

Novel simulations for energy management of mine cooling systems

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ABSTRACT

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The South African mining industry purchased 13.8% of the electricity supplied by Eskom in 2015. Deep-level mines are some of the largest electricity consumers in the mineral extraction industry. The electricity costs of these mines contribute to approximately 20% of their operational costs.

Deep-level gold mines require mine cooling systems (MCSs) to safely operate at the increasing depths and underground temperatures associated with deep-level mining. MCSs account for 41% of the electricity consumption of these mines. Various initiatives aimed at improving energy efficiency of MCSs have been implemented in the past. However, further operational improvements on these systems are still possible.

Operational improvements can be identified with integrated transient response simulations. These simulations can highlight possibilities for new energy saving initiatives and could enable successful energy management. The successful implementation of these initiatives according to design will also be possible due to the forecasting ability of transient response simulations.

A comprehensive review of published work revealed a need for simulations that can simulate the transient response of integrated and complex MCSs. Novel transient response simulations and an approach to energy management were developed. Procedures were also developed for new applications from the applied simulations.

The models and approach were verified by comparing the actual operation of a deep-level gold mine with the simulated results. A combined accuracy of 97% was achieved. Approximately 74 combined resource hours were required to conduct the integrated MCS simulation of Mine P. A validation case study was conducted on Mine A where a simulation accuracy of 94% was obtained.

The complete simulation study on Mine A required 560 combined resource hours, with 144 of those hours used for conducting the simulations. From literature, it was found that a similar approach requires an estimated 1 700 hours. By applying the new models, potential daily energy savings of 145.4 MWh were identified. Potential cost savings of R31 million per annum were identified with the new simulations and approach.

In conclusion, novel transient response MCS simulations were developed and tested. The potential power demand reductions and energy savings from widespread adoption of the technologies developed in this thesis could make significant contributions towards national energy efficiency targets. The various capabilities of the novel simulations can still be expanded to optimise the ventilation processes of deep-level mines and thereby reduce the electricity consumption of these systems.

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LIST OF UNITS

Symbol	Description	Unit of measure
°C	Measure of temperature	Degrees Celsius
ft	Measure of distance	Feet
g	Measure of weight	Gram
G	Denotes 1×10^9	Giga
h	Measure of time	Hour
k	Denotes 1×10^3	Kilo
L	Unit of depth	Level
ℓ	Measure of volume	Litre
m	Measure of distance	Metre
M	Denotes 1×10^6	Mega
m ²	Area	Square metre
a	Acceleration	m/s ²
m ³	Volume	Cubic metre
N	Rotational speed	rpm
Pa	Measure of pressure	Pascal
Q	Measure of water flow rate	m ³ /s
s	Measure of time	Second
t	Measure of mass	Ton
Ẇ	Measure of power	Watt
Wh	Measure of energy	Watt-hour

LIST OF SYMBOLS

Symbol	Description	Unit of measure
CL1	Control limit 1	–
CL2	Control limit 1	–
C_o	Control output	–
C_{om}	Control output minimum	–
c_p	Specific heat	kJ/kg.K
COP	Coefficient of performance	–
COP_{rating}	Coefficient of performance rating	–
D	Diameter	m
d_{Pr}	Delta pressure ratio	–
H	Pressure head	m
h	Enthalpy	kJ/kg
h_{ai}	Inlet air enthalpy	kJ/kg
h_{ao}	Outlet air enthalpy	kJ/kg
h_{wo}	Outlet water enthalpy	kJ/kg
K_i	Integral gain	–
k_v	Valve dynamic loss coefficient	–
\dot{m}	Mass flow	kg/s
\dot{m}_a	Air mass flow	kg/s
\dot{m}_{ai}	Mass flow of air in	kg/s
\dot{m}_{ao}	Mass flow of air out	kg/s
\dot{m}_{ar}	Air mass flow ratio	–
\dot{m}_{ci}	Mass flow condenser inlet	kg/s
\dot{m}_{co}	Mass flow condenser outlet	kg/s
\dot{m}_{ei}	Mass flow evaporator inlet	kg/s
\dot{m}_{eo}	Mass flow evaporator outlet	kg/s
\dot{m}_w	Water mass flow	kg/s
\dot{m}_{wi}	Mass flow of water in	kg/s
\dot{m}_{wo}	Mass flow of water out	kg/s
\dot{m}_{wr}	Water mass flow rating	kg/s
N	Rotational speed	rpm
P	Pressure	kPa
P_{ai}	Pressure of air inlet	kPa
P_{ao}	Pressure of air outlet	kPa
P_{ci}	Pressure of condenser inlet	kPa
P_{co}	Pressure of condenser outlet	kPa
$P_{coefficients}$	Pressure coefficients	kPa

Symbol	Description	Unit of measure
P_{ei}	Pressure of evaporator inlet	kPa
P_{eo}	Pressure of evaporator outlet	kPa
P_{kw}	Power	kW
P_{inlet}	Inlet pressure	kPa
P_{outlet}	Outlet pressure	kPa
P_{ref}	Compressor motor power	W
P_w	Power	W
P_{wi}	Pressure of water inlet	kPa
P_{wo}	Pressure of water outlet	kPa
\dot{Q}_c	Condenser cooling duty	W
$Q_{chiller}$	Cooling duty of chiller	W
\dot{Q}_e	Evaporator cooling duty	W
$\dot{Q}_{evaporator}$	Energy absorbed by the evaporator	kWh
\dot{Q}_{rating}	Chiller cooling duty rating	W
RH	Relative humidity	%
RH_{ai}	Relative humidity of air inlet	%
RH_{ao}	Relative humidity of air outlet	%
ST	Set point	–
T	Temperature	°C
T_{amb}	Ambient temperature	°C
T_{ai}	Air inlet temperature	°C
$T_{ai(WB)}$	Wet-bulb temperature in	°C
T_{ao}	Air outlet temperature	°C
T_{ci}	Evaporator temperature inlet	°C
$T_{ci,rating}$	Condenser inlet temperature rating	°C
T_{co}	Evaporator temperature outlet	°C
$T_{co,rating}$	Condenser outlet temperature rating	°C
T_{ei}	Evaporator temperature inlet	°C
$T_{ei,rating}$	Evaporator inlet temperature rating	°C
T_{eo}	Evaporator temperature outlet	°C
$T_{eo,rating}$	Evaporator outlet temperature rating	°C
T_{inlet}	Inlet temperature	°C
T_w	Water temperature	°C
$T_{wb,ao}$	Wet bulb temperature of outlet air	°C
T_{wi}	Water inlet temperature	°C
T_{wo}	Water outlet temperature	°C
UA	Convective heat transfer coefficient	kW/kJ/kg
UA_{rating}	Convective heat transfer coefficient rating	kW/kJ/kg
V_a	Air velocity	m/s

Symbol	Description	Unit of measure
V_w	Water velocity	m/s
$\dot{W}_{\text{actual daily}}$	Daily power consumption	W
\dot{W}_c	Compressor power	W
\dot{W}_f	Fan power	W
\dot{W}_p	Pump power	W
\dot{W}_{savings}	Power saving	W
$\dot{W}_{\text{scaled baseline}}$	Scaled daily power consumption baseline	W
$\eta_{\text{coefficients}}$	Efficiency coefficients	–
$\eta_{\text{generator}}$	Generator efficiency coefficient	–
η_m	Mechanical efficiency	–
η_{turbine}	Turbine efficiency	–
η_w	Water side efficiency	No unit
ρ	Density	kg/m ³
ρ_{ai}	Inlet air density	kg/m ³
ρ_w	Water density	kg/m ³
ρ_{wo}	Water outlet density	kg/m ³

ABBREVIATIONS

Symbol	Description
3 CPFS	3 Chamber Pipe Feeder System
BAC	Bulk Air Cooler
CCT	Condenser Cooling Tower
COP	Coefficient of Performance
DSM	Demand Side Management
EPI	Energy Performance Indicator
ESM	Energy Saving Measure
KPI	Key Performance Indicator
MCS	Mine Cooling System
MCU	Mobile Cooling Unit
M&V	Measurement and Verification
OEM	Original Equipment Manufacturer
PCT	Precooling Tower
PFD	Process Flow Diagram
PI	Proportional-integral
PID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
PRV	Pressure-reducing Valve
SCADA	Supervisory Control and Data Acquisition
TOU	Time-of-use
VSD	Variable Speed Drive
WCS	Water Control Station

GLOSSARY

- Calibration:** Calibration is achieved by verifying that the simulation model reasonably predicts the energy patterns of the facility by comparing model results to a set of calibration data. This calibration data includes measured energy data, independent variables and static factor.
- Control emulation:** Process involving the replication of the behaviour of one or more components in a system within a software environment (typically for a system under design).
- Deep-level mine:** Any method of extracting minerals from the subsurface, except open-pit mining and auger mining, and includes methods such as drift mining, shaft mining, and inclined slope mining. Normally this type of mining is deeper than 1.5 km below surface.
- Explicit modelling:** Approach used in numerical analysis. Explicit methods are used to calculate the state of a system at a later period from the state of the system at the present period.
- Energy efficiency:** Defined as the ratio between economic outputs versus energy consumption.
- Geothermal gradient:** Geothermal gradient is the rate of increasing temperature with respect to increasing depth in the Earth's interior.
- Implicit modelling:** Approach used in numerical analysis. Method used to find a solution by solving an equation involving both the present state and the future state of the system.
- Mine cooling system:** Also referred to as MCS. For this study, this term refers to the refrigeration, water reticulation and pumping sub-systems on a typical deep-level mine.
- Mining level:** A mining level can be defined as a certain depth below surface where mining operations are located. As an example, 70L is located 7 000 ft below surface.
- Optimisation:** For this study, this term refers to finding the optimum working point of a system, or a combination of systems.
- Process boundary:** The begin point and end point of a process.

- Steady state:** In terms of steady state simulation, it is the behaviour of a system when a system restores to a point of equilibrium after a disturbance in the system.
- Transient:** In terms of transient (response) simulation, it is the behaviour of a system after a certain action or disturbance in the system, and the action or disturbance does not last a long time.
- Verification:** The evaluation of whether a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process. Contrast with validation.
- Validation:** Validation. The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers. Contrast with verification.

1

CHAPTER 1

INTRODUCTION TO MINE COOLING SYSTEM ENERGY MANAGEMENT

“Many of us crucify ourselves between two thieves – regret for the past and fear for the future.”

~ Fulton Oursler (Writer)

1. INTRODUCTION TO MINE COOLING SYSTEM ENERGY MANAGEMENT

1.1. Background

Worldwide, energy is the key to economic development. Global energy systems are constrained by several factors, which include the inefficiency of the energy systems themselves, and social and environmental problems [1]. In order to promote a growing economy, South African industries will have to focus on water and energy efficiency during future expansion [1].

Improving the energy efficiency of systems is internationally considered as a method for ensuring the security of energy supply [2]. The energy demand profile of South Africa, which is characterised by high energy intensity, highlights the importance of energy and water efficiency. Energy innovation is thus also required for industries to be able to develop in the energy-constrained economy of South Africa.

The South African power utility, Eskom, was strained by the ever-expanding industrial sector. The rapid expansion of the mining, industrial and public sectors in South Africa was one of the cited issues straining the electrical energy grid [3]. An efficient, cost-effective and reliable energy supply is crucial for any further economic and social expansion to be supported.

Some literature states that the electricity shortage experienced in the country was related to the lack of energy systems research, and the absence of independent power producers in the market [4, 5]. Although the energy supply is now sufficient, future constraints can be mitigated.

Fragile labour relations and significant economic pressure highlight the importance of South African mines reducing operating costs, ensuring safe working conditions, improving energy efficiency, and minimising unwanted downsizing. Mining companies historically focused on capturing rapid cost saving gains, but are seeking further solutions for operational improvements. These solutions can be found in implementing operational improvement efficiency programmes, adopting lean practices and investing in innovation [1].

Energy efficiency will mean a stronger economy, a cleaner environment and greater energy independence for South Africa. It is therefore required that companies invest in a diverse portfolio of energy efficiency technologies. The mineral extraction and processing industry makes up the bulk of the South African economy. These industries consume more electrical energy in the country than other industries [5].

Fossil fuels are the primary source of energy supply to these industries [6]. The supply of non-renewable resources is depreciating, which directly influences the industries relying on these sources [7]. In order to promote the sustainability of the mineral extraction and processing industries, mines need to increase their energy efficiency and reduce their water consumption [8]. Energy management has also become critical for companies in these industries to achieve carbon emission goals and to become more energy efficient in their operations [9].

The mining industry made up 13.8% of Eskom's total 216 274 GWh electricity sales in 2015 [10]. Figure 1 illustrates that mining consumes more electricity than other significant electricity-consuming industries [10]. In particular, deep-level mining is one of the largest electricity consumers in the mineral extraction industry. The electricity cost of deep-level mines in South Africa accounts for over 20% of the operational cost thereof [9].

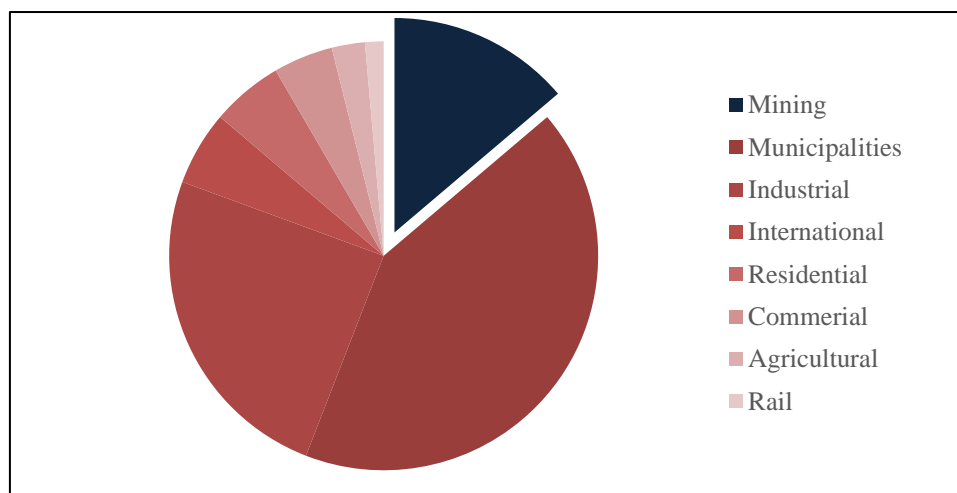


Figure 1: Eskom electricity sales to industries in 2015 [10]

The South African government has launched several funding models to motivate industries to reduce their energy consumption. Some of the models include Demand Side Management (DSM), and section 12L and 12I incentives [11]. These funding models have successfully

reduced electricity demand in the country [12]. However, additional energy efficiency improvements are still possible in these high energy demand systems.

The objective of extracting minerals from a mine is achievable due to a variety of energy intensive complex systems cooperating in unison. These systems, which include cooling, water reticulation and dewatering, ventilation, compressed air and hoisting systems, are operated to ensure ore extraction takes place [13]. South African deep-level mines are some of the deepest in the world, with some mines developing and mining ore up to 4 km deep [14].

Gold mines are also some of the largest electricity consumers in South Africa. These mines consume approximately 8% of the electricity supplied to deep-level mines [15]. Operating mines at these depths require significant mine cooling systems (MCSs). MCSs, consisting of mine refrigeration and water reticulation (pumping) sub-systems, are used to maintain underground working conditions below the legal limit of 32 °C wet bulb, and provide cold water for mining purposes [16].

Approximately 41% of the electricity consumed by a deep-level gold mine is used by these processes combined. Figure 2 illustrates the percentage of the total electricity consumption of a mining group's deep-level gold mines. Identifying, innovating and implementing projects to reduce energy consumption on the cooling and water reticulation systems can lead to significant energy and cost savings.

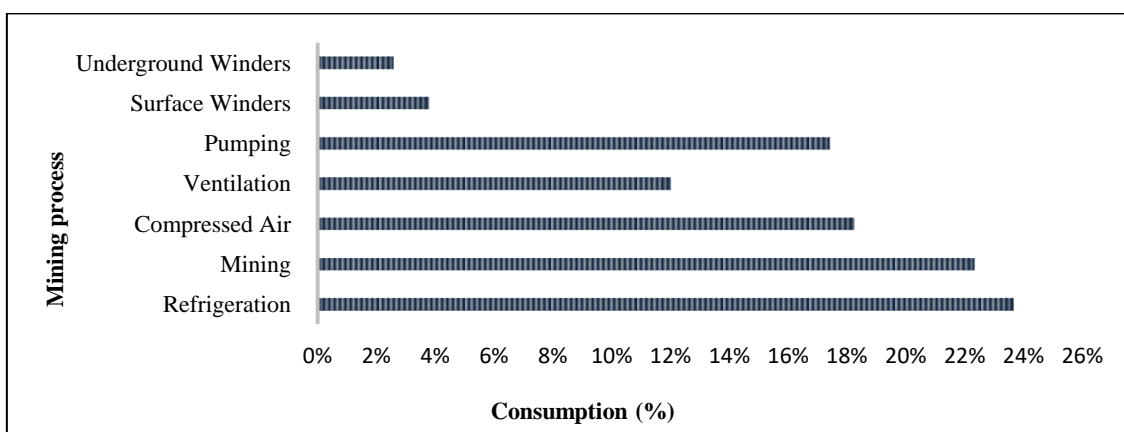


Figure 2: Percentage electricity consumption per mining process¹

¹ Average of processes within a mining group – actual data from 2015

For this study, the refrigeration, pumping and air cooling systems are collectively defined as the MCS, which will be explained further in Chapter 2. MCSs have been integrated in previous studies, with energy saving measures identified and implemented. The dynamic operation and combination between these systems in terms of an integrative approach to combine them, and the optimisation of these systems have been investigated in published work [14, 17, 18, 19, 20].

However, there is still a need for energy management on MCSs. This thesis is aimed at developing novel simulations for the energy management on these systems. A critical literature review and the need for this thesis will be discussed in the following section. New simulations developed in this thesis will enable mines to become more efficient in their mine cooling processes by implementing the suggested operational improvements.

The following section will discuss previous published work, which drives the hypothesis of this thesis. The research objectives and the novel contributions will also be defined in this chapter. The aim of this thesis is to develop new dynamic models for efficient integration of MCSs to allow energy management studies to be conducted.

1.2. Critical analysis of previous research

1.2.1. Overview of the literature

The previous section provided a condensed background on the need for energy efficiency in the mining industry. The mining industry has experienced a significant change over the past 20 years, in terms of equipment, technologies and human resources policies [21]. The fact that technology in the mining industry is continuously expanding, creates many opportunities for improving operations and ensuring a safe and sustainable industry.

In the previous section, MCSs of deep-level mines were identified as significant energy consumers. Simulations recently developed in industry use various models. These models are accompanied by various approaches in industry, and vary from system to system. These simulations and approaches are rarely aimed at energy management and integrated system optimisation. A need for transient simulations that focus on energy management of an integrated system was therefore identified.

Figure 3 illustrates the problem of specifically integrating MCSs. As can be seen, an MCS is a complex system consisting of various sub-systems. However, most studies focus on the component integration with the sub-system, and rarely on the inter-related dependency of the components in the sub-system and the system as a whole. Any changes on component or sub-component level significantly influence the entire combined MCS.

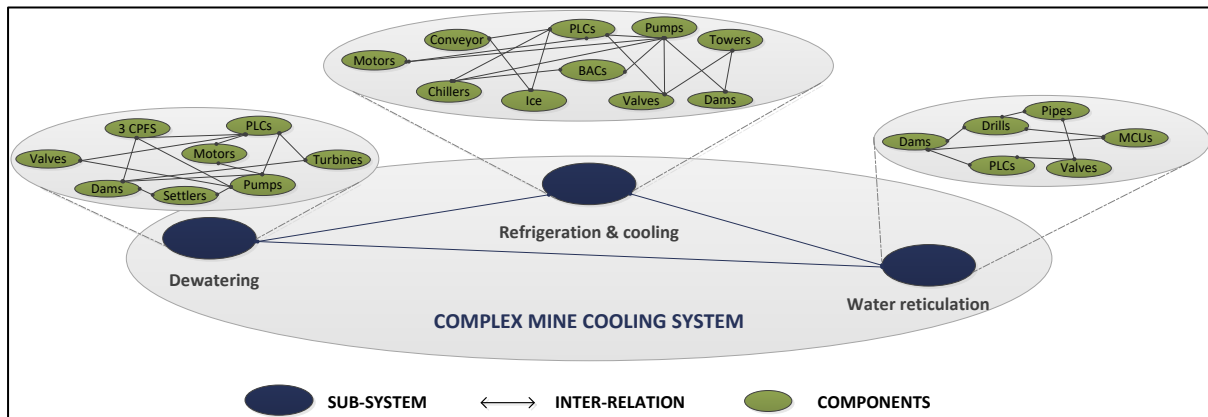


Figure 3: Simplified illustration of a complex MCS

A critical literature survey was conducted that focused on the industry's approach to energy management of MCSs, as well as the approach to simulations for integrated MCSs. The survey endeavoured to find publications and previous work focusing on a simulation approach to energy management and all relevant topics relating thereto. Numerous methods exist for energy management of MCSs.

However, this critical evaluation only focuses on work that considers studies where the approach is similar to that developed in this study. The publications considered for this study spanned a wide range of contexts. They produced significant numbers of facts, details and methods. A summary of the critical review is therefore presented in this section. A total of 38 studies were reviewed as part of the critical literature review.

The literature that did not fully apply to this study was retained and used as additional consideration for the methods and procedures developed in this thesis. The studies reviewed in the following sections will be discussed in more detail in the comprehensive literature study represented in Chapter 2. Table 1 illustrates the critical literature reviewed for this chapter.

Table 1: Published work relevant to the critical evaluation

Table of critical published work								
No.	Author(s)	Cit.	System	Application	Transient (TR)/steady state (SS)	Integrated system	Main task	Main finding
1	Loredo, Roqueñí and Ordóñez	[22]	Geological	Planning	N/A	No	Geological planning	Modelling with numerical and analytical models
2	Holman	[23]	Mine surface refrigeration	Energy management	TR	No	Simulation to determine effect of improved maintenance	Approach to maintenance procedures - COP improvement
3	De Souza	[24]	Mine ventilation system	Optimisation	N/A	No	Computer network modelling used for optimisation study	Optimisation through modelling is possible
4	Liu, Diedrich and Suchold	[18]	Factories	Control	SS	Yes	Feature based modelling, semantic based	Control emulation through modelling
5	Reddy	[25]	Buildings	Design	N/A	Yes	Design simulations used for modelling and simulations were calibrated	N/A
6	Bunse et al.	[26]	Factories	Energy management	N/A	Yes	Production management	Energy management of factories
7	Zhang	[27]	Mine ventilation	Planning	TR	No	Determine if Flownex can be coupled with CFD software, use for mine planning	Flownex can be used with CFD - Hybrid model
8	Slabbert	[28]	Reactor design	Design	TR	No	Used for reactor design	N/A
9	Olivier	[29]	Reactor design	Design	TR	No	Implicit and explicit in separate study	N/A
10	Du Plessis 2013	[30]	Mine surface refrigeration	Energy management	SS	No	Optimisation of surface mine refrigeration system with VSDs	VSDs can be used for optimisation of MCSs
11	Swart	[31]	Underground cooling	Energy management	SS	Yes	Heat transfer networks - underground mine refrigeration system optimisation	Optimisation for minimum cost saving
12	Van Der Bijl	[19]	Mine surface refrigeration	Energy management	SS	No	Sustainable DSM through implementation of energy management system	DSM performance sustained
13	Calitz	[32]	Mine surface refrigeration	Energy management	SS	No	Surface mine refrigeration system - scheduling of chillers	Load reduction achieved through scheduling
14	Environ 1997	[33]	Mine ventilation	Planning	SS	Yes	Full thermodynamic analysis, heat, recommend design	Mine ventilation planning software
15	Wu and Topuz	[34]	Mine ventilation	Design	SS	Yes	Integration of ventilation system and analysis of system	Mine ventilation system analysed with operations research
16	Bluhm et al, 2014	[35]	Mine ventilation	Planning	SS	Yes	Full thermodynamic analysis, heat, recommend design	Ventilation planning - procedure not relevant
17	Vosloo et al.	[14]	Mine water reticulation	Energy management	SS	Yes	Integration of the pumping and water reticulation system	Efficient integration, power savings
18	Bouwer	[36]	Mine surface refrigeration	Energy management	TR	Yes	Development of new thermal systems simulation tool	New simulation scheme tested on building and surface mine refrigeration system
19	Arndt	[37]	Buildings	Energy management	SS	No	Building application, developed and tested for mining application	Integrated simulations possible
20	Schutte 2013	[13]	Bulk air cooling system	Energy management	SS	No	Mine air cooling - BACs peak clipping	BAC peak clipping successful, power savings
21	Schutte 2007	[38]	Mine surface refrigeration	Energy management	SS	No	Cascade pumping system optimisation	Optimisation possible, power savings
22	Van Vuuren	[39]	Mine water reticulation	Energy management	SS	No	New three pipe system savings potential optimisation	Three pipe system optimised
23	Bluhm et al, 2001	[40]	Ventilation	Planning	SS	No	Ventilation planning - procedure not relevant	Mine ventilation planning
24	Bluhm et al, 2001	[41]	Mine cooling system	Design	TR	No	Variations in ultra-deep, narrow reef stoping configurations	Energy costs considered, effects on cooling and ventilation
25	Von Glehn et al.	[33]	Mine water reticulation	Design	SS	No	Mine ventilation and cooling network simulation tool used - VUMA	Applications and use of simulations
26	Webber Youngmann	[17]	Mine ventilation	Optimisation	SS	No	Air cooling, air supply and water pumping analysed	Prediction through simulation - ventilation
27	Webber Youngmann		Mine ventilation	Planning	TR	No	Ventilation planning with software	Ventilation planning is possible with simulations
28	Cilliers	[42]	Mine surface refrigeration	Energy management	SS	No	Benchmarking mine energy consumption using simulations to verify benchmarks	Benchmarking models
29	Booyesen	[43]	N/A	Measurement & verification	N/A	Not mentioned	M&V conducted for mine DSM projects	M&V option D can be used for simulations
30	Anibas et al.	[44]	Hydrology	Investigation	TR&SS	No	Heat balance model implemented in FEMME water and energy model VS2DH	Hydraulic and thermal simulation - water bodies
31	George, Davood and Pierre	[45]	Mine ventilation	Planning	TR	Yes	The rock mass model is interfaced to Multiflux using numerical models	Mine ventilation planning, HSE
32	Biffi et al.	[46]	Mine ventilation	Planning	N/A	No	Mine ventilation, only mentioned that transient conditions should be considered	Platinum mine ventilation planning
33	Wallace et al.	[47]	Mine ventilation	Planning	Not mentioned	No	Mine ventilation services - fire, airflow etc.	Ventilation and ventilation control

No.	Author(s)	Cit.	System	Application	Transient (TR)/steady state (SS)	Integrated system	Main task	Main finding
34	Mackay et al.	[48]	Mine cooling system	Planning	Not mentioned	Not mentioned	Platinum mining future expansion etc. reviewed different technologies	Platinum mining future expected development
35	Du Plessis, J.J.L	[49]	Mine cooling system	Energy management	Not mentioned	No	Mine cooling system analysed, not entire system - financial considerations	Energy trade-off studies of various technologies
36	Tveit	[50]	Production lines or factories	Energy management	SS	Yes	Energy audits and analysis of sulphuric plant system with power plant commercial simulation	Sulphuric acid plant energy analysis
37	Stanton	[51]	Underground mine refrigeration	Design	TR	No	Developed technology for cooling for large scale implementation - calibrated with design values	Simulated 16 system configurations
38	Van Antwerpen et al.	[52]	Mine cooling system	Optimisation	SS	Yes	Energy saving measures identified through integration, integrated simulation conducted, steady state, found merit in integration	Simulated mine cooling system

1.2.2. Industry's approach to integrated transient response simulations

Achieving effective system integration provides a framework for optimisation and process improvements, as well as a platform for energy management. A single dynamic optimisation model allows for the optimisation and process improvements of a system. However, considerable work has been done on individual system integration and optimisation.

These methods will also be incorporated into the new dynamic integration models where applicable. Mines can realise cost and energy savings using integrated models for integration and optimisation of MCSs. Simulating thermal and energy systems is considered internationally as one of the most effective tools for improving the overall energy efficiency of such systems [36]. A simplified representation of the difference between transient and steady state simulations is illustrated in Figure 4.

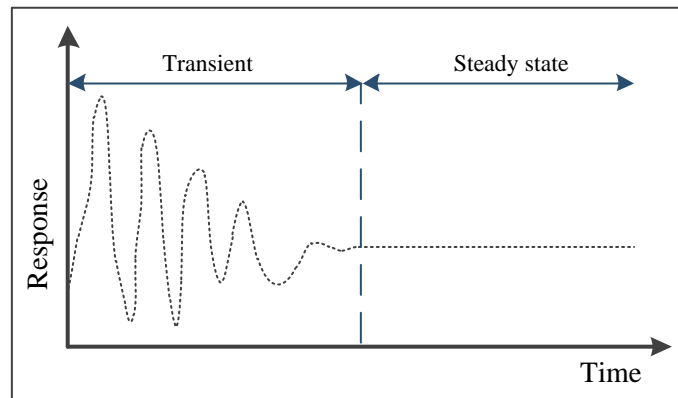


Figure 4: Transient response versus steady state simulation

Transient and dynamic simulation is used in industry to produce a more “realistic” model of real-world processes and systems. In a system that is fully integrated, one system component will either have an immediate or delayed response on all other related and connected system components [36]. Various powerful simulation tools and models are available in industry that can simulate nearly any imaginable system.

Figure 5 illustrates a simple MCS with the simulations conducted in the studies reviewed for the critical literature survey. Integrated system simulation refers to the way that individual system components react to other components in the same simulated system [53].

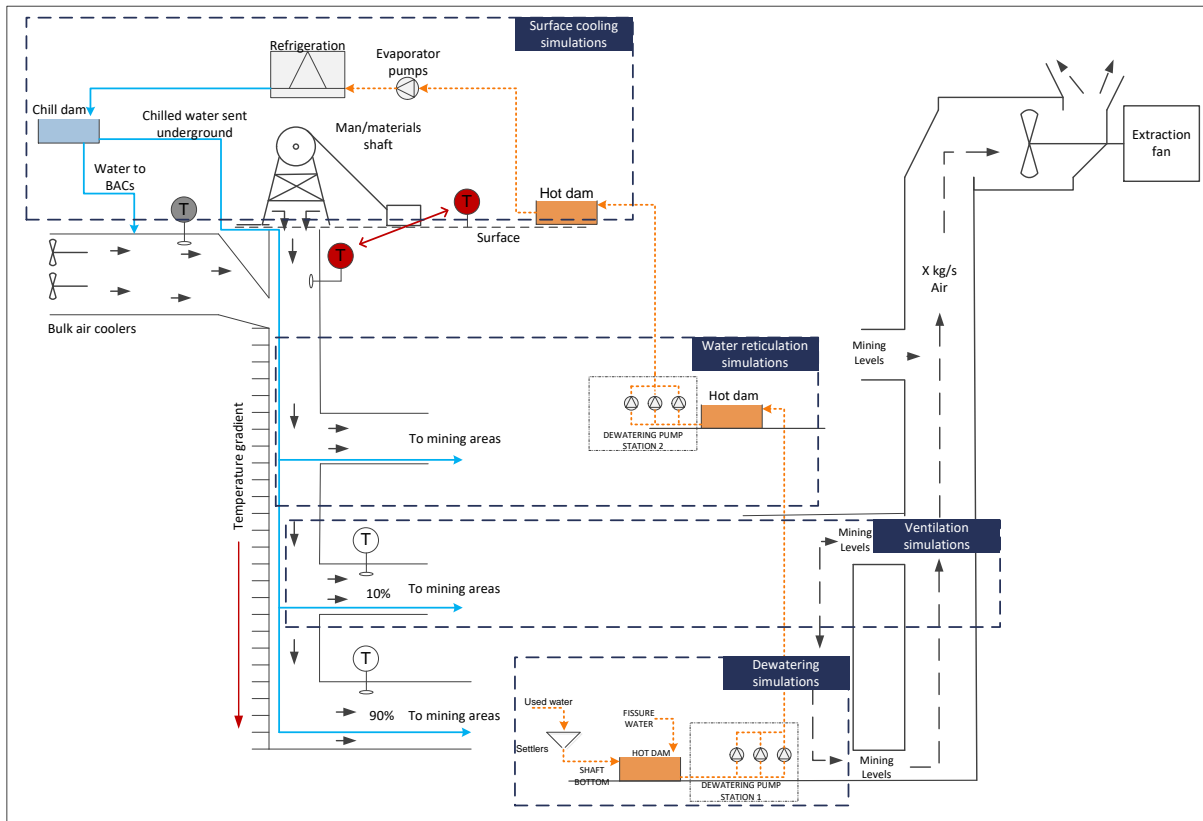


Figure 5: Illustration of various individual simulations of the MCS

This study mainly focuses on the simulations that can be used for **integrated transient response** simulations for energy management of MCSs. However, there are numerous studies that focus only on steady state simulations, but similar models and approaches were developed when compared with this thesis. Figure 6 illustrates the percentage of studies reviewed that focuses on integrated and non-integrated system simulations.

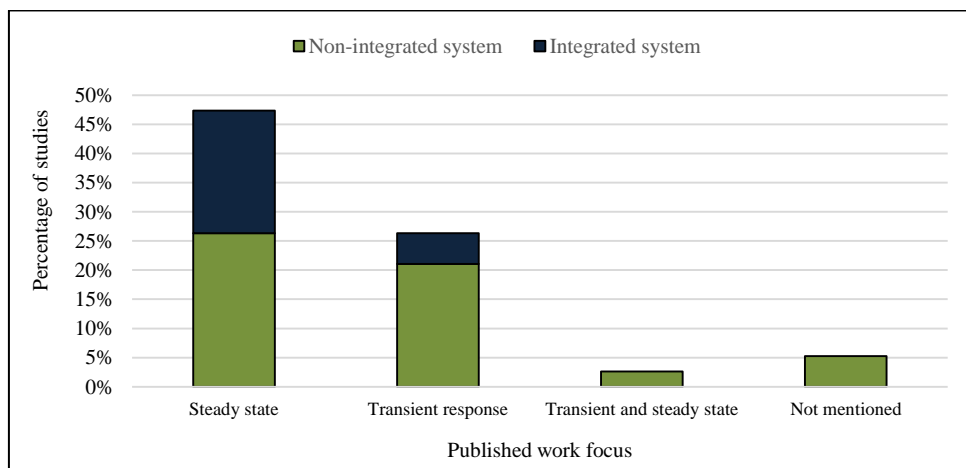


Figure 6: Percentage of studies focusing on transient response simulations

When reviewing the general approach to simulations in industry, it was found that 47% of the studies reviewed conducted steady state simulations of integrated and non-integrated systems. It was also found that 21% of the studies reviewed simulated transient non-integrated systems. An additional 3% focused on simulating transient and steady state conditions of non-integrated systems to determine the sensitivity of conducting the simulations in each manner. Only 5% of the studies focused on transient response simulations of the integrated system [36, 45].

When reviewing these studies (5% simulating transient response of integrated system), the first study only simulated the integrated surface MCS [36]. The second study conducted mine ventilation planning studies with Multiflux™ code. A rock mass model was simulated and integrated into the Multiflux code with a numerical analysis [45]. This study is not relevant to the simulations that will be developed in this thesis, but the information and approach are retained for developing models in this thesis.

