

Quantifying the cost of load curtailment on mine dewatering systems

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Dissertation accepted in fulfilment of the requirements for
the degree *Master of Engineering in Mechanical
Engineering* at the North-West University

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Graduation: April 2024

ACKNOWLEDGEMENTS

I am delighted to extend my heartfelt gratitude to the following individuals and organisations for their assistance and support throughout the course of this study:

- I extend my sincere thanks to all the mining personnel who generously shared their expertise with me and remained available throughout this endeavour. Your insights were fundamental to the success of this study.
- I am profoundly grateful to ETA Operations (Pty) Ltd for providing both the opportunity and financial support that enabled me to pursue my postgraduate studies.
- My heartfelt gratitude goes out to my study leader, Dr Johan Marais, whose guidance and profound insights were indispensable in shaping the outcome of this research. Your mentorship has been a cornerstone of this study.
- I extend my thanks to Dr Jean van Laar for encouraging me to ask questions and providing me with invaluable feedback. Your support and expertise have been a great asset in this academic venture.
- To my colleagues, I am deeply appreciative of your support, collaboration, and assistance with numerous underground audits.
- I owe a debt of gratitude to my parents, Johan and Annette, for their enduring support, both through my academic journey and in life. Without your unwavering encouragement, the realisation of this study would not have been possible.

Your collective contributions have played a significant role in the completion of this master's dissertation, and I am truly thankful for your support and assistance.

ABSTRACT

Title: Quantifying the cost of load curtailment on mine dewatering systems

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Degree: Master of Engineering in Mechanical Engineering

Keywords: dewatering, load curtailment, demand-side management, cost-efficiency, simulation.

South Africa is experiencing severe electricity supply shortages, leading to rolling blackouts and soaring electricity prices. In response, demand-side management (DSM) measures are crucial to ensure grid stability and to alleviate electricity costs. Alongside load shedding, mandatory load curtailment by key consumers is being enforced during critical periods to alleviate the strain on electricity supply. As a result, mining operations have been significantly impacted by the enforced load curtailment measures.

Mine dewatering systems have long been considered suitable for DSM measures, with load shift away from peak time-of-use easily implemented due to the built-in water storage capacity in the systems. Additionally, pumping systems have been halted for prolonged periods as part of load reduction strategies for Eskom's load curtailment, intensifying the strain on mine dewatering systems. It is, therefore, challenging to find a balance between load reduction, meeting dewatering requirements, and maintaining load shift.

A lack of information regarding the cost of load curtailment on mine dewatering systems presents a significant challenge in devising clear strategies for load reduction and comparing alternative load reduction approaches. Currently, there is no existing model that relates the incidence and duration of load curtailment events to the electricity cost of mine dewatering operations, necessitating an in-depth investigation.

This study aims to quantify the cost of load curtailment on the mine dewatering systems. A method was developed to assess the cost implications under various load curtailment scenarios at mine dewatering systems, involving the creation of a digital twin simulation model of the dewatering system.

The method was implemented at a case-study mine shaft A, located at mining operation 1. The simulation was adjusted iteratively to examine the relationship between load curtailment duration and pumping electricity cost, DSM performance, and meeting dewatering requirements over a 30-day test period.

The case study simulation results revealed that pumps can be stopped for up to 135 hours a month while still meeting dewatering requirements. The cost of electricity for pumping increases with each additional instance of curtailment, totalling R5.52 million in winter and R990 thousand in summer for 135 hours of load curtailment, based on 2023/24 tariffs. Peak pumping is necessary after 32 hours of pump stoppages, and load shift performance declines after that. Nevertheless, the evening load shift project performance remains above the 6.7 MW target, as curtailment often aligns with evening peak periods.

Initiating diesel generators for load reduction costs around R80 000 per hour, totalling R11.4 million over 135 hours. Pump stoppage costs start low but peak at R90 000 per hour after 127 hours in winter. Therefore, it appears that pump stoppages represent a viable load reduction strategy at shaft A for up to 123 hours per month in winter and 135 hours in summer.

The developed method proved effective in determining the cost of load curtailment on mine dewatering systems for any given shaft. The findings of this study will help mining industries to devise more informed strategies for managing load curtailment while ensuring the efficient and cost-effective operation of their dewatering systems.

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LIST OF ABBREVIATIONS

CBL	Curtailment Base Load
DR	Demand Response
DSM	Demand-side Management
DXF	Drawing Exchange Format
EAF	Energy Availability Factor
ESCo	Energy Service Company
EUf	Energy Utilisation Factor
GDP	Gross Domestic Product
kVA	Kilovolt-amperes
kW	Kilowatt
kWh	Kilowatt-hour
MD	Maximum Demand
MVA	Megavolt-amperes
MW	Megawatt
NERSA	National Energy Regulator of South Africa
NMD	Notified Maximum Demand
NRS	National Rationalised Specifications
OCGT	Open Cycle Gas Turbine
PDR	Proxy Demand Response
PF	Power Factor
PLC	Programmable Logic Controller

POD	Point of Delivery
PTA	Peak-to-average
PTB	Process Toolbox
SCADA	Supervisory Control and Data Acquisition
S/V	Sub-vertical
TOU	Time-of-use
US	United States
VFD	Variable Frequency Drive

CHAPTER 1 INTRODUCTION AND LITERATURE STUDY

1.1 Background

1.1.1 Electricity situation in South Africa

Electricity is a fundamental driver of South Africa's economic and social development [1]. It is essential for production and an important determinant for the competitiveness of the country's industrial sector [2], the primary contributor to South Africa's gross domestic product (GDP) [3]. The government's utility company, Eskom, generates, transmits, and distributes electricity across South Africa [4]. Eskom is one of the biggest utilities in the world [5] and generates approximately 95% of South Africa's electricity [6]. Eskom owns and controls the country's grid of high voltage transmission lines, supplying approximately 40% of the electricity directly to consumers and the rest to municipalities [6].

According to Eskom's 2022 Integrated Report, Eskom owns and controls 30 power stations with a total nominal capacity of 47 145 MW [7]. This includes coal power stations, a nuclear power station, diesel-powered open cycle gas turbine (OCGT) peaking power stations, pumped storage schemes, hydro-electric schemes, and wind farms [4]. Coal-fired power stations account for the vast majority (more than 80%) of power generation [8]. South Africa has estimated coal reserves of 50 billion tons in the ground, according to Mineral Council figures [9].

Historically, utilisation of these vast coal reserves and considerable investment in generation and transmission allowed South Africa to reap the benefits of low electricity tariffs [10]. This led to widespread ignorance regarding the risks of excessive energy usage. South Africa subsequently developed an energy-intensive economy, with the electricity intensity more than doubling between 1990 and 2007 [2].

Ongoing economic growth, together with the government's policy to provide affordable electricity to more people, effectuated an increase in electricity demand of 4% per year after 1994 [6]. Between 1994 and 2007, the electricity demand in South Africa increased by approximately 50% [11]. However, insufficient investment in generation and transmission infrastructure between 1990 and 2004 has led to an electricity supply deficit and a drastic decrease in the reserve margin [6]. The reserve margin represents the difference between generation capacity and demand and has decreased from 25% in 2001 [10] to well below the 15% reference margin level suggested by the North American Electricity Reliability Corporation [12]. Demand outpacing supply is causing an energy crisis that threatens the sustainability of the grid and the country's economy overall [6].

Over the last few years, Eskom's run-down coal-generating units have experienced severe breakdowns [13] due to the deferral of critical maintenance for ageing plants, design flaws at the new power stations Medupi and Kusile, and sabotage [7]. The delays in the Medupi and Kusile projects, with a planned capacity of 4 800 MW each, forced unreliable mothballed power stations to be used to keep the lights on [14]. A significant shortfall in generation capacity was experienced due to the numerous unplanned losses in power generation capacity [15]. To protect the system, rolling blackouts, known as "load shedding" and other load reduction measures, have been implemented nationwide since 2007 [16]. These measures are designed to protect the system from a blackout in case of a system emergency [17].

Of particular relevance is the energy availability factor (EAF), the percentage of available generation capacity at any given time. EAF is a good measure of the effectiveness of power plants [18]. South Africa's EAF has seen a steady decrease over the last two decades [1, 15]. The EAF in 2022 was 62,02%, down from 64,19% in 2021 [15], and is well below 60% for 2023 [19]. This means that, in the 2021-2022 financial year, only an average of 29 240 MW was available out of a nominal generation capacity of 47 145 MW. Furthermore, the energy utilisation factor (EUF) of the country's coal plants was 93,98% in 2022, well above the international norm of 75% [15]. This leaves little time for the necessary routine maintenance. Figure 1 shows Eskom power plants' EAF for April 2022 to October 2023 to 2022 [19].

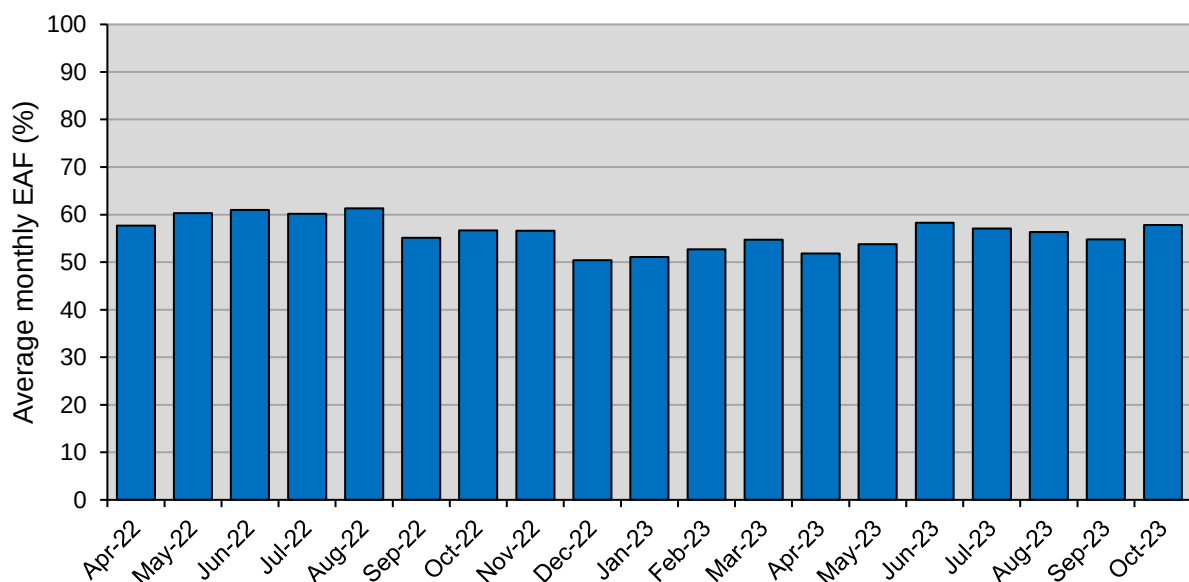


Figure 1: Eskom EAF (adapted from [19])

To alleviate the electricity availability crisis, Eskom uses OCGT peaking power stations to meet the demand during peak times and emergencies [13]. Among conventional plants, OCGTs have

the highest variable (fuel) cost, and overusing them is therefore costly [20]. Continuous unplanned capacity losses forced Eskom to utilise the OCGTs extensively to minimise countrywide load-shedding [13]. As a consequence, the load factor for OCGTs far exceeded regulatory approved volumes, accumulating considerable costs [21]. In 2022, the OCGT load factor was 8,7%, up from 6,9% in 2021 and well above the target of 1% [15].

Eskom revises its tariffs on an annual basis, and from 1988 until 2008, electricity tariffs in South Africa did not keep up with inflation due to the government's policy to maintain low electricity rates to protect impoverished communities [22]. During that time, electricity tariffs increased by 223%, while inflation increased by 335% [22]. However, since 2008, the National Energy Regulator of South Africa (NERSA) approved tariff increases for Eskom that exceeded the inflation rate. These increases were aimed at financing the electricity generation expansion programme. From 2007 to 2022, electricity prices increased by 653%, while inflation only increased by 129% [22]. This means that the cost of electricity quadrupled in real terms during the last 14 years [22]. Figure 2 shows the Eskom tariff increase plotted against the consumer price index for the 2007-2022 period.

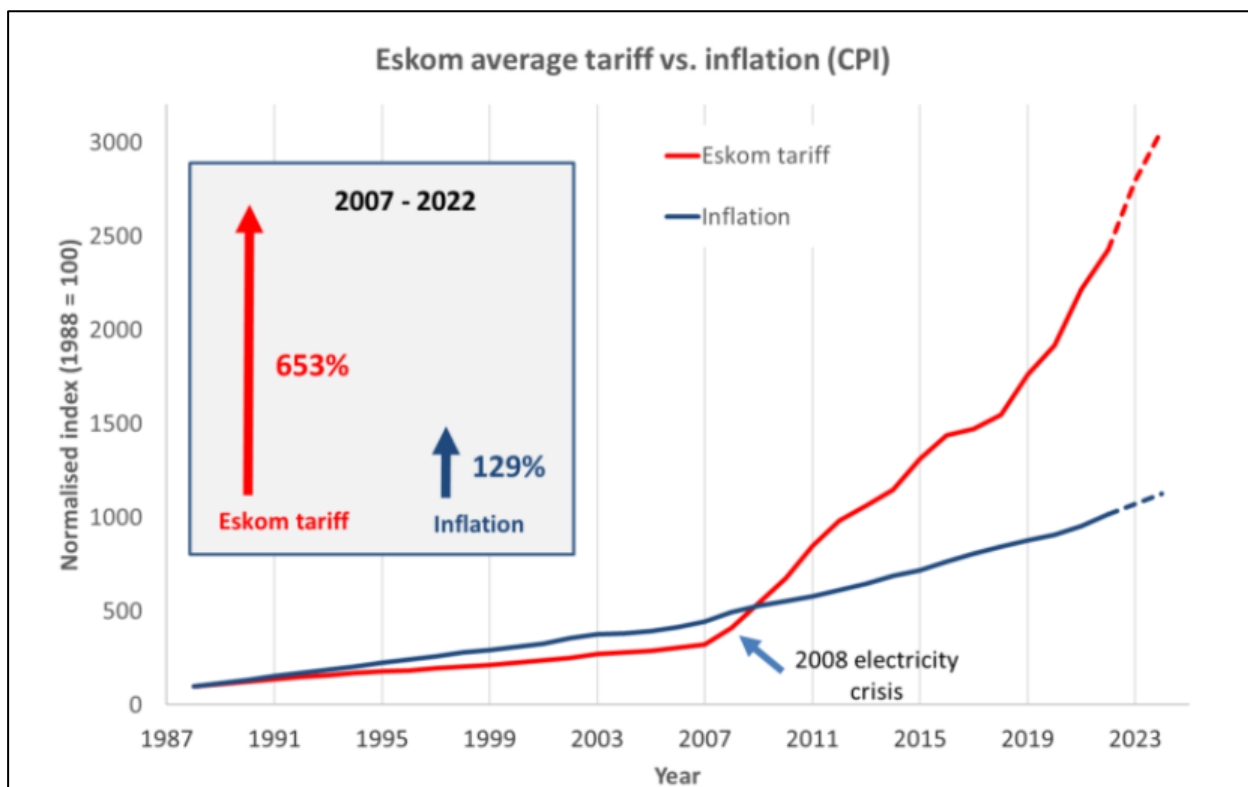


Figure 2: Eskom tariffs versus inflation [22]

The increasing price of electricity, coupled with supply shortages and subsequent load reduction measures, have placed the economy under strain, specifically the industrial sector [8]. Large consumers are especially hit hard and Eskom has warned that despite plans to alleviate the problem, companies can expect load-shedding and load curtailment to continue for the foreseeable future [9]. This has culminated in a full-scale power crisis, classified as a disaster by the National Disaster Management Centre [8]. In the State of the Nation address on 9 February 2023, the government officially declared a National State of Disaster to respond to the energy crisis and its effects [8].

1.1.2 Energy usage in deep-level gold mines

Due to South Africa's abundant mineral deposits, the mining industry has historically been the bedrock of the country's economy and is critical to socio-economic development [23, 24]. South Africa's emergence as the most industrialised nation in Africa began when gold was discovered in the Witwatersrand basin in 1886 [25]. Ever since, mining has played an important role in attracting foreign investment and generating export revenues [23]. Mining and quarrying make up more than 10% of the country's GDP [25] and more than half of its export revenues [26]. Additionally, the mining industry contributes to the economy by means of:

- It provides over 1.3 million jobs and every wage paid by the mining industry supports, on average, an additional ten people [23].
- Mining companies alone pay almost a fifth of corporate taxes in South Africa [23].
- Mining accounts for 29% of the total value of the Johannesburg Stock Exchange [23].

South Africa has 10,5% of the world's gold reserves and 80% of the world's known Platinum Group Metal reserves [25]. According to Ericsson and Löf [27], the value of South Africa's mine production was USD 40.4 billion by the mid 2010's, ranked sixth globally. Even though gold production has decreased significantly over the last few years, South Africa was still the world's tenth largest gold producer in 2021 with 113.6 tonnes mined, comprising 3,2% of the global production [28].

Mining is an energy-intensive industry, especially deep-level mines where water needs to be pumped to surface to prevent flooding and hoists are needed to transport men and materials to underground working areas [9]. South Africa has some of the world's deepest mines, reaching depths of close to 4 km [29]. Virgin rock temperatures of up to 60°C are experienced at the stope faces, necessitating the extensive use of ventilation and refrigeration to maintain a comfortable working environment [29]. In deep-level gold mines, the three major electricity consumers are

pumping systems, refrigeration systems, and compressed air systems [30]. Mining activities accounted for 11,9% of national electricity usage in 2021 according to Stats SA [31]. Electricity represents a substantial portion of the operating costs for mining companies in South Africa, accounting for as much as one-third of their overall costs [9]. In recent years, the increasingly higher cost of electricity has severely damaged the global competitiveness of South African mining companies [32].

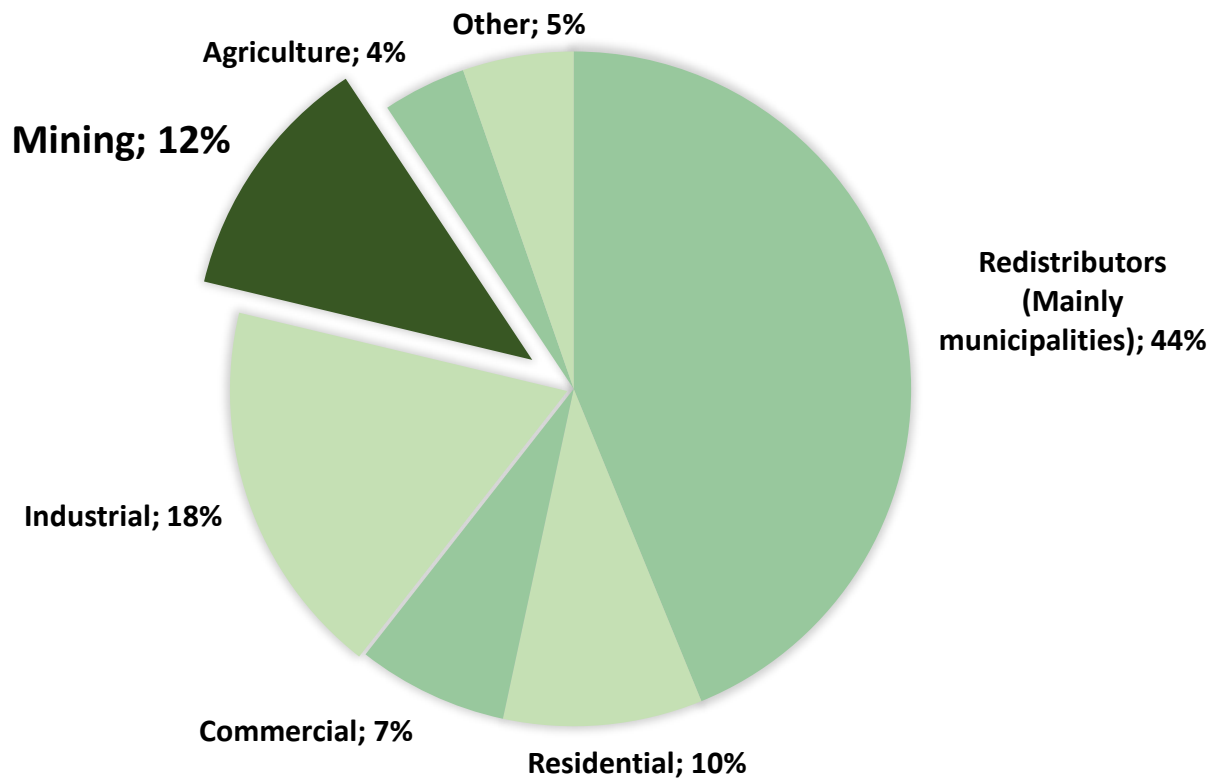


Figure 3: Electricity use by industry (adapted from [31])

The decreasing reliability of Eskom's electricity supply has a significant impact on mining costs and operations [26]. The mining sector is vulnerable to electricity supply interruptions [33]. As a result of the high power demands, most mines do not have the necessary backup generation to keep operations running [9]. Due to safety aspects, most mines will not experience blackouts from Eskom and would rather have arrangements in place for self-reduction of their energy demand [17].

1.1.3 Demand side management (DSM)

1.1.3.1 Need for DSM

Growing concerns regarding global warming and climate change have led to ambitious commitments aimed at integrating renewable energy sources, with the goal of decreasing the energy sector's greenhouse gas intensity [34]. California, for instance, has pledged to achieve 60% renewable energy integration by 2030 and transition to 100% clean energy by 2045 [35]. Similarly, Europe has set its sights on reaching a 45% renewable energy integration target by 2030 and achieving carbon neutrality by 2050 [36].

The incorporation of renewable energy sources, particularly wind and solar generation, has introduced new operational complexities for energy systems due to their intermittent, variable, and non-dispatchable characteristics [37]. These challenges are exacerbated by the limited availability of large-scale energy storage options, resulting in the need to immediately utilise most of the generated energy [38]. Consequently, renewable energy generation leaves significant temporal gaps in energy supply.

Energy utilities have taken steps to address these challenges by encouraging customers to manage their energy consumption during specific periods [39]. Customers can play a crucial role as demand resources by reducing their energy usage during peak demand hours or when the grid experiences significant imbalances [40]. Furthermore, if energy consumers can shift their energy usage to align with periods of high renewable energy generation, they can contribute to increased adoption of renewable energy and subsequently reduce greenhouse gas emissions [41].

South Africa is currently facing an electricity supply crisis that has led to soaring electricity prices and immense pressure on consumers. Figure 4 illustrates the average energy demand profile on a typical winter and summer weekday in South Africa.

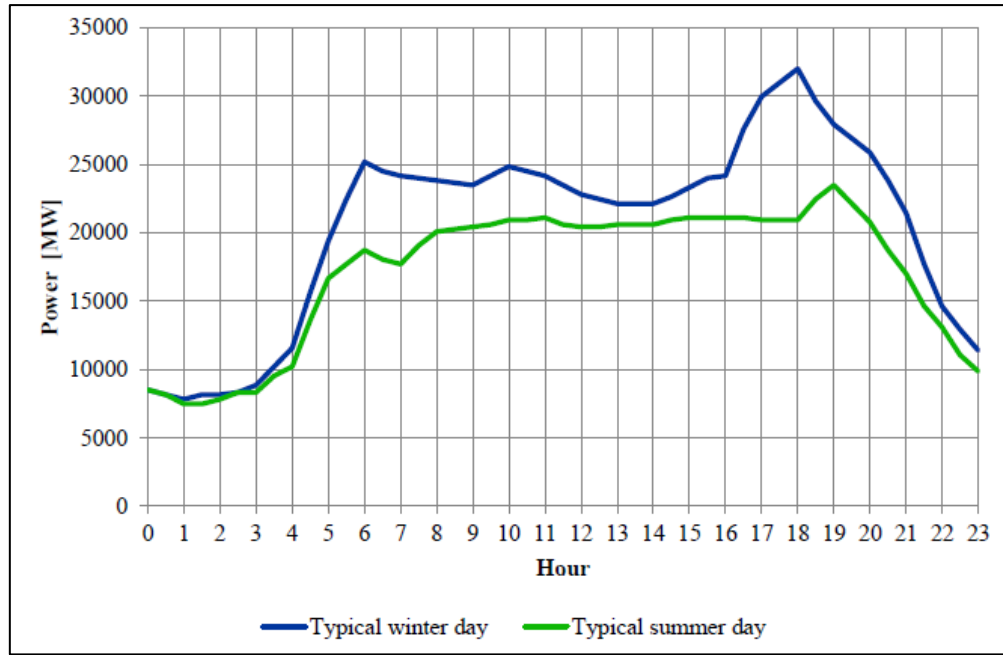


Figure 4: South Africa's typical energy demand profiles

Examining the daily profile depicted in Figure 4 reveals two distinct peaks in energy demand, occurring during the early morning and late afternoon hours. Meeting these peak energy demands has been a challenge for Eskom. Expanding the generation capacity is a lengthy process, as it takes approximately 8 to 10 years to construct a new coal-fired power station [42]. While OCGTs offer a temporary solution, their operational costs are prohibitively high, as discussed earlier. Given the considerable lead times associated with supply-side strategies, alternative solutions have become necessary, leading to the adoption of DSM [43].

Therefore, DSM finds application in response to variable energy supply in both developed and developing regions. In developed countries, its primary function is to counter the intermittent supply of renewable sources, and in developing countries, it is deployed to mitigate the fluctuations in supply stemming from generation shortages. In both these contexts, the effective management of energy demand contributes towards a more sustainable and reliable energy landscape.

1.1.3.2 Tariff structure

In an effort to decrease peak energy consumption, Eskom implements time-of-use (TOU) tariff structures. Large industrial consumers with a notified maximum demand greater than 1 MVA and the ability to do load shift make use of Megaflex TOU. This tariff structure is specifically designed for industries such as mines, which maintain a continuous 24-hour production schedule. The

Megaflex tariff structure charges consumers for three distinct periods: peak, standard, and off-peak, each with its corresponding electricity charges. Furthermore, the cost of electricity also varies based on the day of the week and the season. The winter months, spanning from June to August, are categorised as the high-demand season, whereas the low-demand season spans from September to May. Figure 5 indicates the Megaflex tariff structure's different time intervals.

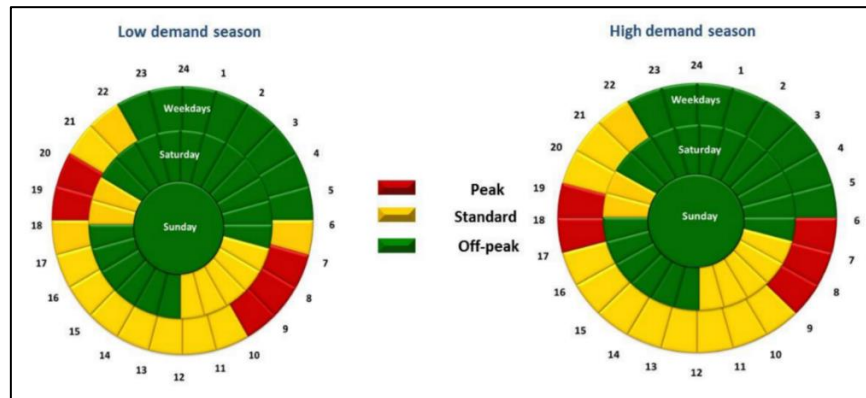


Figure 5: Megaflex TOU tariff structure

1.1.3.3 DSM strategies

DSM, as defined by Arteconi *et al* [44], encompasses the strategic planning, implementation, and monitoring of utility activities aimed at influencing consumer electricity consumption to achieve desired changes in the utility's load profile. DSM involves assessing the feasibility of various measures, devising and executing strategies, and continuously monitoring the system's sustainability [42, 44]. DSM projects provide mutual benefits for both Eskom and consumers by optimising the consumer's electricity usage, reducing subsequent costs, and alleviating the strain on the power grid, particularly during peak hours [45]. Jordehi [46] classifies DSM into two main categories: energy efficiency programmes and demand response (DR) programs. In his review study, DR programs are further classified into incentive-based DR and price-based DR. Figure 6 illustrates this detailed classification of DR programs.

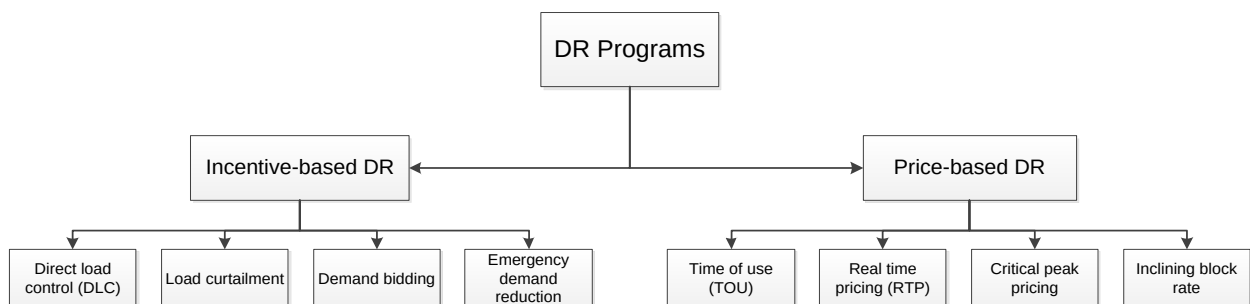


Figure 6: Classification of DR programs (adapted from [46])

In South Africa's incentive-based DR programs, customers enter into agreements with Eskom, offering a portion of their load at specified rates for the purpose of load reduction [17]. By incentivising customers to reduce demand or sell their excess electricity, the utility can optimise energy usage and improve the overall energy management process. These customers can be categorised as Instantaneous DR, Emergency DR, or Supplemental DR participants [17].

Price-based DR entails optimising power consumption according to TOU tariffs and includes load shifting, peak clipping, and maximum demand control strategies [42, 47]. These measures are typically adopted by large consumers such as deep-level mines. A comprehensive description of energy efficiency measures and price-based DSM strategies is presented below.

Energy efficiency

The primary goal of energy efficiency measures is to decrease the average electrical energy consumed by a client within a 24-hour period [48]. This reduction in energy consumption will benefit both the consumer and supplier, as it decreases the demand while also saving the client money. Energy efficiency can be attained by employing more efficient equipment or by optimising the processes to enhance their efficiency [30]. The objective is to achieve the same level of production while utilising less energy [30]. Figure 7 presents the demand profile of a typical energy efficiency DSM initiative in comparison to the pre-DSM baseline.

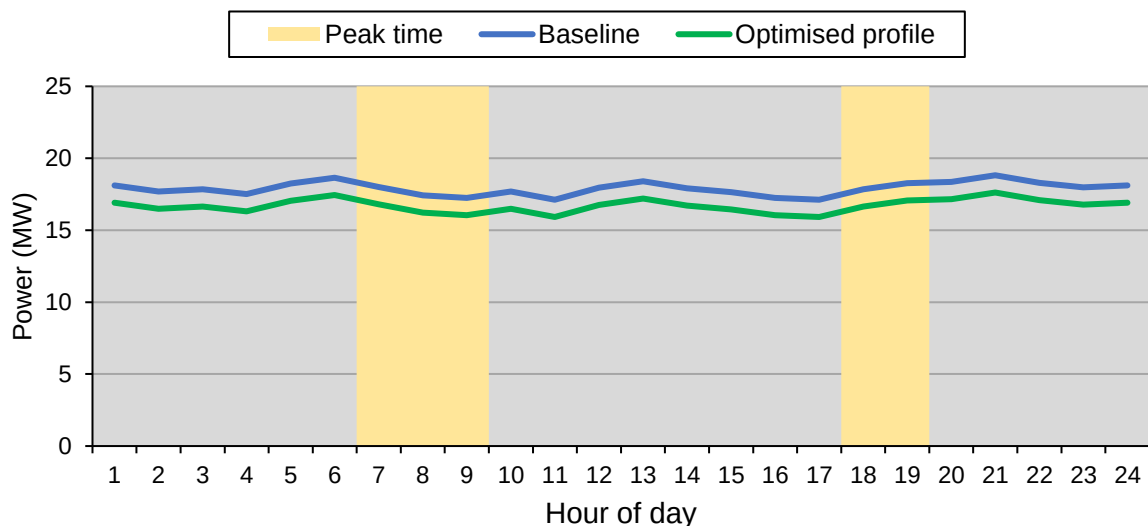


Figure 7: Energy efficiency (adapted from [42])

Load shifting

Load shifting initiatives gained prominence after Eskom introduced the TOU tariff structure. This tariff structure served as a motivation for users to reduce their energy consumption during high-cost peak hours, leading to the emergence of load shifting strategies. The objective of load shifting is not to decrease the overall energy consumption, but rather to shift the demand from peak periods to times when the demand is lower and tariffs are more affordable [49]. By strategically redistributing the energy demand, clients can achieve cost savings, while suppliers can benefit from improved load management during peak times [42]. Therefore, load shifting has become an effective approach for optimising energy usage and mitigating peak demand challenges. Figure 8 presents a demand profile demonstrating a morning and an evening load shift.

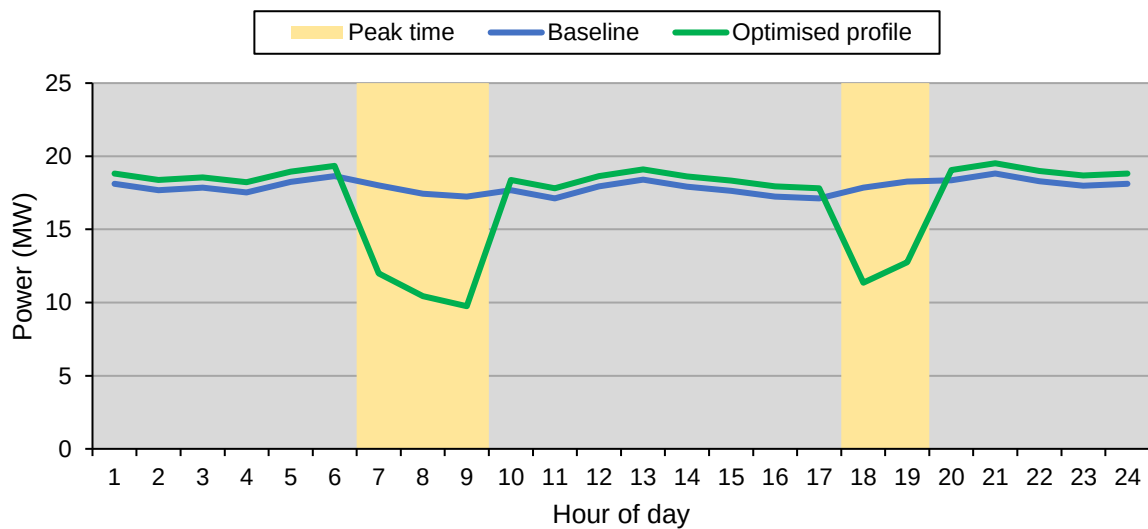


Figure 8: Load shifting (adapted from [42])

Peak clipping

Peak clipping is a strategy aimed at reducing a client's energy demand only during peak TOU periods. This approach involves temporarily switching off a process or system, which may result in a decrease in production [30]. By curtailing the electrical demand during peak periods, clients can achieve cost savings by using less energy. It is important to note that peak clipping differs from load shifting, as the reduced loads during peak periods are not shifted to other times of the day [45]. Figure 9 presents a demand profile demonstrating a 3 MW average peak clip during the evening peak TOU period.

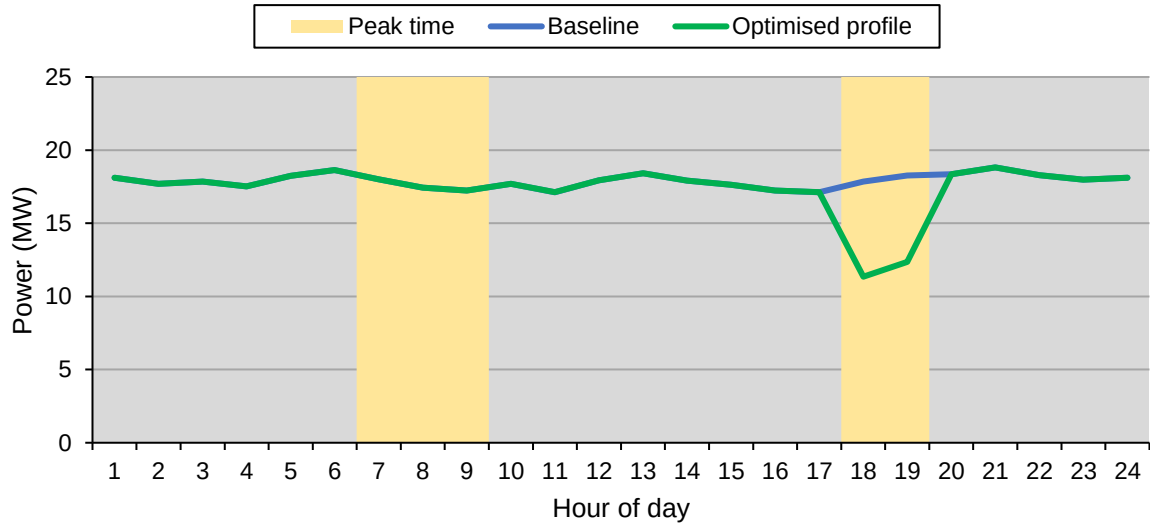


Figure 9: Peak clipping (adapted from [42])

Maximum demand control and power factor correction

Eskom applies charges to customers based on their maximum energy demand (expressed as apparent power in kVA), which significantly contributes to the utility bills of industrial facilities, accounting for approximately 35% or more of their total electricity costs [50]. To manage these costs effectively, implementing energy management techniques can prove valuable, particularly when consistently high maximum demand (MD) is observed [50]. MD is closely linked to the power factor (PF), because poor PF control results in an elevated MD. This is shown in Equation 1.

$$P_{real} = PF * P_{apparent} \quad (1)$$

Where: P_{real} = Real power [kW]

$P_{apparent}$ = Apparent power [kVA]

PF, defined as a measure of electrical power efficiency, ranges between zero and one, with a higher value indicating greater energy conversion efficiency [50]. Rectifying or improving low PFs can be achieved by introducing capacitors to low PF consumers to offset their reactive effect [51].

By achieving a PF closer to one through correction measures, significant savings in maximum demand can be realised [50]. Bokaba [50] advises that, in cases where the PF falls below 0.9, it is advisable to explore the installation of PF correction equipment, aiming to optimise energy conversion and lower reactive charges associated with maximum demand.

1.1.3.4 Load curtailment

In addition to the aforementioned demand response and DSM strategies, mandatory emergency load reduction measures are implemented when the available power system capacity falls short of meeting the demand [17]. These emergency load reduction measures may take the form of load shedding, load curtailment, or a combination of both [17]. Load shedding involves scheduled supply interruptions, affecting customers on a rotational basis [17]. Load curtailment is an option available to certain, typically larger, consumers who commit to reducing a predetermined load within a two-hour notice period, sparing them from being subject to load shedding [17]. Most mining operations belong to this category.

Load curtailment is essentially a self-imposed reduction in electricity consumption by customers, carried out in response to directives from the system operator. Unlike voluntary load reduction initiatives within a DR program, load curtailment does not involve financial compensation [17]. Importantly, it grants large consumers the autonomy to choose how to reduce their energy demand. By reducing electricity usage during emergency periods, load curtailment helps maintain grid stability, alleviate strain on the power system, and mitigate the impact of electricity supply shortages.

Load curtailment comprises four levels: for stage 1 and 2, a 10% reduction in power is required, stage 3 takes 15% of power, and stage 4 takes 20% [17]. The baseline for achieving these reductions is calculated using the method specified by the national rationalised specifications (NRS) [17]. To determine the Curtailment Base Load (CBL) profile for each day of the week, historic demand consumption is considered [17]. An average daily demand profile is established using the half-hourly averages of past days with similar demand profiles [17].

During the load curtailment period, the customer's actual load profile is compared with the relevant CBL [17]. The difference between the two profiles is used to determine an average percentage reduction, which is then compared to the targets for the applicable load curtailment stages [17]. Load curtailed is calculated by subtracting the actual load from the CBL for the duration of the load curtailment period [17]. For each load curtailment occurrence, the CBL is adjusted proportionally to align with the actual load [17]. Figure 10 illustrates a typical power profile with CBL scaling.

