative of the system that is being

tested. Comparing the simulated power profile to the baseline will indicate the effect that pump availability has on the load shift performance.

Examples of a baseline and the simulated power profile are shown in Figure 3-11 to Figure 3-13. These examples simulate the effect of a reduction in pump availability for the time intervals 02:00 – 02:59 (hour two), 03:00 – 03:59 (hour three) and 04:00 – 04:59 (hour four) of the day.

The first example, illustrated in Figure 3-11, shows that one pump was unavailable for the time interval 02:00 – 02:59 (hour two). This is marked with the letter A on Figure 3-11. The simulated power profile of the reduced availability during the time interval is shown with the letter B on the figure during the evening peak.

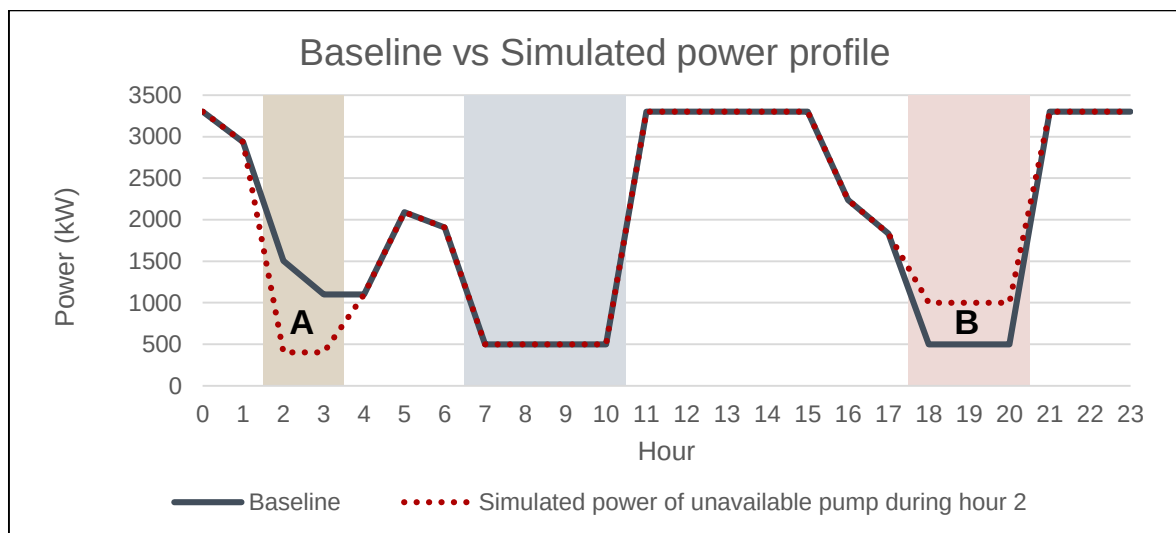


Figure 3-11: Example 1 of power profile with reduced availability

It will be seen, when analysing Figure 3-11, that the reduced availability during the morning hours (Point A) of the day led to an increase in electricity usage during the evening peak period (Point B). The increased electricity usage during the evening peak period (Point B) indicates a negative effect on the load shift performance. The difference between the baseline and the simulated power profile quantifies the impact of reduced pump availability.

The second example is similar to the first example. The availability of one pump is reduced during the 03:00 – 03:59 time interval (hour three). The reduced availability is indicated with the letter C on Figure 3-12 and the simulated power profile of the reduced availability is indicated with a D.

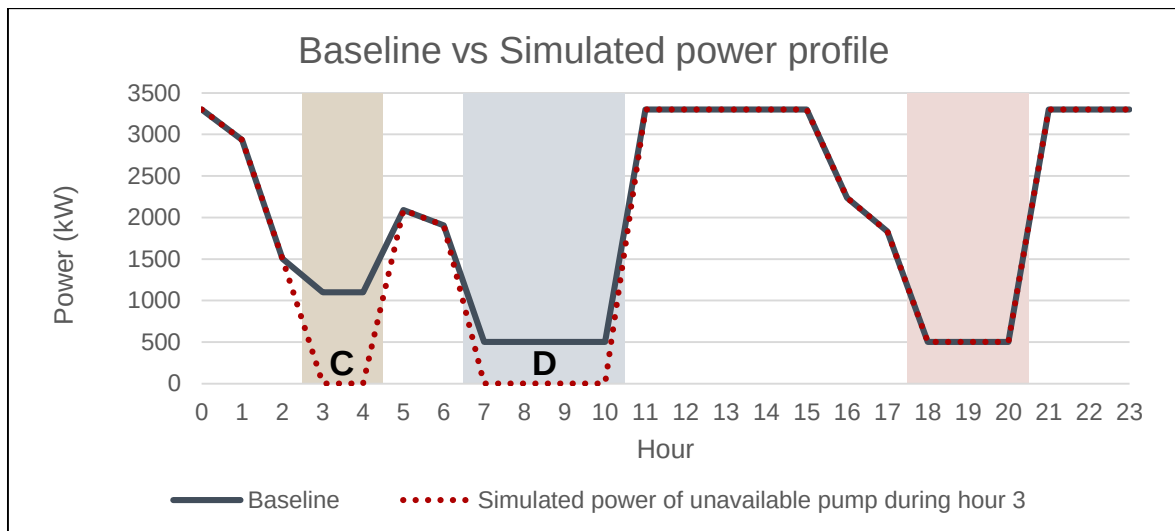


Figure 3-12: Example 2 of power profile with reduced availability

Analysing Figure 3-12, it will be seen that less electricity is used during the morning peak period as a result of the reduced availability. This can be seen when the baseline is compared to the simulated power profile (Point D). Less electricity used during the morning peak indicates that the reduced availability positively influenced the morning peak period. Less energy used during the peak period (Point D) compared to the baseline indicates that more load could be shifted out of the peak period into the remaining periods of the day.

The third example is a combination of the first two examples as illustrated in Figure 3-13. The availability of one pump has been reduced during the 04:00 – 04:59 time interval (hour four) and indicated with an E on the figure. The result of the reduced pump availability is shown with an F and a G on the figure below.

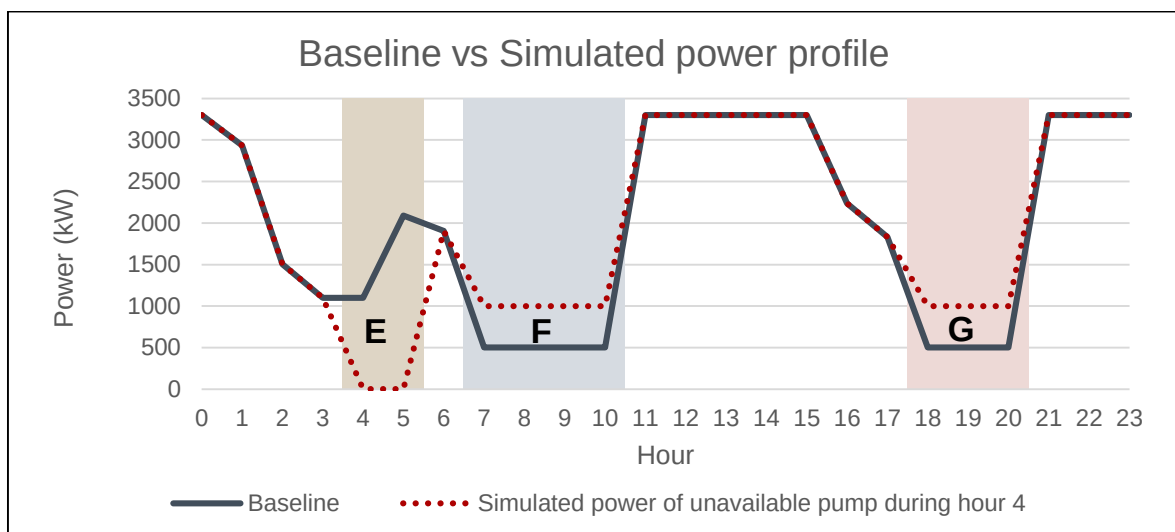


Figure 3-13: Example 3 of power profile with reduced availability

Analysing Figure 3-13, it can be seen that the reduced availability during hour four resulted in an electricity usage shift to the morning and evening peak period. The energy usage shift

is due to system parameters that are exceeded. To ensure system parameters are met, more pumps are utilised during the peak periods. The increase of electricity usage during the peak periods (Point F and Point G) indicates that the reduced availability negatively impacts the load shift performance.

To enable a holistic understanding of the effect that pump availability has on the load shift performance, the simulated power profile of each individual simulation conducted should be represented as one. The amount of simulations that should be conducted will be determined with the DOE techniques discussed in the previous section. The results of the reduced availability are determined by quantifying the difference between the baseline and the simulated power profile for each simulation during the morning and evening peak periods. The holistic representation can be done by representing the results of the reduced availability on one graph. The graph will illustrate the hour of simulated reduced availability and the effect on load shift performance for both the morning and evening peak periods.

The effect of the availability on load shift performance will be determined by calculating the average power consumed during the individual peak periods and how this differs from the baseline period values of points B, D, F and G. The results obtained from the calculation will then be illustrated as bar graphs for each simulation conducted. A typical bar graph, used for the representation of the effect that unavailable pumps have on the load-shift performance, is illustrated in Figure 3-14

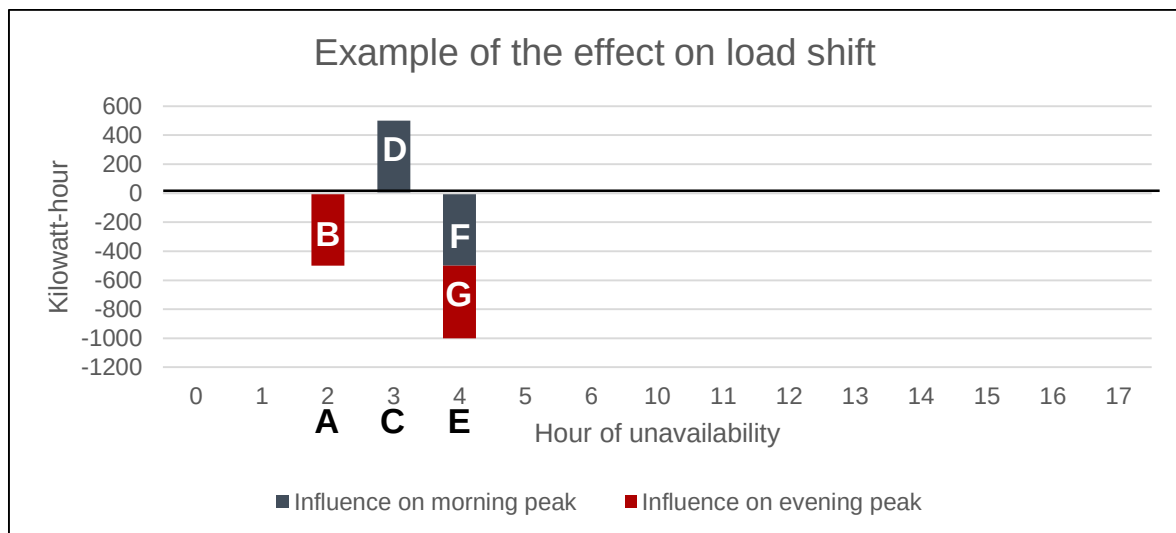


Figure 3-14: Example of the effect on load shift

Figure 3-14 is marked with the letters A to G. These letters link the information represented in Figure 3-14 back to the illustrations in Figure 3-11 to Figure 3-13. Each letter indicates the hour of simulated reduced availability and the results obtained from the three examples previously discussed. On the X-axis, the hours of the day are indicated when availability

was influenced. On the Y-axis, the influence of the availability on the respective morning and evening load shifts is indicated.

A positive influence on the peak periods is indicated with a positive bar graph and a negative influence is indicated with a negative bar graph. The bars showing the effect on the morning and evening load shift performance are stacked on top of each other to determine the overall effect on the load-shift performance.

The examples, given in Figure 3-11 to Figure 3-13, show that pump availability has been reduced for hour two (Point A), hour three (Point C) and hour four (Point E). The negative influence on the evening peak of the first example is indicated with the letter B on Figure 3-14. The positive influence on the morning load shift of Example 2 is indicated with the letter D. The negative influence on the morning and evening peak periods of Example 3 is indicated with the letters F and G in Figure 3-14.

No examples are given on the remaining hours of reduced availability. Therefore, no influence can be seen on the peak periods as indicated on Figure 3-14. In the case that the reduced pump availability has no effect on the load shift performance, no bar graph will be shown. This will be represented in the same manner as the hours where there was no example.

3.6 CHAPTER CONCLUSION

To be able to investigate the effect of pump availability on load-shift performance, a step-by-step methodology was developed. The methodology consists of four main phases and a total of eight steps. The four main phases of the methodology are as follows:

1. Develop simulation model;
2. Verify simulation model;
3. Implement simulation model for results;
4. Evaluate simulation model.

The first phase of the methodology consists of four steps. The four steps stipulate what type of information is needed to develop a simulation model for a dewatering system. It also discusses how to analyse data and aids in the development process for simulation model.

The second phase of the methodology provides the verification process that should be followed to determine if the simulation model developed is correct and accurate. The third phase of the methodology discusses how to use the simulation model to get viable results.

The last part of the methodology discusses how the results from the simulation model should be evaluated and quantified.

The step-by-step methodology easily enables a person to investigate the effect of pump availability on load-shift performance. It does so by helping to develop a simulation model and by discussing how the simulation model should be implemented to get results. It also discusses how the results should be interpreted to give a quantifiable effect on load shift performance.

In Chapter 4, the step-by-step methodology will be applied to dewatering systems on three different mines. The results will then be validated to determine the accuracy of the methodology and conclusions will be drawn from the results obtained.

Chapter 4:

Application of methodology



Platinum and gold bar⁵

At its heart, engineering is about using science to find creative, practical solutions. It is a noble profession.

(Queen Elizabeth II)

⁵ Available: <https://warosu.org/biz/thread/902177>

4 APPLICATION OF METHODOLOGY

4.1 INTRODUCTION

Chapter 1 and Chapter 2 led to the development of a step-by-step methodology to investigate the effect of pump availability on load shift performance. The step-by-step methodology will now be applied to three different mines. The results are used to validate the methodology and show that the problem statement has been addressed.

Different mines have been selected to ensure that a broad range of scenarios are covered. The basis on which the mines have been evaluated to use as case studies includes:

1. A load shift project that should already be implemented;
2. The amount of pumping stations of the mine;
3. The number of pumps on each pumping station that are operating simultaneously.

The mines are arranged according to the complexity of the dewatering system. The least complex dewatering system will be discussed first and the most complex system will be discussed last. The complexity of the dewatering system is determined by the amount of dewatering levels and the amount of pumps operating simultaneously on one level of the mine.

As discussed in Chapter 3, each dewatering level of the applicable mine will be isolated from the interacting dewatering levels and discussed as a case study on its own. This will ensure that the effect of pump availability on the load shift performance for each dewatering level can be determined.

The step-by-step methodology will be applied to the first mine and discussed in detail for each case study. The step-by-step methodology will also be applied to the remaining two mines. However, the methodology will not be discussed in detail. All the relevant steps and information gathered during the application of the methodology will be supplied in the appendices as proof of application.

4.2 CASE STUDY A – SMALL DEWATERING SYSTEM

4.2.1 INTRODUCTION TO MINE A

The first mine to which the step-by-step methodology will be applied, is a gold-producing mine situated in the Free State province of South Africa. The mine bottom is roughly 2200 m below surface. Water utilised on five main mining levels, along with fissure water, is collected on 2180L roughly 2180 m below surface.

The water collected in the hot water dams on 2180L is then pumped back to surface for cooling via another pumping station. This pumping station is situated on 1200L, 1200 m below surface. From the 1200L, the water is transferred to the surface precool dam. The water reticulation system for mine A can be seen in Figure 4-1.

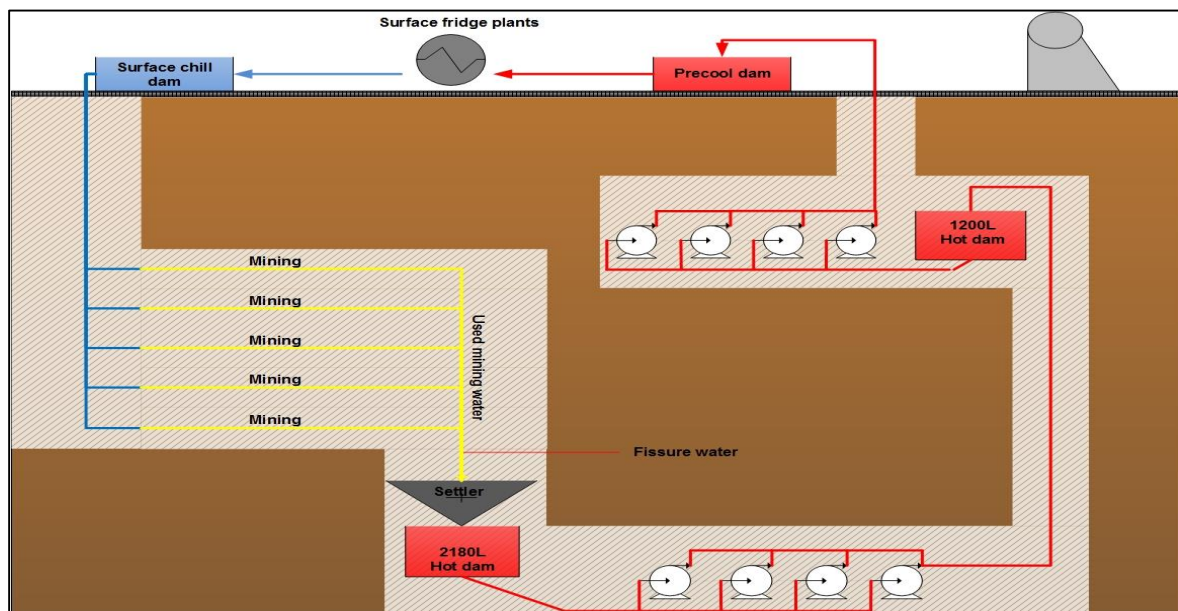


Figure 4-1: Mine A water reticulation

Three 1.25 MW and one 1.5 MW multistage centrifugal pumps are installed on 2180L to transfer the water to 1200L. Four 1.5 MW multistage centrifugal pumps are located on 1200L to transfer the water to the precool dam located on the surface.

4.2.2 DEVELOP SIMULATION MODELS

Step 1: Project background

In order to complete step 1 of the methodology, information was gathered from mine personnel, project documentation and the maintenance crew. The information gathered for mine A is summarised in Table 4-1.

Table 4-1: Mine A – Step 1 information

Step 1 – Case study A	
Implementation date	2005-08-16
Project maintenance	Yes – ESCO
Control mechanism	Main control of pumps is done by a control program along with a SCADA and PLC setup
Layout	Supplied in mine A introduction

From the information received in step 1, it can be noted that the project is old and already out of the PT period. However, an ESCO company is responsible for the maintenance on the load shift project. This could give an indication that good care is taken of the project and sustainability can be realised.

From the layout illustrated in Figure 4-1, it can be seen that the dewatering of mine A is relatively straightforward. Only two dewatering pumping stations are needed for the dewatering of mining- and fissure water. This, again, is an indication that sustainability of the load shift project can be achieved if proper maintenance is done on the project.

Step 2: Control parameters of project

In step 2, all the control parameters of each dewatering level (case study) should be obtained from mine personnel and the maintenance crew. For both 2180L and 1200L, the control parameters and constraints are gathered as seen in Table 4-2 and Table 4-3.

Table 4-2: Case study A1 – 2180L control parameters

Case study A1 – 2180L		
Hot water dams		
Total capacity (m³)	5000	
Pumps		
Pump 1	Flow (l/s):	95
	Power (kW):	1250
Pump 2	Flow (l/s):	95
	Power (kW):	1250
Pump 3	Flow (l/s):	95
	Power (kW):	1250

Case study A1 – 2180L		
Pump 4	Flow (l/s):	95
	Power (kW):	1500
Maximum number of pumps allowed to run at a time	2	
Minimum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	79% for (00:00 – 05:59) 85% for (06:00 – 09:59) 79% for (10:00 – 17:59) 85% for (16:00 – 19:59) 79% for (20:00 – 23:59)	
Minimum dam level	45% for (00:00 – 17:59) 65% for (18:00 – 19:59) 45% for (20:00 – 23:59)	
Control ranges	20% for (00:00 – 06:59) 5% for (07:00 – 09:59) 20% for (10:00 – 17:59) 5% for (18:00 – 19:59) 20% for (20:00 – 23:59)	
Control offset top	8%	
Control offset bottom	5%	
Logged data		
Dam levels	1 Month	
Pump status	1 Month	
Pump schedule	1 Month	

Table 4-3: Case study A2 – 1200L control parameters

Case study A2 - 1200L		
Hot water dams		
Total capacity (m³)	1508	
Pumps		
Pump 1	Flow (l/s):	95
	Power (kW):	1500
Pump 2 Pump 2	Flow (l/s):	95
	Power (kW):	1500
Pump 3	Flow (l/s):	95
	Power (kW):	1500
Pump 4	Flow (l/s):	95
	Power (kW):	1500
Maximum number of pumps allowed to run at a time	2	
Minimum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	69% for (00:00 – 04:59) 80% for (05:00 – 05:59) 85% for (06:00 – 09:59) 69% for (10:00 – 16:59) 85% for (17:00 – 19:59) 69% for (20:00 – 23:59)	
Minimum dam level	45% for (00:00 – 04:59) 60% for (06:00 – 06:59) 45% for (07:00 – 17:59) 55% for (18:00 – 19:59) 45% for (20:00 – 23:59)	
Control ranges	20% for (00:00 – 06:59) 9% for (07:00 – 09:59) 20% for (10:00 – 17:59) 9% for (18:00 – 20:59) 20% for (21:00 – 23:59)	

Case study A2 - 1200L	
Control offset top	4%
Control offset bottom	4%
Logged data	
Dam levels	1 Month
Pump status	1 Month
Pump schedule	1 Month

From the data received in step 2 of the methodology, it will be clear that the maximum and minimum DL is not constant throughout the day, as discussed in the literature. The reason why the maximum and minimum DL is changed during the day is to ensure enough capacity during high water-flow periods. The DL has been adapted to support the control philosophy to ensure that a maximum load shift is achieved.

Step 3: Analyse data

Applying the data analysis discussed in step 3 of the methodology, the average daily pump availability for mine A was calculated to determine a day that can be used to develop the simulation models. The daily average pump availability calculated for the monthly data recorded can be seen in Table 4-4.

Table 4-4: Mine A – daily average pump availability

Day	Average availability (%)
1	99
2	77
3	94
4	94
5	97
6	98
7	94
8	97
9	93
10	95
11	93
12	95
13	99
14	86
15	86
16	79
17	82
18	87

Day	Average availability (%)
19	92
20	90
21	94
22	92
23	86
24	92
25	89
26	97
27	92
28	98
29	100
30	100

It can be seen from the calculated average availability that two days within the data pool resulted in a 100% availability. Any of the two days can be utilised to develop the simulation models, however day 30 will be used as this day resulted in a perfect load shift.

Step 4: Develop simulation models

In order to develop the simulation models, the steps discussed in step 4 of the methodology will be used. Firstly, the inputs and outputs should be categorised. See Table 4-5 for the classification of the information.

Table 4-5: Mine A – classification of information

Information classification document		
Nr	Fixed inputs	Variable inputs
1	Dam capacity	Fissure water inflow
2	Number of pumps	Mining water inflow
3	Flow of pumps	Control ranges
4		Control offsets
5		Maximum number of pumps
6		Minimum number of pumps
Nr	Variable outputs	
1	Pump status	
2	Dam level	

On completion of the information classification document, an assumptions document was compiled for the case studies; see Table 4-6.

Table 4-6: Mine A – assumption document

Assumption document for simulation model A		
Revision number : 01		Date: 2015/08/01
Nr	Assumption	Justification for assumption
1	Pumping stations do not influence the performance of other pumping stations	Simulation model focusses on a pumping station and not on the whole system
2	Raw data logged is correct	Instrumentation is frequently calibrated
3	Inflow of water into the hot water dam is equal to the dam water volume change minus the outflow of water	Water balance
4	No flow losses are present (ideal system)	The flow losses are accounted for in the actual flow data recorded.
5	Information received by mine personnel is correct	Constant measuring and calculations are done by mine personnel to verify validity of information
6	Total flow of two pumps running at a time is equal to 95% of the sum of the two pumps' installed flow capacity. In scenarios where three pumps run at a time the delivered flow is 90% of the sum of the three pumps' installed flow capacity	Increased friction reduces the total flow
7	Pump start-up instantaneous with status change. Therefore, delivered flow is instantaneous	Flow takes a few seconds to reach maximum flow as the pump starts up. However, it does not influence the simulation as raw data collected takes place in two-minute intervals.
Accepted by:		Name: Hannes de Jager

After the classification of the information is done and the assumptions document has been accepted by mine personnel and the programmer, the programming can commence. All the control parameters are used along with the data received for the 100%-pumps-available-day to do the programming of the simulation models. A simulation model will be developed

for each dewatering level or case study. This means two simulation models have to be developed for mine A.