The remaining studies (5% of the critical literature reviewed) gave no indication whether the simulations were transient or steady state, but simply stated that simulations were done. Few studies focused on transient response simulations of integrated systems. As stated previously, it is required to simulate the entire MCS in an integrated approach to enable various applications through the simulations.

When conducting energy management investigations and implementing these initiatives it is required to determine the control of the relevant MCS. No transient integrated simulation studies for MCSs were found. Published literature was reviewed to determine the capabilities of simulations used in the relevant studies.

The approach in this case was also considered. The percentage of studies that was reviewed is illustrated in Figure 7. It was found that 26% of the studies focused on steady state simulations of the integrated and non-integrated system. These studies also conducted some form of energy management with these simulations.

However, only 8% of the published work simulated the system in a transient approach and conducted some form of energy management [36, 23, 37]. However, these studies did not consider control emulation of the energy saving measures that were identified. Only 3% of studies considered the integrated system in the simulation [36].

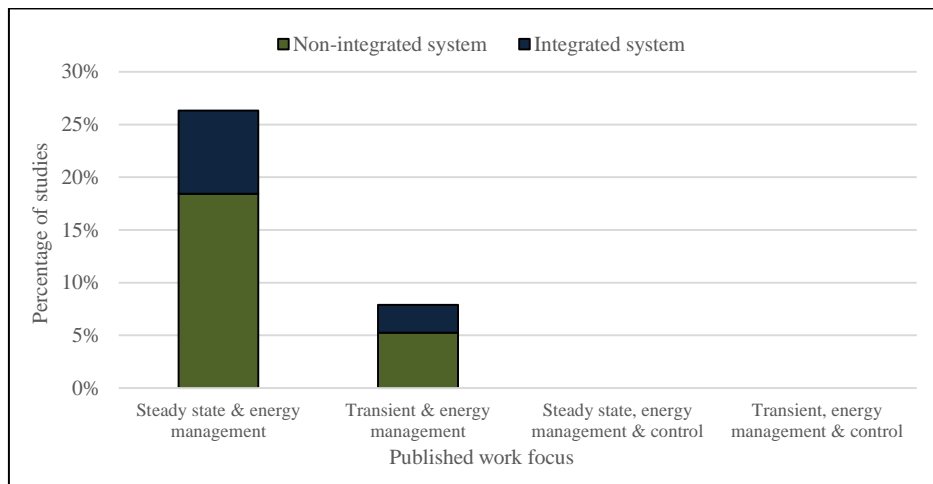


Figure 7: Percentage of studies focusing on energy management and simulation control

However, it was not clear if the author calibrated the simulations and whether the approach followed for the simulations was sufficient. The software used could only simulate mass and energy, and not momentum, which is required for full transient simulations. This will be discussed in more detail in Chapter 2.

When comparing the reviewed work with the need identified for this thesis, it was found that none of the studies focused on simulating the relevant system with a transient approach, whilst still conducting energy management practices and simulating the control effect on the integrated MCS. When reviewing studies specifically relevant to cooling and ventilation of deep-level mines, very few studies focused on transient response simulations for integrated MCSs.

Figure 8 illustrates the percentage of studies that used transient and steady state simulations for simulating the individual sub-systems in an MCS. From the total reviewed studies, only 8% conducted transient and steady state simulations of the entire MCS [13, 40].

The study conducted by Bluhm et al. [35] focused on the design of the ventilation system and the integration thereof into the MCS. However, the study did not focus on the control emulation or other applications that can promote energy management. Only the energy costs were considered in the design. The study conducted by Schutte [13] only simulated steady state conditions, and considered the effect of the bulk air coolers (BAC) on the MCS. The control effect on the system was also not considered.

However, these studies were mostly design-based and did not primarily consider the energy management of the simulated system. The relevant studies were also aimed mainly at the

effect of the MCS on the ventilation system, and only considered load management as part of energy management.

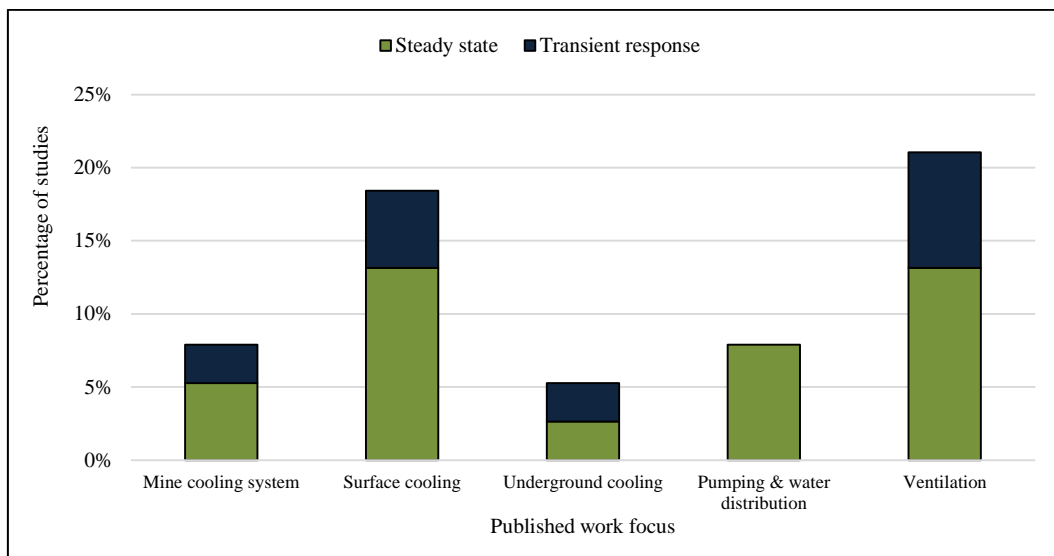


Figure 8: Studies using simulations for deep-level mines

This study is therefore also aimed at managing the dynamic effect of the integrated system on the energy consumption through simulation. When considering the literature, it becomes evident that there is a significant need for simulations and an approach for the integrated energy management of MCSs, which also considers the transient system response.

When conducting energy management studies, it is a requirement to simulate control on the system. Several studies have been conducted on control emulation with software and models. However, no published work could be found that simulated the integrated MCS, and conducted energy management and control emulation studies with the same simulations. From this section of the critical review, it is evident that the existing approach in industry is not sufficient for the objectives of this study.

The simulations and approach developed in this thesis need to consider the factors identified in the comprehensive literature study, but the unique approach required for energy management, integration of MCSs and transient simulations thereof will need to be considered.

1.2.3. Software used in industry and capabilities

Different software packages and simulation models are available in industry for numerous applications. These software packages are reviewed as part of this thesis to determine a

suitable simulation package to develop novel simulations for energy management of MCSs. The capabilities and application of the software used in various studies were also reviewed.

Figure 9 illustrates the percentage of studies reviewed that used software that can simulate integrated systems, considering both steady state and transient models. Figure 9 shows that most simulation software reviewed can simulate steady state, integrated systems. Only Process Toolbox (PTB), VUMA3D, Flownex®, QUICKcontrol and VisualQEC can simulate transient systems. However, very few of these models can simulate transient integrated systems.

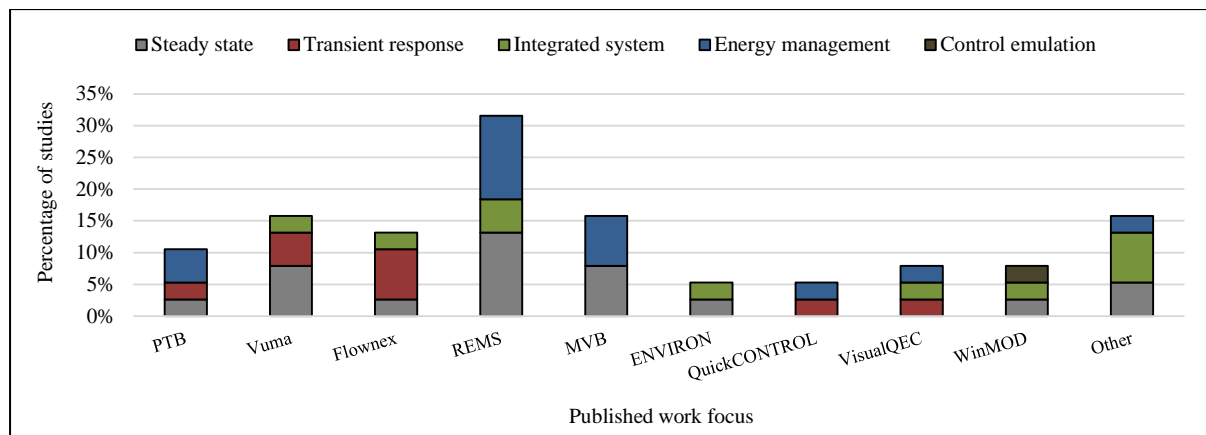


Figure 9: Software and capability of software used in published work

It was therefore required to investigate these packages in more detail to determine whether the software could be used for the simulations and approach required in this thesis. The exact functioning and capabilities of the software will be reviewed in Chapter 2. The capabilities of the software and models used in industry span a significant spectrum of applications, but the development of new models and a new approach to energy management of MCSs have certain requirements.

The software, models and existing simulations were reviewed in terms of three main capabilities, namely, 1) the ability for emulating control, 2) energy management of MCSs, 3) and the ability of integrating MCSs. The main focus was to find published work that employed software capable of integrated system simulations that can emulate control on the integrated system, and that can conduct energy management studies on MCS.

The software identified that could emulate control was WinMOD® [18] and PTB [23]. Further investigation into the WinMOD software revealed that there is no published work on

the software being used for emulating control of MCSs, especially when considering the energy management aspect of this study. The software also cannot conduct integrated system simulations.

Investigating the applications of the PTB software revealed that the package can simulate the control and energy management of systems. It was also found that this software is based on previous work conducted by Arndt [37], where QUICKcontrol was developed from building simulation software for simulating mining systems and Bouwer [36] that developed VisualQEC from the QUICKcontrol software, also for application in the building and mining industry.

PTB therefore has similar capabilities. The exact functioning of PTB as well as the models and method used to develop the software will be discussed in the comprehensive literature review. From the critical survey, it was found that only PTB met the requirements of the industry demand and could potentially be used for new simulations of the integrated MCSs. This software is therefore also suitable for control emulation of projects on MCSs, as well as for energy management of MCSs.

1.2.4. Energy management of MCSs

Figure 10 illustrates the percentage of studies focusing on energy management initiatives on MCSs as well as the integrated or non-integrated approach. This figure shows that no integrated energy management studies were conducted on the entire MCS. Numerous studies have, however, been conducted on sub-systems such as the surface cooling, underground cooling, pumping and water reticulation and ventilation systems.

From the critical analysis of published literature, it was found that most studies employed Real-time Energy Management System (REMS) software for energy management of individual mine cooling sub-systems as well as the entire MCS. In most of these studies, the authors mentioned that REMS can simulate, optimise and control the MCS. However, it was determined that these simulations were only conducted in a steady state approach, and did not consider the transient effect of the energy management of the entire system.

The methodologies developed in these studies will be reviewed and considered for developing the simulations and approach of this study. However, it is still clear that the need for this study has not been addressed by previous literature.

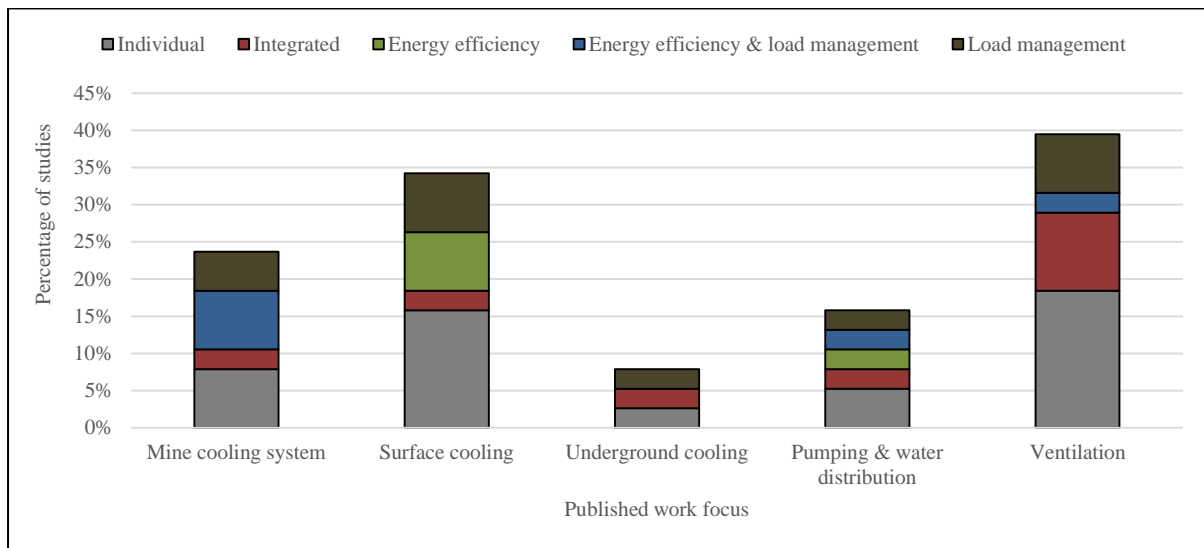


Figure 10: Energy management initiatives on non-integrated and integrated MCSs

The detailed approach followed for energy management of MCSs is described in Section 2.3. Simulations were mostly used to identify energy saving measures to be implemented on the MCS, its sub-systems and on component level. However, this study will be aimed at not only identifying new studies for energy management practices, but also energy forecasting for energy management, and continuously enabling energy scenario evaluations for the mining industry.

1.2.5. Summary of the critical evaluation

In this section, a critical literature review was summarised to give the reader an understanding of what existing studies and published work focused on. It was found that numerous similar studies were conducted by previous authors, but none of the literature reviewed focused on energy management through a simulation approach for MCSs.

It is important that the approach and simulations developed in this thesis must account for the effects of the transient nature of thermodynamic conditions encountered at depth as well as those imposed on MCSs. None of the literature reviewed focused on this. No further publications were found that are similar to the new simulations and approach as those that will be developed in this study.

In summary, all individual system improvements, projects and optimisation of different mine cooling sub-systems need to be integrated as a new approach and subsequently managed to achieve energy management. This approach must be integrated into the new simulations to be

used for the energy management of the MCS. From the preceding critical analysis of published literature, the need for this study and study objectives can now be defined.

1.3. Need for this study and objectives

1.3.1. Need for this study

From the critical analysis of the previous work, a certain need was identified. The models and approach to be developed in this thesis must address the need identified.

The need for this study can be described and summarised as:

- No previous studies conducted energy management with transient response simulations. New simulations must therefore be developed to reduce the operating cost of MCSs using simulations and a new approach.
- To determine the effect of control on MCSs. The transient response simulations must therefore be constructed to be used for control emulation on MCSs.
- Energy management of MCSs includes that an energy forecasting and energy scenario analysis have to be conducted. Novel simulations are therefore required to determine the integrated effect of system changes and to evaluate the operational effects on the system.
- To determine the effect of the transient nature of thermodynamic conditions encountered at depth as well as those imposed on MCS.
- An easy-to-use model to save resource cost and time.

From the critical analysis and need of this study, the objectives can now be clearly defined.

1.3.2. Objectives

The need for this study was defined in the previous section. The existing approach in industry was defined through a critical evaluation of published literature, with the shortcomings and needs also identified. The objectives of this study are therefore:

- To select appropriate software for transient simulations for energy management of integrated MCSs.
- To develop a new transient response simulation approach for simulating MCS energy consumption through an integrated approach.

- To develop a novel component control emulation method for system evaluation or energy saving project commissioning on MCSs.
- To develop an approach for dynamic energy forecasting of MCSs with transient simulations.
- To verify and validate simulations.

The novel contributions of this study can now be defined. The novel contributions will be discussed in the following sections.

1.4. Novel contributions

1.4.1. New transient response simulations to integrate MCSs for energy management

Existing approach:

Existing simulations used in industry are mostly design-based and have not been specifically developed for integrated energy management of MCSs [28, 29, 34, 33]. Existing systems can analyse both steady state and transient design conditions, but lack the ability to dynamically integrate the entire MCS and solve transient conditions [17, 23, 28, 29, 27, 46]. The existing models are also limited to either using simulations of energy and mass, or rarely considering the momentum of a dynamically integrated system [36, 45].

Shortcomings and needs:

Simulations are required that can simulate the energy consumption of MCSs and predict the transient response of MCS components. No previous published work was found in the critical review process that meets the requirements of integrated transient simulations for MCS energy management. Simulations are therefore required that can dynamically simulate MCSs in an integrated approach. An easy-to-use simulation approach required for such a model has also not yet been defined.

Description of contribution:

Energy cost and efficiency of MCSs can be managed with energy saving projects. However, the dynamic effect of implementing these projects are rarely predicted or analysed before implementation. Transient integrated system simulations will be developed and used to simulate, predict and manage the energy consumption of MCSs as well as consider the energy impact of significant changes to operations. It will be possible to predict the effect on

system response and energy consumption of any equipment or process alterations accurately and quickly.

This approach allows for implementing MCS energy saving projects effectively, as well as saving costs on the investigation, commissioning, and maintenance of these projects.

1.4.2. Novel control emulation method with integrated transient response simulations for energy saving measures on MCSs and their controls

Existing approach:

Existing models used in published literature are used for industries other than MCSs [18, 30]. This is because the control requirements for energy saving measures are unique, with control philosophies only being finalised during the commissioning phase of these projects. Control emulation studies are therefore determined through a trial-and-error approach [35, 30]. Additionally, the control development of energy saving measures for MCSs is simulated in steady state, and rarely in an integrated dynamic approach.

Shortcomings and needs:

In the comprehensive literature review, models capable of dynamically simulating the integrated MCS were identified [36, 37]. The shortcomings of the existing approach were identified as the inability of existing models to dynamically simulate the response of the integrated system. Therefore, the control impact on such a system cannot be accurately identified through simulation alone. Integrated transient simulations are required to emulate the control impact.

Description of contribution:

New simulations to predict the effects on the integrated system after implementing the proposed control and new equipment will be developed. A procedure is required for the new control emulation model to determine the practical control to be implemented on the specific system. Such a procedure was developed in this study. This procedure is beneficial since the models and approach have already been clearly defined for the entire MCS.

New control methodologies for energy saving measure on MCSs can thus be evaluated for effectiveness. By applying the new simulation model and approach, combined with the new simulation procedure, the implementation time of energy saving measures on MCSs can now

be reduced. The new control emulation method will result in shortened implementation and commissioning times, resulting in resource cost savings.

1.4.3. Unique dynamic energy forecasting of MCSs

Existing approach:

Mines are dynamic and are continuously expanding, resulting in dynamic energy requirements. Dynamic changes to integrated systems are not simulated by existing transient models and the approach to evaluate any operational changes to MCSs is therefore outdated.

Shortcomings and needs:

Design models and principles are used for existing studies when evaluating MCSs. An easy-to-use simulation model and approach are required for mines to predict the impact on energy consumption and to aid energy engineers in evaluation studies. Energy forecasting of MCS operation is limited with existing models and procedures.

A new approach and simulations are required to predict the effect that operational changes will have on the existing MCSs, as well as forecast the energy consumption after system changes. A detailed system analysis that includes the dynamic integrated system response on energy consumption needs to be evaluated. No previous approach or model was found in the comprehensive literature study.

Description of contribution:

New dynamic MCS energy forecasting approach and simulations will be developed. The simulations and approach will be used to determine significant system operational changes and the effect on energy consumption of the MCSs. Solutions for system changes can be simulated to determine the most effective option.

A new dynamic energy forecasting approach and simulation model will aid mines in analysing the effect that system changes have on the energy consumption of MCSs. These analyses can then be used to determine the most viable solution to the prescribed changes.

1.4.4. New easy-to-use approach for integrating MCSs through transient response simulations

Existing approach:

Existing procedures, found from published literature, focus on the steady state simulation procedure for integrating MCSs in simulations. Most of the studies only indicate how the relevant software works, and do not indicate the approach or procedure to be followed when simulating integrated systems.

Shortcomings and needs:

The lack of existing studies simulating the transient effect of energy management on MCSs means that there is no existing procedure for this process. The various schemes, procedures and approaches that were identified do not indicate the process to be followed in such a study. Therefore, there is a need to develop a new transient response simulation strategy for integrating MCSs in transient simulations. The new approach should also ensure that the simulations can be conducted in a timely manner, saving resource costs and time through the application of the approach.

Description of contribution:

A new transient response simulation strategy for the integration of MCSs will be developed. This strategy will also indicate the procedure to be followed when developing simulations for all the case studies conducted in this study. The new simulation strategy will allow energy engineers to use transient response simulations for the integration of MCSs, allowing for multiple energy scenarios and process operational changes to be simulated. The efficacy of conducting simulation and energy studies will therefore be approved if a published procedure exists.

1.5. Overview of the thesis

Chapter 1: Introduction

Chapter 1 focuses on the background of this study, briefly describing the crucial elements contained in the rest of the study. In the chapter, a critical analysis of previous published work is discussed to formulate the need for the study and the objectives. The novel contributions of this thesis are determined and conveyed in this chapter.

Chapter 2: Industry's approach to MCS energy simulation

Chapter 2 focuses on the research relevant to this study. A comprehensive literature survey was conducted and is represented in this chapter. Deep-level MCSs are discussed to give background. Thereafter, transient response simulations models and the existing approach in industry are revised. Shortcomings of existing studies and published work are also discussed in this chapter.

Chapter 3: New transient response simulation design and approach

The methodology of this study is developed in this chapter. The novel contributions are developed individually, and then combined to form an integrative approach. In this chapter, the new transient response simulation procedures are developed, as well as a new approach with simulations. A novel component control emulation methodology and approach are developed. A new method for practical application of the methods, procedures and models together with the new approach are developed.

Chapter 4: Model verification

The verification of the new models and approach is discussed in this chapter. The developed contributions are verified and new methods, models and tools are discussed and compared with actual and external methods.

Chapter 5: Validation through a case study

The new models and methods are validated in this chapter. An actual study is conducted on a case study mine by using the new models and approaches developed. Quantifiable results are obtained by applying the models and methodologies developed in this study.

Chapter 6: Conclusions and recommendations

The conclusion of the study is discussed in this chapter. This chapter also provides recommendations for future work and further model or method development. The feasibility of replicating the models to other industries is also discussed.

1.6. Summary

The introductory chapter of this thesis highlighted the existing state and importance of energy sources worldwide. Energy and water efficiency was found to be crucial for sustainable development. The chapter also focused on defining deep-level gold mines as significant energy consumers in the mineral extraction industry.

A critical review and shortcomings of previous studies are discussed and the need for this study is also identified. It was found that there is a need for new dynamic integration models and simulations to efficiently integrate the mine refrigeration, water reticulation and ventilation systems of deep-level mines. Energy management also needs to be possible through the new simulations. Using the simulations, energy saving initiatives can be identified, and the transient effect on the integrated system can be determined.

It was also determined that a new method or approach is required to efficiently integrate the MCS and conduct energy management studies. Since no previous work has been identified, the need for the new approach was identified. The objective of this study was also defined in this chapter. The contributions of this study were defined in detail from the findings presented in this chapter.

A comprehensive and relevant literature review will follow in Chapter 2. Mining systems relevant to this study will also be explained in more detail. The potential for mine energy optimisation and integration will be investigated and existing models are reviewed in detail. The energy saving benefits of such a study are also investigated.

2

CHAPTER 2

INDUSTRY APPROACH TO SYSTEM ENERGY SIMULATIONS

“No one is dumb who is curious. The people who don’t ask questions remain clueless throughout their lives.”

~ Neil deGrasse Tyson (Astrophysicist and cosmologist)

2. INDUSTRY APPROACH TO MCS ENERGY SIMULATION

2.1. Preamble

Chapter 1 highlighted the importance of efficiency programmes to ensure a sustainable and growing mining environment in South Africa. Deep-level gold mines were identified as significant electricity consumers in the South African mining environment. The MCSs of these deep-level mines were also identified as potential systems where efficiency programmes could benefit existing mines. It was also stated that energy and cost savings can be identified using simulations.

A critical analysis of previous published work, focusing on simulations for energy management of these MCSs, was conducted and summarised in Chapter 1. It was identified that there is a need for new simulations that can be used to simulate the integrated transient operation of MCSs for various applications. These applications include simulating new energy saving measures, emulating control of these systems and forecasting of energy consumption of MCSs to promote energy management on the entire MCS.

Unfortunately, official and published literature on the topic was limited. A comprehensive literature review was therefore conducted to analyse numerous publications to ascertain the approaches and models used in industry. The results of the comprehensive literature review are therefore conveyed in this chapter. A total of 86 studies were reviewed as part of the comprehensive literature review.

This thesis is aimed at developing novel simulations for energy management of MCSs, and will address the need identified in Chapter 1. By applying the novel simulations, the additional needs as stipulated above will also be addressed. The novel contributions of this thesis were also indicated in Chapter 1. These contributions were formulated from the need of this study.

The comprehensive review includes numerous factors to consider when developing novel simulations for the energy management of these systems. The focus of the literature review was on the following aspects:

- Researching energy management and energy savings through integrating MCSs;

- Evaluating the approach, procedures and models currently used in industry for transient integrated energy management simulations;
- Investigating the requirements of transient response system simulations; and
- Reviewing the shortcomings of the existing models and approaches.

A typical deep-level gold MCS will now be discussed to give the reader background on the operation and constraints of such a system.

2.2. Deep-level MCSs

2.2.1. Preamble

Previous studies have shown that South African mines consume more energy per kilogram produced than other mines in the world [54]. The high electricity demand of mining in South Africa is mainly due to the extensive depths related to operating these mines. The ore bodies in South Africa are located deep below the surface and mines are continuously deepening to access ore beyond 3 km [55].

Apart from the significant rise in temperature due to the unique geothermal gradient, which is typically between 10 °C/km and 20 °C/km, there are other heat sources contributing to heat loads in mines. These heat sources include exposed rock faces, machinery, fissure water and adiabatic compression [41]. The adiabatic or auto-compression process is the conversion of potential energy into internal energy due to the atmospheric air mass applying pressure to the air mass sent down the mineshaft [56].

Due to these heat loads, artificial cooling needs to be introduced. This process ensures safe working areas for workers. Artificial cooling is typically required when the average temperature of a working area exceeds 32 °C wet bulb [16]. This temperature limit is also governed by operating equipment at these depths. MCSs are therefore used to ensure that operating temperatures of mines stay within this legal limit.

MCSs can have various configurations depending on the type of mine, which use different sub-systems to operate. When referring to an MCS, these sub-system(s) should also be discussed. The individual function of these sub-systems will be discussed in later sections.

A typical MCS consist of the following sub-systems:

- Chiller plants;
- BACs;
- Water reticulation system; and
- Dewatering system.

The layout and operation of these cooling systems on a typical deep-level gold mine in South Africa are explained in the following sections.

2.2.2. Layout and operation

Surface or underground MCSs can be used to supply chilled water, and cold dehumidified air to underground workplaces. Centralised surface MCSs are normally used due to their increased heat rejection capacity, whereas underground systems use upcast ventilation from shaft bottom to reject heat [57].

MCSs can have different configurations, depending on the age, depth and type of mine. A schematic layout of a centralised surface MCS is illustrated in Figure 11. Such a system typically consists of precooling towers (PCTs), BAC towers, condenser cooling towers (CCTs), chiller plants and auxiliaries, hot and cold water storage dams, pumping stations, and water reticulation networks to mining areas.

Figure 11 shows how used mining service water (A) is pumped from hot water dams, which are situated underground, through several levels, depending on the depth of the mine. The used hot water enters a hot dam (B) on surface, typically at a temperature of 28 °C. The hot water from the mining operations is pumped (C) through the PCTs (D) situated on surface. The water, which has been precooled, is collected in the precooling sump (E).

From the PCT sump, the evaporator pumps (F) are used to pump the water through the chillers (G), which can be arranged in various configurations. The water is cooled to temperatures that meet the requirements of the specific mine, which vary depending on the geographic location. The cooled water is then temporarily stored in the chilled dam (H) on surface. The chilled water dam is used as a storage dam to compensate for the fluctuation in chilled water demand of the mine.

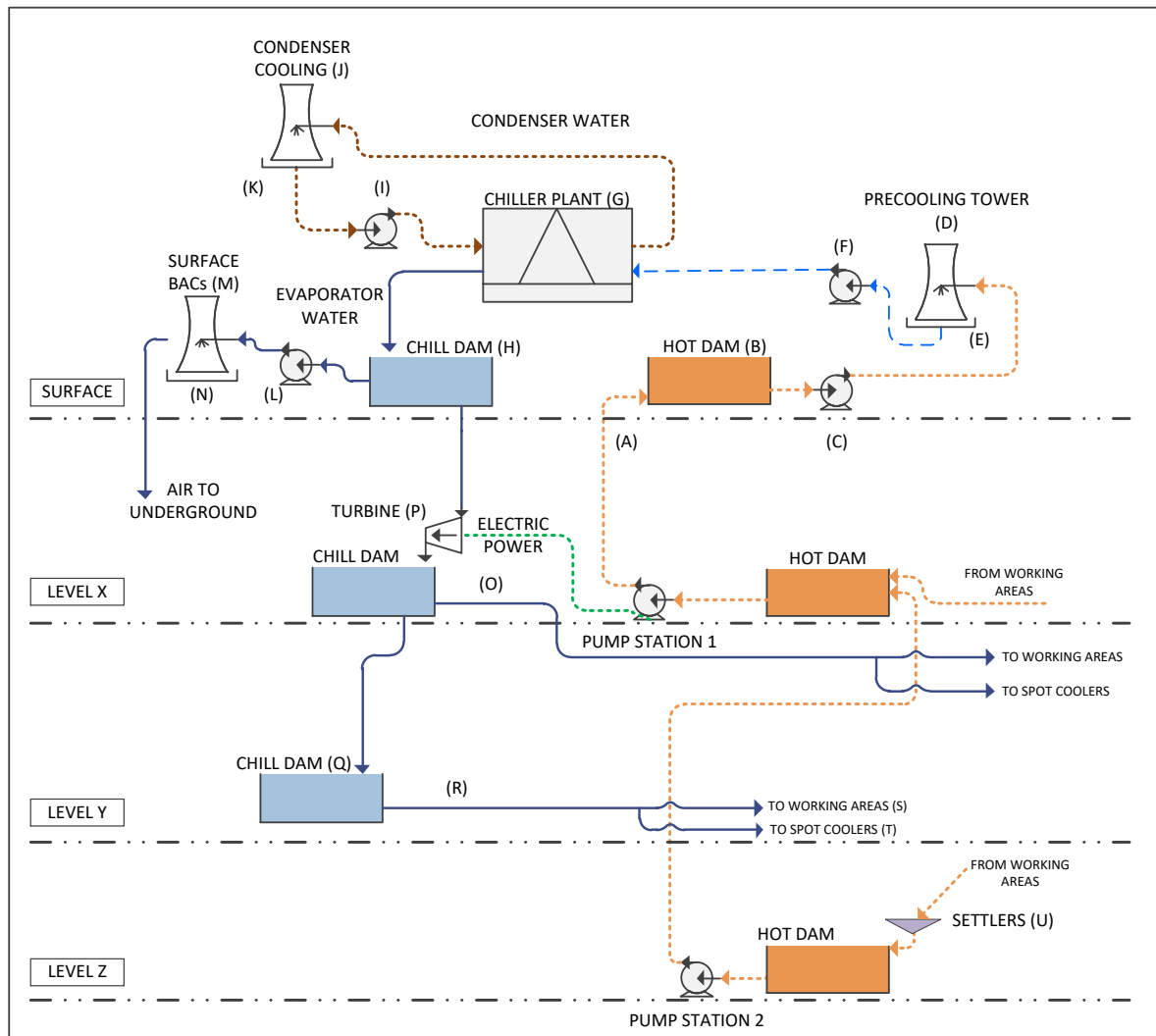


Figure 11: Schematic layout of a typical centralised plant layout (adapted from [55])

The condenser pumps (I), situated near the chillers, are used to circulate condenser water through the CCT (J) spray nozzles for heat rejection into the atmosphere. The condenser water is then collected in the condenser sump (K) whereafter the process is completed and repeated. The BAC pumps (L) are used to pump chilled water through the BACs (M). The BACs can also be situated underground, as is the case in some deep-level mines. The BAC water is collected in the BAC sump (N) and circulated back to the hot dam with return pumps.

The chilled water, collected in the chill dam, is sent underground for mining services and operations (O). From surface, the water can be used in energy-recovery devices (P) situated underground. The chilled water then flows into a dam situated on a specific level underground (Q). The process of energy recovery can be repeated numerous times until the water reaches the active mining levels (R). From the mining level stations, the cold water is

then sent to the relevant mining operations (S). The chilled water is also used to supply localised coolers (T) of cold water for cooling working areas.

Thereafter, the used mining water is collected in the settlers (U) at shaft bottom and the process is repeated. The detailed functioning and description of the individual equipment and components of the MCS illustrated in Figure 11 are conveyed in Appendix I – MCS components.

As indicated in numerous studies, the original design features present on any MCS should be investigated and selected optimally to enable energy efficient operation [58]. However, this can only be fully compensated for when considering a significant system, such as an MCS, in retrospect.

Various alternative configurations of these systems and sub-systems, and the operational methods, cannot be comprehended fully by only considering atmospheric conditions, thermal loading and required operational conditions. Therefore, there is a need to integrate these systems.

Performance of MCSs

The performance of MCSs must be identified to determine the potential system constraints that are applicable. The dynamic integration model must adhere to the constraints that are identified, and must ensure that the performance of the MCS is not adversely affected.

Boundary conditions of operation can be defined which will give a guideline of performance of the operations. The main requirements for the MCS to be considered are the productivity and safety of the mine and mineworkers [38]. This is because the main priority of the MCS, and all other sub-systems that operate in unison, is to function reliably when supplying chilled water and air to be circulated underground [59].

The new dynamic integration model will therefore have to adhere to the original equipment manufacturer (OEM) specifications and should compensate for the service delivery requirements or allow the required adjustments to be made. The performance of any system will, however, still be measured and compared.

The chilled water flow rate and temperature have been identified as crucial system requirements in previous studies. These parameters therefore give an indication of the system performance and the level of adherence to the requirements [32].

These limits are, however, different for each mine and its sub-systems and will have to be tested practically and verified in each case. However, these requirements should be similar for mines operating in the South African environment. Another requirement to consider is the BAC air outlet temperature. By ensuring that the delivered temperature is within tolerable boundaries, productivity and worker safety will not be compromised [60].

Literature shows that chilled water supply temperatures between 3 °C and 6 °C will be adequate [23, 61]. This requirement will also be revised in this thesis and will be discussed in later sections. Literature also indicates that the working area temperatures should be maintained below 32 °C wet bulb to create a safe working environment, and below 27.5 °C wet bulb to create a comfortable working environment. Environmental personnel at mines therefore ensure that surface BAC outlet air temperatures are below 8 °C wet bulb when designing surface cooling systems [62].

The boundaries of operating all sub-system components are therefore governed by these limitations and are a function of the operation of the entire cooling system. These boundary conditions will be defined in the sections to follow. The following section discusses the need for integrating MCSs for energy efficient operation, as well as reviews existing studies.

2.3. Energy and cost saving by integrating MCSs

2.3.1. Preamble

MCSs are often controlled inefficiently and lack integrated management [63]. There was a significant drive in industry to research and develop new energy efficiency and load management strategies to reduce the electricity consumption and electricity cost of MCSs. This section reviews the existing strategies used in industry as energy saving measures on MCSs.