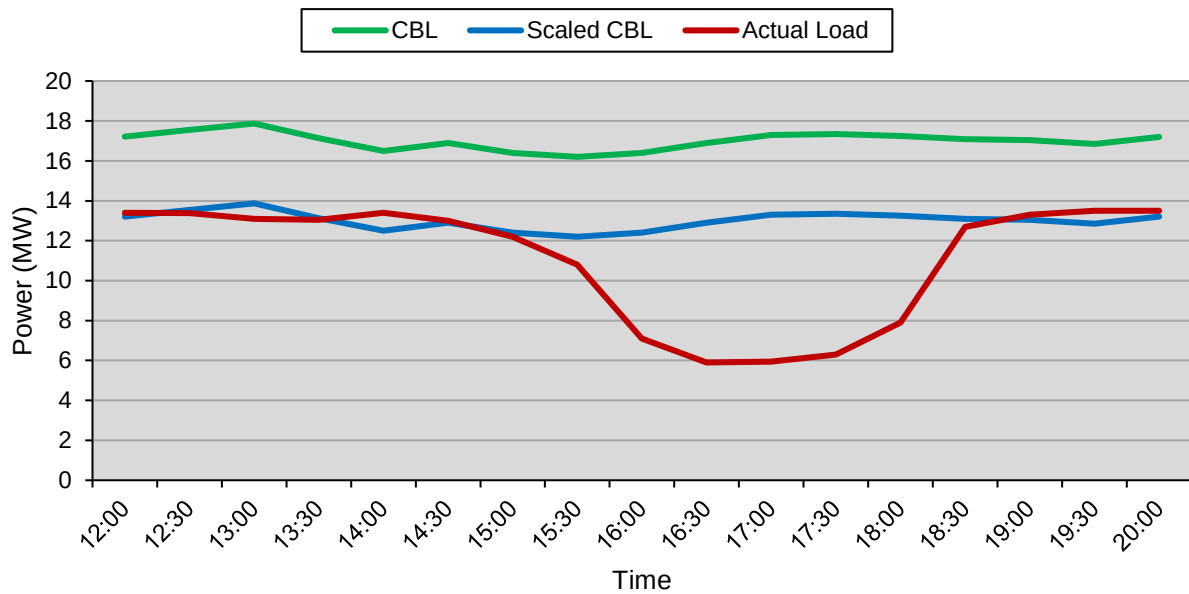


Figure 10: Curtailment baseline measurement (adapted from [17])

1.1.3.5 Eskom DSM Projects and the ESCO model

Small DSM projects have been funded by Eskom since 1994 [48]. In the last quarter of 2002, Eskom began supporting larger DSM projects that require significant capital expenses in collaboration with registered energy services companies (ESCOs) [52, 53]. ESCOs play a crucial role in implementing energy saving initiatives in South Africa [54]. ESCOs typically implement energy efficiency, peak-clipping, and load-shifting projects, which are funded through Eskom's DSM program [55].

Under the ESCo model, these ESCOs are contracted to achieve and sustain energy savings targets for a three-year period divided into 12 three-month performance assessment periods [42, 56, 57]. To secure funding from Eskom, an ESCo must submit a proposal for a potential electricity cost savings project with a savings potential of more than 100 kW [30].

Ensuring the long-term savings of DSM projects is crucial. ESCOs play a vital role in ensuring that the necessary maintenance is done on DSM projects to ensure sustainability. Under the current model, ESCOs have to sustain DSM projects for five years after implementation [58], during which time continuous performance assessments are conducted.

1.1.3.6 DSM applications on mine dewatering systems

The mining industry, due to its substantial electricity consumption, offers significant potential for DSM initiatives [59]. The supply of chilled water for mining and cooling purposes necessitates continuous dewatering to prevent flooding. Appendix A provides comprehensive information on mine dewatering systems, including detailed descriptions of components and control mechanisms. Energy systems that possess high levels of energy load flexibility are ideally positioned to serve as demand resources [60]. Amongst the various systems at a mine, the dewatering system stands out as a prime candidate for DSM interventions [61]. Dewatering systems can cease pumping for extended periods when sufficient water storage capacity is available. Within dewatering systems, two distinct DSM initiatives are commonly implemented, namely water supply optimisation and pumping load shift.

Water supply optimisation involves the reduction of the amount of water sent underground for mining operations [45]. At the shaft bottom of a mine, fissure water and service water accumulate and need to be pumped out. Although the rate of fissure water inflow cannot be reduced, optimising the water volume sent underground can reduce the volume of water to be pumped out and subsequently decrease electricity consumption [45]. This optimisation process often includes the installation of control valves on chilled water columns supplying each mining level, resulting in reduced water flow [45, 62]. Studies have shown that the water consumption of a deep-level gold mine in South Africa can be reduced by 7% to 30% through water supply optimisation [63].

Pumping load shift, where pumping is stopped during peak TOU periods, is another commonly implemented DSM measure within mine dewatering systems [64]. Successful implementation of pumping load shift initiatives requires adequate infrastructure, including pumps, columns, and dam capacity [65]. Hot water dams, situated on pumping levels, store water during peak periods, enabling pumps to be switched off [45]. To ensure proper implementation of a pumping load shift initiative, dam preparation is crucial. Dam preparation involves emptying hot water dams during off-peak periods so that they are close to their minimum level when peak TOU starts, preventing overflow when pumping is stopped.

1.2 Literature Study

DSM initiatives are implemented worldwide across various countries and sectors, each with its own distinct motivations, incentives, and challenges. This chapter aims to explore previous work done on the implementation of DSM in diverse environments, with a specific focus on the encountered challenges and the strategies employed to mitigate them.

The chapter will examine real-world examples of energy management initiatives in different countries, highlighting the driving factors behind their adoption and the barriers faced during implementation. Initially, a comprehensive overview of load management implementation across various sectors will be presented, with particular emphasis on the industrial sector, which accounts for a significant portion of energy consumption [50]. Additionally, a more focused investigation will be conducted into contemporary energy management practices in the mining sector, specifically addressing mine dewatering.

The unique energy landscape in South Africa presents its own set of challenges, including severe electricity supply shortages and industrial load curtailment. Therefore, this study will delve into current DSM strategies and solutions specifically tailored for the South African context. Finally, the chapter will explore previous approaches and current methods for quantifying the performance of DSM projects and measuring the impact of constraints. Figure 11 outlines the layout of the literature study.

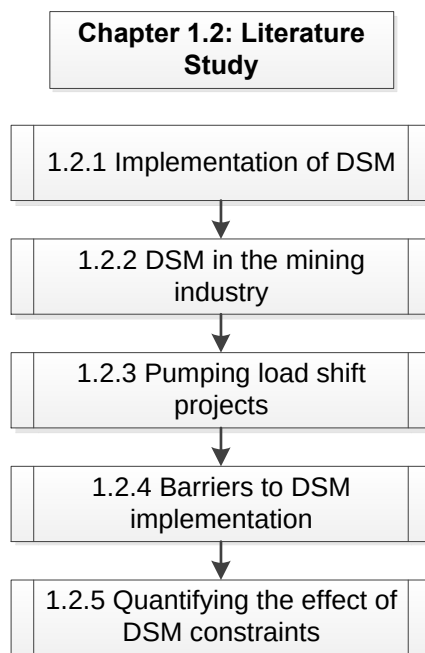


Figure 11: Literature study layout

The aim of this chapter is to provide an overview of the existing literature pertaining to DSM in general, and constraints to its application, with a particular focus on addressing energy supply variability. To achieve this, a systematic literature review approach is employed [66]. The identification of relevant literature was carried out through targeted keyword searches, including terms such as "demand-side management," "mine dewatering," "load curtailment," "pumping load shift," and "cost-efficiency." Google Scholar served as the primary search engine for this purpose.

The relevance of each study was determined based on the information provided in its title and abstract. Full-text studies were then thoroughly reviewed to assess their suitability for inclusion in the literature review, as well as to identify any additional literature requirements. In the selection process, a preference was given to books and journal articles published by reputable publishers, as these sources typically represent high-quality research. From the final set of literature that was considered for this review, the most pertinent articles and studies were synthesised in a state of the art table, presented in section 1.2.6.

1.2.1 Implementation of DSM

Global energy demand is experiencing significant growth due to the growing population and industrial advancements, with fossil fuels currently accounting for approximately 80% of supply [67-69]. DSM initiatives are implemented worldwide across various sectors to address the increasing global energy demand and promote sustainability. Motivated by environmental concerns and the need to reduce greenhouse gas emissions in accordance with the Paris Agreement, many developed countries prioritise energy usage reduction [70]. Globally, DSM is employed to mitigate the impact of electricity supply shortages, ensure grid stability, and accommodate the variability of renewable energy sources [71]. Moreover, energy efficiency initiatives through DSM enhance the profitability and competitiveness of companies.

Numerous studies have examined the implementation of DSM in different environments. For instance, in the United Kingdom, energy efficiency initiatives targeting industrial sectors such as iron and steel and food and drink industries have shown potential for a 38% reduction in CO₂ emissions [72]. In Sweden, successful DSM implementation in the industrial sector has been attributed to combining energy efficiency technology with effective energy management practices [73]. Similarly, research in Latvia has identified significant load shift potential in the household and industrial sectors, further supporting the adoption of DSM [74].

Within the South African context, DSM plays a critical role due to energy supply shortfalls and high electricity costs. Energy management techniques such as maximum demand control, load

shifting, energy-efficient equipment, PF control, and process optimisation have been identified as effective strategies in the industrial sector [75]. DSM initiatives also focus on commercial buildings, where studies have shown they account for a substantial portion of energy consumption [76, 77]. Implementation of energy management practices in buildings in Italy, China, and South Africa have successfully resulted in reduced energy consumption [78-80].

DSM initiatives extend beyond buildings and industries. Pumping schemes, such as the Usuthu-Vaal water distribution scheme in South Africa, have implemented load shifting measures to achieve substantial energy savings [81, 82]. Moreover, DSM strategies have been effective in improving the profitability of marginal cement grinding plants [83, 84]. Compressed air systems in industrial settings have also benefited from local energy benchmarking methodologies, resulting in significant reductions in energy demand [85]. Furthermore, a study conducted in Northern Ireland [86] explored load shifting for cascade heat pumps coupled with thermal energy storage. The research demonstrated that by strategically shifting the operation of cascade heat pumps to off-peak periods, lower running costs (16-34%) and reduced carbon emissions (20-37%) could be achieved.

These examples demonstrate the global implementation of DSM initiatives across various sectors and countries. Through energy efficiency, load shifting, and effective energy management practices, DSM provides a viable solution to address energy challenges and promote sustainable energy usage.

1.2.2 DSM in the mining industry

Several studies have explored the implementation of DSM in the mining industry, highlighting its potential for energy savings and cost reductions. These studies focused on different aspects such as water reticulation systems, processing plants, refrigeration systems, and conveyor systems.

Jordaan and Van Rensburg [87] identified DSM opportunities in the South African precious metals industry, specifically in gold and platinum plants. Their research revealed that load shifting was feasible in large mills on carbon in pulp gold plants, reducing peak demand without compromising production. Mulder [88] demonstrated the potential of reviving redundant DSM projects in the mining industry, emphasising the attractive energy savings and cost reductions achievable through the reinstatement of neglected projects. Similarly, Van der Merwe [54] investigated strategies to revive old DSM mine pumping projects, focusing on developing sustainable project strategies under the new ESCo model. This study delivered positive results and achieved significant savings. Additionally, Pelzer [59] developed a tool for achieving maximum DSM results

in deep-level South African mines, particularly in complex multi-level pumping systems. Simulations from this study showed that energy management initiatives could significantly reduce the evening peak demand.

Semenov [89] implemented energy-saving measures in electric drive and power supply systems at Russian mining enterprises, resulting in significant annual savings of 9 million Rubles. Efremenko [90] utilised artificial neural networks for accurate short-term power consumption forecasting at coal mines. Machalek [91] demonstrated the value of DSM in mineral processing as a grid asset. By optimising dewatering and product transport systems through load shifting, substantial savings of US \$570,000 and US \$180,000 were achieved in two separate cases respectively.

Notably, research has been conducted on deep-level mine refrigeration systems. Schutte [92] investigated the possibility of implementing DSM at a cascade mine surface refrigeration plant, emphasising the potential for load shifts during the evening peak period. The study demonstrated that a 4.2 MW load shift is achievable, highlighting the effectiveness of DSM in refrigeration systems. Similarly, Van der Bijl [93] developed an innovative approach for sustainable DSM on deep-level mine refrigeration systems. By utilising mathematical models and automated control software, the energy management of the refrigeration system was optimised for load shift purposes. The study showcased the significant potential of automated and optimised control in reducing demand during peak periods and achieving electricity cost savings for mining operations.

Water reticulation systems also offered potential for DSM interventions. A study conducted at deep-level South African gold mines [94] suggested reconfiguring the mine's water reticulation system. By replacing cooling cars with centralised bulk-air coolers, the study achieved significant energy and cost savings over a 24-hour period. Van Niekerk [30] successfully demonstrated the feasibility of DSM interventions at dewatering systems in marginal mines, exemplified by a load shift project that achieved a payback period of less than two years. Another study by Marais [95] analysed the DSM opportunities in conveyor systems of South African coal mines. By utilising simulation models, the study demonstrated that implementing load shifts in conveyor systems can lead to substantial cost savings for mining operations.

These studies collectively highlight the value of DSM in the mining industry and its potential to address energy challenges effectively. Through the adoption of energy-saving measures, including forecasting techniques, automated control software, reconfiguring water reticulation system, and VFDs, mining enterprises can achieve substantial energy savings, reduce costs, and

contribute to grid stability. The successful implementation of DSM measures in the mining sector showcases its effectiveness as a sustainable energy management strategy.

1.2.3 Pumping load shift projects

Various studies demonstrate the effectiveness of pumping load shift as an efficient DSM strategy. A study by Van Staden [96] focused on a water purification plant in Tshwane municipality where a closed-loop optimal control strategy was implemented, reducing the TOU energy costs by 1,81% and the MD costs by 3,94%. Zhuan and Xia [97] proposed a Reduced Dynamic Programming Algorithm for optimal scheduling of a pumping station. This method resulted in significant reductions in operational costs compared to conventional control strategies at a water purification plant in South Africa.

Research by Musabandesu [34] highlighted the load shifting potential of wastewater treatment plants, where the Laguna plant in Santa Rosa, California achieved up to 4,8% energy cost savings while maintaining effluent water quality. The plant participates in a proxy demand response (PDR) program, utilising its flexibility to compensate for temporal gaps in supply caused by renewable sources. The study emphasised the importance of accurately timing reduction periods and adjusting baseline calculations to develop a cost-benefit model. According to this model, the facility could save US \$68 344 annually through its participation in the PDR program and load shift savings.

In addition to municipal applications, pumping load shift projects have proven beneficial in mine dewatering systems as well. Prinsloo's [98] work on energy cost optimisation at Elandsrand mine, as part of Eskom's DSM initiative, serves as a noteworthy example. The pumping system was analysed and simulated, whereafter the pumping system was fully automated and remotely controlled within certain constraints. An average load shift of 3.66 MW was achieved over a five-month period, resulting in an average monthly cost saving of R60 000. This is a demonstration of the success and viability of load shift initiatives in mine dewatering systems.

However, as Oberholzer [99] discovered, pump failures due to overheating and cavitation can present significant barriers to successful DSM implementation. In response, the author sought to enhance pump automation procedures by developing revised system control parameters, ensuring that pumps operate within their design specifications. Such improvements are essential for the long-term sustainability and effectiveness of pumping load shift projects.

Building upon existing advancements, Cilliers [42] further refined the pumping load shift approach by focusing on reducing preparation and comeback loads around peak times. The development

of a step-by-step control technique led to substantial cost savings on dewatering systems. This approach involves dynamically adjusting the control ranges of underground dam levels, in contrast to the conventional method of using a fixed control range and has proven to be more cost-effective.

These studies showcase how load shift projects can be effectively integrated into existing infrastructure, yielding tangible economic benefits while also contributing to the broader goals of sustainable energy management.

1.2.4 Barriers to DSM implementation

All systems encounter operational factors that can impede the adoption of DSM strategies. Barriers to the adoption of energy management measures in industry can be broadly categorised into economic, behavioural, and organisational factors [100, 101]. Cagno et al. [102] extended this categorisation and identified a more comprehensive list of barriers. This includes technology-related, organisational, information-related, economic, behavioural, market-related, competence-related, awareness-related, and government/politics-related barriers.

Numerous studies have acknowledged and highlighted these constraints and barriers in the successful implementation of DSM strategies. It is crucial to recognise and address these challenges to ensure the effective adoption of energy-efficient practices and DSM initiatives in various industries and systems.

In a study by Johansson and Thollander [73] on efficient DSM implementation in the Swedish industrial sector, a case study approach involving approximately 300 semi-structured interviews was used. The findings revealed several key barriers and success factors. The most significant barriers were identified as 'Other priorities for capital investments' (behavioural), 'Lack of time or other priorities' (organisational), 'Technical risk such as risk of production disruption,' and 'Lack of access to capital' (both economic). These barriers were consistently rated as highly important by the majority of the companies studied.

When considering mine dewatering systems, unique challenges emerge, and several studies have delved into identifying the most pertinent barriers. Many of these barriers are directly related to the operational nature of dewatering systems. For example, a study conducted by Van der Merwe [54] underscored that the water requirements of gold plants and the need to control plug dam levels for maintaining water quality were major barriers in the specific mining systems investigated. Similarly, Van der Bijl [93] emphasised the importance of infrastructure requirements, particularly dam capacities, as a significant constraint.

Mitigating these internal barriers often involves upgrading the mine's infrastructure or implementing effective water supply management techniques. These steps can help alleviate some of the limitations to DSM implementation within the mine's operational framework. However, it's important to acknowledge that external factors unrelated to system operation can also jeopardise successful DSM initiatives. These external challenges are often more complex and harder to manage effectively. An example of such external barriers is the behavioural challenges identified by Van Niekerk [30], where marginal mines with smaller systems were not prioritised for DSM due to the perceived low savings potential.

In the South African context, one of the most critical factors posing a significant barrier to successful DSM initiatives in mine dewatering systems is energy supply shortages. With the country facing intermittent power supply issues and energy constraints, mining operations are particularly susceptible to disruptions, affecting not only production but also the implementation of energy-efficient practices. Load curtailment measures enforced by Eskom put immense strain on dewatering systems, making it extremely challenging to implement normal load shift strategies, resulting in elevated electricity costs.

The aforementioned studies identified the risks and barriers in DSM implementation but did not quantify their effect. To implement effective DSM strategies, it becomes essential to not only recognise these barriers but also to assess their impact on the overall energy management efforts in mine dewatering systems. Understanding the magnitude of these challenges will enable stakeholders to prioritise their responses and allocate resources accordingly, ensuring a more efficient and targeted approach to DSM implementation.

1.2.5 Quantifying the effect of DSM constraints

Previous studies have examined and quantified the effect of electricity supply shortages and other barriers on successful DSM implementation. For instance, Bothelo [103] developed a general equilibrium model to estimate the effects of power system rationing on overall GDP and consumer welfare. By applying mainstream economic theory, a relationship between GDP and power supply was established. The approach followed in this study is applicable for estimating the costs related to various types of infrastructure failures associated with restrictions on production.

However, the focus of Botelho's study was primarily on assessing the overall macroeconomic impact of electricity supply shortages and did not specifically quantify the effects on particular systems or industries. Furthermore, DSM performance was not considered as a parameter in the cost analysis, and simulations of different scenarios were not conducted.

Similarly, Allcott [104] estimated the effects of 2012 electricity supply shortages on Indian manufacturers. Simulations were used to analyse input choices, revenue, and productivity, revealing a reduction of five to ten percent in average plant revenues and producer surplus. Notably, plants without generators were the most severely affected. However, this study primarily focused on the impact of poor electricity supply on business growth and did not specifically address DSM implementation. Moreover, it did not consider DSM performance in its analysis.

Fisher-Vanden [105] used data from 23 000 Chinese firms in 11 industries to examine how they responded to severe power shortages in the early 2000s. The study found that Chinese firms invested in energy-efficiency improvements and explored options such as self-generation and outsourcing the production of energy-intensive, intermediate goods. The study used an empirical model to analyse the data and determine the effect on unit production costs. It was found that from 1999 to 2004, companies experienced an eight percent increase in costs, mainly attributed to input factor substitutions.

A study conducted by Walsh [106] aimed to estimate the historical economic cost of load shedding in South Africa. It utilised a classical linear regression model and estimated that load shedding cost the South African economy approximately R35 billion over a period from 2007 to 2019. While this study looked at the economic cost of load shedding across various industries, including mining, it did not focus on specific systems like mine dewatering systems. It made use of an econometric approach to find the historical relationship between incidents of load shedding and the impact on quarter-on-quarter GDP growth. Load curtailment was included in the 'power not served' calculation for this study, indicating the magnitude of a load shedding event. Furthermore, it only considered short-term impacts and estimated the cost of unserved energy at R9.53/kWh.

These studies provide valuable insights into the economic impact of electricity supply shortages and related challenges. However, when it comes to DSM implementation in mine dewatering systems, more targeted research and analysis are required to understand the specific effects of these barriers and optimise energy management efforts effectively.

Recognising the importance of maximising DSM cost savings, a study by Pelzer [64] focused on quantifying the cost effect of non-performing DSM projects. The study delved into investigating the issues associated with DSM sustainability, particularly technical problems leading to project failure. Key factors contributing to the failure of DSM projects included control system malfunctions, changes in communication networks, alterations to operational environments, process changes, and conflicting priorities. These barriers resulted in R3.7 million potential cost savings being lost at a case study in less than 18 months. To address these challenges, the study

emphasised the importance of maintaining DSM projects for their long-term effectiveness and financial benefits.

Stols [45] aimed to quantify the effects of system constraints on the electricity cost of dewatering pumps in DSM initiatives. The study focused on identifying various constraints that negatively impact the savings potential of DSM projects related to mine dewatering pumps. These constraints included factors such as low pump efficiencies, limited pump availability, inadequate water storage capacity, and high water inflow rates. By conducting simulations, the study determined the cumulative cost effect that these constraints had on dewatering pumps. The results demonstrated that by effectively reducing the impact of these constraints, potential annual savings of R21.57 million could be achieved at a specific case study site. The study highlighted the significant financial benefits of overcoming system constraints in DSM projects.

De Jager [55] developed a method for evaluating the effect of pump availability on load shift performance. Maintenance emerged as a critical constraint for successful DSM implementation. A simulation model was developed that enabled the scheduling and prioritisation of maintenance activities on a dewatering system. By utilising this model, the study aimed to optimise pump availability and enhance the overall load shift performance.

1.2.6 State of the art summary

Table 1 provides a summary of the most relevant literature that fell within the boundaries of the present study. Each study was evaluated based on five criteria to assess its relevance to the research:

1. **DSM:** Did the study investigate the performance of DSM initiatives? This is important, as the study focuses on DSM savings affected by load curtailment.
2. **Mine dewatering:** Did the study specifically investigate the effect on mine dewatering systems? This aspect is essential, as the study's focus is on mine dewatering systems.
3. **Electricity curtailment:** Did the study specifically consider variable electricity supply as a factor influencing electricity cost or DSM performance? This factor is vital, as the study aims to determine the cost of load curtailment on mine pumping systems.
4. **Cost effect:** Did the study determine the cost implication of barriers to DSM implementation? This criterion is significant, as the study aims to determine the cost effect of a specific constraint on mine pumping.
5. **Simulation:** Did the study simulate the impact of a constraint using simulation software? This is necessary due to the simulation-based approach adopted in the study.

Table 1: State of the art summary

SOURCE	DSM	MINE DEWATERING	ELECTRICITY CURTAILMENT	COST EFFECT	SIMULATION	COMMENTS
[54]						Strategy to revive mine pumping DSM projects.
[93]						DSM at mine refrigeration systems.
[95]						DSM at mine conveyor systems.
[94]						Reconfiguring mine water reticulation systems for energy cost savings.
[30]						DSM at dewatering systems in marginal mines.
[34]						Load shift at wastewater treatment plants for DR program.
[98]						Energy cost optimisation of mine pumping with load shift.
[99]						Improvement of pump automation procedures.
[42]						Reduce dewatering cost by decreasing preparation and comeback loads.
[73]						Identified and ranked barriers and success factors for efficient DSM implementation in the Swedish industry.
[103]						Estimate effects of power system rationing on GDP and consumer welfare.
[104]						Estimate the effect of supply shortages on Indian manufacturers using simulations.
[105]						Analyse the effect of severe power shortages on production costs of Chinese firms.
[106]						Estimate the historical economic cost of load shedding in South Africa.
[64]						Determine cost effect of non-performing DSM projects.
[45]						Quantify the effects of system constraints on the electricity cost of dewatering pumps.
[55]						Investigate the effect of pump availability on load shift performance.

From the extensive review of the literature, it is evident that there exists significant potential for the implementation of DSM initiatives to achieve substantial energy savings within mine dewatering systems. Several studies identified barriers to successful DSM implementation, but most did not quantify the actual financial impact. Notably, studies conducted by Botelho [103], Allcott [104], Fisher-Vanden [105], and Walsh [106] examined the impact of electricity supply variability but focused on macroeconomic effects, with quantification limited to the industry level or the economy as a whole.

However, the evaluation identified three studies [45, 55, 64] that developed methods for quantifying the effect of DSM constraints on mine dewatering systems. Yet, none of these studies specifically investigated electricity load curtailment as a constraint. It is worth noting that many of the studies that were reviewed employed a simulation-based approach to determine the pumping cost under various operating scenarios. Such simulation-based analyses hold significant potential for gaining valuable insights into the cost implications of different constraints on mine pumping.

1.3 Problem Statement and Need for the Study

The state of the art matrix presented in Table 1 highlights a significant gap in the existing literature regarding load curtailment's specific effect on mine dewatering systems. This gap underscores the need for conducting this study.

Considering the background information provided on the current electricity situation in South Africa and its specific implications for the mining industry, the urgency for implementing DSM initiatives in mine dewatering systems becomes evident. The escalating energy crisis has compelled Eskom to impose additional load curtailment requirements, putting mines under increasing pressure to manage their energy demand effectively. However, most mines lack a well-defined strategy to reduce their electricity loads during load curtailment situations. As a result, pumping operations, which are critical for dewatering systems, have been the default option for load reduction. Unfortunately, this approach has proven to be challenging, leading to a considerable surge in pumping costs due to missed load shift and DSM project targets.

The core issue lies in the scarcity of information available on the specific effects of load curtailment on mine pumping costs. The lack of data makes it challenging for mines to develop a clear load reduction strategy or make informed comparisons of alternative load reduction approaches. Prior studies aimed at enhancing DSM performance in mine dewatering systems have not considered the severe forced pump stoppages experienced during load curtailment. Consequently, there is an urgent need to investigate the precise cost of load curtailment on dewatering systems. This

investigation will enable mines to determine the most optimal load-reduction strategy, considering the cost implications of curtailing pumping for extended periods.

This study aims to fill this critical knowledge gap, providing valuable insights into the effects of load curtailment on mine pumping costs and DSM performance. Armed with this information, mines can make well-informed decisions on load reduction strategies, ultimately contributing to more efficient and cost-effective energy management practices in the mining sector.

1.4 Study Objectives

The objective of this study is to develop a method for quantifying the cost of load curtailment on mine dewatering systems. To achieve this, the study is further guided by the following sub-objectives:

1. Determine the effect of load curtailment on the pumping system's ability to meet shaft dewatering requirements.
2. Assess the effect of load curtailment on pumping electricity cost.
3. Investigate the effect of load curtailment on the performance of pumping load shift.
4. Investigate the feasibility of pump stoppages as a load-reduction strategy during load curtailment events.

Realising these study objectives will provide valuable insights into the effect of load curtailment on mine dewatering systems. The outcomes of this research will contribute to enhancing the overall energy efficiency and resilience of mine operations.

1.5 Research Methodology

Guba and Lincoln [107] define a research paradigm as “a basic belief system or worldview that guides the investigator” and introduced a typology of research paradigms. The typology distinguishes between positivism, postpositivism (sometimes called critical realism), constructivism (also known as interpretivism), and critical theory [107]. Given that the primary goal of this study is to acquire objective knowledge for establishing cause-effect relationships, it naturally aligns with the positivist paradigm [107, 108]. Within this paradigm, it is presumed that an impartial researcher is observing a quantifiable reality [107, 108].

The research aim of this study is to examine the impact of one variable on another; more specifically, the effect of load curtailment on mine dewatering costs. Therefore, the research question driving this study is empirical and predictive in nature. Mouton's [109] classification of

inquiry strategies further differentiates empirical studies by whether they employ primary or secondary data. In this study, primary data is analysed and used to develop a mathematical simulation model aimed at quantifying the influence of load curtailment on mine pumping costs.

For this study, research will be conducted through case study investigations, aiming to provide a detailed description of a limited number of cases [109]. Case studies produce knowledge that is case-specific, making them particularly suitable for acquiring expertise in a specialised field [110]. Conducting case study research provides a comprehensive and nuanced understanding of a phenomenon within its natural setting. This approach allows researchers to delve deeply into the intricacies of a phenomenon and is well-suited for investigating domains with limited prior research [111].

The chosen methodological approach for this study is quantitative research. Quantitative research is preferred because it involves the collection and analysis of numerical data with the goal of revealing patterns and trends [108]. The mode of reasoning employed in this study is inductive, with no initial hypothesis formulated. The inductive research approach moves from specific observations to the development of general concepts based on empirical observations.

The research method employed in this study follows a systematic literature review and simulation approach. The study is divided into three phases, satisfying the research objectives. The initial stage comprises an extensive literature review discussing relevant theories, concepts, and calculations to gain a comprehensive understanding of the cost implications of load curtailment on mine dewatering systems, presented in chapter 1. The second phase comprises constructing a digital twin simulation of the dewatering system of a deep-level mine. Finally, the results derived from the simulation model are analysed to determine the cost effect of load curtailment on mine pumping costs. A detailed and systematic explication of the research method employed is provided in chapter 2.

1.6 Layout of the Study

Chapter 1 – Introduction and Literature study

This chapter serves as the introduction and motivation for the study. It begins with an overview of South Africa's current electricity landscape. This provides a valuable context for the study and the delineation of the research problem. Furthermore, it introduces DSM initiatives, with a specific focus on their application in the mining sector. Detailed explanations are provided for Eskom's tariff structures, load curtailment practices, and other relevant DSM projects, all of which provide additional contextual information.

Additionally, within this chapter, a systematic review of contemporary literature relevant to the topic is conducted. The objective of the literature study is to investigate how others have addressed similar problems, culminating in a summary of the current state of the art. Furthermore, this chapter provides a detailed exposition of the research problem, providing clarity on its scope and significance. This chapter compounds upon the need for the study, elucidates the precise objectives of the study, and delineates the research methodology that will be employed.

Chapter 2 – Development of Solution

This chapter outlines the systematic procedure undertaken to establish a general solution for quantifying the cost of load curtailment on mine dewatering systems. The primary outcome of this chapter is the development of an integrated, calibrated, and verified digital twin simulation model specifically designed to be adaptable for application across various mine shafts. The digital twin simulation model will be utilised to calculate the parameters needed to satisfy the study objectives.

Additionally, this chapter highlights the value of simulations in addressing complex problems and delves into the process of selecting the most suitable software package for this research. A detailed description of the methodology is presented, comprising four distinct and coherent steps. This includes clarification of methods for acquiring essential system information, the process of developing the simulation model, the implementation of the model to yield the necessary results, and a comprehensive guide on how to analyse these results.

Chapter 3 – Implementation of Strategy

Chapter 3 discusses the implementation of the developed method into practical application through a real-life case study. The application serves as validation for the method outlined in chapter 2. The outcomes derived from the implementation of the model at the case study mine shaft are presented and investigated. Specifically, a dedicated digital twin model is created, enabling the simulation of various operational scenarios. The resulting electricity costs for each of these scenarios are thoroughly examined.

The results of the case study are discussed to determine whether the study's objectives have been met. This involves an in-depth analysis of the findings, culminating in the formulation of site-specific recommendations. These recommendations are invaluable, as they enable the mine to formulate and implement optimised load-reduction strategies in compliance with load curtailment requirements.

Chapter 4 – Conclusion and Recommendations

In chapter 4, the key findings of the study are summarised. The chapter evaluates whether the study's objectives have been successfully achieved and discusses the identified shortcomings of this study, contributing to a comprehensive understanding of the research's scope and limitations. Finally, recommendations for future research are provided, offering guidance for further studies in this field.

CHAPTER 2 DEVELOPMENT OF SOLUTION

This chapter focuses on devising a method to assist deep-level mines in quantifying the cost of load curtailment on pumping systems, including the assessment of load shift performance. Investigating the cost of load curtailment on mine dewatering is challenging due to the complex and interconnected nature of the system. Therefore, a step-by-step methodology needs to be developed to quantify this cost [55].

Many studies have developed methods to find solutions to complex problems in mine water reticulation systems [55, 94, 99, 112, 113]. In a study conducted by Venter [112], a solution development process comprising five main steps is described. For this study, the methodology focused on reconfiguring a mine's water reticulation system for improved management of high water volumes, but the general method can be applied to solving other issues in mine water reticulation systems. A short description of the five steps from that study is provided below:

- **Step 1: Data acquisition** is to acquire all the necessary data regarding the mine's water reticulation system.
- **Step 2: Development of solution** is to use the information gathered in step 1 to devise a solution to the problem.
- **Step 3: Validation of solution** is done to see if the proposed solution will be feasible. The study suggests that validation should be done by means of simulation.
- **Step 4: Implementation** is the physical implementation of the proposed solution.
- **Step 5: Results quantification** is the final step of the method and can be performed during the implementation phase.

A study done by de Jager [55] proposed simulations as a solution to quantifying effects of constraints on mine pumping systems. The author proposed the following method for developing solutions by means of simulation, comprising four main phases:

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

Taking inspiration from these previous studies, a new systematic method to assess the effects of load curtailment on mine dewatering systems was developed. This systematic method incorporates the development of a digital twin model, along with techniques for data acquisition,

model implementation, and analysing the obtained results. The model must align with a particular set of objectives [114] and strive for simplicity while remaining purposeful [115].

A case study approach is followed to determine the validity of the proposed method in reaching the objectives of the study. A case study approach involves implementing the solution on an actual system and evaluating the findings. Figure 12 presents the four-step process flow diagram that will be used to meet the objectives of this study.

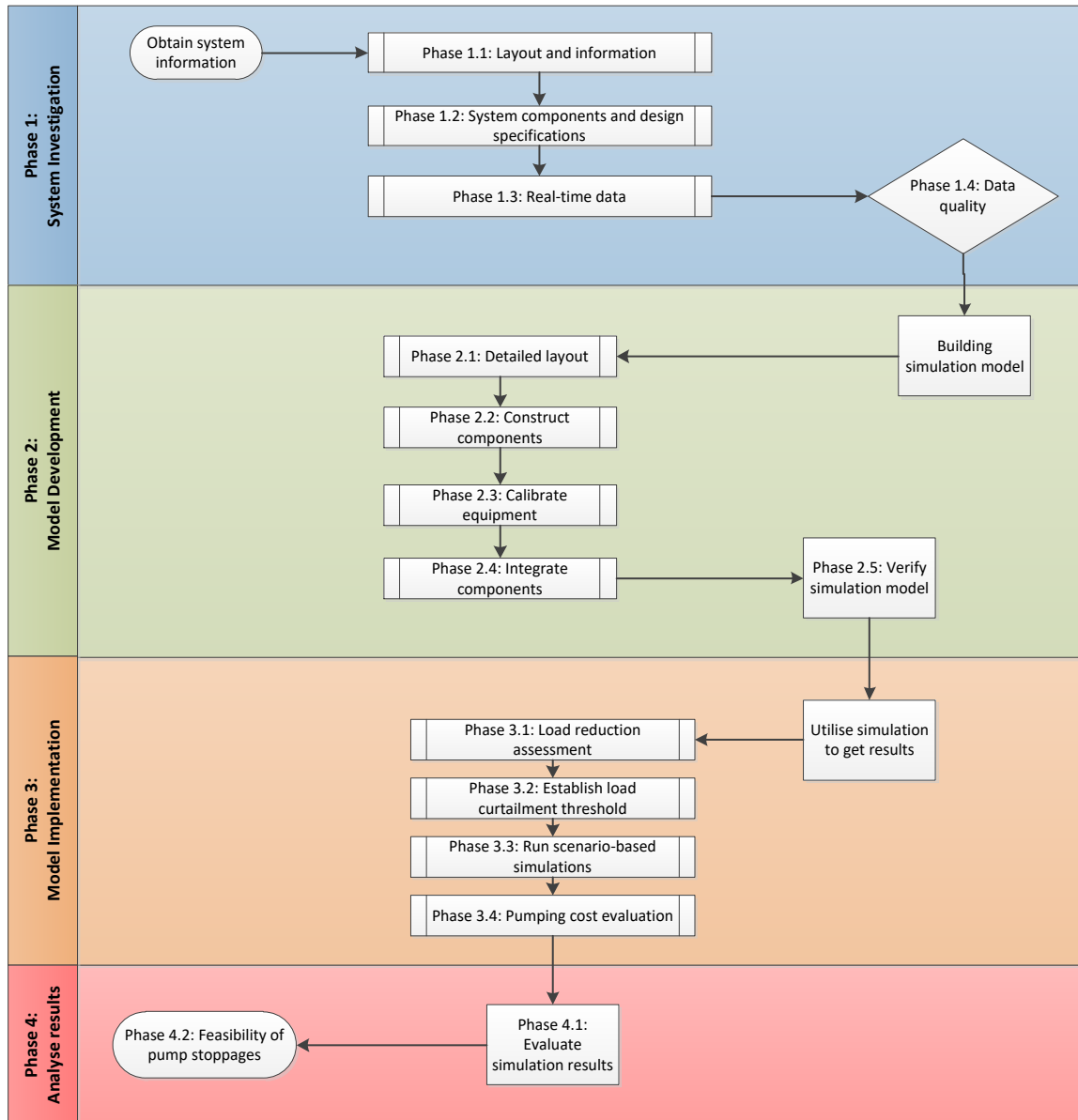


Figure 12: Development of solution flowchart

2.1 Phase 1 - System Investigation

In order to meet the study objectives, it is crucial to have a comprehensive understanding of the mine under consideration's unique dewatering system [112]. Hence, prior to commencing the solution development process, it is vital to accumulate background information regarding the pumping system and its daily operation. This section will discuss various methods for obtaining information related to a mine dewatering system, outline the specific data requirements essential for developing a reliable simulation model, and finally, discuss data processing methods to ensure the quality of the acquired data.

2.1.1 Methods to obtain system information

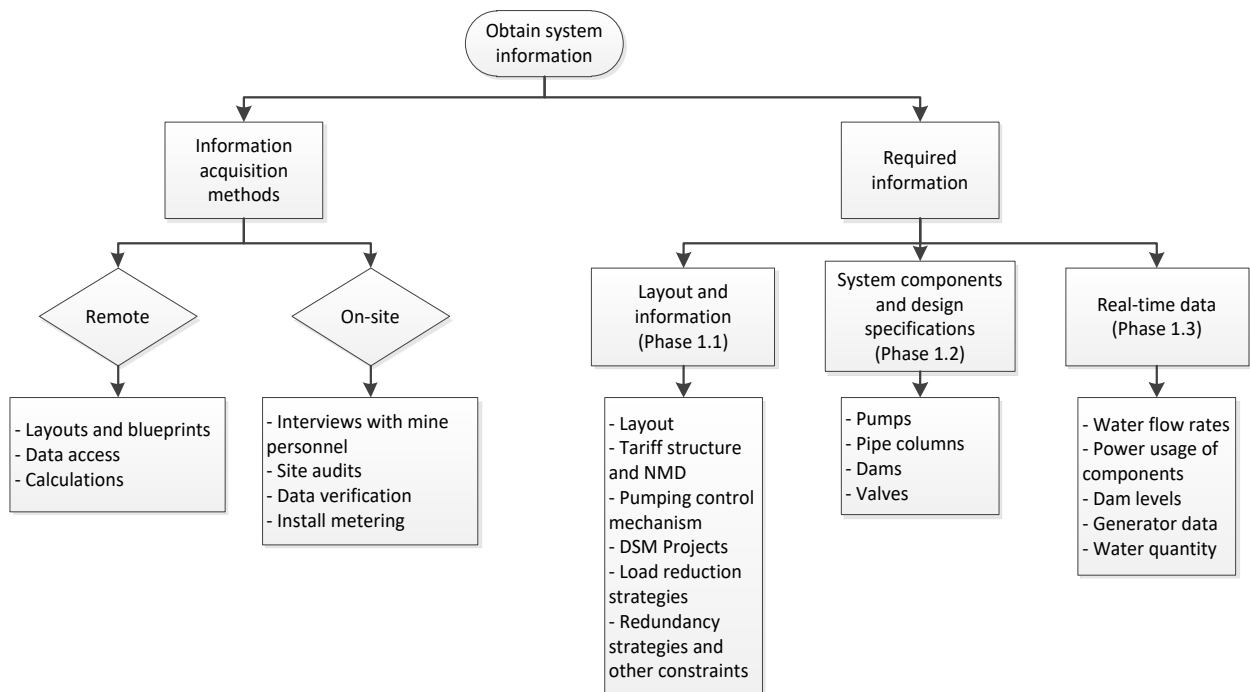


Figure 13: Method for obtaining system information

To quantify the electricity cost of load curtailment on mine dewatering systems, the locations and specifications of all the major components of the dewatering system should be obtained [112]. The components of a dewatering system are described in detail in Appendix A. This information provides crucial insights into water control and the flow path within the system [55]. Furthermore, the layout of the dewatering system, the utilised control mechanisms, tariff structure, and the specific details of possible Eskom DSM projects should be included [55]. It is essential to incorporate this information into the simulation to accurately replicate the system's behaviour.