4.2.3 VERIFYING SIMULATION

Step 5: Verify simulation

With the completion of the simulation models, the validity of the simulation model has to be tested. This is done with a verification process as discussed in the literature and the methodology. For these case studies, the verification of the simulation model will be done through comparison of the simulation results and the actual system. The verification will be done for each simulation model developed.

The simulated pump status will be compared to the actual pump status and the same will be applied on the dam levels. Both the status and the dam level correlation will then be used to evaluate if the dewatering system stays within control parameters.

Case study A1 verification

Pump status verification

Illustrated in Figure 4-2, the status verification can be seen for the simulation model developed for case study A1.

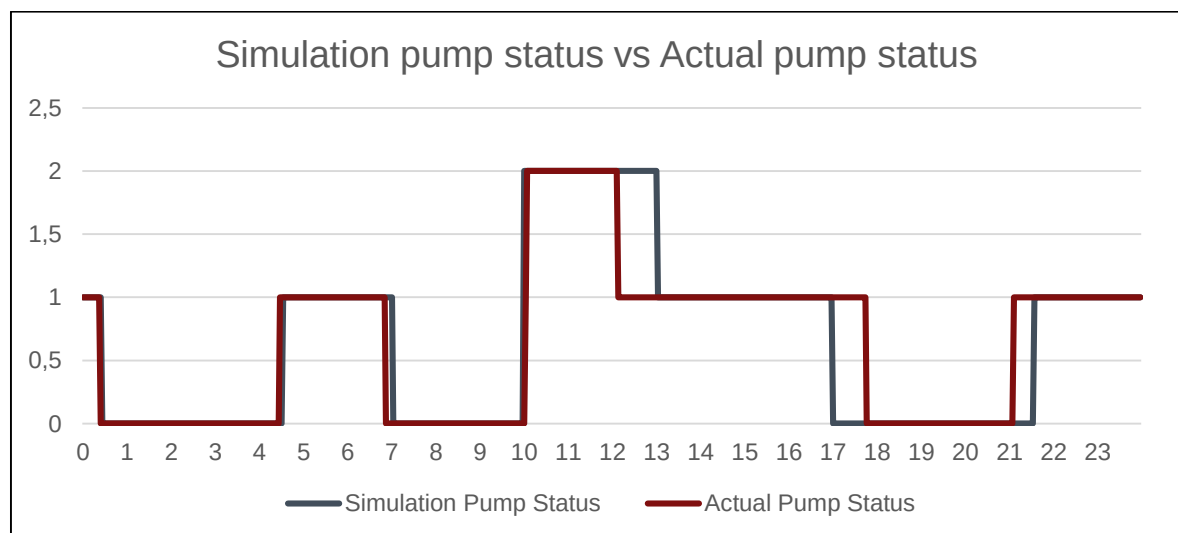


Figure 4-2: Case study A1 – pump status verification

An average status correlation of 92% is achieved with the simulation model. For the hours that resulted in a correlation of less than 100%, a reason is listed and whether it is acceptable, as illustrated in Table 4-7.

Table 4-7: Case study A1 – status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference acceptable
0	97	1. Control mechanism reacts in secondly intervals whereas the simulation model decision-making is done every two minutes	Yes
4	93		Yes
6	90		Yes
7	93		Yes
10	95		Yes
12	58	1. Dewatering system reacted on emergency control and this is not accounted for in the simulation model. 2. Control mechanism reacts in secondly intervals whereas the simulation model decision-making is done every two minutes	Yes
13	97		Yes
17	23		Yes
21	53		Yes

All the differences in status correlation are found acceptable and thus the simulation model is deemed as verified for the status scheduling. The second part of the verification process consists of the comparison of dam levels.

Dam level verification

Illustrated in Figure 4-3, the dam level verification can be seen for the simulation model developed for case study A1.

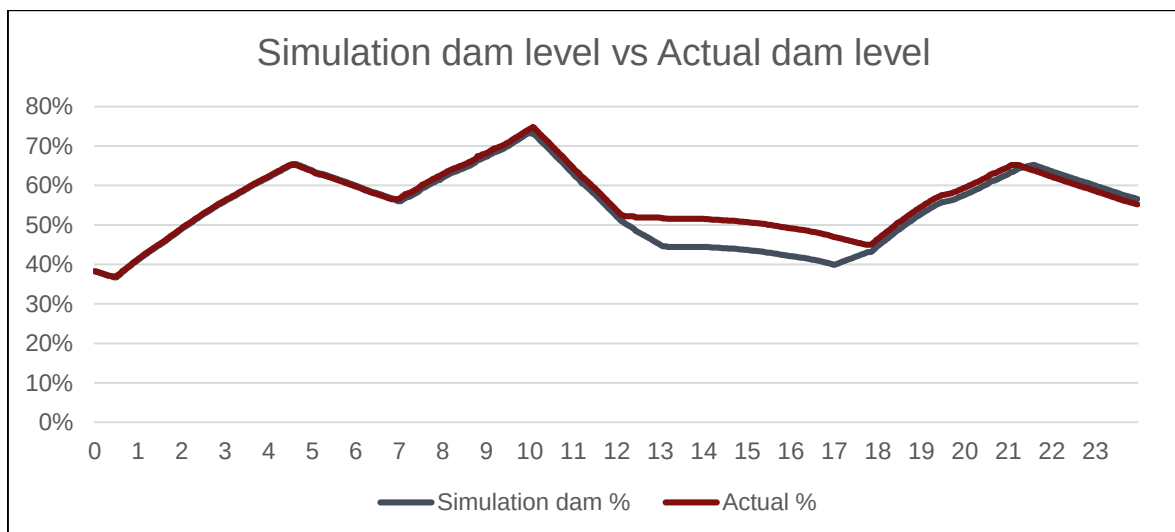


Figure 4-3: Case study A1 – dam level verification

Dam levels are influenced by the pump status. Therefore, where a difference can be seen between the actual dam level and the simulated dam level, it can be accounted for in the status difference. Reasons for dam level differences will not be discussed, as this has already been accounted for in the status verification. The dam levels of the simulated results have also stayed within the control parameters of the dewatering level. As a result, the simulation model can be deemed as valid and verified for case study A1.

Case study A2 verification

Pump status verification

Figure 4-4 illustrates the correlation between the actual system pump status and the pump status simulated for case study A2.

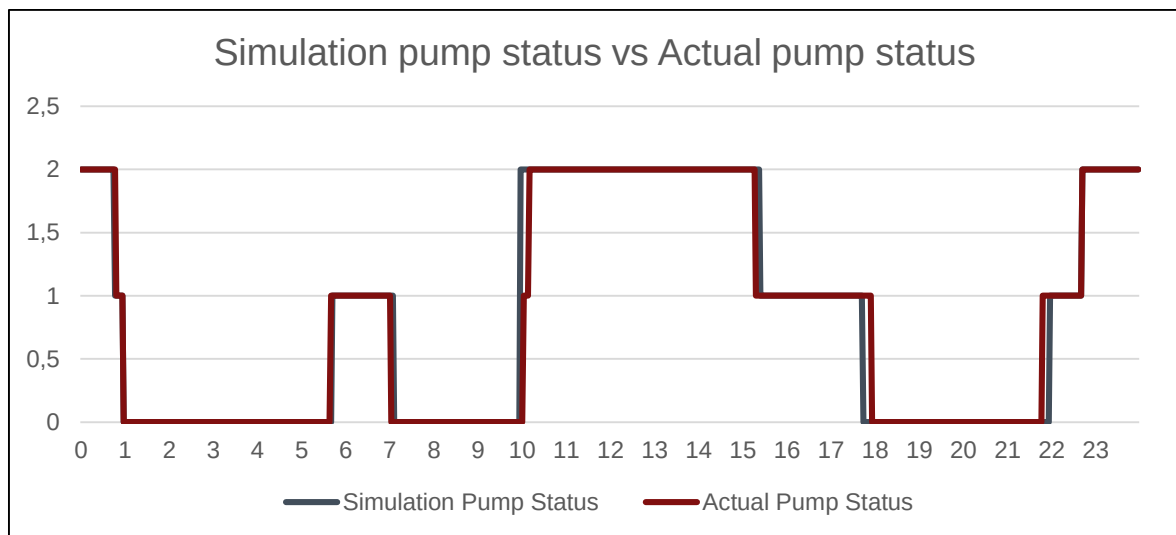


Figure 4-4: Case study A2 – pump status verification

An average pump status correlation of 97% is achieved with the simulation model developed for case study A2. In the hours where the actual system status and the simulation status do not correlate 100%, reasons are listed and discussed as depicted in Table 4-8.

Table 4-8: Case study A2 – status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference acceptable
0	98	1. Control mechanism reacts in secondly intervals whereas the simulation model decision-making is done every two minutes	Yes
5	97		Yes
7	93		Yes
10	87		Yes

15	95	1. Control mechanism reacts in secondly intervals whereas the simulation model decision-making is done every two minutes	Yes
17	80		Yes
21	83		Yes

All the status differences between the actual system and the simulation can be accounted for and reasons listed are found to be acceptable. Thus, the first part of the simulation verification process is complete. The simulated dam levels will now be discussed.

Dam level verification

Figure 4-5 illustrates the correlation between the actual system dam level and the dam level simulated for case study A2.

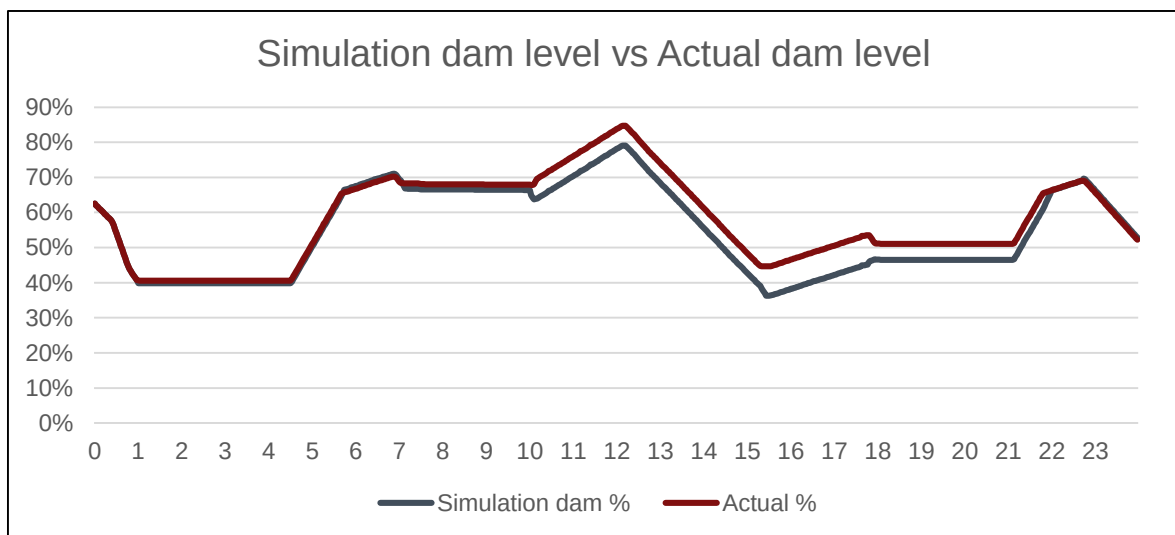


Figure 4-5: Case study A2 – dam level verification

Similar to case study A1, the dam percentage difference can be attributed to the fact that there is a status difference. As this difference is accepted, the difference in dam levels is also acceptable. Furthermore, the simulation model stayed within the control parameters of case study A2 and, as a result, the simulation model for case study A2 is valid and verified.

4.2.4 IMPLEMENTING SIMULATION FOR RESULTS

Step 6: Apply DOE technique

Upon completion of the verification process, simulations have to be conducted. In order to develop an experiment, the DOE technique was applied to determine how many runs and for what increments the simulation should be conducted.

Applying the DOE technique, it was determined that for each case study, the availability has to be reduced for hourly and two-hourly intervals. The hourly availability change simulations

will be conducted for all the hours of the day, excluding peak TOU hours. For the two-hourly availability reduction, the simulations have to be conducted for four hours preceding peak TOU hours.

Therefore, a total of 18 hourly simulations have to be conducted and four two-hourly simulations. The availability of pumps will be reduced by reducing the amount of pumps scheduled for the specific time interval.

In the instances where there are two scheduled pumps, only one pump will be run. In the instances where one pump is scheduled, no pumps will be run. In the instances where zero pumps are scheduled, then zero pumps will be run. All the simulation runs and the hours of reduced availability can be seen in Table 4-9.

Table 4-9: Simulation variations and availability influenced

Simulation variations and availability influenced			
Hourly reduction of availability			
Run no	Availability reduced for:	Run no	Hours
1	00:00 – 00:59	10	13:00 – 13:59
2	01:00 – 01:59	11	14:00 – 14:59
3	02:00 – 02:59	19	15:00 – 15:59
4	03:00 – 03:59	13	16:00 – 16:59
5	04:00 – 04:59	14	17:00 – 17:59
6	05:00 – 06:59	15	20:00 – 20:59
7	10:00 – 10:59	16	21:00 – 21:59
8	11:00 – 11:59	17	22:00 – 22:59
9	12:00 – 12:59	18	23:00 – 23:59
Two-hourly reduction of availability			
Run no	Availability reduced for:	Run no	Hours
19	03:00 – 04:59	21	14:00 – 15:59
20	05:00 – 06:59	22	16:00 – 17:59

Step 7: Run simulations

Upon completion of the DOE technique, simulations for the different time intervals have to be conducted. The hourly increments of the reduced availability were applied to 00:00 – 06:59, 10:00 – 17:59 and 20:00 – 23:59 time intervals. For instance, the available pumps to run were reduced for simulation run 1 for the hour 00:00 – 00:59. For simulation

run 2, the availability was reduced for the time 01:00 – 01:59, while during the other hours of the day, the availability stayed at 100%.

The results obtained from the simulation model will be compared to a power baseline. The power profile of the simulated 100% pump availability will be used as the baseline. The power profile for both case studies can be seen in Figure 4-6 and Figure 4-7.

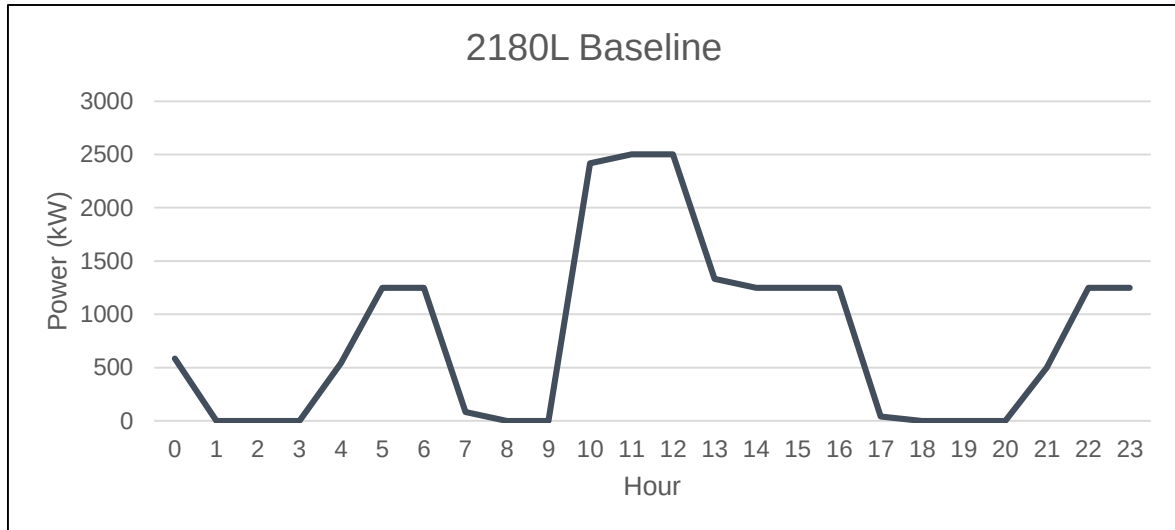


Figure 4-6: Case study A1 – baseline

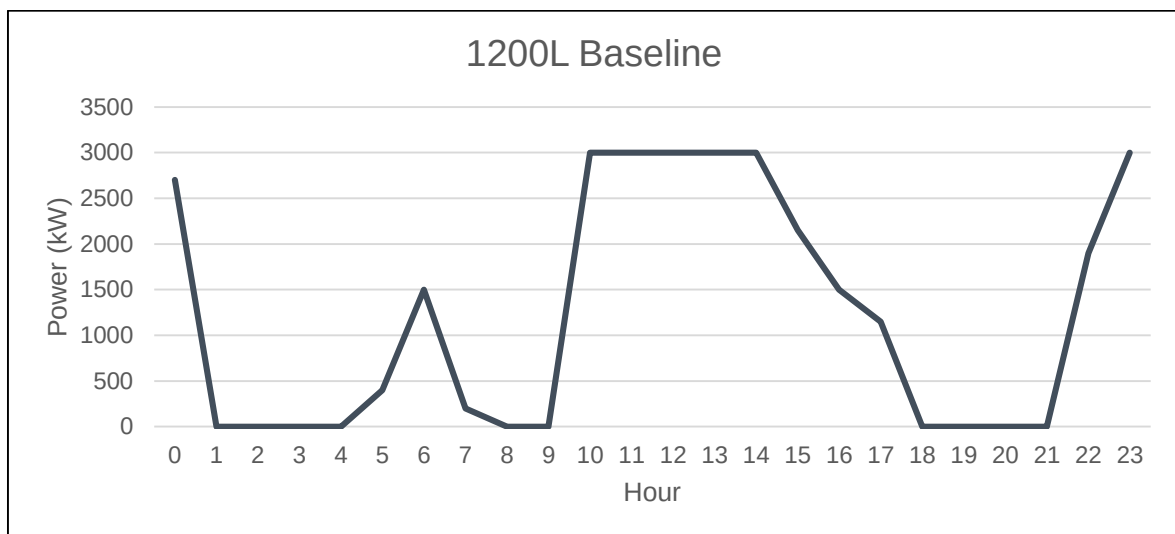


Figure 4-7: Case study A2 – baseline

The baseline will not, however, be scaled as discussed in Chapter 2. In instances where the total amount of energy is lower than the baseline for the 24-hour period, the scaled baseline profile will be lower. As a result, an influence on load shift will be seen when in fact, no influence on the load shift is present. This will be true for hours after the evening peak period specifically. Therefore, to maintain an energy-neutral system, the total energy usage during the 24-hour period will be discussed separately.

4.2.5 CASE STUDY RESULTS

Step 8: Conclude results

To evaluate the results of reduced availability, the power profile for each scenario is compared to the baseline. Each of the simulation results will be depicted in a bar graph as discussed in Chapter 3. The results are depicted as a positive or negative influence on load shift performance, expressed in kilowatt-hour. Thus, a positive kilowatt-hour indicates that the unavailability for that specific hour had a positive influence on the load shift achieved. This means that less energy is used during the peak TOU period. The inverse will reflect a negative influence.

The X-axis on the bar graph indicates the hour of unavailability, so a zero indicates that the availability has been reduced for the zero hour, which is the time period from 00:00 – 00:59. A 'one' indicates that the availability has been reduced for the one hour, i.e for the time period 01:00 – 01:59. For the two hours of reduced availability, the X-axis indicates the two hours for which the availability has been reduced. Instance 3-5 on the X-axis indicates that the availability has been reduced for the interval between 03:00 – 04:59 and 5-7 indicates that the availability has been reduced for 05:00 – 06:59.

For each of the levels, the effect of reduced availability in terms of kilowatt-hour will be discussed, followed by the discussion of the total energy used during the 24-hour period. The total energy for the 24-hour period is also expressed in kilowatt-hour (energy) and the X-axis is the hour of reduced availability.

Case study A1 results

The results obtained from the simulation model runs conducted for each hour of reduced availability are compared to the baseline. Figure 4-8 illustrates such a comparison of the baseline and the simulated power profile when the pump availability has been reduced for hour zero. Due to the baseline power being so close to zero in the morning peak period, the effect on the load shift is difficult to see. Figure 4-9 illustrates the morning peak period of Figure 4-8.

It will be seen, when analysing Figure 4-9, that the reduced availability during hour zero reduced the electricity usage during the morning peak period. Thus the reduction in pump availability during hour zero had a positive influence on the morning load shift. The quantified results of the reduced availability are shown as having a positive influence on the morning load shift in Figure 4-10.

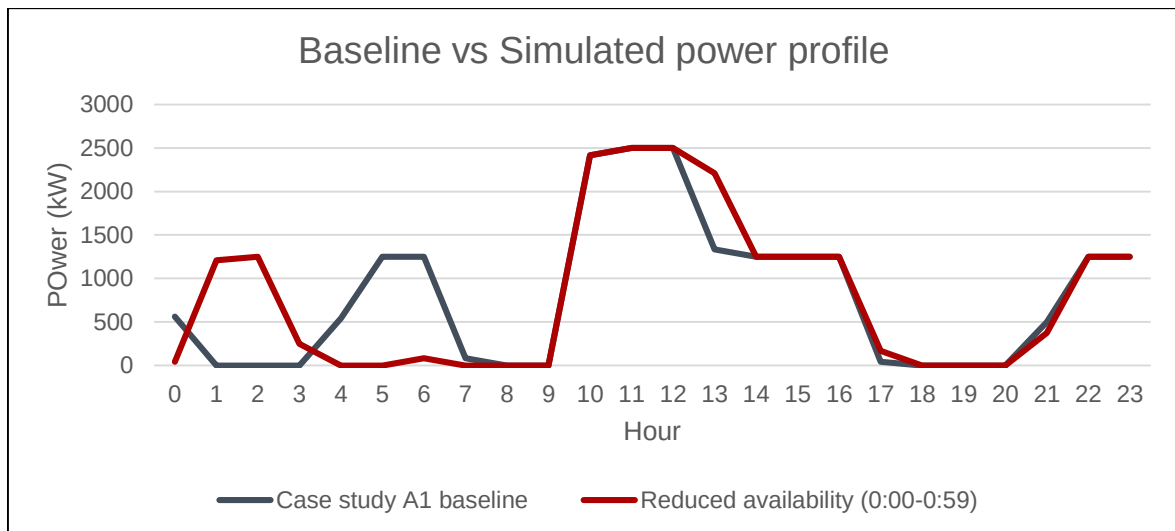


Figure 4-8: Case study A1 baseline comparison of the reduced availability for zero hour

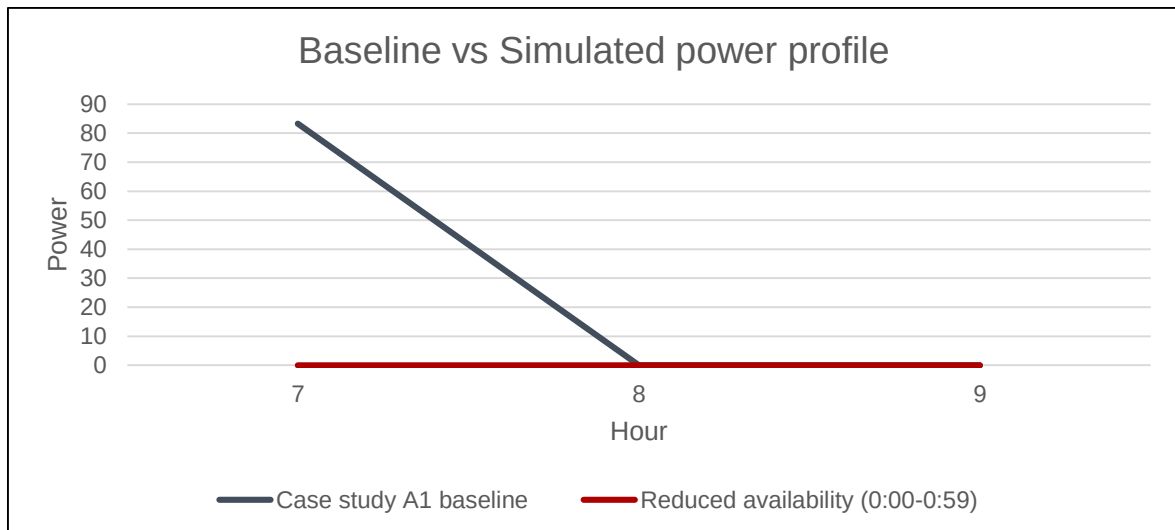


Figure 4-9: Exploded view of Figure 4-8

The remaining simulations conducted (simulated power profiles) are all compared to the baseline and the effect on load shift performance is shown in Figure 4-10 and Figure 4-11. The power profiles of all simulations conducted for all the case studies are compared to a baseline in the similar manner and represented in one results graph.