Energy efficiency strategies

Energy efficiency projects are aimed at reducing the amount of power required or the amount of time that power is required. Various energy efficiency strategies have been implemented in

industry. Most of these strategies involve equipment retrofits and implementation of certain energy saving measures, as well as the implementation of energy management software. One of the technologies gaining popularity in industry is variable speed drives (VSD).

Applying VSDs offers significant energy savings in industry, as illustrated in various studies [30, 55, 64, 65]. Beside these merits, the major obstacles for implementing VSDs are mainly technical (constant torque applications), economic (high price) and awareness issues (site personnel scepticism about technology). However, these issues have been addressed in many previous studies [21].

Variable flow control

Variable flow control strategies have been widely implemented in the mining industry and have been proven to be one of the most efficient methods of achieving energy efficiency savings on large deep-level MCSs. The installation of VSDs on electric motors of pumps is required to enable the control of flow in various MCS circuits.

The VSD controls and modulates the torque, mechanical power and speed of an electric motor. Applying VSDs to the MCS can therefore result in efficient control and use of the MCS [66]. VSD technology must therefore be integrated into the design strategy for the mine cooling and water reticulation systems to achieve significant power savings.

Variable flow control strategies are mainly aimed at pump power savings and reduced chiller loads, which also result in chiller compressor power savings [63]. Variable flow control strategies are applied to various circuits of MCS sub-systems, namely:

- Evaporator flow circuit;
- Condenser flow circuit;
- BAC flow circuit; and
- Precooling flow circuit.

The exact functioning of the flow control strategies for these circuits are discussed in detail in Appendix III. The evaporator flow control can be summarised as a strategy that was developed for the evaporator circuit of the chillers [30]. The evaporator flow rate is controlled by installing VSDs on the evaporator pumps. The flow is controlled by using proportional-integral (PI) control logic to control the speed of the pump to maintain a set chill dam level. The flow rate is maintained within OEM specifications.

The condenser flow control can be summarised as a strategy that was developed for the condenser circuits of chillers. The condenser water flow rate is controlled with PI control logic to maintain a set delta temperature over the condenser vessel. This strategy is similar to the evaporator control as it is based on the principle of variable thermal loads throughout a typical day [62].

The BAC flow control strategy was developed in a previous study which was constrained by the requirement to cool and dehumidify ventilation air to 8 °C dry bulb [30]. The strategy is based on the principle of variable thermal loads on the BAC. During cooler months, overcooling in BACs is a result of operating at full-load conditions. The precooling flow control is required due to the variance in evaporator flow rate. The precooling flow control must be included to ensure that all dams are kept in balance.

Energy-recovery devices

Energy-recovery devices are also widely used in industry to ensure energy efficiency of mines. South African gold mines operate at significant depths, resulting in significant potential energy. Mines normally utilise this energy by installing energy-recovery devices to convert this energy to power [54]. Some energy-recovery devices that are used in industry include:

- Turbines;
- Three-chamber pipe feeder system (3CPFSs); and
- U-tube systems.

The detailed operation of these systems is discussed in Appendix I. Some consideration is, however, required when implementing energy-recovery devices on mines. Mine water quality can affect the use of these systems adversely. Systems such as the 3CPFS and U-tube systems also require additional pumping as they cannot be 100% efficient. These systems are also maintenance intensive and pose a significant risk to service delivery. Mines therefore must consider the specific system constraints when planning the installation of such devices.

Ice systems

Some mines also use ice systems as an energy efficiency strategy to reduce the amount of water circulated and save on pumping energy. Ice systems either produce hard ice or soft ice; both are difficult to transport to the point of use. Literature shows that ice is an alternative to

mine refrigeration, but it can only produce energy efficiency savings when used in mines deeper than 1.9 km [13]. The detailed operation of ice systems is discussed in Appendix I.

Water supply optimisation

Water supply optimisation strategies are also implemented on mines to save power, and thus, pumping and refrigeration costs. By implementing the strategy according to the mining schedule, the water to the mining sections can be controlled at specific time intervals. Through smart control and equipment retrofits, the efficiency of the water reticulation system can be improved.

This strategy normally involves installing water control stations (WCSs) on each station on a mining level. A mining level can be defined as the depth below surface where mining operations are located, for example, 68L is located 6 800 ft below surface. A WCS consists of control valves and required instrumentation such as pressure and flow meters. WCSs are controlled by programmable logic controllers (PLC) situated on each level. The PLCs open and close the valves when necessary. The detailed operation of a WCS is discussed in Appendix I.

Underground closed-loop BACs

Underground closed-loop BACs can be stopped during certain periods of a typical mining schedule. It was found from literature that these strategies can result in significant energy and cost savings, but the effect of reduced cooling during these periods have to be evaluated as part of the integrated system. There is a significant risk for workers. The strategy depends significantly on monitoring and controlling infrastructure on the specific mine.

Efficiency strategies have also been developed for ventilating deep-level mines which include:

- Main fan control;
- Main fan carbon blades; and
- Booster fan control.

These strategies will also be considered in this thesis, but they are focused on ventilating deep-level mines. This thesis only considers the effect of the BAC ventilation component and its effect on the MCSs.

Load management strategies

Load management strategies in the South African environment focus mainly on the Eskom time-of-use (TOU) structure. These strategies are implemented mainly to reduce the operating cost of MCSs during the most expensive periods of a typical production day. The Eskom TOU structure is illustrated in Table 50 in Appendix VII.

Dewatering pumps

Load management strategies have been developed for dewatering pumps of mines [54, 67]. Dewatering pumps are an integral sub-system of an MCS. Load shifting can be classified as a load management strategy. Load-shifting strategies for pumps have been successfully implemented on several deep-level mines in South Africa. This strategy is aimed at managing the water storage capacity of a specific mine, and stopping the relevant dewatering pumps during the more expensive TOU periods of the day. The detailed operation of such a strategy is discussed in Appendix III.

Chiller load management

Chiller load management strategies were developed to manage the chiller operation for the most cost-effective operating schedule, whilst considering the installed capacity and thermal storage of a mine. These strategies require real-time control, as there is a significant risk associated with reducing the cooling of chilled water by the chillers.

Thermal ice storage

Thermal ice storage strategies were developed to operate the chillers and auxiliaries less during the more expensive TOU periods. The cost savings of such a strategy is counteracted by increased electricity consumption during other periods of the day. These systems also use cooling capacity and thermal storage to reduce the cost of cooling and chilling mining water.

Conclusion

Integrating the operation of various sub-systems of an MCS also proved to aid energy efficiency initiatives on these systems. The following sections, firstly, elaborate on chiller plants and auxiliaries and, secondly, deep-mine water reticulation systems. The energy saving measures described in this section is used in most of the integration models that were reviewed.

Applying the models and approaches developed in this study will also lead to the development of possible new energy saving strategies. The energy saving strategies for MCSs are significantly dependent on the configuration of the relevant mine. Each mine has unique constraints that need to be considered when identifying, investigating and implementing energy saving measures.

The energy and load management strategies discussed in the previous section can result in significant energy and cost savings when implemented on deep-level mines. In most cases, the literature discussed and evaluated the effect of the implemented measure on the relevant sub-system. However, these measures can have an adverse effect on either the operation or energy consumption of other sub-systems in the integrated system. It is therefore required that the novel system simulations must consider the effect of the measures to be implemented on the entire integrated system.

Numerous other initiatives for energy and cost savings exist and will be discussed additionally in the context of this thesis.

2.3.2. Chiller plants and auxiliaries (refrigeration systems) integration models

The energy efficiency of large refrigeration systems has been investigated in various studies. A new DSM strategy for variable flow was developed [30]. The strategy involved modulating the evaporator, condenser, BAC and precooling water according to partial load conditions. In this case, variable flow strategies were used to efficiently integrate the refrigeration system. Du Plessis [30], and Du Plessis, Liebenberg and Mathews also investigated using VSDs to achieve the mentioned energy savings [66].

The strategy developed by Du Plessis et al. [66] was implemented successfully on the surface cooling plant of the Kusasalethu gold mine. The strategy involved matching the supply of cold water and ventilation air to the demand of the mine. VSDs were fitted on the evaporator and condenser pumps to realise the variable water flow control. Control valves were installed on the BAC supply lines to control the flow of chilled water through the BAC to match the ventilation air temperature demand.

The study conducted by Du Plessis et al. also involved replacing CCTs with new, more efficient towers [66]. Installing new equipment or replacing old outdated equipment can therefore also be considered in the new dynamic integration model. Du Plessis also

highlighted that optimised system control should occur as close to real-time as possible to maximise energy savings, which was also shown by Van Staden, Zhang and Xia [68].

Developing a REMS for Cooling Auxiliaries (REMS-CA) was also an objective. Du Plessis et al. implemented REMS-CA and used feedback parameters from the refrigeration system to continuously ensure that the system operates optimally [66]. It was mentioned that the new system, REMS-CA, controlled the components of the integrated MCS. However, the review shows that the study only considered the boundaries around the surface cooling plant, and did not integrate the rest of the water reticulation and possible other BACs underground.

Load-shifting possibilities for underground cooling systems in combination with using thermal storage optimally in the form of underground chilled water dams were investigated [31]. A simulation model was developed to simulate and optimise the energy costs of underground cooling systems of one mine. The potential for thermal storage and load shifting was therefore only applicable to that specific mineshaft.

The developed mathematical model enabled mine operators to minimise the costs of electricity consumed by the underground cooling systems in the mine. The objective of the study was to maintain favourable environmental conditions underground while optimising the systems for mining operating costs. Electricity costs were optimised by developing load-shifting strategies.

Air velocity and air temperature are the two primary parameters when optimising the ventilation system of a mine. The study also demonstrates that by using the developed simulation model effectively and by optimising calculations, significant energy cost savings are possible. It was indicated that the optimisation models developed in this study could be used to explore energy storage potential and optimise these systems in warm mines [31]. It is clear from the study that the system was not integrated with other relevant systems.

Certain studies focus on individual equipment, such as cooling towers, for optimised energy consumption. A forced draft cooling tower was investigated experimentally using trickle, film and splash fills in one study [69]. Performance parameters, such as the range, characteristic ratio, effectiveness and water evaporation rate, were considered for each fill type. The work used a multi-objective optimisation problem to optimise the four parameters simultaneously for each film.

The study revealed that wire mesh fill was the most favourable type of fill operating under a set of conditions. The method was also generalised to be easily implemented on forced draft cooling towers operating under a wide range of temperatures. Similar other studies, focusing on individual equipment optimisation, need to be included into the refrigeration system, and finally into the dynamic integration model for more efficient operation of the entire MCS.

In 2010, Pelzer et al. developed a fridge plant control and optimisation system, REMS-FPTM [70]. This system uses simulation capabilities to optimise the scheduling for minimum electricity cost given a fixed set of parameters. This system can control the amount of water through cooling towers and optimising back-pass flow in some systems for reduced dam temperatures. The system was tested and proven to be able to provide cost savings on three deep-level mines.

However, as with similar other studies, the integrative effect on the entire system was not considered. The daily cooling load caused by the recirculation of water was not considered and therefore the achieved savings of 32 416 MWh that was reported was not offset to this cooling load. This initiative should be reconsidered as part of the entire MCS.

When considering energy usage reductions on MCSs, it is important to consider the possibility of lowering the demand for cooling. This can only be done when the opportunity for simple control is available, such as in residential applications or commercial building cooling systems [71, 72]. However, mine cooling demands are more complex because of the variety of chilled water consumers. Integrated strategies are therefore required.

In a study conducted by Schutte in 2013, energy cost and energy saving projects for mine ventilation and cooling were summarised [13]. The study presented a sequential implementation guide for a mine energy engineer considering the risk, appeal and cost savings of a project. A risk evaluation matrix was developed to consider the risk to service delivery, production, environmental, health and safety, and overhead costs. This led to a project appeal indicator being developed for each energy saving project identified in the study.

The project appeal indicator was based on installing new equipment, upgrading existing equipment, extending the control and instrumentation infrastructure, implementation time and little downtime, and finally interacting with other systems. It was then determined which

projects should be combined with each other upon implementation. The study then identified that there were several opportunities for peak-clipping strategies for closed-loop surface BACs.

It was found that the integrated management of BACs and the implementation of energy saving measures, such as a peak-clipping initiative, can subsequently result in a 3.2 MW Eskom peak-clipping saving as achieved on a case study mine. Implementation on other mines can result in a total peak clipping of 24.5 MW. Similar strategies such as those developed in this study can be used to integrate the BACs into a combined MCS as part of the new integration models [13].

However, the various energy saving projects investigated in this study must be reviewed to investigate the feasibility and impact of implementation on the MCS. The previous published work on mine refrigeration system energy optimisation is listed in Table 2. As can be seen from the table, significant energy savings are possible when optimising mine refrigeration systems.

Table 2: Previous published work on mine refrigeration system energy optimisation

Authors	Energy/cost saving p.a.	Description	Reference
Schutte	R30 million	Integration of energy efficiency strategies on MCSs	[13]
Bornman	201.15 GWh	Surface cooling auxiliary system optimisation	[73]
Holman	52.13 GWh	Improved performance monitoring of a surface mine refrigeration system	[23]
Van der Bijl	66.57 GWh	Sustainable DSM on mine refrigeration systems	[19]
Du Plessis et al.	15 GWh	Effects of variable flow control on deep MCSs	[66]
Swart	21.02 GWh	Optimising underground mine refrigeration systems	[31]
Van Greunen	20.15 GWh	Variable speed drive control of mine auxiliary systems	[74]
Uys, Kleingeld and Cilliers	13.14 GWh	Ice storage to chilled water system conversion	[75]

2.3.3. Deep-mine water reticulation systems integration models

Various studies have developed and implemented measures to reduce and manage water consumption in water reticulation systems of mines [8, 14]. These measures were aimed at reducing the cooling load by reducing the water volume to be chilled. However, as indicated in previous studies by Du Plessis [30], the effects on the energy usage of the entire MCS have not been quantified properly.

The full energy and cost saving potential can be influenced by operating MCS components inefficiently. The cooling demand side and control of these systems have been addressed in previous studies, but available technologies, energy saving measures and integration strategies to ensure MCSs are efficiently managed are still not being implemented.

In a study by Vosloo, Liebenberg and Velleman in 2012 [14], a system was developed that simulates, optimises and controls dewatering pump systems of mines. This study gives insight into the energy-conscious control of mine water systems and is therefore relevant to this study, as the dewatering system must form part of the new integration model.

The study by Vosloo et al. focused mainly on an integrated and automated load-shifting strategy with real-time control of deep-mine water reticulation systems [14]. After implementation of the integrated control strategy, a load shifting and an energy efficiency impact on the water pumping system were achieved. This also resulted in a considerable peak-load reduction on the refrigeration plant.

However, there are numerous system components that were not included in the integration strategy developed in this study. The efficient control of chilled water sent underground was optimised, but the study did not include the use of water from each distribution point on the mining levels. Du Plessis also reviewed this study while developing a new variable flow control strategy, and it was highlighted that the integrated operation of the various cooling systems and the combined water reticulation merited further investigation [30].

Most present energy saving and management initiatives, including DSM, only consider specific control volumes. The various control volumes of a given MCS must be integrated, with the given sub-system boundaries as parameters, as an entire operating system. This further indicates the importance of this study.

2.3.4. Summary

Previous studies that developed integration models for MCSs were reviewed. The approach followed in each study and the overall impact in industry were considered. The significance of the previous studies was highlighted and used in the development of this thesis to address the need identified.

The energy and cost saving measures identified will be used to optimise the MCSs with the aid of the new simulations. These measures can also prove useful for the energy management

approach that will be followed when these new simulations are applied. It was also considered how the existing approach in industry is conducted and aids the energy or utility engineers on mines.

It was found that the existing models and approaches were limited. Most of the objectives of this study that were identified cannot be achieved without considering the integrated transient response of the system in simulations. The effect of component or equipment control, energy forecasting or energy management cannot be achieved without considering the transient effect on the integrated system. The possible solution is therefore in the novel simulations that will be developed in this thesis. It was also found that a trial-and-error approach was an alternative to simulations.

However, there is still a need to determine how integrated transient simulation models are currently used in industry, as well as the approach that is followed. Integrated process simulations found in published work will therefore be reviewed, and thereafter the requirements for an effective transient response simulation and approach can be determined. The models in industry will also be evaluated to determine the most suitable package to build the new simulations in.

2.4. Transient response simulation models and approach in industry

2.4.1. Traditional approach to simulating thermal and energy systems

Simulation capabilities through a software tool have been available since the 1970s. However, its use has been limited to industrial processing and manufacturing industries [36]. Negative perceptions exist that system simulation is too unstable and often cumbersome because of the extreme mathematical nature usually used in algorithms of simulation models.

Conventional system simulation implies solving various sets of equations, which model numerous components of a system [36]. As found in literature, thermal simulation is the calculation of operating variables (such as temperatures, pressures, and flow rates of energy and fluids) in a thermal system operating at steady state [76].

More generally, unsteady conditions and the evolution of system variables with time are also emphasised. The traditional simulation procedure or scheme for simulating large thermal energy systems, as indicated by Bouwer [36], is summarised as follows:

1. Configuring system component models for all relevant systems;
2. Establishing system connections or relations between components;
3. Establishing correct order of component solution; and
4. Solving the system variables numerically.

This scheme uses methods such as the Newton–Raphson method to find solutions. However, in previous studies conducted by Arndt [37] and Bouwer [36], a new simulation scheme was developed. This scheme does not consider simulation of dynamic elements such as control. The basic scheme can be summarised as:

1. Configuring existing system components required graphically;
2. Generating mass flow simulation through the system;
3. Simulating the system mass flow at the beginning of each simulation interval;
4. Solving each system component explicitly for several iterations in a time interval;
and
5. Repeating the process for the time intervals required.

Although this scheme is mainly aimed at the functioning of a thermal system simulation solver, the general traditional functioning is still required to develop novel simulations for the energy management models and approaches in this thesis.

Analytical models are employed in industry because the exact mathematical solutions of flow and heat transport equations are used. These models are mainly suitable for homogenous systems and simple processes [22]. These models are easy to use as they use simple spreadsheets or a sequence of calculations in a software package, thus resulting in quick problem-solving.

However, most real-life systems are heterogeneous, as described by Loredó, Roqueñí and Ordóñez [22]. The role of analytical models is therefore limited to feasibility studies. In the case of real-life heterogeneous systems, numerical models can be used where numerical approximations are used to solve flow and heat transfer equations. They therefore constitute a more powerful tool suitable for a complex system and the non-linear equations associated with the system. However, as is well-known in industry, the costs and time to set up numerical models are significantly higher than those associated with analytical models [22].

2.4.2. Existing procedures and approaches for transient simulations of MCSs

Numerous mathematical models have been developed in industry. Most of these models are based on the basic laws of conservation of mass, momentum and energy transport. However, most models have been developed for quantifying the effect of gases and particulates in the mining environment, and the effect of heat and moisture on mine airflow. These models include thermodynamic models, pollutant-dispersion modelling and fire simulation [24].

Most models developed in published work and industry focus on the ventilation of mines and the optimisation thereof [17, 24, 27, 40, 49, 77]. Analytical models are normally used as a starting point of a study, whereafter numerical modelling is used in cases where a system has to be assessed in more detail. As indicated in literature, the most appropriate models and code should be selected, considering the capabilities and limitations, when developing simulations for a specific application [22].

However, when reviewing the literature for simulation studies applicable to MCS simulations, only a few relevant published works were found. The study most relevant to the models and approaches developed in this thesis was conducted by Van Antwerpen et al. [52] in 2014.

The study aimed to determine whether recently developed simulation technology could be applied to a mine as vast and complex as AngloGold Ashanti's Mponeng mine. The study determined that it was possible to conduct a mine-wide simulation of compressed air flow, psychrometric ventilation air studies and water refrigeration systems. The approach that was followed in the study can be summarised as:

1. Evaluating the mine water system layout and system operational parameters;
2. Balancing mass and energy of the system from measurements and conservation calculations;
3. Compiling simulations in software that can solve momentum mass and energy;
4. Solving the mass, momentum and energy conservation equations in the same network;
5. Validating simulated results; and
6. Conducting optimisation studies.

Van Antwerpen et al. mentioned that the approach of carefully planning the network set-up enabled several people to work on the same system simulation. The authors also found merit in conducting integrated system simulations, and that optimisation studies can be conducted through this approach [52]. This was also the case in a publication by Du Plessis et al. in 2013 [49]. Energy saving measures were identified which can lead to potential cost savings after implementation. However, there were several factors that were not reflected in these studies.

The authors did not develop a generalised approach to enable more efficient simulation studies. There is still a need for easy-to-use simulations, as the authors indicated that considering the transient effects on the system will be cumbersome for inexperienced personnel. There is therefore a need to develop an approach to follow which will save resource time and which will be easier to use.

The studies reviewed did not focus on applying the simulations for energy management of the integrated MCSs. Although energy saving measures was identified, the relevant control of the identified measures was not considered. The most important factor to consider is therefore the transient effect of the integrated MCS. A study conducting or considering all the above-mentioned factors could not be found in published work.

Du Plessis, Arndt and Mathews [78] developed a simulation model to determine the effect of implementing the variable flow strategies developed by the authors. The simulations were compiled to predict the potential impact on power consumption of the system. The approach followed the process of considering the hourly ambient conditions, hourly mine demands for chilled water and the overall system parameters to predict the effect of the strategy.

Although Du Plessis et al. mentioned that integrated simulations in a dynamic model were conducted for the entire MCS, it was determined that the simulation boundary only included the surface refrigeration systems. The combined power usage of the system was the main goal of the simulations. An average overall error of 4.1% in power usage was determined [78]. The simulations were also verified and validated through experimental applications. However, the exact approach followed for the simulations could not be determined from the publication.

A procedure that was developed by Bouwer [36] was identified as part of the literature review. The procedure was aimed at providing a method to verify the integrated simulation that was developed in the study. The procedure is summarised below:

1. Develop schematic layout of the system to determine the configuration of simulations and measuring points.
2. Take measurements of all dams, temperatures, water flows, running schedules and power consumption.
3. Take additional measurements for process data not recorded on the supervisory control and data acquisition (SCADA) system.
4. Select a typical mining operating day for simulating a relevant operation.
5. Consider the ambient effect on the system by including the weather data into the operational analysis.
6. Do a simulation set-up with the relevant data and start the simulation.
7. Compare measured data with the simulation outputs and make modifications to iterate the process.
8. Repeat the process until the simulation delivers a suitable accuracy for outputs.

The procedure developed by Bouwer gives a guideline on how to approach thermal system simulations; however, there is still a need for an easy-to-use approach. The procedure to follow for simulating the transient effect on the system was also not developed in Bouwer's study.

Du Plessis et al. [66] conducted a case study to optimise ventilation and cooling systems for an operating mine using network simulation models. The method followed by the authors included matching the network simulation models with the ventilation and cooling design criteria. The simulations were then conducted with the approach of varying the configuration of the system. The simulation study presented the relevant mine with two configurations for the refrigeration system.

Energy efficiency considerations were part of the study, with an examination of the system energy consumption. However, the exact approach followed was not highlighted, and replicating the same study on a different mine will be dependent on the individual conducting the simulation and will not be governed by a procedure or approach.

Du Plessis et al. [49] also did not consider the transient effect of the configuration changes on the system, and only considered the steady state effect on the operational constraints. Similar findings were also presented by Du Plessis, Marx and Nell in another publication [9]. No further energy management approach with the simulations was conducted, even though the authors state that the study was done as part of an integrated energy and carbon management strategy. However, the results of this study will be retained and considered in the validations of this thesis.

Most existing simulation inputs are limited and have predefined control sequences with only schedules or set points that can be adjusted by the user. However, with the introduction of modern energy management systems, the control algorithms quickly transcended the operational strategies that are found in most simulation programs [79].

2.4.3. Integrated process simulation models available in industry

Most mathematical simulation models require some form of software coding to be useful in industry. Using network simulation programs eliminates the need for calculating procedures, processes and system effects manually. Programs are also an important resource when it comes to the utility, process or energy engineer. Several simulations can be performed easily and rapidly in a single set of data input. The results can then be evaluated to determine the practical and economic solutions [24].

It is therefore required to also review the software that is available in industry. Following a comprehensive review of literature, a few models were identified that can be used for MCS energy studies. The identified models will be discussed as well as their limitations. The review only focused on publications or studies that used the simulations for the respective applications. Although numerous other software packages are also available, it is difficult to determine the exact ability because marketing by the software developers also becomes a factor.

ENVIRON [33]

ENVIRON was developed as part of a research programme launched by the Council for Scientific and Industrial Research (CSIR) in South Africa. The software was developed in the late 1980s and served as an important tool for the environmental or ventilation engineer. The software can simulate cooling and ventilation systems on gold mines [33].

The programme consists of two primary modules, namely, HEATFLOW and VENTFLOW. HEATFLOW calculates all heat loads and the effect of air coolers in the mine, whereas VENTFLOW estimates the airflow distribution. However, ENVIRON is static and cannot solve a gold mine's ventilation and heat flow in an integrated fashion over time. This was also found to be the case by Bouwer [36].

This thesis is aimed at developing new simulations that can be empirically developed, whereas ENVIRON is mostly design-based.

Flownex

Flownex is a thermal-fluid network analysis code that can perform detailed analysis and design of complex systems. Flownex uses nodes and elements to represent a complex thermal network. Flownex performs steady state and dynamic analysis, and solves the momentum and energy equation in each node [29].

An important study of a mine-wide combined simulation of MCSs was identified as part of the comprehensive literature review. The study conducted by Van Antwerpen et al. [52] focused on simulating the entire MCS as an integrated system. The authors also simulated the compressed air flow and ventilation air psychrometry as part of the investigation of using Flownex.

The software can integrate with other software such as Ansys and Fluent. Flownex was also used in some ventilation optimisation studies [27], and for some studies on reactors and simulation of their operation [28]. An example of the transient-solving ability of Flownex was found in a study that modelled a transient heat exchanger performance [29].

Although Flownex seems to be able to conduct simulations required in this thesis, very limited studies were found that utilised Flownex for energy management simulations for MCSs considering the transient effect on the system. The few studies that have been found [52, 80] and their relevance to this thesis was discussed in the previous sections.

VUMA3D

The VUMA3D suite of software was specifically designed to assist ventilation control engineers to plan, design and operate a mine ventilation system. The software and its models can be used for steady state simulations of airflow, air thermodynamic behaviour and gas and

dust emissions underground [40]. Since its development, VUMA3D has expanded to simulate transient variations of airflow and inlet temperatures for cost saving interventions.

The models have been used in previous studies, such as the life-of-mine planning study conducted by Bluhm et al. in 2014 [35]. Bluhm et al. indicated the importance of using simulations, because the alternative is using a trial-and-error approach. Other studies were also considered to evaluate VUMA3D's potential use in this thesis [9, 48]. However, the software does not meet all the requirements for novel simulations to be conducted as part of this thesis.

REMS

The REMS software was used in numerous studies relating to energy management of cooling and water reticulation systems [13, 23, 30, 54, 81, 82]. However, the software is limited to steady state simulations and only serves as a tool to simulate, optimise and control these systems after a specific change in the system. No system predictions can be made.

The software was mainly installed as part of energy saving measures on mines to realise energy and cost savings on isolated mine cooling and water reticulation systems [14]. However, the software was used in various integration strategies that have already been discussed in Section 2.3.2.

QUICKcontrol, VisualQEC

The simulation program, QUICKcontrol, was identified by previous studies [36, 78] as having the potential to contribute to the design and implementation of a dynamic integrated thermal and energy simulation tool. Bower [36] therefore developed VisualQEC from the basis of QUICKcontrol.

Implicit equations for system component models cause slow and unstable simulations, whereas explicit equations ensure stable results with a significant increase in simulation speed. There is therefore no need for iterative solvers. VisualQEC was created specifically to design and implement energy efficiency practices for mainly the building environment. However, Bower mentioned that the software could also be used for mining applications.

Bower also mentioned that the practicality of the new simulation and scheme must be tested using case studies. It was also mentioned that the accuracy and stability of some of the component models and new procedures still need to be verified.

Process Toolbox

A component-based simulation package was developed that stemmed from the design of QUICKcontrol and VisualQEC. The package is known as Process Toolbox (PTB). From previous literature, it was determined that the software can simulate integrated mining systems [23]. Although software has been used in previous studies, there is still a need for further development of the software. However, the basic functioning of the software will be sufficient for the novel simulations that will be developed in this thesis. The exact functioning of the models and the further developments will be discussed in Chapter 3.

2.4.4. Benefits of integrated system simulations

Integrated system modelling has become more popular over the years. It is becoming less difficult to conduct system simulations due to recent technology developments and since models developed by industry and are not only academically driven [36]. Arndt [37] mentioned in 2000 that it is almost a requirement that a user who attempts to use simulation tools has at least one PhD.

The benefits of integrated system simulations have been mentioned in the few publications that attempted to conduct integrated system studies [23, 80]. There are various benefits to setting up a simulation model. These benefits are summarised as:

- The simulation model provides a form of documentation of the system functioning and layout.
- The analyst and modeller are forced to grasp the process being simulated.
- The simulation model provides a basis form for component selection and design.
- The simulation model provides a high-level fault-finding approach.

One of the main benefits identified was the potential resource savings when implementing integrated system simulations. However, it was determined that this is mostly governed by the simulation package or model that is used. This thesis will also aim to reduce the time assigned to compile integrated system simulations by providing an easy-to-use simulation procedure.

2.4.5. Summary

The evaluation of transient response simulations in this section focused on firstly identifying the traditional approach to simulating thermal systems as an introduction. Thereafter, the

existing procedures and approaches for transient simulations were reviewed. It was found that no transient integrated MCS studies have been conducted before. However, the existing studies gave some indication of development that is still required in industry.

This section also reviewed various simulation packages to determine a suitable package for the objectives of this study. PTB was identified as the most appropriate software package for further development and for conducting energy management of MCSs through an integrated approach. The benefits of system integration and simulations thereof were also discussed.

It was also determined that there is no sufficient strategy, procedure or approach for simulating integrated transient simulations for MCSs. Such an approach is required for resource cost savings.

2.5. Approach to energy management using simulations

2.5.1. General approach for using simulation models for energy management

Most approaches to energy management using simulations were mainly developed to be used in buildings and for commercial applications [37, 79]. Various energy management methods and tools have been developed for the building and commercial industry [25]. However, this has not truly been the case for MCSs. As identified previously, there are several benefits related to system integration, and doing so using simulations. However, there is also a significant need for new approaches to apply these novel simulations to the MCS industry.

Traditionally, energy simulations were used as a cost-effective means of identifying energy saving opportunities on energy intensive systems [36, 30]. The information collected from system performance monitoring tools in most cases can be included in simulation models for higher reliability. The use of energy simulations was therefore limited to these applications. However, as described in Chapter 1, this thesis will also apply the novel integrated MCS simulations in various applications to develop the field of energy management on MCSs further.

Customers in these industries express the need for software that can help them visualise energy efficiency and key performance indicators (KPIs), and simulation tools that can integrate the energy efficiency performance [26]. Standards for energy management already exist nationally and internationally. However, this thesis is not aimed at developing new

standards for energy management. New simulations for energy management of MCS can rather be applied in the implementation or act stage of standards such as ISO 50001.

The following sections are aimed at reviewing literature that specifically focuses on developing approaches for the various new applications that are developed in this thesis.

2.5.2. Energy forecasting techniques employed by industry

Forecasting techniques in general deals with a level of uncertainty and is an indicative tool that uses historical information to estimate future values. There are a limited number of publications for energy forecasting when considering the mining industry, and specifically sub-systems of the South African mining industry. Greyling [83] also found this to be the case – not only for South African mines, but also for the global mining industry. Greyling also assumed that energy forecasting therefore never really made an impact on cost savings.

The assumption can therefore also be made that energy forecasting techniques also did not contribute to energy management of MCSs through a simulation approach. Simulation models are used for forecasting maintenance schedules, performance and future projects on MCSs [23]. In addition, simulation models used in previous studies are mainly used for identifying electrical energy savings potential on MCSs (as discussed in Section 2.3).

However, no previous studies were found where integrated transient response simulations were used for energy management or energy forecasting of MCSs. The only relevant publication was the life-of-mine planning studies that were conducted by different authors [35, 84]. A simulation approach was followed in these studies whereby the prefeasibility analysis phase was used where energy requirements were considered.

Energy forecasting techniques through analytical models and simulation have been developed for buildings. However, this is again not the case for deep-level mines. Generally, mines manage according to KPIs that have been identified by the utility or energy engineer [42]. The mining industry already applies energy budgeting principles through benchmarking of energy systems, however, there is still scope for improved approaches [42].

In some cases, mines do not have the personnel or resources to do simulations, even with simulation software available. As indicated by numerous published works, running 10–20 transient simulations of a basic pumping system requires several weeks of computing time [22]. It is therefore a requirement that the novel simulations developed in this thesis

must reduce the time required to conduct these strategies. It was also determined that a trial-and-error approach is an alternative to simulations.

Do to the complexity of mine operations, a trial-and-error approach could lead to an estimated combined resource cost of 1 700 hours to identify potential opportunities for operational efficiency improvements. The accessibility limitations of most gold mines also govern this.

In most previous studies focusing on energy forecasting, a statistical approach was followed without using simulation models. A study by Tshisekedi [85] investigated and compiled a model whereby the intensity (kWh/t) of systems were used to benchmark and forecast the energy consumption and, therefore, the efficiency of mining systems. In a study by Cilliers [42], models for the mine refrigeration and mine water reticulation systems for both average and best practice benchmarking of energy intensive systems were developed based on actual mine data.

However, by using these approaches it is clear that limited external factors are considered when budgeting or forecasting the energy consumption of MCSs. In addition, as mentioned by Greyling [83], companies (and therefore mines) need to know their future energy consumption (kWh) and associated costs (c/kWh). This was somewhat addressed by Greyling from a whole facility perspective, but using simulations will allow mine engineers to do these predictions faster and more accurately.

2.5.3. Requirements for effective energy management simulations and approach

The reviewed literature showed that there are very limited approaches of simulation and energy management. However, a few requirements for effective management through simulations were identified through the limited references found.

It is essential that more attention must be given to present energy management strategies and further improvements have already been shown to be sustainable and profitable. Significant savings through integrated energy management strategies have been shown and the requirements accompanying these management strategies have been successful [54]. Energy management strategies such as the ISO 50001 strategy have had a significant impact on the electricity consumption of industries, but the requirements accompanying the strategy have only recently been tested on mines [86].

As indicated in the preceding sections, the new energy management approach through simulations must include a developed simulation procedure to be followed for using transient simulations for energy management. The novel simulation must also enable the mine utility or energy engineer to forecast energy consumption, provide a basis for identifying energy saving measures (ESM) and the control accompanied and provide a methodology for a what-if analysis. Including these requirements in the same approach and simulations would make a significant contribution to the MCSs energy management field.

Present control emulation models and strategies

As indicated by Bagdasaryan [87] regarding modelling and control complexity, complex systems have specific characteristics, which are:

- Heterogeneity of elements comprising the system;
- The composite nature of the system;
- The ambiguity of factors affecting the system;
- Multi-criteria nature of systems properties and their estimation;
- Uniqueness of systems.

These characteristics are generally descriptive of MCSs as well. Control emulation can therefore be applied through mathematical or network modelling to define component control in such a unique system. There are various software packages available to achieve this goal in the general industry [18], but no study was found where these models or packages could be used for MCSs.

The uniqueness of this thesis demands novel simulations that can also simulate the transient effect of control on systems, and the effect this will have on the energy in the system. Packages such as WinMOD provide virtual commissioning or control emulation functionality, but this package does not meet all the other requirements as highlighted in this chapter.