Additionally, gathering information about other operating conditions that may have an effect on the dewatering system is vital. Each mine shaft may have unique considerations, including maintenance schedules and shift schedules, that must be quantified and integrated into the simulation. Collaborating with mine personnel to identify any constraints or specific arrangements that can affect the overall operation of the dewatering system is essential. By incorporating these factors, the simulation can provide a detailed representation of the system's performance and support effective decision-making.

Methods for collecting data on a mine's dewatering system can be categorised into two main approaches. The first approach involves remotely accessing the mine's data, typically facilitated by employing a supervisory control and data acquisition (SCADA) system and working with mine personnel to obtain the relevant information regarding the installed infrastructure [116]. The second approach entails conducting on-site visits to physically observe the different components of the dewatering system and collecting additional information if needed [117].

Remote data

Most deep-level mines have a SCADA system from where data can be obtained [112]. The SCADA system consists of multiple programmable logic controllers (PLCs) that enable end users to monitor operating parameters and remotely control equipment [118]. The SCADA system logs timestamped data on a database, often referred to as a historian [119]. Obtaining technical layouts and blueprints can also be achieved remotely.

On-site data

Nell [113] emphasised that a thorough understanding of a mining system can only be achieved through direct manual inspection. Conducting site visits enhances the information-gathering process and minimises the risk of inaccurately receiving or interpreting the data [119]. Engaging in conversations with experienced mine personnel during a site visit will facilitate the familiarisation process with the mine dewatering layout [112]. Conducting a walk-through audit enables the generation of a detailed pipe layout of the dewatering system [119].

In cases where SCADA is unavailable, alternative measures can be taken, including the installation of logging equipment and performing spot-checks using portable measuring equipment such as clamp-on ultrasonic flow sensors. These measures serve to verify the accuracy of data and identify any faulty equipment [112, 120, 121]. Figure 14 shows a clamp-on ultrasonic flow sensor used to verify the water flow in a column.



Figure 14: Clamp-on ultrasonic flow sensor [118]

To assess the cost of load curtailment on mine pumping systems, a combination of on-site and remote data should be utilised as far as possible. The steps shown in Figure 15 outline the process for acquiring the required information. A short description of each step is also given. The order in which the steps are implemented is not important and certain steps may not be feasible due to limited site access or other constraints. However, the objective should be to accomplish as many steps as possible to ensure reliable data is used for the simulation.

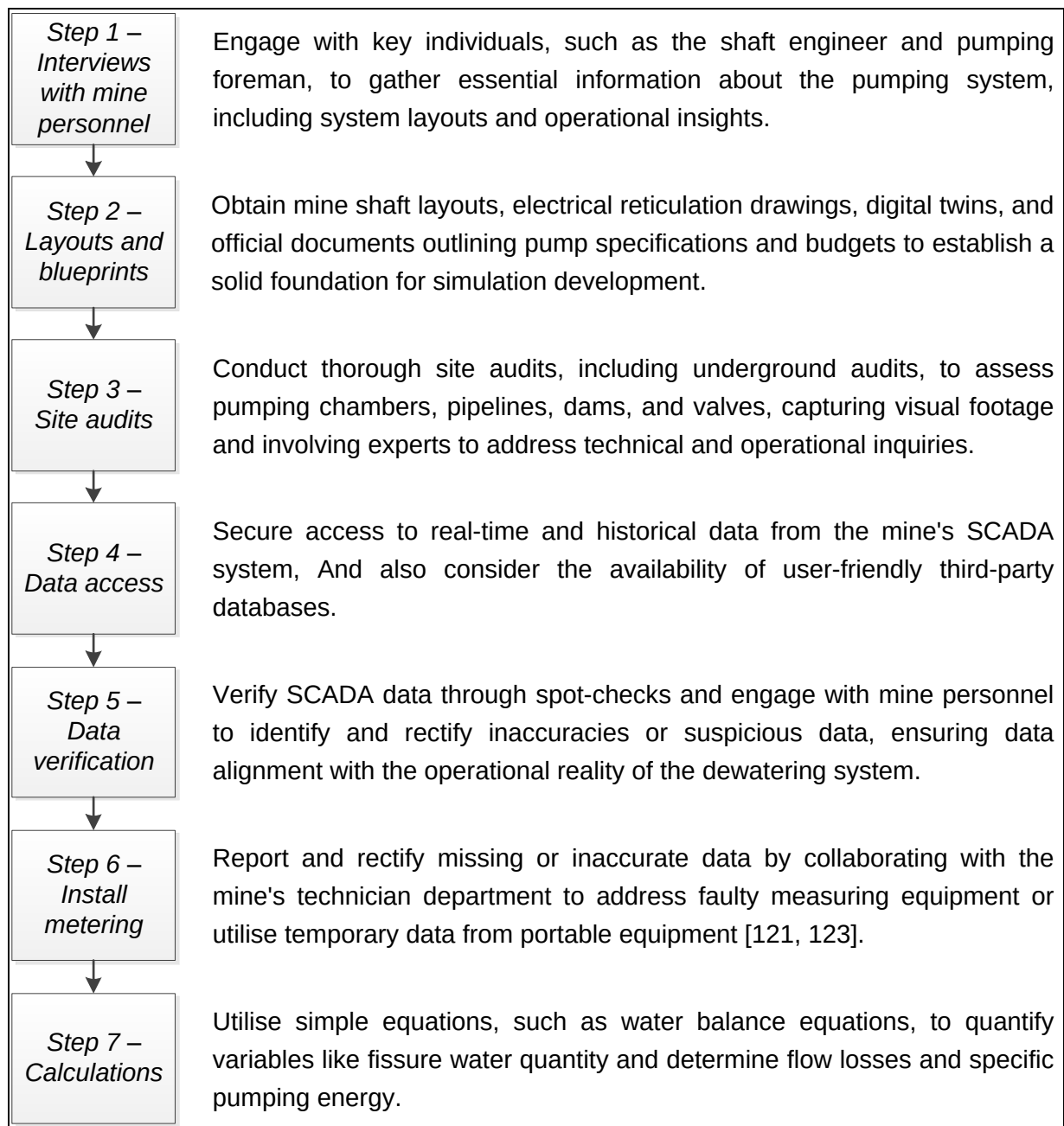


Figure 15: Data acquisition steps

Required information about the dewatering system can be divided into three groups and is discussed in the upcoming sections:

1. Layout and information
2. System components and design specifications
3. Real-time data

2.1.2 Phase 1.1 - Layout and information

According to Maré [135], understanding a system begins with acquiring its layout, which enables an understanding of the interaction between the components of the dewatering system and the collection of essential information [122]. In addition to the system layout, several other critical background details and information are necessary for developing a simulation model. Information regarding general and site-specific limitations can be gathered by consulting with mine personnel. A summary of the most important information that must be collected is given in Figure 16 and a detailed description follows in the upcoming section.

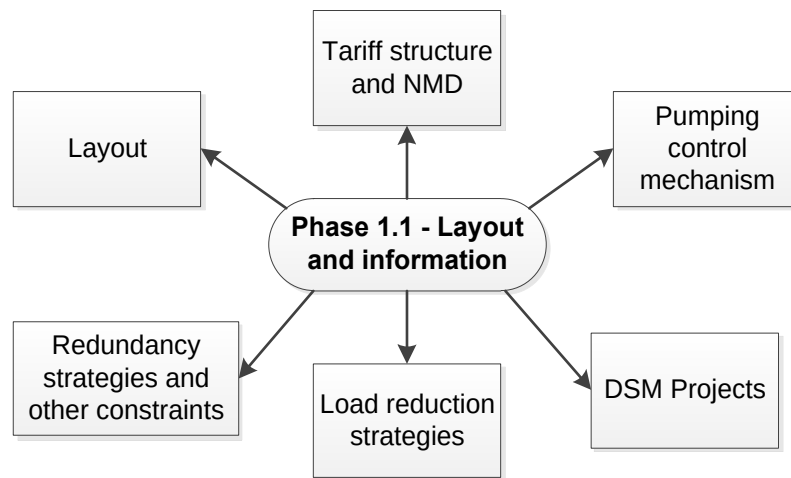


Figure 16: Layout and information

Layout

The system layout includes the layout of the water reticulation system and the locations of all main components. Tunnel layouts of all the developed sections of the mine are typically accessible in drawing exchange format (DXF), which provides the necessary physical coordinates for constructing the simulation model [119]. It is essential to identify the locations of essential dewatering components such as settlers, pumps, dams, pipes, and valves [113]. Additionally, conducting site walkthroughs further enhances familiarity with the system layout [113]. Armed with this information, a simple two-dimensional layout of the dewatering system and its components can be developed.

Tariff structure and NMD

To develop a precise costing model for the dewatering system, it is essential to acquire the tariff structure and NMD specific to the mineshaft's electricity point of delivery (POD). In the case of most mines, they are categorised under the Megaflex non-local authority tariff structure. Megaflex

is a TOU tariff structure designed for customers with an NMD exceeding 1 MVA. Understanding the NMD is critical, as it provides insights into the system's limitations regarding the maximum number of pumps that can operate simultaneously.

Pumping control mechanism

Gaining an understanding of the control philosophy employed in the dewatering system involves determining whether the pumps are controlled by a PLC, control room operators through SCADA, automated pre-determined setpoints and schedules, or manually by pump attendants. The control strategy plays a significant role in the maintainability of energy savings [55] and is, therefore, a key factor to consider when developing a solution.

DSM projects

DSM projects, as part of Eskom's DSM program, are often implemented at South African mines. If this is the case at the mine under consideration, it is important to collect crucial details about these projects, including the type of project, performance assessment period, and targets. Eskom's DSM load shift projects focus on load reduction during peak times, aiming to achieve a specific energy reduction target in MW, averaged over a three-month period. Failing to meet these targets can have significant consequences, such as not receiving monetary incentives and the project being at risk of cancellation after repeated failures. When quantifying the cost of missed pumping load shifts due to load curtailment, it is crucial to consider this factor and its potential implications.

Load reduction strategies

Because this study focuses on quantifying the cost effect of Eskom load curtailment, it is important to understand the mine's typical load reduction strategy. To curtail their energy load, mines have two options: curtail energy usage of energy-intensive systems or generate their own electricity to reduce the demand from Eskom. As discussed in chapter 1, deep-level gold mines have various energy-intensive systems. Some of these systems are essential for sustaining life underground, such as ventilation, refrigeration, and compressed air, and cannot be curtailed without evacuating personnel. The systems that can contribute towards load reduction strategies include winders, pumping, milling plants, and housing. Additionally, mines often employ diesel generators as backup power sources in the event of supply shortages. A typical load reduction strategy for mines involves reducing energy demand from pumping, winders, and milling systems, implementing load shedding in housing areas, and utilising diesel generators. It is important to find out what preferred load curtailment strategies are adopted by the mine under investigation.

Redundancy strategies and other constraints

To ensure the safety and uninterrupted operation of the dewatering system, incorporating redundancy is essential. Redundancy allows for maintenance and repairs to be carried out on certain components while the system maintains its full operational capacity. The availability of spare capacity is a critical factor to consider, as it can impose limitations on the dewatering system's capabilities. There may be other unique shaft-specific factors that need to be considered. For example, individual pump sets can sometimes not be run simultaneously due to the limitations imposed by the start-up current [122]. Understanding operational constraints of the dewatering system is crucial for developing an accurate simulation that aligns with the actual operational practices.

2.1.3 Phase 1.2 - System components and design specifications

To build a credible simulation model of the dewatering system, it is essential to gather comprehensive information about the key components involved. The design specifications of these components play a crucial role in accurately representing the system. Figure 17 presents the key components of the dewatering system that should be investigated.

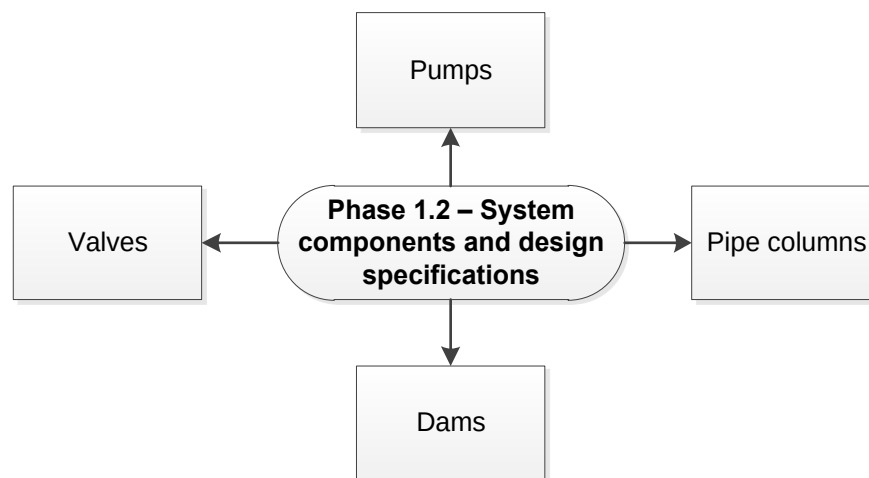


Figure 17: System components and design specifications

Table 2 presents the design specifications that are required for the key components of the dewatering system, which will be discussed in more detail later in this section.

Table 2: Component design specifications (adapted from [119])

Component	Parameter	Unit
Pumps	Rated power	<i>kW</i>
	Head	<i>m</i>
	Flow	<i>L/s</i>
	Efficiency	<i>%</i>
Pipe columns	Nominal bore (diameter)	<i>mm</i>
	Length	<i>m</i>
Valves	Type	–
	Pressure	<i>kPa</i>
Dams	Volume (capacity)	<i>ML</i>
	Maximum level	<i>%</i>
	Minimum level	<i>%</i>
	Elevation	<i>m</i>
Other components in water reticulation system	Water demands	<i>L/s</i>

Pumps

For each pumping level, it is necessary to gather details regarding the number of installed pumps and their design specifications [119]. Obtaining precise location data, including specific coordinates for the pumping stations, is crucial, as it helps specify the head. Additionally, important pump parameters, including rated power, discharge flow, and efficiency, need to be gathered for each individual pump. Mining personnel can provide much of this information, while the running status data of the pumps can be obtained from SCADA, which greatly assists in the development of the simulation model.

Pipe columns

It is important to know the number of columns and their respective nominal bore sizes and lengths [119]. Additionally, understanding the pipe network layout, specifically the connection of each column to a pump, is necessary.

Valves

The pipe network layout includes valves that enable adjustments to the dewatering system's configuration. Valves control the discharge of most pumps into multiple columns. It is essential to determine whether these valves are manually controlled or operated by actuators. It should be noted that manually controlled valves may affect the accuracy of the simulation due to the time taken to open or close a valve.

Dams

Knowing the number of available water dams on the pumping levels, as well as the dams currently in use, is vital. Gathering information about the location, capacity, and functionality of hot and cold dams, along with settlers, is valuable for the study. To avoid flooding or pumps running dry, mines establish maximum and minimum dam levels as control ranges. Larger plug dams also have their own maximum and minimum levels to ensure the safe functioning of the dewatering system and to maintain sufficient capacity in case of system failure [55]. Furthermore, these limits are implemented to maintain good water quality standards.

2.1.4 Phase 1.3 - Real-time data

Once the system layout and component design specifications have been collected, it becomes essential to obtain real-time and historical data for all primary components. Most mines have real-time data available in digital form via SCADA systems [116]. Each component is assigned a unique tag name that serves as its identification within the SCADA system.

In cases where SCADA or similar data acquisition systems are not available at the mine, manual data audits should be conducted. This involves installing measuring equipment like temperature sensors, pressure logging devices, and ultrasonic flow meters with data logging capabilities at the desired locations to record accurate measurements [112]. Calibration of instrumentation should be arranged if any inaccuracies are identified.

Figure 18 presents the data that should be gathered to serve as the foundation for developing a comprehensive dewatering simulation.

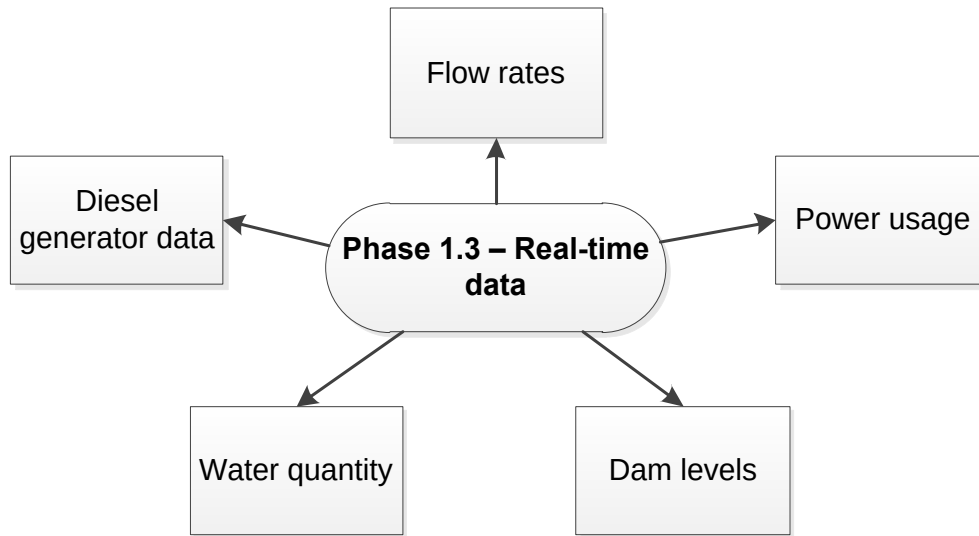


Figure 18: Real-time data

Water flow rates

The flow rates in the dewatering columns must be determined for each pump combination connected to the column. The flow rate varies for each pump depending on the column it discharges into and whether it operates in parallel with other pumps. When multiple pumps in parallel discharge into the same column, the total flow rate increases, but significant losses occur, reducing system efficiency. Therefore, it is crucial to have knowledge of the flow rates for each pump combination rather than relying solely on the individually designed flow rate of each pump. The term "pump combination" refers to the specific pumps and columns utilised at any given time.

Power usage

Determining the power requirements of each component within the dewatering system is crucial for developing the energy demand aspect of the simulation. The power consumption of a pump is dependent on the flow and can vary when operating in parallel with other pumps. Thus, it is essential to ascertain the power demand for each utilised pump combination. In cases where data is unavailable, temporary installation of power loggers can be employed to gather the necessary information [55].

Dam levels

In mine dewatering systems, underground dams are equipped with level sensors that measure pressure and are calibrated to provide a percentage or meter value using the hydrostatic pressure equation. The hydrostatic pressure equation is given below.

$$P = \rho gh \quad (2)$$

Where: $P = \text{Fluid pressure [Pa]}$

$\rho = \text{Fluid density [kg/m}^3\text{]}$

$g = \text{Gravitational constant [m/s}^2\text{]}$

$h = \text{Fluid depth [m]}$

Extracting this data is important for accurately simulating the time it takes for the dams to fill up or empty. By incorporating the measured pressure values from the sensors, the simulation can replicate the behaviour of the dams with greater precision.

Diesel generators

By calculating the cost of generator usage, a comparison can be made to the costs incurred due to pump stoppages. Acquire information regarding the number of diesel generators that can be utilised by the mine, along with the power output of each generator. Typically, data regarding the diesel usage and power generation for each generator is logged either through SCADA systems or manually, and this data should also be obtained. Additionally, it is important to know the price at which the mine purchases diesel, specified in Rand per litre. It should be noted that the mine may be eligible for discounts or rebates on diesel purchases, and these factors need to be considered as well.

For the purposes of this study, it is crucial to calculate the consumption of a mine's generators. Generator consumption is measured as the amount of diesel a generator uses, in litres, to generate one *MWh* of power. To determine this value, all the acquired diesel usage and power data for a given time period, t , should be considered, and the following formula used:

$$Consumption_{gen} = \frac{Diesel_{used}}{P_{gen}} \quad (3)$$

Where: $Consumption_{gen} = \text{Generator consumption [L/MWh]}$

$Diesel_{used} = \text{Total diesel used [L]}$

$$P_{gen} = \text{Total power generated [MWh]}$$

From the diesel consumption, the cost per MWh generated can be determined, using Equation 4.

$$\text{Specific cost}_{gen} = \text{Cost}_{diesel} * \text{Consumption}_{gen} \quad (4)$$

Where: $\text{Specific cost}_{gen} = \text{Generator specific cost [R/MWh]}$

$$\text{Cost}_{diesel} = \text{Cost of diesel [R/L]}$$

Water quantity

The total dewatering requirements of a shaft may include both service water and fissure water. Quantifying the water demand of various components within the mine's water reticulation system is crucial. Components such as refrigeration plants, turbines, cooling cars, and bulk air coolers rely on water, and their water requirements directly impact the operation of the dewatering system. Additionally, understanding the timing of water demand is equally important. For instance, service water needed at mine working areas for mining and cooling purposes may be required during peak times, which can pose challenges in implementing a full pumping load shift.

Furthermore, water exchange may occur between connected underground levels in different shafts. It is necessary to account for these water volumes by adding or subtracting them from the total dewatering requirements. Determining the quantity of fissure water introduced to the system can be achieved through a simple water balance equation [112], which involves measuring the inflow and outflow of water within the mine.

$$\text{Amount of fissure water} = \text{Water flow out of shaft} - \text{water flow into shaft} \quad (5)$$

2.1.5 Data quality

Before being employed in a simulation, the data needs to be evaluated to ensure its reliability [119]. Various approaches exist for assessing data quality, and in this case, the data evaluation method proposed by Booysen [123] was employed. Figure 19 illustrates Booysen's methodology for evaluating a data set [123].

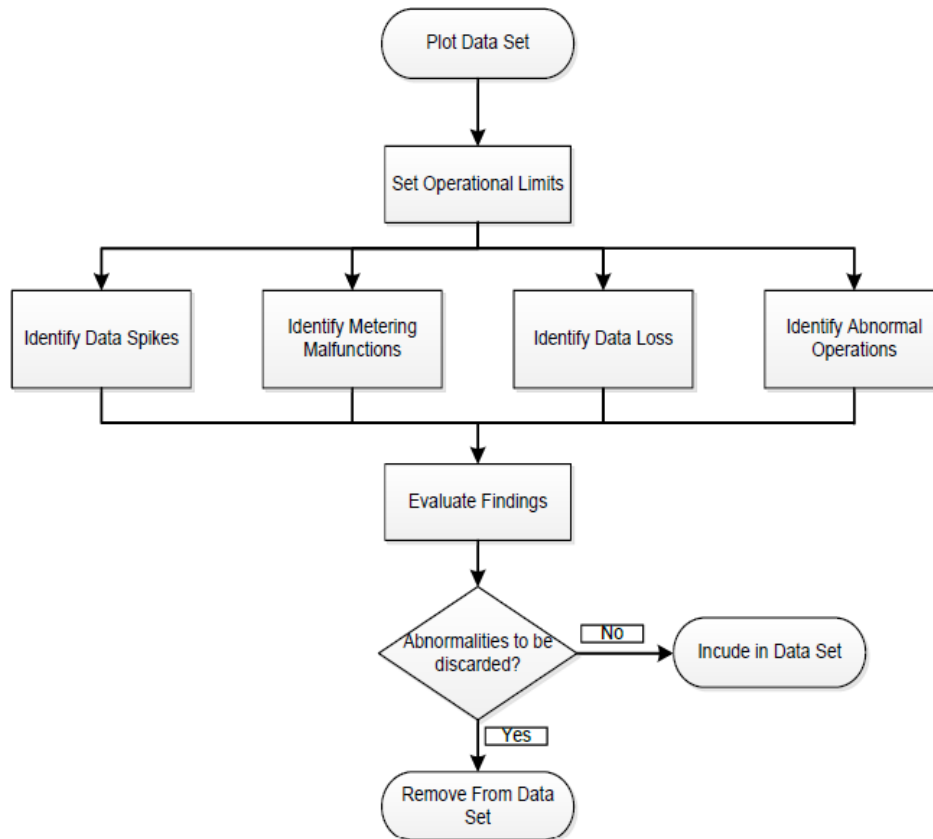


Figure 19: Data quality control process (adapted from Booysen [122])

The first step is to extract raw data from the SCADA's historian and plot it on a spreadsheet, usually in Microsoft Excel [117, 123]. Limits for the data must then be determined, correlating to the operating value of the equipment [123]. There are three main ways of establishing parameter limits: (1) statistical analysis of historical data, (2) technical specifications from the original equipment manufacturer, and (3) from experienced maintenance personnel [124]. For instance, in the context of the dewatering system, the measured water flow on the pump's delivery side cannot be negative due to the presence of one-way valves that prevent backflow [125]. Therefore, the minimum limit is zero, while the maximum limit corresponds to the combined flow of all the pumps connected to the selected column.

Values that fall outside the predetermined limits should be treated as data spikes and excluded from the data set [123]. Malfunctioning instrumentation is a common occurrence in mining operations, leading to data loss or inaccurate measurements recorded in the historian [120]. Static values in the data set represent inaccuracies and the affected values should be omitted, resulting in blank cells in the data [119]. The data quality process is complete once all irregular data are removed [123].

2.2 Phase 2 - Simulation Model Development

Phase 2 of this methodology aims to develop and verify a digital twin simulation model of the dewatering system at a shaft, based on the system information gathered. A digital twin serves as a direct simulation replica of the integrated system [113].

2.2.1 Value of simulations

Investigating the cost of load curtailment on pumping systems by conducting real-world experiments is seldom a viable option. Experimentally testing the effect of different operational scenarios can be disruptive, expensive, and time-consuming [45, 114]. Using a simulation model serves as a substitute for conducting experiments with the physical system [114] and is a more economical and time-efficient method to test the impact of constraints on system performance [45]. The simulation environment provides a comprehensible representation of the real world with reduced costs [126]. As demonstrated by various studies, simulations provide significant benefits in planning and correcting DSM initiatives.

The benefits of using simulations to optimise a mining complex was investigated in a study by Dimitrakopoulos and Lamghari [127]. The study demonstrated that simulations provide valuable benefits for mining operations. These benefits include enhanced decision-making for life-of-mine production schedules, increased production, and a notable boost in net present value [127].

A study by van Niekerk [128] highlights how simulations enable the analysis of energy consumption in complex technical systems and quantification of potential savings from DSM interventions. The study proved that simulation models play a crucial role in determining precise compressed air demand, selecting appropriate compressors, establishing control procedures, and ensuring energy savings in compressed air systems [128]. By comparing theoretical and measured values in well-instrumented compressed air systems, simulations identified discrepancies and aided in proposing corrective measures [128].

In addition, simulations serve as a powerful tool for evaluating the feasibility of DSM projects and exploring further energy-saving potential by improving control mechanisms for valves, pumps, compressors, and supply-demand management [128]. Simulations assist in detecting leaks, assessing different plant design configurations, and optimising energy control strategies [128].

A study by Holman [129] further highlights the benefits of specific simulation models in evaluating electrical savings potential in a mine cooling system. The study found that simulations identified

issues that would have been encountered during installation and predicted significant demand savings.

Overall, simulations are invaluable tools for adding value to projects [126], maximising energy savings, avoiding costly trial-and-error approaches, and optimising design based on accurate understanding and assessment. Therefore, to effectively address the study's primary objective and its various sub-objectives, the most suitable approach involves employing a digital twin simulation model of the system. Utilising the model allows for a systematic exploration of different scenarios and provides valuable insights into how load curtailment affects the operation of the system.

2.2.2 Software package selection

It is essential to choose an appropriate software package that can effectively support the study objective. The selected software will be utilised to construct a simulation model of the mine's dewatering system, allowing for accurate analysis and evaluation of the cost implications associated with load curtailment.

This section discusses the selection of an appropriate software package for conducting the simulation. Several studies have implemented a selection process to choose a suitable software package for simulation development. To ensure a well-informed decision, the selection criteria were adapted from previous studies [99, 119, 130]. These criteria include:

- **Digital twin:** The requirement for a digital twin capability to model the entire dewatering system accurately. The software package must be able to produce an accurate digital replica of the mine.
- **Dynamic analysis:** The ability to perform dynamic analysis considering various dynamic variables.
- **Scenario investigation:** The capacity to simulate multiple scenarios for investigating the effects of load curtailment measures.

For deep-level mine dewatering systems, computational fluid mechanics solvers can be used [131]. These solvers are employed to solve the thermodynamic and fluid mechanical properties of a modelled system as it evolves over time, considering the specified initial properties. Differential equations are utilised to derive fluid properties across a continuous model, adhering to the principles of mass, momentum, and energy conservation [132, 133]. For a mine dewatering system, this means determining the thermodynamic and flow characteristics of pipes, pumps, and valves and other components within the model to accurately represent real-world conditions [131].

With this in mind, there are many different simulation software packages available for modelling mine dewatering processes at deep-level mines [99]. For this study, seven software packages were considered and evaluated based on the aforementioned criteria. Table 3 summarises the evaluation of various software packages.

Table 3: Simulation software summary

No.	Software	Description	Digital twin	Dynamic analysis	Scenario investigations
1	EES	Program capable of solving coupled non-linear algebraic and differential equations.	N	N	Y
2	Excel	Use spreadsheets to organise, calculate and analyse data with formulas and functions.	N	N	Y
3	VumA	Interactive 3D simulation of underground mine ventilation and environmental conditions.	Y	Y	Y
4	Flownex	1D simulation for design and optimisation of flow and heat transfer systems.	Y	Y	Y
5	AFT Fathom	Fluid dynamic simulation software used to calculate pressure drop and pipe flow distribution in liquid piping and ducting systems.	Y	Y	Y
6	PTB	Transient thermal-hydraulic 3D system simulation tool for liquid-flow analysis.	Y	Y	Y
7	EPANET	Software application used to model water distribution systems and design water infrastructure.	Y	Y	Y

After evaluating several software packages, as well as considering the availability of the software, Process Toolbox (PTB) was chosen as the most suitable software for modelling the mine's dewatering system. PTB is specifically designed for the mining environment and offers 3D modelling capabilities, which is advantageous for developing an accurate representation of the dewatering system. PTB is a transient thermal-hydraulic system simulation tool known for its optimisation capabilities and utilises an incompressible quasi-steady-state semi-implicit solver for liquid flow analysis. VumA is the only other software with 3D modelling capabilities; however, it is

specifically designed for mine ventilation applications and does not cater to water reticulation systems, which are the focus of this study.

The accuracy of PTB has been validated in various studies, making it a reliable choice for this simulation [119, 134, 135]. Mathews [135] and Maré [134] compared simulation software for transient systems and came to the conclusion that PTB stands out as the ideal choice for simulating mine systems due to its capabilities for emulating real-time monitoring and control.

2.2.3 Building simulation model

After the suitable software package has been selected, the simulation must be developed using the data acquired from the mine, including the system constraints. The construction of the model is divided into five phases:

1. Detailed layout
2. Construct components
3. Equipment calibration
4. Integrate components
5. Verify simulation

2.2.3.1 Phase 2.1: Detailed layout

The purpose of this phase is to introduce underground tunnel layouts of the mine to build a skeleton layout of the dewatering system under investigation. The DXF files of the mine acquired in phase 1.1 offer a good starting point. Notably, DXF files contain the coordinates of the important underground locations that should be imported to PTB. Figure 20 provides an example of the DXF layout of a level imported to PTB.

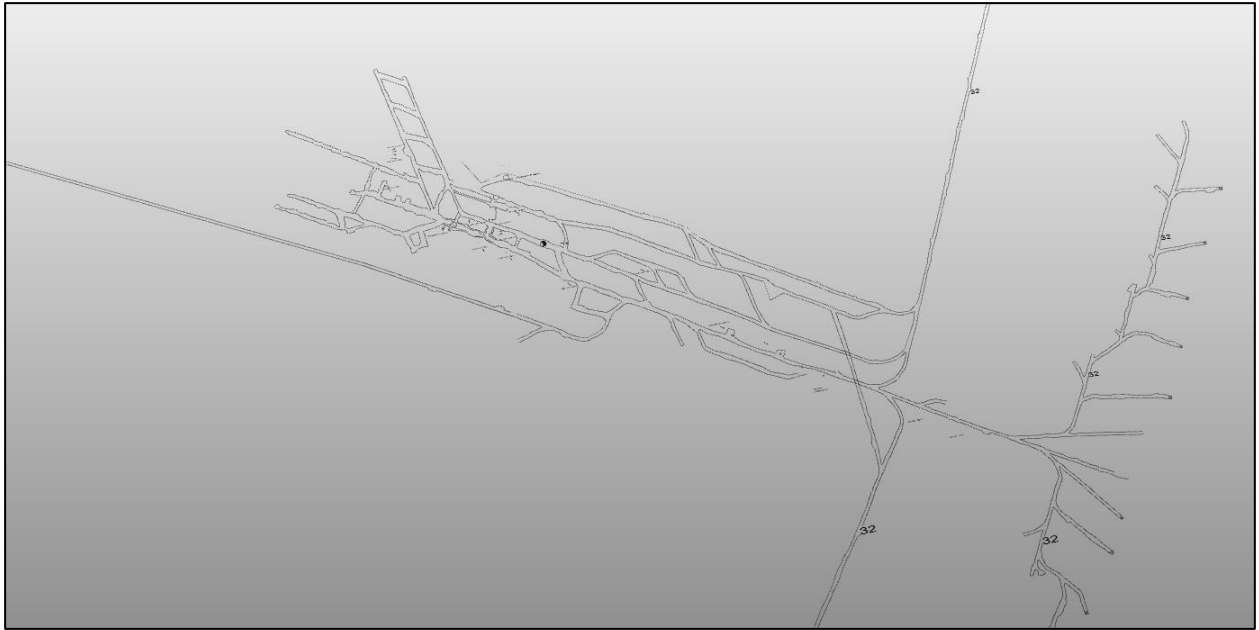


Figure 20: Imported DXF file in PTB

In scenarios where DXF files of layouts are unavailable, alternative avenues for acquiring essential coordinates need to be explored. At the bare minimum, the depths below surface of key underground locations like pumping stations should be obtained. This is significant when calculating pumping heads and facilitating accurate simulation development. The mine's ventilation department can prove instrumental in procuring this information, owing to the regular ventilation audits conducted by them, aiding the construction of ventilation models incorporating all underground haulages.

2.2.3.2 Phase 2.2: Construct components

Phase 2.2 entails the construction of all dewatering components in the simulation environment. These components include pumps, dams, settlers, pipelines, and valves. The positions of pumps, dams and other dewatering components must be confirmed with audits and inserted into the model at the correct location. PTB enables the user to insert a component directly onto the exact coordinates of the DXF file obtained in Phase 2.1 using a drag-and-drop feature. Figure 21 illustrates this concept.

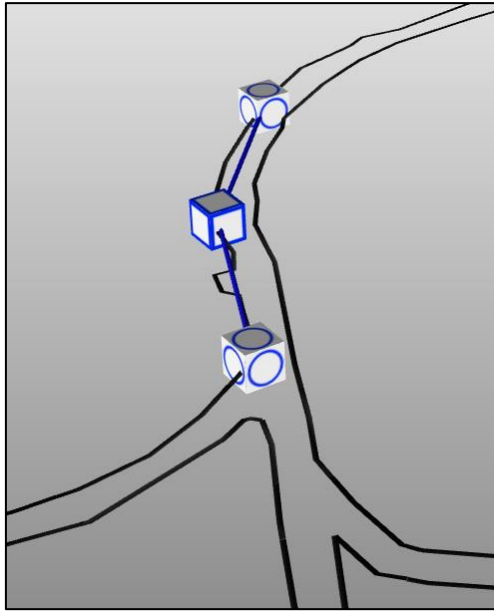


Figure 21: Water components on the DXF file

During phase 2.2, all the components are inserted to the pumping levels, further developing the layout of the shaft's dewatering infrastructure. Figure 22 provides a visual illustration of a fully assembled pumping level, depicting the locations of pumps and dams as verified during on-site audits. This process should be replicated for all the pumping levels within the examined shaft.

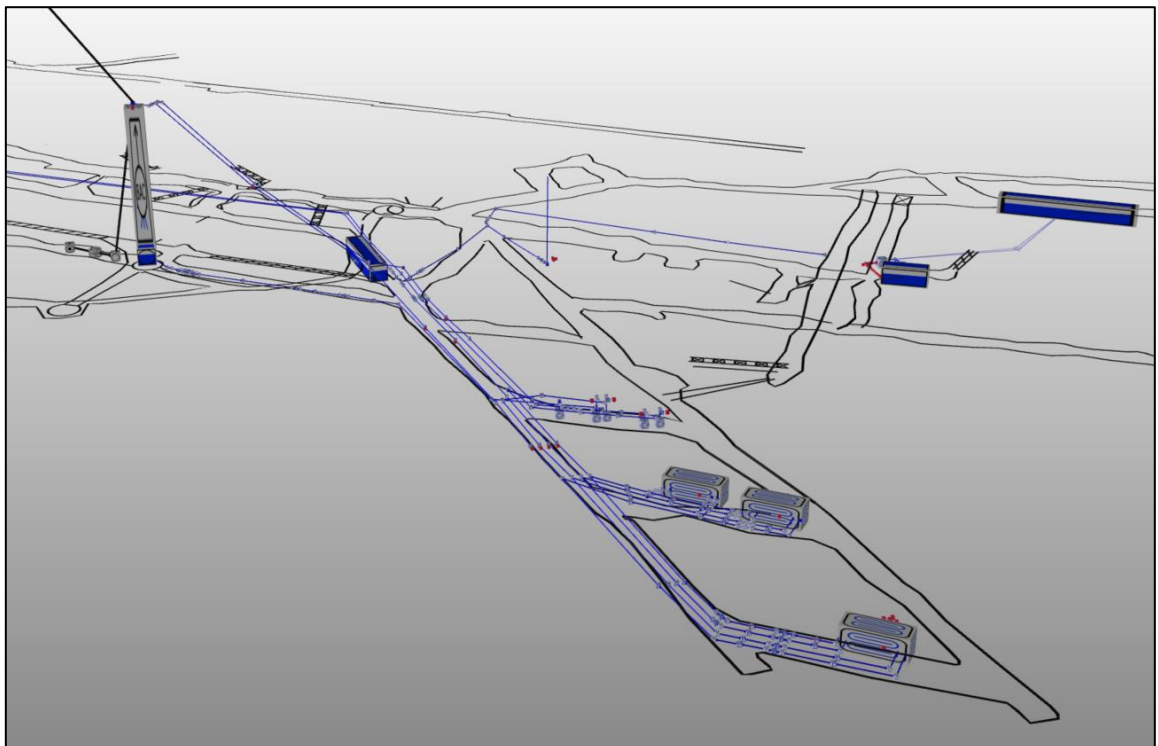


Figure 22: Dewatering infrastructure on pumping level constructed in PTB

2.2.3.3 Phase 2.3: Equipment specification

After the pumping levels have been constructed and connected, the next phase can commence. This phase involves adding the design specifications of the dewatering equipment, obtained in phase 1.2, to the digital twin model. The sizes and specifications of pipes, dams, and pumps must be included in the model. The incorporation of all component design specifications into the simulation is an important step in guaranteeing that the simulation truly mirrors the real system. PTB enables the user to import pipes of standard sizes from a built-in library. Figure 23 illustrates the library of standard pipe sizes.