The effect on load shift performance for each of the simulations conducted for 2180L is depicted in Figure 4-10 and Figure 4-11. When analysing the results obtained from the simulation model, it can be noted that the reduction in availability for hours zero, four and six of the day all had a positive influence on the morning load shift.

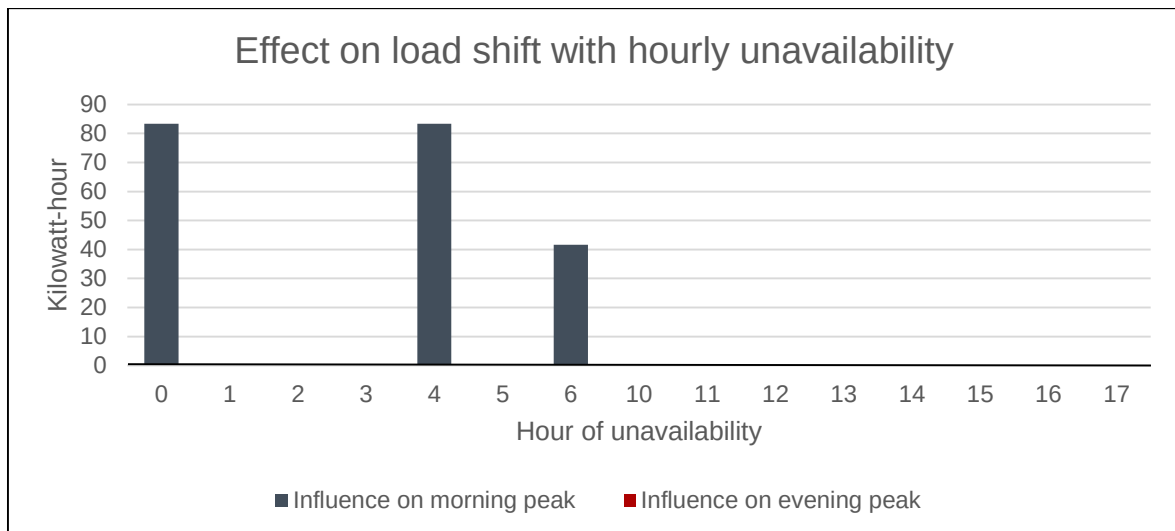


Figure 4-10: Case study A1 – results of hourly unavailability

Reducing the availability for the 5-7 time interval, a negative influence on the morning peak can be seen. A negative influence on the evening peak period can be seen if the availability is reduced for the 14-16 and 16-18 time periods.

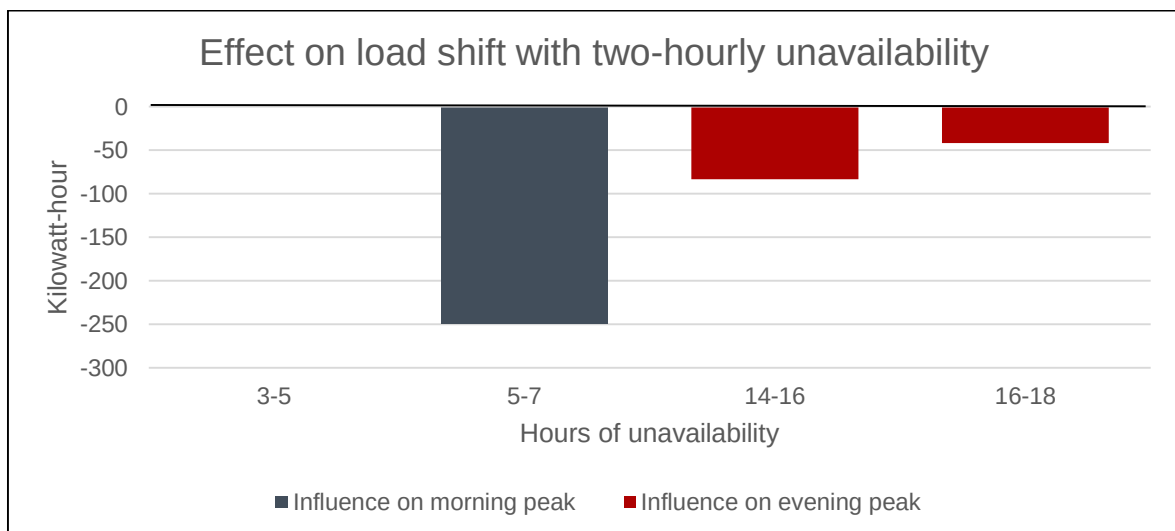


Figure 4-11: Case study A1 – results of two-hourly unavailability

It will be clear that unavailability of pumps during certain times of the day can either positively influence or negatively influence the load shift. From the figures above, it can be seen that the two-hourly unavailability is more likely to negatively influence the load shift performance for case study A1.

After conducting all the simulations, it was found that the availability of the pumps has an impact on the amount of energy used during a day. The simulation model developed only focuses on a 24-hour period and does not simulate the effect of availability on the days to follow.

The baseline was not scaled and the total energy used to dewater the system has to remain neutral. Thus, by comparing the total energy of the baseline and the total energy of the simulation, it can be determined how the availability influences the load shift. In some cases, the total energy used during the day may differ and has to be accounted for in the days to follow. The total energy that has to be accounted for, in the days after the unavailability of pumps occurred, can be seen in Figure 4-12 and Figure 4-13.

It is evident that, in some instances, the total amount of energy used for the day is increased or decreased due to a reduced availability. In cases where the total amount of energy is increased during the 24-hour period, a decrease in energy can be expected in the days to follow to ensure system equilibrium. The opposite will also be true. If less energy is used during the day than what should have been used, then an increase in energy is necessary in the days to follow to keep the dewatering system in equilibrium.

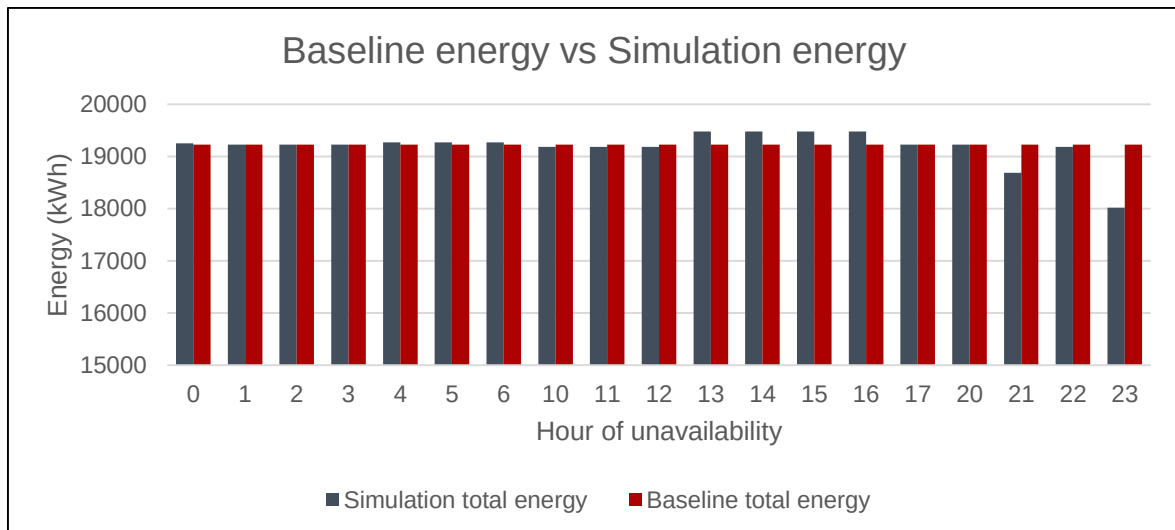


Figure 4-12: Case study A1 – total energy comparison for hourly unavailability

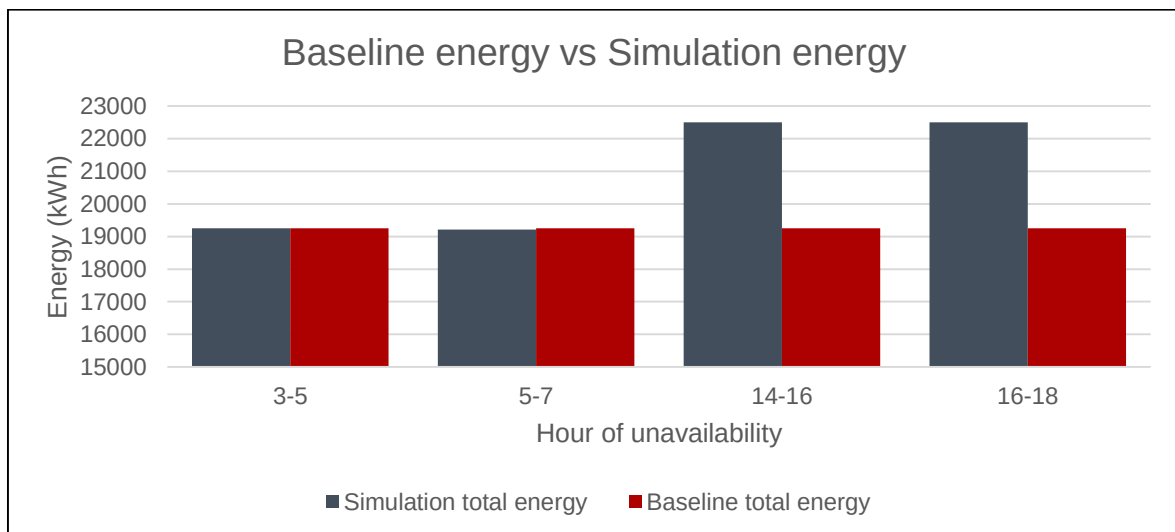


Figure 4-13: Case study A1 – total energy comparison for two-hourly unavailability

It is clear from the results obtained that the availability of dewatering pumps can either have a positive influence on the load shift or a negative influence on the load shift. A positive influence on the load shifting could be an indication that the control philosophy is not optimised. However, the influence of availability is only tested on one day and further investigation is needed to determine if the control philosophy needs to be optimised.

Case study A2 results

Simulations conducted for case study A2 are done in exactly the same way as for case study A1. Results from the experiments conducted on case study A2, for the hourly-reduced availability, are illustrated in Figure 4-14.

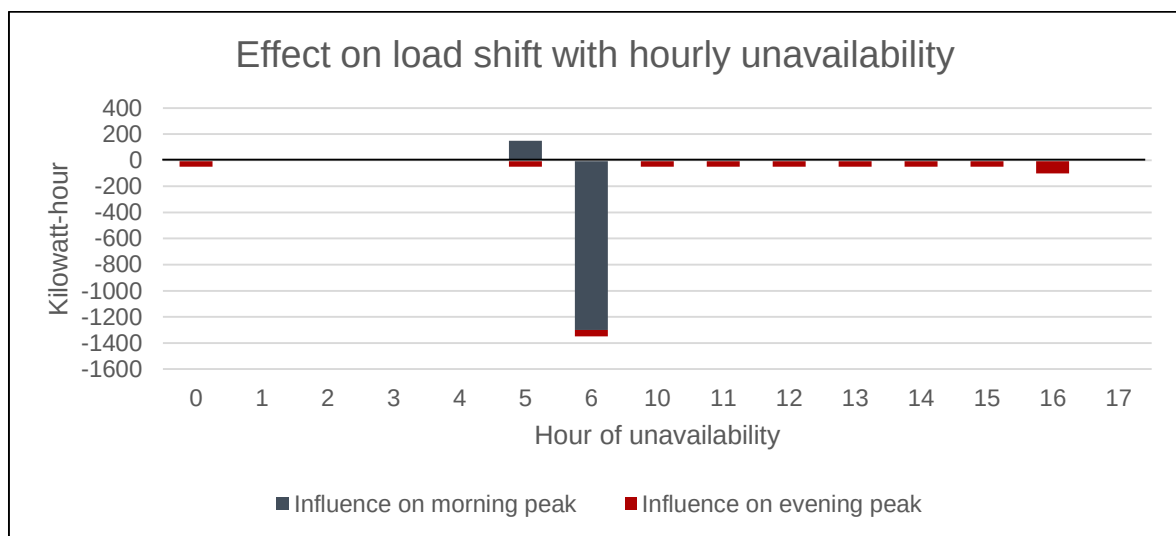


Figure 4-14: Case study A2 – results of hourly unavailability

The morning peak is positively influenced if availability is reduced during hour five. The morning peak is negatively influenced when the availability is reduced during hour six. The evening peak is negatively influenced in most cases of reduced availability.

Results obtained from the experiments by reducing the availability for two-hour intervals are illustrated in Figure 4-15. A negative influence on the morning load shift can be seen when availability is reduced during the 5-7 hours. A negative influence on the evening peak periods can also be seen when the availability is reduced for 3-5, 14-16 and 17-18 hours. It is evident from the results that the reduced availability for two hours is more likely to negatively influence the load shift than the hourly unavailability.

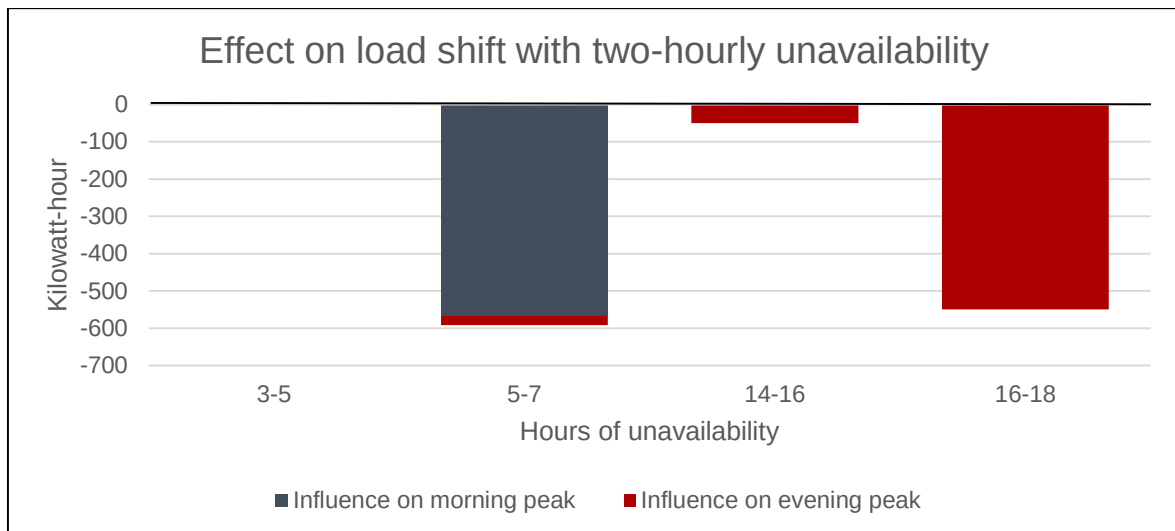


Figure 4-15: Case study A2 – results of two-hourly unavailability

Similar to the simulations done for case study A1, a positive or negative influence on the load shift can be seen with the simulations done for case study A2, although the simulations conducted for 1200L resulted in a greater chance of a negative influence on the load shift. Fifteen out of the 22 simulations conducted for case study A2 resulted in a negative influence on the load shift performance, in particular the evening load shift.

The total energy used during the simulations, with hourly-reduced availability, is compared to the actual system total energy as illustrated in Figure 4-16.

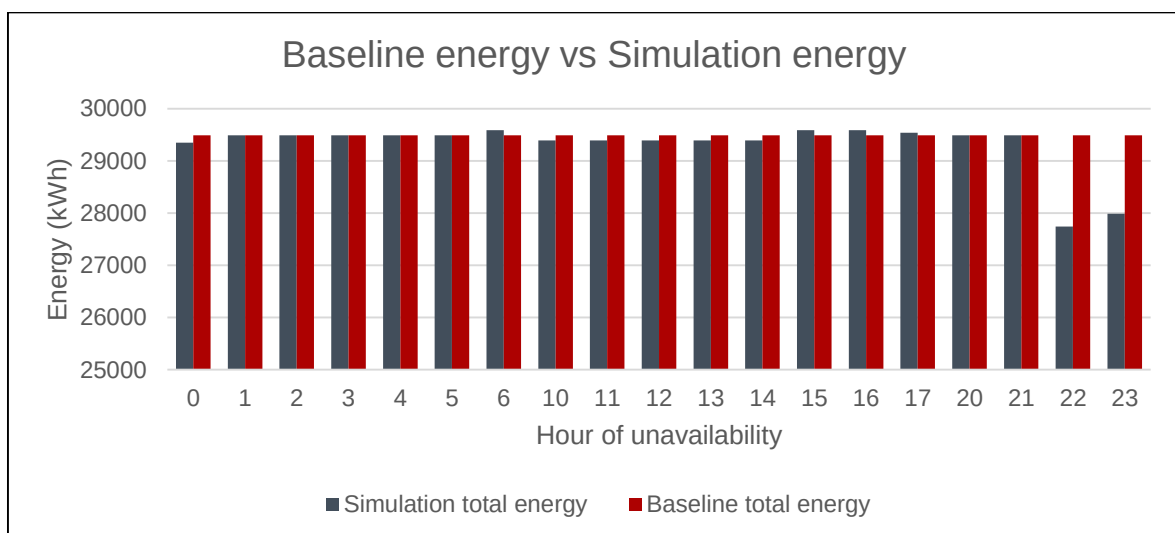


Figure 4-16: Case study A2 – total energy comparison for hourly unavailability

Very little difference can be seen in the total energy of the simulations and the baseline. Hour 22 and hour 23 of reduced availability, however, show a decrease in energy. This will lead to an increase in energy in the days to follow and could result in reduction of load shift performance. The increased energy usage that should take place in the days to follow will

indirectly reduce the capacity of the system and therefore, it could negatively influence the load shift.

The total energy used during the simulations, with two-hourly reduced availability, is compared to the actual system total energy as illustrated in Figure 4-17.

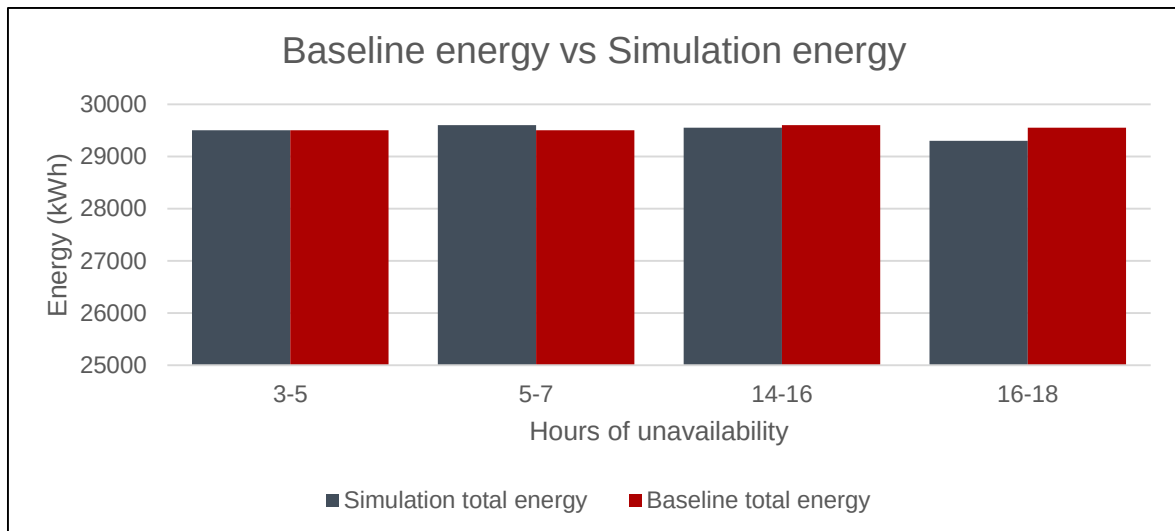


Figure 4-17: Case study A2 – total energy comparison for two-hourly unavailability

Very little to no difference will be seen when the total energy of the baseline is compared to the total energy of the simulations conducted. As a result, the effect of reduced availability on the days to follow will have little to no impact on the load shift performance.

4.3 CASE STUDY B – MEDIUM DEWATERING SYSTEM

4.3.1 INTRODUCTION TO MINE B

The second case study, to which the step-by-step methodology will be applied, is a gold-producing mine situated in the Welkom (Free State province) area. It consists of three dewatering pumping stations. Hot mining and fissure water collected on 67L are pumped back to surface for cooling via two other pumping stations, i.e. 53L and 30L, respectively. Figure 4-18 illustrates the water reticulation of mine B.

On each of the pumping stations, three 1100 kW multistage centrifugal pumps are installed. This dewatering system has been selected to be investigated second because it has one more level than the first mine. Furthermore, the control philosophy of the second mine is more complex than the first mine, as only one pump is allowed to run at a time.

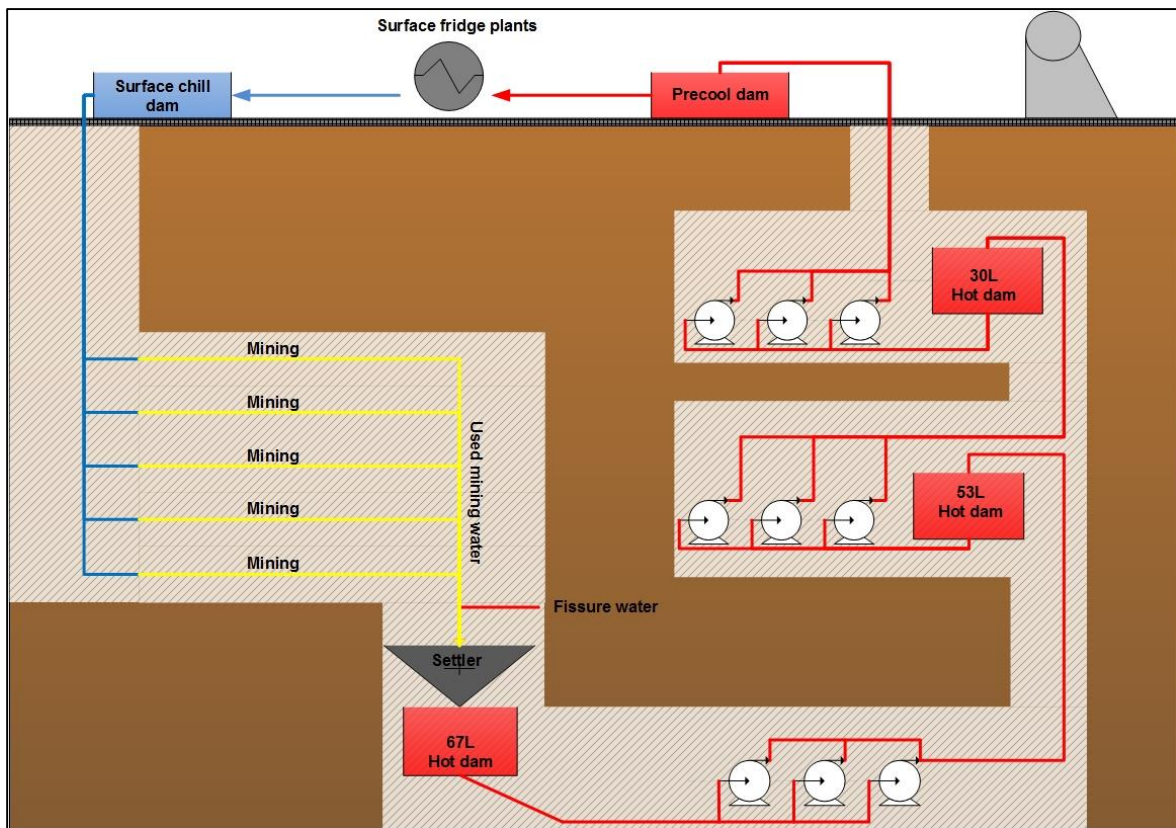


Figure 4-18: Mine B water reticulation

The reduced number of pumps that are allowed to run at a time also reduces the capacity of the system. Therefore, the pumps should run for more hours during the day to keep the dewatering system within safe operating conditions. This leaves smaller chances of achieving a full load shift during the peak periods.

4.3.2 DEVELOP SIMULATION MODELS

The simulation models for mine B have been developed in a similar manner to mine A. Applying the first four steps of the methodology, simulation models have been developed for each case study. All the steps completed for the case studies to develop the simulation models can be seen in Appendix B.

4.3.3 VERIFYING SIMULATION

Verification of the simulation models has been done in the same manner as was done for the simulation models developed for mine A. To prevent repetitiveness, the verification is illustrated in Figure 6-1 to Figure 6-3 attached in Appendix B. Reasons for status correlation at less than 100% are illustrated in Table 6-9 to Table 6-11 respectively, attached in Appendix B.