The need for control emulation stems from commissioning of automated systems being an important and resource-intensive phase in a project life cycle. Control emulation provides the project engineer, or in this case, the energy or utility engineer, with the facility to compile a virtual model of the system. The exact implementation set points, PLC control and effect of the system can then be considered. However, this has not been developed for MCSs.

As can be seen in Figure 12, the cost incurred by correcting errors during each of the project phases increases significantly over time. Control emulation can therefore be used to predetermine commissioning set points for implementing energy saving projects on MCSs. This in turn will result in significant resource cost savings if an effective approach and simulation or virtual model for the system can be presented.

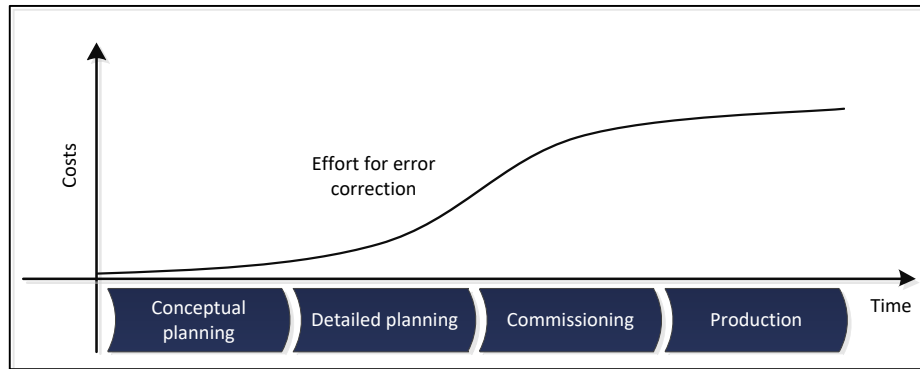


Figure 12: Costs incurred by an extended implementation time

Throughout the comprehensive literature review, various requirements were identified for an integrated transient response simulation model and approach. The summarised requirements, as highlighted by the preceding sections, are illustrated in Table 3.

Table 3: Integrated transient response simulation requirements

Requirement	Result
Transient system simulation	Will be evaluated
Accurate simulation of dynamic energy systems	
Ability to dynamically integrate systems	
Easy-to-use model	
Reduce resource time	
Simulate MCS control	
Customisable to meet system constraints	

The requirements of the integrated transient response simulation will be evaluated in Chapter 4. From the background and need of the study, the developed models and approach will be verified using Table 3.

2.5.4. Summary

From the comprehensive research that focused on the approach to energy management using simulations, very few studies were found. In most cases, these approaches were well developed for the building and commercial sectors. However, limited studies were found where simulations were used for energy management. These simulations were mainly used for identifying cost saving measures on deep-level gold mines.

For the simulations to be useful for energy management, some sort of forecasting methodology is required. From literature, it is evident that very few of these approaches exist. However, no previous studies were found where integrated transient response simulations were used for energy management or energy forecasting of the MCSs of deep-level gold mines. Therefore, there is a significant need for transient simulations and approaches to enable energy management of MCSs on deep-level gold mines. These simulations also have to include other functionality such as control emulation and energy forecasting capabilities.

2.6. Summary

A comprehensive and relevant literature study was conducted and conveyed in Chapter 2, which was continued from the critical literature evaluation in Chapter 1. The main focus of the literature review was on the following aspects:

- Researching energy management and energy savings by integrating MCSs;
- Evaluating the approach, procedures and models currently used in industry for transient integrated energy management simulations;
- Investigating requirements of transient response system simulations; and
- Reviewing shortcomings of the existing models and approaches.

Deep-level gold mines were reviewed to give the reader a basic understanding of the mine operation. Thereafter, the existing published work on energy and cost savings using an integrative approach was reviewed. It was found that the possible solution to additional savings could be found in the novel simulations that will be developed in this thesis. It was also found that a trial-and-error approach was the alternative to integrated simulations.

Transient response simulation models employed by industry were also reviewed to gain an understanding of the models currently used in software, as well as the analytical approaches which are limited to homogenous applications. The benefits of system integration were also reviewed. It was also found that existing approaches in industry do not supply a sufficient solution to the objectives of this thesis.

Chapter 3 will focus on the design and development of novel simulations for energy management of MCSs. Chapter 3 conveys the new strategy for energy management and new transient response simulations will be developed. The chapter is also aimed at developing approaches for the application of the novel simulations through an integrative approach.

3

CHAPTER 3

NEW TRANSIENT RESPONSE SIMULATION DESIGN AND APPROACH

“The real composer thinks about his work the whole time; he is not always conscious of this, but he is aware of it later when he suddenly knows what he will do.”

~ Igor Stravinsky (Composer, pianist and conductor)

3. NEW TRANSIENT RESPONSE SIMULATION DESIGN AND APPROACH

3.1. Preamble

The need for a simulation strategy was identified in Chapter 1 from the critical review. From the comprehensive review in Chapter 2, it was found that no existing transient response simulation strategy for MCSs exists in published works. Furthermore, it was found that integrated transient response simulations of MCSs have also not been developed.

In this chapter, new transient response simulations will be developed to conduct energy management studies on integrated MCSs. A new simulation approach is also required due to the new models and approach for energy management of integrated MCS simulations developed in this study. This approach will also be developed in this chapter.

3.2. Transient response simulation model development

3.2.1. Background on PTB

In a transient system simulation, such as that simulated in PTB, mass flow rates, energy and momentum can change over time and, therefore, over each time interval. Mass flow components are thus required to set up the flow in a configured system. To configure flow in system networks, the following components were developed; 1) Pumps, 2) Fans, 3) WaterMassFlow and 4) AirMassFlow [36].

The flow solver employed in PTB is a transient thermal hydraulic system simulation and optimisation solver. Flow paths are specified by using system pressure nodes and pipes, namely, network modelling. The flow networks consist of pressure boundaries, nodes and components (pipes, pumps, fans, etc.). However, the model had to be adapted to be used for the novel simulations in this thesis.

The model is designed to simulate integrated systems, is dynamic and component-based, and functions on a network-modelling principle. The model was empirically developed; the simulations constructed in this thesis are also empirically verified and validated. This will be discussed in the chapters to follow.

As indicated in the comprehensive literature review in Chapter 2, most simulation packages available cannot conduct integrated system transient response simulations. Furthermore, these packages are not tailor-made for mining applications. Although the thermal hydraulic solvers might be similar, PTB has been developed to be easy to use – specifically simulating mine water reticulation and refrigeration systems.

Various models, for example mine chillers, are already developed in the component-based platform making it easy to use and eliminating the need for cumbersome construction of MCS components. PTB also employs an explicit solver; meaning that the existing state of the system is calculated later, resulting in much faster solvers. However, the accuracy is compromised by using explicit solvers rather than implicit methods. The accuracy of the simulated system will be discussed in later sections.

A brief overview of the mathematical models used in the simulations is given in Appendix II. Arndt [37] and Bouwer [36] give detail of the simulation development, which is proprietary information. Software code and modelling details are not included because developing the simulation package is not the main focus of this study. The models used in the simulations are rather adapted and used as part of compiling new simulations for MCSs.

PTB's dynamic simulation ability will be used to develop new simulations for an integrated simulation approach, used to predict and manage the transient effect on MCSs. In the following sections, simulation models will be developed to serve as preconstructed models. Specific components are also available to simulate all mining components.

Verification of PTB

Although integrated transient simulations of MCSs have not been developed in previous studies, they are required to verify the use of PTB. PTB has not been used in published work to simulate integrated transient MCSs. However, it was used for individual sub-system simulations by Bouwer [36], Arndt [37] and Holman [23].

The models employed in PTB were mostly verified in the studies mentioned. However, the newly developed models in this thesis will be verified in Chapter 4.

3.2.2. Modelling of sub-systems

Precooling circuit

The model development for a generic precooling sub-system is illustrated in Figure 13. These precooling systems are used in surface refrigeration systems, as discussed in Appendix I. A precooling system consists of:

- A PCT (component 2).
- A PCT fan (component 8).
- Water inlet and outlet connections (components 11, 12, 10, 14) consisting of boundaries, pressure nodes and pipes.
- Air inlet and outlet connections (components 1, 7, 5, 6, 4, 3, 15) consisting of boundaries, pressure nodes and pipes.
- A PCT sump (component 12).

As can be seen in Figure 13, the components are connected to one another with connectors. The components and connectors can be arranged to reflect the actual process flow of the sub-system being simulated. Precooling systems are used on most mines. The developed model can be used as a generic model that can be applied by the simulation engineer to the specific system being simulated.

However, the component inputs and project properties need to be adjusted for the relevant site and specifications. This will be discussed during the development of the new approach.

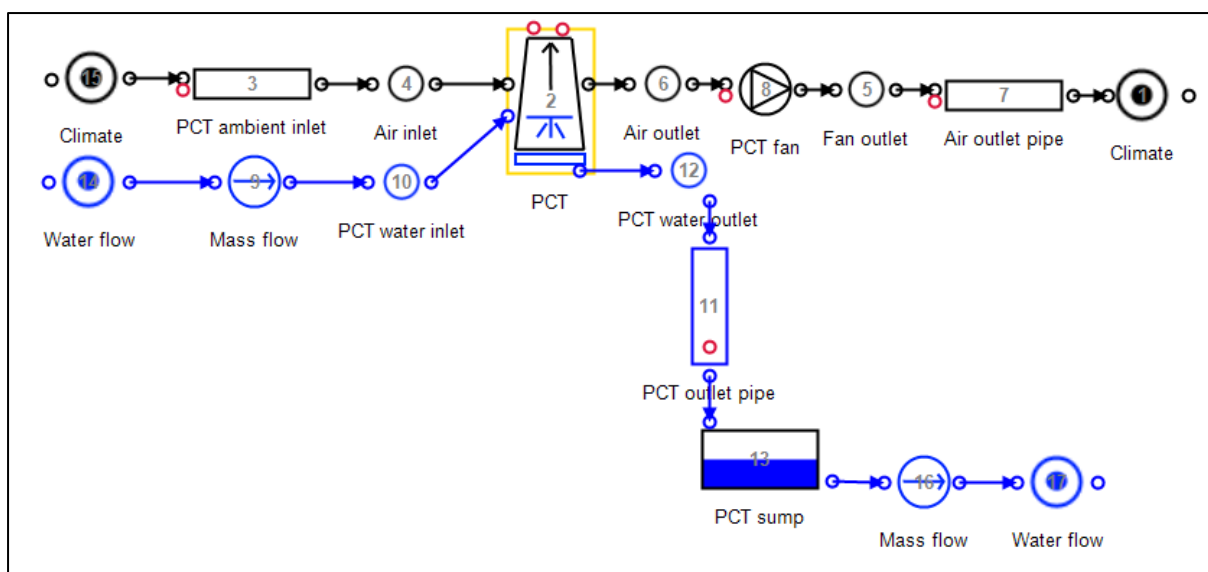


Figure 13: Precooling sub-system – generic model

The inputs and outputs required for the components in this sub-system are illustrated in Table 4. The same components will be used in other similar systems and will therefore not be repeated for each sub-system. The symbols and their meanings are given in the List of Symbols (page xiv).

Table 4: Precooling sub-system inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
Climate	Air boundary	15, 1	P, T, RH	$h, w_{ao}, P, \rho, T_{ao}, T_{wb,ao}$
PCT ambient inlet	Air pipe	3, 7	$P_{inlet}, P_{outlet}, T_{inlet}, \dot{m}, k_v$	\dot{m}_a , Heat autocompression
Air inlet, outlet	Air node	4, 6, 5	V_{ai}, UA, T_{amb} , Heat load	$h, w_{ao}, \rho, T_{ao}, T_{wb,ao}$
PCT	Water-air cooling tower	2	$T_{wi}, \dot{m}_w, T_{ai}, h_{ai}, w_{ai}, \dot{m}_a$	T_{wo}, T_{ao}, h_{ao}
PCT fan	Air fan	8	$P_{coefficients}, \eta_{coefficients}, N, \rho_{ai}$	T_{ao}, P_{kw}
Water flow	Water boundary	14, 17	P_w, T_w	$P_{wo}, h_{wo}, \rho_{wo}, T_{wo}$
Mass flow	Water mass flow	9, 16		\dot{m}_{wo}
PCT water inlet, outlet	Water node	10, 12	V_w, UA, T_{amb} , Heat	h_{wo}, ρ_w, T_{wo}
PCT outlet pipe	Water pipe	11	P_i, P_o, \dot{m}_w, k_v	\dot{m}_w
PCT sump	Water dam	13	P_w, UA, T_{amb} , Heat load, V_w	$h_{wo}, \rho_w, T_{wo}, level$

BAC sub-system

The model development for a generic BAC sub-system is illustrated in Figure 14. The BAC system is similar to the precooling model previously developed. However, the inputs of the BAC differ from those of the PCT. The components used in the sub-system are also similar to those of the PCT sub-system. The pump component is additionally added to the model.

There can be numerous BAC towers on a specific site. The sub-system can therefore be duplicated to match the number of towers, pumps, fans and their configuration on the simulated site. Duplication in PTB is easy using a simple copy and paste function. However, each tower, pump and fan need to be calibrated to match the corresponding component performance on-site. This should be done in accordance with the energy management specifications.

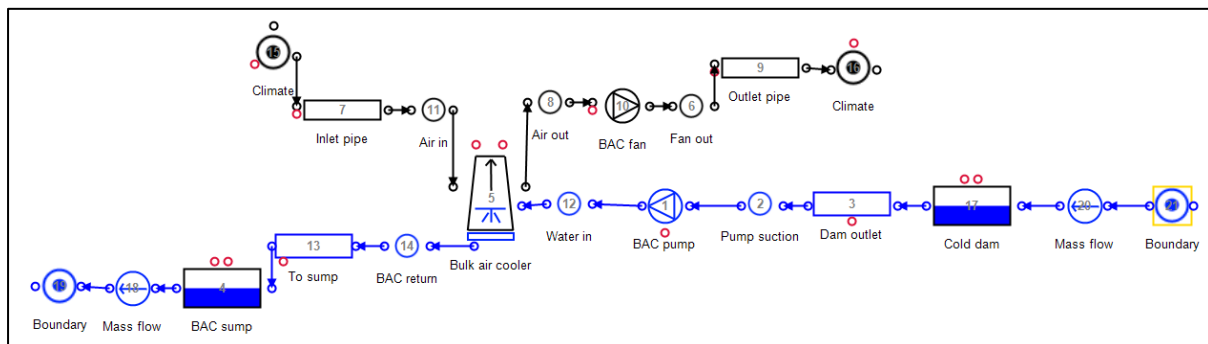


Figure 14: BAC sub-system – generic model

The inputs and outputs required for the components in this sub-system are illustrated in Table 5. The same components will be used in other similar systems and will therefore not be repeated for each sub-system. The symbols and their explanations are given in the List of Symbols (page xiv).

Table 5: BAC sub-system inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
Climate	Air boundary	15, 16	P, T, RH	$h, w_{ao}, P, \rho, T_{ao}, T_{wb,ao}$
Inlet pipe, outlet pipe	Air pipe	7, 9	$P_{inlet}, P_{outlet}, T_{inlet}, \dot{m}, k_v$	\dot{m}_a , Heat autocompression
Air in, out	Air node	11, 6	V_{ai}, UA, T_{amb} , Heat load	$h, w_{ao}, \rho, T_{ao}, T_{wb,ao}$
BAC tower	Water-air cooling tower	5	$T_{wi}, \dot{m}_w, T_{ai}, h_{ai}, w_{ai}, \dot{m}_a$	T_{wo}, T_{ao}, h_{ao}
BAC fan	Air fan	10	$P_{coefficients}, \eta_{coefficients}, N, \rho_{ai}$	T_{ao}, P_{kW}
Boundary	Water boundary	19, 21	P_w, T_w	$P_{wo}, h_{wo}, \rho_{wo}, T_{wo}$
Mass flow	Water mass flow	18, 20	\dot{m}_{wi}	\dot{m}_{wo}
Water in, BAC return, pump suction	Water node	14, 12, 2	V_w, UA, T_{amb} , Heat	h_{wo}, ρ_w, T_{wo}
To sump, dam outlet	Water pipe	13, 3	P_i, P_o, \dot{m}_w, k_v	\dot{m}_w
BAC sump, cold dam	Water dam	4, 17	P_w, UA, T_{amb} , Heat load, V_w	h_{wo}, ρ_w, T_{wo} , level
BAC pump	Water pump	1	$P_{coefficients}, \eta_{coefficients}, N, \rho_w, \eta_m$	P_{kW}

The developed sub-system can be used for surface and underground simulations. However, the elevation of components and their respective climate inputs need to be updated for underground or surface applications.

Condenser sub-system

The model development for a generic condenser cooling sub-system is illustrated in Figure 15. The condenser cooling sub-system is mainly connected to the chillers and can be situated on surface or underground. The condenser cooling circuit also has a CCT, functioning on the same principles as that of the precooling and BAC towers.

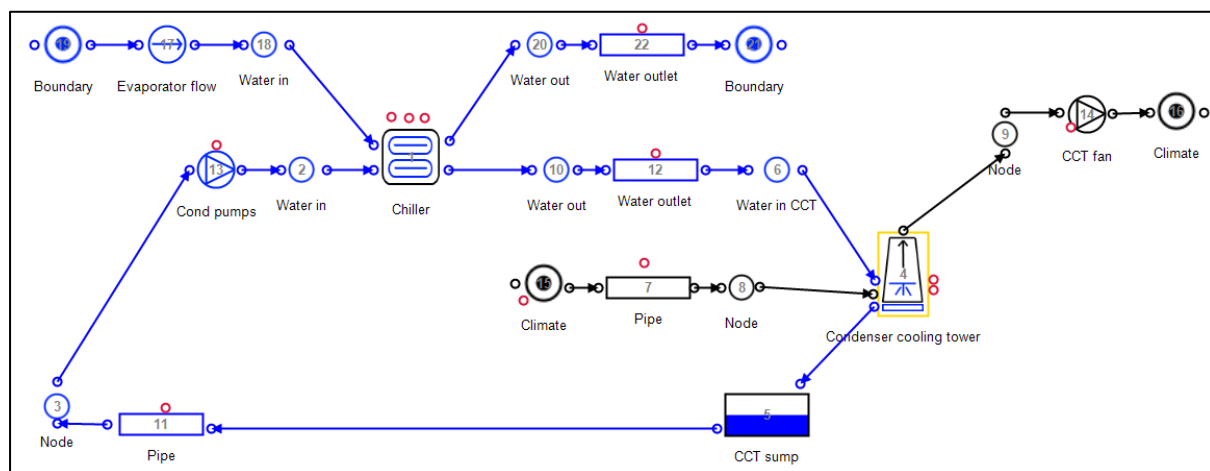


Figure 15: Condenser cooling sub-system – generic model

The chiller used in this sub-system is explained in Figure 16. These sub-systems can have multiple cooling towers and condenser pumps. This is dependent on the specific application but can easily be added to the sub-system. MCS can have various arrangements for the condenser cooling pumps. In the generic model described above, only one condenser pump supplies water to the chiller/cooling tower.

However, a common manifold set-up can also be present on a specific site. This will be discussed in later sections. The common manifold set-up can be duplicated easily for use in this sub-system. The inputs and outputs required for the components in the condenser sub-system are illustrated in Table 6. The symbols and their explanations are given in the List of Symbols (page xiv).

Table 6: Condenser sub-system inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
CCT	Water-air cooling tower	4	$T_{wi}, \dot{m}_w, T_{ai}, h_{ai}, W_{ai}, \dot{m}_a$	T_{wo}, T_{ao}, h_{ao}
CCT fan	Air fan	14	$P_{coefficients}, \eta_{coefficients}, N, \rho_{ai}$	T_{ao}, P_{kW}
CCT sump	Water dam	5	$P_w, UA, T_{amb}, \text{Heat load}, V_w$	$h_{wo}, \rho_w, T_{wo}, \text{level}$
Cond. pumps	Water pump	13	$P_{coefficients}, \eta_{coefficients}, N, \rho_w, \eta_m$	P_{kW}
Chiller	Water-water chiller	1	$Q_{rating}, COP_{rating}, T_{co,rating}, T_{ci,rating}, T_{co,rating}, T_{ci,rating}$	$Q_e, Q_c, Q_{chiller}, COP, P_{kW}$

Chiller sub-system

The model development for a generic lead-lag series-parallel chiller sub-system is illustrated in Figure 16. The generic model represents one of the more common configurations used on MCSs. Variations of this generic model can also be constructed from this model with proper planning and configurational changes.

The chiller sub-system is connected to evaporator and condenser pumps, and to the relevant sub-systems such as the condenser cooling system. The boundary components currently inserted in the sub-system should then be replaced with the evaporator and condenser circuits respectively. The chilled water pipes should be connected to the chill dam.

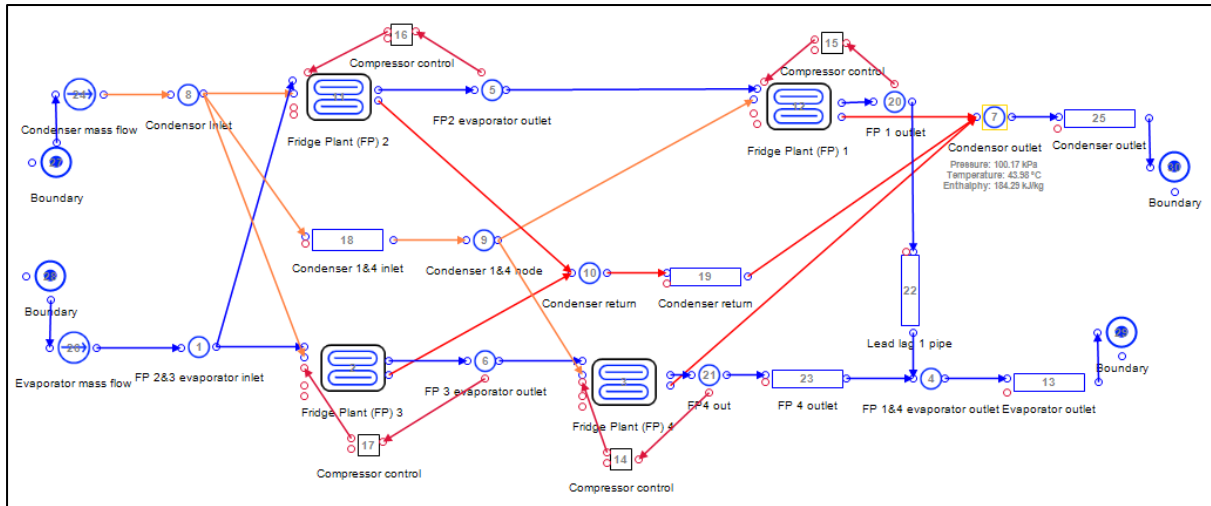


Figure 16: Lead-lag, series-parallel chiller sub-system – generic model

Similarly, the series-only and parallel-only configurations were also built. The exact functioning of these arrangements is illustrated in Figure 100, and discussed in Appendix I. The various configurations also employ chiller inlet valves to throttle the evaporator or condenser water flow through the chiller to match the design flow. These valves can be simulated by emulating the control on the inlet or outlet evaporator and condenser pipes respectively. This type of control will be discussed in Section 3.4.

Dewatering pump sub-system

The generic dewatering sub-system is illustrated in Figure 17. This is a simplified model of a pump configuration of a dewatering system. These systems normally consist of three or more pumps and can easily be added to the model. The inlet pipe and nodes, as well as the outlet pipe and nodes, should be altered to represent the actual simulated system. Care should be taken when simulating a common manifold to obtain an accurate representation of the process parameters of such a set-up.

As illustrated in Figure 17, two additional mass flow sections have been added. The ‘mining water return’ mass flow segment represents the amount of water returned from the mining levels, which flows through the settlers into the hot dam. The ‘leaks and fissure inlet’ represents all leaks and fissure water flowing into the hot dam. These parameters are difficult to measure, but can be calculated by conducting a mass flow calculation of the entire mine water system. The exact functioning of the dewatering pumps, dams and settlers is discussed in Appendix I.

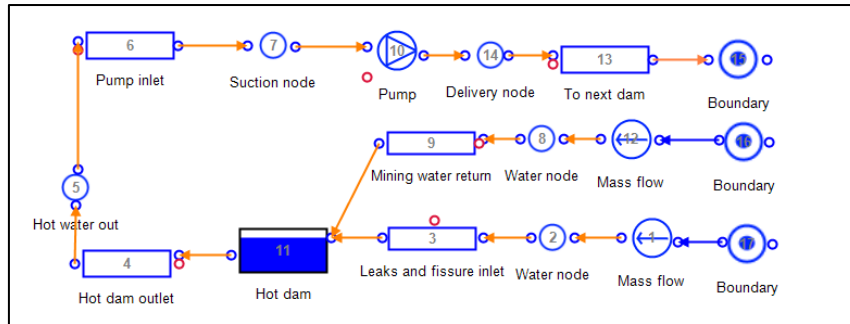


Figure 17: Dewatering sub-system – generic model

The dewatering sub-system inputs and outputs for each component are illustrated in Table 7. The symbols and their explanations are given in the List of Symbols (page xiv).

Table 7: Dewatering sub-system inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
Pump	Water pump	10	$P_{coefficients}, \eta_{coefficients}, N, \rho_w, \eta_m$	P_{kw}
Hot dam	Water dam	11	$P_w, UA, T_{amb}, \text{Heat load}, V_w$	$h_{wo}, \rho_w, T_{wo}, \text{level}$

Mobile cooling units and drilling

The mobile cooling unit (MCU) and drilling sub-systems are illustrated in Figure 18. The functioning of an MCU is discussed in Appendix I. As illustrated in the figure, this sub-system consists of two parts, the MCU and the drilling sub-system. In this case, the MCU is simulated as a component receiving cold water either directly from a chiller or from a chilled dam. The air is cooled by the water flowing through the MCU heat exchanger. The water is supplied to the drills.

This configuration is used commonly. However, there are some mines that dump water on the mining wall once it has passed through the MCU. This can easily be changed in the model by inserting a boundary on the outlet pipe of the MCU. The drilling connection will then have to be moved to represent the actual configuration. The ‘to drills’ pipes illustrated in Figure 18 is representative of water supplied to the drills. This can be controlled per usage profile using a controller. This type of control will be discussed in Section 3.4.

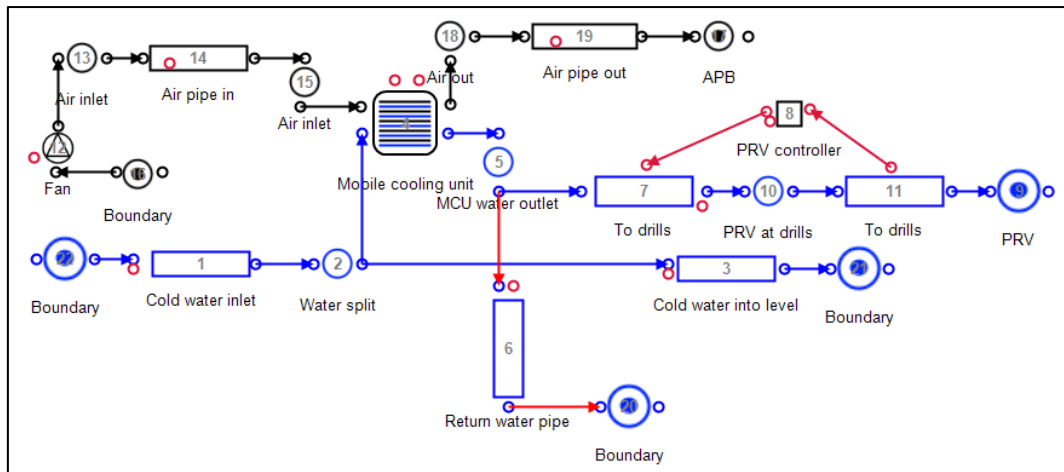


Figure 18: MCUs and drilling sub-system – generic model

The inputs for the additional components illustrated in Figure 18 are listed in Table 8. In most cases, there are numerous MCUs arranged in different configurations (series/parallel). These units are also scattered throughout a mining level. The process flow diagrams (PFDs), as discussed in the following sections, must indicate the correct process flow of the water mass flow through a mining level. This can only be determined by a manual audit or through layouts supplied by mine personnel.

Table 8: MCU and drilling inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
MCU	Water-air heat exchanger	4	$UA_{rating}, \dot{m}_{wr}, \dot{m}_{ar}$	$T_{wo}, T_{ao}, h_{ao}, w_{ao}$
Pressure-reducing valves (PRV) controller	PI control	8	$CL_1, CL_2, K_i, C_{om}, ST$	C_o
Fan	Air fan	12	$P_{coefficients}, \eta_{coefficients}, N, \rho_{ai}$	T_{ao}, P_{kw}

The drilling model must also be adapted correctly to reflect the correct number of active drills on a mining level. However, if this information is limited or not available, the approximations in this generic model would be sufficient and can be adapted with a mass flow balance.

Ice plants and circuits

Most of the components or equipment present on an MCS is available in PTB. However, ice plants and their relevant circuits have not yet been developed in the software. For this study, an ice plant was constructed with the limited models available. The generic model for the ice-plant sub-system is illustrated in Figure 19. The mass flow and energy balance over the system must be calibrated when it is used in an integrated simulation.

The mass flow, pumps and chiller components were used to construct the model to be able to account for the correct mass flow of chilled water (at almost 0 °C) and energy (of a generic ice plant). The functioning of an ice plant is discussed in Appendix I. The model was

constructed to be simulated in a similar fashion. The use of this model will be discussed in Chapter 5.

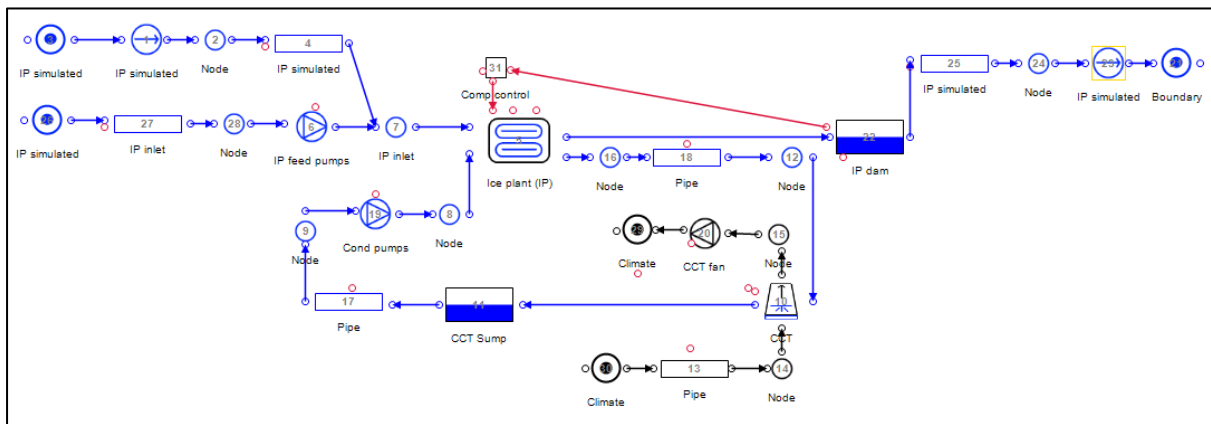


Figure 19: Ice-plant sub-system – generic model

Turbine sub-system

The generic model for a turbine sub-system is illustrated in Figure 20. The detailed operation of a turbine and the system is described in Appendix I. The turbine system is a relatively simple model. However, turbine operation in real-life applications is not as simple. Turbines are often underutilised or bypassed. The model can therefore be adapted to cater for the bypass of a turbine.

A dissipater valve function was added (in a pipe component) to be able to bypass the mass flow past the turbine. The control emulation of such an operating scenario will be discussed in more detail in Section 3.4.

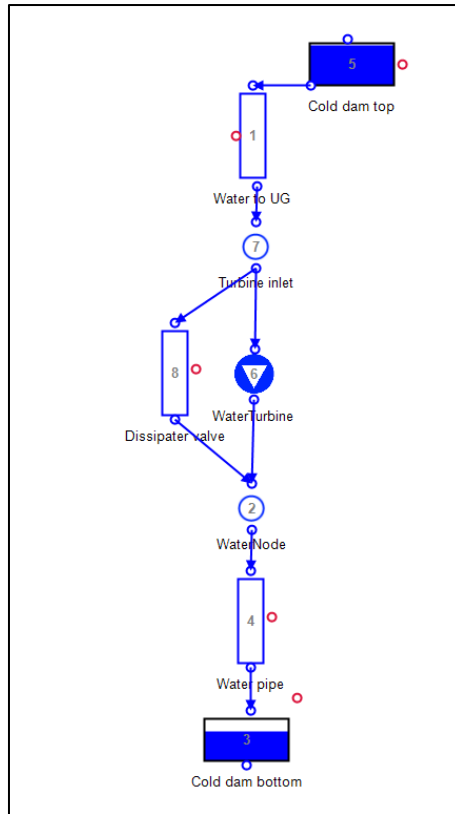


Figure 20: Turbine sub-system – generic model

The turbine sub-system component inputs and outputs for each component are illustrated in Table 9. The symbols and their explanations are given in the List of Symbols (page xiv). The dissipater valve (K_v) and the change in pressure across the turbine are some of the most important inputs. Default values have, however, been determined and already inserted in the model.

Table 9: Turbine sub-system inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
Dissipater valve	Water pipe	13, 3	P_i, P_o, \dot{m}_w, k_v	\dot{m}_w
Water turbine	Turbine	6	$\dot{m}_{wr}, dP_r, \eta_{turbine}, \eta_{generator}$	P_{kW}
Cold dam	Water dam	5, 3	$P_w, UA, T_{amb}, \text{Heat load}, V_w$	$h_{w0}, \rho_w, T_{w0}, \text{level}$

3CPFS sub-system

Figure 21 illustrates a customised 3CPFS sub-system. Similar to the ice-plant scenario, there is currently no 3CPFS model available in PTB. However, the existing components were manipulated into a generic system to simulate the 3CPFS systems of the MCSs. The turbine component, together with the pump component, was manipulated to construct a 3CPFS-equivalent system. This was done by ensuring that the simulated mass flows and energy are that of a real-life 3CPFS system.

The constraint was that the momentum and heat transfer between the cold and hot water cannot be simulated. However, the generic model will be sufficient for this study. The booster pump (also present on a 3CPFS) is controlled to deliver the required cold water to the 3CPFS system. The power absorbed by the 3CPFS filler pumps is compensated for in the 3CPFS pump equivalent. The 3CPFS pump equivalent should also be calibrated to simulate the correct power between the 3CPFS-pump configurations. The nett energy should therefore be calculated carefully by the simulation engineer.