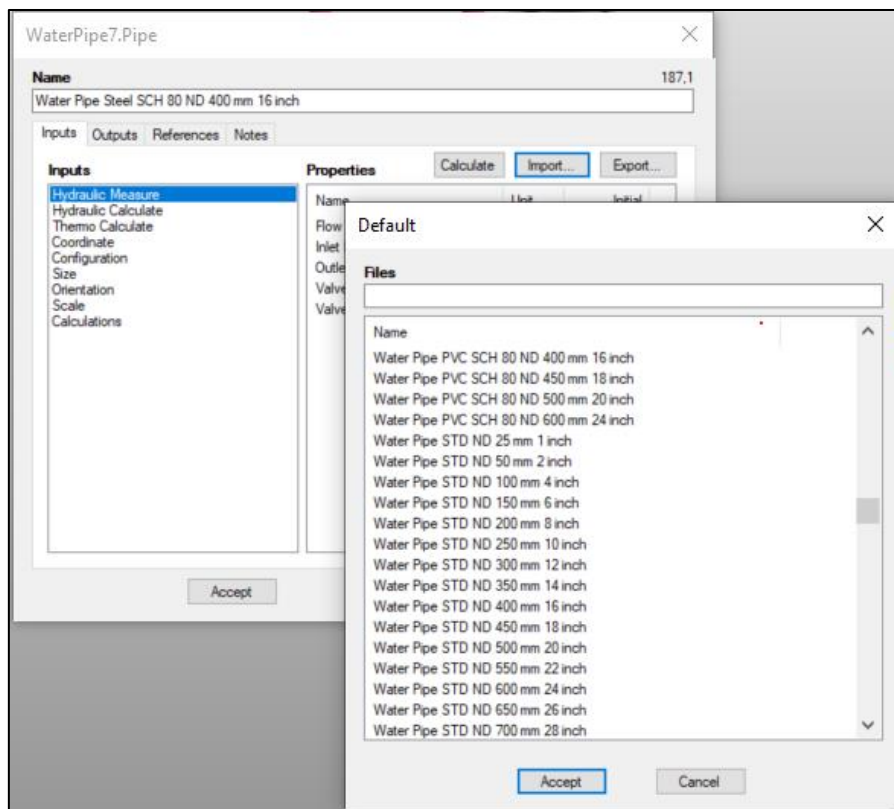


Figure 23: PTB built-in library of standard components

2.2.3.4 Phase 2.4: Integrate components

After all the components of the dewatering system have been constructed and calibrated, phase 2.4 can be initiated. This phase comprises the seamless integration of these components. To achieve this, the initial model is simulated to verify the connections between all components and to ensure an error-free simulation process. Regularly simulating the model is essential to preempting the emergence of errors within the simulation [113]. Specific attention is given to connecting all component nodes in the appropriate flow direction.

Following the integration process, the baseline simulation model should accurately mirror the real-world dewatering system. An integrated simulation model in PTB should function flawlessly when reasonably expected operating conditions of the dewatering system are used as inputs for the model. This entails the prevention of issues such as dam levels or temperatures exceeding limits, and the correct alignment of all flows. If the model exhibits errors or warnings during simulation, these issues must be rectified before progressing to the next phase.

2.2.3.5 Phase 2.5: Verify simulation

Verifying the model is crucial to establishing its credibility [114]. To facilitate reliable predictions, it is crucial that the developed simulation model accurately represents the current system for the study's specific goals [55, 113]. Hence, the next step in ensuring credible results is to verify the reliability of the digital twin.

A simulation model can only serve as an approximation of the actual system [114]. Absolute model validity is neither achievable nor desirable because a model is meant to simplify and abstract reality [114]. However, if the model deviates significantly from the real system, it can lead to erroneous conclusions and costly decisions [114]. The development of a validated simulation model is an iterative process involving the creation of multiple versions of the model before achieving a validated one [115].

Comparing the results of a model to those of an existing system is considered the most definitive validation technique [114]. To facilitate this comparison, access to actual data of the system is necessary [129]. The verification process for the simulation model used in this study consists of the following steps:

1. Comparing the model outputs with the measured data of the actual system [113].
2. Calibrating the model.

Previous literature has suggested that a simulation model should not deviate by more than 5% from the measured results to be deemed accurate [125, 134, 135]. The simulation error can be determined by comparing the average values of real-time data with the average values of simulated data over a 24-hour period [113]. If the simulation results exceed the 5% error threshold, the model should be recalibrated until it can be considered accurate [113].

In addition, visual assessments of plotted data profiles should also be employed to identify deviations within a 24-hour time period, as recommended by Maré [134]. If the system

investigation and simulation model development were accurately performed, the simulation output should align with the real-time data, exhibiting small deviations.

The verification of the simulation model in this study involves comparing the simulation results to the actual system data in three aspects:

1. Water flow rates
2. Pump power usage
3. Dam levels

For verification, the dewatering simulation is executed by specifying the actual pump schedules on PTB. The running status of the pumps, obtained from the mine's SCADA system, is utilised as inputs for the model. It is advisable to simulate a minimum period of 24 hours. The simulation results, including water flow rates, pump power usage, and dam levels, are compared to the actual values during the same period.

There may not be a perfect correlation between the simulated values and the actual data. This discrepancy can be attributed to the fact that pumps do not always start precisely at the simulated start time. However, it is expected that all three parameters exhibit a minimum accuracy level of 95%. For dam levels specifically, it is important to evaluate the graphic comparison to ensure that the simulation follows the correct trend.

After reviewing several previous studies that have conducted the verification of simulated water flow rates [99], pumping power demand [45, 47, 112, 125], and dam levels [136], a specific verification method has been developed for this study. The simulation will be performed at hourly intervals, allowing for a comparison of flows in each individual column, power demand for each individual pump, and dam levels with the corresponding actual data. This verification process will be conducted over one week, preferably covering a wide range of operating conditions. The results will be graphically plotted to provide a visual representation of the comparison between simulated and actual values.

The dewatering equipment needs to be calibrated to give the correct water flow, power, or dam level values. PTB allows users to define the pump curve of a component, using the pump specifications obtained from the supplier or mining personnel.

The required inputs to plot a pump curve on PTB are presented in Figure 24.

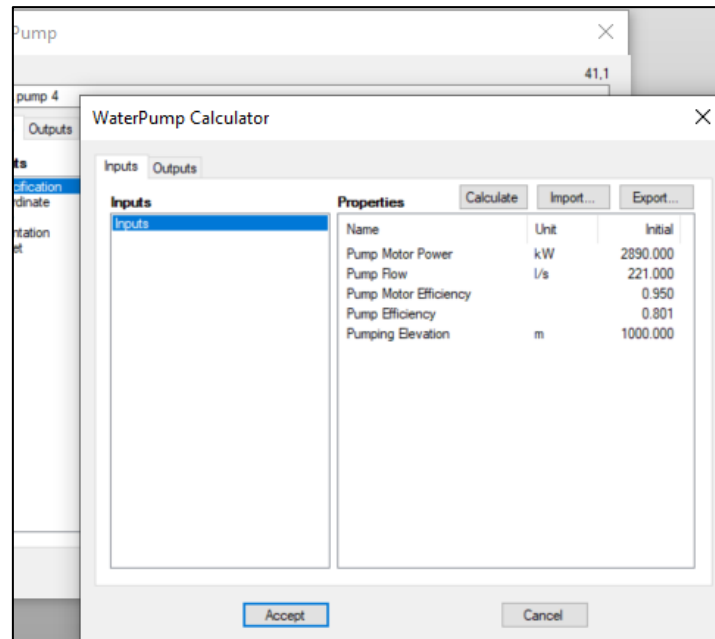


Figure 24: Water pump calculator

Calibration involves fine-tuning the pump's parameters to align its performance with the measured flow in the mine. Throughout the calibration process, the only known constant values for the pump are the power, water flow, and pumping elevation. Primarily, the adjustable values pertain to the pump's efficiency parameters. An example of a pump performance curve in PTB is illustrated in Figure 25.

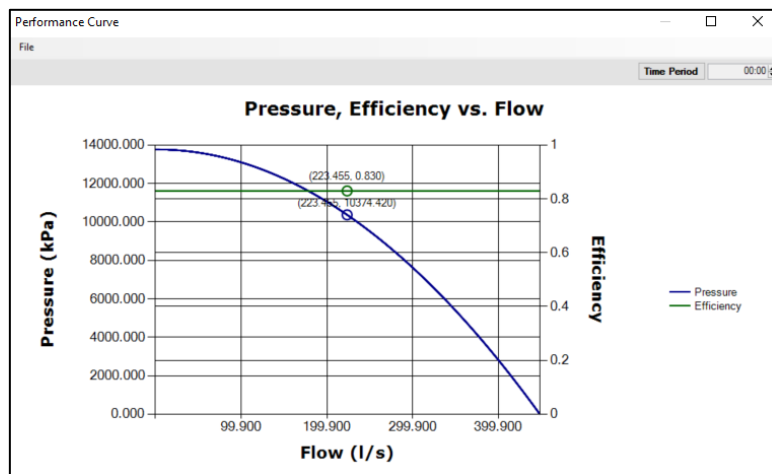


Figure 25: Pump performance curve in PTB

The calibration process is repeated for each component until the variance between the simulated and measured values is less than 5%. Figure 26 illustrates an example of a comparison profile between simulated and actual water flow values.

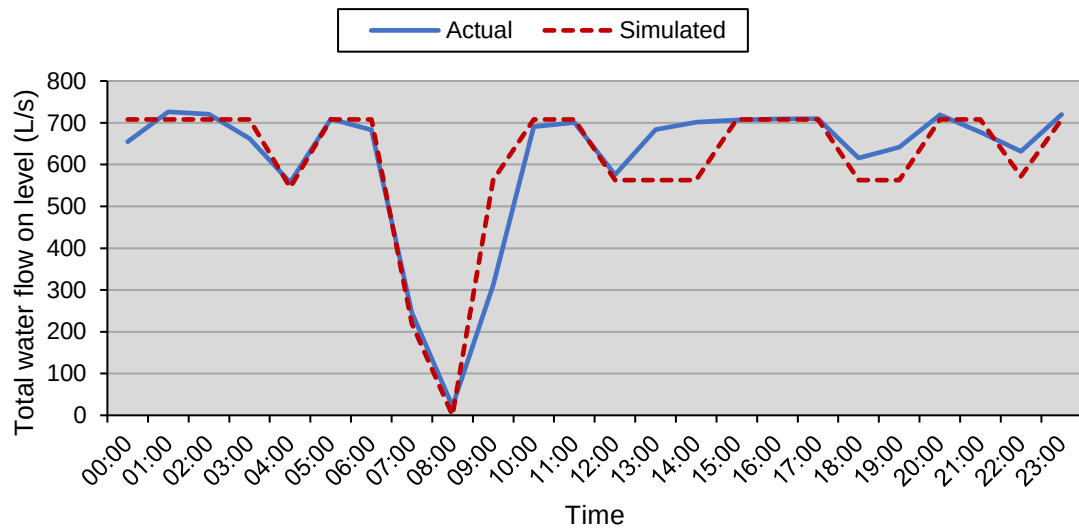


Figure 26: Verification example for simulated versus actual water flow values

The same procedure should be applied to the analysis of pump power and dam levels within the dewatering system of the relevant shaft to attain a level of accuracy of more than 95%. Moreover, the graphical representations should demonstrate a good correlation between the simulated data and the actual values.

2.3 Phase 3 - Model Implementation

Once the simulation model has been developed and verified, experiments should be designed to investigate the cost of load curtailment on dewatering systems. This involves investigating various load curtailment scenarios and quantifying the cost implications on the dewatering system. The simulation model developed in section 2.2 will be utilised to conduct these experiments and obtain results. The simulation method entails running multiple iterations of the simulation, each with different input variables representing various load curtailment events, particularly the duration of pump stoppages, and calculating the corresponding pumping electricity cost for each scenario.

To ensure a fair comparison between simulated scenarios, the operating conditions should remain consistent across all simulations, ensuring that components and parameters remain the same. It is crucial to maintain a constant dewatering volume throughout the simulations. Following a flow-neutral approach, the output flow of the system should be identical for each scenario to facilitate accurate comparison of electricity costs. This can be achieved by ensuring that the dam levels are equal at the beginning and end of each simulated scenario.

To accurately assess the cost effect of load curtailment, which is incurred after the load curtailment event itself, the simulation will consider the electricity cost over an extended period. Specifically for the simulation scenarios, a one-month test period will be utilised to determine and compare the pumping cost. While keeping the total monthly flow and other component parameters constant, the only variable parameter will be the duration and frequency of load curtailment. This independent variable represents the duration of pump stoppages, while the pumping cost serves as the dependent variable. It is essential to align these pump stoppages with Eskom's normal load curtailment schedule and the shaft's load reduction strategy to accurately reflect the system's behaviour. By considering these factors, the simulation can effectively evaluate the relationship between load curtailment and pumping cost, satisfying the study's second sub-objective.

Utilising the simulation to obtain results comprises four steps:

1. **Load Reduction Assessment:** Determine the extent of load reduction achieved through pumping stoppages at the mine shaft.
2. **Establish load curtailment threshold:** To ensure the fulfilment of dewatering requirements, it is essential to determine the maximum allowable load curtailment in terms of hours per month. This analysis aims to establish the threshold beyond which load curtailment compromises dewatering requirements, satisfying sub-objective 1.
3. **Run scenario-based simulations:** Simulations are conducted for various scenarios, with incremental increases in the number of hours dedicated to load curtailment. These simulations allow for a comprehensive evaluation of different load curtailment intensities and their effect on overall pumping cost-efficiency.
4. **Pumping cost evaluation:** The financial implications of varying load curtailment intensities can be accurately estimated by assessing the pumping costs associated with each scenario, satisfying sub-objective 2.

By following this methodology, a comprehensive understanding of the relationship between load curtailment, dewatering requirements, and pumping costs can be obtained, providing valuable insights for effective decision-making and optimisation of dewatering operations.

2.3.1 Phase 3.1: Load Reduction Assessment

In order to develop an effective load reduction strategy for the mine, it is crucial to accurately determine the actual load reduction achieved by ceasing pumping activities at a specific mine shaft. The mine is required to reduce its electricity load by a certain percentage dependent on the

stage of load curtailment enforced. This reduction must be achieved on average over a given period.

The baseline for this reduction, referred to as the curtailment baseload (CBL), is established using standards set out by NERSA, as explained in section 1.1.3.4. The specific method may differ depending on the agreement between Eskom and the client and this information should be determined from the mine so that a realistic CBL can be simulated. Even if the CBL is determined for the mining group overall it is essential to calculate the CBL specifically for the dewatering system of the shaft. This allows the mine personnel to precisely determine the amount of load reduction resulting from curtailing pumping activities and assess the need for implementing alternative strategies.

The CBL for the dewatering system represents the baseline load during the designated period of load curtailment. For instance, if load curtailment is implemented from 14:00 to 22:00 on a weekday, the baseline load during this period is considered as the CBL for that particular load curtailment event. Since pumping activities typically increase over weekends, ceasing pumping during weekends will result in a higher load reduction.

Equation 6 outlines the methodology employed to determine the load reduction:

$$\text{Load Reduction} = \text{CBL} - \text{Actual Load during Load Curtailment Period} \quad (6)$$

By accurately calculating the load reduction, the mine can gain insights into the effectiveness of pumping cessation in achieving load curtailment objectives. This information allows for informed decision-making and the exploration of additional strategies, if necessary, to optimise load reduction efforts.

Figure 27 below provides an illustration of the CBL, the required load curtailment (CBL minus the percentage reduction), and the actual energy profiles for a specific day.

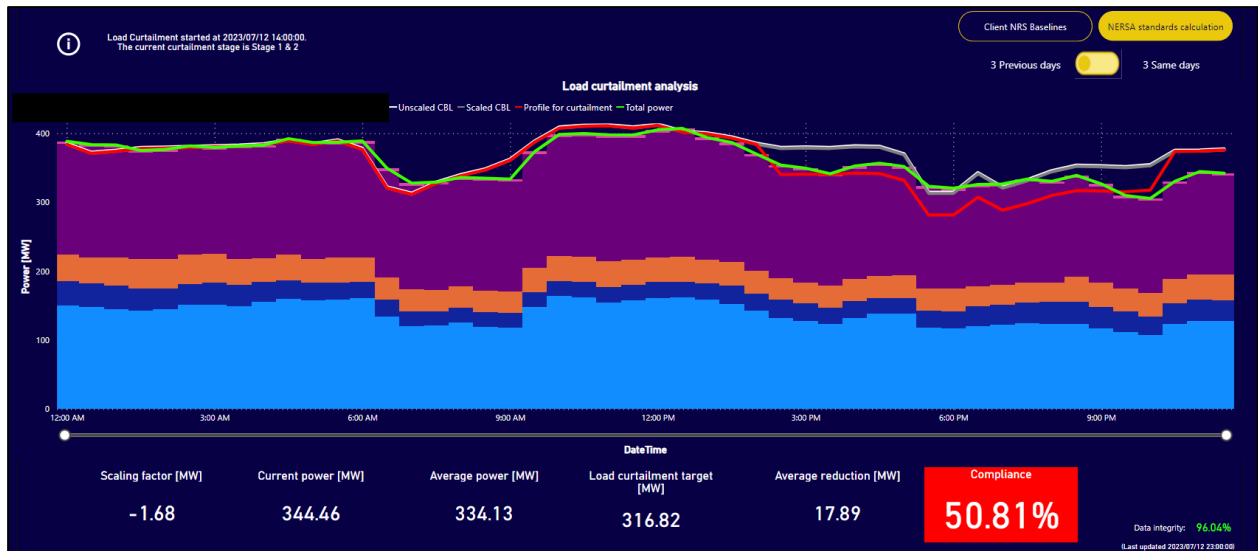


Figure 27: Curtailment baseline

For this study, the load reduction figure achieved through pumping stoppages holds significant importance, as it serves as a benchmark for comparing alternative load reduction strategies such as the utilisation of diesel generators. This is particularly important when pumping stoppages cannot be implemented, as the equivalent load reduction must be compensated for through the use of generators. Therefore, understanding the load reduction achieved by pumping stoppages allows for a meaningful evaluation and comparison of the effectiveness and feasibility of alternative strategies, such as employing diesel generators, enabling the achievement of sub-objective 4.

2.3.2 Phase 3.2: Establish load curtailment threshold

In order to analyse the cost of load curtailment on mine pumping systems using a simulation model, the load curtailment threshold for the dewatering system needs to be established. This step involves identifying the maximum duration of pump stoppages that the system can accommodate while still meeting the overall dewatering requirements of the shaft. Because the cost analysis is conducted over 30-day periods, monthly dewatering requirements are considered to determine the allowable load curtailment duration per month. To satisfy sub-objective 1, it is crucial to determine the threshold beyond which stopping pumps for load curtailment becomes unfeasible.

For simulation purposes, maintaining constant dam levels after a 30-day period is necessary, despite fluctuating values within the month. The dewatering requirements, in ML per month, are determined through system investigations and water balance equations outlined in chapter 2.2.

Once the dewatering requirements of the mine shaft are obtained, the corresponding pumping requirements can be determined. The maximum water outflow achievable is provided by the calibrated simulation model. Subsequently, the minimum number of hours per month of continuous pumping needed to meet the dewatering requirements is calculated. The remaining time in the month represents the maximum load curtailment duration threshold for the shaft, beyond which stopping pumps for load curtailment jeopardises the dewatering process.

In summary, the four steps to determine the load curtailment threshold for the shaft are as follows:

1. Establish the dewatering requirements for the shaft.
2. Determine the maximum achievable water outflow using the simulation model.
3. Calculate the minimum duration of pumping required to fulfil the dewatering requirements.
4. Determine the maximum load curtailment threshold for the shaft.

These steps allow for a comprehensive assessment of the dewatering system's load curtailment capacity and provide valuable insights for optimising load management strategies while ensuring effective dewatering operations. The rest of section 2.3.2 provides a detailed explanation of these four steps.

Establish the dewatering requirements

The dewatering requirements of the shaft forms part of the system information that needs to be gathered before developing the simulation model. Typically, data regarding the water inflow and pumped outflow of the shaft is available, and water balance calculations should be employed to determine the exact dewatering requirements, in ML per month.

Determine the maximum achievable water outflow

Next, the simulation model is utilised to determine the maximum achievable water outflow. By employing the most efficient pumping strategy that adheres to the operating constraints of the shaft, the simulation model calculates the maximum water flow rate. These operating constraints are obtained during the system investigation discussed in section 2.1. Specifically, the maximum number of pumps that can run simultaneously influences this determination and is dependent on the NMD and redundancy strategies. The simulation model considers the maximum number of pumps and the most efficient pumping strategy to calculate the maximum achievable outflow. It is important to consider the maximum flow rate for extended periods to accommodate the complexities of the dewatering system, including pump start-stop cycles.

Calculate the minimum pumping required

To determine the maximum pump stoppages that the system can accommodate, it is helpful to first calculate the minimum pumping required in a month. This calculation provides insight into the system's excess capacity and its ability to meet the pumping requirements.

Equation 7 is used to calculate the minimum pumping required in a month:

$$\text{Minimum pumping required} = \left(\frac{\text{Dewatering required}}{\text{Maximum outflow}} \right) * \text{Time period} \quad (7)$$

For the purposes of this study, the following units should be used:

Table 4: Units for minimum pumping calculation

Parameter	Units
Minimum pumping required	Hours per month
Dewatering required	ML per day
Maximum outflow	ML per day
Time period	720 hours (30 days)

By employing Equation 7 with the specified units, the minimum pumping required can be determined, providing valuable information for understanding the system's capacity and its ability to maintain effective pumping operations.

Determine the maximum load curtailment threshold

Finally, the maximum load curtailment threshold of the shaft's dewatering system can be determined. This threshold represents the maximum duration for which the pumps can be stopped without compromising the dewatering objectives, determined by calculating the remaining time in the month after achieving the dewatering requirements.

Thus, the load curtailment threshold is the minimum pumping required, as calculated from Equation 7, subtracted from the total time in the month. The result represents the remaining time available for load curtailment. The equation for determining the maximum load curtailment threshold in hours per month is as follows:

$$\text{Load curtailment threshold} = \text{Total time} - \text{Minimum required pumping time} \quad (8)$$

By performing this calculation, the maximum load curtailment threshold can be determined, thereby offering the solution for achieving sub-objective 1. This information provides valuable insights for load management strategies and optimising the balance between load reduction and dewatering requirements.

2.3.3 Phase 3.3: Run scenario-based simulations

The simulation model developed in section 2.2.3 will now be utilised to conduct tests simulating various pumping operation scenarios. These scenarios are designed to mimic different levels of load curtailment, characterised by the frequency and duration of pump stoppages, serving as inputs for the model.

Each simulation scenario involves incremental increases in the number of hours dedicated to load curtailment. The duration of pump stoppages starts at zero in the initial iteration and gradually extends until it reaches the load curtailment threshold time for the shaft under consideration. These increments should align with the actual load curtailment schedule experienced by the shaft, considering weekdays and the specific times when curtailment is implemented. This load curtailment schedule should be determined beforehand and should be based on historical data of load curtailment events at the mine, typically selecting a particularly severe month and adjusting the schedule accordingly. The total load curtailment duration for this schedule must be at least as long as the load curtailment threshold time calculated in phase 3.2.

For each scheduled load curtailment event, the CBL should be calculated. The CBL is derived from the baseline described in phase 3.1 and is specific to the weekday and time of each event. While this method may not precisely match Eskom's approach, it provides a close estimate without needing to account for all the slight variations in real-time calculation methods.

The PTB simulation tool allows for the specification of running schedules for dewatering pumps by defining the speed fraction of the pump for each period as demonstrated in Figure 28. In the initial iteration, the optimal scenario is established, representing no interruptions for load curtailment, maximum load shifting, and minimal electricity cost. This is achieved by running the most efficient pump combinations with maximum outflow, implementing optimal peak load shifting while meeting the shaft's dewatering requirements over a 30-day period. This optimal scenario serves as a benchmark against which the subsequent simulation iterations will be compared.

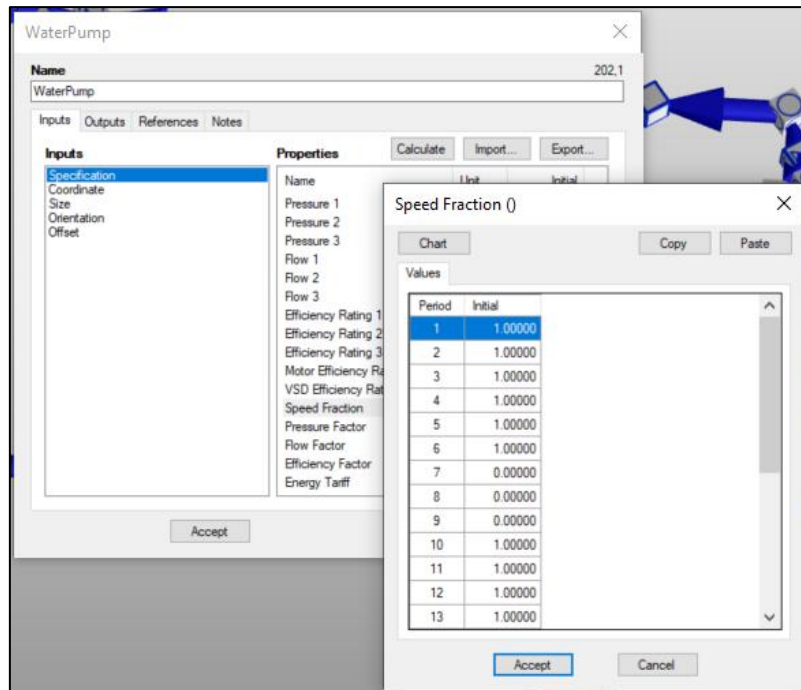


Figure 28: PTB pump schedules from speed fraction specification

The predetermined load curtailment events are then introduced one by one. In each iteration, the 30-day hourly pumping schedule is adjusted within the PTB model to maintain a consistent monthly outflow, matching the dewatering requirements. After each adjustment, the PTB simulation is run, and the following output results are recorded for each scenario:

- The cumulative number of load curtailment events and their duration (in hours).
- The overall average energy demand, average energy demand during peak times, and average energy demand during any DSM project assessment periods, if applicable.
- The total dewatering achieved over the 30-day period, which should align closely with the dewatering requirements. The deviation should be no more than 0.5 ML over the entire period.

The first iteration of the simulation needs to represent an ideal scenario in which no load curtailment is imposed, facilitating seamless pumping load shift during peak times. The integration of subsequent forced pump stoppages into the simulation continues until a point is reached where it is no longer possible to achieve the dewatering requirements without violating redundancy or safety protocols. These simulation results allow for a comprehensive evaluation of different load curtailment intensities and their effect on overall pumping cost efficiency, helping achieve sub-objectives 2 and 3.

2.3.4 Phase 3.4: Pumping cost evaluation

The final step in implementing the simulation model involves recording the pumping electricity cost associated with each simulated scenario. The PTB software includes a functionality that calculates the electricity cost for each component in the simulation. The power usage of all the pumps is plotted against the TOU tariff structures, allowing for the calculation of the corresponding electricity cost. The energy tariff for every time interval can be specified in PTB as shown in Figure 29.

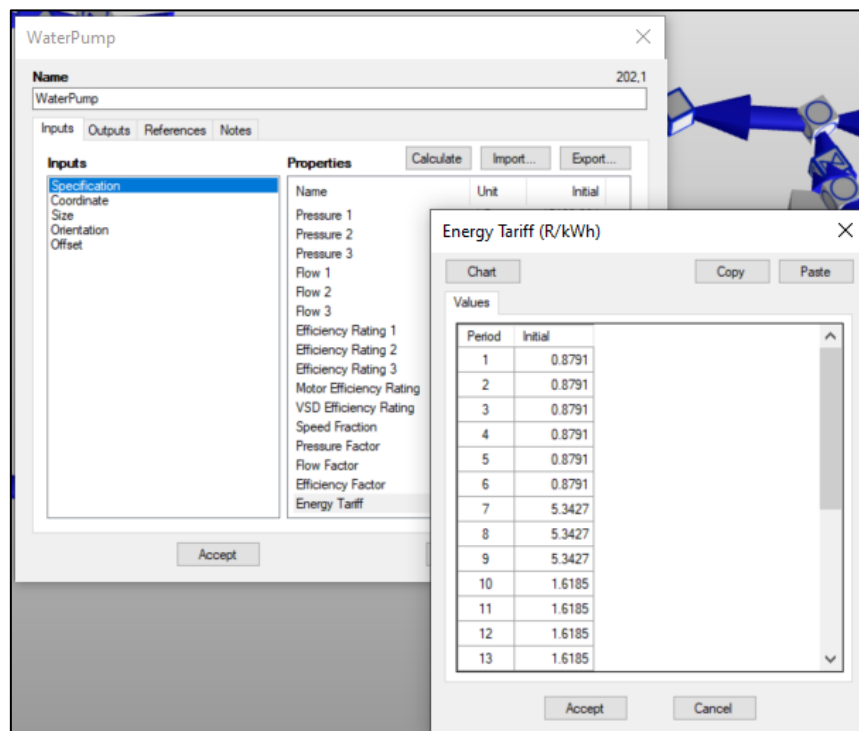


Figure 29: Energy tariffs in PTB

The total electricity cost associated with the dewatering system over the 30-day test period should be determined for each simulation scenario. The cost will be different for winter (high demand) and summer (low demand) periods. Therefore, for each scenario, a cost for summer and winter tariffs should be calculated and recorded. These results are crucial for evaluating the economic implications of different load curtailment scenarios and will be evaluated in the final phase of the methodology (Chapter 2.4).

2.4 Phase 4 - Analyse Results

2.4.1 Phase 4.1 - Evaluation of simulation results

The objective of this study is to determine the electricity cost implications of load curtailment on mine dewatering systems. Due to the inherent variability of mining operations, and mine dewatering specifically, it is challenging to precisely determine the expected savings or costs associated with implementing specific strategies.

To address this challenge, a simulation model is used to determine the pumping electricity cost under specific load reduction scenarios. Once the simulation experiments are conducted and results are generated, it is necessary to evaluate the obtained outcomes [55]. Breytenbach [137] suggests that an effective approach involves comparing the data to a power baseline.

A baseline serves as a reference point for comparing energy usage after a change in operation, such as the implementation of load curtailment, to the "normal operation". It represents the power usage trend of the system under normal circumstances. The baseline used for result interpretation should be representative of the system being tested. The difference in cost between the baseline and the simulated power profile quantifies the additional cost incurred due to load curtailment. By comparing the 24-hour power profile to the baseline, the cost effect can be calculated.

Several studies have investigated different approaches to establish baselines for evaluating system performance and cost effectiveness. To create a reliable baseline, de Jager [55] recommends incorporating data from an extended period and averaging energy usage over a 24-hour profile.

Van Niekerk [30] suggests that, given the variable nature of mining operations, the cost effects of interventions need to be calculated using energy neutrality. Energy neutrality requires scaling the baseline appropriately for accurate performance measurement [30, 57, 137]. Scaling involves adjusting the baseline by a factor based on the total power used during a reference period to match the total power used [55].

A study by Musabandesu [34] outlines a baseline calculation method employed in a DSM project in California. Separate baselines are determined for weekdays, weekends, and holidays, based on averaging energy consumption from non-participation days within a specific window. On the participation day, the raw calculated baseline can be adjusted using a same-day adjustment multiplier derived from the event day.

An example of the adjusted baseline, as used by Musabandesu [34], is shown below:

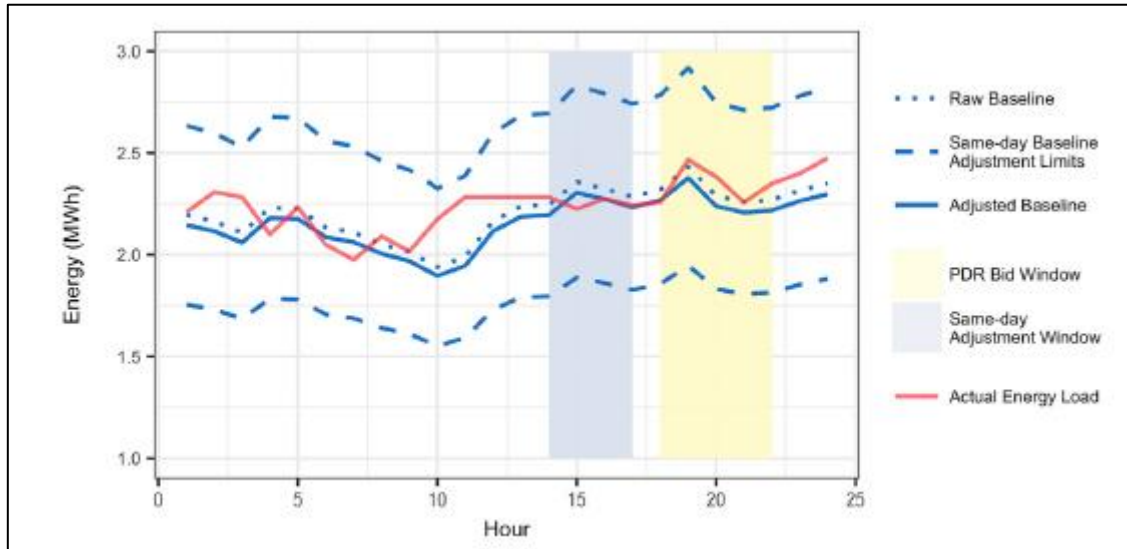


Figure 30: Example of adjusted baseline [34]

Sub-objective 3 is directed at assessing the effect of load curtailment on the performance of load shift in pumping operations. The performance of load shift projects in dewatering systems depends on the pumping period and the electricity cost during that period. The evaluation is typically conducted using a baseline on an energy-neutral basis, where the energy used before and after interventions should be equal [55]. For Eskom DSM projects, the assessment involves averaging the adjusted baseline minus the actual energy usage over a predefined period to determine if it meets a specific target.

Energy-neutral scaling and subsequent calculations have a limitation in that they may inadvertently penalise energy efficiency measures, potentially leading to lower perceived load shift savings despite actual cost savings due to energy efficient pumping. Additionally, different scaling methods can yield different results depending on the reference period. The variability introduced by different scaling methods and the confusion it can create prompts the decision not to utilise an energy-neutral adjusted baseline in this study for determining the pumping cost due to load curtailment.

Instead, an optimised baseline approach will be adopted, focusing on maintaining a constant eventual outflow. The PTB simulation model will be employed to determine an optimal energy usage profile [30]. This baseline represents the optimal operation of the pumping system and does not require scaling if the total outflow for all simulation iterations matches the total water

outflow of the simulated baseline. This constitutes *flow neutrality* rather than *energy neutrality* and is a more suitable method for calculating load shift savings at dewatering systems.

The power baseline will be established by running a simulation on the developed model under specific operating conditions. These conditions include:

- No forced pump stoppages due to load curtailment or any other reasons.
- Implementation of an optimal pumping load shift strategy.
- Total monthly water outflow that precisely matches the monthly dewatering requirements of the shaft.

In essence, the pumping schedule specified in the PTB simulation should prioritise pumping during off-peak TOU periods and align precisely with the dewatering requirements of the shaft over a 30-day period.

In the subsequent iterations of the simulation, which maintain the same flow requirements but incorporate load curtailment scenarios of varying severities, the additional electricity cost associated with each scenario can be determined. The cost incurred due to missed load shift savings resulting from load curtailment can be calculated using Equation 9:

$$\text{Cost due to load curtailment} = \text{Total simulated cost} - \text{Baseline cost} \quad (9)$$

This calculation is performed for each scenario, as specified in section 2.3, and the results are recorded, satisfying the main objective of the study as well as sub-objective 2.

In the case of an Eskom DSM load shift project taking place at the shaft, the simulation model is also used to assess the effect of load curtailment on the project's performance. The project will have a predetermined energy reduction target for a specified period (usually the evening peak period), which is obtained during the system investigation phase outlined in section 2.1.

During the assessment period for each simulated scenario, the average load reduction achieved is evaluated in comparison to the target set for the project. In each iteration of the simulation, it is determined whether the target is reached or not. If the target is not met, the percentage of the load shift target that is achieved is calculated, satisfying sub-objective 3.

After all these results are calculated, the following analyses need to be made:

1. The relationship between monthly load curtailment occurrence and the additional pumping electricity cost incurred.

The calculated cost of load curtailment resulting from pump stoppages and subsequent inefficient recovery pumping is graphed against the monthly load curtailment occurrence. The objective of this analysis is to investigate whether there is a correlation between the increased hours per month of load curtailment enforcement and the corresponding increase in electricity costs. To facilitate this analysis, a graph is created, with the monthly load curtailment duration depicted on the x-axis and the additional electricity cost represented on the y-axis. This analysis aims to meet sub-objective 2.

2. The relationship between monthly load curtailment occurrence and the performance of the load shift project.

The performance of a load shift project is assessed based on the average energy load reduction achieved during the assessment period. Using the results from the simulation scenarios, a graph is created with the monthly load curtailment duration on the x-axis and the average energy load reduction on the y-axis. The purpose of this analysis is to determine the threshold at which the DSM project at the shaft will begin to be compromised due to load curtailment, providing a solution to sub-objective 3.

2.4.2 Phase 4.2 - Feasibility of pump stoppages

In this study, starting diesel generators to offset electricity demand and achieve load reduction targets will be the only alternative strategy considered. The cost of using diesel generators will be compared to the strategy of stopping pumps for the same load reduction. By evaluating these options, the study aims to determine the most cost-efficient approach for load curtailment in mine operations, satisfying sub-objective 4.

The cost of operating diesel generators in a mine depends on the efficiency of the generators and the cost of diesel. The method for calculating the diesel generator consumption (in L/kWh) is described in phase 1.3. To calculate the total diesel generator cost required to achieve load reduction, Equation 10 can be used.

$$Cost_{gen} = Specific\ cost_{gen} * Energy\ reduction\ needed\ [MWh] \quad (10)$$

This equation allows for the determination of the comparative cost of diesel generators for each simulated scenario. The "load reduction achieved" results from each simulation iteration are utilised as inputs in the equation to represent the "energy reduction needed". As a result, for each load curtailment duration iteration, there will be a corresponding generator cost calculation.

With the information obtained from each simulated load curtailment duration scenario, including (1) additional pumping electricity cost, (2) energy load shift achieved, and (3) generator cost to achieve energy load reduction, a comprehensive feasibility analysis can be conducted. This analysis aims to determine the sustainable duration of pump stoppages by a mine's dewatering system. To visualise the data and draw meaningful conclusions, all the gathered information can be plotted on a single graph.

On the graph, the load curtailment duration in the month will be represented on the x-axis, while the y-axis will display the three data sets mentioned above for each load curtailment duration. The graph should clearly indicate the following key points:

- The threshold where the dewatering requirements can no longer be met, addressing sub-objective 1.
- The threshold where pumping during peak times becomes necessary, addressing sub-objective 3.
- The threshold where DSM load shift targets are not being met, further addressing sub-objective 3.
- The threshold where it becomes more cost-effective to operate diesel generators rather than stopping pumps, highlighting the tipping point where alternative strategies become more favourable, addressing sub-objective 4.

This graph provides a visual representation of the relationships and trade-offs between load curtailment compliance, dewatering requirements, cost implications, and the achievement of load shift targets. It serves as a valuable tool for assessing the feasibility and cost-effectiveness of load curtailment strategies in mine dewatering systems.

To account for seasonal variations in energy demand and tariff structures, it is crucial to conduct all the analyses and gather results separately for both summer and winter periods. Different tariffs are applicable during these seasons, with distinct pricing structures for low-demand and high-demand periods. By examining the data and outcomes specific to each season, a more comprehensive understanding of the cost implications and feasibility of load curtailment strategies can be obtained.

Figure 31 illustrates an example of a graph that will convey the necessary results in a legible manner.

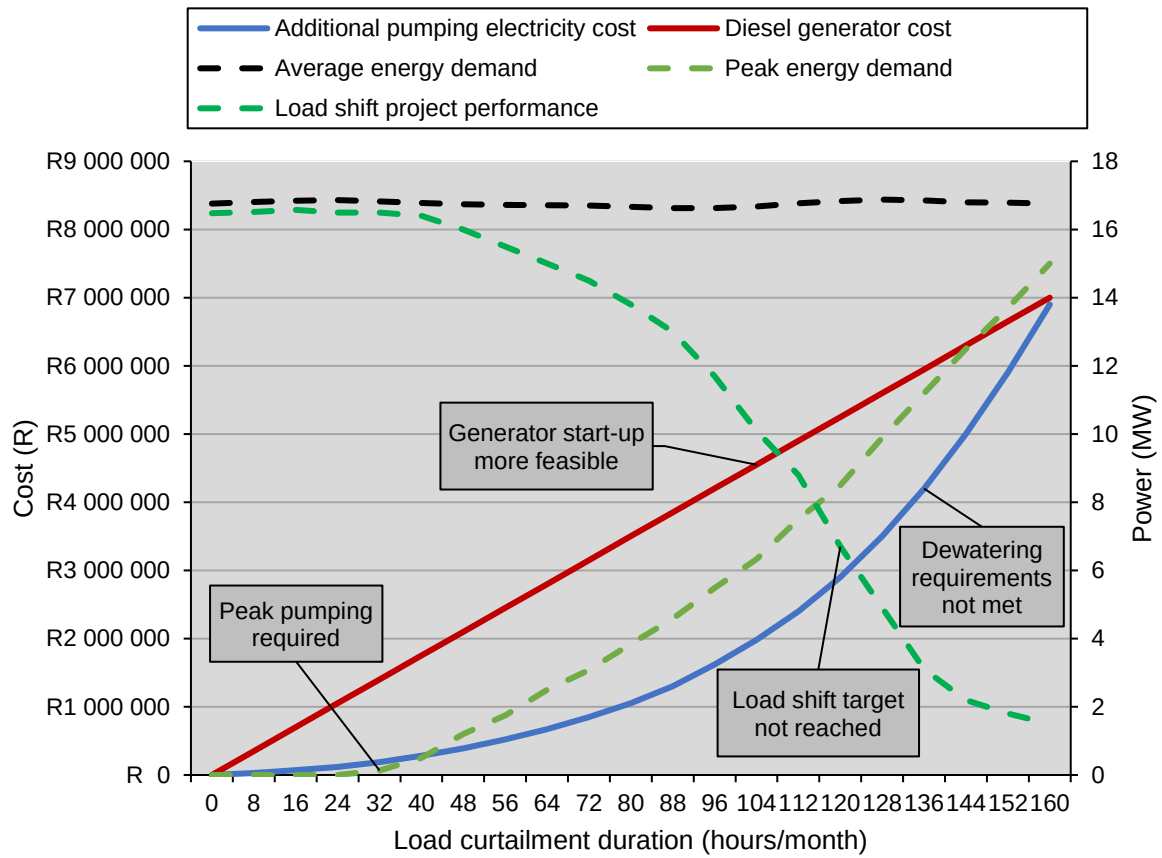


Figure 31: Template for load curtailment effect graph

CHAPTER 3 IMPLEMENTATION OF STRATEGY

Chapter 2 introduced a method for quantifying the cost of load curtailment on mine dewatering systems. The methodology, detailed in chapter 2, encompassed a comprehensive description of the required procedures, including the establishment of a digital twin simulation. This simulation facilitates the modelling of water flow and power consumption, thereby enabling the computation of electricity costs. By comparing the simulated costs with an optimal power baseline, any additional expenses due to load curtailment measures can be determined.