4.3.4 IMPLEMENTING SIMULATION FOR RESULTS

The experimental setup for the case studies is done in the same manner as was done for case studies of mine A. Applying the DOE technique yielded that hourly and two-hourly reduced availability simulations should be conducted.

The simulations that should be conducted are illustrated in Table 6-12 attached in Appendix B. Hourly and two-hourly simulations were conducted to investigate the effect of pump availability on load shift performance for each case study.

4.3.5 CASE STUDY RESULTS

Case study B1 results

Reducing the availability of the pumps for hour 17 resulted in a positive influence on the evening load shift achieved, as seen in Figure 4-19. The remaining hours of reduced availability did not influence the load shift when the availability was reduced for hourly intervals.

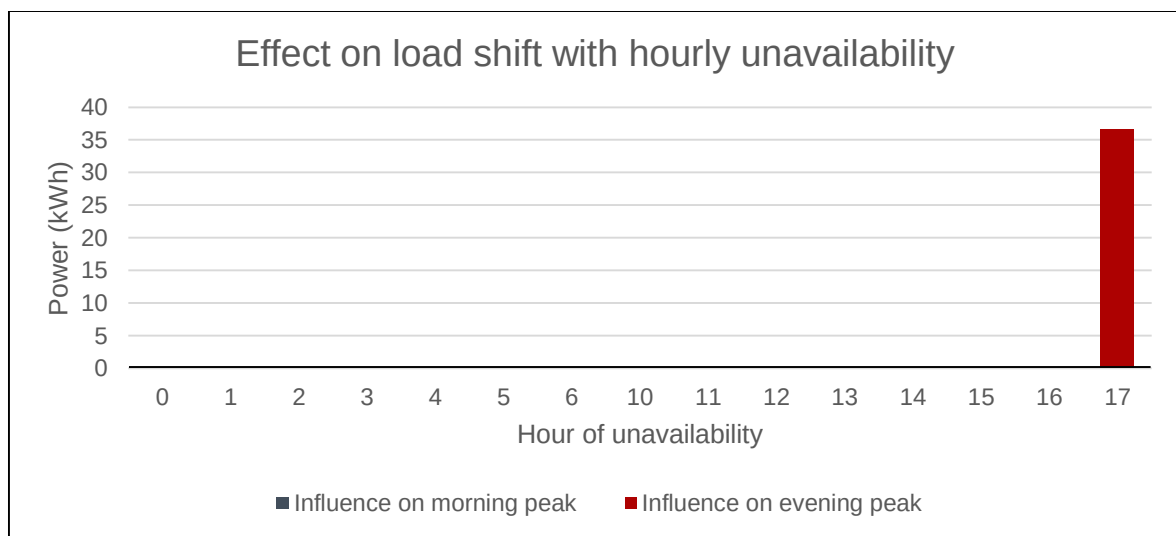


Figure 4-19: Case study B1 – results of hourly unavailability

The results obtained from two-hourly reduction in availability yielded a negative performance in morning load shift and positive influence in evening load shift for the hours 3–5 and 16–18 respectively. This can be seen in Figure 4-20.

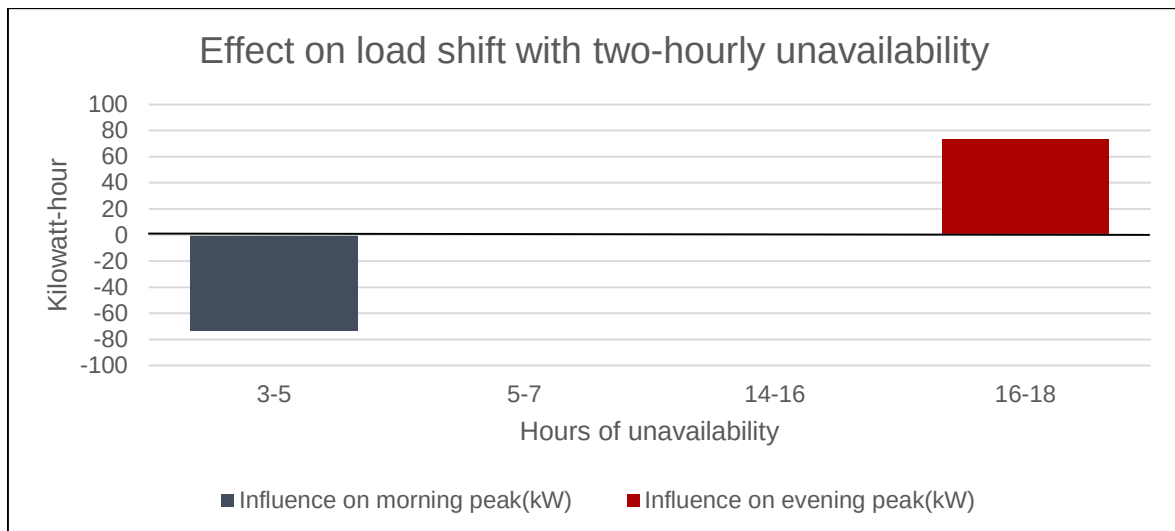


Figure 4-20: Case study B1 – results of two-hourly unavailability

From the simulations conducted, it can be seen that reducing the availability of pumps resulted in higher possibility of a positive influence on load-shift performance. As a result, the control philosophy should be reviewed by mine personnel and the maintenance crew. Reducing the amount of hours that the pumps operate on this dewatering level could still result in full load shift achieved. As a result, less energy is used during the day. Less energy used will reduce the operating cost of the dewatering system.

Comparing the total amount of energy used during the 24-hour period of the baseline, and the simulations conducted for hourly-reduced availability, are illustrated in Figure 4-21. It can be seen that the reduction of availability during hour 13 resulted in an excess energy usage to stabilise the dewatering level.

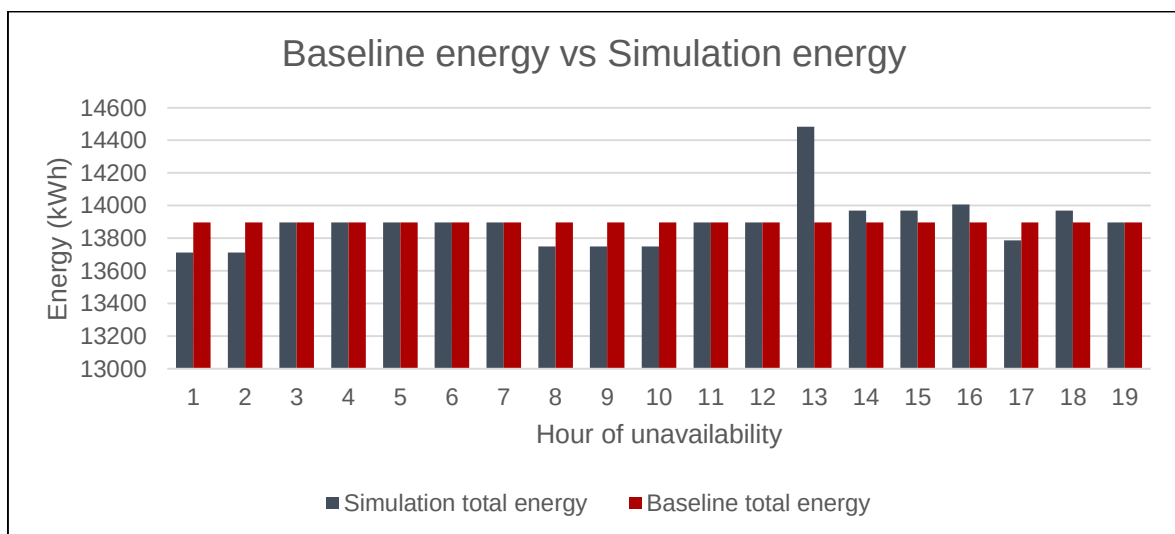


Figure 4-21: Case study B1 – total energy comparison for hourly unavailability

During other hours of reduced availability, little to no change in the total energy can be seen when compared to the baseline. As a result, the load shift performance of the days to follow will be influenced little to none.

Figure 4-22 illustrates the comparison of the baseline total energy and the simulation total energy for the two-hourly reduced availability. Reducing the availability during the 14–16 hour interval resulted in excess energy used to keep the simulation model within safe operating parameters.

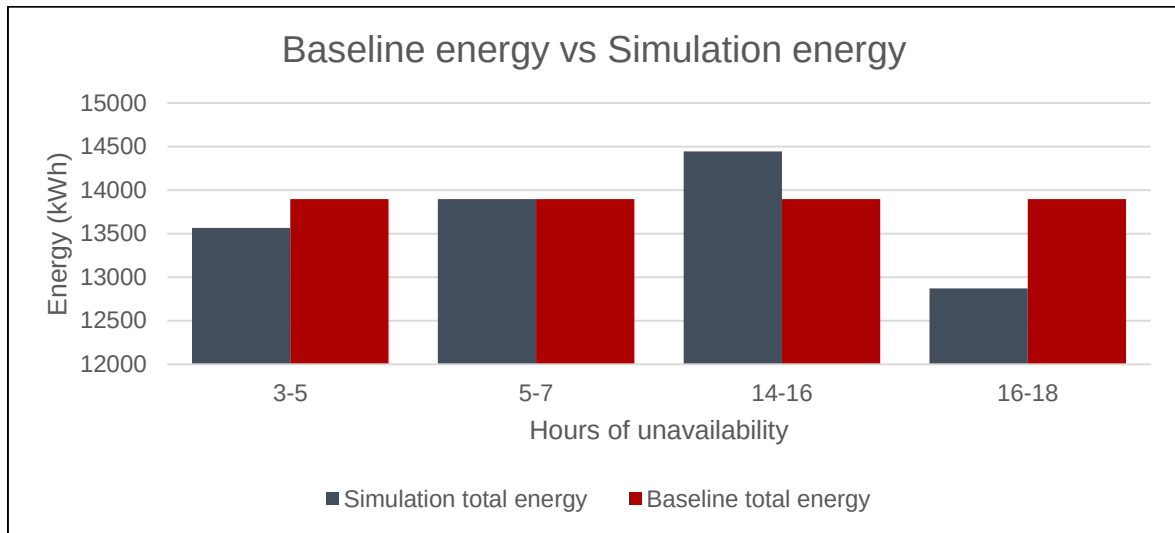


Figure 4-22: Case study B1 – total energy comparison for two-hourly unavailability

A similar trend can be seen than in the case studies of mine A. In some instances, less energy is used when conducting the simulations and this could lead to a reduced performance of load shift in the days to follow. Simulations of excess energy usage can also be seen, which will result in a reduction of energy in the days to follow.

Case study B2 results

The simulation model developed for case study B2 once again yielded a positive and negative influence on the load shift performance. Figure 4-23 illustrates the results obtained by reducing the availability for hourly intervals.

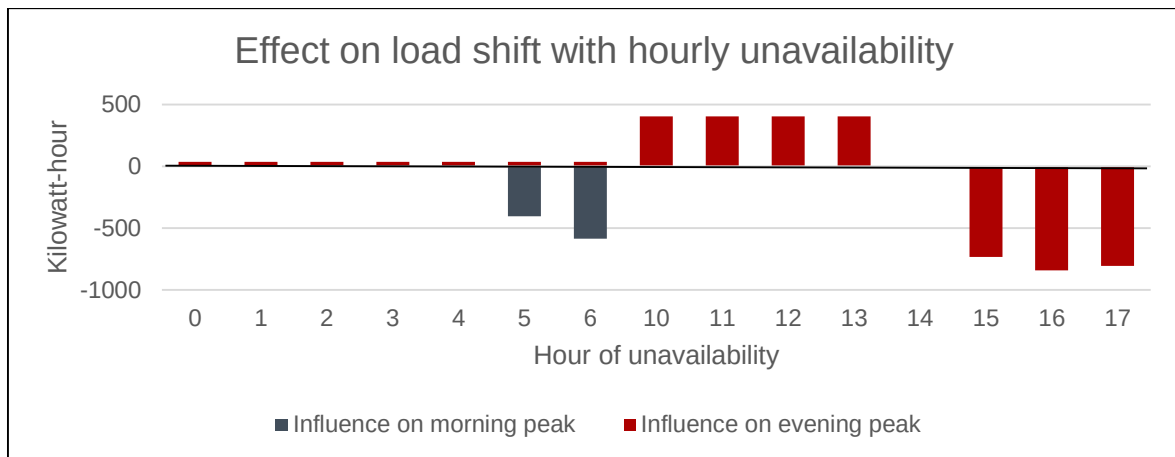


Figure 4-23: Case study B2 – results of hourly unavailability

A negative influence is seen on the morning load shift when availability is reduced for hours 5 and 6. A negative influence can also be seen on the evening load shift for reduced availability of hours 15 to 17 of the day.

A positive influence on the evening peak can be seen when the availability of the 53L pumps is reduced from hour 0 to hour 13. Similar to case study B1, the control philosophy has to be investigated to determine if the control is optimised.

Figure 4-24 illustrates the results obtained from the simulations by reducing the availability for two-hour intervals. A negative influence on the morning and evening peak can be seen when the availability is reduced for two-hourly intervals. The reduction of the availability from hour 3 to hour 7, in two-hour intervals, resulted in a negative influence on the morning peak load shift, reducing the availability for two-hour intervals from hour 14 to hour 18 resulted in a negative influence on the evening peak.

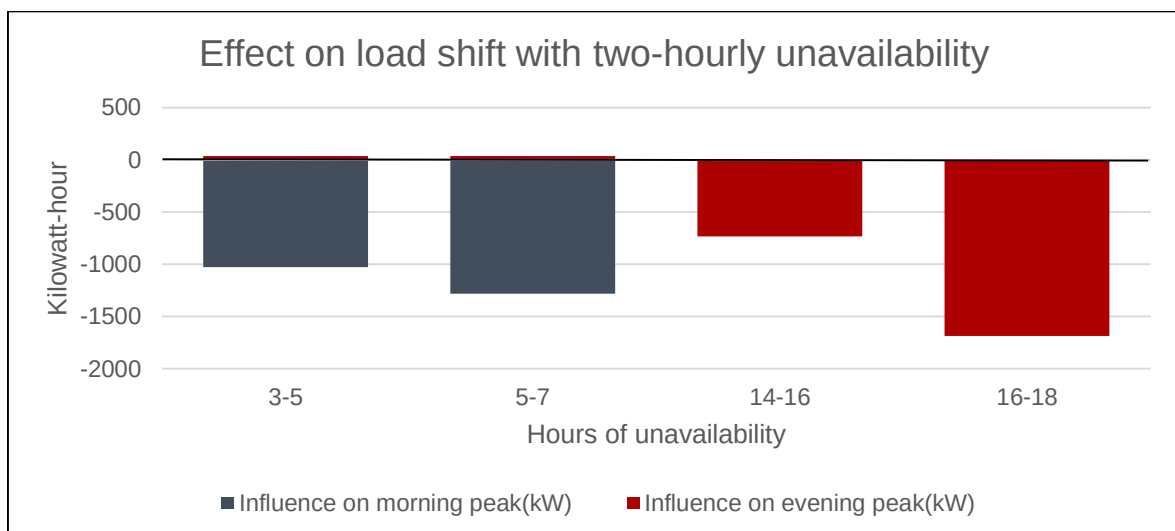


Figure 4-24: Case study B2 – results of two-hourly unavailability

The total energy for the baseline period and the simulations are compared, as seen in Figure 4-25, for hourly-reduced availability.

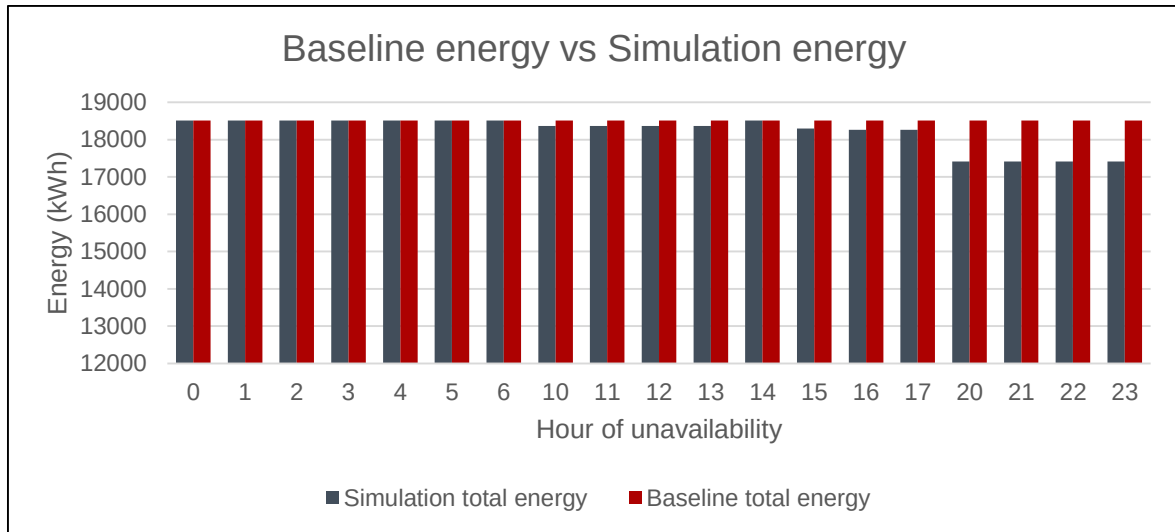


Figure 4-25: Case study B2 – total energy comparison for hourly unavailability

It will be seen that simulations conducted with reduced availability, for hours after hour 17, reduced the total amount of energy more than in the preceding hours. The reduced energy usage will result in an increase in energy usage in the days to follow. As a result, the reduced availability could negatively influence the load shift performance.

Figure 4-26 illustrates the comparison between the total energy for the baseline and the simulations conducted for two-hourly reduced availability. In the two-hourly interval reduction of availability, very little difference can be seen when the total amount of energy for the baseline is compared to the simulation total energy. As a result, the load shift performance on the days to follow will be affected very little because of the reduced availability.

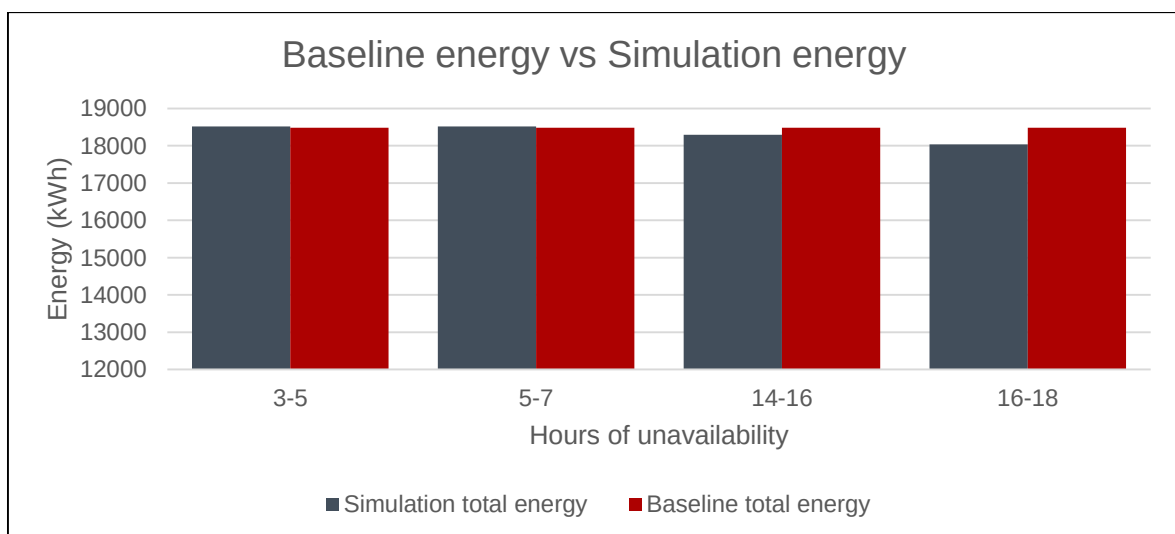


Figure 4-26: Case study B2 – results of two-hourly unavailability

Case study B3 results

Simulations conducted using the simulation model developed for case study B3, with an hourly reduction of availability, had no effect on the load shift performance. A negative influence on the evening peak can be seen when the availability is reduced for hours 16-18. The results obtained for the simulations conducted with two-hourly unavailability can be seen in Figure 4-27.

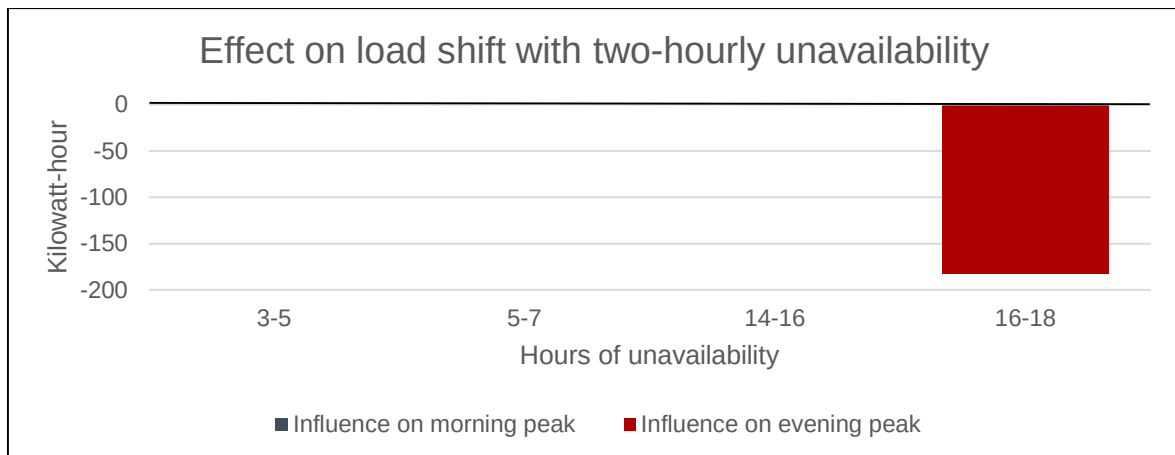


Figure 4-27: Case study B3 – results of two-hourly unavailability

The results obtained from the conducted simulations indicate that enough capacity is available on the dewatering level. Reducing the availability of the pumps had no effect on the load shift, except for one instance.

Comparison of the total energy for hourly availability reduction can be seen in Figure 4-28. Very little difference can be seen in the total energy consumed during the baseline period compared with the simulation total energy for each simulation conducted.

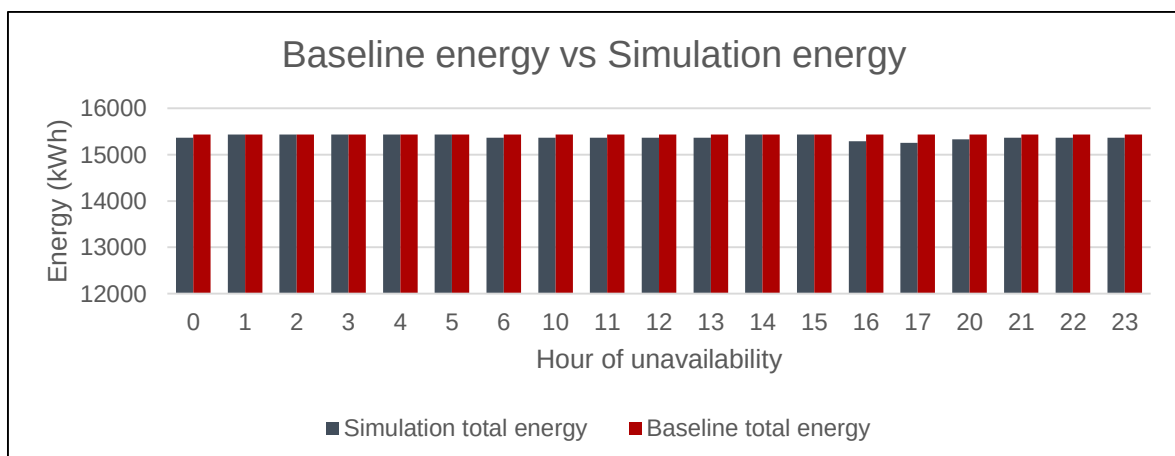


Figure 4-28: Case study B3 – total energy comparison for hourly unavailability

A larger difference can be seen when the availability is reduced for the 16-18 time interval as seen in Figure 4-29.