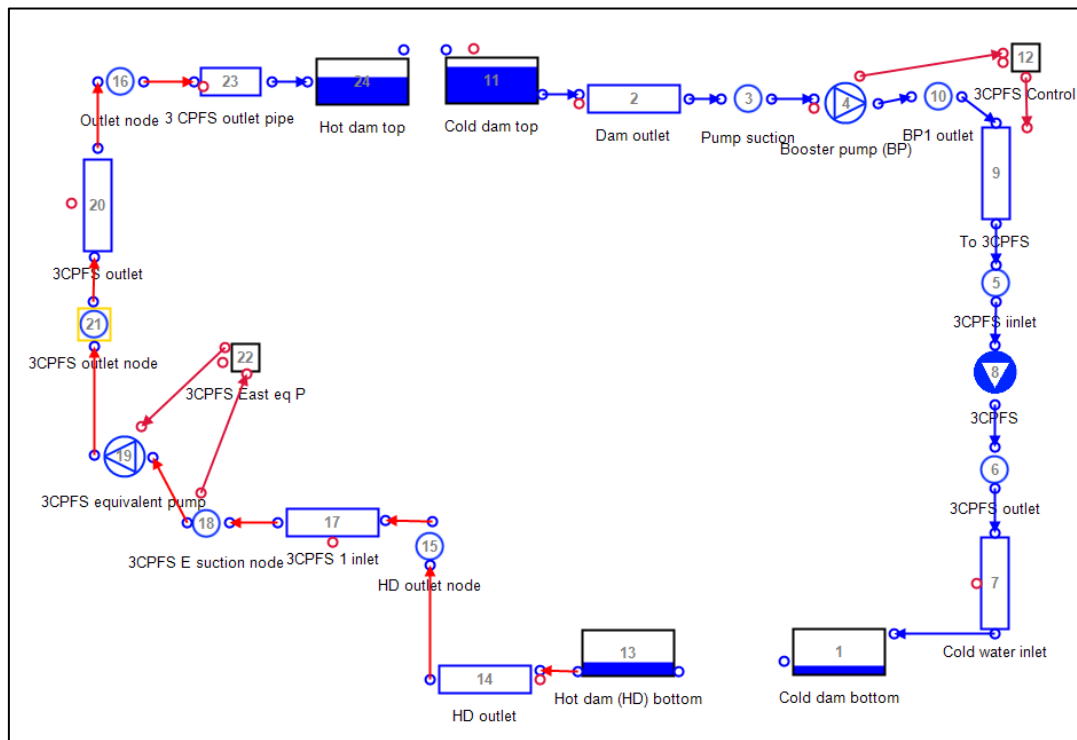


Figure 21: 3CPFS sub-system – generic model

The 3CPFS sub-system inputs and outputs are listed in Table 10. The symbols and their explanations are given in the List of Symbols (page xiv). As discussed, the 3CPFS was then simulated as a turbine-pump configuration. The generic model can therefore also be used for systems that use a turbine-pump configuration.

Table 10: 3CPFS sub-system inputs and outputs for each component

Component name	Component type	Component no.	Inputs	Outputs
3CPFS Eq.	Water pump	19	$P_{coefficients}, \eta_{coefficients}, N, \rho_w, \eta_m$	P_{kW}
Booster pump	Water pump	4	$P_{coefficients}, \eta_{coefficients}, N, \rho_w, \eta_m$	P_{kW}
3CPFS	Turbine	6	$\dot{m}_{wt}, dP_t, \eta_{turbine}, \eta_{generator}$	P_{kW}
Cold dam	Water dam	5, 3	$P_w, UA, T_{amb}, \text{Heat load}, V_w$	$h_{w0}, \rho_w, T_{w0}, \text{level}$

3.2.3. Summary

Background on the development of PTB as a thermal hydraulic simulation software was given and the relevance of its use in this thesis was presented. Previous studies verified the models and components, especially referring to the models similar to those found on MCSs. New sub-systems were developed to make the model easier to use and to reduce simulation engineer resources when simulating a new system. These models are generic and can be adapted for any site that needs to be simulated.

The aim of developing these models is to significantly save the time of the simulation engineer. When starting with the simulations, the engineer can continue with predefined models and there is therefore no need for time-consuming construction or calibration of models. The models can then be used in various simulations as first iteration models.

The sub-systems and their components can now be used to construct an entire integrated surface refrigeration system. The integration of various systems will be discussed in the sections, focusing on the ability of PTB to integrate various systems to form the integrated MCS. It is also clear that the required number of inputs in the simulation model is limited, which therefore simplifies the simulation procedure.

Although these components and circuits are uniquely developed for specific mining applications, the model and approach can be duplicated in various other software packages to accomplish the same goal. It is recommended that similar models must be developed for the specific software used for the simulations. In this case the models were developed in PTB, but the benefits of preconstructed systems are notable.

3.3. Simulation approach for energy management of MCSs

The new transient response simulation models were developed in Section 3.2. The new model can now be applied to simulate the integration of MCSs in a dynamic fashion. However, because of the unique model, a new approach is required to enable energy, utility and simulation engineers to apply the model on various MCSs in South Africa.

It is important for the approach to be easy to use and be economically viable to apply in industry, thus saving time and resources. This can be a difficult task, as not all mines are similar. Some mines have data and information that can be used for the simulations readily available. However, all mines differ in terms of layout, operation and information

availability. There are several elements that need to be considered when developing the new simulation approach. These elements include the following:

- Location and operability of the specific mine;
- Configuration and layout of the MCS;
- Dynamic operational conditions and constraints on the system;
- Measuring equipment and data availability;
- Availability of component design specifications;
- Boundary conditions of operation;
- Empirical measurement requirements;
- Period of simulation; and
- Application of the simulation.

The new simulation approach must therefore meet the following criteria to be useful in the general mining industry:

- Be easy to use;
- Enable fast and easy construction of mining systems;
- Provide a guideline for simulating any mining configuration;
- Provide a generic approach to simulations to compensate for different mines and unavailability of data and measurements;
- Include a detailed procedure to calibrate, verify and validate the simulations;
- Reduce resource costs effectively and, therefore, reduce resource time.

Considering the elements and criteria that the approach must consider, the new simulation approach can now be developed. The following sections provide the approach that was developed for the novel simulations for energy management of MCS.

3.3.1. Develop new system simulation approach

The combined system simulation approach overview is illustrated in Figure 22. The simulation overview provides a summary of the combined simulation approach. The simulation approach was developed specifically for simulating integrated transient response simulations for MCSs. The simulation overview will be discussed in more detail in this section, and the breakdown of each procedure will be discussed in the sections that follow.

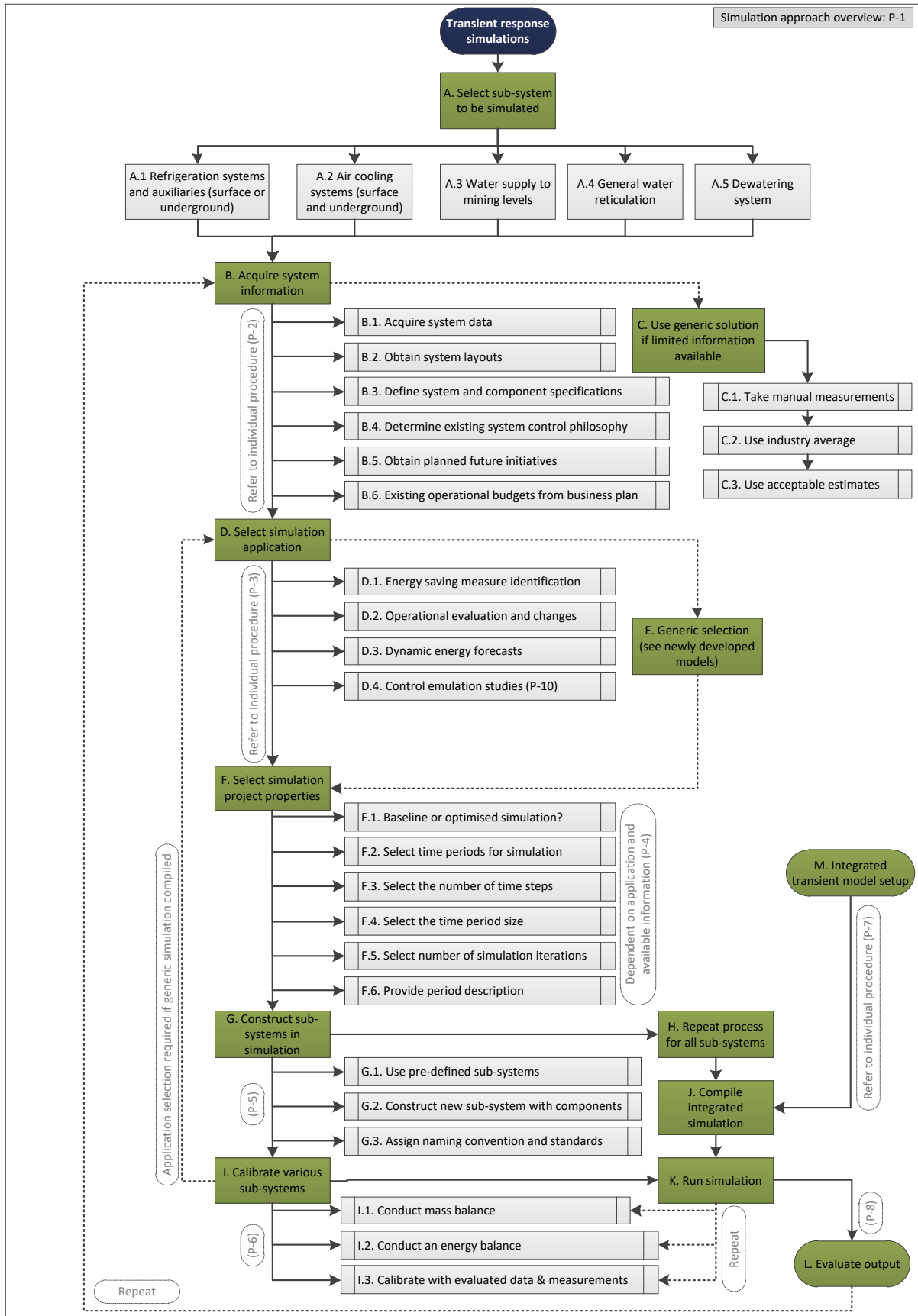


Figure 22: Simulation approach overview (reference: P-1)

The integrated transient response simulations start off by selecting a sub-system that will be simulated. A new simulation project file must be created. Normally, the simulation engineer will identify the system that needs to be simulated. The sub-systems comprise the integrated MCS, which include:

- A.1: Refrigeration systems and auxiliaries (surface or underground);
- A.2: Air cooling systems such as BACs (surface and underground);
- A.3: Water supply to mining levels;
- A.4: General water reticulation; and
- A.5: Dewatering systems.

After selecting the relevant system to be simulated, Procedure B (acquire system information) must be followed. The detailed description for Procedure B is illustrated in Figure 23 (P-2) and will be discussed in Section 3.3.2.

Procedure B consists of various sub-level procedures, including:

- B.1: Acquire system data;
- B.2: Obtain system layouts;
- B.3: Define system and component specifications;
- B.4: Determine existing system control philosophy;
- B.5: Obtain planned future initiatives; and
- B.6: Obtain existing operational budgets from the operational plan.

In most cases, some of the information required in Procedure B will not be available. For such a case, a generic procedure was developed where only limited information is available. This procedure is illustrated as C.1 to C.3. As illustrated for C.1, manual measurements can also be taken with calibrated measurement equipment.

If it is not possible to take manual measurements, the industry averages (B.2) can be assumed for the simulated system. However, this will affect the accuracy of the simulations.

Another compromise is using acceptable estimates (B.3) as determined by experienced simulation engineers. This information can also be obtained from site personnel. After the system information has been acquired or estimated, the next procedure can be started. Procedure D involves selecting the simulation application. The simulation application can be:

- D.1: Identify energy saving measures for the system;
- D.2: Conduct operational evaluation studies;
- D.3: Apply dynamic energy forecasting procedures; and
- D.4: Study control emulation.

The detailed description for Procedure D is illustrated in Figure 24 (P-3) and will be discussed in Section 3.3.2.

New simulation models were also created for selecting a general application for the simulations (Procedure E). The development of these models will be discussed in the simulation approach P-5, in Section 3.3.3. After selecting the application for the simulations, the simulation engineer can continue to select the simulation properties (Procedure F).

Selecting the simulation project properties (Procedure F) are subject to various conditions. The procedure to follow for the project property establishment is:

- F.1: Determine if a baseline or optimised system simulation must be conducted;
- F.2: Determine the time periods for the simulation;
- F.3: Determine the number of simulation time steps;
- F.4: Select the time period size;
- F.5: Select the number of simulation iterations; and
- F.6: Provide a period description for the simulation time periods.

The simulation properties are dependent on the application and availability of system information. The detailed description for Procedure F is illustrated in Figure 25 (P-4) and will be discussed in Section 3.3.2.

After the simulation properties have been determined, the sub-systems (Procedure G) can be constructed. The sub-systems can be constructed by using predefined sub-systems (G.1) that have been developed in this thesis. If the system being simulated is unique, then new sub-systems can be constructed with existing component models (G.2). After constructing the sub-systems, it is important to assign a naming convention (G.3) to all equipment and sub-systems.

This is important because the integrated transient simulation model can become fairly large, proving it difficult to find components in the integrated project. This procedure is explained in more detail in Figure 26 (simulation approach P-5) in Section 3.3.3.

This construction procedure must be repeated for all other sub-systems (Procedure H). The next important procedure is calibrating the sub-systems and components (Procedure I). The detail of this procedure is illustrated in Figure 27 (simulation approach P-6) in Section 3.3.4.

The first step (I.1) is to conduct a mass balance over the entire system, ensuring that the simulated mass flow is comparative with the actual system mass flow and collected measurements. Thereafter, the energy balance (I.2) can be calibrated similarly. It is important to calibrate the simulation with evaluated data or measurements (I.3).

The simulation can now be compiled and run (Procedure K) to evaluate the simulated values. However, this process must be repeated until the simulation outputs (Procedure L) are accurate when compared with the actual system data and measurements. The procedure for the output evaluation is illustrated in Figure 29. If a relatively accurate simulation has been compiled, all other systems can be integrated (Procedure J) into one simulation project.

Furthermore, Procedure D to Procedure I must be repeated for the integrated system. The integrated transient model set-up (Procedure M) is an input for Procedure J. This procedure is illustrated in more detail in Figure 28 in Section 3.3.5. Each procedure in the simulation approach will now be discussed in more detail.

3.3.2. Consider simulation for various applications of the models

The detailed simulation approach for acquiring system information is illustrated in Figure 23. The acquisition starts off with acquiring operational system data as illustrated by Procedure A. The operational data that must be obtained is all data that is relevant to the various mining systems comprising the MCS. These systems include:

- A.1: Refrigeration system;
- A.2: Dewatering system;
- A.3: Water supply and reticulation systems;
- A.4: Air cooling systems; and
- A.5: Any other MCS sub-systems.

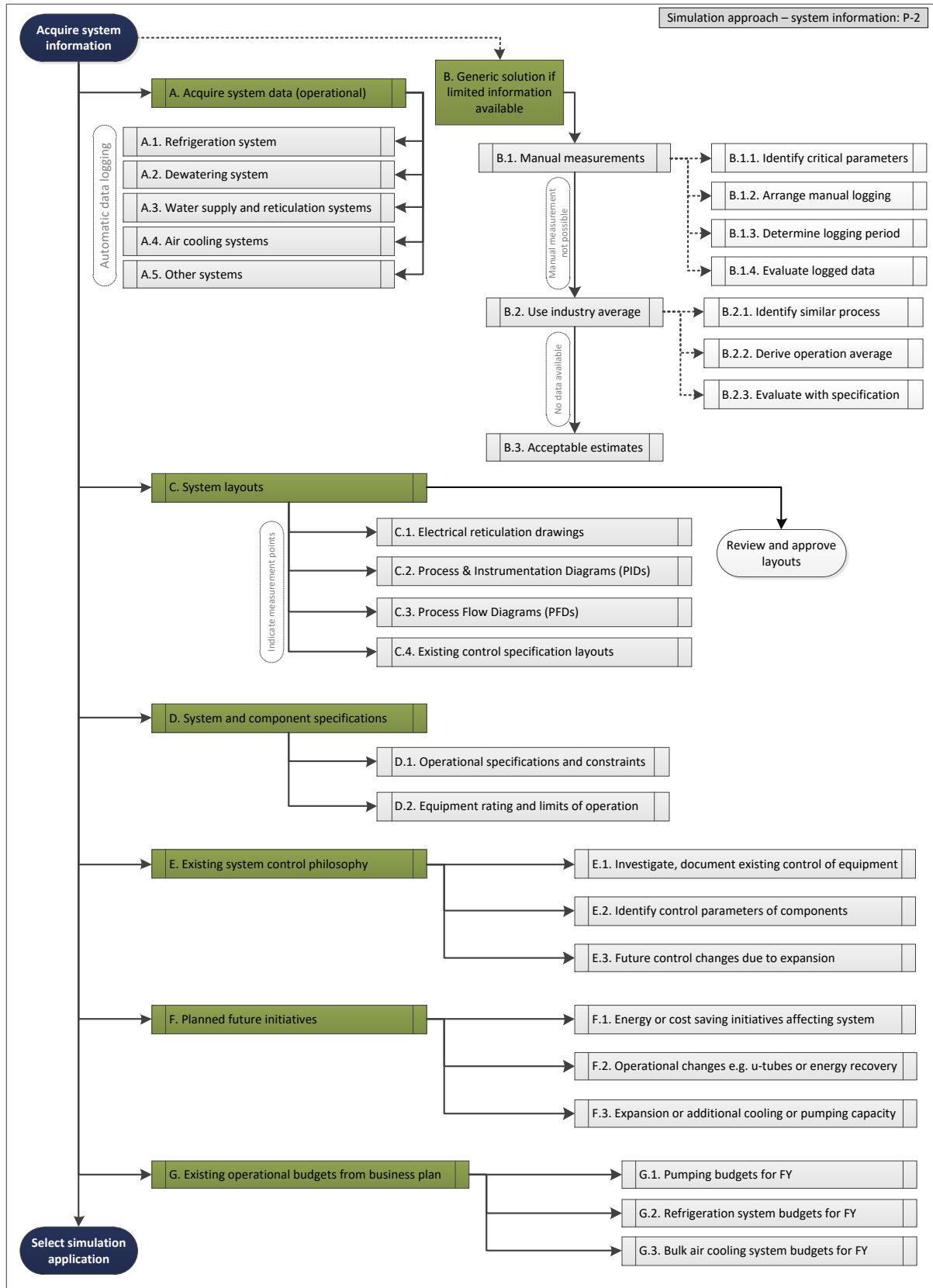


Figure 23: Simulation approach – system information (reference: P-2)

This data is normally obtainable from the mine SCADA system situated on-site. However, it can also be the case that trends for the data are not available, or are only available for a limited period. In such a case, the simulation engineer can follow the generic procedure as illustrated from B.1 to B.3. Where manual measurements are possible, it is crucial to identify critical parameters to be measured (B.1.1). These parameters can include water flow, water pressure and water temperature. Additionally, air thermal properties can also be measured. However, portable measurement devices are not always readily available, and manual measurements are restricted.

Manual logging procedures can commence (B.1.2) where the logging period (B.1.3) is crucial. The logging period is dependent on the application and properties of the simulations (discussed later). After logging has been completed, the data needs to be evaluated (B.1.4). Such an evaluation includes checking consistency and other operational values thoroughly, as well as calibrating the logging device.

Industry average values (B.2) can also be used in the case where manual measurements are not available. Mining groups normally have access to a large array of data recorded at neighbouring mines. This data can be used where identical processes are present (B.2.1). An operational average can be recorded or derived (B.2.2), which can be used in the simulations. These values can then be evaluated (B.2.3) and verified by examining the OEM specifications of the equipment on the relevant mine.

If no manual measurements can be taken, and no industry average is available for the relevant sub-systems, using acceptable estimates (B.3) is the only option. An experienced simulation engineer must make these estimates. Mining personnel can also be consulted to determine acceptable estimates.

The next procedure is acquiring system layouts (Procedure C). To ensure accurate system simulations, the following layouts need to be obtained or compiled:

- C.1: Electrical reticulation drawings, indicating measurement points of system power;
- C.2: Piping and instrumentation diagrams (PIDs) indicating the availability of process instruments;
- C.3: PFDs indicating the process flow of the system; and
- C.4: Existing component control specifications for simulating the present system control accurately.

The existing control specification indicates important control parameters, limits and specifications that are crucial for the transient system simulations. After the layouts have been obtained/compiled, it is crucial for stakeholders to review and approve them. This will ensure that the correct process will be simulated. An example of each of the layouts is illustrated in Appendix II.

System and component specifications (Procedure D) have to be acquired as the next step in the simulation approach. As illustrated in D.1, operational specifications and constraints have to be identified, documented and included in the simulation procedure. Equipment ratings and limits of operation (D.2) also have to be determined. An example of the system and component specification is illustrated in Chapter 4.

It is crucial to investigate the existing equipment control philosophy as illustrated in Procedure E. As part of E.1, the control philosophy for each of the sub-systems needs to be investigated and documented. Thereafter, control parameters (E.2) need to be identified to duplicate the control in the simulation. Future control changes (E.3) also need to be included as these can potentially influence the simulation application and, therefore, the inputs and outputs.

Investigating planned future initiatives was developed as a separate procedure as indicated in Procedure F. Energy or cost saving initiatives that are planned for implementation (F.1) can influence the rest of the MCS, and therefore the integrated simulations must already include the planned initiatives. Significant operational changes (F.2) can adversely influence the simulation results if a thorough investigation has not been done. Such changes will also influence the proposed initiatives that the simulation engineer identifies. Expanding (F.3) installed equipment also influences energy budgeting and forecasting, and this must therefore be included in the operational plan.

Finally, the existing operational budgets (Procedure G) from the operational plan must be investigated. These budgets include the following budgets for the financial year:

- G.1: Pumping system budgets;
- G.2: Refrigeration system budgets; and
- G.3: Bulk air cooling budgets.

The next step in the simulation approach can now be started.

The detailed simulation approach for the simulation application selection is illustrated in Figure 24. The novel simulations developed in this thesis can be applied to various applications. The approach for these simulations has been subsequently developed for the simulations. The first procedure in Figure 24 is to identify energy savings measures (Procedure A). As indicated by A.1, initial system investigation procedures for new project identification have to be followed (as developed by Maré [62]). A similar investigation procedure has been summarised in Appendix V. Thereafter, the detailed project investigation must be followed (A.2).

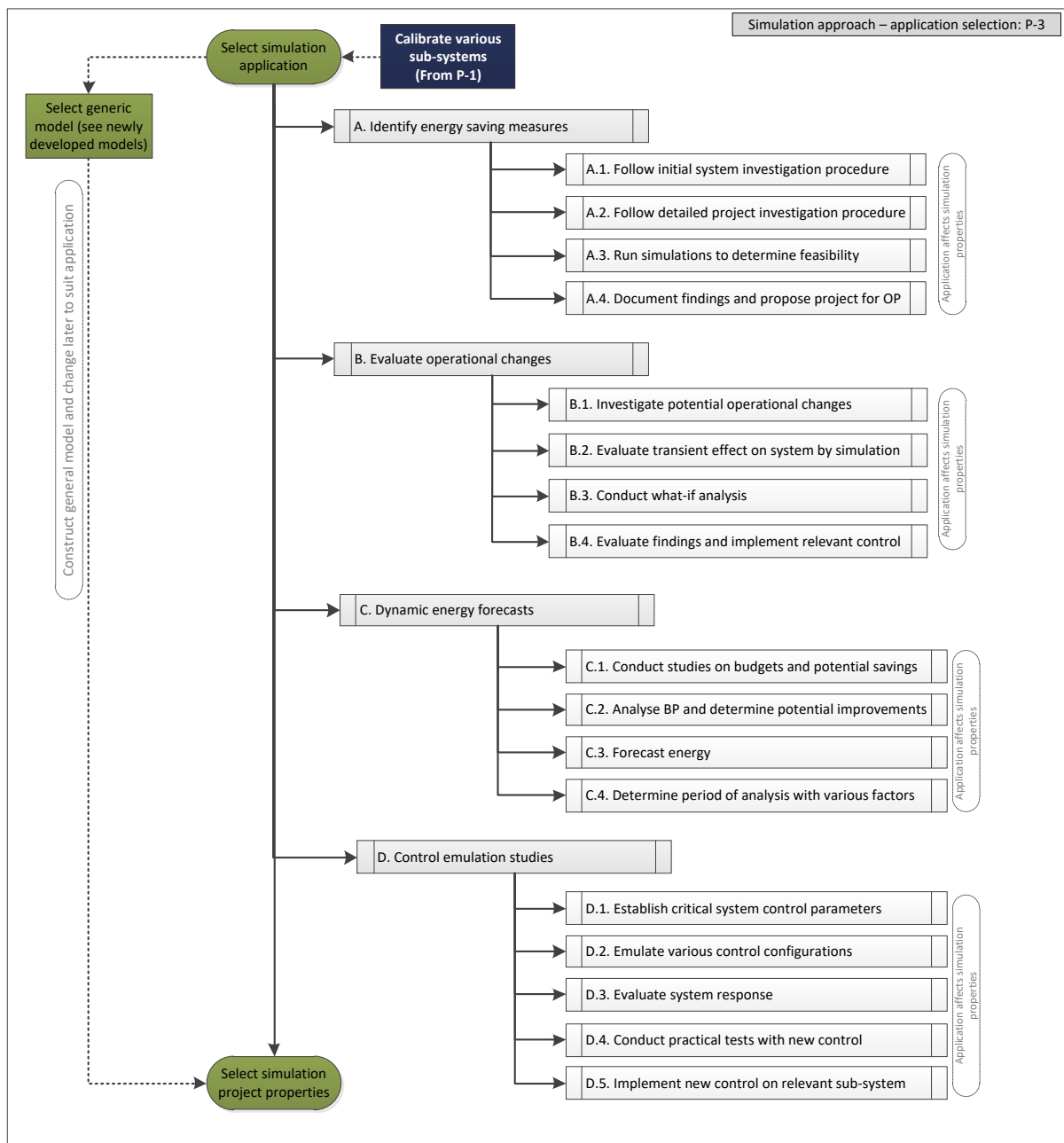


Figure 24: Simulation approach – application selection (reference: P-3)

After the simulation approach has been followed, simulations can be conducted to determine the feasibility of the proposed project (A.3). The application selection affects the simulation properties. After the simulations have been conducted and the relevant results have been identified, the findings can be documented in the form of a proposal (A.4). This proposal can be submitted to obtain project funding.

The next application that can be selected is Procedure B (operational evaluation and changes). In this application, the system being simulated can be evaluated to determine the transient effect of a proposed operational change (B.1) on the system or the integrated system. The transient effect on the integrated system can only be determined by compiling the new simulations (B.2). In addition, what-if analyses (B.3) can also be conducted. These analyses can include ‘replacing’ a system such as a U-tube, with for example, a turbine. Furthermore, the evaluation of the findings of the operational evaluation can be presented similarly than the findings in Procedure A.

The following application is Procedure C (dynamic energy forecasts). With this application, an approach is developed to conduct studies on budgets and potential savings (C.1). The operational plan is analysed and the potential improvements are determined (C.2). In this approach, it is important to consider several factors, such as climate, on the MCS energy budgets (C.3). In this approach, the period for analysing budgets and the period for forecasting have to be considered (C.4). The detailed approach for this model is discussed in Section 3.5.

Finally, the new simulation approach includes applying control emulation studies (Procedure D) in Figure 24. This approach can be used to establish critical system control parameters (D.1). Various control configurations can also be emulated using the new simulation model (D.2). Through the application, the system response due to control configurations can be evaluated (D.3). Practical tests can therefore be conducted after the practical control limits and parameters have been programmed to PLCs relevant to the MCS (D.4). Furthermore, the new control can be implemented in a shorter time due to the control emulation (D.5).

The detailed simulation approach for selecting the project properties of the integrated simulation is illustrated in Figure 25. The first selection (Procedure A) is to evaluate the simulation procedure and to determine which other procedures are influenced by the

‘baseline’ or ‘optimised’ simulation selection (A.1). The system baseline simulations must be compiled first (A.2). System baseline simulations are a simulation duplicate of the actual system being simulated. It is therefore crucial that the simulations are accurate, and are conducted as per the calibration procedure (illustrated later in Figure 27).

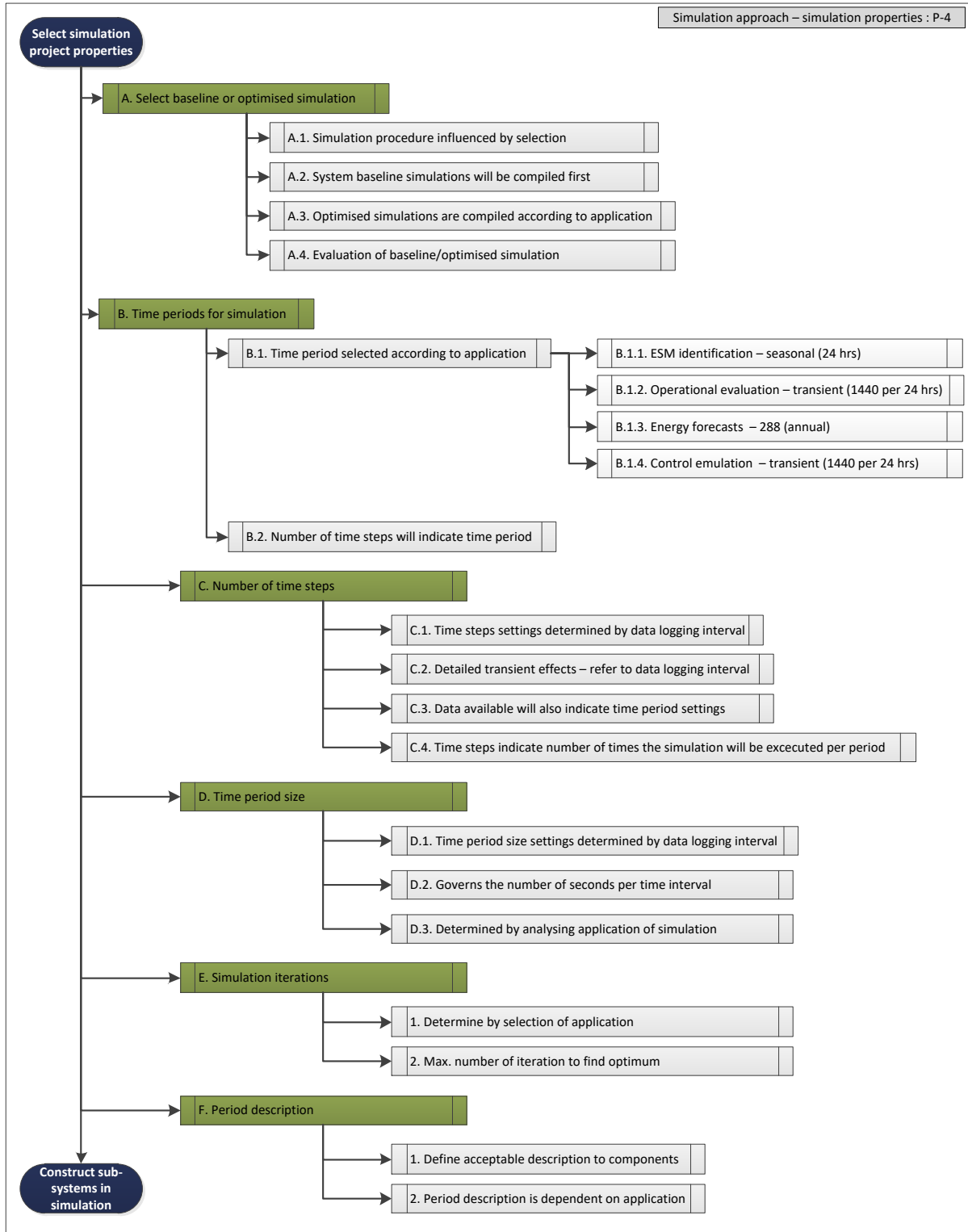


Figure 25: Simulation approach – simulation properties (reference: P-4)

The optimised simulations are compiled according to the selected application (A.3 – discussed further in P-3). The baseline and optimised simulations are evaluated where after the correct simulation properties are determined (A.4). The next step is determining the time periods for the simulation (Procedure B). The time period selection allows the simulation engineer to specify the number of time periods for simulation execution.

The first step (B.1) is to select the time period according to the application. The time period selection for ESM identification (B.1.1) should be selected as 24-hour profiles, for four seasons, which equals 96 simulation time periods. The selection for operational evaluations (B.1.2) should be selected for simulating transient effects in detail, which means that there should be at least 1 440 periods (two-minute intervals for 24 hours) for a 24-hour profile. This will allow the simulation engineer to investigate transient effects in detail considering two-minute intervals.

For simulations of dynamic energy forecasting applications (B.1.3), 288 periods (24 hours, 12 months) should be selected to simulate monthly effects. For control emulation studies (B.1.4), 1 440 time periods need to be considered. The time period in this application can be doubled in cases where one-minute logging data intervals are available. Table 11 shows a summary of the simulation properties of the time period, time steps and time period size settings.

Table 11: Simulation properties – detailed selection of parameters

Application	Time period	Time step	Time period size	Comment
B.1.1 – ESM identification	96	60	3 600	Seasonal effects only
B.1.2 – Operational evaluation	1 440		120	Small intervals – at least two minutes
B.1.3 – Energy forecasts	288		3 600	Monthly effect only – match budgets
B.1.4 – Control emulation	1 440		120	Small intervals – at least two minutes

However, it is very rare that historical data on MCS SCADA systems are available for these intervals. The periods for each application are not static, and can be changed at any time. However, the logging intervals of the input data should be considered when changing the time periods.

The next step is to select the number of time steps for the simulation properties (Procedure C). This selection determines the number of times the simulation will be executed per time period. The logging interval of the available data determines the time step settings (C.1). This should be evaluated in each simulation project. For detailed transient effects, smaller

time intervals are required (C.2). The data available will determine the time period settings (C.3).

The next step is to select the simulation time period size (Procedure D). The time period size should be selected in seconds (s) for each individual time period. The data-logging interval determines the time period size settings (D.1). By analysing the application of the simulation, the time interval can be determined (D.2). This also dependent on the availability of the data.

The next step is to select the simulation iterations (Procedure E). The simulation iterations are firstly governed by the selection of the simulation application (E.1). The iterations are the maximum number of times the optimisation solver will iterate to determine an optimum global solution. For applications B.1.1 and B.1.3, the number of iterations can be set to 2. For applications B.1.2 and B.1.4, the iterations can be set to 5.

The maximum number of iterations to find the optimum (E.2) can be adjusted if the simulated system is being constructed. The final version of the simulation should, however, be adjusted to said selections.

The final step in the simulation project property selection is the period description (Procedure F). This in no way affects the simulations, but rather enables the simulation engineer to quickly find referenced components or systems. The first step is to give acceptable descriptions to components (F.1) and, secondly, to define the periods according to the selected application (F.2).

3.3.3. Develop systems and components in simulation

After the simulation application and project properties have been selected, the sub-systems can be developed. The detailed simulation approach for developing sub-systems for the integrated simulations is illustrated in Figure 26. The first step (Procedure A) is to start off by using predefined or prebuilt systems that are relevant to the system being simulated. The predefined models include the following (A.1):

- Precooling, BAC and condenser cooling sub-systems;
- Chillers (lead-lag, series and parallel);
- Dewatering, 3CPFS and turbine sub-systems;
- MCUs, PRVs and other water consumers; and
- Ice plants and relevant sub-systems.

The next step is to compile sub-system simulations with the simulation models (A.2). The developed models can therefore be used in the simulation procedure to match the actual system with the simulated system. As a final step in the first procedure, generic models can be identified when simulating new MCSs (A.3). These models can be developed, calibrated and added to the models discussed in Section 3.2.