The developed methodology addresses the objectives derived from the shortfalls identified in previous literature, as discussed in section 1.4:

- **Sub-objective 1:** Assessment of load curtailment's influence on the pumping system's ability to meet dewatering requirements.
- **Sub-objective 2:** Evaluation of the effect of load curtailment on pumping-related electricity costs.
- **Sub-objective 3:** Examination of load curtailment's effects on the performance of pumping load shift.
- **Sub-objective 4:** Investigation into the feasibility of pump stoppages as a load reduction strategy during curtailment events.

In this chapter, the method devised in chapter 2 is applied to a real-world case study, specifically focusing on a dewatering system within a deep-level gold mine in South Africa. This case study has been chosen in alignment with the study's objectives. The criteria for the selection of the site as a case study comprise the following factors:

- Substantial volumes of water extraction through the shaft's dewatering system,
- implementation of pumping load shift strategies, and
- load curtailment agreement in place with Eskom.

To provide context, a brief overview of the site is presented, acquainting the reader with the operational environment. Necessary information and data, as outlined by the methodology in chapter 2, is provided.

The case study serves as a test to determine whether the simulation-based method can practically assess the costs associated with load curtailment in mine dewatering systems and effectively meet the study's objectives. For the case study shaft, a dedicated digital twin simulation model is

created. By comparing simulation outputs with actual site data, the model's accuracy is verified. The results of each phase of the methodology are presented and subsequently discussed. Furthermore, the feasibility of pump stoppages as a load reduction strategy is evaluated at the site, culminating in recommendations for load curtailment compliance.

Below, the step-by-step method outlined in chapter 2 is illustrated for reference.

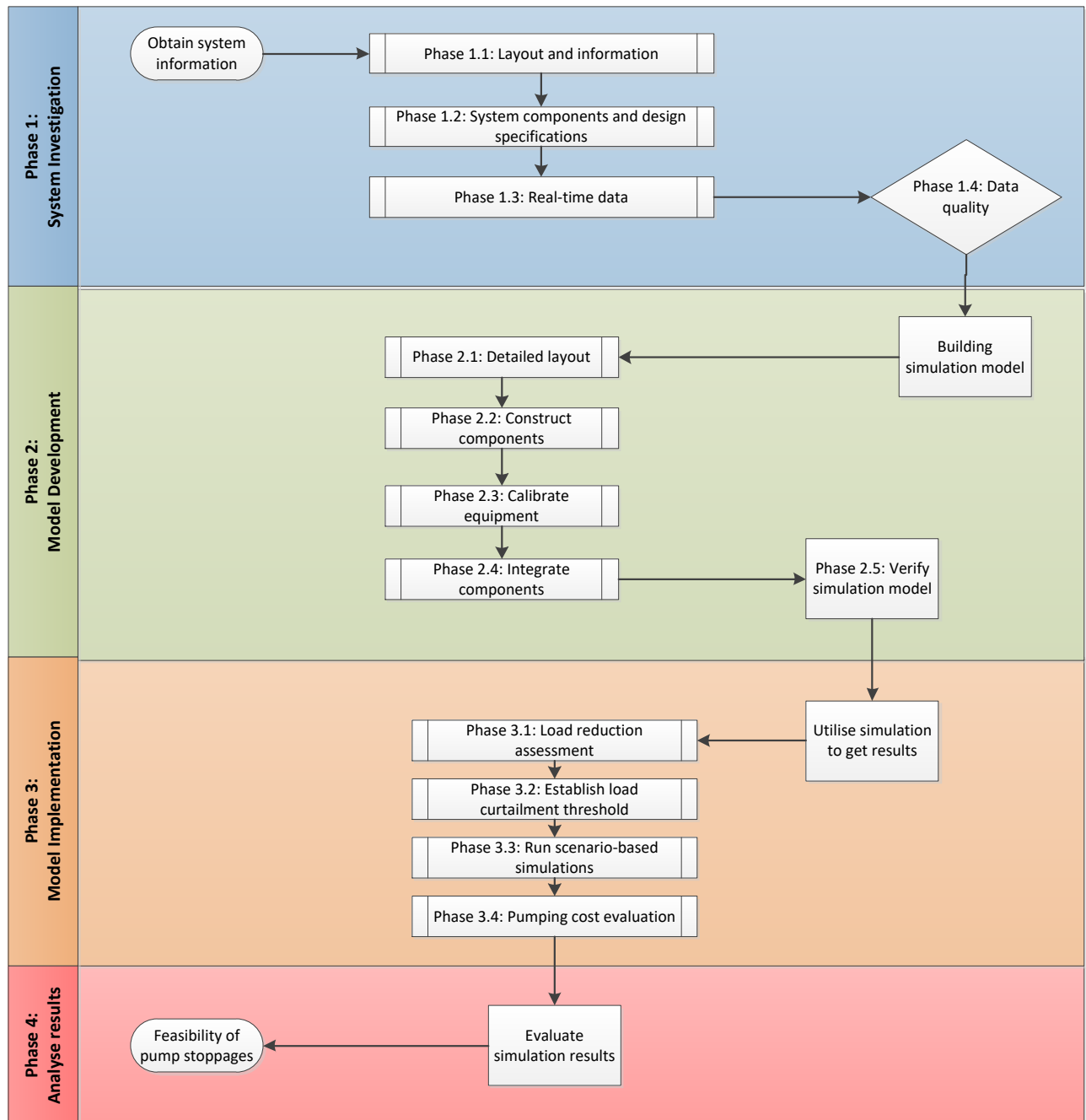


Figure 32: Step-by step methodology

3.1 Case study background

This case study mine shaft forms part of an integrated gold mining complex located in South Africa. For this study, the mining complex is referred to as “Mining Operation 1” and the shaft under consideration is referred to as “Shaft A”. Mining operation 1 is located within dolomitic groundwater compartments [138] and, despite innovative sealing methods, substantial fissure water inflows from the overlying dolomite aquifer continue to permeate the workings through geological features such as dykes and faults [138, 139].

A sub-vertical (S/V) shaft, originally employed for the extraction of gold deposits, was excavated at Shaft A, descending to a depth of more than 2 200 meters below the surface. Presently, Shaft A no longer serves as an active production site; instead, it functions as a care and maintenance shaft dedicated solely to dewatering operations. The primary role of Shaft A is the removal of a significant volume of groundwater from the entire mining complex, preventing flooding in adjacent production shafts.

3.2 Phase 1 - System Investigation

Phase 1 of the method involves the crucial task of information gathering. For the case study, the data acquisition method discussed in section 2.1 was applied, employing a combination of on-site and remote data to comprehensively investigate the system. The prescribed data acquisition steps, as defined in section 2.1.1, are illustrated in Figure 33 below.

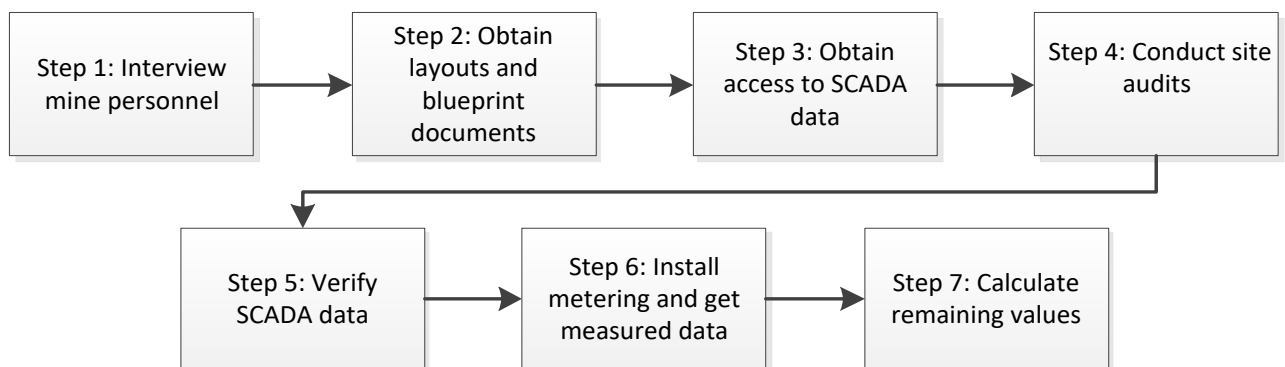


Figure 33: Data acquisition steps

Interviews were conducted with key mine personnel to initiate the process at Shaft A, including the engineering manager, shaft engineer, pumping foreman, and electrical foreman. This engagement was necessary for obtaining essential insights and materials. Layouts and blueprint documents of the shaft were secured, access to the mine's SCADA data was facilitated, and arrangements for underground audits were made. The documents received from these individuals included specification sheets of dewatering components and historical reports.

Real-time and historical data was remotely extracted from the mine's SCADA system. After the necessary training, a series of site audits were conducted to establish familiarity with the dewatering system. These audits included assessments of surface and underground infrastructure, equipment, pump stations, pipelines, and dams. The audits were further enriched by capturing footage of pump chambers and dams, coupled with spot-check flow measurements to corroborate the data retrieved from SCADA.

Validation of the spot-check flow measurements affirmed the reliability of the SCADA data. An anomaly emerged as one flow meter encountered a data transmission issue to the historian and this discrepancy was promptly addressed and rectified upon reporting to mine personnel. No additional meter installations or repairs were necessary.

With all the necessary data available, remaining unknown values such as water inflows and equipment efficiencies could be accurately calculated. The utilisation of the above-mentioned data acquisition steps facilitated the accumulation of the required information as outlined in section 2.1. The following section provides a detailed description of the assembled information.

3.2.1 Phase 1.1 - Layout and information

Chapter 2 suggested a methodology that involved conducting site audits and engaging with mine personnel to gain a thorough understanding of the dewatering system at the case study site. In line with this approach, a wealth of information was successfully gathered, encompassing layouts, essential background information, and operational details related to the dewatering system at Shaft A. This section presents the acquired layout and information, providing an overview of the system within the context of the study.

Layout

As Shaft A is a very old shaft where production was stopped many years ago, no reliable DXF files with level layouts could be obtained. However, the coordinates of the pumping levels and pump stations could be obtained. The depths below collar for each pumping station were provided

by the pumping foreman. Additionally, a ventilation model incorporating Shaft A was obtained from the ventilation department. This model included coordinate information for each node. Figure 34 shows the ventilation model used to find coordinates of key underground locations.

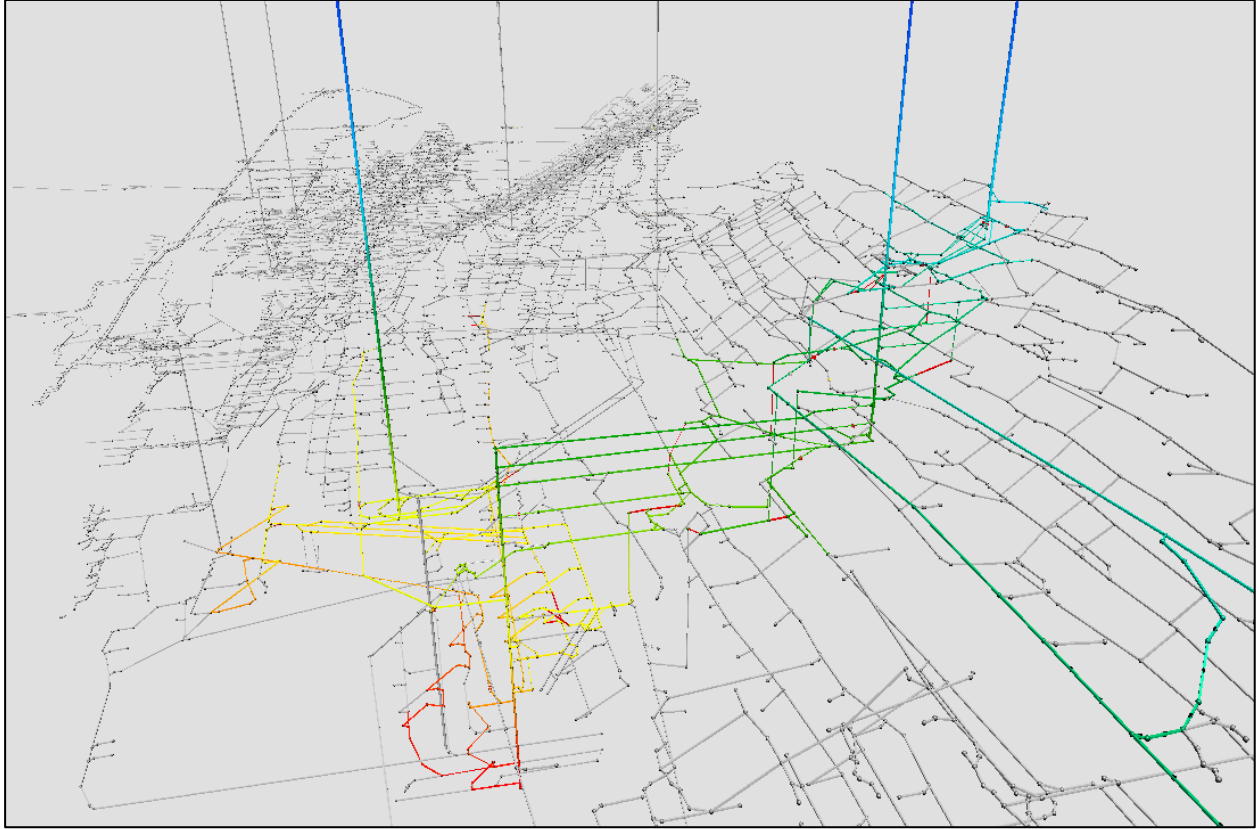


Figure 34: Shaft A - Ventilation model

After extensive deliberation with mine personnel, scrutinising the existing blueprint documents with coordinates, and comprehensive underground audits, the necessary insights into the layout and operation of Shaft A were obtained. The mine's SCADA viewer provided an invaluable contribution, affording an overview of all the dewatering infrastructure on the shaft.

This information was further verified with the conducting of underground audits. It was established that there are two active pumping levels at Shaft A. For the purposes of this study, the top level will be referred to as "level 1" or "L1", while the bottom level will be referred to as "level 2" or "L2". The coordinates obtained that will be used for the development of the simulation model are summarised in Table 5.

Table 5: Shaft A - Coordinates of critical locations

Area	X-coordinate [m]	Y-coordinate [m]	Z-coordinate [m]
Surface	0	0	-9.2
L1 main shaft station	-1	-2	-1217
L1 sub-shaft station	914	478	-1217
L2 sub-shaft station	916	481	-2212

Within these two pumping levels, a total of 12 multi-stage centrifugal pumps are housed across two pump stations. Facilitating the transfer of water between these levels are multiple pipe columns. Predominantly, the accumulation of fissure water transpires in a plug dam located on L2, with a smaller portion gathering on L1. Two hot water dams feature on each level, which serve as reservoirs for water storage.

Figure 35 illustrates a simplified two-dimensional layout of the dewatering system at Shaft A.

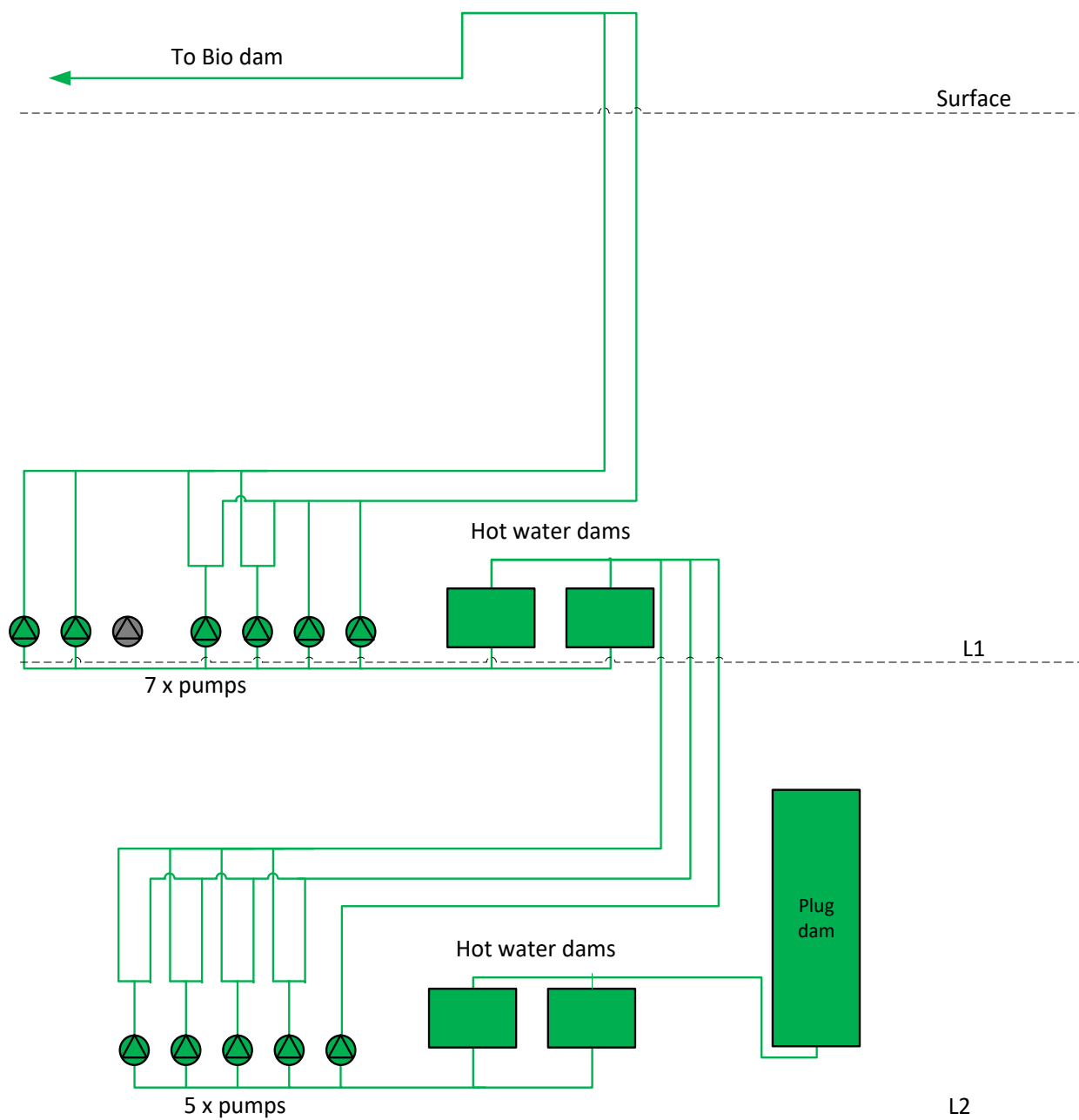


Figure 35: Shaft A - Simplified water reticulation system

Tariff structure and NMD

Similar to other large consumers, Mining Operation 1 makes use of the non-local authority Megaflex tariff structure. This tariff arrangement comprises a dynamic TOU pricing framework, along with charges for maximum demand, quantified in kVA. Mining Operation 1 is considered a key Eskom customer, with a transmission zone under 300 km and a voltage bigger than 500 V and smaller than 66 kV. In alignment with this classification, Mining Operation 1 adheres to the tariffs shown in both Table 22 and Table 23 in Appendix B. It is important to note that the mine

faces elevated charges during the high-demand winter period, which extends from 1 June to 31 August.

The mine sources its power directly from Eskom and does not procure electricity from a municipality. Power supply to Shaft A is facilitated through two PODs, possessing NMDs of 22 000 kVA and 5 200 kVA respectively. Pumps 5, 6, and 7 on L1 are linked to the 5 200 kVA feeder, while all additional pump motors draw power from the 22 000 kVA feeder. To curtail the maximum energy demand, capacitor banks are deployed for PF correction.

In scenarios where the NMD threshold is surpassed, an excess network capacity charge of R42.49 per extra kVA consumed is incurred. This cost is further multiplied by the frequency of NMD breaches in the preceding 12 months. For example, if the NMD has been exceeded in 5 out of the previous 12 months, the charge becomes $5 \times 42.49 = \text{R } 212.45$ per excess kVA.

Pumping control mechanism

Despite the availability of remote-control capabilities for certain pumps at Shaft A, the operational practice still involves pump operators manually initiating the activation or deactivation of pumps as well as the manipulation of valve positions. The mine asserts that this manual involvement is crucial for addressing potential issues promptly. To facilitate this operational framework, a control room operator stationed on the surface continuously monitors the SCADA system. This control room operator is responsible for implementing the pre-established pumping strategy.

DSM Projects

An Eskom DSM project has been introduced at Shaft A from December 2022, aiming to reduce the power consumption of the pumping system during the evening peak periods. The project's target is to achieve an average reduction of 6.7 MW during the evening peak period compared to an official predetermined baseline. The baseline that serves as the reference point for evaluation is graphically presented in Figure 36 and outlined in Table 24 in Appendix C. It is worth noting that this baseline undergoes routine adjustments in accordance with the stipulations outlined in SANS50010, factoring in changes in energy demand at Shaft A. The assessment of project effectiveness transpires in 3-month intervals, during which the average load shift is required to maintain or exceed the 6.7 MW target.

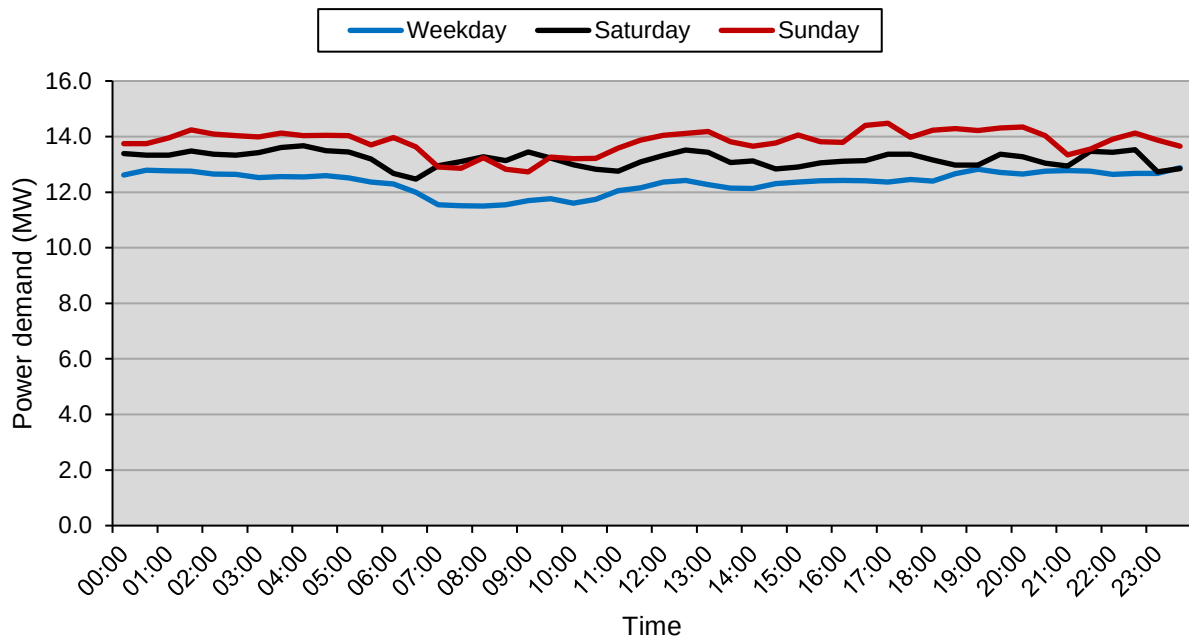


Figure 36: DSM Project power demand baselines

Load reduction strategies

Mining Operation 1 comply with the NRS 048 requirements and are eligible for notified load curtailment. For load curtailment events, a 10%, 15%, or 20% load reduction over the whole mining group must be achieved, depending on the stage of load curtailment. The average energy demand of the mining group is approximately 400 MW, indicating that the amount of load that needs to be reduced at the mining group is as follows:

Table 6: Load curtailment energy reduction

Load curtailment stage	Energy reduction [%]	Energy reduction [MW]
1/2	10%	40 MW
3	15%	60 MW
4	20%	80 MW

The following actions are typically implemented to comply with load reduction targets:

- Normal load shift,
- gold plant mill stoppages,
- pumping stoppages,
- diesel generators,
- load shedding at housing, and
- hoisting stoppage.

Compliance, measured as a percentage value of required reduction, is closely monitored by the mine and Eskom. Although normal load shift measures on mine systems must be implemented during load curtailment events, this is already factored into the CBL and, therefore, does not reduce the energy load sufficiently. Additionally, pump stoppages are prioritised as the preferred load reduction strategy, with the operation of diesel generators the next most suitable alternative. Low-density residential load shedding is only implemented with stage 3 and 4 of load curtailment. Stopping mills and curtailing hoisting is prevented as far as possible, as this negatively effects the mine's production output.

Redundancy strategies and other constraints

Mining Operation 1 has a policy that requires the dewatering system to have 100% redundancy for all components. This means that if, for instance, the minimum number of pumps required to run to achieve the dewatering requirements is two, then there must be four pumps installed. This is also applicable for other components such as dams and columns to ensure that when a breakdown occurs, there is spare capacity to ensure the mine does not flood.

At the time of this study, at Shaft A, one of the pipe columns in the main shaft (from L1 to surface) burst beyond repair and was not in use. A new pumping column was being installed but was not yet finished. Consequently, there was no redundancy with only two columns in operation. Regarding the hot water dams, keeping one dam entirely empty for emergency situations was not deemed necessary. However, it is imperative that dams in active use do not surpass the 100% capacity threshold. Furthermore, they should consistently be kept at levels above 25% to guarantee that no mud is inadvertently pumped into the system.

3.2.2 Phase 1.2 - System components and specifications

For assessing the cost of load curtailment, it's necessary to obtain the characteristics of the machinery employed in dewatering activities at Shaft A. Information regarding design specifications of components, as described in section 2.1.3, was gathered from audits and specification sheets and is discussed in this section.

Pumps

As previously discussed, there are two pumping levels at Shaft A. The L1 pump station houses seven pumps, but one pump is non-operational, leaving only six remaining pumps. The L2 pump station has 5 pumps, all of which are operational. These pumps range from 8-stage to 12-stage configurations, with rated power capacities spanning from 2 750 kW to 3 300 kW. Extensive audits

were done on both levels, gathering all the necessary information about the pump specifications. The information gathered is summarised in Table 7 below:

Table 7: Dewatering pump specifications

Pump station	Pump number	Pump make and model	Rated power	Rated flow	Head
1	1	Sulzer PJ250	3300 kW	200 L/s	1208 m
	2	Sulzer PJ250	3300 kW	200 L/s	1208 m
	3	Sulzer PJ250	3300 kW	200 L/s	1208 m
	4	Sulzer PJ250	3300 kW	200 L/s	1208 m
	5	Sulzer PJ250	3300 kW	Not operational	1208 m
	6	Sulzer PJ250	3300 kW	200 L/s	1208 m
	7	Cemo HPH 58/25	3300 kW	220 L/s	1208 m
2	1	Cemo CPH 580	2750 kW	180 L/s	995 m
	2	Cemo CPH 580	2750 kW	180 L/s	995 m
	3	Sulzer PJ250	2750 kW	200 L/s	995 m
	4	Sulzer PJ250	2750 kW	200 L/s	995 m
	5	Cemo CPH 580	2750 kW	180 L/s	995 m

The actual flow and power values for the pumps as well as the efficiencies will be calculated later. An example of a multi-stage centrifugal pump in an underground pump chamber is shown in Figure 37.



Figure 37: Underground dewatering pump

Pipe columns

Facilitating the transfer of water between levels are multiple pipe columns. There are three operational pipe columns in the sub-vertical shaft between the two pumping levels, and two operational pipe columns in the main shaft between L1 and the surface. The specifications of the pipe columns at Shaft A are shown in Table 8.

Table 8: Shaft A - Pipe column specifications

Area	Column	Nominal bore (diameter)
Sub-vertical shaft	Column 1	300 mm (12")
	Column 2	400 mm (16")
	Column 3	350 mm (14")
Main shaft	Column 1	400 mm (16")
	Column 2	400 mm (16")
	Column 3	Not operational

The length of all the pipes will not be defined but they will automatically be incorporated into the simulation from the defined coordinates of the pumping stations.

Valves

Actuated valves are used to connect pumps with columns. There are also non-return valves. Figure 38 shows an example of the valve setup at one of the pumps.



Figure 38: Valves

To regulate the outflow from the plug dam to the clear water dams on the L2, valves are strategically employed. The water flow is controlled by a manual valve and an actuated valve in the column, shown in Figure 39. This actuated valve is automatically controlled using the dam levels of the clear water dams.



Figure 39: Plug dam valves

Dams

Shaft A has two clear water dams on each of the pumping levels, each with a capacity of 3 ML, meaning that each pumping level has a total water storage capacity of 6 ML. In both cases, the dams are located close to the pump chamber. There is a large plug dam on L2, close to the sub-vertical shaft's bottom.

Due to the nature of plug dams, which are, in essence, merely flooded mine shafts or old mine areas, it is impossible to determine their exact volume. These dams are technically infinitely big; the only constraints on the amount of water volume they can contain are the level at which water starts to flood to active mining areas and the pressure at which the plug wall will break. According to the mine, the maximum allowable dam level is 40 m to ensure the structural integrity of the dam wall. When the dam is at a 40 m level, the approximate water volume in the dam is 640 ML. Figure 39 shows the plug dam wall with the discharge column and valves.

Table 9 provides a summary of the locations of all hot water dams, along with their estimated capacities. The volumes of these dams could only be approximated based on the given length, width, and height information documented in previous dam surveys.

Table 9: Shaft A - Dewatering dam information

Level	Description	Dam capacity
L1	Hot water dam 1	3 ML
	Hot water dam 2	3 ML
L2	Hot water dam 1	3 ML
	Hot water dam 2	3 ML
Total		12 ML

The dam levels at Shaft A do not have rigid minimum and maximum levels. On L1, pumps are switched on and off in reaction to the combined dam level, the average between the two 3 ML dams, and depending on the TOU time. During peak time, the first pump will only be switched on when the virtual dam level reaches 70%, while the first pump will be switched on during other times when the combined dam level is 25%. The dams are never allowed to reach 100%, as this indicates that they are overflowing. However, it is important to note that this process is not automated and that the alarms act as prompts for the pump operators to manually switch pumps on or off depending on the proposed strategy.

On L2, there are also prompts on SCADA that will initiate the pumps starting or stopping. However, the plug valve position is also controlled according to the dam levels. When the combined dam level is 40%, the plug dam will open, and water will flow into the clear water dams. The dams fill up until they reach 70%, at which time the plug valve closes again. In effect, this process overrides the pump scheduling prompts, as there are no other sources of water on L2 apart from the plug dam.

Considering this information, the 2D layout of the dewatering system at Shaft A can be updated.

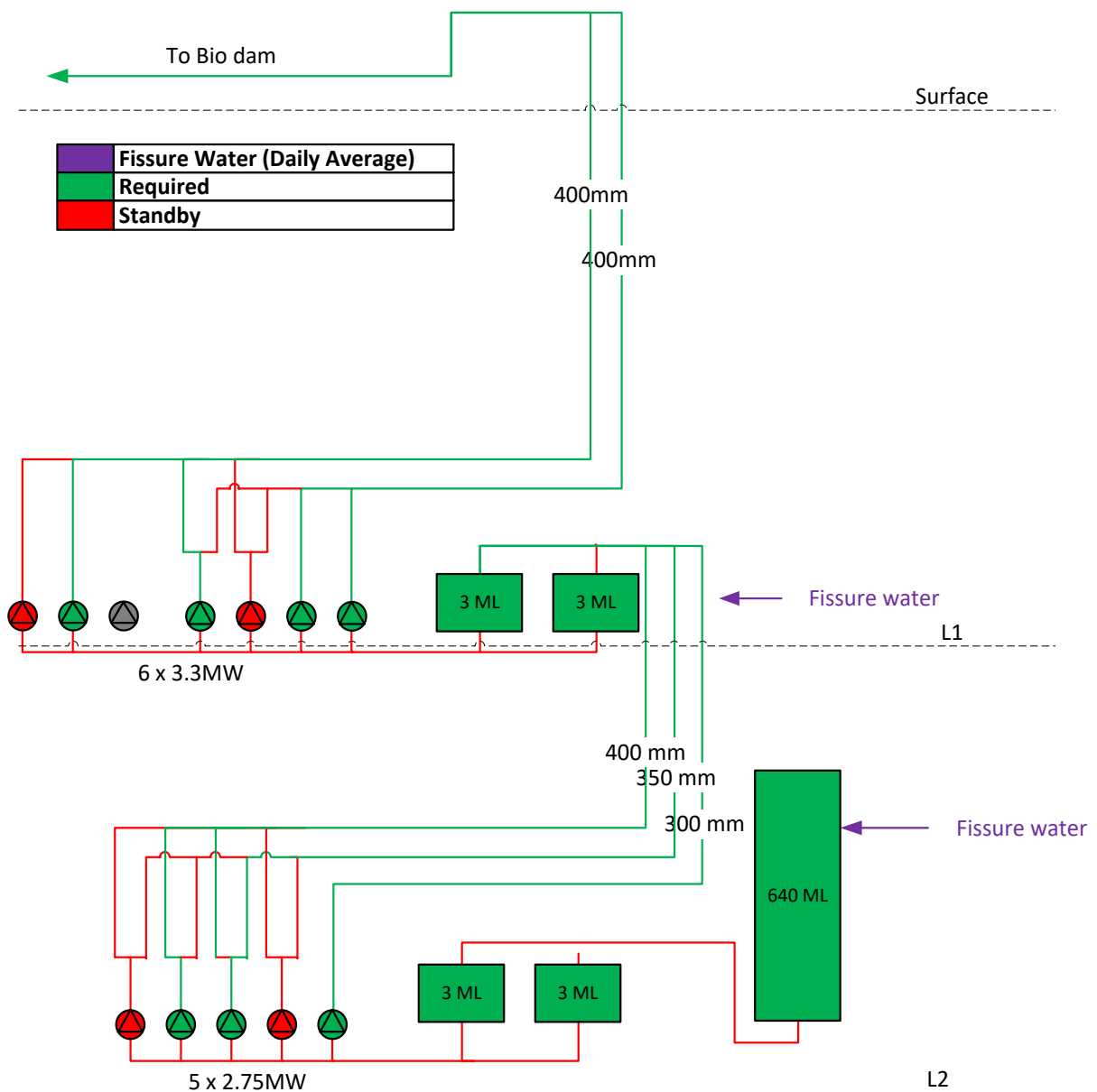


Figure 40: Dewatering layout with valve connections and component specifications

3.2.3 Phase 1.3 - Real-time data

The historical database of the SCADA, referred to as the historian, was used for data extraction. Historical data of all critical measuring instruments, including flow meters, power meters, and dam level transmitters, were logged from the historian and downloaded in CSV format for January 2022 until July 2023. Each parameter is stored under an individual tag name as discussed in section 2.1.4. This data was analysed and used to develop the simulation and create power baselines.

Water flow rates

From the historical data, the flow rates of each pump combination could be obtained. At Shaft A, in-line flow meters are used as shown in Figure 41. These flow meters were verified by comparing their flows measurements to data acquired from portable flow meters used during underground audits. In every instance it was found that the water flow rates given by SCADA were within a 5% accuracy of the measurements taken using portable equipment. The flow meter data was extracted from the SCADA system and analysed.



Figure 41: Water flow meter at Shaft A

A graphical example of water flow data downloaded from the SCADA server is shown in Figure 42. In this instance, the flow between the two pumping levels is shown over a 24-hour period as a stacked area graph.

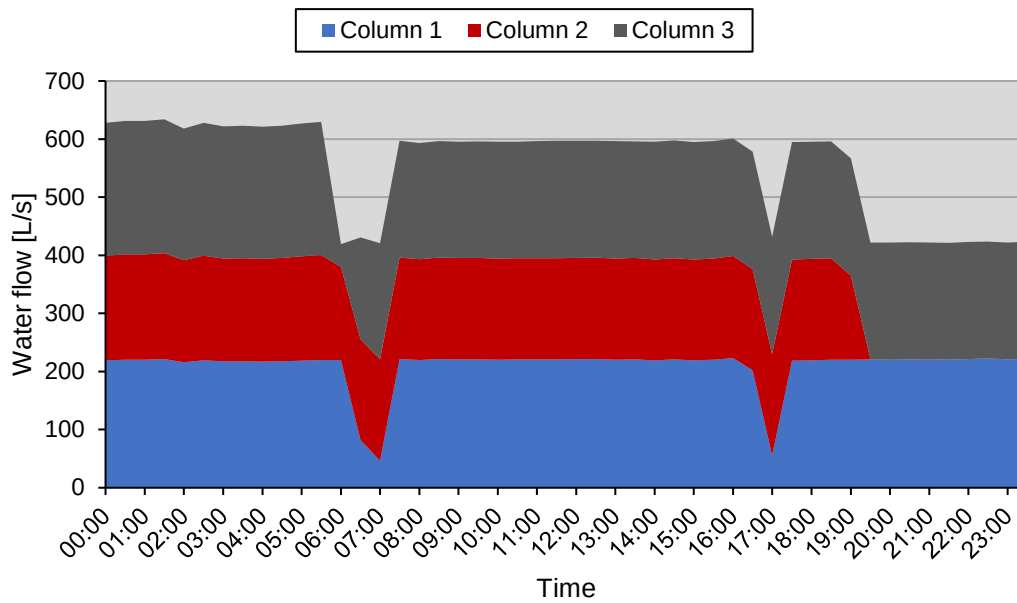


Figure 42: Shaft A - 24-hour water flow profile between pumping levels

The analysis comprised determining the average water flow rates in each column for each combination of pumps. These values will be used in the development of the simulation model and are summarised in Table 25, shown in Appendix D.

Power usage

Similarly, the electricity usage of each pump combination could be obtained from the historical data. Load shift is implemented regularly at Shaft A, which can be seen from the pumping power profile for a typical winter weekday shown in Figure 43. The power for each combination of pumps that will be used for the development of the simulation model is summarised in Table 25, shown in Appendix D.

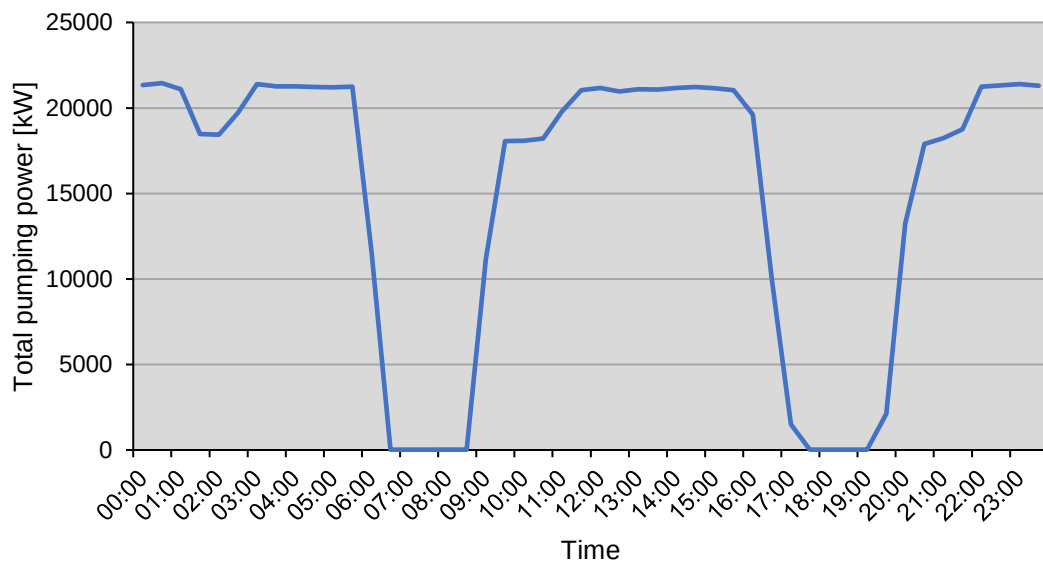


Figure 43: Shaft A - Typical pumping 24-hour profile

Dam levels

The plug dam and the hot water dams on pumping levels have real-time extractable data for dam levels. As previously discussed, the plug dam level is kept at 18m as far as possible. Figure 44 represents the extracted plug dam level data for June and July 2023.