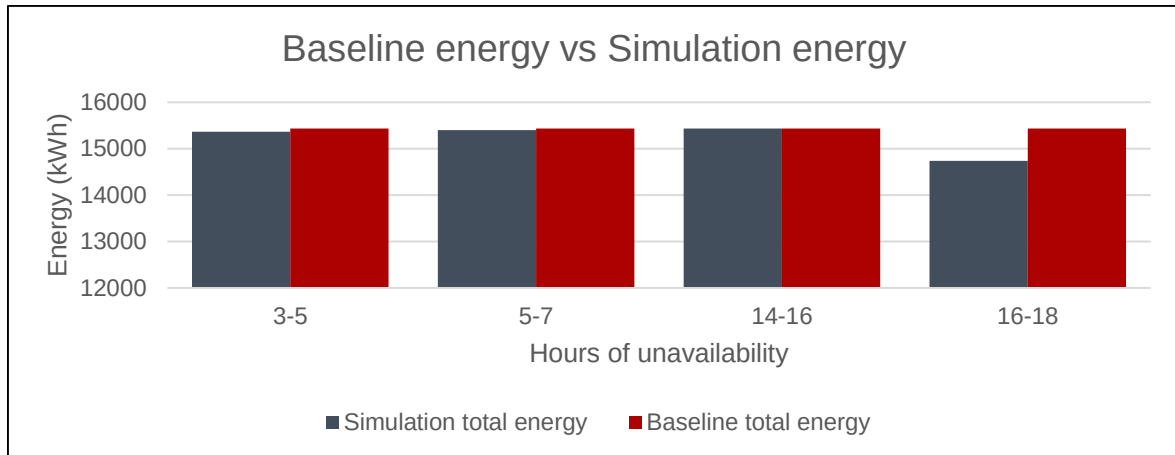


Figure 4-29: Case study B3 – total energy comparison for two-hourly unavailability

The reduced energy usage because of unavailable pumps could lead to a negative influence on the load shift in the days to follow. The total amount of energy that should be used to dewater the system will increase in the days to follow.

4.4 CASE STUDY C – LARGE DEWATERING SYSTEM

4.4.1 INTRODUCTION TO MINE C

The last mine that the step-by-step methodology will be applied to, is located near Theunissen in the Free State Province. The water utilised on the mining levels, along with the fissure water, is collected in hot water dams on 25L as seen in Figure 4-30. The hot water is pumped back to the surface via two other dewatering pumping stations situated on 21L and 5L.

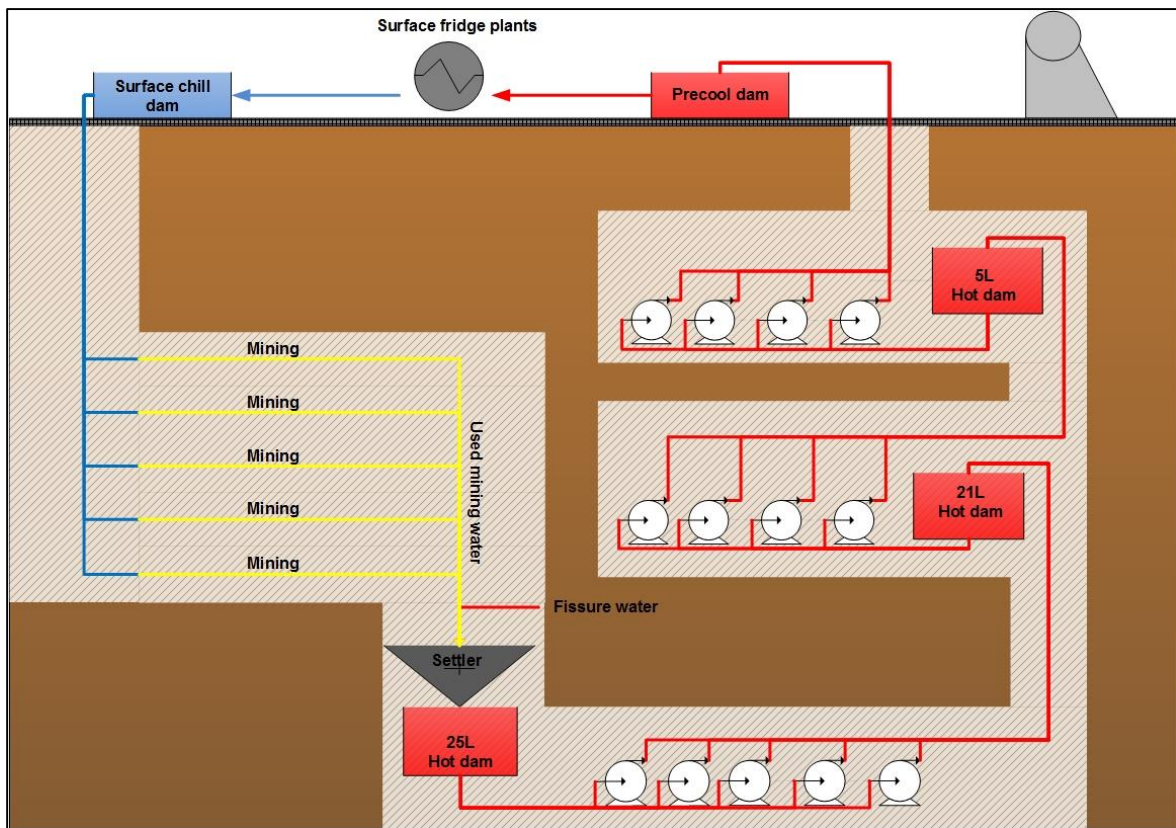


Figure 4-30: Mine C water reticulation

Dewatering of the 25L hot water dams is done by five 1100 kW multistage centrifugal pumps, whereas the other two mining levels both utilise four 3300 kW multistage centrifugal pumps each. The dewatering system of mine C is by far the most complex compared to the previous case studies. The dewatering system not only consists of three pumping stations, but also on each level, more than one pump is needed for dewatering.

4.4.2 DEVELOP SIMULATION MODELS

All the steps discussed in the methodology were applied to the case studies to develop a simulation model for each dewatering level. The methodology steps and results can be seen in Appendix C. The methodology is applied to mine C in the same manner as was done for mine A and mine B.

4.4.3 VERIFYING SIMULATION

After completion of the three individual simulation models. The simulation models were verified in a similar manner to the previous case studies. Comparison of the pump status can be seen in Figure 6-7 to Figure 6-9 attached in Appendix C. Instances where the simulation model status and actual status do not correlate 100% are discussed in Table 6-23 attached in Appendix C.

4.4.4 IMPLEMENTING SIMULATION FOR RESULTS

Step 6, applying the DOE technique, and step 7, run simulations, were applied in the same manner as was done for the case studies of mine A and mine B. Reducing the availability by means of simulations for hourly and two-hourly intervals were done. The simulations that were conducted are illustrated in Table 6-20 to Table 6-22 attached in Appendix C.

4.4.5 CASE STUDY RESULTS

Case study C1 results

Results obtained from the reduced availability using the simulation model developed for case study C1 are depicted in Figure 4-31 and Figure 4-32. Figure 4-31 illustrates the results obtained from hourly-reduced availability

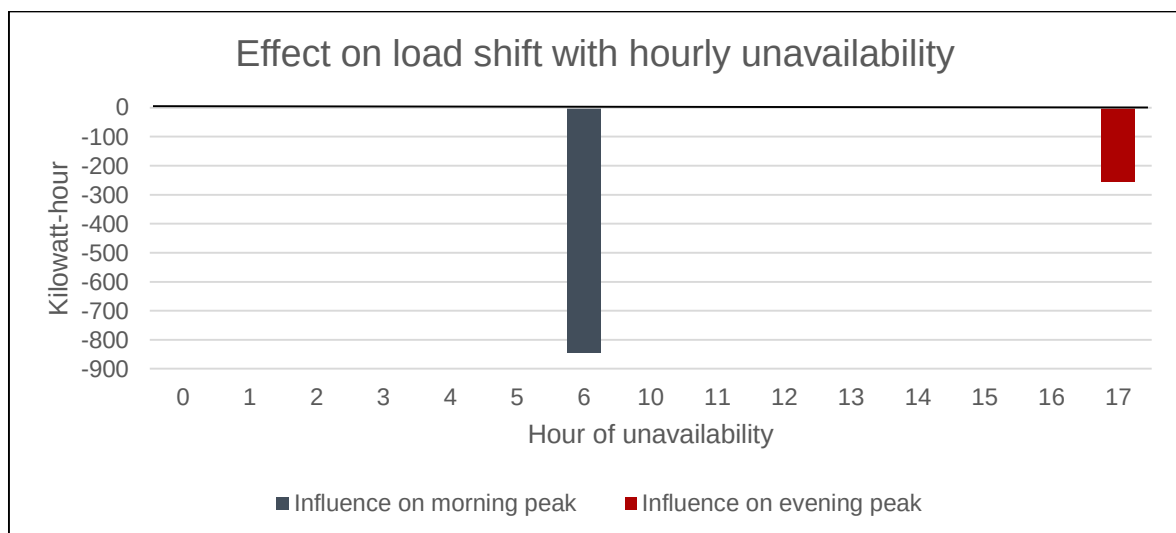


Figure 4-31: Case study C1 – results of hourly unavailability

Reducing the availability of the pumps during hour 6 resulted in an 800 kWh negative influence on the morning peak. A negative influence on the evening peak of 250 kWh can be seen when the availability is reduced for hour 17. The other hours of reduced availability had no effect on the load shift performance.

Figure 4-32 illustrates the results obtained from the simulation model when the availability was reduced for two-hour intervals. A larger negative influence on the load shift performance can be seen when the availability of the pumps were reduced for two-hour intervals.

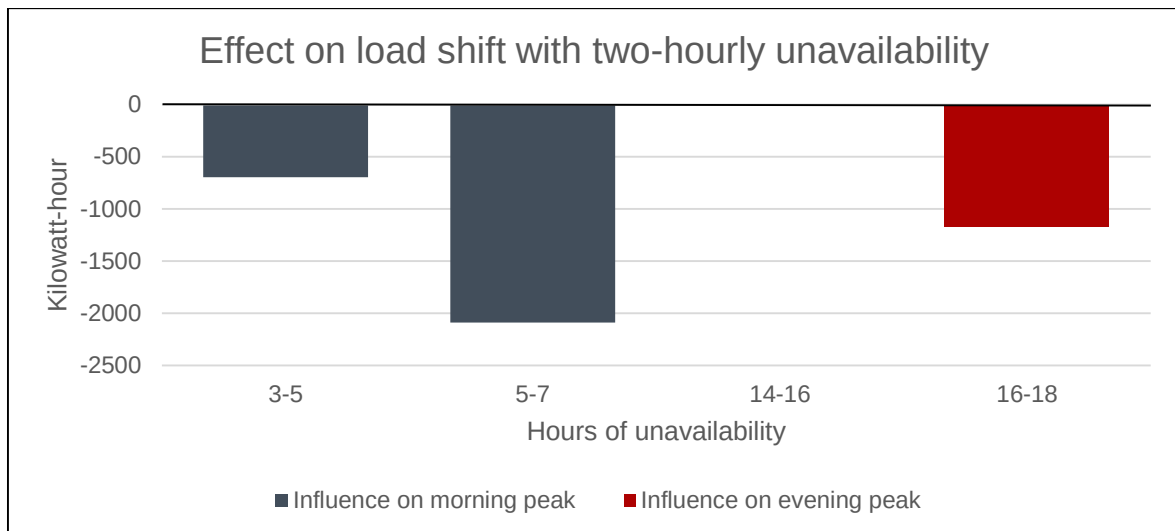


Figure 4-32: Case study C1 – results of two-hourly unavailability

Reducing the availability during the 3-5 interval resulted in negative morning load shift performance of 700 kWh and for the 5-7 hour interval, a negative influence of 2000 kWh. The evening peak was negatively influenced by 1200 kWh when reducing the availability for the 4-6 interval.

Comparing the total amount of energy of the baseline with each individual simulation, total energy is illustrated in Figure 4-33 and Figure 4-34. Figure 4-33 illustrates the total energy when the availability is reduced for hourly intervals.

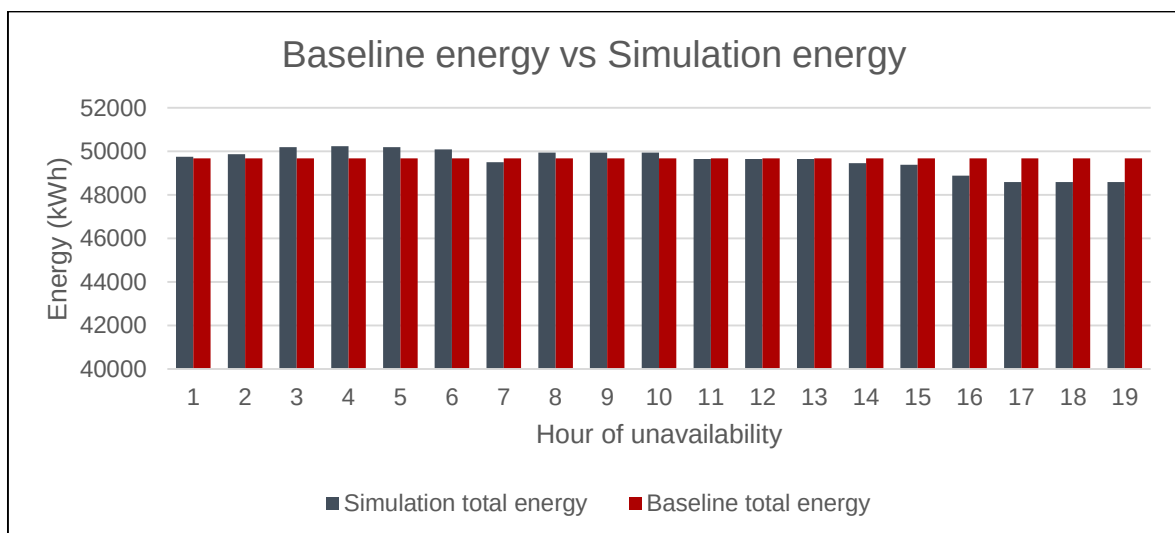


Figure 4-33: Case study C1 – total energy comparison for hourly unavailability

Examining Figure 4-33, it can be seen that the total energy used as a result of reduced availability increased in the early hours of the day. The total energy reduces during the day and then, in the later hours of the day, less energy is used than in the baseline period.

A similar trend can be noted than in the case studies of mine A and mine B. In several instances, the amount of energy used when reducing the availability resulted in more energy used during the day. The increased energy usage during the day will result in an energy usage decrease in the days to follow.

In the remaining simulations, the total amount of energy is either equal to the baseline energy or less than the baseline energy. Hours of unavailability after 13:00 resulted in less energy used during the day than what was used during the baseline period as illustrated in Figure 4-33. The reduction in energy will lead to an energy increase in the days to follow. This could negatively influence the load shift performance of the days to follow, as the system capacity is reduced.

Figure 4-34 illustrates the total energy comparison for the simulations conducted with two-hourly reduced availability.

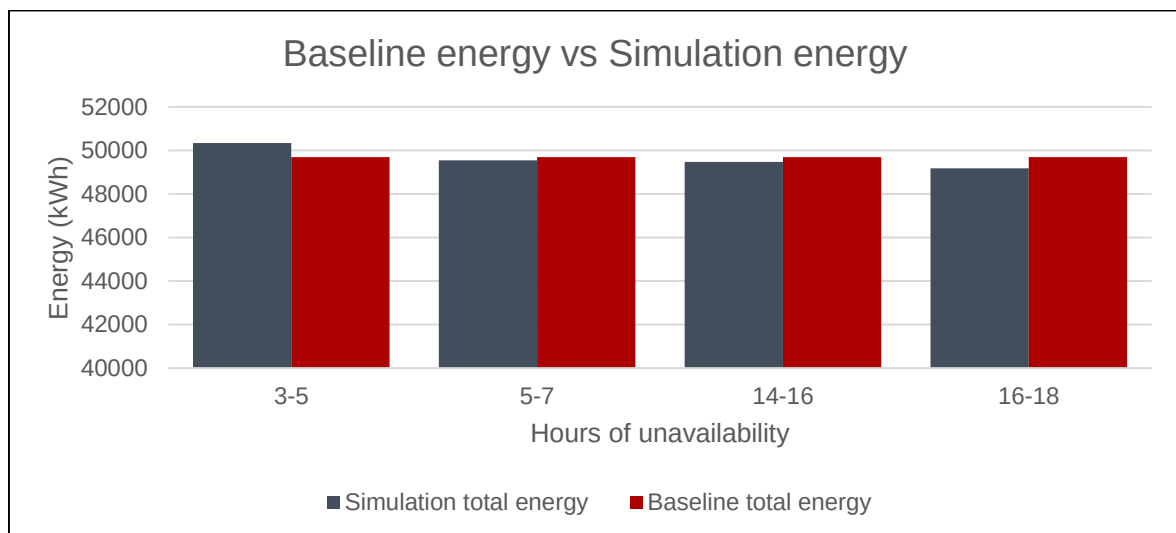


Figure 4-34: Case study C1 – total energy comparison for two-hourly unavailability

Very little change will be noted in the total energy when reducing the availability of the pumps for two-hour intervals. It will be seen, however, that reducing the availability for case study C1 for two-hour intervals will result in a decrease in energy usage for the day. As a result, more energy will be used in the days to follow.

Case study C2 results

The simulation model developed for 21L yielded results as illustrated in Figure 4-35 and Figure 4-36. Figure 4-35 illustrates the results obtained when the availability is reduced for hour intervals.

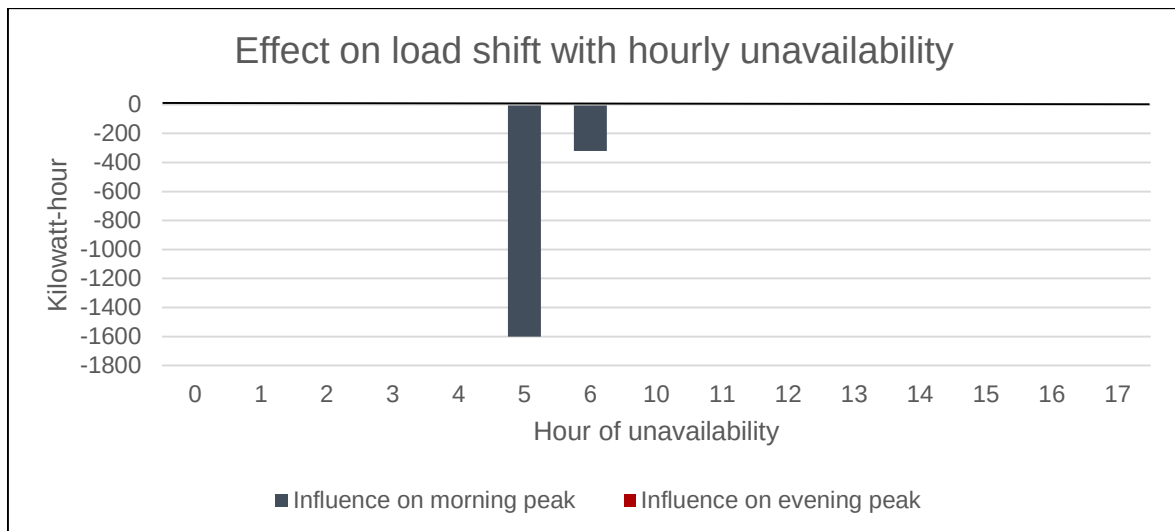


Figure 4-35: Case study C2 – results of hourly unavailability

Negative influences on the morning peak period of 1600 kWh and 250 kWh for the hourly-reduced availability for hours 5 and 6, respectively, can be seen. The remaining hours of reduced availability had no effect on the load shift performance.

Figure 4-36 illustrates the results obtained from the simulation model when the availability is reduced for two-hour intervals. Similar to the simulation results of case study C1, case study C2 resulted in a larger negative influence on the morning and evening peak periods.

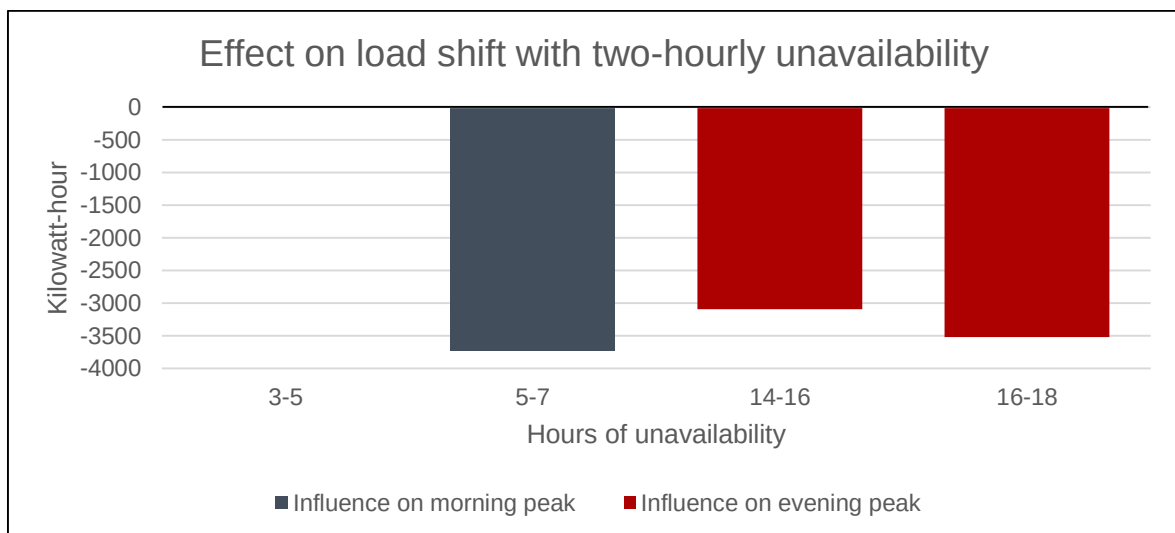


Figure 4-36: Case study C2 – results of two-hourly unavailability

A negative influence on the morning peak period of 3700 kWh was the result of reducing the availability of the pumps during the 5-7 hours of the day. Reducing the availability of the 14-16 and 16-18 hours resulted in a negative influence on the evening peak period of 3100 kWh and 3500 kWh respectively.

Figure 4-37 illustrates the total energy of the baseline compared to the total energy of the simulation results. Reducing the availability for hourly intervals preceding hour 20, excluding hour 4, resulted in more energy used during the 24-hour period. As a result, less energy will be needed in the days to follow.

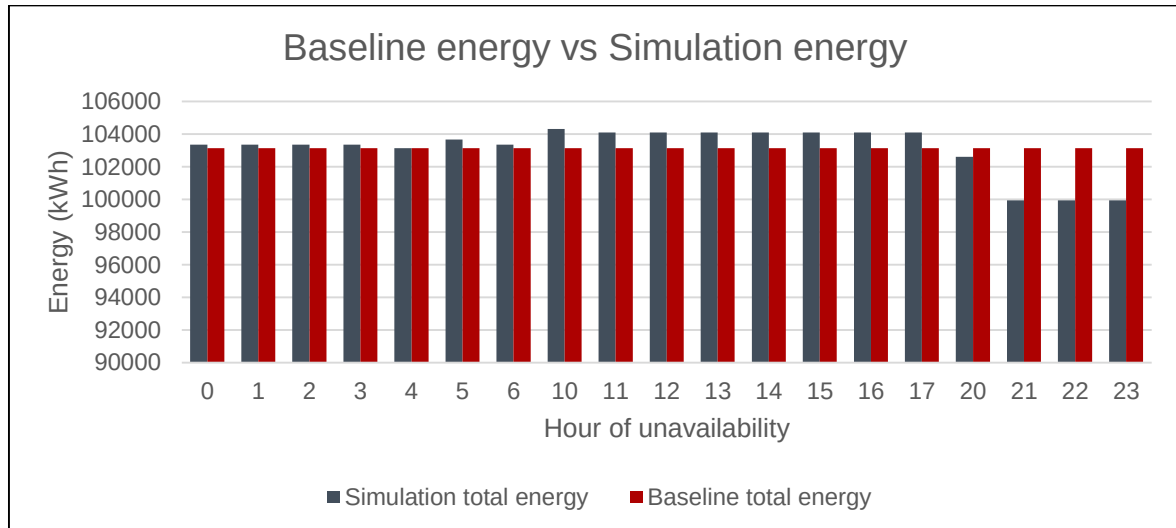


Figure 4-37: Case study C2 – total energy comparison for hourly unavailability

Simulations conducted after hour 20 resulted in less energy used during the day, and could lead to a reduced load shift performance on the days to follow. A reduced energy usage in the hours after hour 20 will also be seen in previous case studies of mine A and mine B.

Figure 4-38 illustrates the total energy comparison if the availability is reduced for two-hour intervals.