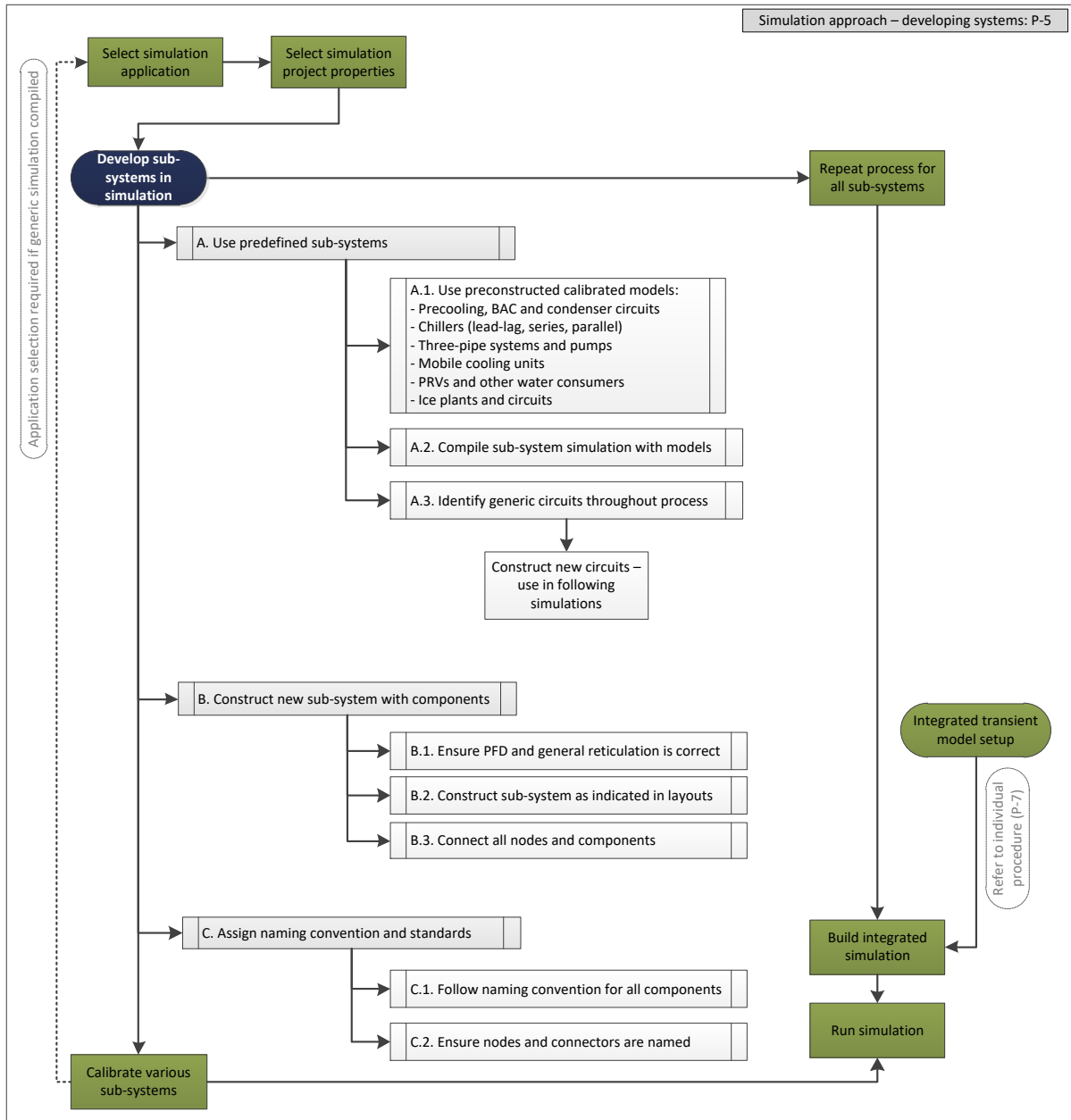


Figure 26: Simulation approach – constructing systems (reference: P-5)

Procedure B should be followed in a scenario where a limited number of developed models can be used. In this procedure, new sub-systems should be constructed with the individual components available in PTB. The first step (B.1) is to ensure that the PFDs are correct and reflect the actual process flow of the system.

Secondly, the sub-system should be constructed as indicated on the site layouts (B.2). The process flow should therefore be duplicated in the simulation model. All components and nodes should be connected to form the sub-system (B.3).

The final step in developing the systems approach is assigning adequate naming conventions (Procedure C). The naming convention as discussed earlier should be followed (C.1) and it should be ensured that the nodes and connectors are named accordingly (C.2). The procedure (P-5) should be repeated for all the sub-systems that form the MCS. The next procedures, namely, calibration, integration and compilation of the simulation can then be followed.

3.3.4. Calibrate new models in simulations

Calibrating new simulation models is the next step after developing the simulations. This procedure is required to ensure that the constructed system in the simulation accurately reflects the operation of the actual system. It is a crucial step since the quality of the simulation results is dependent on the error between the actual and the simulated system. The approach and procedures for the calibration of simulations are illustrated in Figure 27.

The first step in the calibration is the mass balance procedure (Procedure A). Firstly, the mass balance over each component must be calibrated to be similar to the actual system (A.1). One must consider the availability and interval of the data available for each component. The mass balance in each sub-system must then be done (A.2). As a final check, the mass balance over the entire simulated system must accurately compare with the simulated system (A.3).

The next procedure is the energy balance simulation of the system (Procedure B). The energy balance over each component must be calibrated to accurately reflect the actual system energy (B.1). This approach is similar to that of procedure A.1. The next step is to simulate the energy balance of each sub-system (B.2) accurately. Thereafter, the energy balance of the entire system must be calibrated (B.3).

The calibration of the simulation with the evaluated data and measurements is the next procedure (Procedure C). This procedure is required to ensure that all other simulation outputs accurately compare with the system being simulated. The first procedure (C.1) is required to compare the actual data with the simulated data. An acceptable average difference between the actual and simulated data must be below 6. Procedure C.2 states that the entire

calibration process must be repeated to ensure that the average difference between the actual and simulated system is kept minimal.

In a case where there are discrepancies between data (C.3), the simulation engineer must investigate the simulation for input errors first and thereafter the actual system data logging.

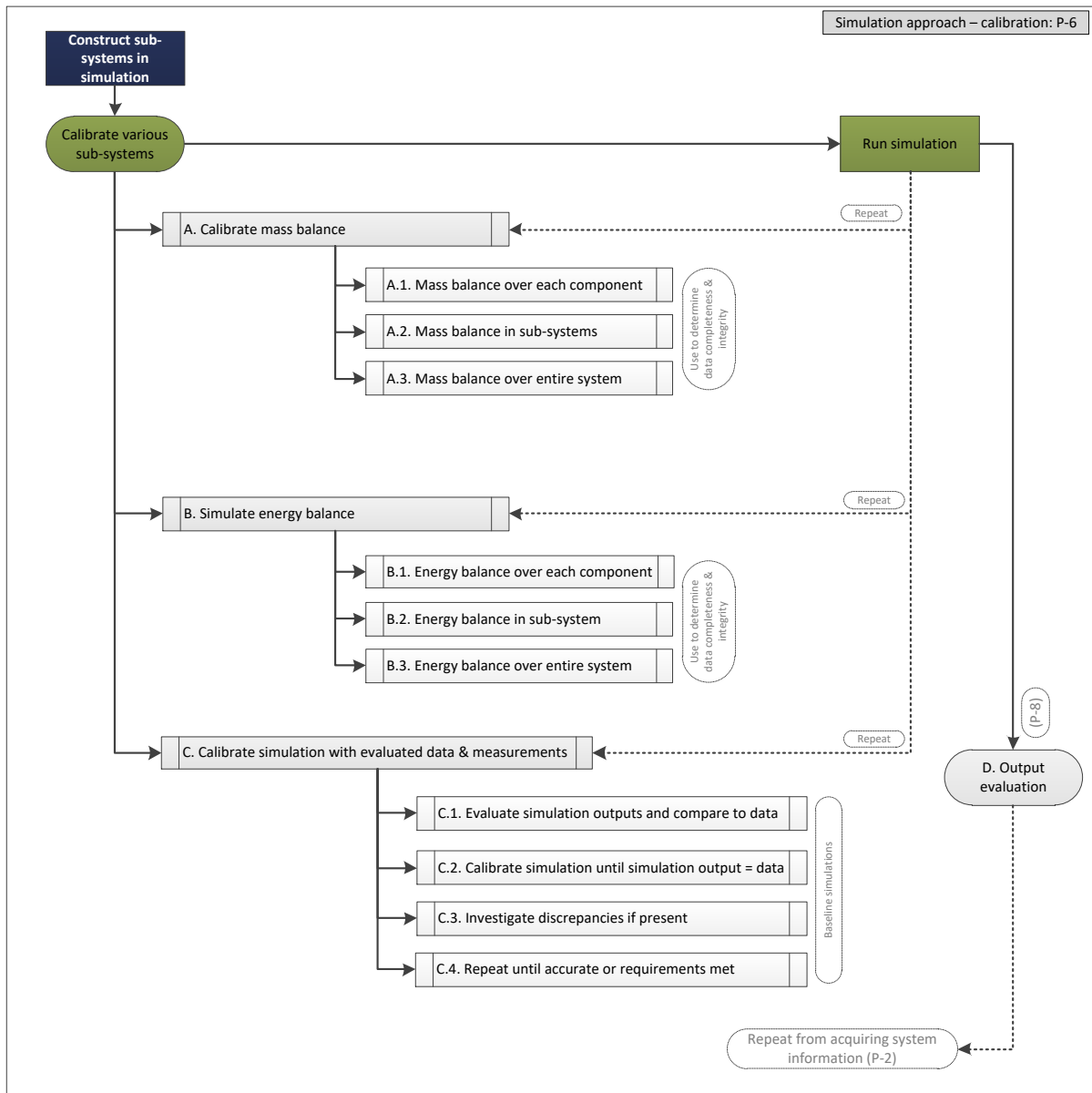


Figure 27: Simulation approach – calibration (reference: P-6)

These procedures must be repeated until all the requirements to obtain a calibrated and accurate simulation have been achieved.

3.3.5. Set up integrated and transient response model

Before the simulations can be compiled and run, the integrated transient model approach must be followed. This approach is illustrated in Figure 28. The integrated transient model set-up is divided into three main procedures. The first is the set-up for sub-systems in the simulations. These are final checks for the simulation engineer and ensure that all the required sub-systems are simulated (Procedure A).

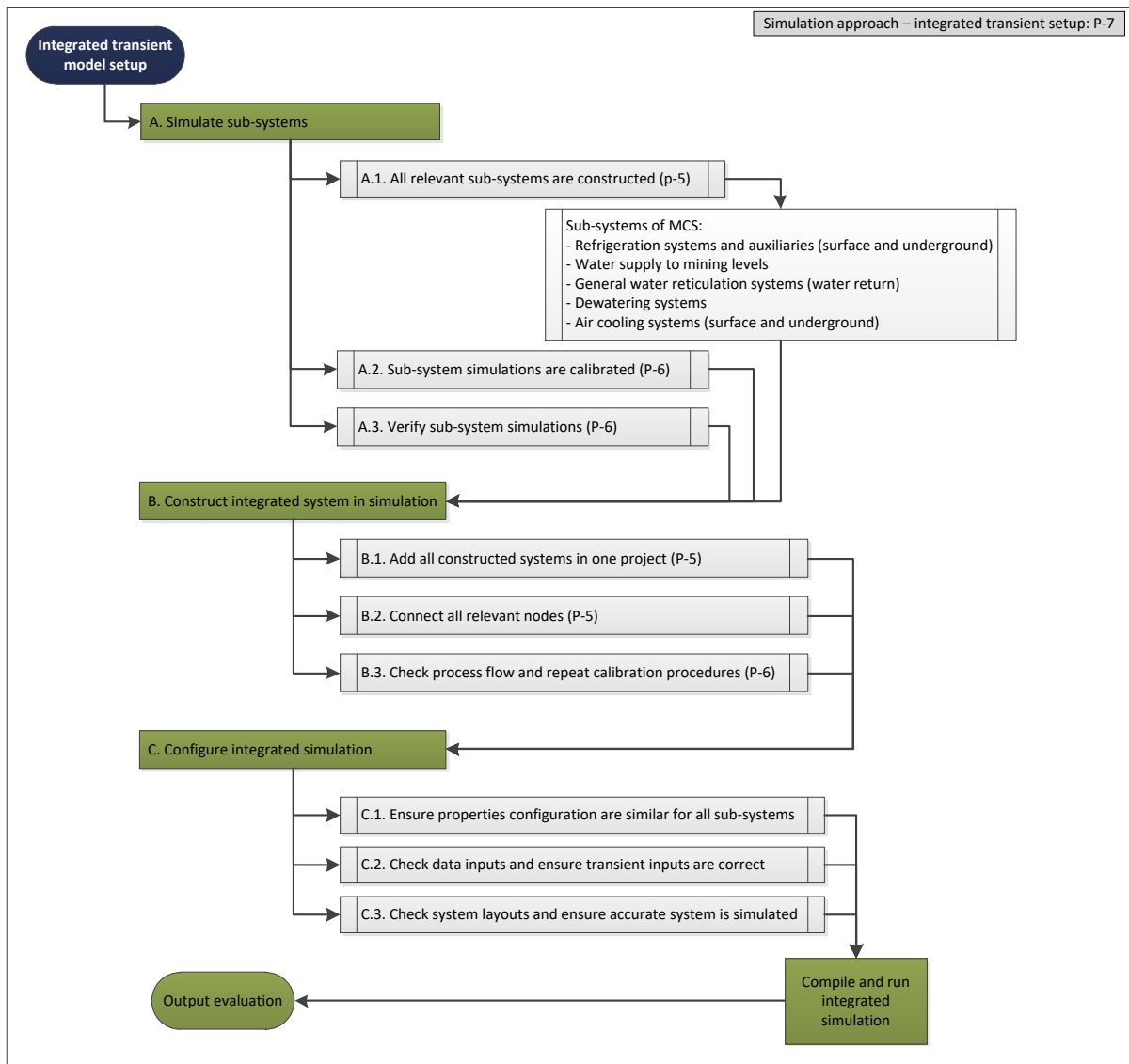


Figure 28: Simulation approach – integrated, transient set-up (reference: P-7)

The sub-systems simulations that can be relevant to one another is illustrated in Figure 28, and form an integral part of the integrated simulations of an MCS. The first step, A.1, is also illustrated in approach P-5 in Figure 26. The next step is to ensure that the sub-systems are calibrated, and that it is the procedure required in approach P-6 (illustrated in Figure 27). The

last step in the first procedure is to ensure all simulations are verified, which have also been indicated in approach P-6.

The next procedure is required to guide the simulation engineer with the integrated simulation project (Procedure B). Firstly, all the sub-systems simulated in approach P-5 should be added into one simulation project, which is the integrated simulation project (B.1). Thereafter, all the relevant simulation boundaries of the sub-systems can be removed, and all connections between nodes, components and required boundaries can be made (B.2). This set-up must also accurately reflect the actual system operation and interaction between the components and sub-systems.

The process flow must be investigated and the simulated system must reflect the actual system (B.3). The calibration procedures, as indicated in approach P-6, must also be repeated for the integrated system. This step should, however, only check if all sub-systems have been calibrated correctly.

The next step is to configure the integrated system (illustrated by Procedure C). All simulation properties must be configured and must be similar for each sub-system (C.1). This procedure is illustrated in Figure 25 (P-4). It might be required to repeat some of the simulation inputs to achieve this goal. The next step is to ensure that all data inputs are correct, and in the case of transient simulations, that all transient data entries are correct (C.2). A final check of the PFDs and simulated system can be conducted (C.3).

The simulation can then be compiled and run after the above-mentioned procedures have been completed successfully. The next procedure indicates the analysis and evaluation approach to follow for integrated transient simulations.

3.3.6. Analyse and evaluate simulation outputs

The approach for the analysis and evaluation of simulation outputs is illustrated in Figure 29. The simulation output evaluation is a critical step in the new approach. The system simulation output comparison is the first step (Procedure A), where the actual and simulated systems are compared in detail.

Firstly (A.1), the simulated power needs to be compared with the simulated power of each component, and subsequently the sub-systems and the entire system. Thereafter, the thermal

properties (A.2) can be compared with the actual system. This can only be done for sites with detailed data logging.

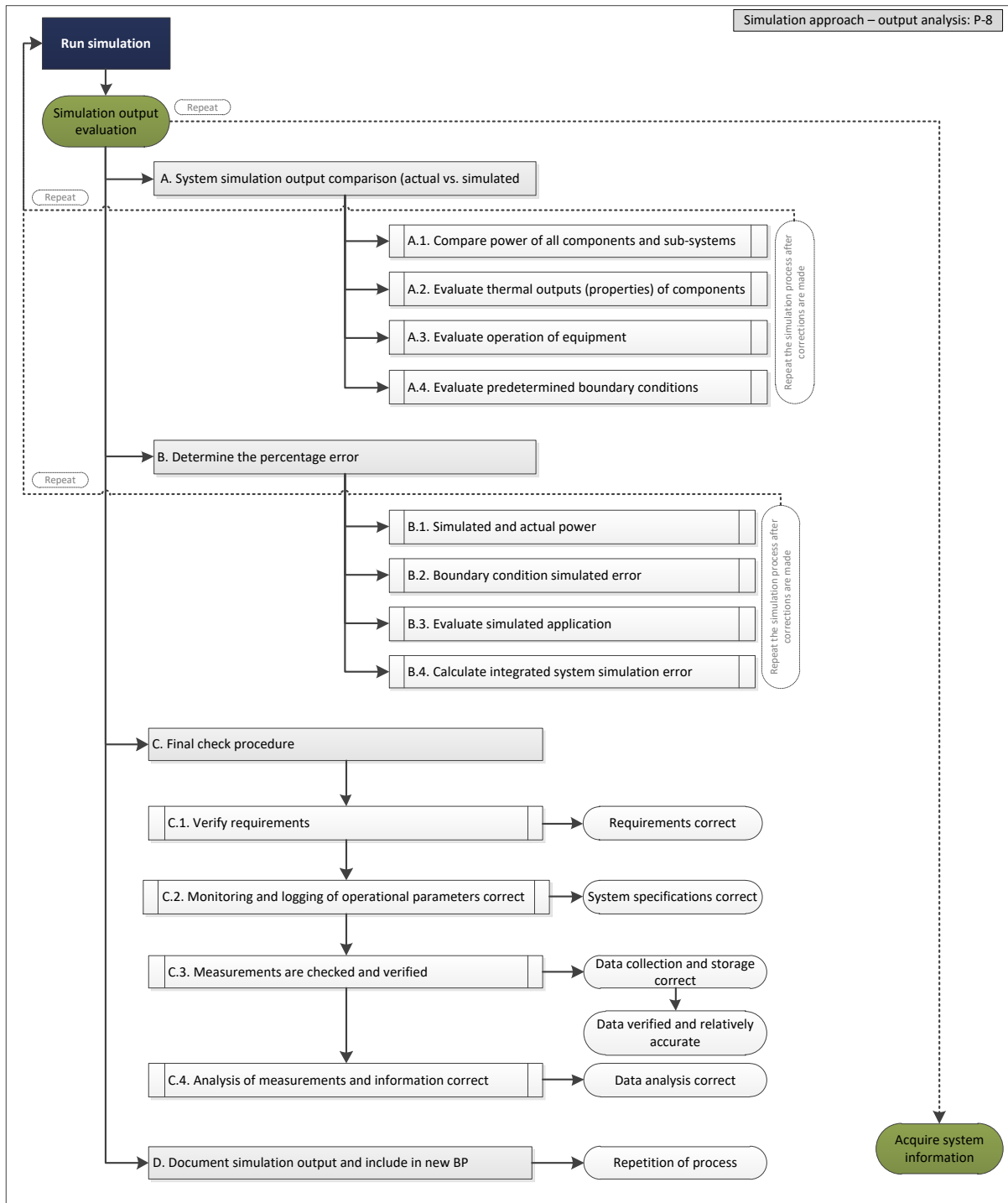


Figure 29: Simulation approach – output analysis (reference: P-8)

The third step (A.3) is to evaluate the operation of equipment and compare it to the simulated output. The operational considerations include equipment running statuses and the required trips etc. The last step of the first procedure (A.4) is to evaluate the relevance of the

predetermined boundary condition of the simulations. If all comparisons are adequate and relevant, the percentage error between the actual and simulated system can be determined (Procedure B). In this procedure, the percentage error needs to be determined for the following:

- B.1: Simulated and actual power;
- B.2: The simulated boundary conditions;
- B.3: The application simulated error; and
- B.4: The integrated system error.

The simulations must be repeated until an adequate percentage error is determined. If data is not available, the required assumptions and theoretical calculations need to be made and then compared with the simulated outputs.

The final check procedure can now be initiated (Procedure C). The requirements for the simulation must first be evaluated, and then determined whether the simulated results are adequate and meet the criteria (C.1). Throughout the simulation, new parameters will be identified. These parameters need to be logged on the SCADA system or any tool available that will serve the purpose (C.2). This can also be used to ensure that the simulation specifications are correct.

The third step in Procedure C is to ensure that the measurements taken are accurate, verified and as far as possible conducted with calibrated measurement instruments (C.3). Thereafter, the analyses, conclusions and assumptions made from the data sets should be evaluated and checked (C.4). This is the final check for the simulations. The final step in the procedure is to document the simulation findings and ensure that all the findings are presented to the stakeholders. This is indicated in Procedure D. This process can be repeated numerous times until all requirements have been met.

The final part of the simulation approach is to combine all the procedures discussed from Section 3.3.1 to Section 3.3.2 and develop the new energy management approach with the new simulations and approach. This approach is discussed in Section 3.3.7 that follows.

3.3.7. Develop energy management approach with new simulation model and approach

In the previous sections, several procedures were developed that form part of the new simulation approach. As part of the comprehensive review, it was determined that this

procedure is unique because the approach to integrated simulations for energy management has not been found in previously published work. The simulation approaches that were developed in P-1 to P-8 can now be used in the new energy management strategy. This strategy is unique because the new simulations and approach are used for energy management of MCSs. The newly developed approach for energy management (approach P-9) is illustrated in Figure 30. The approach starts off with energy planning. The energy planning step is part of the requirement of ISO 50001 [86], and is adapted to suit the new energy management strategy.

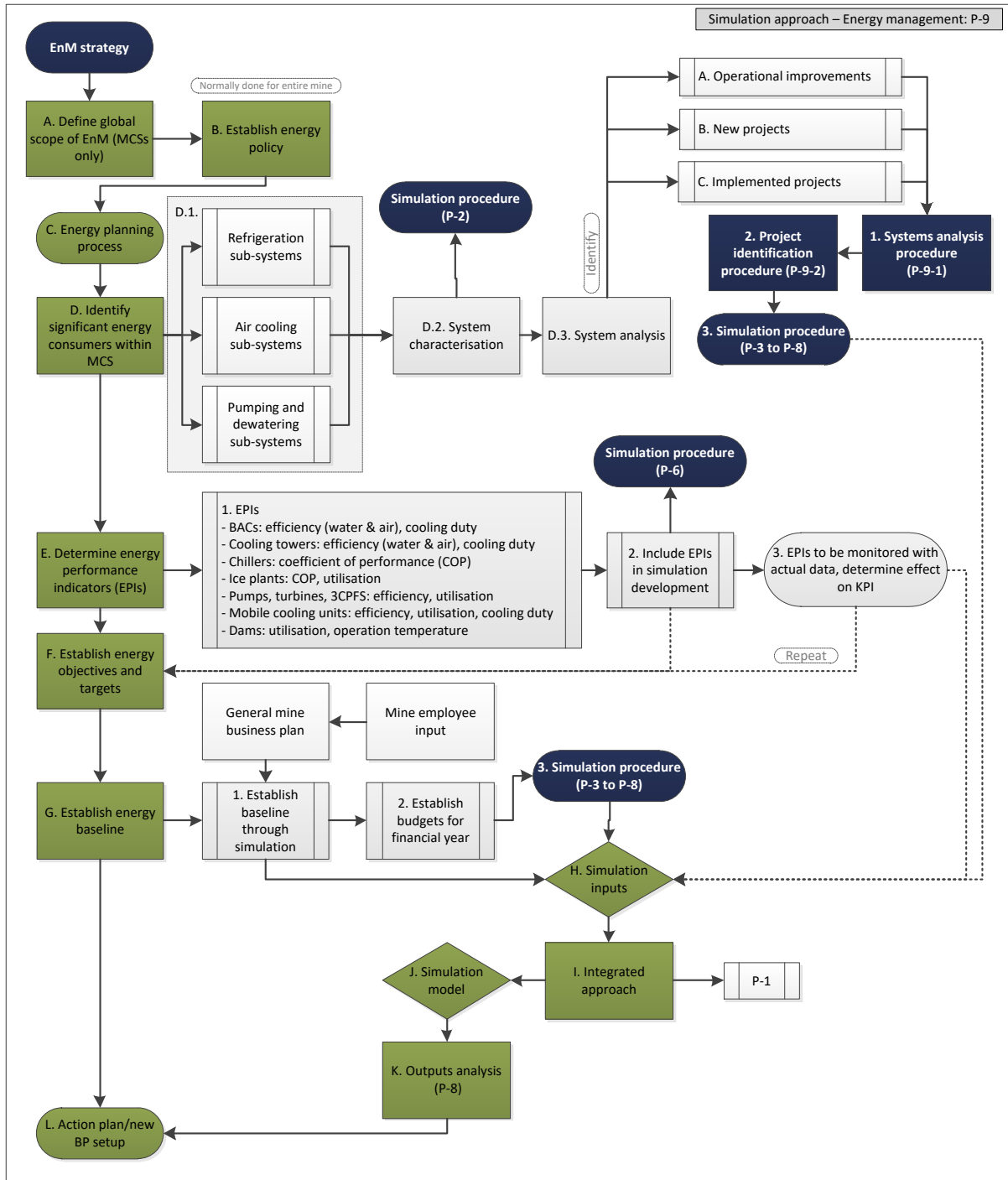


Figure 30: Simulation approach – energy management approach (reference: P-9)

Defining the global scope of energy management of MCSs is the first step in the new approach (A). This process can be followed for most systems on a deep-level mine, but this approach only focuses on MCSs. The energy policy can then be determined and established (Procedure B, as part of the ISO 50001 process). The energy planning procedure can then start (C) by identifying significant energy consumers following (D). The identification of significant consumers can be found in the three main systems of the MCS, namely, 1)

refrigeration sub-systems, 2) air cooling sub-systems, and 3) pumping and dewatering sub-systems.

The second step in Procedure D, where the system characterisation needs to take place as stipulated in the simulation procedure P-2. Focus should also be placed on the measurement procedure in P-2. The identification procedure can then be continued as part of the system analysis. The system analysis can be divided into three identification sections, namely: A) operational improvements, B) new projects, and C) implemented projects. The system analysis also refers to approach P-3.

The system analysis sub-procedures P-9-1 and P-9-2 must be followed as part of Procedure D.3. Procedure P-9-1 is illustrated in Figure 31. Procedure P-9-2 is illustrated in Figure 32. Simulation procedure P-3 to P-8 continues the process and should be completed up to simulation inputs (Procedure H).

Simulation approach – system analysis: P-9-1		
System analysis – data procedures		
Bulk air cooling	Chillers	Cooling towers
Water to/from BAC: - Inlet/outlet T - Flow to/from Air properties: - P, T, RH Mechanical/electrical: - Fan, pump statuses - VSD parameters - Power	Measurements: - Flow to/from - Guide vane position - Set points - Inlet/outlet valve positions Mechanical/electrical: - Status - Compressor power	Measurements: - Flow and T to/from - Valve positions - Fan V, I - Air properties (P, T, RH) Mechanical/electrical: - Fan, pumps statuses - VSD parameters - Power
Calculate: - Approach temperatures - Efficiency (water to air) - Energy saving in circuit - Optimisation of system	Calculate: - Coefficient of performance - Optimal running schedule - Energy saving in circuit - Optimisation of system	Calculate: - Approach temperatures - Efficiency (water to air) - Energy saving in circuit - Optimisation of system
Auxiliary pumps and motors	Dewatering pumps	Energy recovery devices
Pump measurements: - Flow to/from - P, T - Valve positions Motor measurements: - Statuses - I, V, Power Dam measurements: - T, levels	Measurements: - Status - Available/offline status - Control type - Valve positions Mechanical/electrical: - Power consumption - P, T, F	Measurements: - Power generation capacity - F, P, T - Availability - Valve positions
Calculate: - Power consumption - F, P with VSD - Energy saving in circuit - Optimisation of system	Calculate: - Load-shift schedule - Efficiency - Optimisation of system	Calculate: - System optimisation - Turbine schedule - Efficiency - Utilisation
Mobile cooling units	Dams	Underground BACs
Measurements: - Flow and T to/from - Fan status - Valve positions - Fan V, I - Air properties (P, T, RH)	Measurements: - Dam capacity - Flow in/out - Temperatures - Max/min dam limits - Valve positions	Measurements: - Flow and T to/from - Fan status - Valve positions - Fan V, I - Air properties (P, T, RH)
Calculate: - Cooling duty - Efficiency (water to air) - Energy saving in circuit - Optimisation of system	Calculate: - Optimisation - Dam level control capacity - Thermal losses	Calculate: - Cooling duty - Efficiency (water to air) - Energy saving in circuit - Optimisation of system

Figure 31: Simulation approach – system analysis and data procedures (reference P-9-1)

After Procedure D is finalised, new energy performance indicators (EPIs) can be identified. The main EPIs for MCSs sub-systems are illustrated in Figure 30 in Section E.1. The EPIs (E.2) should then be included in the simulation development according to procedure P-6. The

EPIs should also be monitored with actual data (E.3) and should be continuously evaluated to determine the effect on KPIs. This process should be repeated where after the energy objectives and targets can be established (Procedure F).

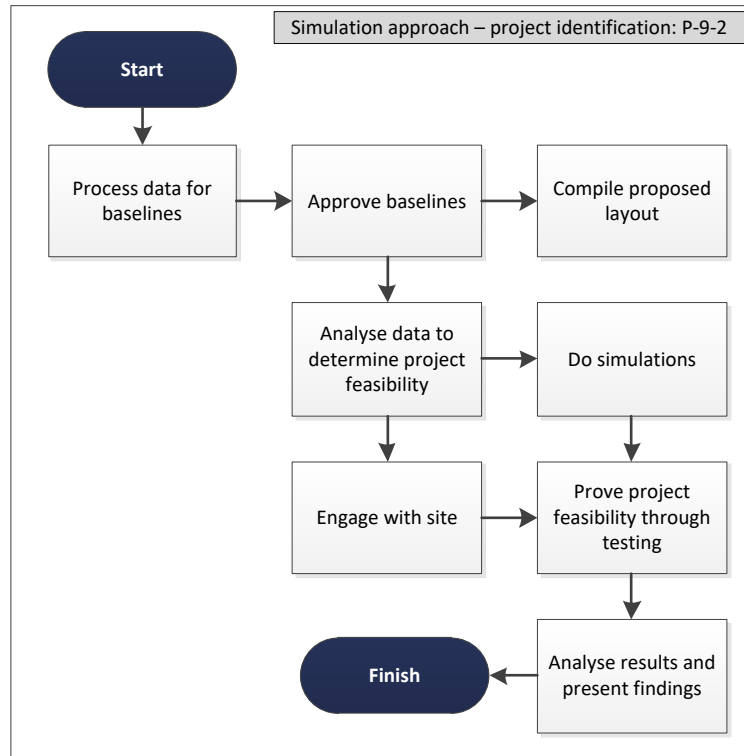


Figure 32: Simulation approach – project identification (reference P-9-2)

After the energy objectives and targets have been identified, the energy baseline (G) can be established. The new energy baseline can therefore be determined for each sub-system and finally the integrated system (G.1). However, the existing mine operations plan needs to be reviewed and inputs from mine personnel will be required at this stage.

The energy budgets can then be determined for the next financial year for each of the systems identified in procedure D.1. The budgets are determined through simulation and the procedures P-3 through P-8 must therefore be followed (G.3). The energy baseline (G.1), annual budgets (G.2) and the EPIs will be used as simulation inputs (Procedure H). From the simulation inputs, the integrated transient approach (I) must be followed, as indicated in simulation approach P-1.

These inputs will then be followed by the simulation model, and finally to the output analysis (approach P-8). From the outputs and results, a new MCS operations plan section can be set up. This can then finally be presented to the relevant stakeholders. This presentation procedure is dependent on the mine personnel requirements. The application of the

procedures of the new energy management approach will be discussed in Chapter 5 – Validation through case studies.

3.4. Component control emulation methodology

3.4.1. Overview of control systems

As discussed in the preceding chapters, existing models for control emulation used in literature are applied in other industries than the mining industry. MCSs are unique and need to be simulated in an integrated approach. Considering control emulation of MCSs, very limited options are available. The new models developed in this chapter, however, provide a platform for efficient emulation of control for MCSs through transient simulation models.

MCS control specifications are only finalised during the commissioning phase of a project, and the control emulation is followed by a trial-and-error approach. Control emulation is also rarely done after a system has been commissioned. In this section, a new approach will be developed that will serve as an integrated approach with transient simulations to emulate control of and serve as a pre-implementation method for MCSs before practical implementation of control. This approach is unique due to various factors:

1. The MCS can be modelled with the new integrated simulation models, and
2. Control can be emulated on the same modelled MCS, allowing the simulation engineer to do various evaluations.

The uniqueness of the new control emulation approach is therefore due to the simulation models allowing integrated models to be constructed and using the same models to emulate control. Considering the control, impact on a system is necessary due to the significant size and operation of the equipment comprising the MCS. Integrated control emulation will provide the simulation engineer with the required results to ensure fast, efficient and safe implementation of new control on a system.

New models and an approach to control emulation will result in shortened implementation and commissioning times of new control. This can also lead to resource savings. Background on control theory will now be conveyed, where after the new control emulation approach will be developed.

Background on control theory

To give the reader a brief understanding of the various control types that will be referred to in this section, a basic background of control theory will be discussed.

Proportional control

Consider proportional control as illustrated in Figure 33. The goal is to keep the process output (PV) fairly close to the set point (ST). If the K_p (proportional gain) value is too large, the system will become unstable. A very small K_p will lead to a less responsive system. The system control action taken to correct the disturbance will be too small in this case.

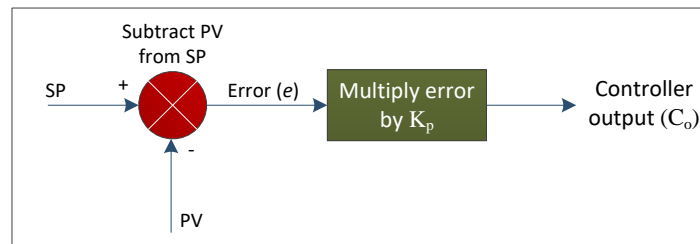


Figure 33: Proportional control

With proportional control, the controller output (C_o , also process input) is simply determined by multiplying the error (e) with the proportional gain (K_p). The error is represented by Equation 1.

$$e = SP - PV \quad \text{Equation 1}$$

To manipulate the process input (or controller output, C_o) in proportion to the error (e), Equation 2 can be used.

$$C_o = K_p (SP - PV) \quad \text{Equation 2}$$

Integral control

The integral component can be referred to as the reset action and is the sum of the error over time. The purpose of the integral component is to drive the steady state error to zero over a certain time. The integral action occurs after the proportional action. An illustration of the integration is illustrated in Figure 34.

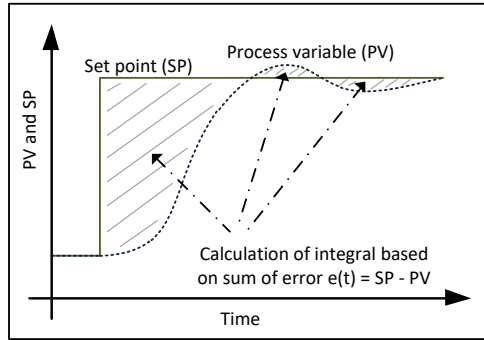


Figure 34: Integral gain example illustration

A very slow reset rate will cause the control to be very inactive, and if the process is subjected to recurrent disturbances, the set point might not ever be reached. A fast reset rate will cause the process value to continuously overshoot the set point, resulting in reset windup. Reset windup is the occurrence of oscillation around the set point. Reset windup usually occurs when the reset action is faster than the process response.