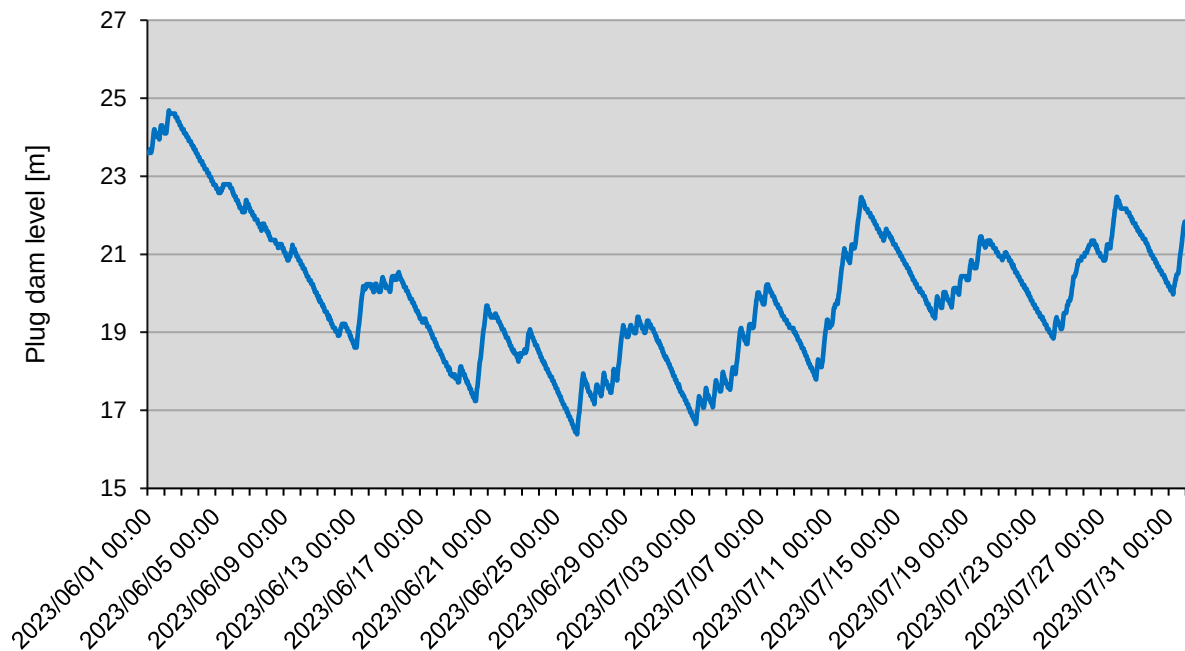


Figure 44: Plug dam level data

The 3 ML dam levels on both levels are controlled according to the TOU times. The data for the combined dam levels were extracted from SCADA. From the data it can be seen that the dam levels are following the set points. Figure 46 illustrates an example of combined dam level data of L2, clearly fluctuating between 40% and 70%.

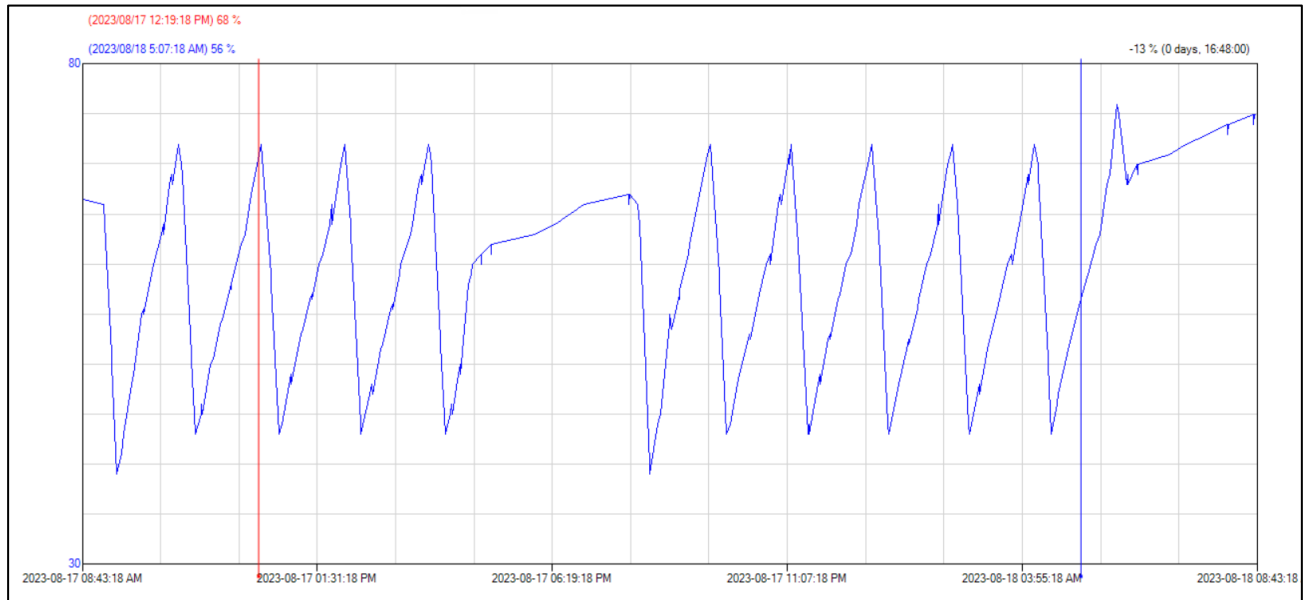


Figure 45: Combined level data of L2 hot water dams

Diesel generators

Mining Operation 1 has 16 generators, eight 1.2 MW generators, and eight 1.0 MW generators. These generators feed directly into the mine's meter panels, mostly those housing essential systems such as winders. Data regarding the power generated by these generators could be extracted from SCADA. The diesel tank levels of each generator are also found on the SCADA system, and the diesel usage can be determined from these values.

The power generated and diesel used could be compared and the diesel generator consumption calculated using Equation 3. For a period where all the generators were in operation during load curtailment, data was extracted, and the specific energy calculations done. Table 10 summarises the extracted diesel usage and power data for the generators.

Table 10: Diesel generator data

Generator	Diesel used [L]	Power generated [MWh]
1.2 MW generators	100 415.4	409.94
1.0 MW generators	95 025.0	357.84
Total	195 440.4	767.78

These values were used to determine the generator consumption using Equation 3. The results are presented in Table 11.

Table 11: Diesel generator specifications

Generator size [MW]	Diesel consumption [L/MWh]
8 x 1.2 MW	245.0
8 x 1.0 MW	265.6
Average	254.5

If all the generators are running simultaneously, a total of 17.6 MW can be generated. The diesel consumption for the entire generator system is then calculated as 254.5 L/MWh. At the time of this study, Mining Operation 1 purchased wholesale diesel at R22.83 per litre. The cost per kWh of running diesel generators was then calculated with Equation 4.

$$Specific\ cost_{gen} = Consumption_{gen} * Cost_{diesel} \quad (4)$$

$$= 0.2545 * 22.83$$

$$= R\ 5.81/kWh$$

Thus, the cost of generating one Megawatt-hour of electricity from the Mining Operation 1 generators is R5 811.50.

Water quantity

As Shaft A does not engage in production activities, service water is not introduced into the system. There is no underground machinery, mining activities, or cooling operations that require chilled water. Consequently, the dewatering process is exclusively concerned with fissure water. Underground fissure water sources discharge mainly into the plug dam. Table 26, shown in Appendix E, provides a summary of the average daily water pumped to the surface over 12 consecutive months from August 2022 to July 2023. This information is graphically shown in Figure 46.

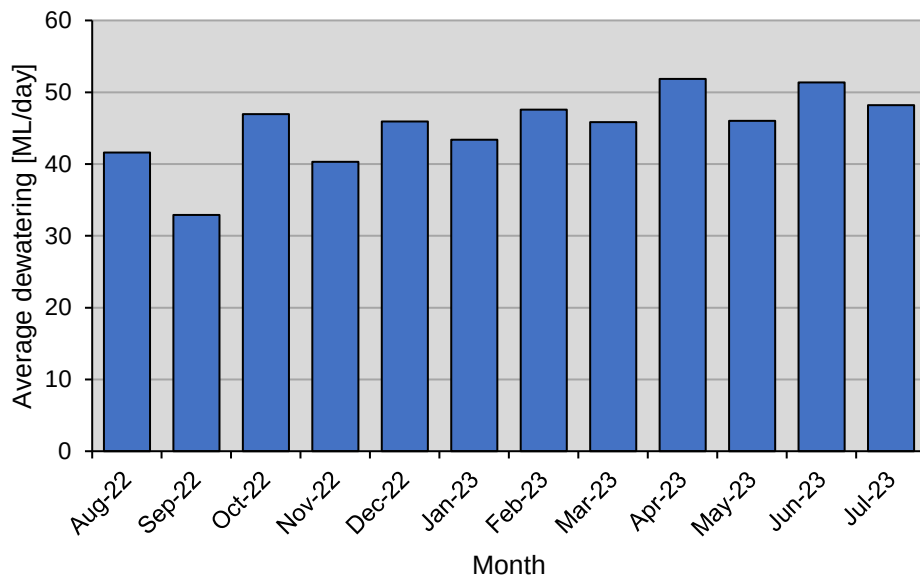


Figure 46: Shaft A dewatering quantity

However, these monthly average values were found to inadequately represent the actual water inflow into the shaft. This discrepancy arises from the omission of considerations for fluctuations in underground dam levels. For example, the plug dam level at the start of a month may be low and subsequently increase throughout the month due to insufficient dewatering. Consequently, more dewatering becomes necessary during the next month to reduce groundwater levels. While the water inflow itself may remain relatively constant, the outflow data can mistakenly convey significantly different dewatering requirements between these two months.

To rectify this issue, a comparative analysis was undertaken by selecting five time periods of approximately a month each during which the start and end plug dam levels were identical. The objective was to calculate the average flow from the shaft over the duration of these intervals as measured by the installed flow meters. This approach helps ensure that distinct pumping strategies do not influence the results. The results of this analysis, as applied to flow and dam level data from June and July 2023, and presented in Table 12, provide a more accurate determination of the recent inflow of fissure water at Shaft A.

Table 12: Shaft A dewatering quantity calculation

		Period 1	Period 2	Period 3	Period 4	Period 5	Average
Date and Time	Start	2023/07/06 23:00	2023/06/30 19:00	2023/06/07 22:30	2023/06/17 15:00	2023/06/12 03:00	
	End	2023/07/31 06:30	2023/07/24 07:00	2023/07/12 17:00	2023/07/10 20:30	2023/07/09 02:00	
	Total (days)	24.31	23.50	34.77	23.23	26.96	
Plug dam level	Start	19.96	19.00	21.69	19.05	19.02	
	End	19.97	19.00	21.66	19.02	19.00	
Average flow out Level 1	L/s	571.71	570.20	572.00	571.48	572.54	571.59
	ML/day	49.40	49.27	49.42	49.38	49.47	49.39
Average flow out Level 2	L/s	490.15	487.90	488.74	488.13	489.18	488.82
	ML/day	42.35	42.15	42.23	42.17	42.26	42.23
Error margin	ML/day	0.25	0.26	0.17	0.26	0.22	0.23
	%	0.50%	0.52%	0.35%	0.52%	0.45%	0.47%

From this analysis, an average daily water inflow of 49.4 ML is experienced at L1, and an average daily water inflow of 42.2 ML is experienced at L2. Additionally, these calculations enabled the estimation of the quantity of fissure water reporting at L1 by subtracting the contribution from L2 from the total inflow. Assuming there are no additional fissure water sources contributing to the total, the average inflow at L1 was determined to be 7.15 ML/day or 82.8 L/s.

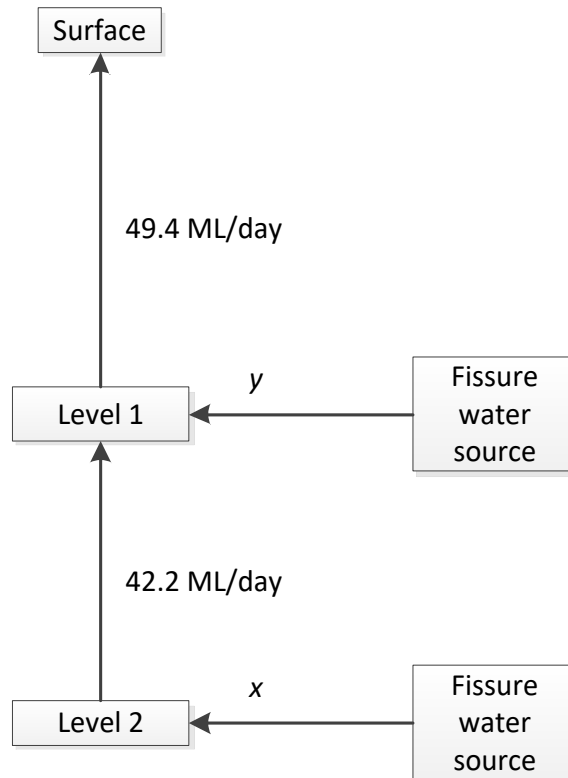


Figure 47: Shaft A - Water balance equation

The water balance diagram above yielded values for x and y , shown in Table 13.

Table 13: Shaft A - Fissure water quantity

Source	Fissure water quantity
L1 (y)	7.2 ML/day (82.8 L/s)
L2 (x)	42.2 ML/day (488.8 L/s)
Total	49.4 ML/day (571.6 L/s)

3.2.4 Data quality

In accordance with Booyesen's method [123] described in section 2.1.5, the quality of the acquired data was evaluated. From analysis of the historical data extracted from SCADA, as well as utilising information from specification documents and mine personnel, upper and lower limits for data points were established. Any data falling outside these predefined parameters, along with static values and periods of data loss, were systematically reviewed and excluded from consideration. The average flow and power values, as discussed in the previous section, were calculated from data sets that had undergone thorough filtering to remove irregular values. The maximum and minimum water flow limits employed in the calculations are summarised in Table 14.

Table 14: Dewatering system flow limits

Column	Minimum flow limit [L/s]	Maximum flow limit [L/s]
S/V shaft Column 1	0	300
S/V shaft Column 2	0	450
S/V shaft Column 3	0	450
Main shaft Column 1	0	450
Main shaft Column 3	0	450

Figure 48 illustrates the application of Booyesen's method [123] on flow data for column 3 between the two levels, with specific data from the 4th of July 2023, including upper and lower limits depicted in the graph. Evaluation of this data clearly reveals instances where the flow data fell below the established lower limit of 0. Additionally, a brief period of data loss was observed. These data points were excluded from the calculations. Several similar occurrences were identified from the flow meter measurements and the data was adapted accordingly.

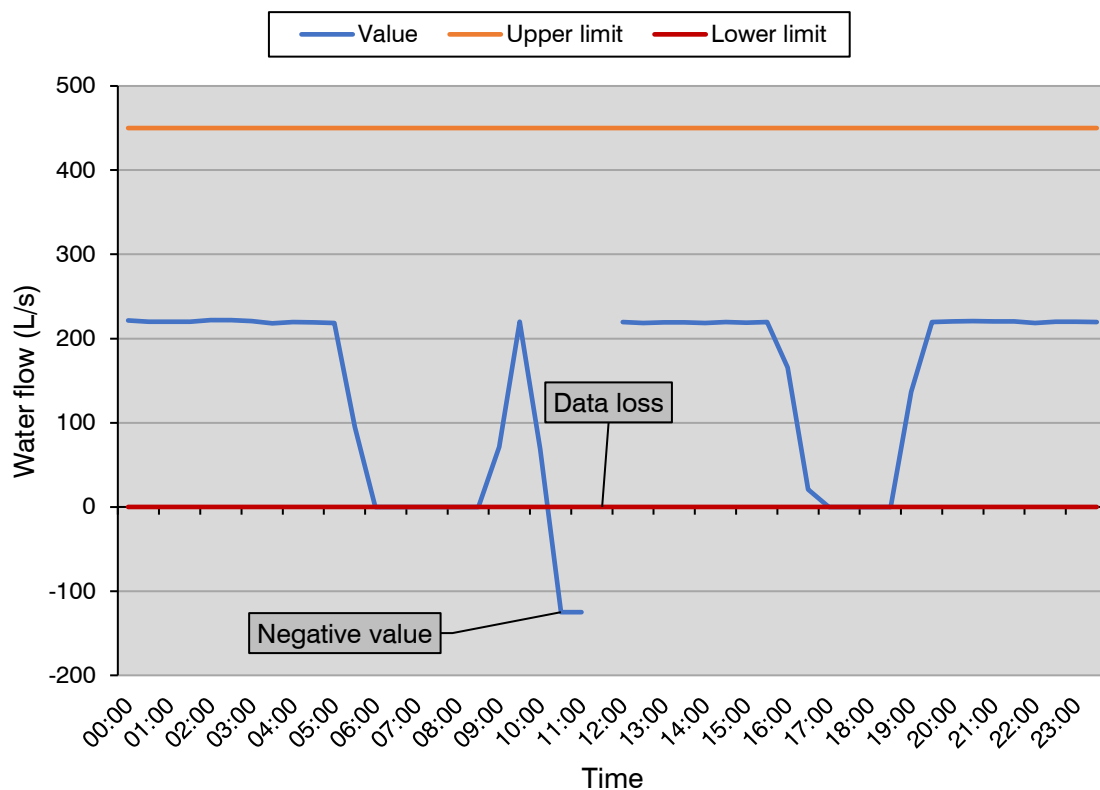


Figure 48: S/V shaft column 3 flow data for 4 July 2023

For the flow meter on column 1 in the S/V shaft, extended periods of no data were observed. Upon identification of this issue, an investigation was conducted revealing actual flow in the column. The matter was reported to the mine's technicians and promptly resolved. The flow meter was repaired, and the values subsequently showed on SCADA. The value was verified using a portable ultrasonic flow meter and the measurements with this device correlated within a 5% accuracy to the values on SCADA. Hence, the data from the historian was deemed reliable and used for calculations.

For L1 to surface column 1, the exhibited data fluctuated around zero. This column was found to have been decommissioned, a conclusion reached through investigation and interviews with mine personnel. Subsequently, all the data from this flow meter were considered as 0.

Regarding the pump power data, specific data limits were defined, as shown in Table 15.

Table 15: Dewatering system pump power limits

Pump	Minimum power limit [kW]	Maximum power limit [kW]
L1 Pump 1	0	4000
L1 Pump 2	0	4000
L1 Pump 3	0	4000
L1 Pump 4	0	4000
L1 Pump 6	0	4000
L1 Pump 7	0	4000
L2 Pump 1	0	3500
L2 Pump 2	0	3500
L2 Pump 3	0	3500
L2 Pump 4	0	3500
L2 Pump 5	0	3500

Fortunately, no irregularities or data loss were encountered for the pump power data set. However, several instances of data loss were observed in the pump running status tags. An investigation revealed that these data gaps typically occurred during maintenance periods when a pump's running status data was temporarily unavailable because the pump was not operational. In such cases, the values were consistently adjusted to zero. It was crucial to cross-reference this with water flow data to ensure that the pumps were indeed non-operational. If flow was detected during a period of missing running status data, the running status information was disregarded and not utilised for simulation development.

Concerning the clear water dams and the plug dam, no irregularities or data loss were observed in the data obtained from dam level transmitters. The predetermined minimum and maximum limits for the clear water dams were 0% and 100% respectively.

3.3 Phase 2 – Development of simulation

Having acquired a comprehensive repository of dewatering component locations and design specifications, the digital twin model can be created. Executed within PTB, this phase encompassed the construction (phase 2.2), calibration (phase 2.3), and integration (phase 2.4) of all requisite components. The rationale for the selection of PTB simulation software is discussed in section 2.2.2.

The model construction process, explicated in section 2.2.3, was meticulously followed. To mirror this procedure, the construction of the simulation model was methodically compartmentalised into five distinct phases, illustrated in Figure 49, reiterating the sequential steps taken to actualise the digital twin model within the PTB simulation environment.

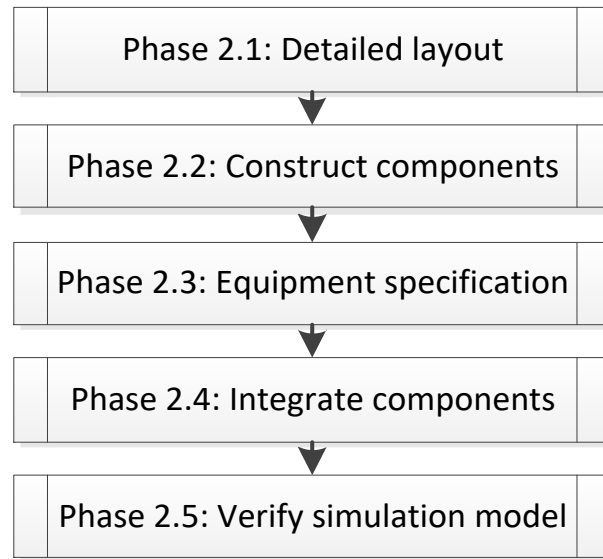


Figure 49: Simulation model construction process

3.3.1 Phase 2.1 – Detailed layout

The first step in the simulation development involves constructing the foundational framework of the dewatering system using layouts. However, in alignment with the circumstances described in phase 1.1, the absence of DXF files necessitated an alternative approach for generating a skeleton layout for Shaft A. Coordinates provided by mine personnel and extracted from a ventilation model comprised the sole available layout data. These coordinates were effectively employed to delineate the positions of the pump chambers. This process involved the insertion of nodes at these specified locations, facilitating the conceptualisation of the shaft's layout, crucial for the simulation's progression.

3.3.2 Phase 2.2 – Construct components

After the skeleton model was built, the components of the dewatering system were imported as specified in section 2.2.3.2. After the locations of the pumps and dams were confirmed through audits, they were placed in their positions, and pipes were used to connect these components. This was done for both pumping levels. PTB allows the building of the model for each level separately, which can be connected in a combined view.

For the L2 pumping layout, the plug dam, two clear water dams, five pumps, and the relevant pipe connections and valves were added to the model. L2 is shown in Figure 50.

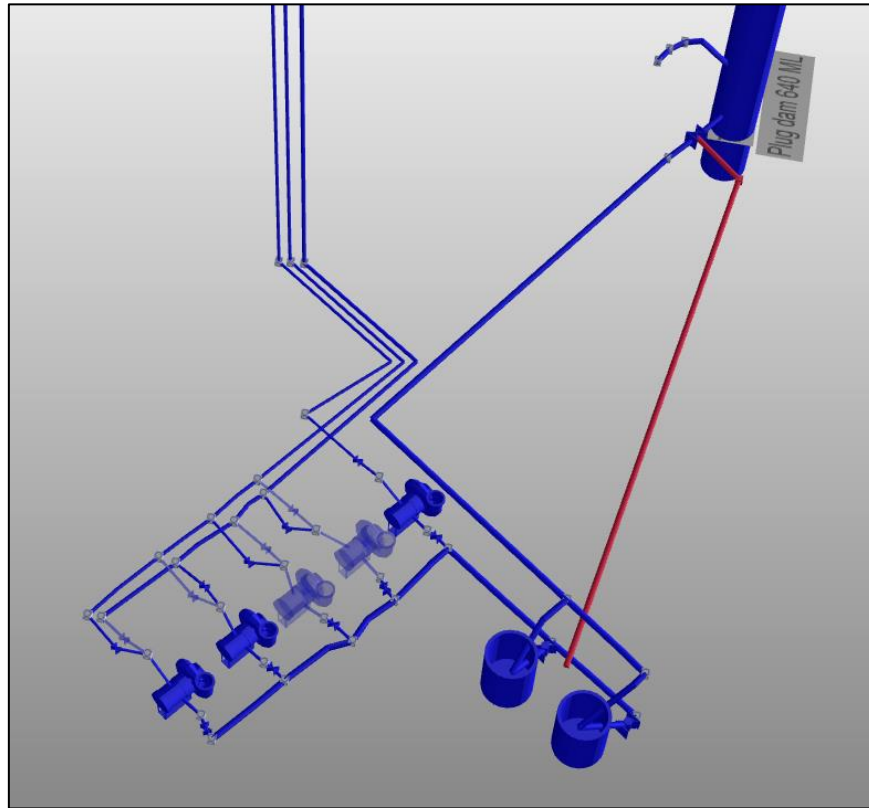


Figure 50: L2 components

This process was repeated for L1, with seven pumps, two dams, and the relevant connections added to the model, depicted in Figure 51.

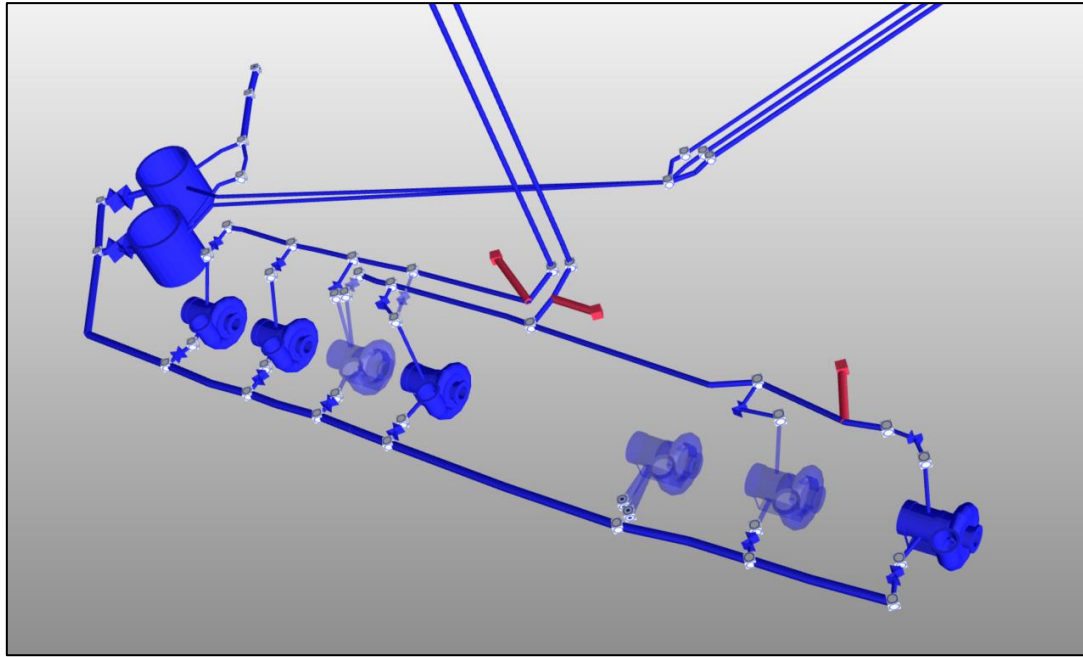


Figure 51: L2 components

Lastly, a dam on surface was inserted at the correct location, concluding phase 2.2, the construction of the components in the simulation environment.

3.3.3 Phase 2.3 – Equipment specification

The equipment comprising the dewatering system of Shaft A was specified in accordance with the prescribed methodology discussed in section 2.2.3.3. This calibration process was meticulously executed using the average flow rates, power consumption values, and dam level measurements gathered during phase 1.3.

Visual representations of the design specifications imported to PTB are shown in Figure 52. These specifications were derived from the data compiled in phase 1.2 and are catalogued within Table 7, Table 8, and Table 9. Concerning the pumps stationed on L1, all were characterised by 3 300 kW power capacity, corresponding to a head of 1 217 m, and on L2 these values were 2 750 kW and 995 m respectively.

The WaterPump Calculator dialog box has tabs for Inputs and Outputs. The Inputs tab is active, showing a list of inputs on the left and a table of properties on the right. The properties table includes Name, Unit, and Initial values.

Name	Unit	Initial
Pump Motor Power	kW	3330.000
Pump Flow	l/s	230.000
Pump Motor Efficiency		0.950
Pump Efficiency		0.870
Pumping Elevation	m	1210.000

Buttons: Calculate, Import..., Export..., Accept, Cancel.

Figure 52: Pump specifications

Furthermore, column dimensions, dam capacities, and dam elevations were integrated to the model from the data collection conducted during phase 1.1. Figure 53 shows an example of dam specifications imported to PTB.

The Dam specifications dialog box has tabs for Inputs, Outputs, References, and Notes. The Inputs tab is active, showing a list of inputs on the left and a table of properties on the right. The properties table includes Name, Unit, and Initial values.

Name	Unit	Initial
Pressure	kPa	100.000
Temperature	°C	20.000
Volume	m³	3000.000
Level	%	50.000
Heat	kW	...
Top Elevation	m	-1216.693
Bottom Elevation	m	-1217.693
Heat Transfer Coefficient	kW/...	0.000
Heat Transfer Area	m²	0.000
Ambient Temperature	°C	0.000

Buttons: Calculate, Import..., Export..., Accept, Cancel, Help.

Figure 53: Dam specifications

3.3.4 Phase 2.4 – Integrate components

With all three levels' components constructed, pipelines were included to connect the levels in the simulation model's combined view.

The components of the dewatering system were connected and integrated as discussed in section 2.2.3.4. All water pipes were connected to the relevant pumps and dams, with the necessary valves included. Figure 54 illustrates the integrated dewatering system.

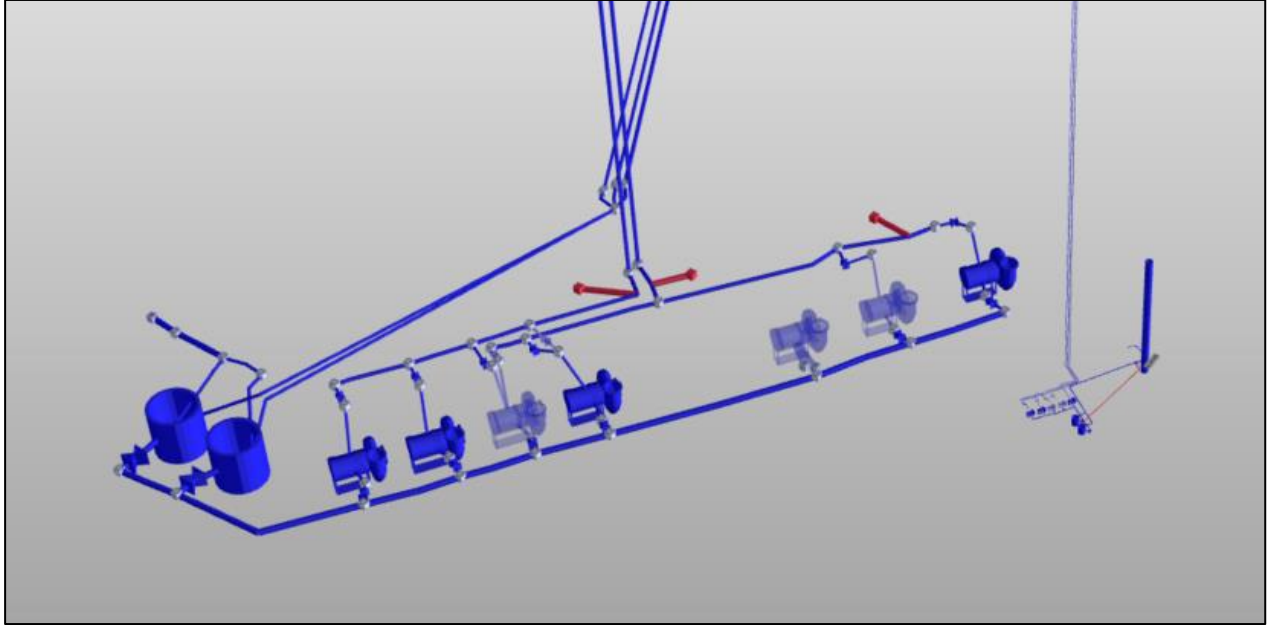


Figure 54: Shaft A integrated simulation model

The model underwent multiple simulation iterations to rectify integration errors, addressing issues arising from unconnected components and incorrect flow directions. An essential part of this process involved verifying the accuracy of flow directions within the pipelines to ensure proper flow alignment. To facilitate this process, a comprehensive 24-hour simulation was conducted, which offered a satisfactory indication of the overall viability of the simulation.

3.3.5 Phase 2.5 – Verify simulation

For the verification step of the digital twin simulation at Shaft A, the simulation outputs are compared to the actual data received from the mine's SCADA system, following the approach outlined in phase 2.5 as detailed in section 2.2.3.5. The simulation model was calibrated and verified until the simulation results converged within the specified 5% accuracy range. Key performance indicators, comprising actual and simulated values of the water flows from each level, total pump power, and the plug dam level, served as the primary metrics for assessing the congruence between the simulation and real-world data. In addition to quantitative evaluations, visual assessments of the simulated and actual profiles were conducted to further evaluate the alignment of the simulation with real-world conditions.

Pump schedules were integrated to the PTB simulation using the 'speed fraction' setting. The actual pump running statuses were extracted from SCADA as per the data acquisition method detailed in phase 1 of the methodology. 10 July to 16 July 2023 was selected as the test period for the comparative analysis between the actual data and the simulation outputs, as it was the most recent full week of data without data loss or other data quality concerns, exhibiting a wide range of pumping strategies.

Hourly data points were extracted for comparison with the simulation outputs, which were provided as hourly averages. The error margin over the week was calculated for pump power, water flow, and the plug dam level. Additionally, graphical representations of the profiles were generated to visually evaluate the model's accuracy.

The calibration of the individual pumps in PTB, conducted in phase 2.3, proved to be effective in ensuring the accuracy of the simulation, as the simulated power and flow values closely resembled real-life data. The error margin for the simulated power and flows from both levels remained below 5%, with the comparison graphs affirming the precision of the model.

Figure 55 displays the trend of actual total dewatering flow rate from the L1 pumping station to surface compared to the simulated profile for the 7-day period.

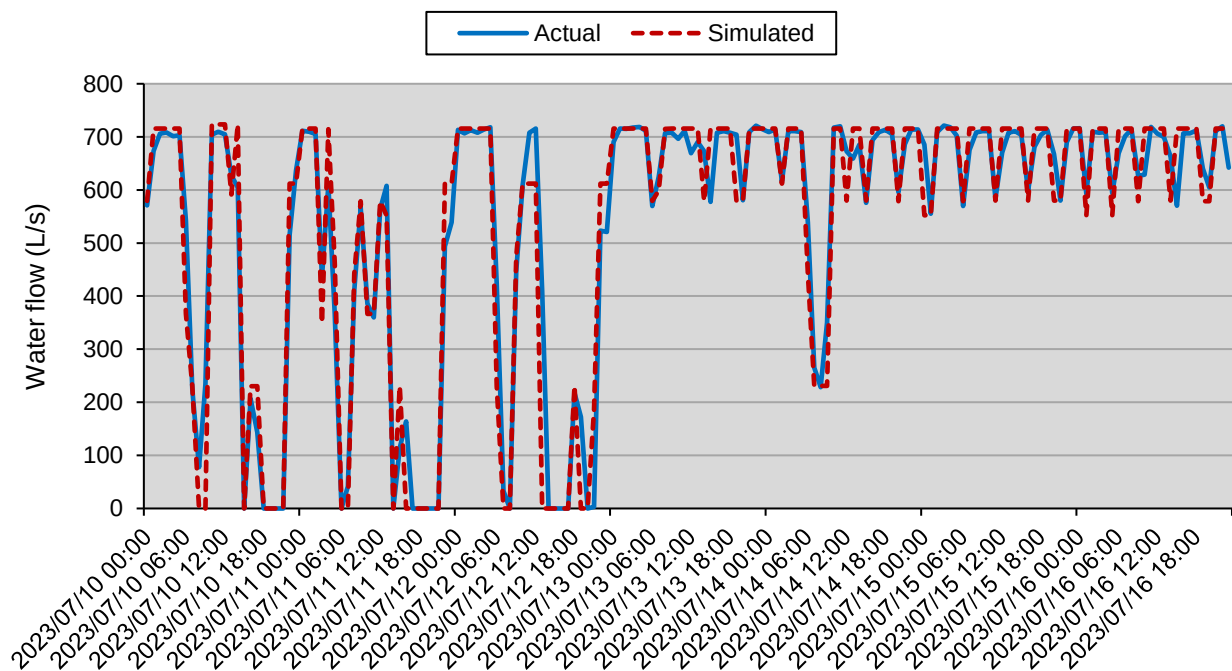


Figure 55: L1 to Surface Actual vs Simulated flow

Figure 56 displays the trend of actual total dewatering flow rate from L2 to L1 compared to the simulated profile for the same period.

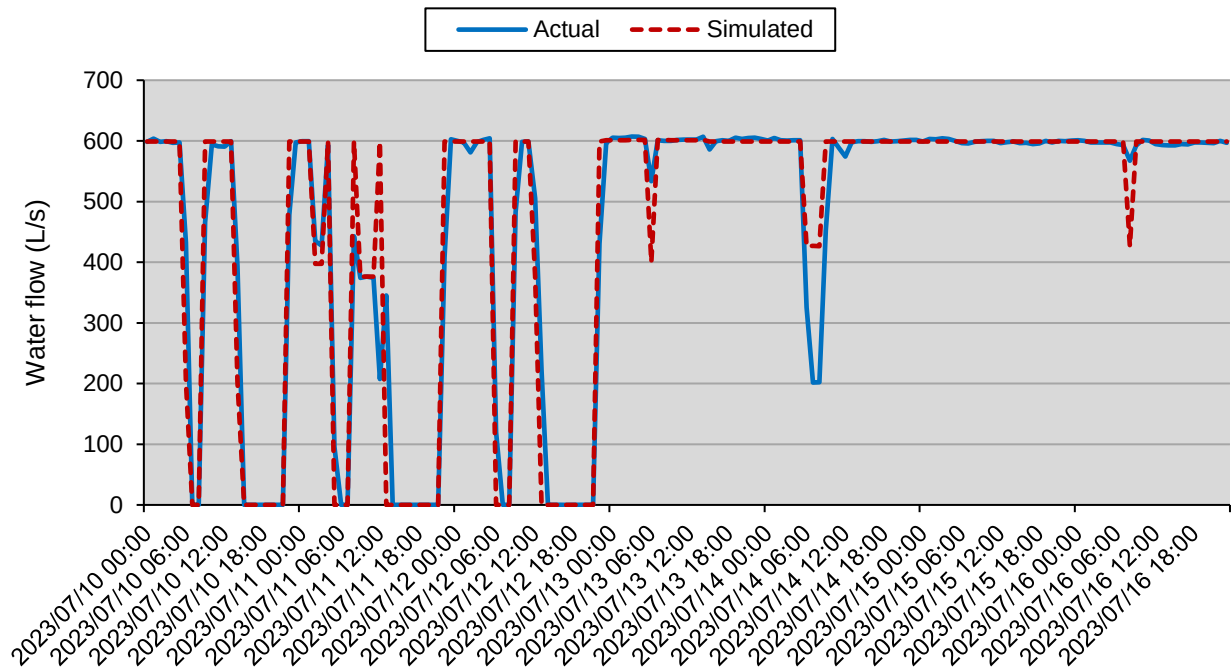


Figure 56: L2 to L1 actual versus simulated flow

For the verification of pump power data, Figure 57 illustrates the daily simulated and actual power profiles.