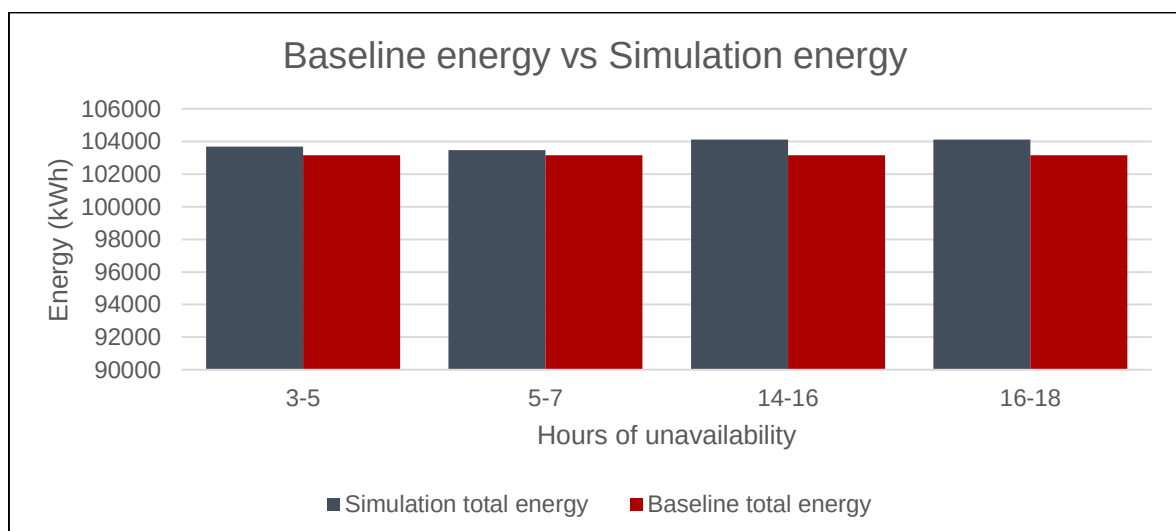


Figure 4-38: Case study C2 – total energy comparison for two-hourly unavailability

More energy is used during the day with a reduced availability. As a result, less energy is needed in the days to follow to keep the dewatering system within operating parameters.

Therefore, the capacity of the dewatering system has been increased and could lead to an increased possibility of load shift.

Case study C3 results

Results obtained from the 5L simulation model are illustrated in Figure 4-39 and Figure 4-40. Figure 4-39 illustrates the results obtained when the availability is reduced for hourly intervals.

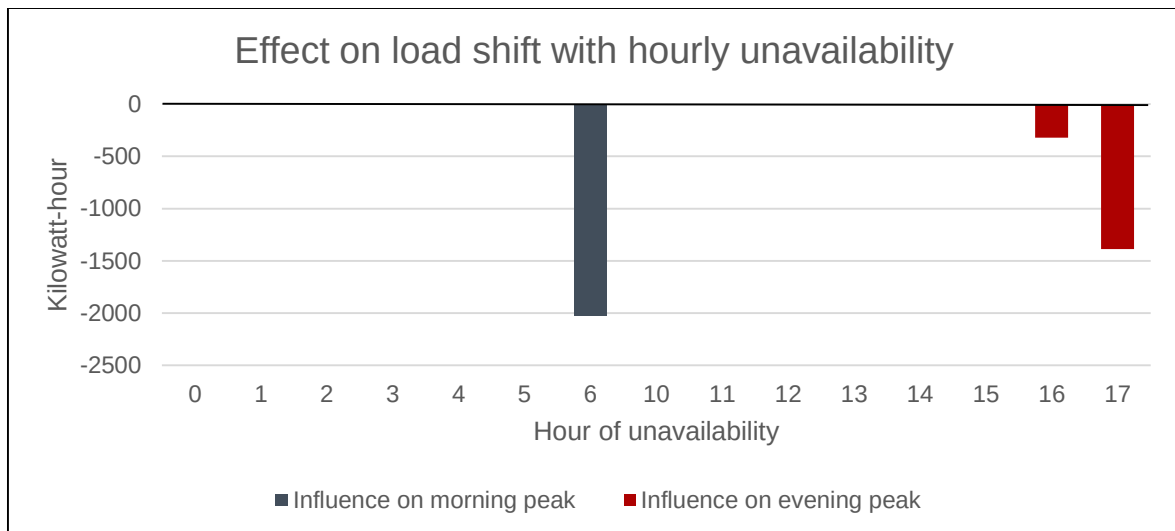


Figure 4-39: Case study C3 – results of hourly unavailability

Negative influences can be seen on the morning and evening peak periods. Reduction of the availability of hour 6 resulted in a 2000 kWh negative influence on the morning peak. Reduction of the availability for hours 16 and 17 of the day had a negative influence on the evening peak of 250 kWh and 1400 kWh, respectively.

Figure 4-40 illustrates the results obtained when the availability is reduced for two-hour intervals. Reduction of the availability for the 5-7 hour interval resulted in a negative influence on the morning peak of 3800 kWh. A negative influence of 3200 kWh and 6000 kWh on the evening peak can be seen when the availability is reduced for the 14-16 and 16-18 hour intervals, respectively. Reduction of the availability during the 3-5 interval had no effect on the load shift performance of the dewatering level.

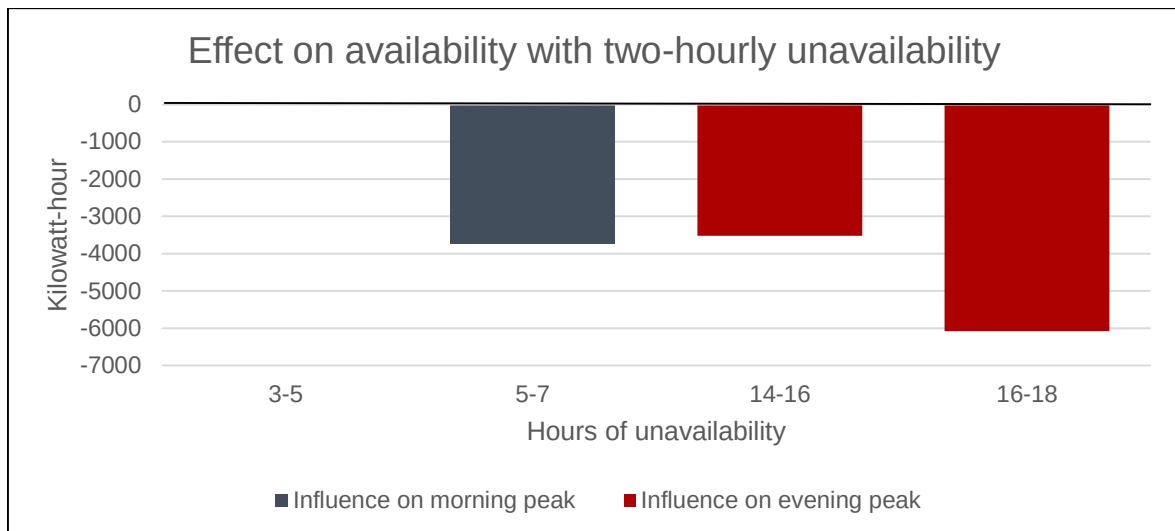


Figure 4-40: Case study C3 – results of two-hourly unavailability

The baseline total energy and simulation total energy for each simulation conducted are illustrated in Figure 4-41 and Figure 4-42. Figure 4-41 illustrates the total energy of the simulations and the total energy of the baseline if the availability is reduced for hourly intervals.

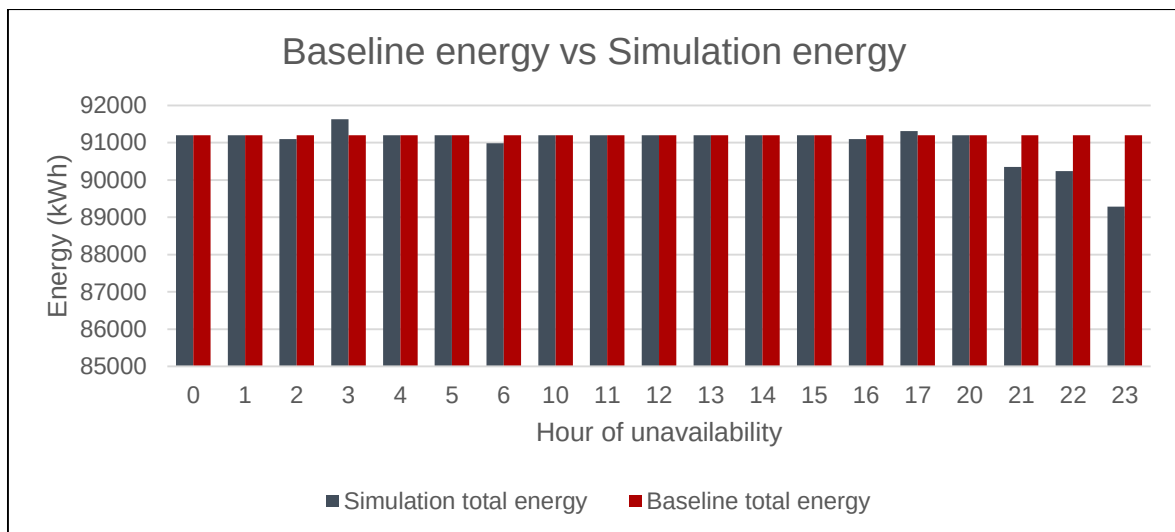


Figure 4-41: Case study C3 – total energy comparison for hourly unavailability

Reduced availability had very little influence on the total amount of energy when conducting the simulations except for hours after hour 20. Reduced availability of hours after hour 20 resulted in less energy used when compared to the baseline. As a result, more energy is needed during the days to follow, to get the dewatering system within safe operating parameters. This could lead to a reduction in load shift performance in the days to follow.

Figure 4-42 illustrates the total energy comparison for the simulations conducted with two-hourly reduced availability.

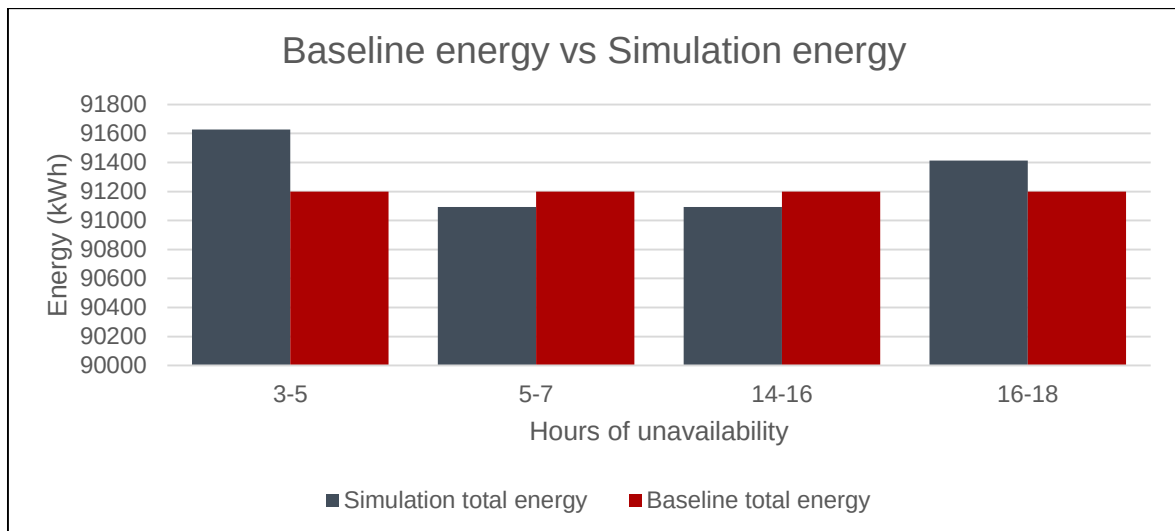


Figure 4-42: Case study C3 – total energy comparison for two-hourly unavailability

Reducing the availability for two-hour intervals, both an excess and less energy consumption for the simulations can be seen when compared to the baseline. Reduction of the availability for the 3-5 and 16-18 hours resulted in more energy used, whereas the 5-7 and 14-16 hours resulted in a decrease in energy usage.

4.5 VALIDATION AND QUANTIFICATION OF RESULTS

4.5.1 VALIDATION OF RESULTS

The results obtained from the simulation models have to be validated to ensure the correctness of the method used to investigate the effect of pump availability on load shift performance. Previous studies conducted on DSM interventions focused on optimising and improving the system control. Validation of the methodology developed in previous studies that focussed to improve the control strategies is done through means of comparison.

The methodologies developed in previous studies are used to improve control strategies, and are implemented on actual systems after simulations were conducted on the actual system. The results obtained from the actual system after implementation of the methodology were applied, and the simulations results are compared. If the actual system results and the simulation results compare, then the methodology is validated.

Validation of the methodology in other cases is done by comparing the actual system performance before and after the implementation of the methodology. If the performance increased, or if cost savings are achieved after the implementation of the methodology, then the methodology is validated.

However, the same method of validation cannot be used in this study. Reduction of the availability of pumps will have a negative effect on the project performance, as seen in the results obtained. Therefore, to validate the methodology, an alternative validation technique will be used.

Validation of the methodology will be done by comparing all the results obtained from the simulations in order to find a general trend. Validation of the methodology consists of the following steps, i.e.:

1. Normalise simulation results;
2. Compare normalised results;
3. Discuss outlying results;
4. Determine if a general trend is present;
5. Compare results to previous studies done on maintenance of equipment.

Normalise results

In order to compare the results obtained from the simulations conducted, the results should be normalised. Each case study consists of different parameters and cannot be compared to the other case studies done in this research scope if not normalised. Normalisation of simulation results will be done by determining the percentage of the average effect on the load shift to the average power used during the day. To calculate the normalised results, the average effect on peak periods in kilowatt-hour are divided into the average kilowatt-hour consumed during the day.

Compare results

The results for the peak periods of each case study are then combined in one table. The effect of the morning peak and the evening peak are combined to get a resultant effect of the total peak period influence. For each simulation conducted, the results are listed as illustrated in Table 4-10 and Table 4-11.

The normalised results obtained from the simulations conducted when the availability was reduced for an hour are illustrated in Table 4-10. Normalised results obtained when the availability is reduced for two-hour intervals are illustrated in Table 4-11. Each case study's results are depicted in the tables and the normalised results for each hour can be seen in the columns.

Table 4-10: Normalised results for hourly unavailability

Normalised results for hourly reduced availability																			
	0	1	2	3	4	5	6	10	11	12	13	14	15	16	17	20	21	22	23
A1	3.5	0	0	0	3.46	0.0	1.73	0	0	0	0	0	0	0	0	0	0	0	0
A2	-2.0	0	0	0	0	2.0	-37.2	-2.0	-2.0	-2.0	-2.0	-2.0	-2.0	-4.0	0	0	0	0	0
B1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3.15	0	0	0	0
B2	1.6	1.6	1.6	1.6	1.6	-15.8	-23.8	17.6	17.6	17.6	17.6	0.0	-32.0	-37	-35.3	0	0	0	0
B3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
C1	0	0	0	0	0	0	-13.6	0	0	0	0	0	0	0	-6.2	0	0	0	0
C2	0	0	0	0	0	-12.3	-2.5	0	0	0	0	0	0	0	0	0	0	0	0
C3	0	0	0	0	0	0	-17.8	0	0	0	0	0	0	-4.2	-18.2	0	0	0	0

Table 4-11: Normalised results for two-hourly unavailability

Normalised results for two-hourly reduced availability				
	3-5	5-7	14-16	16-18
A1	0.0	-10.4	-4.4	-2.2
A2	0.0	-16.3	-2.0	-22.53
B1	-4.32	0.0	0.0	6.8
B2	-42.0	-53.1	-48.1	-112.2
B3	0.0	0.0	0.0	-14.9
C1	-11.1	-33.8	0.0	-28.6
C2	0.0	-28.9	-35.66	-40.6
C3	0.0	-32.8	-46.4	-79.8

Outlying results

Analysing the results illustrated in Table 4-10, it can be seen that the results obtained from case study A2 and B2 do not compare to the rest of the results obtained. Case study A2 resulted in a constant negative influence if the availability is reduced for hourly intervals between hour 6 and hour 16. The constant negative influence could be an indication that the case study does not have enough capacity to accompany unavailable pumps.

Case study B2 resulted in a constant positive influence on the peak periods when the availability is reduced for hourly intervals for the hours 0 to 4 and 10 to 13. This could indicate that the case study control philosophy should be revised. Less pumps could run during the day to dewater the system and a full load shift could still be achieved.

No outlying results can be seen when the results are analysed for the simulations conducted with two-hourly unavailability.

Average trend

To determine if the availability has an average trend or influence depending on the time of day, the normalised results are analysed. Figure 4-43 illustrates the percentage of the case studies that resulted in a positive and negative influence on the peak periods for each hour of reduced availability.

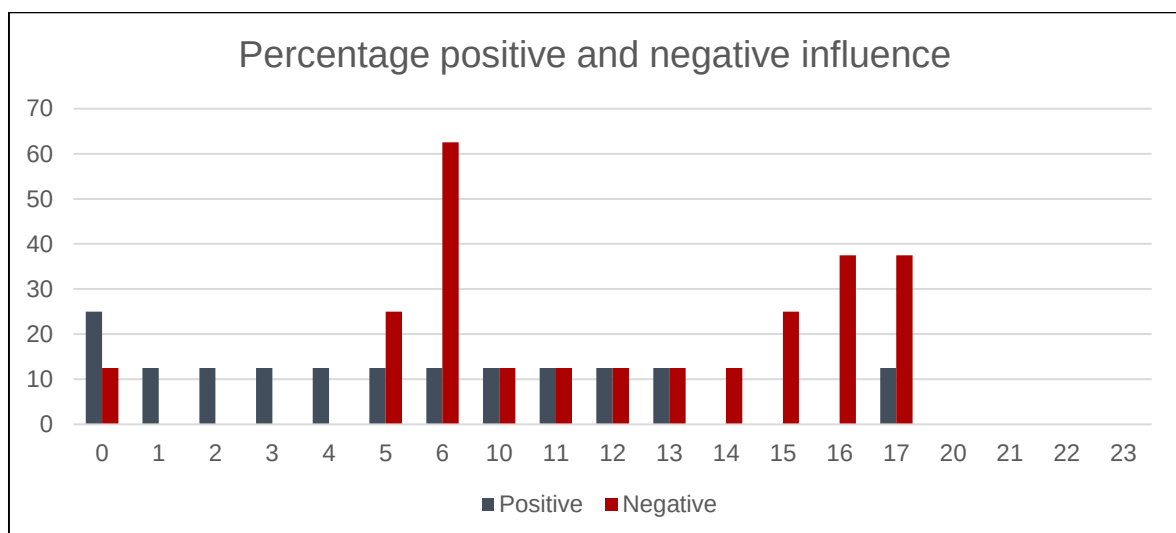


Figure 4-43: Percentage of positive and negative influences (one-hour intervals)

It is evident from Figure 4-43 that hours 6, 16 and 17 of reduced availability have a definite negative influence on the peak periods. Higher chances exist if the availability is reduced during these hours.

When removing case study A2 and B2 because of the outlying results, the percentage of case studies that resulted in a positive and negative influence are illustrated in Figure 4-44.

A negative influence once again can be seen when the availability is reduced for hours 6 and 17.

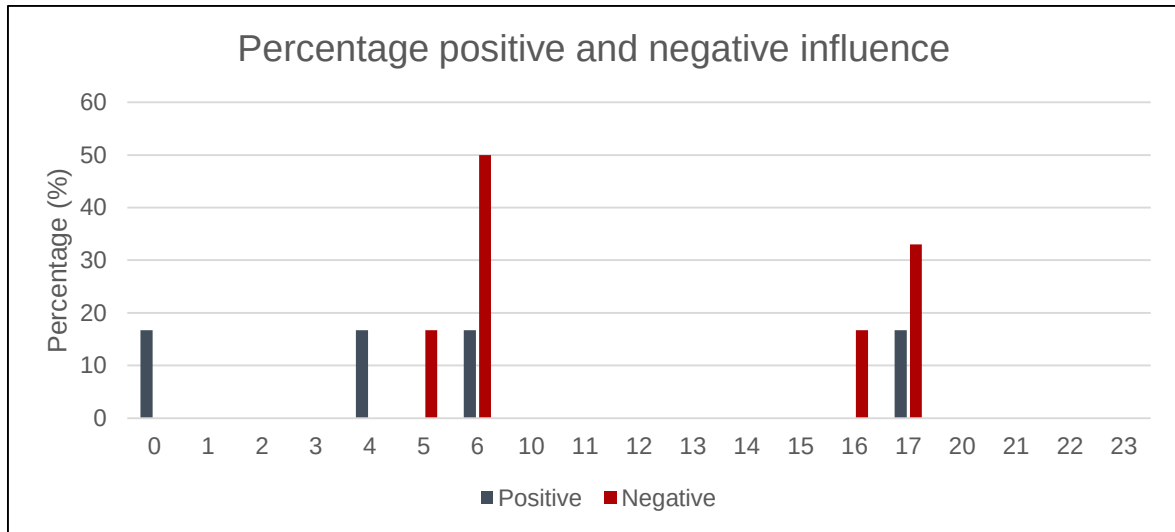


Figure 4-44: Percentage of positive and negative influences excluding outlying results

Reducing the availability for hour 6 of the day resulted in a 50% chance of negatively influencing the peak periods. Reducing the availability during hour 17 resulted in a 33% chance of a negative influence on the peak periods.

Figure 4-45 illustrated the percentage of case studies that resulted in a positive and negative influence on the load shift when the availability is reduced for two-hour intervals. From the figure, it is evident that reduced availability has a negative influence on the load shift performance.

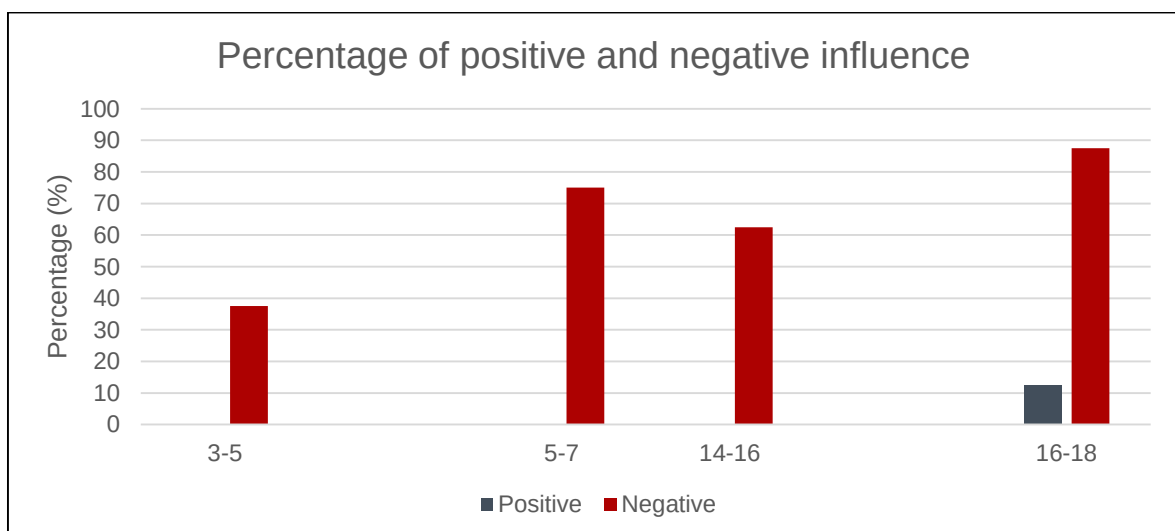


Figure 4-45: Percentage of positive and negative influences (two-hour intervals)

All the simulations conducted with a reduced availability of two-hour intervals resulted in a negative influence. It is also evident that the hours just before peak periods are more likely to have a greater negative influence on the load shift.

Comparing Figure 4-43 to Figure 4-45 with each other, it can be seen that an influence, specifically a negative influence, is more likely to occur in the hours just before the peak periods. In the hourly-reduced availability, hours 6 and 17 had greater negative influences. In the two-hour interval reduced availability, hours 5 to 7 and 16 to 18 are more likely to have a negative influence.

Compare results and previous studies

In Chapter 1, it was stated that maintenance has a positive influence on project performance. Maintenance on dewatering systems influences many factors, one of which is an increase in availability. Lack of maintenance, on the other hand, could reduce the number of available pumps and, as a result, lead to weak project performance.

This could also be seen when applying the methodology and investigating the effect of pump availability on the load shift performance – thus, the methodology and the results obtained from the methodology are validated.

4.5.2 RESULTS QUANTIFICATION

Upon completion of the validation of the simulation results, the effect of pump availability on load shift performance can be quantified. To quantify the effect of pump availability on the load shift performance, the results obtained from the simulation models will be evaluated.

Focus is placed on the hours of reduced availability that have the greatest effect on load shift performance. Thus, for hourly-reduced availability, the results will be quantified for hours 6 and 17 of reduced availability. For the two-hourly reduced availability, the results will be quantified for the 5-7 and 16-18 time intervals. The results obtained from the simulation models will be summated in one table to get a total effect on the load shift performance, as seen in Table 4-12.