PI control

Combining proportional and integral control results in a fast control reaction. The added benefit is the compensation for the remaining system deviation. PI control is illustrated in Figure 35.

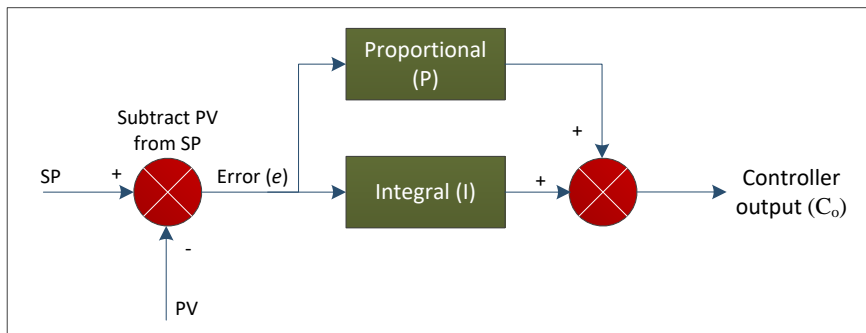


Figure 35: PI control diagram

In the case of PI control, the control output is determined by Equation 3.

$$C_o = K_p E_p + K_i E_i (SP - PV) \tag{Equation 3}$$

Using Equation 3 and substituting for E_p , the equation now becomes (Equation 4):

$$C_o = K_p (PV - SP) + K_i (E_i + (PV - SP)dt) \tag{Equation 4}$$

where E_i is the integral error.

Tuning

The gains of a PI controller are obtained through trial and error. Once an engineer grasps the significance and functioning of each gain parameter, the method becomes easier. Often, engineers need to trade off one characteristic of a control system for another to better meet their requirements.

Now that the basic control definitions have been explained, the new control emulation approach can be developed. The simulation model will also be developed and adapted to supplement the new approach.

3.4.2. Transient response control emulation and approach

The development and alteration of the new simulations will now be discussed. A new set of controllers has previously been developed for PTB. These controllers are:

- Step controller;
- PI controller;
- Maximum converge controller;
- Minimum converge controller; and
- Average converge controller.

The functioning of the controllers and the alterations to their functioning will be discussed in this section.

Step controller

The step controller allows the simulation engineer to define a maximum of five on and off steps. This controller is especially useful when the engineer requires a control output of either a 0 or 1. The step controller is therefore not for variable control. A PI controller can be used in this case, but will be discussed later in this section.

The inputs required for the step controller are listed in Table 12. The description of each input is also explained. The exact functioning of the step controller will be shown in Chapter 4. The step controller is mostly used in applications for dewatering pumps. These controllers can be used on any mass flow component.

Although the functioning of the step controller is unique in PTB, and uniquely adapted for this thesis, a controller can be developed in other packages using similar models.

Table 12: Step controller inputs – control emulation

Input name	Input	Description
Number of steps	Integer	Defines the number of steps (ex. maximum five)
Slope	+1	C _o increases with an increase in C _i (vice versa)
	-1	C _o increases with a decrease in C _i (vice versa)
Maximum start	Integer	Max _{start, input} < Max _{stop, input} & L _i < Max _{start, input} then control activated
		Max _{start, input} > Max _{stop, input} & L _i > Max _{start, input} then C _o = 1 control deactivated
Maximum stop	Integer	Max _{start, input} < Max _{stop, input} & L _i < Max _{start, input} then C _o = 0 and control deactivated
		Max _{start, input} > Max _{stop, input} & L _i > Max _{start, input} then control activated
Minimum start	Integer	Min _{start, input} < Min _{stop, input} & L _i < Min _{start, input} then C _o = 1 and control deactivated
		Min _{start, input} > Min _{stop, input} & L _i > Min _{start, input} then C _o = 1 and control deactivated
Minimum stop	Integer	Min _{start, input} < Min _{stop, input} & L _i > Min _{stop, input} then control activated
		Min _{start, input} > Min _{stop, input} & L _i < Min _{start, input} then C _o = 0 and control deactivated
Limit input	Any component output	L _i – limit input connector on the step controller

PI controller

The PI controller allows the simulation engineer to have a control output signal that ranges between 0 and 1. The PI controller can be used in any application where a variable output is required. An example of this is using the controller for simulating VSDs on auxiliary pumps or actuated control valves. The PI controller inputs are illustrated in Table 13.

Table 13: PI controller inputs – control emulation

Input name	Input	Description
Control limit 1	Integer	Limit 1 – used to calculate proportional gain (CL ₁)
Control limit 2		Limit 2 – used to calculate proportional gain (CL ₂)
Integral gain		Integral gain value of controller – high value = fast control, low value = slow control
Minimum output		Minimum control output value between 0 and 1 and C _o will be limited to this value
Set point		Control set point for each time period

CL₁ and CL₂ are used to calculate the proportional gain (K_p). The calculation of the proportional gain is shown by Equation 5.

$$K_p = \frac{1}{CL_2 - CL_1} \tag{Equation 5}$$

A positive proportional gain will result in a control output increase when the control input increases. A negative proportional gain will result in a control output increase when the control input decreases. The integral gain must be selected for each application. However, default values will be determined for the validation of this study.

Maximum converge controller

The maximum converge controller converges four inputs to one output control signal. Four various controllers can therefore be connected to one component’s control. The equation used to calculate the maximum control output is shown by Equation 6.

$$C_o = \text{Maximum} (C_{i1}, C_{i2}, C_{i3}, C_{i4}) \quad \text{Equation 6}$$

Minimum converge controller

The minimum converge controller functions in a similar fashion as the maximum converge controller. However, the controller converges four input signals to calculate one minimum output. The equation used to calculate the minimum control output is shown by Equation 7.

$$C_o = \text{Minimum} (C_{i1}, C_{i2}, C_{i3}, C_{i4}) \quad \text{Equation 7}$$

Average converge controller

The average converge controller converges four input signals to one average output. The function used to calculate the average converge controller output is illustrated by Equation 8.

$$C_o = \text{Average} (C_{i1}, C_{i2}, C_{i3}, C_{i4}) \quad \text{Equation 8}$$

All the above-mentioned controllers can now be used in the method development for the control emulation of components and systems. The control emulation approach was developed first. The control emulation approach is illustrated in Figure 36 and is referred to as approach P-10.

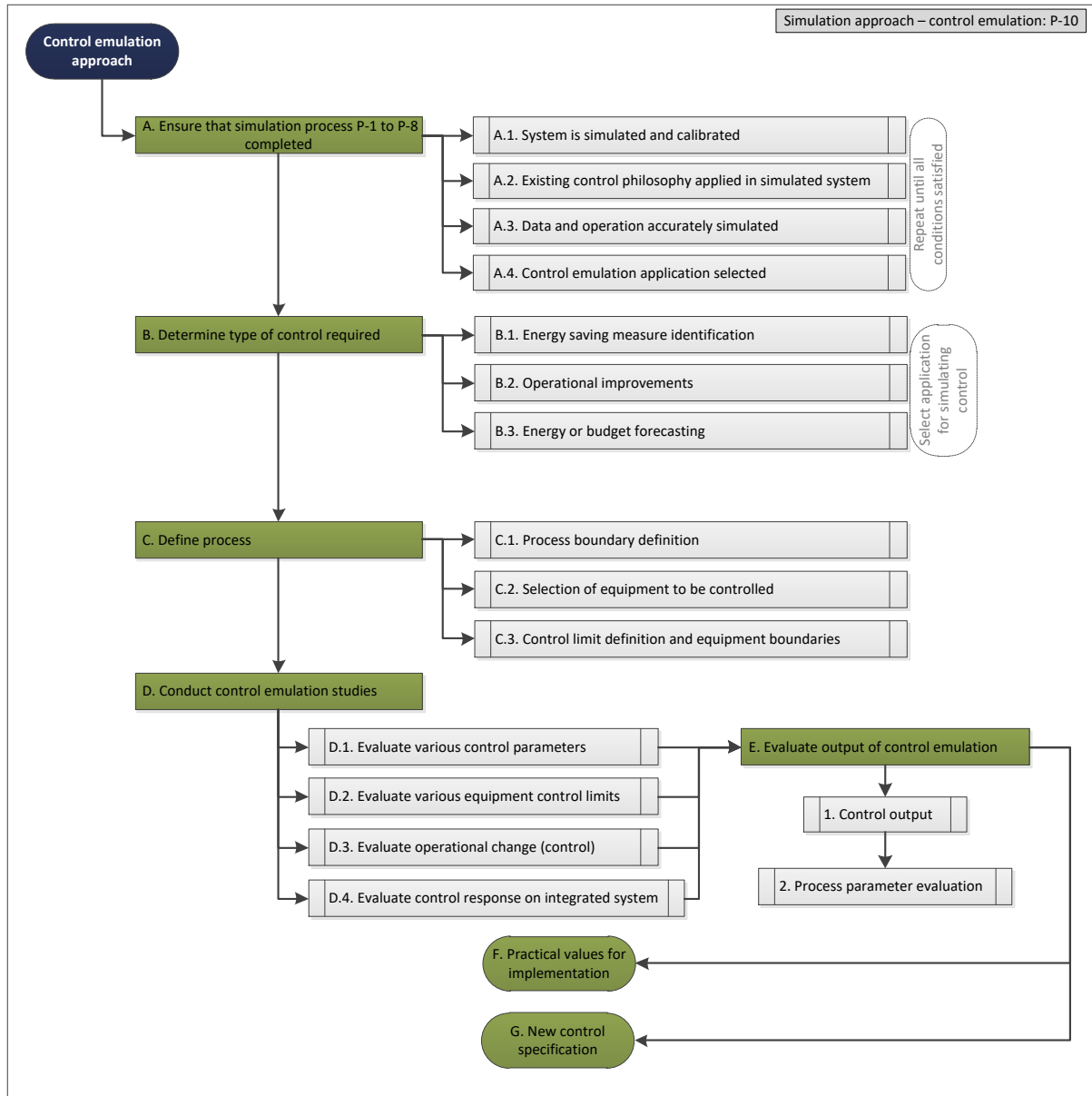


Figure 36: Simulation approach – control emulation overview (reference: P-10)

The first procedure (Procedure A) in the approach is to ensure the completion of the simulation approaches P-1 to P-8. This procedure consists of four steps. The first step is to ensure the system is simulated and calibrated (A.1). The second step is to ensure the existing control specification of the system is applied in the integrated transient simulation (A.2).

The control specification can be determined by examining the existing system control limits, set points, process parameters governing the control and the equipment limitations. This should be documented in the project investigation phase. The third step (A.3) is to ensure the process data and operation are simulated accurately and that it reflects the actual system. The final step (A.4) is to select the control emulation application from approach P-1.

Procedure B is to select the type of control required for the application. The four options are:

- B.1: Identify energy saving measure identification;
- B.2: Do operational evaluation and improvements;
- B.3: Do dynamic energy forecasting; and

An approach will be developed for each of the applications. The approach will also include the control emulation studies in each scenario. After the type of application has been selected, the process definition can start (Procedure C). From the completed simulations, the process boundaries need to be defined (C.1).

The second step (C.2) is to select the equipment that will be controlled as well as the equipment that will be indirectly affected by the control. The final step (C.3) is to identify the control limits of the equipment that will be controlled. This includes for example, the maximum stops/starts, minimum speed for effective operation etc.

The control emulation studies can now be conducted (Procedure D). The detailed development of the studies will be discussed in the next section. The evaluation of various control parameters is the first application (D.1). Secondly, the various equipment control limits need to be evaluated through the simulations (D.2). The third step (D.3) is to evaluate the need for operational changes and determine the impact thereof. Finally, the control response of the integrated system needs to be determined (D.4).

The last step is to evaluate the output of the selected application (Procedure E). The control output (E.1) needs to be analysed. The process parameters (E.2) also need to be considered. The practical values for implementation have been determined (F) and the new control specification can be presented (G).

The new general approach to the control emulation for MCSs has been developed. From the approach, it is now required to develop the models for emulating the control for each application. The final process from the control emulation to practical implementation will also be developed.

3.4.3. Develop practical control from the simulation process

The control emulation approach has been developed in Figure 36. As Procedure A and Procedure B were discussed in Section 3.3, the development of the practical approach for

control emulation will be done in this section for Procedure C and Procedure D in Figure 36. Procedure C and Procedure D have to be iterated to determine various control configurations. The output can then be evaluated as discussed in Procedure E.

Process definition (Procedure C)

The first step in the process definition procedure is to define the process boundary for emulating control. This process contradicts the integrated approach. However, the control that will be determined can easily be implemented later in the system simulation and adapted accordingly.

Process boundaries must be selected for various components. A typical selection of a process boundary for a simplified pumping system is illustrated in Figure 37. The figure illustrates a mass flow into and out of the system. This is the start and end points of the system (known as the process boundaries). Similar process boundaries can be selected for all sub-systems of an MCS (such as illustrated in Figure 11 in Section 2.2.2).

A process boundary can therefore be defined between two system buffers, such as the dams in the case of Figure 37. The reason for the sub-system definition is to enable the simulation engineer to define the sub-system first, study the effects of the control on the relevant equipment, and then identify start values for the integrated system control of the same sub-system. The control might differ between the two simulated systems.

The next step (C.2) involves selecting the equipment to be controlled. This is significantly dependent on the application of the simulation. The relevance of this procedure will be illustrated in Chapter 4 and Chapter 5. In the case of the illustrative example above, the equipment that can be controlled is either the actuated valve or the pump set.

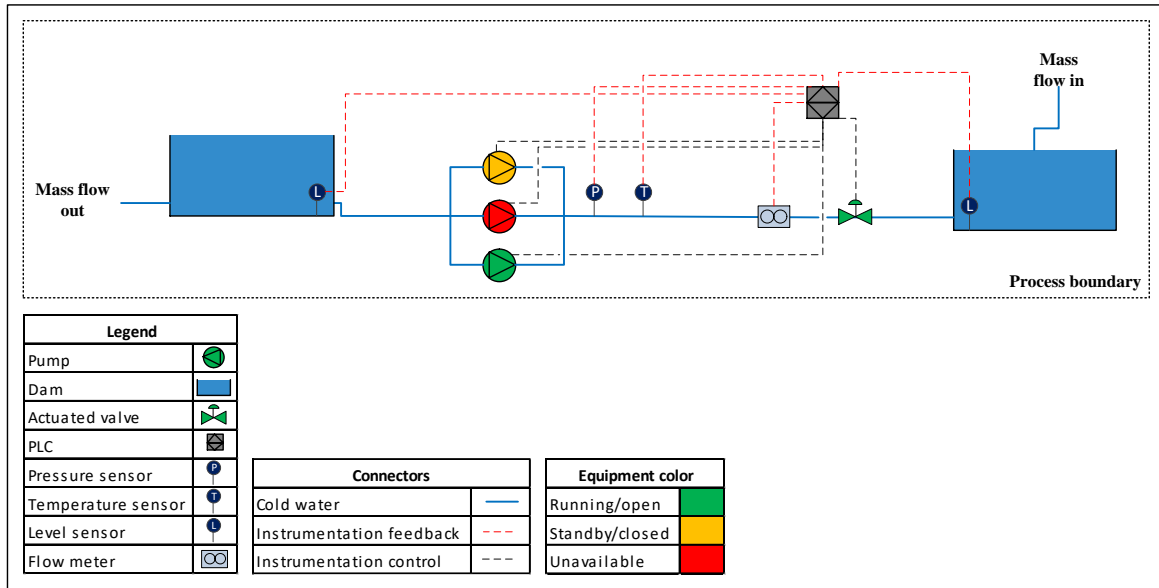


Figure 37: Process boundary definition – pumping system

The next step is to define the component control limits and boundaries. The component control limits for Figure 37 include the dam capacity for control, the pumping head and the possible valve restrictions. The various component control limits for equipment in a typical MCS are illustrated in Table 14. Considering the equipment control limits below, and the process boundaries, the control emulation studies can be started (Procedure D).

Table 14: Various component control limits

Component	Control limit
Chillers	Min., max. flow
Ice plants	Min., max. flow
Pumps	Min., max. pressure
	Min., max. flow
Fans	Min. fan flow
Turbine	Min. and max. flow
	Max. pressure head
3CPFSS	Min., max. flow
	Min., max. pressure
Dam	Min., max. level
Cooling tower	Min., max. airflow
	Min., max. water flow
MCUs	Min. airflow
	Min. water flow
BACs	Min. airflow
	Min. water flow

Control emulation studies (Procedure D)

The first step in the control emulation studies is to evaluate various control input parameters (D.1). A new approach was developed to evaluate various control parameters. The control parameters that are typically applicable to MCSs are:

- Ambient temperature or enthalpy;

- Mass flow demand;
- Water demand temperatures;
- Dam levels; and
- Water pressures;

These parameters need to be evaluated for all the various applications, and also differ from equipment and their relevant sub-systems. A visual representation of the control parameters that can influence a generic component in an MCS is illustrated in Figure 38. To evaluate the control parameters of a specific system, a simulation model is required.

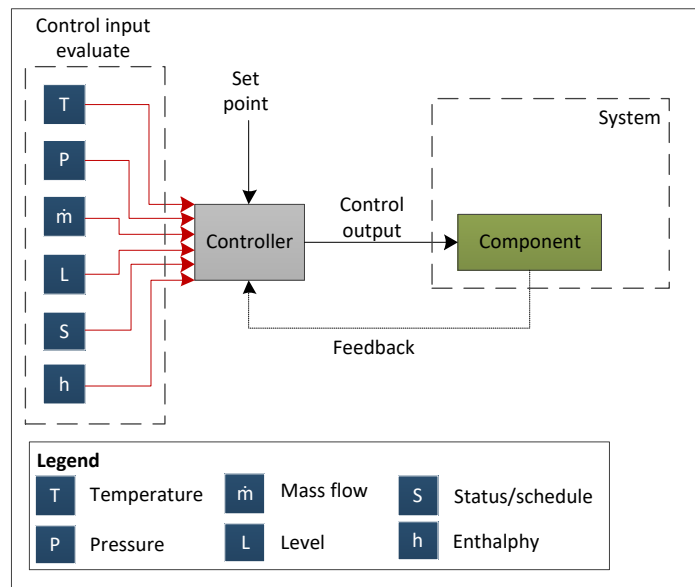


Figure 38: Control parameters influencing a generic MCS component

The various control parameters influencing the process boundary must be simulated. However, there are industry best practices to consider. These parameters and control must first be evaluated. The control emulation parameters can be evaluated by inspecting the controller output for each control parameter and by determining the relevance of the parameter.

Thereafter the P or the PI values can be determined for each of the controllers in the system. Numerous simulations can be iterated to determine the best parameters. The process to follow is therefore:

1. Ensure simulated model is correct per the procedure developed in Section 3.3;
2. Simulate the selected process boundary with various control parameters;
3. Compare the process and control outputs of the various parameters; and

4. Select the best control parameter and determine the P or PI values.

The determined values can then be prepared for the process engineer as a guideline when implementing the control that has been emulated (Procedure F and Procedure G). An example of the format in which the control and parameters can be presented is illustrated in Figure 125, Appendix VI. An example of a control specification for a BAC sub-system is illustrated in Figure 126, Appendix VI.

3.4.4. Summary

The new control emulation approach and model were developed in this section. With the new approach, various equipment control parameters as well as control output can be determined in the same simulation model used for integrated transient simulation. With the new model, the process boundaries can be determined and the range of equipment control can be inserted in the simulation. The focus of the new control emulation model is specifically for energy management; however, operational evaluation and control changes studies can also be conducted with the same simulation controllers and approach.

After the control studies have been conducted, the control specification of the equipment can be supplied to a project engineer. This approach and model will significantly reduce the implementation time of a project. The effect of the new model and approach will be evaluated in Chapter 4 and Chapter 5. The following section focuses on the model development for new applications for the developed models and approach.

3.5. Dynamic energy forecasting with the simulations and approach

The development of new integrated simulations with the ability to simulate transient response of systems allows the simulation engineer to apply the models to various applications. A new approach therefore also needs to be developed for the application of dynamic energy forecasting relating to energy management of MCSs. There are also numerous other applications for the new models.

The new approach to dynamic energy forecasting is illustrated in Figure 39. The approach starts (Procedure A) with the simulation process P-1 to P-8 (discussed in Section 3.3) already completed. This means that:

- The system is simulated and calibrated,

- The existing control philosophy is applied in the simulated system,
- The data and operation are simulated accurately, and
- The dynamic forecasting application is selected.

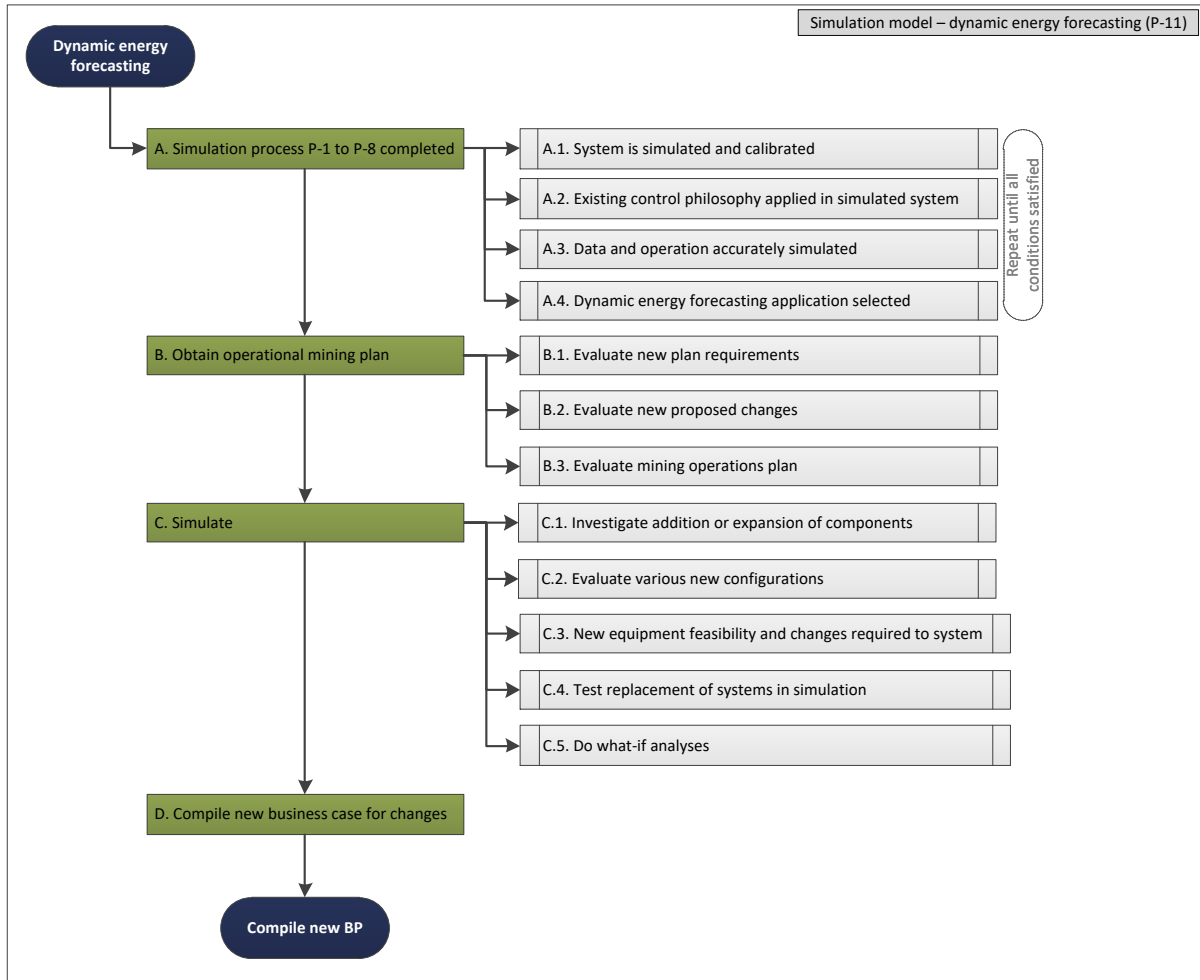


Figure 39: Simulation approach – dynamic energy forecasting (reference: P-11)

The second procedure involves obtaining the operational plan (Procedure B). This plan can easily be obtained from the mineshaft engineer. The simulation engineer can then evaluate, with the inputs of the shaft engineer, what the new requirements (B.1) for mining activities will be. This can be any of the following factors:

- The expansion or closure of certain mining levels;
- The mining water and ventilation requirements on certain levels; and
- Changes in service delivery requirements etc.

The new operational plan can then be evaluated (B.2) and the proposed changes can be simulated in the integrated system simulation. The simulation process of these changes is

shown by Procedure C. With these simulation studies, the effect on the overall energy consumption of the MCS needs to be determined. This can potentially influence the new financial budgets for the next financial year.

The addition or expansion of components can be investigated (C.1). This can be investigated by duplicating the required systems or adding the preconstructed models into the simulation and evaluating the effect on the service delivery as well as energy consumption. Various new MCS configurations can also be evaluated (C.2). The feasibility (financial and process-related) of installing new equipment and process-related changes to the system can also be simulated (C.3). The replacement of systems in the simulation can be tested (C.4). Additionally, a what-if analysis can be conducted with the operational plan (C.5).

The final procedure in this approach (Procedure D) is compiling a new business case and plan for any changes that are feasible. These evaluations, however, have to be seen as prefeasibility studies. A final in-depth study considering capital expenditure, other resources and operational risks must be conducted.

The new dynamic energy forecasting procedure will allow the simulation engineer to determine the impact of any changes to the integrated system. Part of the impact on a system is the effect on energy consumption. An additional application for the new simulation model and approach can be the ability to conduct M&V studies on ESM projects on MCSs. This approach was, however, not developed, but can be developed in future studies.

3.6. Summary

Chapter 3 focused on developing the new transient response simulation models and approach. The transient response simulation models were developed first with the focus on the integrated transient response simulations. In this model, various sub-systems were defined and preconstructed for use in the integrated system simulations. Significant focus was placed on reducing the simulation studies time to save resource costs. The models were unique and were adapted to suit the need for this study.

Thereafter, the new simulation approach was developed for using simulations for energy management of MCSs. The simulation approach was developed in various phases, and a model for each of the phases was developed. The new simulation approach is unique because

no integrated transient simulations were conducted in previous work, no approach or method could be identified. The simulation approach is therefore also unique.

A novel component control emulation method was developed. The control emulation method will allow the simulation engineer to emulate control of various applications on the MCS to determine the integrated effect on the process control and energy consumption. These effects ultimately influence the energy management of the MCS. The new component control emulation method can lead to reduced implementation time of projects.

New applications were also identified and are now possible due to the new simulation models and approach. These applications include what-if analyses and dynamic energy forecasting for mining operations. However, the simulations for these applications are mostly conducted as prefeasibility studies.

Most of the procedures and approaches developed in this chapter will be demonstrated by an illustrative example and case study in Chapter 4 and Chapter 5. The new models and approach will be verified in the following chapter.

4

CHAPTER 4

VERIFICATION OF THE NEW MODEL AND APPROACH

“Invention is the most important product of man’s creative brain. The ultimate purpose is the complete mastery of mind over the material world, the harnessing of human nature to human needs.”

~ Nicola Tesla (Inventor)

4. VERIFICATION OF THE NEW MODEL AND APPROACH

4.1. Preamble

In the previous chapter, the new models were developed for the integrated transient response simulations as well as the new approach for energy management of MCSs. The transient response model and approach need to be verified and validated to prove the integrity and applicability of the model.

Verification, in general, refers to a process where inspection and reviews are carried out to ensure that the developed model or system was established with adequate accuracy [38]. Validation, in contrast, means that the developed model or system meets the needs and objectives as identified in Chapter 1. The purpose of Chapter 4 is to verify the models of the novel contributions of this study.

The novel contributions were defined in Chapter 1 as:

1. Transient response simulations to uniquely integrate MCSs for energy management.
2. Novel transient response simulation approach for integration of MCSs.
3. Unique control emulation approach with integrated transient response simulations for energy saving measures on MCSs.
4. New dynamic energy forecasting applications for MCSs through transient response simulations.

Modelling the MCSs in a transient fashion presents a problem too complex to verify with analytical solutions. However, the ability to simulate steady state and transient effects with the new simulations and approach has to be verified. Numerical, mathematical and experimental methods are known methods to analyse such a complex system in a simpler fashion [88].

Experimental results for comparing the new simulation model and approach are very limited. The validity of the results for the complex problem of integrated transient simulations is therefore questioned. To address these questions, a simpler system is considered first. In the publications reviewed for the literature study, it was found that PTB has adequate functionality to simulate the various surface refrigeration and dewatering systems individually.

In these publications, the basic models used were verified [23, 42]. However, the integrated transient response and approach still require verification. For verification purposes, the various new models and approaches will be verified by comparing the simulated results with an actual MCS. The verification and validation will be done for each new model as developed in Chapter 3.

4.2. Transient response simulation model and approach verification

A deep-level gold mine was selected for the simulation model verification. The mine is named Mine P due to confidentiality agreements. The mine has a shaft depth of 2 600 m and produces approximately 3.3 tonnes of gold per annum. Mine P is a marginal mine, which is a mine that is barely profitable. It was selected due to the simplicity of the systems and present operation. Mine P furthermore stores all the most important data with reasonably accurate measurements.

Additionally, Mine P has already implemented various energy and cost saving initiatives, with the information and background of these initiatives readily available and well documented. As discussed in Chapter 3, the new simulations must be able to integrate the entire MCS. The simulations must also be used to predict the effect of system changes and control on the MCS. These scenarios contribute to energy management studies that can then be conducted.

These saving initiatives were implemented before developing the new simulations and can therefore be used in the comparison to verify the model. The following section focuses on the verification of the new models and approach by using Mine P.

4.2.1. Simulation approach

The energy and cost saving initiatives implemented on Mine P were reported in previous studies [14, 55]. The actual implemented system control as well as energy and cost saving initiatives were investigated. From the investigation, the simulation approach P-1 can be followed. The first step of the procedure was to select sub-systems for simulation. To verify this study, the integrated MCS will be simulated from the start.

Procedure B requires that system information be acquired. The system data (B.1) can be gathered from the SCADA system of Mine P. The SCADA system logs all data required for

the integrated system simulation. The manual logging procedure is therefore not required in this case. However, this might not be the case on other mines. Important simulation data was logged on the SCADA system in two-minute intervals. The data will be shown and discussed later in this section.

The system layouts (procedure B.2) were also compiled after system investigations. The simplified overview of Mine P's surface and underground MCS is illustrated in Figure 40. The illustration is divided into the surface system and the underground system. The system operation starts off with hot water entering the surge dam on surface at a temperature of 26 °C. During an average mining production day, 20 Mℓ water is pumped per day from underground to the surge dam.

The water is then pumped from the surge dam through precooling circuit 1 and precooling circuit 2, by using precooling pump 1 and precooling pump 2. Thereafter, water is transferred by the transfer pumps from precooling sump 2 to the hot dam. The temperature in the hot dam is approximately 12 °C. The precooled water from the hot dam is then pumped through a set of six chillers arranged in parallel configuration.

The chillers cool the water to a set point of 3 °C and the water is then stored in the surface cold dam. The combined nominal cooling capacity of the chillers is 36 MW. The combined coefficient of performance (COP) at nominal design conditions is 5.7. The chilled water is supplied to the three BACs by the feed pumps and returned to the hot dam after passing through the towers.

The remaining chilled water is sent underground through either a turbine or a dissipater valve situated on 38L. The water is then stored in the 39L cold dam at approximately 6.5 °C. From the 39L cold dam, the chilled water is supplied to the mining levels (44L to 70L). On each level, the water passes through a PRV station to reduce the water pressure to about 16 bar.

Thereafter, water passes through a control valve station and enters the relevant mining sections with a series of pipes and manual valves. The water is used for mining processes (as discussed in Appendix I), whereafter it is directed to the settlers on 75L where the water is collected in the 75L hot dam. From there, the hot water is pumped to the 38L hot dam by using the four 75L dewatering pumps. Next, the 38L dewatering pumps pump the hot water from the 38L hot dam to surface whereafter the process is repeated.

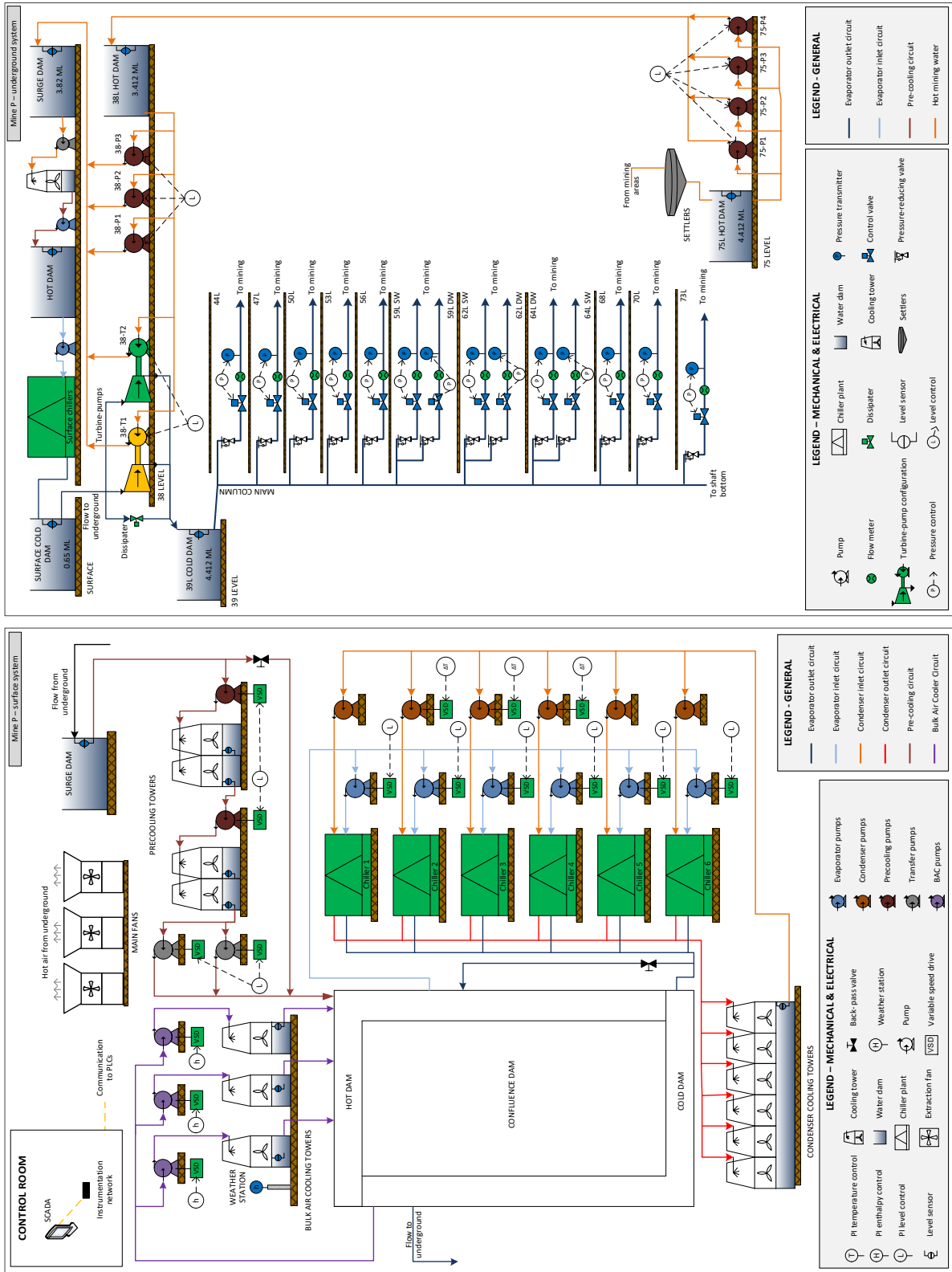


Figure 40: Mine P – surface and underground mine cooling process flow layout

Procedure B.3 involves acquiring the relevant system and component specifications. The equipment and specifications for the main equipment of Mine P's cooling system are illustrated in Table 15. The equipment specifications were used as input values for the simulation model. The simulation inputs will be discussed in the sections to follow.