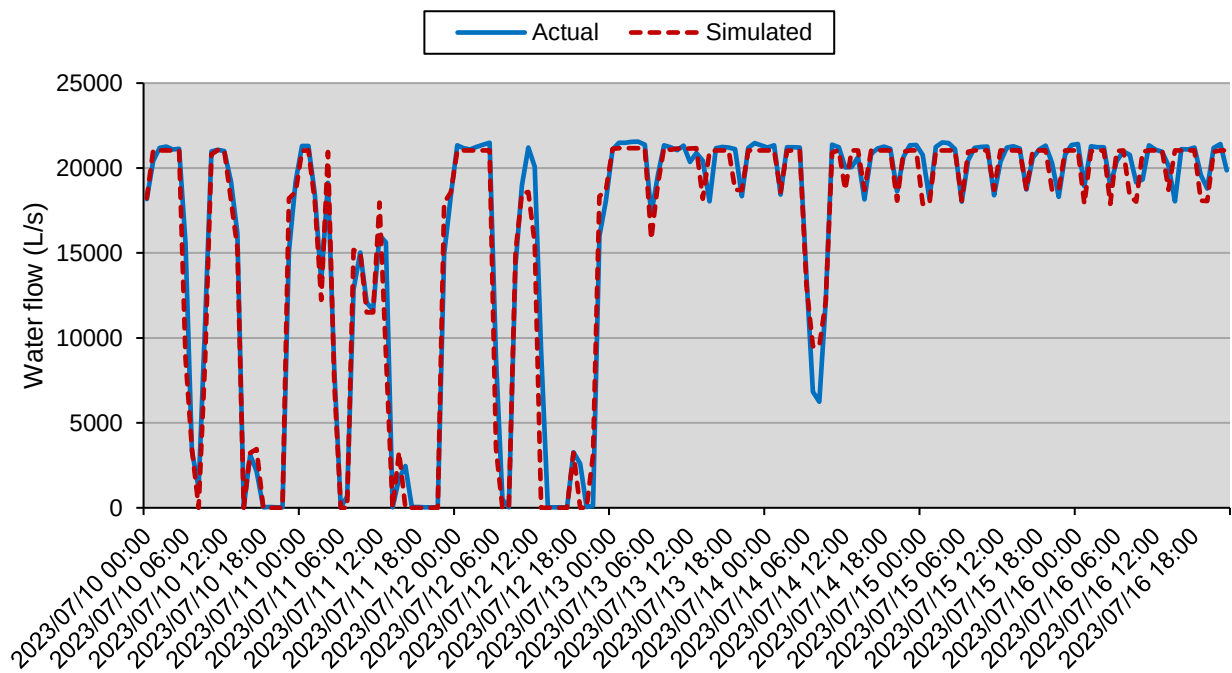


Figure 57: Total pump power profile: Actual versus simulated

The verification results are presented in Table 16, showcasing the comparison of daily average power and flow values and the corresponding error margin.

Table 16: Simulation verification results - 14 June

	L1 to Surface flow	L2 to L1 flow	Total pump power
Simulated average	537.6 L/s	463.8 L/s	15.85 MW
Actual average	540.2 L/s	461.7 L/s	16.10 MW
Error margin	0.5%	0.5%	1.6%

The plug dam level was calibrated by adjusting the dam capacity until the percentage level profile of the dam in the simulation matched the actual data. With the pumping schedules for the 7-day period executed, the plug dam level output of the simulation was 19,41 m, only 0,21 m off the actual value of 19,62 m. This translates to an error margin of 1,1%. The plug dam level profiles are shown in Figure 58.

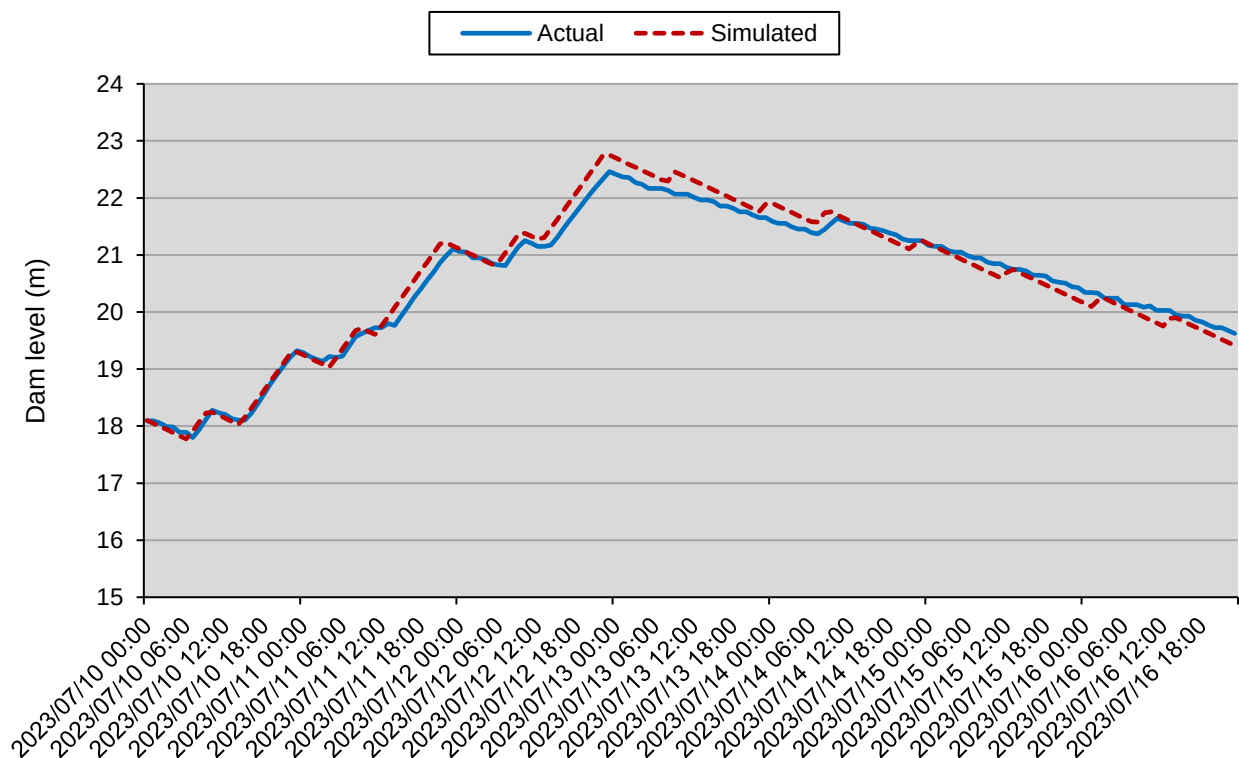


Figure 58: Plug dam level: Actual versus simulated

It is evident from these figures that the simulated profiles closely align with the actual data for all parameters, with discrepancies primarily observed during pump startup or shutdown periods.

Nevertheless, the error margin for the simulation during this 7-day period remained within 2%, comfortably meeting the 5% error margin requirement.

The slight deviation can be attributed to the time delay associated with the pumps being started underground. The pump startup procedure is complicated and needs to be initiated manually by the pump operators. This process is not instantaneous, while the simulation assumes instant hourly status changes. Hence, it is more appropriate to compare water flow and pump power values when the pumps are already running. When this approach is employed, both pump power and flow values align within a 1% accuracy threshold.

Considering these findings, it can be confidently asserted that the simulation effectively mirrors the actual dewatering system. The digital twin model has been verified within the stipulated accuracy range as indicated by the literature in chapter 2.

3.4 Phase 3 - Model implementation

Using the simulation model, a series of experiments were conducted to explore the electricity cost of load curtailment on mine dewatering pumps. Multiple iterations of the simulation were performed, each incorporating distinct input values to represent different operational scenarios. The pump schedules in the model were changed to align with Eskom's load curtailment schedule and the typical load reduction strategies employed by the mine. For Shaft A, it was observed that load curtailment periods typically spanned approximately eight hours, usually occurring between 14:00 and 22:00 on weekdays.

To facilitate a standardised evaluation of the relationship between load curtailment and pumping electricity cost, flow neutrality was upheld throughout the simulations. This means that the water outflow remained consistent for all iterations of the simulation. As per the guidance presented in chapter 2, a period of 30 days was employed to specify the pump schedule for the simulation to ensure a robust assessment of the effects of load curtailment on the dewatering system.

3.4.1 Phase 3.1 - Load reduction assessment

Determining the achieved load reduction from pump stoppages at Shaft A is critical. Mining Operation 1 uses this value to determine the demand response strategy for every load curtailment event based on the amount of load that can be reduced with each intervention by subtracting the average energy demand over the load curtailment period from the CBL. Although the CBL is specified for the entire mining group, for the purposes of determining the dewatering system's contribution to overall load reduction, a CBL for the dewatering system is developed.

The CBL used for Shaft A's dewatering system depends on the time of day and the type of day. The mine's CBL is determined using three previous like days (weekdays or weekend days), but for the purposes of this study, a baseline will be developed using data from June and July 2023 as suggested in section 2.4.1. These months were selected due to their representation of the most recent fissure water quantity at Shaft A. As pointed out by de Jager [55], it is a long enough period to factor in typical load curtailment frequency and load shift performance. Separate baselines for weekdays, Saturdays, and Sundays are utilised. This provides a good indication of the actual load reduced by curtailing pumping operations at Shaft A.

The system-specific baseline profiles are presented in Figure 59 and summarised in Table 27, shown in Appendix F.

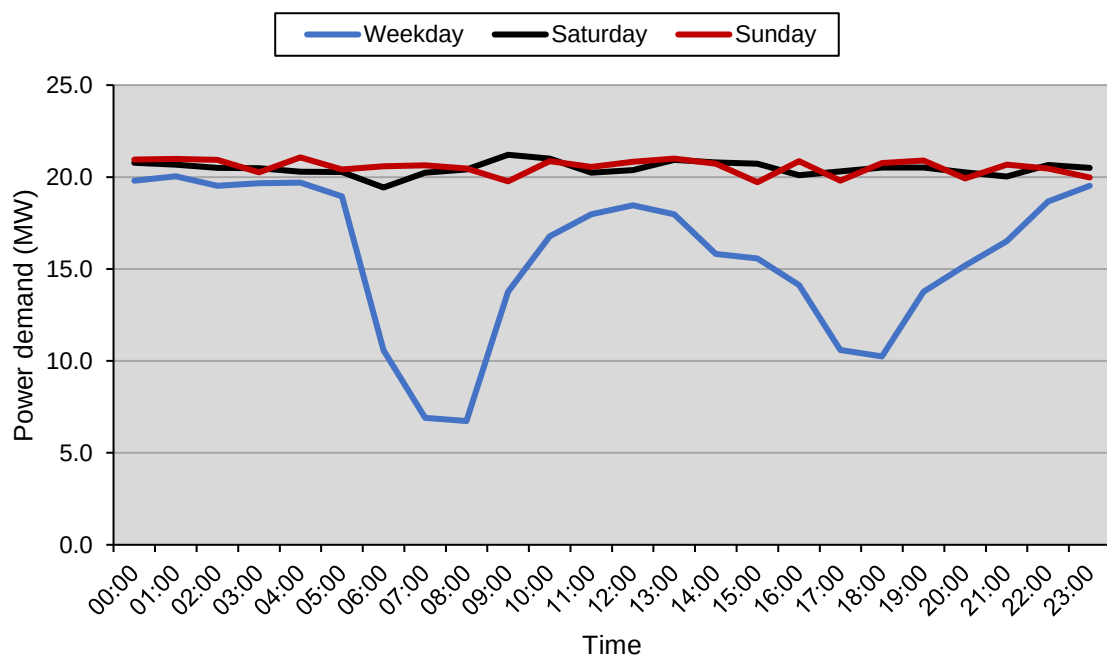


Figure 59: Dewatering system CBL profile

The baselines can be used to determine the load reduction achieved for every individual load curtailment event. The average load for the time when load curtailment is implemented is used as the CBL. For example, if load curtailment is implemented from 14:00 to 22:00 on a weekday, the CBL will be 13.98 MW, the average of the energy demand for these time periods in the baseline. If load curtailment is announced over weekends, the amount of load reduced will be more, because the baseline is higher for Saturdays and Sundays.

For each simulated load curtailment scenario, the specific CBL and the subsequent load reduction amount will be calculated by subtracting the simulated energy demand during the load curtailment

period from the CBL. If all pumps are stopped, as is done in most cases for Shaft A, the energy demand will be zero and the load reduction is equal to the CBL. This assists with the comparison to the cost of other load reduction strategies.

3.4.2 Phase 3.2 - Establish load curtailment threshold

The load curtailment threshold at Shaft A was determined using the steps outlined in section 2.3.2. The first step involves determining the dewatering requirements to maintain the groundwater levels at the shaft. The daily dewatering requirements were already obtained in phase 1 and presented in Table 13. Extrapolating from this information, the monthly dewatering requirements at Shaft A were determined and are presented in Table 17. The total dewatering requirement is 1 481.6 ML per month.

Table 17: Shaft A dewatering requirements

Location	Monthly dewatering requirement
S/V shaft	1267.0 ML
Main shaft	1481.6 ML

The maximum achievable water outflow is achieved when the maximum allowed number of pumps are running, and the most efficient pump combination is utilised. To ensure that the NMD at Shaft A is not exceeded, the dewatering system is limited in terms of how many and which pumps can operate simultaneously. A maximum of seven pumps in total, with only one pump out of pump 5, 6, and 7 on L1 can operate at a given time. The pump combination that achieves the highest outflow is determined and presented in Table 18 using values from the simulation model.

Table 18: Pump combination for maximum achievable flow

	Pumps running	Water flow (L/s)
Main shaft Column 1	Pump 1 & Pump 2	375.5
Main shaft Column 2	Pump 4 & Pump 7	365.3
Main shaft total	4	740.7
S/V shaft Column 1	Pump 1	224.0
S/V shaft Column 2	Pump 5	176.2
S/V shaft Column 3	Pump 4	202.7
S/V shaft total	3	602.9

With this configuration, the L1 pump station achieves 137.8 L/s more flow than the L2 pump station. However, it was previously established that the inflow of fissure water at L1 is only 82.8 L/s. This means there is a bottleneck at L2 and one of the pumps on L1 will need to be stopped and started to prevent the clear water dams on that level from becoming empty.

Converted to ML, 52.1 ML can be dewatered per day from L2. Using Equation 7, the minimum pumping duration required when implementing the aforementioned strategy can be calculated.

$$\text{Minimum pumping required} = \left(\frac{\text{Dewatering required}}{\text{Maximum outflow}} \right) * \text{Time} \quad (7)$$

$$= \left(\frac{42.23}{52.1} \right) * 720$$

$$= 583.65 \text{ hours}$$

Thus, approximately 584 hours of full pumping per month is required to meet the dewatering requirements of Shaft A. The load curtailment threshold can be determined using Equation 8.

$$\text{Load curtailment threshold} = \text{Total time} - \text{Minimum required pumping time} \quad (8)$$

$$= 720 - 583.65$$

$$= 136.35 \text{ hours}$$

It can be concluded that the theoretical maximum duration of pump stoppages at Shaft A is 136 hours per 30-day period. This indicates the threshold after which pump stoppages stops being feasible for achieving load reduction.

3.4.3 Phase 3.3 - Scenario-based simulations

The next step involves running scenario-based simulations, with each scenario iteration representing a certain monthly occurrence of load curtailment events. The load curtailment events intended for integration into the Shaft A dewatering simulation are detailed in Table 19 along with the corresponding CBL for each. This load curtailment schedule is adapted from the load curtailment events experienced by Mining Operation 1 in May 2023, which was a particularly severe month.

Table 19: Load curtailment events schedule for simulation scenarios

Day	LC events (<i>n</i>)	Weekday	Time	Hours	Cumulative hours	CBL
1	1	Monday	06:00-14:00	8	8	13.64
2	2	Tuesday	14:00-22:00	8	16	13.98
3	3	Wednesday	14:00-22:00	8	24	13.98
4	4	Thursday	14:00-22:00	8	32	13.98
5		Friday				
6		Saturday				
7	5	Sunday	15:00-24:00	9	41	20.34
8	6	Monday	14:00-24:00	10	51	15.00
9	7	Tuesday	14:00-22:00	8	59	13.98
10	8	Wednesday	14:00-24:00	10	69	15.00
11	9	Thursday	14:00-22:00	8	77	13.98
12		Friday				
13		Saturday				
14		Sunday				
15	10	Monday	15:00-22:00	7	84	13.72
16	11	Tuesday	15:00-22:00	7	91	13.72
17	12	Wednesday	14:00-22:00	8	99	13.98
18		Thursday				
19		Friday				
20		Saturday				
21		Sunday				
22	13	Monday	14:00-22:00	8	107	13.98
23	14	Tuesday	14:00-22:00	8	115	13.98
24	15	Wednesday	14:00-22:00	8	123	13.98
25	16	Thursday	18:00-22:00	4	127	13.93
26		Friday				
27		Saturday				
28		Sunday				
29	17	Monday	14:00-22:00	8	135	13.98
30	18	Tuesday	14:00-22:00	8	143	13.98

The first iteration of the simulation model represents an optimal scenario where no load curtailment is enforced, and maximum load shift is implemented. This scenario is characterised by the lowest electricity cost for the pumping system. A summary of the results of the optimal

scenario simulation outputs are provided to serve as a benchmark, specifically for the total outflow that should be matched by each additional iteration.

Table 20: Optimal scenario simulation outputs

Parameter	Unit	Value
Average energy demand	MW	16.04
Peak energy demand	MW	0.00
Main shaft total dewatering	ML	1481.8
S/V shaft total dewatering	ML	1266.6

Using the optimal pumping schedule as a starting point, the load curtailment events stipulated in Table 19 are integrated into the simulation one by one. For each iteration, constituting a new 30-day pumping schedule, the resulting simulation outputs are recorded. The recorded results include:

- The number of load curtailment events,
- the total hours of total forced pump stoppages,
- average energy demand and peak energy demand, and
- total dewatering achieved on each level (which should always match the requirements).

An illustration of a pump schedule integrated into PTB is presented in Figure 60.

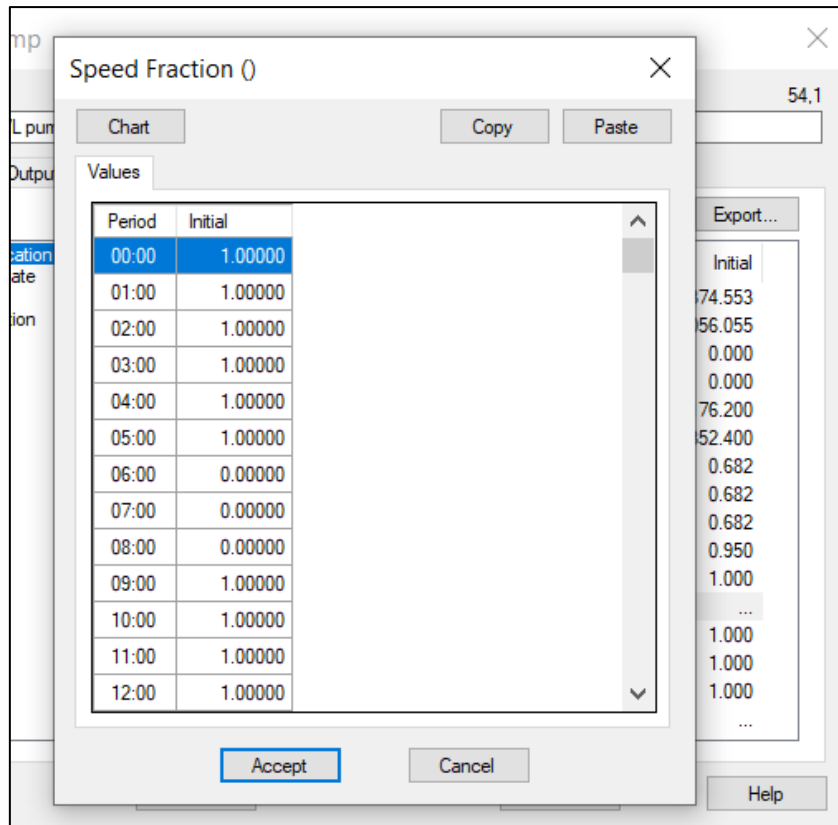


Figure 60: Pump schedule imported to PTB

These simulation iterations continue until a point is reached where the shaft's dewatering requirements are no longer met, indicating that the load curtailment threshold has been reached. The results are recorded and presented in Table 28, shown in Appendix G. The average energy demand results are also graphically represented in Figure 61.

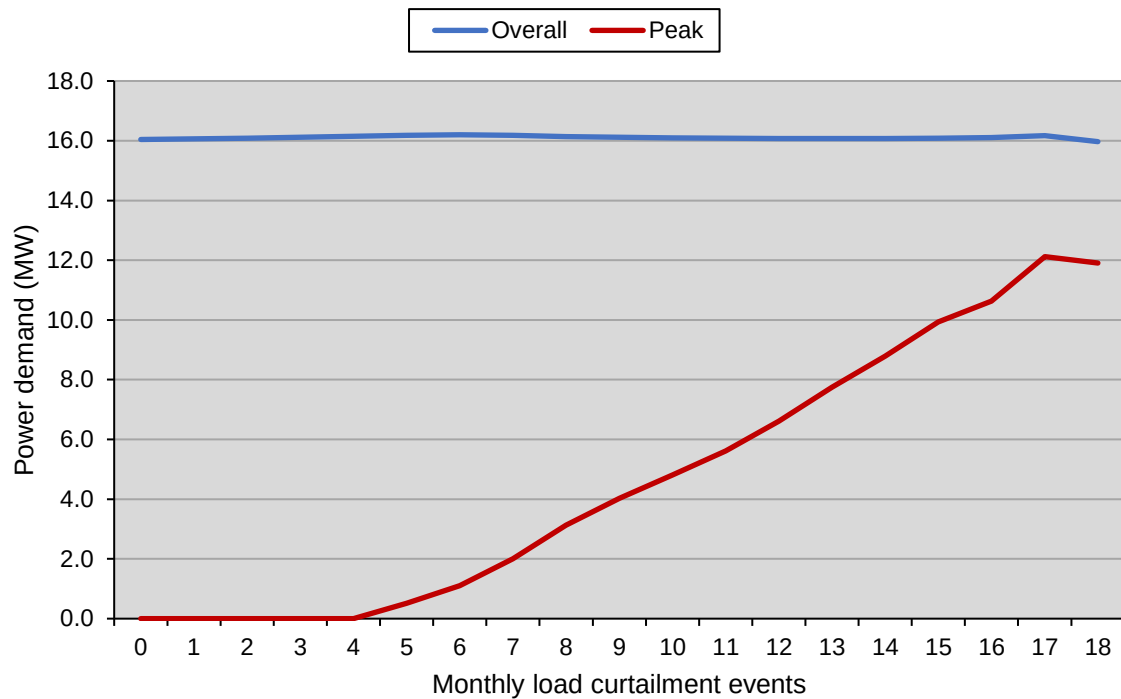


Figure 61: Power demand results

The load curtailment threshold was attained by the 17th iteration of the simulation. An additional iteration was conducted thereafter to demonstrate the continued decline in dewatering totals, falling below the requirements. With all the requisite power and flow values determined, the simulation running steps are concluded, enabling the undertaking of further calculations.

3.4.4 Phase 3.4 - Pumping cost evaluation

Using the recorded simulation outputs for flow and power in each simulation iteration, a thorough evaluation of pumping costs was conducted. This assessment enabled the quantification of the electricity cost associated with the pumping system under varying load curtailment scenarios.

To calculate the electricity cost, Eskom's TOU tariffs were integrated into the PTB simulation tool as detailed in section 2.3.4. The process involved the multiplication of recorded power values, in kWh, by the corresponding TOU tariff rates.

For each scenario, the total pumping cost was recorded, considering both winter (high demand) and summer (low demand) tariff structures separately. This separation allowed for a precise assessment of the economic implications of load curtailment scenarios in different seasonal conditions.

The outcomes of these cost evaluations are presented in Table 29, shown in Appendix G. The total cost results are also presented in Figure 62, providing valuable insights into the financial aspects of the simulations and facilitating a comprehensive analysis of load curtailment scenarios.

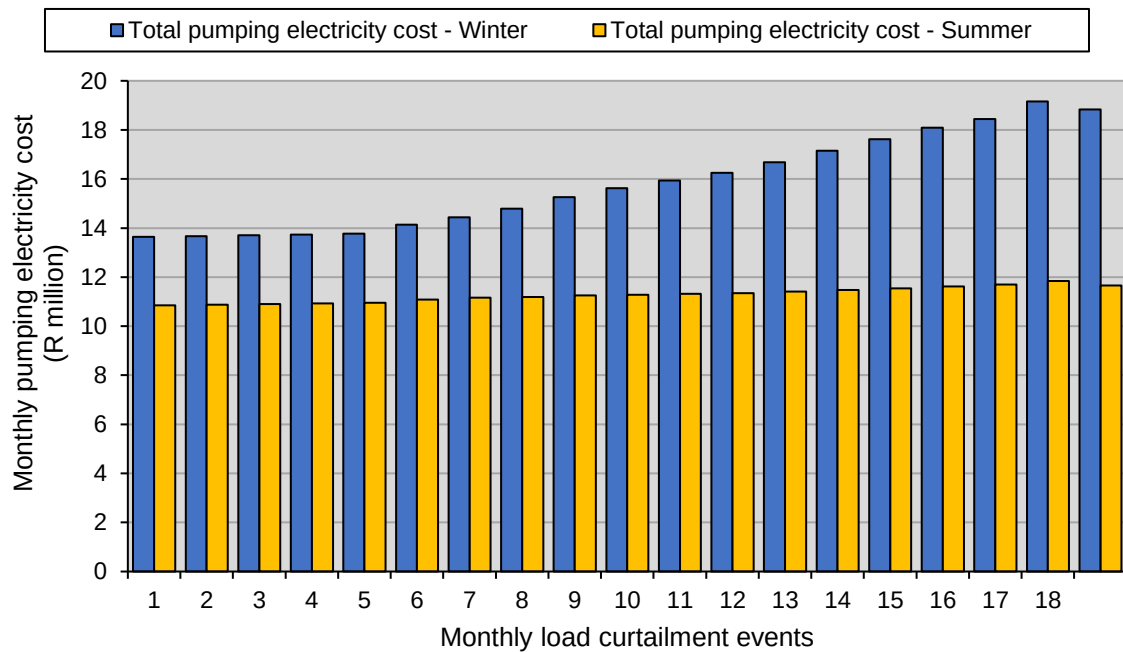


Figure 62: Monthly pumping electricity cost

3.5 Phase 4 - Analyse results

3.5.1 Phase 4.1 – Evaluation of simulation results

From the simulation output results, critical insights into the cumulative duration of pump stoppages and the corresponding energy demand and total electricity cost were obtained. To ensure a fair comparison between scenarios, constant dewatering outflow and dam levels were maintained across all simulation iterations, with the sole variable being the duration of load curtailment. These results are evaluated to determine the cost of load curtailment on pumping systems.

To achieve the study's main objective, the sub-objectives include establishing a comprehensive understanding of the relationship between the monthly occurrence of load curtailment and three key factors:

1. The shaft's ability to meet its dewatering requirements,
2. the additional electricity cost from the pumping system components, and
3. the pumping load shift performance.

With each iteration of the simulation, which corresponds to a specific monthly duration of load curtailment, it is important to test whether the minimum dewatering requirement of 1481 ML is met. When this is no longer attainable, pumps cannot be safely stopped to achieve load reduction. Beyond this point, the total monthly dewatering falls below 1481 ML as shown in Table 28 in Appendix G.

To establish a baseline for the calculation of additional electricity costs, the results of the simulated optimal pumping scenario were leveraged. By deducting the electricity cost of the optimal pumping scenario from the total electricity cost of each simulation scenario, the additional cost incurred due to the implementation of load curtailment is unveiled. This analysis is conducted separately for winter and summer periods to assess the divergent effect of load curtailment on pumping costs during different demand seasons. The results of this calculation are presented in Table 30 shown in Appendix G.

Assessing the effect of load curtailment on load shift performance, three key parameters were employed: (1) The average overall load shift achieved, (2) the load shift attained during the DSM project performance assessment period (in this case, the evening peak period), and (3) the peak-to-average (PTA) ratio.

To realistically determine the load shift performance, an adjusted baseline approach is adopted as outlined in section 2.4.1. Following Musabandesu's [34] method for baseline adjustment to account for structural changes in demand, the baseline was scaled using an adjustment multiplier. This factor was derived from the average energy usage during the assessment period, typically a 30-day test period, divided by the average energy demand of the official baseline. Given that Shaft A had experienced an increase in fissure water quantity since the baseline's determination, upward scaling of the baseline was predominantly necessary. The scaled baseline for each simulated scenario enabled the calculation of the average load shift, evening load shift (for the DSM project), and PTA ratio. The results of these calculations are presented in Table 31 shown in Appendix G.

Upon examination of these results, several conclusions can be drawn. Firstly, the point at which load curtailment causes the shaft's dewatering requirements to not be met is revealed. Secondly, a clear correlation between the monthly occurrence of load curtailment and additional pumping electricity costs incurred is observed. Thirdly, a relationship emerges between the monthly load curtailment frequency and load shift performance. The findings are visually represented in Figure 63. This graph illustrates the significant electricity costs and the notable reduction in pumping load shift performance associated with pump stoppages for load curtailment.

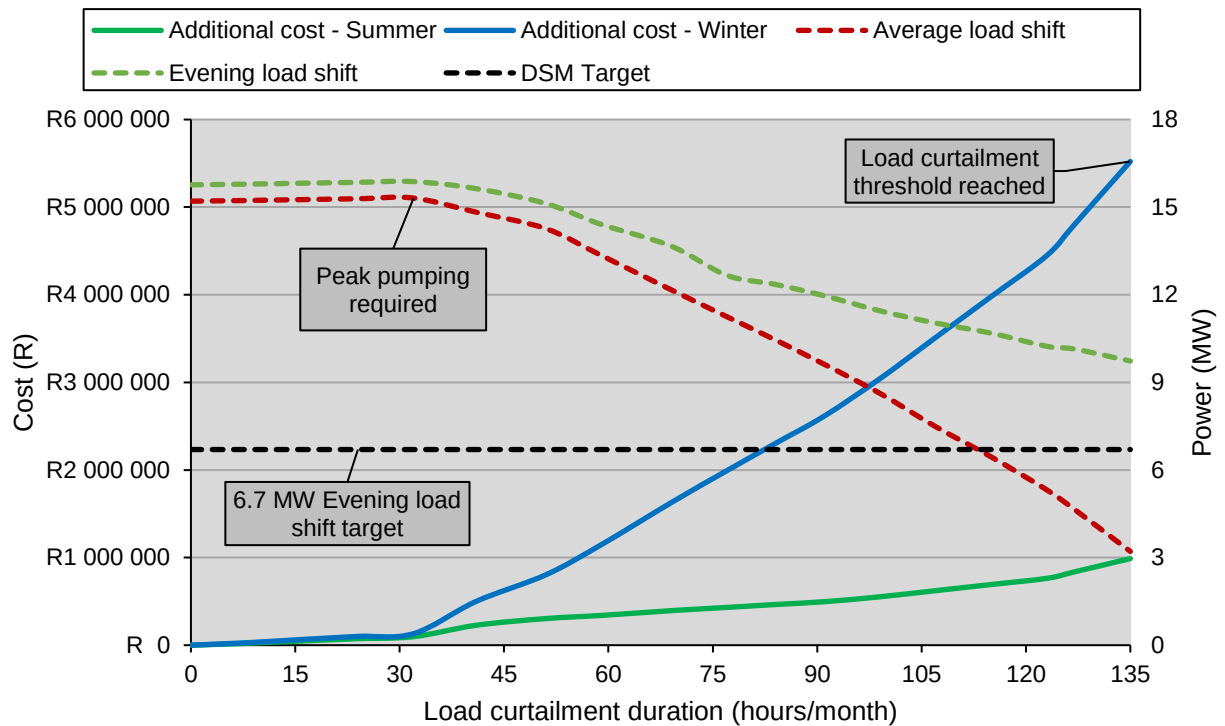


Figure 63: Additional cost and load shift performance

The analysis revealed that Shaft A's dewatering system can accommodate up to 17 load curtailment events and 135 hours of pump stoppages while still meeting dewatering requirements. This closely aligns with the theoretical value calculated in phase 3.2. Beyond this point, further pump stoppages would jeopardise the system's primary objective to maintain groundwater levels and prevent flooding in neighbouring shafts. The simulation's 18th iteration confirms this, as it demonstrates the system's inability to provide the required monthly dewatering of 1 481.6 ML when subjected to 143 hours of pump stoppages.

Within 32 hours of load curtailment, by the fifth occurrence in the month, a critical juncture is reached where pumping during peak times becomes necessary. This marks the point at which Shaft A's dewatering system can no longer achieve 100% load shift. Subsequent load curtailment events incur considerable costs due to missed load shift opportunities.

During the high-demand winter season, the additional pumping electricity cost resulting from missed load shift savings amounted to R5.2 million for 135 hours of forced pump stoppages. Conversely, during the low-demand season, the simulation outputs indicated a significantly lower figure of R990 000. This substantial difference can be attributed to Eskom's pricing, with charges at R1.74 per kWh for peak energy during summer months and a notably higher rate of R5.34 per kWh from June to August.

With no peak pumping and with a PTA ratio of 0, Shaft A achieves a load shift of approximately 15.2 MW. However, as peak pumping initiates after the fifth load curtailment event in the month, the load shift performance exhibits a steady decline. After 135 hours of forced stoppages, only 3.21 MW of load shift is achieved, accompanied by a PTA ratio of 0.75.

Evening load shift performance at Shaft A appears to be less affected by load curtailment. The Eskom DSM project's load shift target of 6.7 MW is consistently met for all simulated scenarios, with the lowest value being 9.7 MW of load shifted during evening peak times. This outcome may be attributed to load curtailment primarily being implemented during evening hours, aligning with the project performance assessment period. Forced pump stoppages due to load curtailment happen to often coincide with the evening peak period. While this may be happenstance, it suggests that if Eskom continues to implement load curtailment primarily between 14:00 and 22:00, Shaft A can reasonably expect to meet project targets.

However, if load curtailment is predominantly enforced during other time periods, especially weekends, the overall load shift performance could be markedly different. The analysis revealed that after 115 hours of pump stoppages due to load curtailment, the overall load shift performance fell below the 6.7 MW threshold.

3.5.2 Phase 4.2 – Feasibility of pump stoppages

The comprehensive cost analysis of forced pump stoppages allows for a comparison with alternative load reduction strategies, primarily diesel generator operation. This investigation seeks to provide valuable insights for Mining Operation 1 in devising an optimal load reduction strategy when load curtailment is necessitated.

Diesel generators function as a substitute for load reduction, essentially reducing Eskom's demand. As established in phase 1.3, the cost incurred to generate one MWh of energy using diesel generators amounts to approximately R5 800. To determine the corresponding generator running cost for each load curtailment scenario simulated in phase 3.3, the required load reduction value derived from a baseline in phase 3.3 is used. This value is multiplied by the duration of the load curtailment event and the generator's average specific cost to ascertain the generator cost per load curtailment event. The cumulative cost of generator operation required to achieve a load reduction equivalent to pump stoppages is presented in Table 32 shown in Appendix G.

The cost associated with missed load shift savings due to pump stoppages depends on the timing of dam level recovery and escalates with an increasing frequency of load curtailment events. In contrast, the cost of achieving the same load reduction through diesel generator operation follows

a linear curve, primarily dependent on the timing of the load curtailment event itself, as this directly affects the CBL. A graphical representation of the cost comparison between these two load reduction strategies is presented in Figure 64.

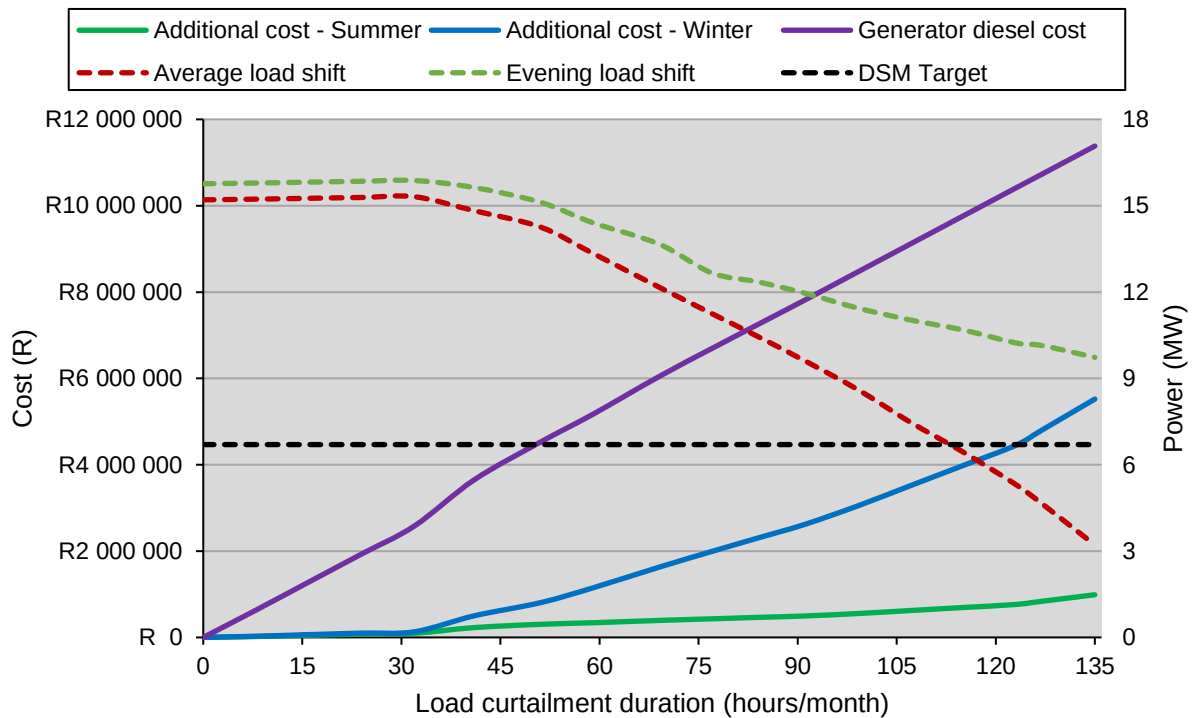


Figure 64: Cost of load reduction strategies

The cost of diesel generator operation to achieve a 1 958.5 MWh load reduction, equivalent to the load reduction achieved by 135 hours of pump stoppages, amounts to about R11.4 million. This is more than double the cost of pump stoppages for the same period. While the cost of generator operation remains relatively stable over time, the electricity cost incurred due to prolonged pump stoppages appears to escalate with time. Figure 65 and Figure 66 provide a detailed breakdown of the cost per event of load curtailment for both load reduction strategies during winter and summer periods.

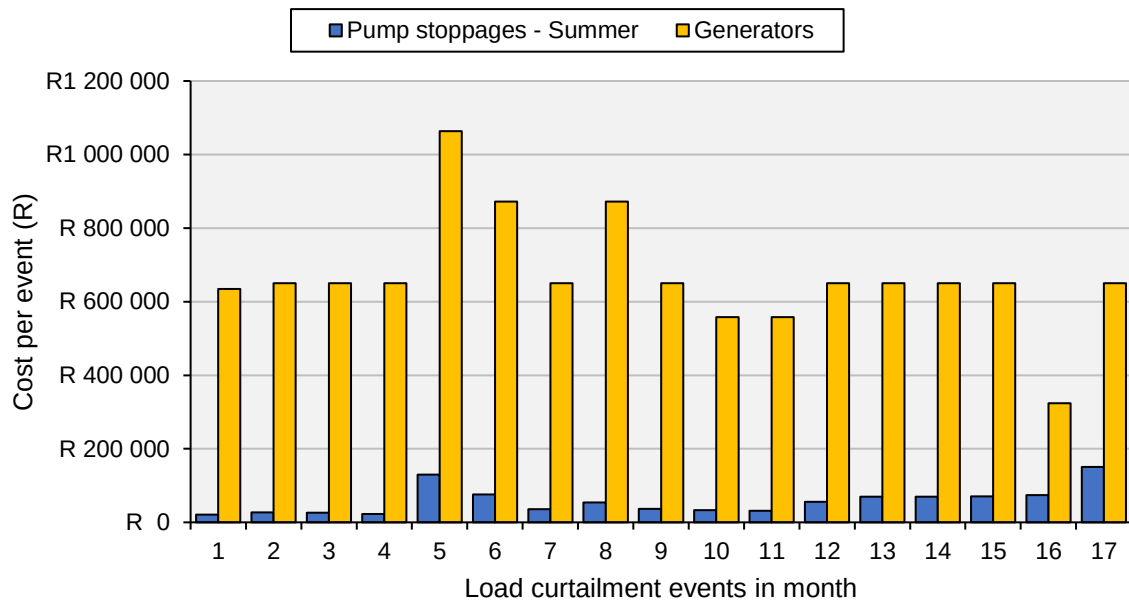


Figure 65: Cost per load curtailment event comparison - Summer

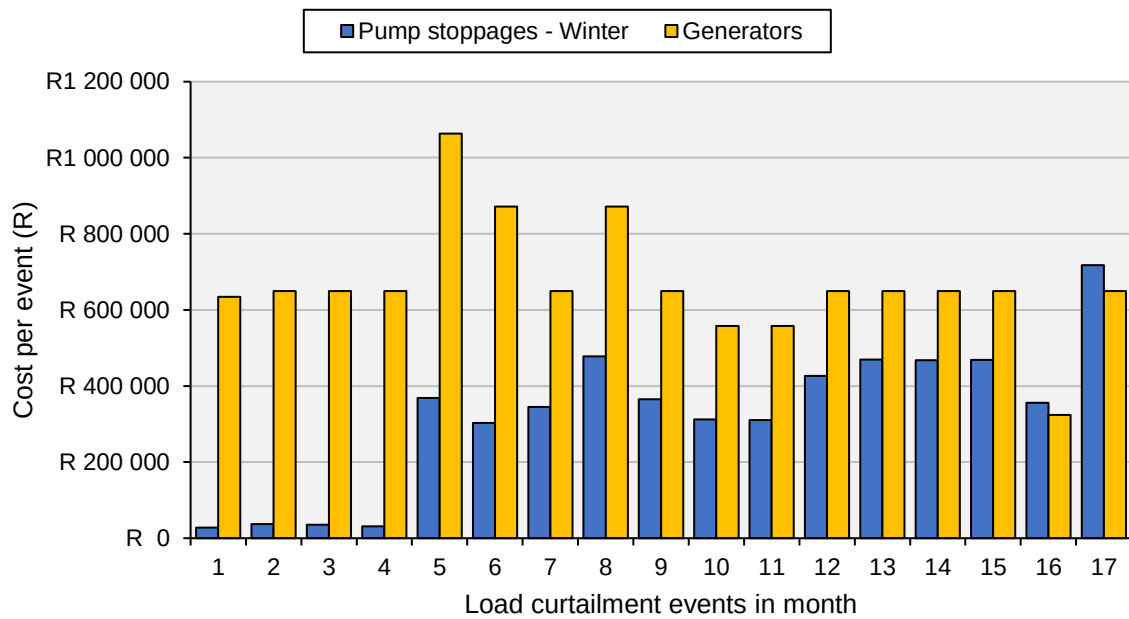


Figure 66: Cost per load curtailment event comparison - Winter

In the low-demand season, the cost of missed load shift due to pump stoppages is considerably lower than the cost of diesel generator operation. However, during the winter months with higher peak tariffs, the event-specific cost of stopping pumps surpasses the cost of diesel for the 16th and 17th simulated events. This is attributed to the immense strain placed on the dewatering system when approaching the load curtailment threshold. In this scenario, not only is load shifting

skipped, but the shaft is compelled to operate sub-optimal pump combinations to meet the required dewatering, leading to increased dewatering costs. Figure 67 compares the cost per hour of load curtailment for each of the strategies.