Table 4-12: Quantified results

Case study	Hours of reduced availability			
	6	17	5-7	16-18
A1(kW impact)	42	0	-250	-42
A2(kW impact)	-1350	0	-592	-550
B1(kW impact)	0	37	0	73

Case study	Hours of reduced availability			
	6	17	5-7	16-18
B2 (kW impact)	550	-807	-1247	1687
B3 (kW impact)	0	0	0	183
C1 (kW impact)	-843	-257	-2090	1173
C2 (kW impact)	-320	0	-3733	3520
C3 (kW impact)	-2027	-1387	-3733	6080
Total kW impact	-3948	-2413	-22645	-13162
Total yearly loss	R1 365 091	R 834 390	R 4 026 104	R 4 550 481

As seen in Table 4-12, the three mines can have an excess of R 4.5 million additional operating costs per annum on the dewatering systems. This amount is calculated with the 2015-2016 Eskom tariffs. The amount calculated excludes the other hours of reduced availability that has been simulated.

As a result, it is important to keep the pumps available for control during the four hours preceding the peak periods. The remaining hours of pump operation have less impact on the peak period load shift. This means that, if maintenance should be carried out on dewatering pumps, then the maintenance should preferably be done during the peak periods or alternatively in hours not within the four hours preceding peak periods. If maintenance should be carried out during hours other than peak periods, then the time interval that the pump is unavailable for control should be less than one hour. Pumps that are unavailable for more than one hour have a greater impact on the load shift performance, as seen in the results.

4.6 CHAPTER CONCLUSION

In Chapter 3, a step-by-step methodology was developed to investigate the effect of pump availability on load shift performance. This methodology developed was utilised and applied to three different mines. Each dewatering level of the mines was isolated to investigate the effect on each specific level. The step-by-step methodology was applied to eight dewatering levels in total.

Upon completion of the investigation, the methodology was validated by determining a general trend and comparing the results to other studies conducted on maintenance. The

methodology was validated and found correct. The methodology thus made it possible to address the problem statement.

The results obtained from the investigation showed that reduced availability is more likely to negatively influence load shift performance and in particular, the hours of reduced availability during the hours preceding the peak periods. Furthermore, it was noted that if the availability is reduced for more than one hour, the influence is more likely to be negative and greater.

The results obtained from the case studies show that if the availability of the pumps is reduced for one hour preceding the peak periods, the additional operating cost could increase up to R1 365 091 combined for the three mines. If the availability is reduced for two hours preceding the peak periods, the operating cost could increase to a combined R4 550 481 for the three mines. It is evident from these findings that the availability of pumps preceding the peak periods is of utmost importance to effectively shift load out of the peak periods.

From the results, it is also seen that if maintenance should be conducted on the dewatering system, that it should be done during the peak periods. In the case where this is not possible, the maintenance should be conducted before the four hours preceding the peak periods. If maintenance is carried out during these periods, the maintenance period should be kept as short as possible, preferably under an hour.

It is evident from the results that the methodology developed addresses the problem statement. The step-by-step methodology enables one to investigate the effect of pump availability on load shift performance. The methodology also enables one to quantify the effect and identify the hours in which maintenance should be conducted on the system while minimising the impact on the load shift performance.

Chapter 5:

Study conclusion



Power lines⁶

Nothing is a waste of time if you use the experience wisely.

(Auguste Rodin)

⁶ Jesse Wilson, "Strengthening the grid to protect against terrorist attacks." Connect, 2015. [Online]. Available: <http://connect.xcelenergy.com/colorado/strengthening-the-grid-to-protect-against-terrorist-attacks/>

5 STUDY CONCLUSION

5.1 INTRODUCTION

Global and local energy demands increase due to continued economic development. South Africa's biggest power utility is struggling to meet the rising electricity demand. DSM interventions were implemented to reduce strain on the South African electric grid. DSM interventions focus on reducing the peak TOU demand by means of load shift and energy-efficiency-improving initiatives.

After the implementation of the DSM interventions project, performance tends to decrease during the PT period as a result of poor maintenance. Lack of maintenance results in reduced pump availability and, in turn, influences the load shift performance of projects.

The need to investigate the effect of pump availability on load shift performance was identified to highlight the importance of maintenance. A further need, namely to identify and prioritise the maintenance schedules on the system, was also established.

5.2 HOW THE PROBLEM WAS ADDRESSED

Extensive research on dewatering systems was conducted. The research included how dewatering systems operate and what components are used in dewatering systems. Previous studies were analysed to determine how dewatering systems are automated, optimised and maintained.

Further research was done to determine how the effect of pump availability can be investigated. It was found that simulation models could be developed and utilised. Research was conducted, outlining simulation model development, simulation model verification and evaluation of simulation model results. Upon completion of the simulation model development research, an investigation was done on how to utilise the simulation model. The DOE process was used to determine how to conduct experiments with the simulation models.

A step-by-step methodology was derived from the research. The step-by-step methodology consists of four phases and a total of eight steps. The methodology assists in the process of developing a simulation model for each dewatering level. Additionally, the methodology assists in verifying the simulation model. The methodology also determines how many, and for which time intervals, simulations should be conducted. Lastly, the methodology assists with the evaluation of the simulation results to enable one to quantify the results.

The final step of the study was to implement the methodology on different case studies. The dewatering levels of three mines were isolated. At the three mines, the effect of pump availability was investigated using eight different dewatering levels.

The case study results proved that reduced availability of pumps negatively influences load shift performance. It was shown that the longer the pumps are unavailable, the greater the impact on the load shift performance. It was also proved that reducing the availability of the pumps can increase the operating cost to R4.6-million per annum on the considered dewatering systems. Lastly, the results showed that maintenance should be conducted during the peak TOU periods.

The step-by-step methodology succeeded in addressing the problem statement. The methodology enabled one to investigate the effect of pump availability on load shift performance by using simulation models. The methodology also enabled one to determine when maintenance should be conducted on the dewatering system of a mine.

5.3 BENEFITS FROM THE STUDY

The need of this study was to investigate the effect of pump availability on load shift performance. By investigating the effect of pump availability on load shift performance, the importance of maintenance could be stipulated and the maintenance shutdown timing determined.

Investigating the effect of pump availability on load shift performance further contributed to the industry by determining at what time of day pump availability is critical. By implementing the developed methodology, one is able to investigate the effect that pump availability has on the load shift performance. The effect on load shift performance will also be quantifiable. Not only will the effect be seen, but one can also determine when to do maintenance. Determining when maintenance on the dewatering system can be conducted will ensure maximum pump availability and load shift performance.

5.4 RECOMMENDATIONS FOR FURTHER STUDY

In this study, certain limitations and parameters were identified. The limitations of the study were identified as being:

1. Extensive amount of pump availability scenarios;

Numerous and different scenarios exist that could influence pump availability. As a result, many simulations can be conducted, all with different results.

2. Interactions between dewatering levels;

In this study, the interacting dewatering levels were isolated to investigate the effect of availability on each level. In the real system environment, the dewatering levels are interacting and complex. The complexity of the interacting levels made it difficult to pinpoint the effect of pump availability on each level.

3. Time period of influence.

It was found in this study that the load shift performance is influenced by the time and length of the unavailability. In this study, the effect of pump availability was only tested in a day interval. The effect in the days to follow was not determined.

As a result, it is suggested that availability be further investigated by:

1. Investigating different scenarios of pump availability to those already done;
2. Determining the effect of pump availability on the whole dewatering system;
3. Determining the effect of reduced pump availability in the long term.

5.5 CLOSING ARGUMENT

To address the stated problem, investigation was done to determine the effect of pump availability on load shift performance. This was executed by conducting extensive research on dewatering systems and simulation models. The research that was conducted assisted in the development of a step-by-step methodology to compile a simulation model, which enables one to investigate the effect of pump availability on load shift performance.

This study contributed to the industry by assisting in the development of a simulation model to investigate the effect of pump availability on load shift performance. By being able to investigate this, one can quantify the effect on load shift performance and, in so doing,

stipulate the importance of maintenance. Additionally, it can then be determined when maintenance should be carried out.

The results obtained from the case studies showed that reduced pump availability negatively influences load shift performance. Reduced availability for the four hours preceding the peak TOU has the greatest negative impact. It was shown that if one pump's availability is reduced for one hour before peak TOU, then the operating cost could increase by a total of R1.4-million per annum on the three considered mines. If the availability is reduced for two hours before peak TOU, then the operating cost can increase by a total of R4.6-million for the three mines.

Lastly, it was shown that maintenance should be conducted during the peak TOU periods. If this is not possible, the maintenance should be conducted for the shortest time interval and not within the four hours preceding peak TOU.

6 REFERENCES

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Appendices



Mine tunnel⁷

⁷ "Ikuno mine - inside." Follow Rory, 2015. [Online].
Available at: <http://followrory.blogspot.co.za/2014/03/ikuno-mine-inside.html>

APPENDIX A: TIME OF USE STRUCTURE

High demand season or winter months include June to August and low demand season is for all the other months.

Table 6-1: Time-of-use structure

Hour	Low demand season	High demand season
00:00	Off peak	Off peak
01:00	Off peak	Off peak
02:00	Off peak	Off peak
03:00	Off peak	Off peak
04:00	Off peak	Off peak
05:00	Off peak	Off peak
06:00	Standard	Peak
07:00	Peak	Peak
08:00	Peak	Peak
09:00	Peak	Standard
10:00	Standard	Standard
11:00	Standard	Standard
12:00	Standard	Standard
13:00	Standard	Standard
14:00	Standard	Standard
15:00	Standard	Standard
16:00	Standard	Standard
17:00	Standard	Peak
18:00	Peak	Peak
19:00	Peak	Standard
20:00	Standard	Standard
21:00	Standard	Standard
22:00	Off peak	Off peak
23:00	Off peak	Off peak

APPENDIX B: CASE STUDY B - METHODOLOGY RESULTS

Step 1: Project background

Table 6-2: Case study B – Step 1 information

Step 1 – Case study B	
Implementation date	2005-09-13
Project maintenance	Yes – ESCO company started maintenance on the project during 2013.
Control mechanism	Main control of pumps is done by a control program along with a SCADA and PLC setup
Layout	Already given in case study B introduction

Step 2: Control parameters of project

Table 6-3: Case study B1 – 67L control parameters

Case study B1 – 67L		
Hot water dams		
Total capacity (m³)	1800	
Pumps		
Pump 1	Flow:	75
	kW:	1100
Pump 2	Flow:	75
	kW:	1100
Pump 3	Flow:	75
	kW:	1100
Maximum number of pumps allowed to run at a time	1	
Maximum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	92%	
Minimum dam level	40%	
Control ranges	10% for (00:00 – 06:59)	

Case study B1 – 67L	
	5% for (07:00 – 09:59) 13% for (10:00 – 17:59) 3% for (18:00 – 19:59) 10% for (20:00 – 23:59)
Control offset Top	N/A
Control offset Bottom	N/A
Logged data	
Dam levels	1 Month
Pump status	1Month
Pump schedule	1 Month

Table 6-4: Case study B2 – 53L control parameters

Case study B2 – 53L		
Hot water dams		
Total capacity (m³)	1080	
Pumps		
Pump 1	Flow (l/s):	85
	Power (kW):	1100
Pump 2	Flow (l/s):	85
	Power (kW):	1100
Pump 3	Flow (l/s):	85
	Power (kW):	1100
Maximum number of pumps allowed to run at a time	1	
Minimum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	90%	
Minimum dam level	30%	
Control ranges	20% for (00:00 – 03:59) 15% for (04:00 – 05:59)	

Case study B2 – 53L	
	10% for (06:00 – 06:59) 15% for (07:00 – 09:59) 20% for (10:00 – 15:59) 10% for (16:00 – 16:59) 5% for (17:00 – 17:59) 15% for (18:00 – 19:59) 20% for (20:00 – 23:59)
Control offset Top	N/A
Control offset Bottom	N/A
Logged data	
Dam levels	1 Month
Pump status	1Month
Pump schedule	1 Month

Table 6-5: Case study B3 – 30L control parameters

Case study B3 – 30L		
Hot water dams		
Total capacity (m³)	1507	
Pumps		
Pump 1	Flow (l/s):	108
	Power (kW):	1100
Pump 2	Flow (l/s):	108
	Power (kW):	1100
Pump 3	Flow (l/s):	108
	Power (kW):	1100
Maximum number of pumps allowed to run at a time	1	
Minimum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	90%	

Case study B3 – 30L	
Minimum dam level	30%
Control ranges	20% for (00:00 – 05:59) 10% for (06:00 – 09:59) 20% for (10:00 – 15:59) 15% for (16:00 – 16:59) 10% for (17:00 – 19:59) 20% for (20:00 – 23:59)
Control offset Top	N/A
Control offset Bottom	N/A
Logged data	
Dam levels	1 Month
Pump status	1Month
Pump schedule	1 Month

Step 3: Analyse data

Table 6-6: Case study B – daily average pump availability

Day	Average availability (%)
1	52
2	57
3	58
4	57
5	67
6	90
7	61
8	85
9	79
10	74
11	72
12	77
13	74
14	70
15	62
16	85
17	65
18	78
19	66
20	71

Day	Average availability (%)
21	77
22	74
23	76
24	80
25	77
26	68
27	56
28	77
29	80
30	67

Step 4: Develop simulation model

Table 6-7: Mine B – classification of information

Information classification document		
Nr	Fixed inputs	Variable inputs
1	Dam capacity	Fissure water inflow
2	Number of pumps	Mining water inflow
3	Flow of pumps	Control ranges
4		Maximum number of pump
5		Minimum number of pumps
Nr	Variable outputs	
1	Pump status	
2	Dam level	

Table 6-8: Mine B – assumption document

Assumption document for simulation model A		
Revision number : 01		Date: 2015/08/01
Nr	Assumption	Justification for assumption
1	Pumping stations do not influence the performance of other pumping stations	Simulation model focus on a pumping station and not on the whole system
2	Raw data logged is correct	Instrumentation is frequently calibrated

Assumption document for simulation model A		
Revision number : 01		Date: 2015/08/01
Nr	Assumption	Justification for assumption
3	Inflow of water into the hot water dam is equal to the dam water volume change minus the outflow of water	Water balance
4	No flow losses are present (ideal system)	The flow losses are accounted for in the real life data
5	Information received by mine personnel is correct	Constant measuring and calculations are done by mine personnel to verify validity of information
6	Total flow of two pumps running at a time is equal to 95% of the sum of the two pumps' installed flow capacity. In scenarios where three pumps run at a time, the delivered flow is 90% of the sum of the three pumps' installed flow capacity	Increased friction reduces the total flow
7	Pump start-up instantaneous with status change. Thus delivered flow is instantaneous	Flow takes a few seconds to reach maximum flow as the pump starts up. However, it does not influence the simulation as raw data collected takes place in two-minute intervals.
Accepted by:		Name: Hannes de Jager

Step 5: Verify simulation

Status correlations of 88%, 87% and 83% were achieved with each individual simulation model build for case studies B1 – B3. The difference in status between the actual system and the simulation could be explained for every instance and was accepted. Furthermore, a reduced correlation of status can be attributed to the fact that the simulation model is based on data where pumps were only 90% available for control. As a result, the control philosophy was not followed exactly in the actual system, whereas the simulation model followed the control philosophy. All three simulation models were verified and deemed valid. The status correlation for each simulation model can be seen in Figure 6-1 to Figure 6-3.

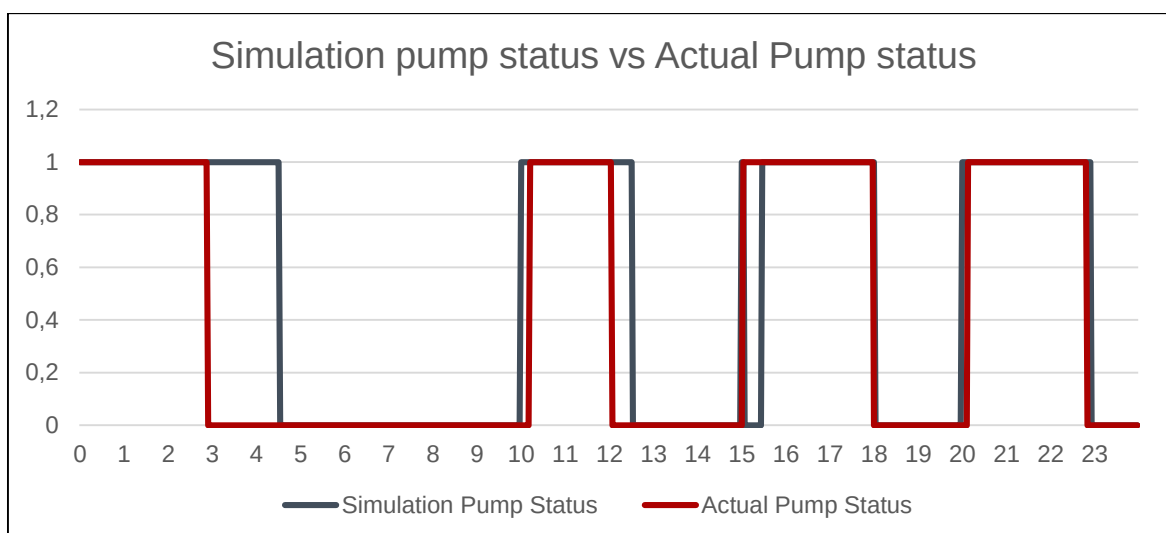


Figure 6-1: Case study B1 – pump status verification

Table 6-9: Case study B1 – status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference acceptable
2	93	1. Control mechanism reacts in second intervals, whereas the simulation model decision-making is done every two minutes. 2. Control philosophy has not been followed by the control mechanism and thus the simulated values may differ	Yes
3	0		Yes
4	43		Yes
10	80		Yes
12	53		Yes
15	57		Yes
18	97		Yes
20	87		Yes
22	90		Yes

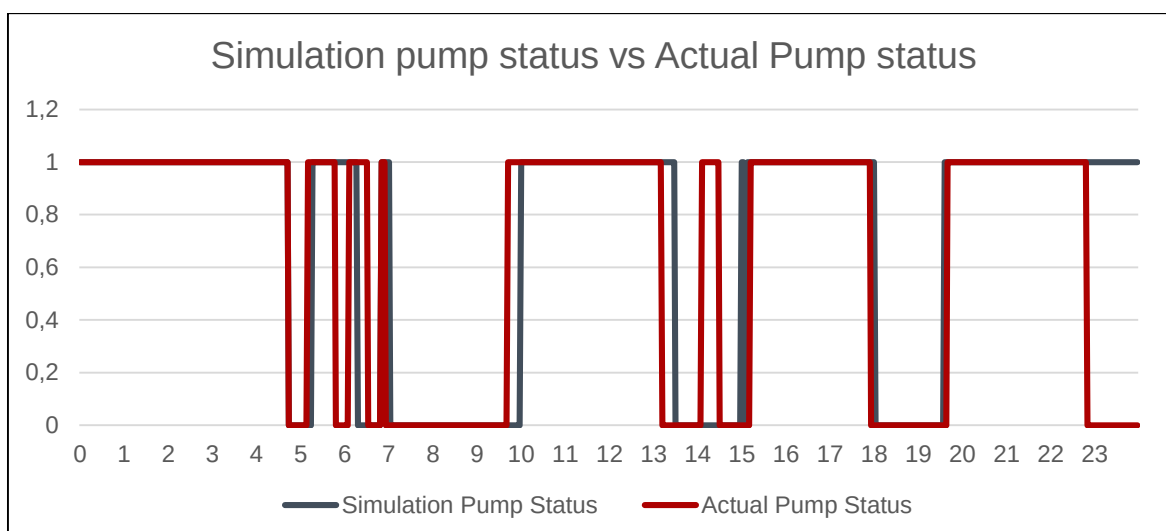


Figure 6-2: Case study B2 – pump status verification

Table 6-10: Case study B2 – status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference Acceptable
0	97	1. Control mechanism reacts in second intervals, whereas the simulation model decision-making is done every two minutes. 2. Control philosophy has not been followed by the control mechanism and thus the simulated values may differ.	Yes
5	73		Yes
6	60		Yes
7	93		Yes
9	93		Yes
10	97		Yes
13	70		Yes
14	60		Yes
15	87		Yes
17	97		Yes
18	93		Yes
19	93		Yes
22	87		Yes
23	0		Yes

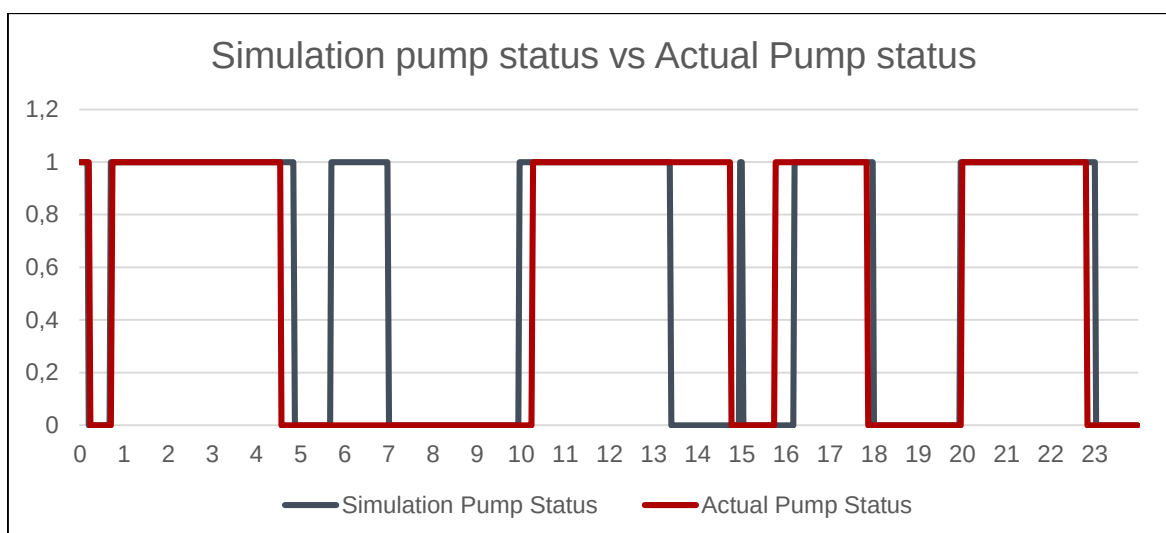


Figure 6-3: Case study B3 – pump status verification

Table 6-11: Case study B3 – status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference Acceptable
0	93	- Control mechanism reacts in second intervals, whereas the simulation model decision-making is done every two minutes. - Control philosophy has not been followed by the control mechanism and thus the simulated values may differ	Yes
4	70		Yes
5	73		Yes
6	0		Yes
7	97		Yes
10	70		Yes
13	43		Yes
14	20		Yes
15	73		Yes
16	77		Yes
17	90		Yes
18	97		Yes
20	97		Yes
22	87		Yes
23	93		Yes

Step 6: Run simulations

Table 6-12: Simulation variations and availability influenced

Simulation variations and availability influenced			
Hourly reduction of availability			
Run no	Availability reduced for:	Run no	Hours
1	00:00 – 00:59	10	13:00 – 13:59
2	01:00 – 01:59	11	14:00 – 14:59
3	02:00 – 02:59	19	15:00 – 15:59
4	03:00 – 03:59	13	16:00 – 16:59
5	04:00 – 04:59	14	17:00 – 17:59
6	05:00 – 05:59	15	20:00 – 20:59
7	10:00 – 10:59	16	21:00 – 21:59
8	11:00 – 11:59	17	22:00 – 22:59
9	12:00 – 12:59	18	23:00 – 23:59
Two-hourly reduction of availability			
Run no	Availability reduced for:	Run no	Hours
19	03:00 – 04:59	21	14:00 – 15:59
20	05:00 – 06:59	22	16:00 – 17:59

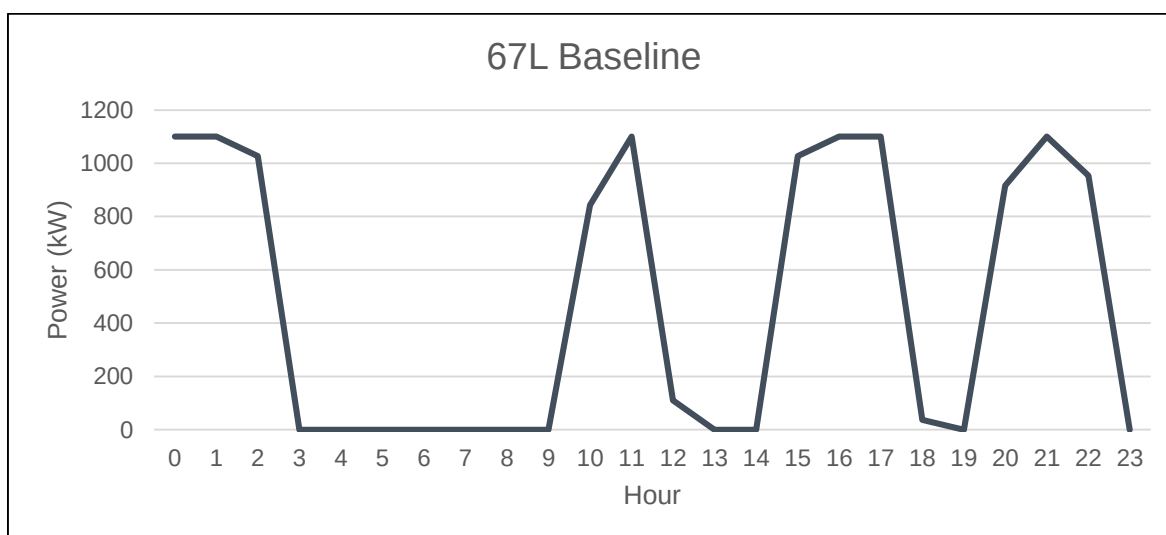


Figure 6-4: Case study B1 – 67L baseline

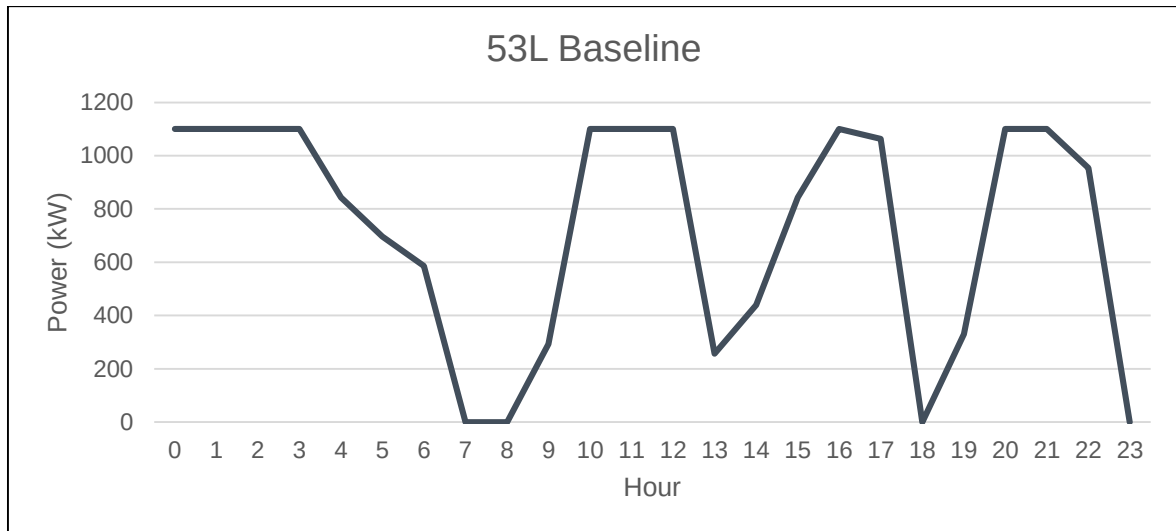


Figure 6-5: Case study B2 – 53L baseline

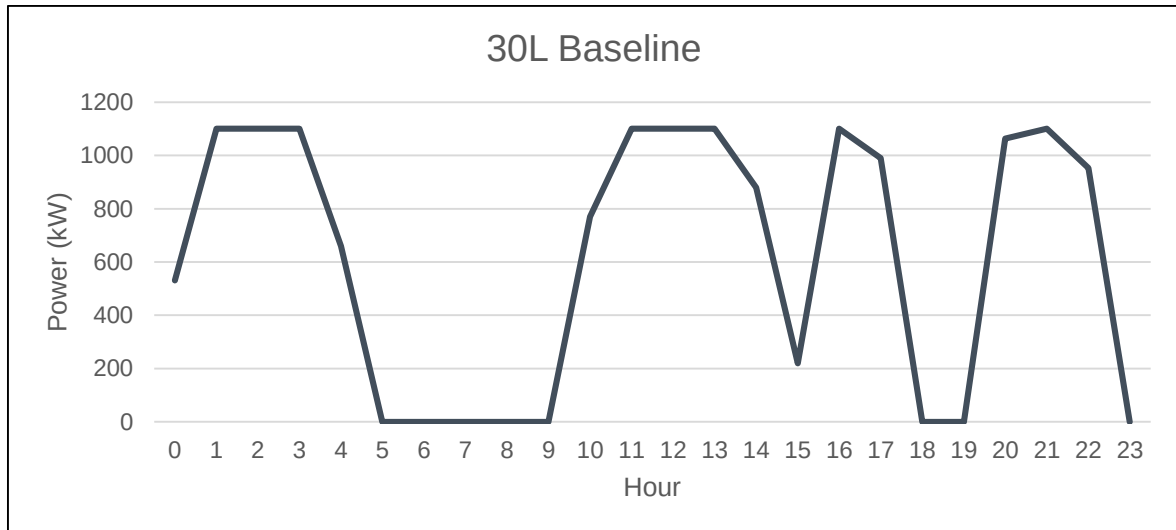


Figure 6-6: Case study B3 – 30L baseline

APPENDIX C: CASE STUDY C - METHODOLOGY RESULTS

Step 1: Project background

Table 6-13: Case study C – Step 1 information

Step 1 – Case study C	
Implementation date	2006-04-04
Project maintenance	Yes – ESCO company started maintenance on the project during 2012
Control mechanism	Main control of pumps is done by a control program along with a SCADA and PLC setup
Layout	Already given in case study C introduction

Step 2: Control parameters of project

Table 6-14: Case study C1 – 25L control parameters

Case study C1 – 25L		
Hot water dams		
Total capacity (m³)	1800	
Pumps		
Pump 1	Flow:	108
	kW:	1100
Pump 2	Flow:	108
	kW:	1100
Pump 3	Flow:	108
	kW:	1100
Pump 4	Flow:	108
	kW:	1100
Pump 5	Flow:	108
	kW:	1100
Maximum number of pumps allowed to run at a time	3	
Maximum number of pumps allowed to run at a time	0	

Case study C1 – 25L	
Control parameters	
Maximum dam level	80%
Minimum dam level	42%
Control ranges	8%
Control offset Top	3%
Control offset Bottom	2%
Logged data	
Dam levels	1 Month
Pump status	1Month
Pump schedule	1 Month

Table 6-15: Case study C2 – 21L control parameters

Case study C2 – 21L		
Hot water dams		
Total capacity (m³)	3000	
Pumps		
Pump 1	Flow (l/s):	300
	Power (kW):	3200
Pump 2	Flow (l/s):	300
	Power (kW):	3200
Pump 3	Flow (l/s):	300
	Power (kW):	3200
Pump 4	Flow (l/s):	300
	Power (kW):	3200
Maximum number of pumps allowed to run at a time	2	
Minimum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	80%	

Case study C2 – 21L	
Minimum dam level	45%
Control ranges	8%
Control offset Top	5%
Control offset Bottom	2%
Logged data	
Dam levels	1 Month
Pump status	1Month
Pump schedule	1 Month

Table 6-16: Case study C3 – 5L control parameters

Case study C3 – 5L		
Hot water dams		
Total capacity (m³)	3000	
Pumps		
Pump 1	Flow (l/s):	300
	Power (kW):	3200
Pump 2	Flow (l/s):	300
	Power (kW):	3200
Pump 3	Flow (l/s):	300
	Power (kW):	3200
Pump 4	Flow (l/s):	300
	Power (kW):	3200
Maximum number of pumps allowed to run at a time	2	
Minimum number of pumps allowed to run at a time	0	
Control parameters		
Maximum dam level	74%	
Minimum dam level	50%	
Control ranges	10%	

Case study C3 – 5L	
Control offset Top	5%
Control offset Bottom	2%
Logged data	
Dam levels	1 Month
Pump status	1Month
Pump schedule	1 Month

Step 3: Annalise data

Table 6-17: Case study C – daily average pump availability

Day	Average availability (%)
1	97
2	96
3	82
4	80
5	69
6	78
7	74
8	85
9	86
10	83
11	79
12	74
13	89
14	77
15	71
16	86
17	84
18	88
19	93
20	96
21	96
22	100
23	95
24	97
25	92
26	86
27	93
28	93
29	68

Day	Average availability (%)
30	85

Step 4: Develop simulation model

Table 6-18: Mine C – Classification of information

Information classification document		
Nr	Fixed inputs	Variable inputs
1	Dam capacity	Fissure water inflow
2	Number of pumps	Mining water inflow
3	Flow of pumps	Control ranges
4		Control offsets
5		Maximum number of pump
6		Minimum number of pumps
Nr	Variable outputs	
1	Pump status	
2	Dam level	

Table 6-19: Mine C – assumption document

Assumption document for simulation model A		
Revision number : 01		Date: 2015/08/01
Nr	Assumption	Justification for assumption
1	Pumping stations do not influence the performance of other pumping stations	Simulation model focus on a pumping station and not on the whole system
2	Raw data logged is correct	Instrumentation is frequently calibrated
3	Inflow of water into the hot water dam is equal to the dam water volume change minus the outflow of water	Water balance
4	No flow losses are present (ideal system)	The flow losses are accounted for in the real life data

Assumption document for simulation model A		
Revision number : 01		Date: 2015/08/01
Nr	Assumption	Justification for assumption
5	Information received by mine personnel is correct	Constant measuring and calculations are done by mine personnel to verify validity of information
6	Total flow of two pumps running at a time is equal to 95% of the sum of the two pumps' installed flow capacity. In scenarios where three pumps run at a time, the delivered flow is 90% of the sum of the three pumps' installed flow capacity	Increased friction reduces the total flow
7	Pump start-up instantaneous with status change. Thus delivered flow is instantaneous	Flow takes a few seconds to reach maximum flow as the pump starts up. However, it does not influence the simulation as raw data collected takes place in two-minute intervals
Accepted by:		Name: Hannes de Jager

Step 5: Verify simulation

A correlation of 98% was achieved for the simulation model of 25L; 97% and 83% were achieved for 21L and 5L respectively. All the differences have been listed and deemed accurate enough and, as a result, all the simulation models developed for mine C were verified. The status correlation for each individual simulation model can be seen in Figure 6-7 to Figure 6-9.

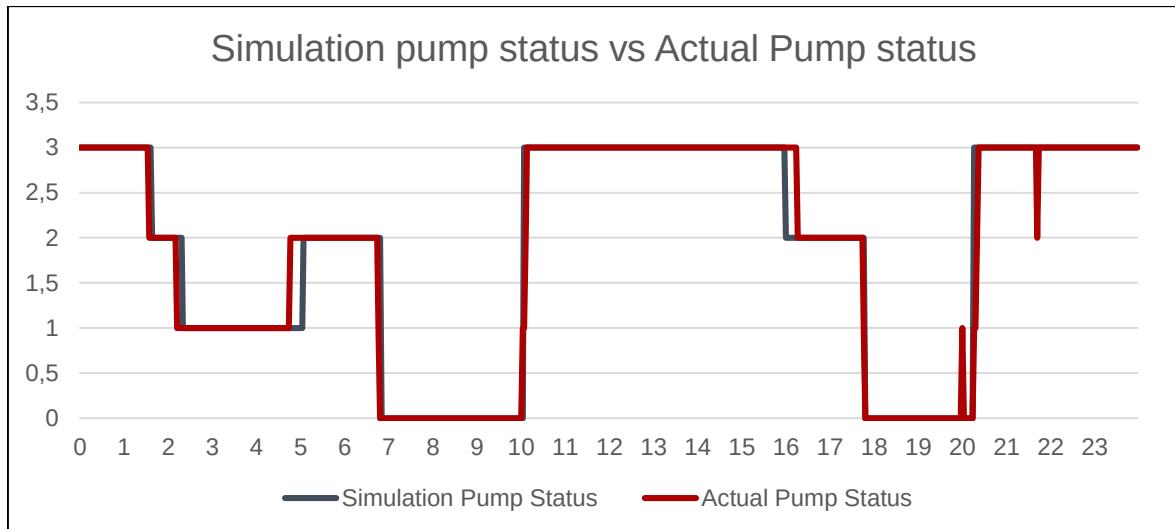


Figure 6-7: Case study C1 – pump status verification

Table 6-20: Case study C1 – 25L status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference Acceptable
1	98	1. Control mechanism reacts in second intervals, whereas the simulation model decision-making is done every two minutes	Yes
2	93		Yes
4	90		Yes
5	95		Yes
6	95		Yes
10	93		Yes
16	91		Yes
17	98		Yes
20	91		Yes
21	99		Yes

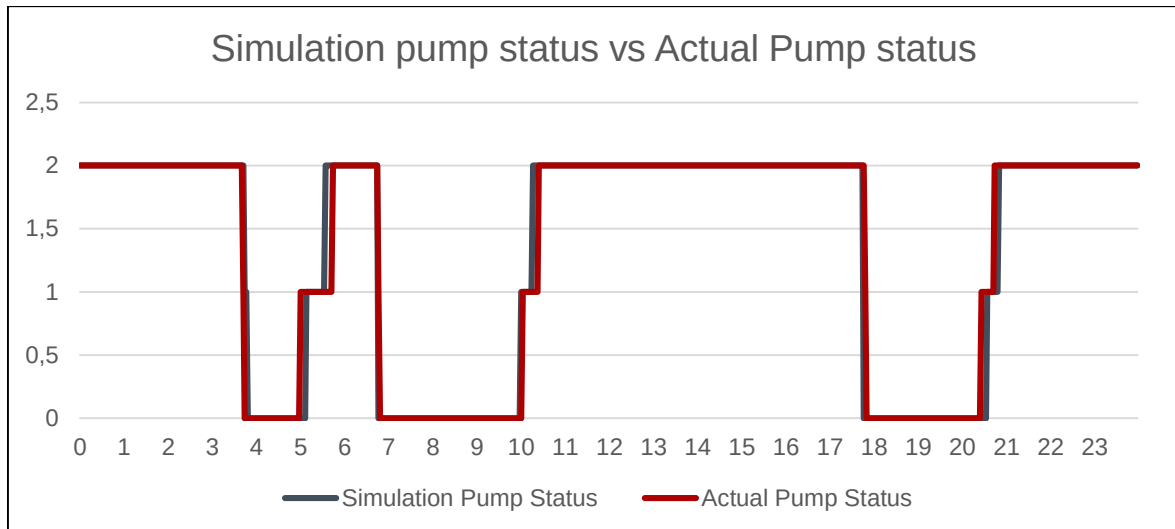


Figure 6-8: Case study C2 – pump status verification

Table 6-21: Case study C – 21L status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference Acceptable
3	92	1. Control mechanism reacts in second intervals, whereas the simulation model decision-making is done every two minutes	Yes
5	78		Yes
6	97		Yes
10	90		Yes
15	95		Yes
17	93		Yes
20	82		Yes

Frequent status change in the 5L (case study C3) control resulted in a weaker status correlation than the status correlation of 25L and 21L. This, however, has been addressed and the simulation model is deemed as accurate enough for this study.

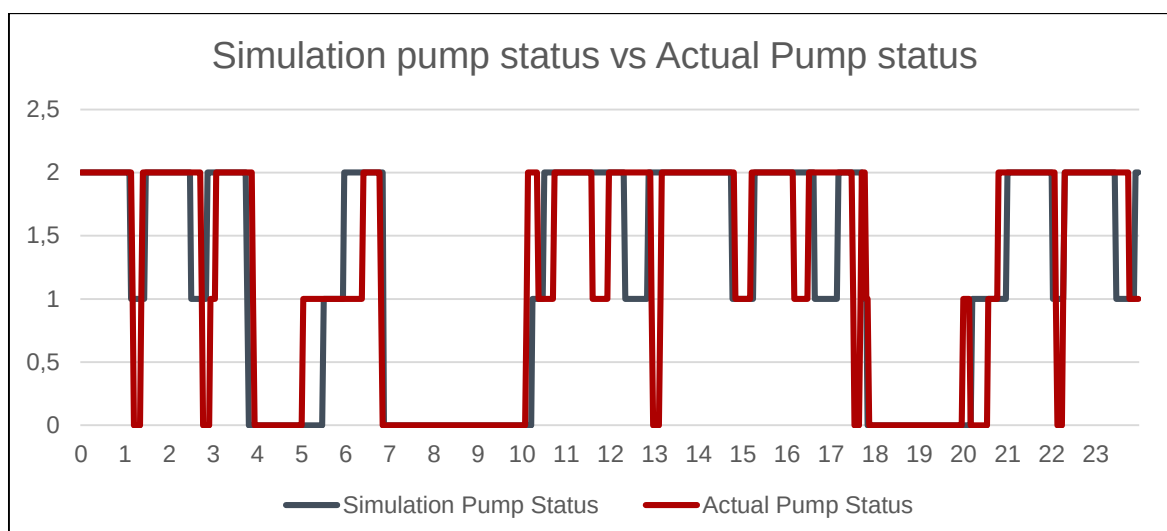


Figure 6-9: Case study C3 – pump status verification

Table 6-22: Case study C – 5L status correlation difference list

Hour	Status correlation (%)	Reason for difference	Difference acceptable
1	78	1. Control mechanism reacts in second intervals, whereas the simulation model decision-making is done every two minutes	Yes
2	70		Yes
3	80		Yes
5	53		Yes
6	73		Yes
10	68		Yes
11	82		Yes
12	72		Yes
13	82		Yes
14	97		Yes
15	97		Yes
16	67		Yes
17	67		Yes
20	38		Yes
21	98		Yes

Hour	Status correlation (%)	Reason for difference	Difference acceptable
22	83		Yes
23	82		Yes

Step 6: Run simulations

Table 6-23: Simulation variations and availability influenced

Simulation variations and availability influenced			
Hourly reduction of availability			
Run no	Availability reduced for:	Run no	Hours
1	00:00 – 00:59	10	13:00 – 13:59
2	01:00 – 01:59	11	14:00 – 14:59
3	02:00 – 02:59	19	15:00 – 15:59
4	03:00 – 03:59	13	16:00 – 16:59
5	04:00 – 04:59	14	17:00 – 17:59
6	05:00 – 06:59	15	20:00 – 20:59
7	10:00 – 10:59	16	21:00 – 21:59
8	11:00 – 11:59	17	22:00 – 22:59
9	12:00 – 12:59	18	23:00 – 23:59
Two-hourly reduction of availability			
Run no	Availability reduced for:	Run no	Hours
19	03:00 – 04:59	21	14:00 – 15:59
20	05:00 – 06:59	22	16:00 – 17:59

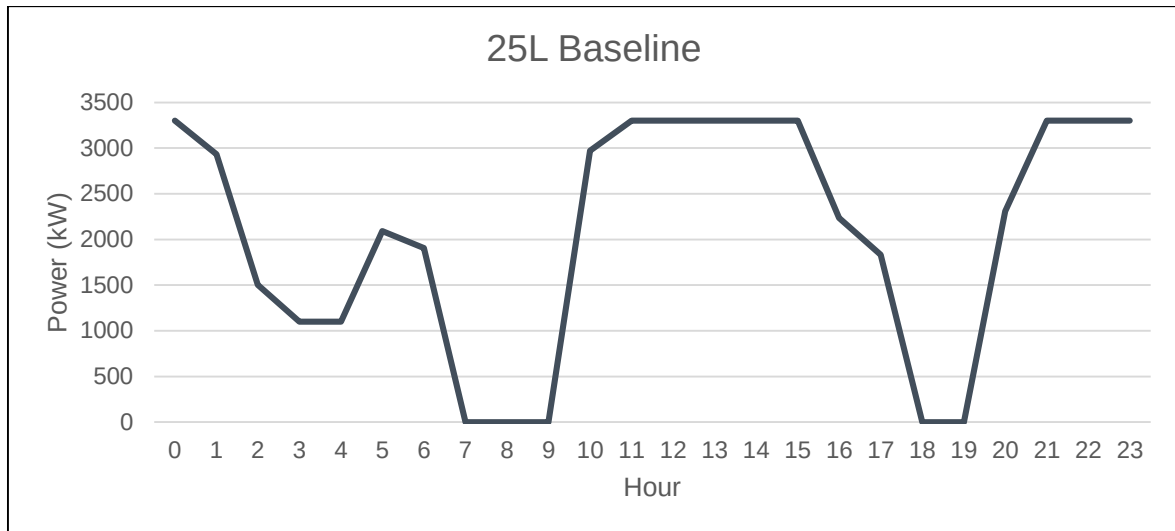


Figure 6-10: Case study C1 – 25L baseline

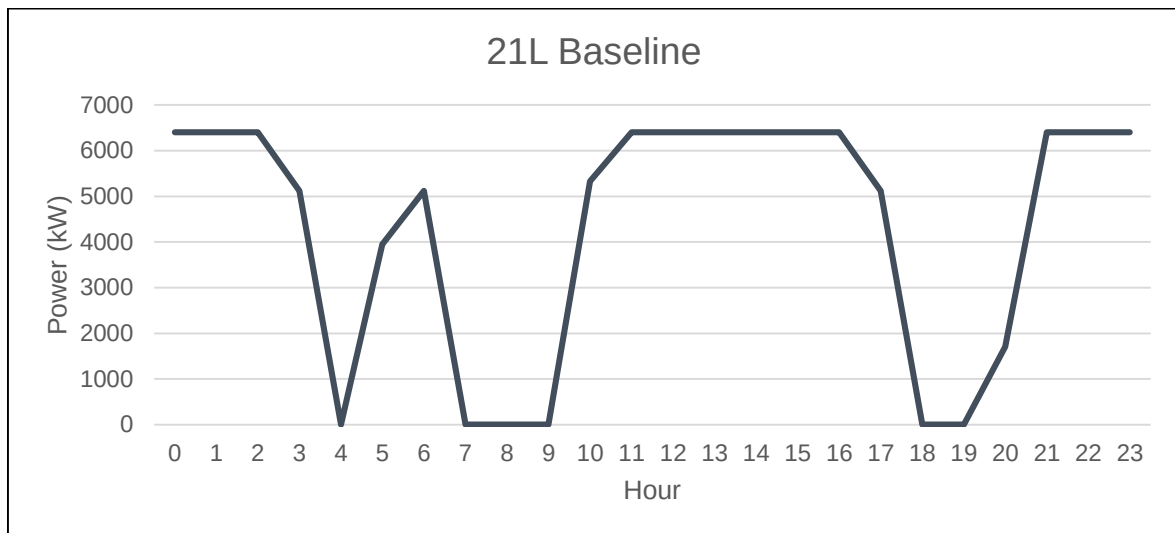


Figure 6-11: Case study C2 – 21L baseline

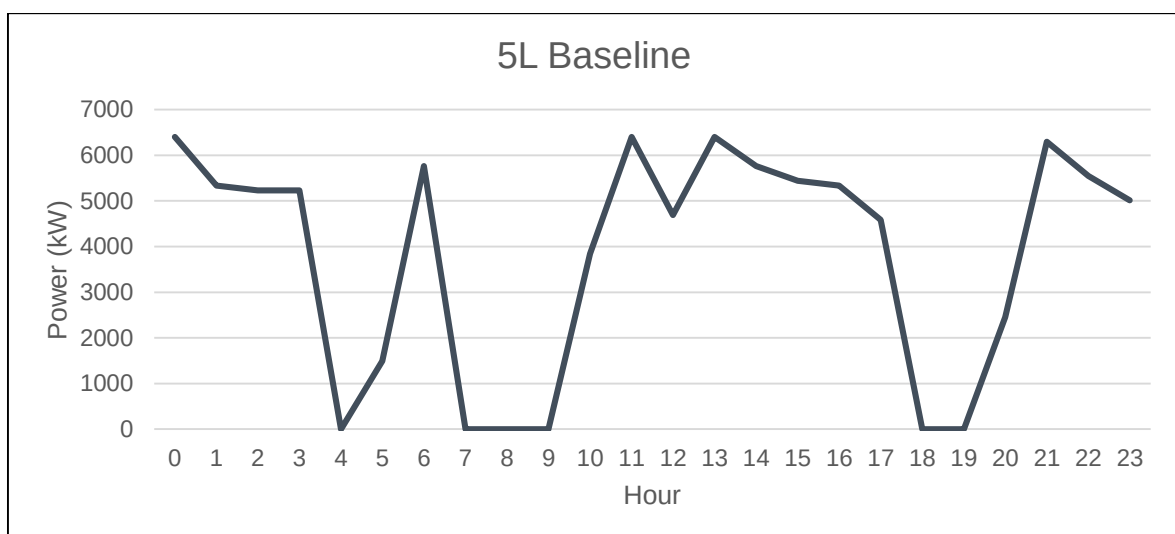


Figure 6-12: Case study C3 – 5L baseline