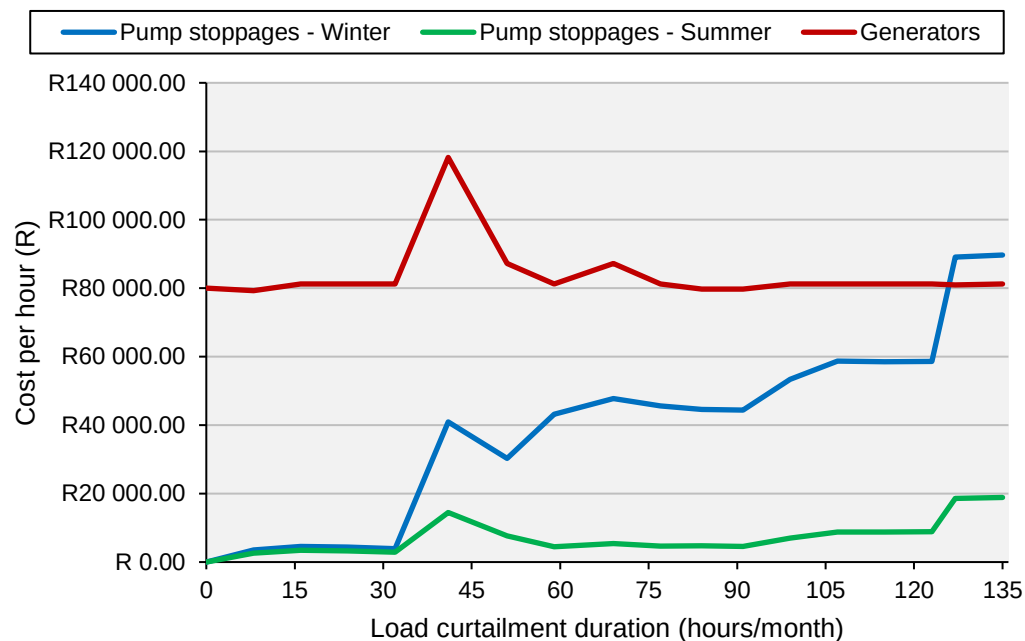


Figure 67: Cost per hour load curtailment comparison

The graph reveals the cost trends for both scenarios. The cost of running diesel generators remains relatively constant with the exception of the load curtailment event occurring on a Sunday, exhibiting higher costs. In contrast, the cost of pump stoppages and the subsequent missed load shift opportunities show a significant increase with time. Starting at a very low cost, this cost escalates to almost R90 000 per hour of load curtailment during winter for the last two simulated scenarios. The point at which it becomes more cost-efficient to operate diesel generators to achieve load reduction, rather than strategically stopping pumps, is identified at 127 hours of load curtailment per month.

Hence, it can be concluded that pump stoppages for load reduction remain a viable option during load curtailment at Shaft A. Load shift performance is compromised after 32 hours of load curtailment and declines significantly after approximately 115 hours of pump stoppages. However, owing to the nature of load curtailment enforcement, it does not adversely affect evening load shift to the extent that DSM targets are unattainable.

During the nine months characterised by low-demand tariffs, it remains feasible to implement pump stoppages for load curtailment for up to 135 hours per month. Beyond this threshold, the

dewatering requirements of the shaft are compromised. Conversely, during the high-demand winter periods, it is more cost-effective to stop pumps than to initiate generators for up to 123 hours per month. After this point, slightly less cost will be incurred by starting generators rather than stopping pumps for each additional load curtailment event.

Therefore, it is recommended that Shaft A continues to employ pump stoppages as the primary load reduction strategy but limit it to 135 hours per month in summer and 123 hours per month in winter. However, significant costs can be expected when this strategy is implemented, especially in winter.

CHAPTER 4 CONCLUSION AND RECOMMENDATIONS

4.1 Conclusion

The South African mining industry faces significant challenges related to electricity supply shortages and soaring electricity prices. In response to these challenges, DSM measures are implemented, specifically mandatory load curtailment for large customers. This places immense strain on mining operations, particularly on critical dewatering systems that play a pivotal role in load reduction strategies during curtailment periods. Furthermore, the TOU tariff structure, with higher rates during peak times, necessitates load shifting for pumping systems. However, prolonged pump stoppages for load curtailment can disrupt the implementation of load shift measures, resulting in increased electricity costs. Striking a balance between load reduction, meeting dewatering requirements, and maintaining load shift proves to be a challenge.

It is evident from the extensive literature review that the cost of load curtailment on mine dewatering systems has been a relatively unexplored area. This knowledge gap makes it difficult for mines to compare various load reduction strategies and develop optimal responses to curtailment events. Notably, no existing model establishes a relationship between the incidence and duration of load curtailment events and the electricity cost incurred by mine dewatering operations.

The primary objective of this study was to address this gap by devising a method to quantify the cost of load curtailment on mine dewatering systems. Specifically, the study aimed to establish relationships between monthly load curtailment occurrences and factors such as a shaft's capacity to meet dewatering requirements, pumping electricity costs, and the effectiveness of load shift initiatives. Additionally, the study sought to evaluate the feasibility of pump stoppages as a load reduction strategy when compared to other alternatives.

To achieve these goals, a case-study approach was adopted, focusing on mine Shaft A, a shaft used solely for the purpose of dewatering underground mining areas for Mining Complex 1. A digital twin simulation model was developed for this shaft, facilitating the exploration of various scenarios reflecting differing intensities of monthly load curtailment. The simulation was adjusted iteratively to examine the relationship between load curtailment duration and pumping electricity cost, DSM performance, and meeting dewatering requirements over a 30-day test period. This verified model allowed for a comprehensive assessment of the cost of load curtailment and provided guidelines for interpreting the results.

The application of this method to Shaft A yielded valuable insights. The simulation results revealed that pumps can be stopped for up to 135 hours per month while still meeting the shaft's dewatering requirements. The need for peak pumping became evident after 32 hours of enforced pump stoppages, with load shift performance deteriorating beyond this point. However, the evening load shift performance remained above its target of 6.7 MW throughout, largely due to load curtailment events often coinciding with evening peak periods.

The pumping electricity cost increased with each additional instance of load curtailment, resulting in substantial additional charges, specifically during peak winter months. The total additional charges for 135 hours of load curtailment amounted to R5.52 million in winter and R990 000 in summer, based on 2023/24 tariffs. Comparatively, the cost of initiating diesel generators to achieve load reduction remained relatively constant at approximately R80 000 per hour of load curtailment, totalling R11.4 million over the 135-hour test duration. In contrast, the cost of pump stoppages peaked at R90 000 per hour during winter after 127 hours of enforced pump stoppages. Therefore, pump stoppages represent a viable load reduction strategy at Shaft A for up to 123 hours per month in winter and 135 hours in summer.

In summary, the developed method has proven to be an effective tool for quantifying the cost of load curtailment on mine dewatering systems for any given shaft. The findings of this study provide valuable insights that can assist the mining industry in formulating more informed strategies for managing load curtailment while ensuring the efficient and cost-effective operation of their dewatering systems.

4.2 Recommendations for future work

To broaden the scope of this study and find effective solutions for the challenges associated with load curtailment, several recommendations for further research can be made.

One avenue for further investigation is to expand the study by replicating it across different mine shafts. This will allow researchers to assess whether the quantification method is effective in a variety of mining settings, ranging from more complex and interconnected water reticulation systems to simpler setups. By examining a wider range of scenarios, deeper insights into the method's adaptability and robustness across different mining contexts can be obtained.

Another possible area for further study is to determine the cost of load curtailment on other critical mining systems, such as ventilation, compressed air, and refrigeration systems. Investigating how load reduction or stoppages affect these systems is essential to understanding the broader implications of load curtailment initiatives.

Additionally, future studies should consider applying similar investigative methods to explore the cost of load curtailment on systems in other industries. This approach would allow researchers to compare their findings with this study, gaining a better understanding of the overall impact of load curtailment measures across multiple sectors.

This study, which comprehensively quantifies the cost of load curtailment on mine dewatering systems, can serve as the foundation for developing strategies to mitigate the incurred costs. Future research should concentrate on identifying and evaluating measures that can be implemented to reduce electricity expenses while still meeting load reduction targets. These strategies may involve technological innovations or the utilisation of alternative power sources such as solar plants or turbines.

Incorporating these recommendations into future research will contribute to a deeper understanding of the cost implications of load curtailment and to more informed decision-making within the field of DSM.

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APPENDIX A – TECHNICAL BACKGROUND ON MINE DEWATERING SYSTEMS

Deep-level mines use water to serve various needs underground. Cold water is used for mining operations and is crucial for providing a safe thermal environment for employees [99]. As underground mines become deeper, the water requirements also increase [140]. Adequate water distribution is, therefore, critical for both cooling and production [140].

Cold water is used for mining operations such as rock drilling, dust suppression, cleaning, and sweeping [55]. Drilling equipment of various shapes and sizes are used to drill holes for explosives or supports for suspended equipment [99]. Hydro drills use water pressure as an energy source and other drill types such as compressed air drills use water to cool the drill and suppress dust [63]. In some cases, the water pressure can be used to operate hydropower loaders and winches [141]. Service water is often sprayed on the rock face to mitigate the temperature rise due to blasting [142]. Due to the pressure of the service water, it is also used for sweeping and cleaning [143] using water-jet nozzles fixed to flexible hoses installed on the service column [99].

Chilled water is used to cool air for ventilation purposes. Cooling systems are essential to provide a safe thermal environment underground [30, 99]. Underground temperatures that are too high have the potential to result in health issues such as heatstroke, heat cramps, or heat exhaustion [30]. It is, therefore, important to comply with the legal temperature limits outlined in the Mine Health and Safety Act shown in Table 21.

Table 21: Legal thermal limits [143]

Parameter	Limit (°C)
Maximum wet-bulb temperature	32.5
Maximum dry-bulb temperature	37

In mine refrigeration systems, hot water is cooled on a large scale using refrigeration plants. These refrigeration plants typically employ the vapour-compression cycle which involves compressing and circulating compressed air through a closed circuit with heat being absorbed and released through heat exchangers [93]. Prior to this process, cooling towers using ambient air are employed to pre-cool the hot water [30]. Further cooling takes place at the refrigeration plants and the desired outlet temperature is normally approximately 3°C [93].

Bulk air coolers are typically used to cool the air that the ventilation system forces down the shaft [98]. A bulk air cooler makes use of horizontal spray chambers, vertical pack towers, or circuit cooling coils to cool the air [145]. At extreme depths, the air is re-cooled using secondary coolers [99], such as underground fridge plants with bulk air coolers or ice plants [146]. Additionally, spot coolers like cooling cars are used for cooling air in stopes and haulages [63].

This constant supply of water causes hot water to accumulate at the bottom of the shaft [55]. To prevent flooding, this water needs to be pumped to the surface [42]. Flooding can be disastrous because it impedes mining and increases the local ambient temperatures [147]. Dewatering is not only necessary for service water, but also fissure water, naturally occurring underground water from surrounding water deposits and aquifers [112]. Data analyses have shown that in some cases, fissure water can have a constant flow of as much as 50 ML/day into a mining area. In many cases, dedicated dewatering shafts are used to dewater an entire mining complex.

A dewatering system mainly comprises dewatering pump stations, hot water storage dams and settlers, as well as instrumentation and control mechanisms [30]. Separation of mud and other debris from the water takes place at settlers [30]. From there it is collected in clear water storage dams and pumped to the surface in pipe columns using large multi-stage centrifugal pumps [30]. To overcome the static head, an upward cascading approach is used where water is pumped in pipe columns from the lowest dam in a mine to dams on upper levels from where it is pumped to the surface [42, 99]. In South African gold mines, the vertical distance between these levels can be more than 1000 meters [148]. The dewatering system is a large energy consumer, accounting for approximately 14% of a mine's total energy consumption [143]. Figure 68 graphically depicts a basic layout of a dewatering system of a deep-level gold mine as described above.

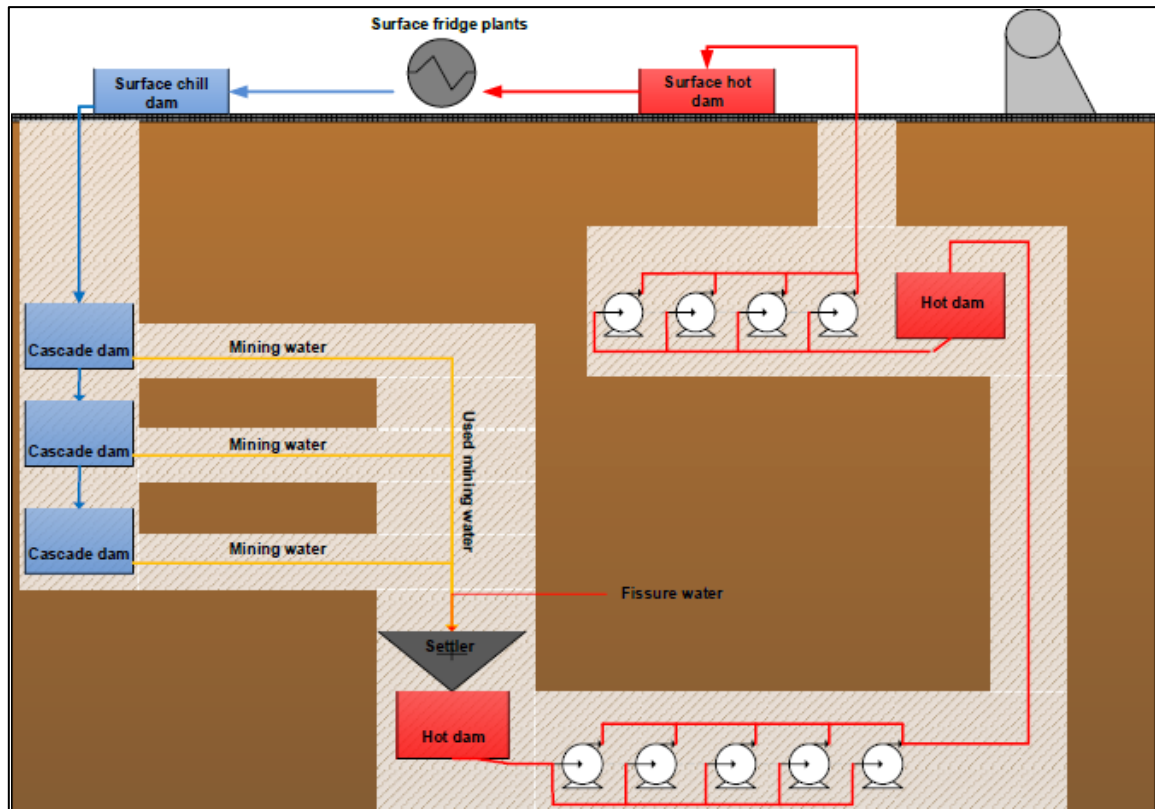


Figure 68: Dewatering system layout [55]

Settlers and Clear Water dams

Due to dust and rock particles in the water, separation is required before water can be pumped to the surface [42]. Many mines make use of settler dams to separate mud from water [30] to prevent mud from causing cavitation in the dewatering pumps, as this can cause significant damage and even failure. Flocculant is added to the water that enters the settler. Flocculant is a chemical that binds with debris to help separate it from the water [55]. The large particles descend to the bottom of the settler as a sediment from where it is removed manually [149]. Using flocculant can increase the performance of a settler by up to 450% [45]. Lime is also added to the water in the settler dams to ensure it stays within the correct pH range [55]. A pH of approximately 8.5 is desirable to reduce corrosion and optimal flocculant efficiency [45]. Clear water then exits the settler and flows to hot water dams [45]. The temperature of this water is typically between 30°C and 35°C [62].

Clear water dams store the hot water that has been processed by the settlers and then pumped to the surface [55]. These dams have large capacities, typically ranging between 0.75 ML and 5 ML [150]. Usually, the dams are built with substantial vertical height to provide adequate head pressure for the suction side of the dewatering pumps [42]. More than one dam is typically located on a level, where one or more of the dams are reserved for emergency use. This enables the mine to have enough storage when dams need to be cleaned [42]. Although settlers extract most of the mud from the water, some of the mud still makes its way to the clear water dams and settles at the bottom of the dam [42]. This decreases the actual storage capacity of the dam and can cause damage to the pumps [42]. The mud build-up in the clear water dams forces the mine to enforce a minimum dam level limit to prevent pumps from pumping mud [42].

Dewatering pumps

Dewatering pumps are used to transfer water from the clear water dams to pumping stations on different levels, ultimately bringing the water to the surface [55]. Pump stations are normally found close to the clear water dams. These pump stations typically have anywhere between two and twelve pumps, depending on the amount of water that needs to be pumped [42].

Pumps can be divided into two main categories depending on how they impart energy to the fluid, namely dynamic and displacement pumps [55]. Within the category of dynamic pumps, there are two subcategories, namely centrifugal pumps and special effect pumps [55]. Displacement pumps can be sub-divided into reciprocating and rotary pumps [151]. This pump classification breakdown can be seen in Figure 69.

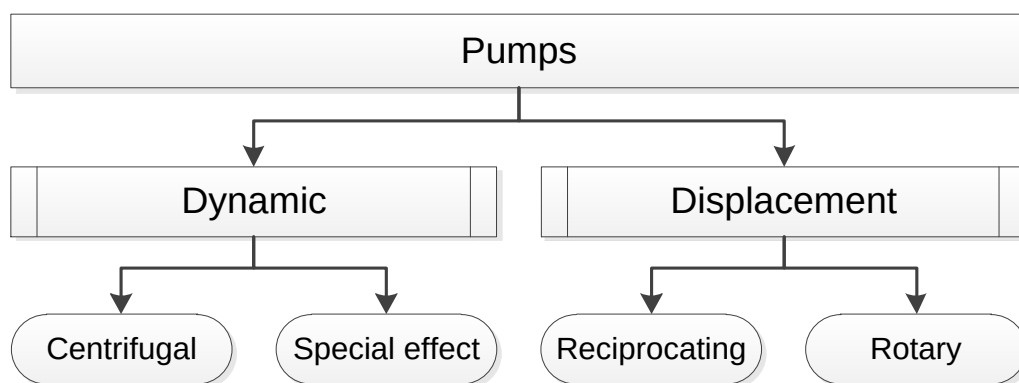


Figure 69: Pump classification

For mine dewatering applications, where extremely high heads need to be overcome, multi-stage centrifugal pumps are preferred [152]. Centrifugal pumps have several benefits; most notably, they can handle high flow rates, provide a smooth and non-pulsating delivery, and are easily

disassembled for maintenance [65]. Multistage centrifugal pumps are equipped with multiple impellers, where the water exiting the discharge side of the one stage enters the suction side of the next stage [42]. Each stage adds a certain amount of head, collectively generating the total head produced by the pump [153]. A cross-section of a multistage centrifugal pump can be observed in Figure 70.

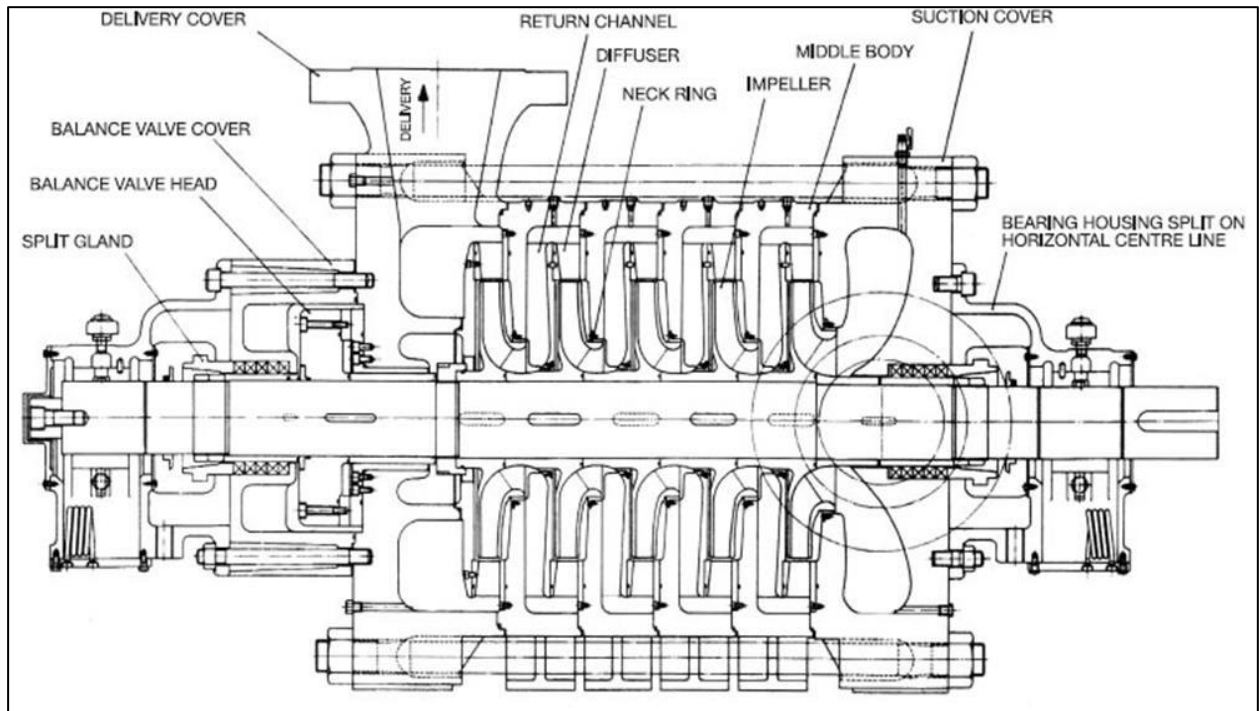


Figure 70: Cross-section through a multi-stage centrifugal pump

Dewatering pumps are operated simultaneously in parallel, discharging into a common manifold for maximum flow delivery [47]. When pumps function in parallel, they exhibit a single combined performance curve [30]. It is ideal to ensure a balanced distribution of the pumping load among the pumps to prevent one pump from overpowering the other, which can lead to a substantial reduction in efficiency [154]. Using more pumps in parallel in a single column will result in a reduced flow rate through each pump [30]. Figure 71 illustrates the performance curve for multiple pumps operating in parallel.

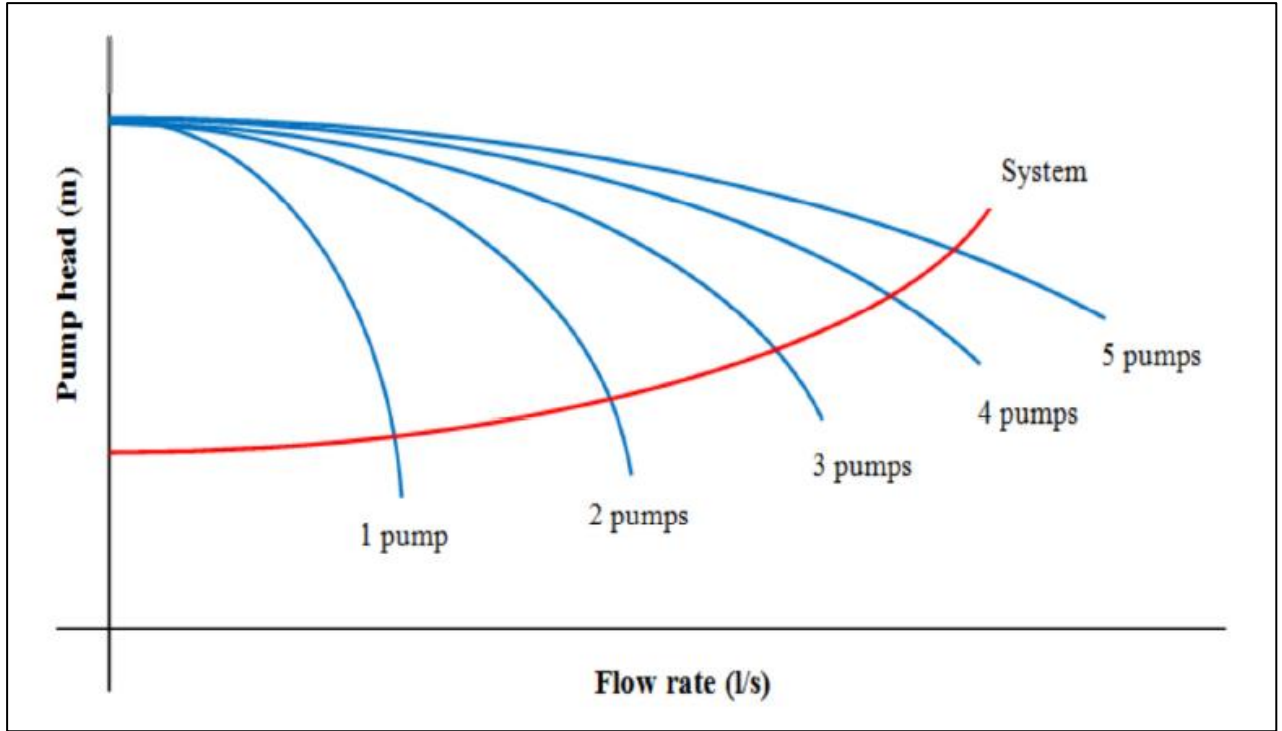


Figure 71: Performance curve for multiple pumps in parallel

The operation of a centrifugal pump is dictated by the fundamentals of fluid mechanics. The pressure difference of water between two elevations can be expressed as [155]:

$$p_2 - p_1 = -\rho g(z_2 - z_1) \quad (11)$$

Where: p_2 = Pressure at level 2 [kPa]

p_1 = Pressure at level 1 [kPa]

z_2 = Elevation at level 2 [m]

z_1 = Elevation at level 1 [m]

If $H = z_2 - z_1$ (the depth from location z_2), then the pressure head (H) can be given as:

$$H = (p_2 - p_1)/\rho g \quad (12)$$

The power gained by the fluid from a pump can be expressed as [156]:

$$P = \dot{m}gH \quad (13)$$

Where: $P = \text{Power [W]}$

$\dot{m} = \text{Mass flowrate [kg/s]}$

$H = \text{Pressure head [Pa]}$

A pump is driven by an electrical motor, typically with a rating of between 500 kW and 4000 kW [99]. If $\dot{m} = \rho Q$, where Q is the volumetric flow rate, then the energy required to pump a liquid at a given flow, head, and duration can be calculated using Equation 14 [156].

$$P = \frac{\rho g Q h}{\eta} t \quad (14)$$

Where: $P = \text{Power [Wh]}$

$\rho = \text{Density of fluid [kg/m}^3\text{]}$

$g = \text{Gravitational constant [m/s}^2\text{]}$

$Q = \text{Flow in [m}^3\text{/s]}$

$h = \text{Head [m]}$

$\eta = \text{Efficiency of system [\%]}$

$t = \text{Time [h]}$

A pump's efficiency deteriorates over its lifetime and adequate maintenance is crucial. In the absence of proper maintenance, a pump can experience a reduction in efficiency of around 10% to 15% within 10 years of operation and may eventually fail completely after approximately 20 years [45]. Every pump has a specific speed, flow rate, and head where it operates at its maximum efficiency, known as its best efficiency point [45].

Instrumentation and Control mechanisms

Certain instrumentation is required to monitor and control a dewatering system. The instrumentation provides real-time information regarding the system and enables mine personnel to remotely control the pumps and valves, ensuring safe operation [55]. Instrumentation usually includes dam level transmitters, temperature probes, vibration sensors, power meters, and flow meters. Dam level sensors are especially important because they are used to determine when pumps should be started and stopped [99]. Flow and power meters are used to help monitor the performance and efficiency of pumps. The control mechanism of a mine dewatering system can be pump operators, SCADA systems, PLCs, control room operators, or a combination of these [55].

APPENDIX B – ELECTRICITY CHARGES

Table 22: Mining operation 1 - Active energy charges

Energy charge (c/kWh)	High-demand season (Jun – Aug)	Low-demand season (Sep – May)
Peak	534.27	174.26
Standard	161.85	119.96
Off-peak	87.91	76.10

Table 23: Mining operation 1 - Other energy charges

Energy charge	Unit	Price
Transmission network charges	R/kVA/month	R 14.19
Network capacity charge	R/kVA/month	R 28.30
Network demand charge	R/kVA/month	R 53.68
Urban low voltage subsidy charge	R/kVA/month	R 0.00
Ancillary service charge	c/kWh	0.70
Service charge	R/account/day	R 6 942.01
Administration charge	R/POD/day	R 221.70
High-season reactive energy charge	c/kVArh	24.95
Electrification and rural network subsidy charge	c/kWh	13.80
Affordability subsidy charge	c/kWh	7.37

APPENDIX C – DSM PROJECT POWER DEMAND BASELINES

Table 24: Shaft A – DSM Project power demand baselines

Time	P [MW] Weekday	P [MW] Saturday	P [MW] Sunday	Time	P [MW] Weekday	P [MW] Saturday	P [MW] Sunday
00:00	12.62	13.39	13.74	12:00	12.36	13.32	14.05
00:30	12.79	13.33	13.75	12:30	12.42	13.52	14.11
01:00	12.77	13.33	13.95	13:00	12.27	13.43	14.18
01:30	12.75	13.48	14.24	13:30	12.14	13.07	13.81
02:00	12.65	13.36	14.09	14:00	12.13	13.12	13.65
02:30	12.64	13.33	14.03	14:30	12.31	12.83	13.77
03:00	12.52	13.42	13.99	15:00	12.36	12.90	14.06
03:30	12.56	13.61	14.13	15:30	12.41	13.05	13.81
04:00	12.55	13.67	14.03	16:00	12.42	13.11	13.79
04:30	12.59	13.49	14.04	16:30	12.41	13.14	14.4
05:00	12.51	13.45	14.03	17:00	12.36	13.37	14.48
05:30	12.36	13.19	13.70	17:30	12.45	13.36	13.98
06:00	12.29	12.68	13.97	18:00	12.40	13.16	14.23
06:30	11.99	12.47	13.63	18:30	12.66	12.97	14.29
07:00	11.54	12.95	12.90	19:00	12.82	12.97	14.22
07:30	11.51	13.10	12.86	19:30	12.71	13.36	14.31
08:00	11.50	13.27	13.24	20:00	12.65	13.27	14.34
08:30	11.55	13.14	12.82	20:30	12.75	13.04	14.03
09:00	11.70	13.45	12.73	21:00	12.78	12.94	13.34
09:30	11.76	13.23	13.26	21:30	12.76	13.47	13.55
10:00	11.6	12.99	13.20	22:00	12.64	13.43	13.91
10:30	11.74	12.82	13.21	22:30	12.67	13.53	14.12
11:00	12.05	12.76	13.59	23:00	12.67	12.73	13.87
11:30	12.16	13.09	13.87	23:30	12.88	12.85	13.65

APPENDIX D – FLOW RATES AND POWER OF PUMP COMBINATIONS

Table 25: Shaft A - Average measured water flows and power demand per pump combination

Level	Column	Pump combination	Average flow [L/s]	Average power [kW]
2	1	Pump 1	224	2942
	2	Pump 3	174	2621
		Pump 5	176	2735
	3	Pump 2	229	3156
		Pump 4	221	2922
		Pump 2 & Pump 4	394	5686
1	1	Pump 1	226	3454
		Pump 2	212	3427
		Pump 3	184	3246
		Pump 1 & Pump 2	375	6652
		Pump 1 & Pump 3	357	6497
		Pump 2 & Pump 3	346	6489
	2	Pump 4	264	3251
		Pump 6	231	3359
		Pump 7	249	3591
		Pump 4 & Pump 6	365	6329
		Pump 4 & Pump 7	367	6558

APPENDIX E – FISSURE WATER QUANTITY

Table 26: Historical fissure water removed from shaft A

Month	Column 1	Column 2	Column 3	Total water flow out [L/s]
August 2022	18.7	22.9	0	41.6
September 2022	13.6	19.3	0	32.9
October 2022	21.7	25.3	0	46.7
November 2022	17.9	22.4	0	40.3
December 2022	21.8	24.1	0	45.9
January 2023	19.7	23.7	0	43.4
February 2023	21.9	25.6	0	47.6
March 2023	21.3	24.6	0	45.8
April 2023	25.1	26.8	0	51.9
May 2023	22.1	23.9	0	46.0
June 2023	24.6	26.8	0	51.4
July 2023	22.8	25.5	0	48.2

APPENDIX F – PUMPING POWER BASELINE

Table 27: Shaft A dewatering system CBL

Time	P [MW] Weekday	P [MW] Saturday	P [MW] Sunday
00:00	19.81	20.77	20.95
01:00	20.04	20.67	20.98
02:00	19.52	20.49	20.93
03:00	19.67	20.48	20.26
04:00	19.69	20.29	21.07
05:00	18.95	20.28	20.41
06:00	10.57	19.43	20.59
07:00	6.91	20.24	20.63
08:00	6.73	20.41	20.47
09:00	13.76	21.21	19.77
10:00	16.78	21.01	20.87
11:00	17.97	20.23	20.55
12:00	18.46	20.37	20.83
13:00	17.98	20.93	21.01
14:00	15.82	20.80	20.72
15:00	15.58	20.73	19.72
16:00	14.13	20.09	20.86
17:00	10.59	20.31	19.81
18:00	10.25	20.52	20.76
19:00	13.77	20.52	20.89
20:00	15.19	20.25	19.92
21:00	16.51	20.02	20.67
22:00	18.67	20.66	20.47
23:00	19.53	20.50	19.97

APPENDIX G – RESULTS

Table 28: Simulation outputs

Number of load curtailment events	Load curtailment duration [hours]	Average energy demand [MW]	Peak energy demand [MW]	S/V shaft dewatering [ML]	Main shaft total dewatering [ML]
0	0	16.04	0.00	1266.6	1481.8
1	8	16.06	0.00	1267.0	1481.4
2	16	16.09	0.00	1267.3	1481.6
3	24	16.12	0.00	1267.5	1481.8
4	32	16.15	0.00	1267.0	1481.3
5	41	16.18	0.51	1266.7	1481.3
6	51	16.20	1.10	1267.1	1481.4
7	59	16.18	2.00	1267.0	1481.9
8	69	16.14	3.13	1266.6	1481.3
9	77	16.12	4.03	1267.2	1481.6
10	84	16.10	4.81	1267.2	1481.9
11	91	16.08	5.62	1267.1	1481.7
12	99	16.07	6.61	1267.1	1481.5
13	107	16.07	7.75	1267.1	1481.9
14	115	16.07	8.79	1267.0	1481.9
15	123	16.08	9.93	1266.7	1481.8
16	127	16.11	10.63	1266.9	1481.5
17	135	16.17	12.12	1266.5	1481.8
18	143	15.97	11.91	1249.2	1463.6

Table 29: Electricity cost results

Number of load curtailment events	Load curtailment duration [hours]	Total pumping electricity cost - Winter	Total pumping electricity cost - Summer
0	0	R13.64 million	R10.85 million
1	8	R13.66 million	R10.88 million
2	16	R13.70 million	R10.90 million
3	24	R13.74 million	R10.93 million
4	32	R13.77 million	R10.95 million
5	41	R14.14 million	R11.08 million
6	51	R14.44 million	R11.16 million
7	59	R14.79 million	R11.19 million
8	69	R15.26 million	R11.25 million
9	77	R15.63 million	R11.29 million
10	84	R15.94 million	R11.32 million
11	91	R16.25 million	R11.35 million
12	99	R16.68 million	R11.41 million
13	107	R17.15 million	R11.48 million
14	115	R17.62 million	R11.55 million
15	123	R18.08 million	R11.62 million
16	127	R18.44 million	R11.69 million
17	135	R19.16 million	R11.84 million
18	143	R18.83 million	R11.65 million

Table 30: Additional electricity cost

Load curtailment monthly occurrence	Load curtailment monthly duration [hours]	Additional electricity cost - Winter	Additional electricity cost - Summer
1	8	R28 000	R21 000
2	16	R65 000	R48 000
3	24	R100 000	R74 000
4	32	R131 000	R97 000
5	41	R500 000	R227 000
6	51	R803 000	R304 000
7	59	R1 148 000	R340 000
8	69	R1 626 000	R394 000
9	77	R1 991 000	R431 000
10	84	R2 304 000	R464 000
11	91	R2 614 000	R496 000
12	99	R3 041 000	R552 000
13	107	R3 511 000	R623 000
14	115	R3 979 000	R693 000
15	123	R4 448 000	R763 000
16	127	R4 804 000	R838 000
17	135	R5 522 000	R989 000
18	143	R5 194 000	R798 000

Table 31: Load shift performance

Monthly load curtailment occurrence	Monthly load curtailment duration [hours]	Average overall load shift achieved [MW]	Evening load shift achieved for DSM project [MW]	PTA Ratio
0	0	15.20	15.76	0.00
1	8	15.23	15.79	0.00
2	16	15.26	15.82	0.00
3	24	15.29	15.85	0.00
4	32	15.31	15.87	0.00
5	41	14.83	15.63	0.03
6	51	14.26	15.12	0.07
7	59	13.34	14.41	0.12
8	69	12.17	13.67	0.19
9	77	11.25	12.67	0.25
10	84	10.45	12.35	0.30
11	91	9.62	11.97	0.35
12	99	8.62	11.45	0.41
13	107	7.49	11.03	0.48
14	115	6.45	10.68	0.55
15	123	5.32	10.23	0.62
16	127	4.64	10.14	0.66
17	135	3.21	9.73	0.75
18	143	3.23	10.33	0.75

Table 32: Generator cost

Load curtailment event	Duration [hours]	CBL [MW]	Load reduction required [MWh]	Generator cost	Cumulative generator cost
1	8	13.64	109.14	R634 000	R634 000
2	8	13.98	111.84	R650 000	R1 284 000
3	8	13.98	111.84	R650 000	R1 934 000
4	8	13.98	111.84	R650 000	R2 584 000
5	9	20.34	183.06	R1 064 000	R3 648 000
6	10	15.00	150.03	R872 000	R4 520 000
7	8	13.98	111.84	R650 000	R5 170 000
8	10	15.00	150.03	R872 000	R6 042 000
9	8	13.98	111.84	R650 000	R6 692 000
10	7	13.72	96.02	R558 000	R7 250 000
11	7	13.72	96.02	R558 000	R7 808 000
12	8	13.98	111.84	R650 000	R8 458 000
13	8	13.98	111.84	R650 000	R9 108 000
14	8	13.98	111.84	R650 000	R9 758 000
15	8	13.98	111.84	R650 000	R10 408 000
16	4	13.93	55.73	R324 000	R10 732 000
17	8	13.98	111.84	R650 000	R11 382 000
18	8	13.98	111.84	R650 000	R12 032 000