Table 15: Equipment specifications of Mine P (adapted from [62])

Surface chillers (individual)	
Evaporator outlet temperature [°C]	3
Evaporator water flow rate [ℓ/s]	250
Condenser inlet temperature [°C]	27
Condenser water flow rate [ℓ/s]	450
Cooling capacity [kW]	6 500
COP [-]	5.0
Refrigerant [-]	R134a
Compressor type [-]	Centrifugal
Surface refrigeration water pumps	
Number of evaporator pumps [-]	6
Evaporator pump motor rating [kW]	110
Number of condenser pumps [-]	6
Condenser pump motor rating [kW]	160
Number of BAC return water pumps [-]	3
BAC return water pump motor rating [kW]	75
Number of precooling pumps [-]	2
Precooling pump motor rating [kW]	70
Number of transfer pumps [-]	2
Transfer pump motor rating [kW]	40
Surface cooling towers	
<i>BACs towers</i>	
Number of towers [-]	3
Water inlet temperature [°C]	3
Water outlet temperature [°C]	9
Water flow rate per tower [ℓ/s]	250
Air outlet temperature (wet bulb) [°C]	7
Air inlet temperature (wet bulb) [°C]	22
Airflow rate per tower [kg/s]	250
Fan motor rating [kW]	250
<i>Condenser towers</i>	
Number of towers [-]	6
Water outlet temperature [°C]	27.5
Water inlet temperature [°C]	31
Water flow rate per tower [ℓ/s]	450
Air inlet temperature (wet bulb) [°C]	22
Airflow rate per tower [kg/s]	266
<i>PCTs</i>	
Number of towers [-]	2
Water outlet temperature [°C]	24
Water inlet temperature [°C]	30
Water flow rate per tower [ℓ/s]	360
Air inlet temperature (wet bulb) [°C]	22
Airflow rate per cell (two cells per tower) [kg/s]	298

Table 16: Equipment specifications of Mine P continued (adapted from [62])

Combined surface plant	
Hot dam temperature [°C]	26
Chilled dam temperature [°C]	3
Combined COP [-]	5.5
Combined cooling capacity	39 000
38L equipment	
<i>Turbines</i>	
Number of turbines [-]	2
Flow rating [l/s]	200
Generator efficiency [%]	90
Turbine efficiency [%]	80
Rated capacity [kW]	2000
<i>Pumps</i>	
Number of pumps	3
Pump flow [l/s]	116
Pumping head [m]	1 163
Rated motor power [kW]	2000
Efficiency	0.75
Motor efficiency	0.95
75L equipment	
<i>Pumps</i>	
Number of pumps	4
Pump flow [l/s]	116
Pumping head [m]	1 163
Rated motor power [kW]	2000
Efficiency	0.75
Motor efficiency	0.95

Procedure B.4 requires the existing system control philosophy to be defined. The existing integrated system control philosophy is required to simulate the actual system accurately. The simulation engineer must understand the control of all system components to translate the actual system to the new simulation models.

As mentioned previously, various energy and cost savings initiatives were implemented on Mine P. The initiatives are implementing variable flow control, load shifting and scheduling of equipment and water supply control. The various initiatives will now be discussed and the existing control combined with these initiatives.

Variable flow control

An energy services company implemented a DSM project on the auxiliaries of the surface cooling system of Mine P. VSDs, and therefore variable flow control, was implemented on the surface system. The aim of the project was to realise a daily energy saving of 40.8 MWh. The control parameters of the implemented variable flow control strategies are illustrated in Table 17.

The various parameters and control limits were established with practical commissioning tests. However, this was a trial-and-error approach. The control parameters listed in Table 17 will be also be used in Section 4.2.4 to verify the new component control emulation method.

Table 17: Control of the surface refrigeration system auxiliaries of Mine P [62]

Description	Implemented control
<i>Transfer pumps</i>	
Minimum VSD frequency [Hz]	20
Maximum VSD frequency [Hz]	50
Dam level set point [%]	80
Control	Variable flow
<i>Precooling pumps</i>	
Minimum VSD frequency [Hz]	37
Maximum VSD frequency [Hz]	50
Dam level set point [%]	85
Control	Variable flow
<i>BAC pumps</i>	
Minimum VSD frequency [Hz]	31
Maximum VSD frequency [Hz]	45
Minimum water flow [ℓ/s]	82
Maximum water flow [ℓ/s]	225
BAC air outlet temperature [$^{\circ}\text{C}$ wet bulb]	< 8
Control	Variable flow
<i>Evaporator pumps</i>	
Minimum VSD frequency [Hz]	37
Maximum VSD frequency [Hz]	45
Minimum water flow [ℓ/s]	190
Maximum water flow [ℓ/s]	253
Cold dam level set point	75
Control	Variable flow
<i>Condenser pumps</i>	
Minimum VSD frequency [Hz]	36
Maximum VSD frequency	45
Minimum water flow [ℓ/s]	350
Maximum water flow [ℓ/s]	435
Condenser temperature difference set point [$^{\circ}\text{C}$]	3.5
Control (three pumps only)	Variable flow
<i>Refrigeration plants</i>	
Chilled water temperature [$^{\circ}\text{C}$]	3

Load shifting and scheduling of dewatering pumps and turbines

A load-shifting initiative was implemented on the 38L and 75L dewatering pumps of Mine P. Pump scheduling is primarily done by using upstream dam level control. As an additional safety measure, the maximum number of pumps is limited according to the downstream dam level. The pumping system is also scheduled to prevent pumps running during the Eskom morning and evening peak periods. The relevant dam level limits are illustrated in Table 18.

Table 18: Mine P – pumping system dam level control

No.	Dam	Minimum level [%]	Maximum level [%]
1	Surge dam	30	95
2	Hot confluence	30	95
3	Cold confluence	30	95
4	39L cold dam	55	95
5	75L hot dam	30	70
6	38 hot dam	30	95

The turbines on 38L use downstream control instead of upstream control to ensure that the cold water dam on 39L always has sufficient water for mining activities. The control philosophy for the turbines is illustrated in Table 19.

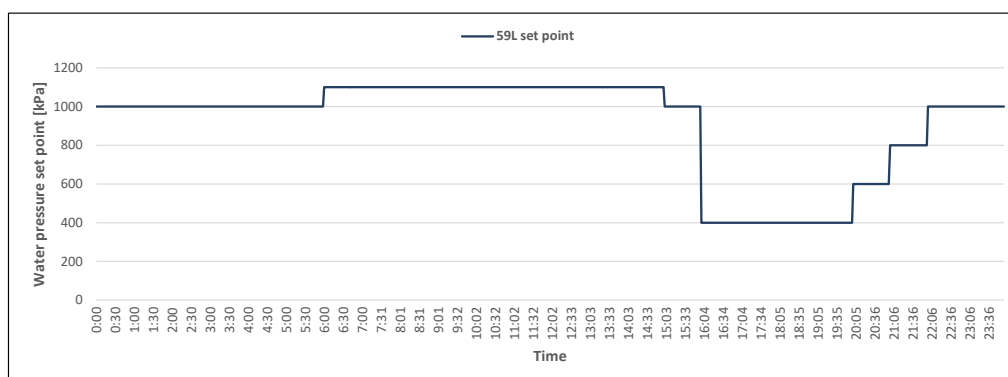
Table 19: Mine P – turbine dam level control

No.	39L dam level [%]	Number of turbines [-]
1	< 55	Start a turbine
2	< 60	Start a turbine
3	> 90	Stop a turbine
4	> 95	Stop a turbine

Water supply control

Through smart control and equipment retrofits, the efficiency of the water reticulation system was improved. The cold water supplied to levels 44L to 70L is also controlled by actuators on the relevant valves. These valves are controlled per a downstream pressure set point. The downstream pressure is therefore used as feedback and the valve is adjusted to match the downstream pressure with the set point.

The valves are controlled over a typical 24-hour period to match the water demand for a typical production day. An example of the water control of a typical production day is illustrated in Appendix I. The set points on each mining level differ, and are determined by mine personnel to match the intensity of production on the specific level. The water-pressure set point for 59L of Mine P is illustrated in Figure 41.


Figure 41: 59L water-pressure set point profile

Each of the mining level set points will be used to simulate the water consumption on the specific mining levels in the new simulations. The set point control is important because of the integrated effect the water demand has on the combined MCS. An alternative to this process is simulating the water flow to the levels by using the actual measured water flow.

Reducing the water consumption of the mining levels has a significant impact on the power consumption of the entire system. Accurate simulation of this type of control can therefore prove valuable for the simulation or energy engineer. The control parameters discussed above will be used to emulate the control already implemented on the system. A comparison of the actual control parameters and simulated parameters can be used to verify the component control emulation.

Simulation Procedure D and Procedure E of the combined simulation approach (P-1) will be omitted because the simulation application is not relevant in this section. The simulation project properties (Procedure F) will therefore be discussed in the next section.

4.2.2. Simulation model

Description

An integrated simulation model was constructed for Mine P. The simulation model that was developed is a dynamic integrated model that simulates the entire MCS in a transient fashion. The methods developed in Chapter 3 were applied and used in the simulation model to verify the requirements and effectiveness of the proposed solutions.

The simulation models were constructed in PTB and were adapted to be applicable to Mine P's configuration and systems. An illustrative summary of the energy management simulation model of Mine P is illustrated in Figure 42. The summary shows the dependency and interrelation of equipment and systems.

Mine P has a simple MCS, with most of the data illustrated in Figure 42 already logged on their local SCADA system. As illustrated, the cold, dehumidified ventilation air from the BACs is only considered up to the outlet of the BAC. Although the BAC has an overall impact on the mine ventilation, it was decided at the start of this thesis that only the BACs, spot coolers and underground BACs will be considered as part of the MCS.

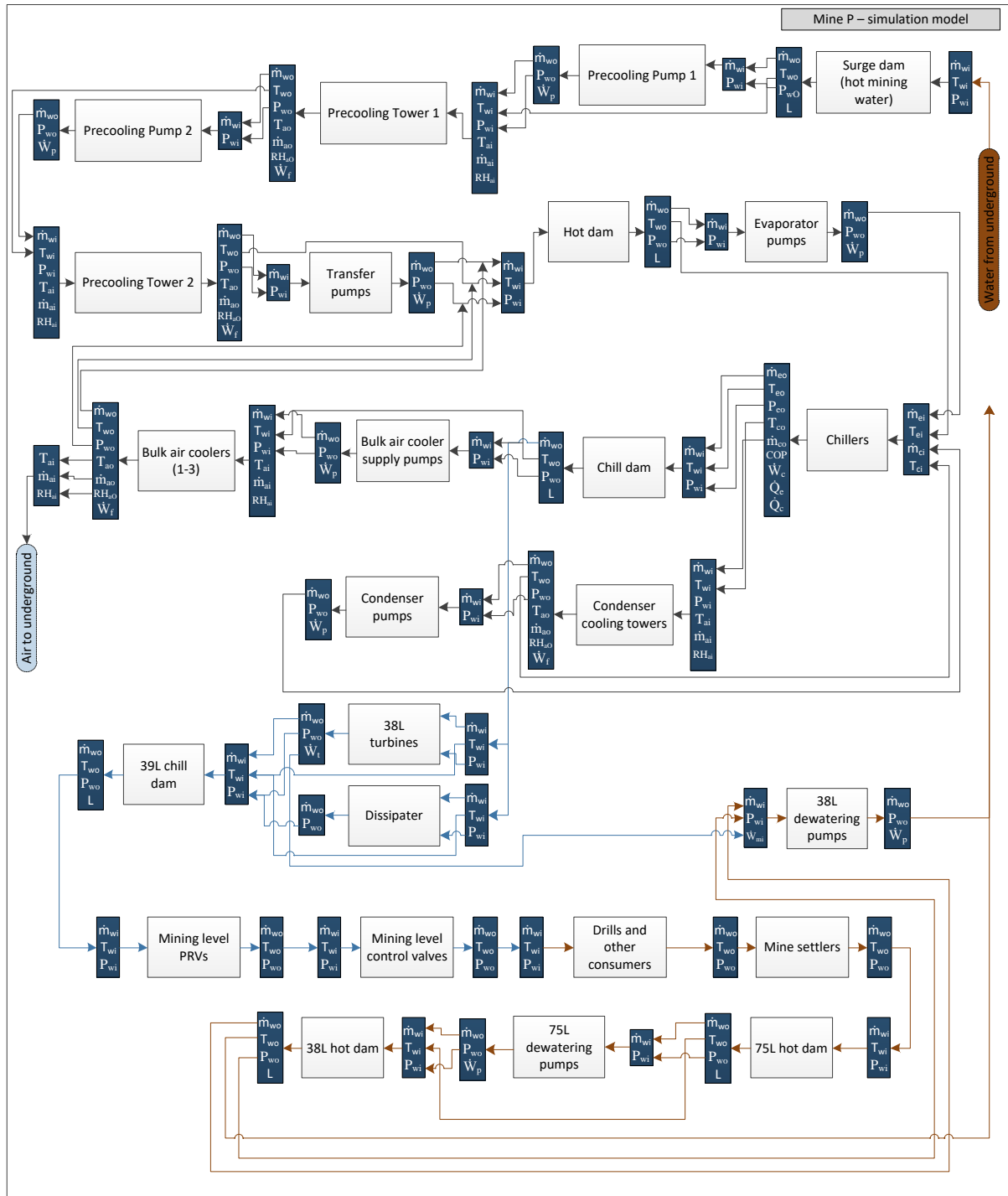


Figure 42: Illustrative summary of Mine P's simulation model

Model assumptions

The following assumptions were made for the integrated transient MCS simulations and comparisons to actual data:

- The selected typical mining day reflects normal operation;
- The readings from the measurement instruments are accurate enough to compare with simulated data; and
- The mass balance included constantly bleed off excess water to the gold plant.

As discussed during the development of new simulations in Section 3.2, certain model inputs are required. The model inputs and the relevant outputs were highlighted from Table 4 to Table 10 in Section 3.2.2. However, the new simulation inputs will also be discussed to show the relevance when comparing simulated and actual data. This will serve as a verification of the models developed in Chapter 3.

Simulation model construction

The simulation model can now be constructed by starting with Procedure F of the simulation approach P-1. This procedure involves selecting simulation properties. The simulation was conducted for verification; therefore, procedure F.1 is omitted. The second procedure (F.2) is determining the time periods for simulation. In this case, the simulation is conducted for 30-minute intervals with 120 time steps per time period to illustrate the transient effect. There are 48 time periods. However, the day was duplicated in the simulation to let the simulation settle.

The number of time steps (F.3) was selected as 120, but 60 time steps are the minimum number for transient simulations. The time period size (F.4) is selected as 1 800 to simulate the number of seconds in one time period. The simulation iterations (F.5) were selected as five water iterations and five air iterations. The periods were named according to the relevant time interval.

Table 20 illustrates the simulation data set, data parameters, and relevant components in the simulation, the data source, the logging interval and what the data set is used for. The simulation was conducted for one typical mining day. The specific mining day was selected by thoroughly analysing the data sets available to determine a typical day with normal equipment operation. The time period, time steps and time period size were therefore selected appropriately.

Table 20: Simulation data set information

No.	Data set	Relevant component	Parameter	Data source	Logging interval	Use
1	Weather data	Climate	$RH_{amb}, T_{DB}, P_{baro}$	Weather station	2 minutes	Simulation input
2	Dams	Simulated	L, T_w	PLCs, SCADA	2 minutes	Output verification
3	Chiller statuses	Chillers	S, T_{ei}, T_{ci}	SCADA	2 minutes	Output verification
4	Chiller power	Chillers	\dot{W}_c	Power meters	30 minutes	Output verification
5	Pumps	Pumps	\dot{m}_w	SCADA	2 minutes	Output verification
6	Pump power	Pumps	\dot{W}_p	Power meters	30 minutes	Output verification
7	Towers	Cooling towers	$\dot{m}_{wi}, \dot{m}_{ai}, T_{wi}, T_{ai}, RH_{ai}$	SCADA	2 minutes	Simulation input
8	Tower fan power	Cooling towers	\dot{W}_f	Power meters	30 minutes	Output verification
9	Turbine	Turbine	T_{wi}, \dot{m}_{wi}	SCADA	2 minutes	Output verification
10	Turbine power	Turbine	\dot{W}_t	Power meters	30 minutes	Output verification
11	Dissipater	Valve	T_{wi}, \dot{m}_{wi}	SCADA	2 minutes	Output verification
12	Mining levels	PRVs/valves	$P_{wi}, \dot{m}_{wi}, T_{wi}$	SCADA	2 minutes	Output verification
13	System power	All	\dot{W}_{total}	Power meter	30 minutes	Output verification

The next step in the new simulation approach is constructing the sub-systems with the new simulations. Procedure G.1 specifies that the predefined systems must be used first. This procedure was followed for all sub-systems of the combined MCS. The following systems were constructed with the predefined simulation models:

- Precooling circuit;
- BAC circuit;
- CCT as part of the condenser circuit model;
- Dewatering sub-system; and
- Turbine sub-system.

Some of the systems in the MCS of Mine P are unique and required new systems to be constructed. The new systems that were constructed included the following:

- Chillers sub-system (parallel chiller configuration); and
- Chilled water to mining levels (new PRV).

After the systems were constructed, the correct naming convention was followed. This allows the simulation engineer to easily refer to the relevant components and aids in fast and effective calibration. The new simulation model for Mine P is illustrated from Figure 116 to Figure 122 in Appendix III. The integrated screen shot could, however, not be shown due to illustration constraints.

Simulation model inputs

The simulation model requires various inputs. Most of the inputs were already logged by Mine P's SCADA system. The climate data for the selected mining day was extracted first.

The mine climate data is illustrated in Figure 43. The climate data was used for all 20 climate air pressure boundaries in the simulation.

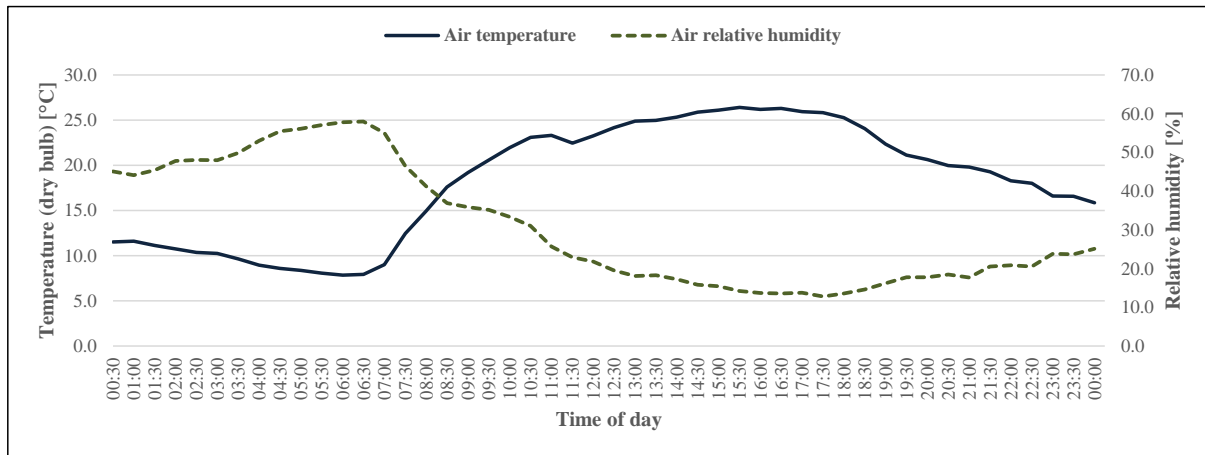


Figure 43: Simulation input – climate data

Climate data is an important factor when considering energy management of MCSs. The climate data for an average year must be used when the integrated system is simulated over all four seasons. The air pressure boundary (climate) calculates the enthalpy and wet-bulb temperature internally. This will be used in the actual data verification section.

The running schedules that were used for the chillers and chiller auxiliaries are shown in Table 21. The plant was not running at full capacity, which was mainly because of the low ambient temperatures and lowered demand for chilled water for the selected simulation day. However, the entire MCS was constructed in the simulation model to enable the simulation engineer to conduct further simulation studies where required.

Table 21: Simulation inputs – chillers and auxiliaries

No.	Component	Schedule
1	Chillers	1
2	Evaporator pumps	2
3	Condenser pumps	1
4	Condenser cooling fans	1
5	BAC pumps	1
6	BAC fans	1
7	Precooling pumps	2
8	Precooling fans	2
9	Transfer pumps	2

The running schedules for the turbines and pumps were also investigated from the actual data. However, the controllers were used to simulate the functioning of the dewatering pumps. The turbine running schedule is illustrated in Figure 44. The two periods where the

schedule are 0 is due to the load shifting on the pumping system of Mine P. During this period, water flow to underground was restricted to 0 ℓ/s .

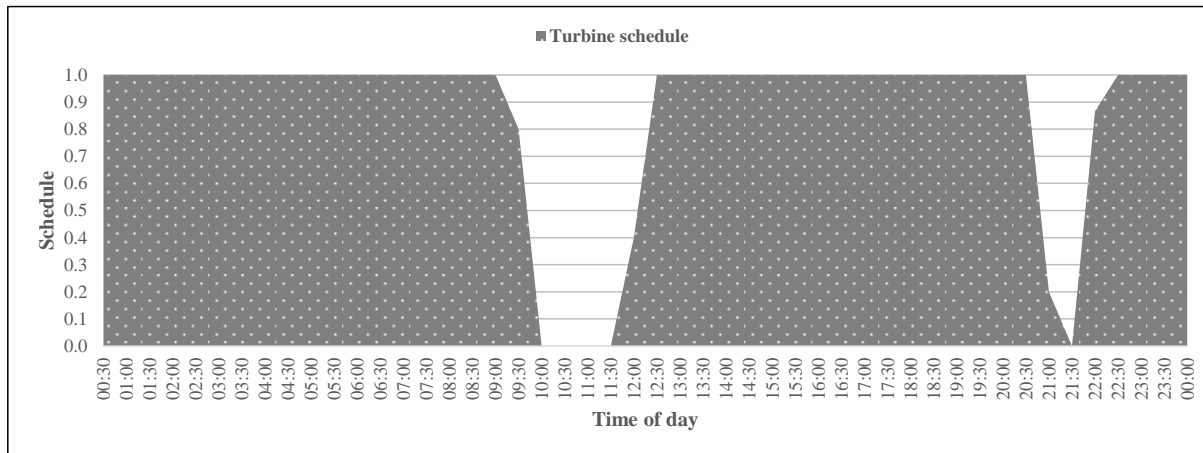


Figure 44: Simulated 38L turbine schedule

Additionally, the flows to the mining levels were inserted into controllers for each level. These inputs are illustrated in Table 47 in Appendix III. The inputs for all the controllers will be discussed in Section 4.2.4. After the inputs have been assigned to the relevant components in the simulation, the calibration procedure (I.1 to I.3 of P-1) can be started.

The next procedure in approach P-1 is to calibrate the various sub-systems (I.1 to I.3). Calibrating the integrated system ensures that the mass and energy balances of the simulated and actual systems are the same. This process is in itself a form of verification.

During the calibration procedure, numerous iterations of the integrated simulations are conducted. This process is repeated until the mass and energy balances (I.1 and I.2) are satisfied. The simulations for Mine P were iterated six times before the mass and energy balances were achieved.

An additional calibration of the component specifications is also required. This will differ depending on the software used for the integrated transient simulations. The relevant component specifications as stipulated in Table 15 were used to calibrate the components in the new integrated simulations.

After the calibration has been completed, the simulation can be run. Procedure J and Procedure M of approach P-1 were omitted because the integrated transient system has already been compiled. The simulation outputs will now be discussed.

4.2.3. Verification through actual data

Procedure I, Procedure J and Procedure M from the simulation approach P-1 were completed. The simulation was compiled and run with equipment specifications as specified in Table 15. The outputs and the verification with actual data will now be discussed. The first step in the verification process is determining if the simulated power of the integrated MCS compares accurately with the actual system power for the selected simulation.

The actual versus simulated power of Mine P's integrated MCS is illustrated in Figure 45. The simulated power was averaged for half-hour periods for the comparison with the actual power. As illustrated in Figure 45, the simulated power profile compares accurately with the actual instantaneous power of Mine P's system.

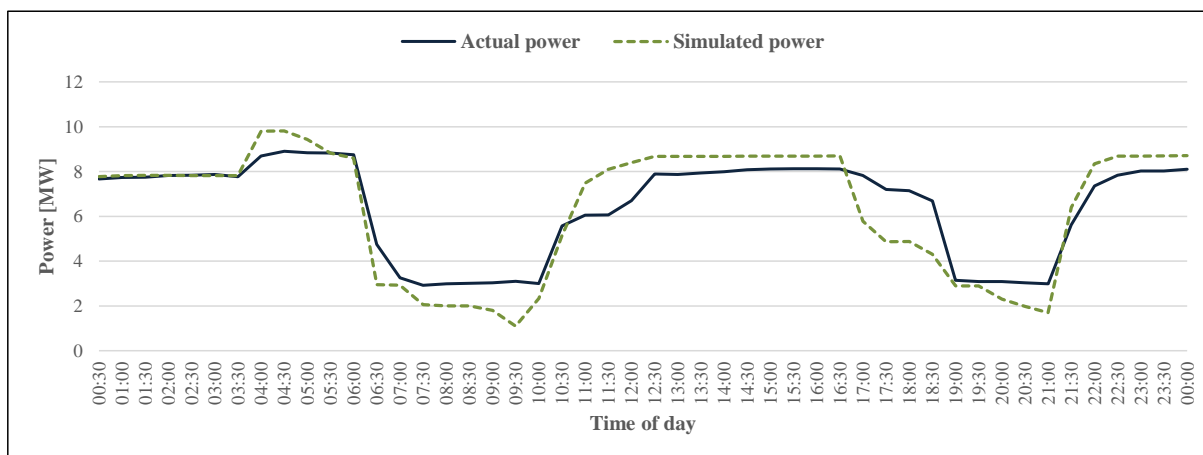


Figure 45: Actual versus simulated power of Mine P

The effect of the pumping load shifting is clearly visible during the periods from 06:00 to 10:00 and from 19:00 to 21:00. The simulated power, however, drops below the 2 MW lower limit, indicating an overshoot. However, this could also be interpreted as additional load-shifting capacity.

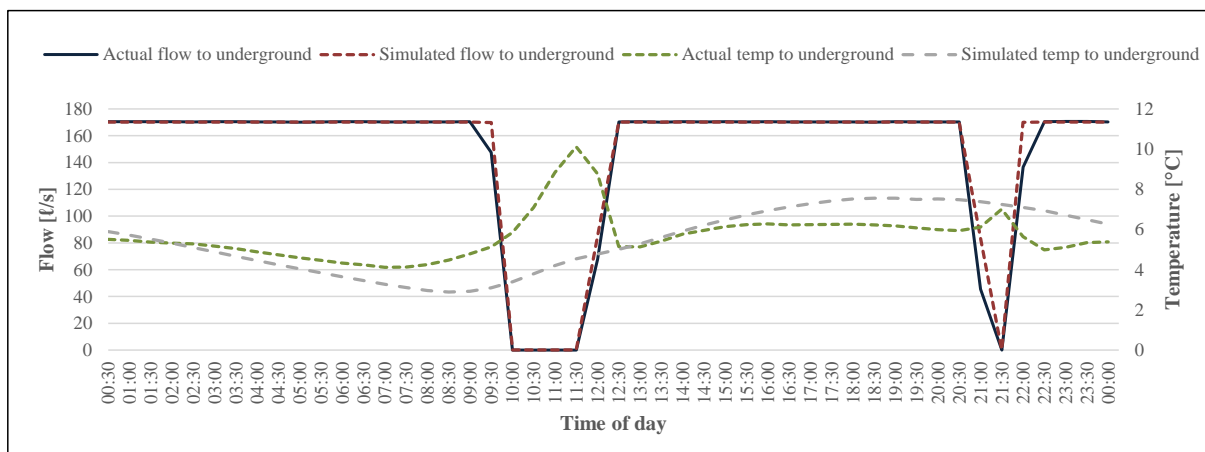
The average daily actual versus simulated power comparison is illustrated in Table 22. The average actual power was 6 464.94 kW for the selected day, whereas the average simulated power was 6 390.02 kW. The simulation error of the power consumed by the system was therefore 1.17%. The accuracy obtained was mainly due to the extensive calibration and verification of all equipment in the simulation.

Table 22: Actual versus simulated power comparison – Mine P

Average power comparison	Value
Actual [kW]	6 464.94
Simulated [kW]	6 390.02
Error [%]	1.17

Simulating the power of the integrated system with good accuracy is a requirement for the new simulation model and approach. Accuracy is required for detailed and precise energy management studies on MCSs. It is clear from Figure 45 and Table 22 that the MCS of Mine P was simulated accurately.

Additional simulation parameters also have to be verified to ensure that the simulation engineer can do the numerous energy management studies as discussed in this thesis. The next parameters to be verified are actual flow and temperature to underground. These parameters influence the service delivery of the simulated system. The actual versus simulated flow and actual versus simulated temperature to underground are illustrated in Figure 46.


Figure 46: Actual versus simulated flow and temperature to underground – Mine P

The actual flow and temperature data for the selected day was analysed and averaged for half-hour periods. As illustrated in Figure 46, the profiles for actual and simulated flow to underground are almost similar. These profiles are compared to ensure that the average of 147 l/s of water flow that is passed through the only running turbine is comparable with actual flows, and therefore comparable with the actual power generation capabilities of the turbine.

From 10:00 to 12:30, and again from 20:30 to 22:30, water flow to underground is restricted daily because of the interaction of the load-shifting project and the water control to the levels.

The initiative aims to ensure that there is enough cold water in the 39L cold dam for the various mining shifts.

It is also important to ensure that the hot water is ready for cooling on surface during these periods. This will be discussed in more detail later. The turbine was scheduled to stop during these periods as no water flow is required. A slight difference between the statuses of the turbine is noticeable in the water flow profiles.

The second parameter, which is the temperature of water to underground, is also illustrated in Figure 46. As the water flow to underground is stopped, the actual temperature peaks at approximately 10 °C due to the water being exposed to ambient conditions, with no more chilled water being added to the cold dam. This occurrence is also clear in the evening period when the water flow is 0 ℓ/s.

However, this was not the case in the simulated temperature to underground. The simulation models can simulate heat transfer through the water and air nodes. This function was not used due to various unknown variables. However, the heat transfer coefficient can be determined by calibrating the simulation and manual temperature measurements as well.

The average difference between the actual versus simulated flow and temperature to underground is illustrated in Table 23. The average daily actual flow was recorded as 146.69 ℓ/s, whereas the simulated flow was 148.81 ℓ/s. The relatively small error of 1.42% is due to the calibration of the turbine flow rating compared with the actual flow rating. The simulated turbine model and sub-system therefore permitted 2.11 ℓ/s on average more than the actual turbine.

The average actual and simulated temperature is also compared. The average simulated temperature of 5.48 °C compares accurately with the average actual temperature of 5.69 °C. The overall average simulation error is 3.85%, which is still a sufficient accuracy.

Table 23: Actual versus simulated flow and temperature to underground – Mine P

Parameter comparison	Value
Average actual flow [ℓ/s]	146.69
Average simulated flow [ℓ/s]	148.81
Error [%]	-1.42
Average actual temperature [°C]	5.69
Average simulated temperature [°C]	5.48
Error [%]	-3.85

The next parameter to verify is the 39L dam temperature. The 39L cold dam stores the water to be used by the various mining levels. The daily average actual and simulated 39L dam temperature is illustrated in Figure 47. The simulated dam temperature decreases significantly towards 10:00 due to the cooling effect as seen in Figure 46. The temperature then stabilises at approximately 4.5 °C for 2.5 hours.

This effect is mainly due to the increased flow demand between 07:00 and 12:30 when the water is used before a saturated temperature can be reached. However, the significant difference with the actual dam temperature can be explained by the heat transfer and ambient conditions close to the actual 39L dam. No manual measurements were taken to confirm this effect. It is, however, clear that the 39L dam reaches a fairly constant temperature. This effect will be explained further in Figure 48.

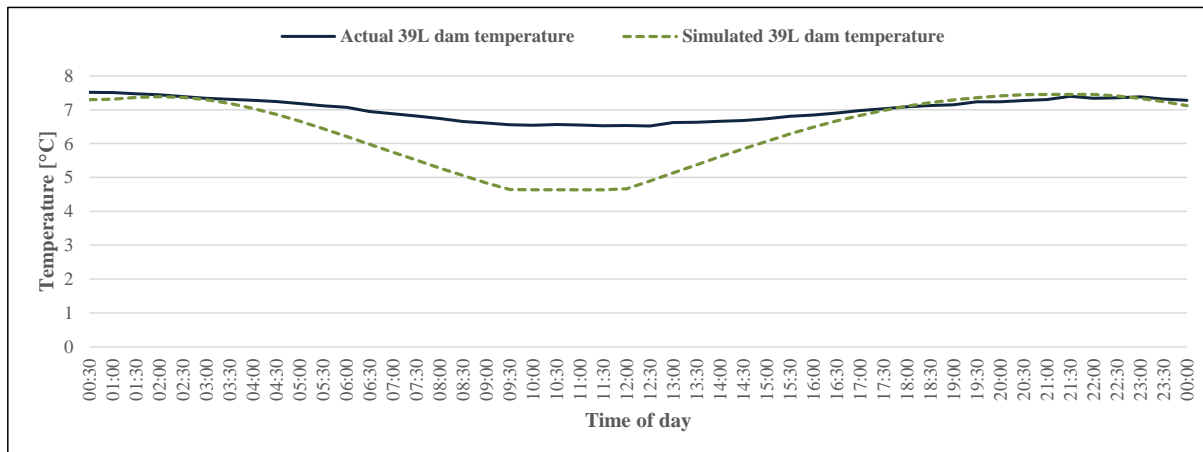


Figure 47: Actual versus simulated temperature of 39L cold dam – Mine P

Table 24 compares the actual versus simulated 39L dam temperature. The daily average actual dam temperature was 7.01 °C, whereas the simulated dam temperature was 6.38 °C. The average error between the simulated and actual dam temperature was found to be 9.96%.

Table 24: Actual versus simulated 39L dam temperature comparison – Mine P

Average 39L temperature	Value
Actual [°C]	7.01
Simulated [°C]	6.38
Error [%]	9.96

Figure 48 illustrates the actual versus simulated flows to mining levels. A reference was made earlier to the peak water demand between 07:00 and 12:30. The mentioned period is the peak drilling shift (as discussed in Appendix I). This is an additional reason for the lower simulated water temperatures as illustrated for the 39L cold dam.

The reduced water demand during the blasting shift, which is the period from 17:30 to 20:30, should also be noted. During this period, the water demand reduces significantly due to very limited to no mining activities consuming water. However, in most cases this can also be an indication of the baseload on the water system, consisting mostly of water leaks on the levels and a supply to MCUs. The actual and simulated flows are almost the same due to the implemented control in the simulation.

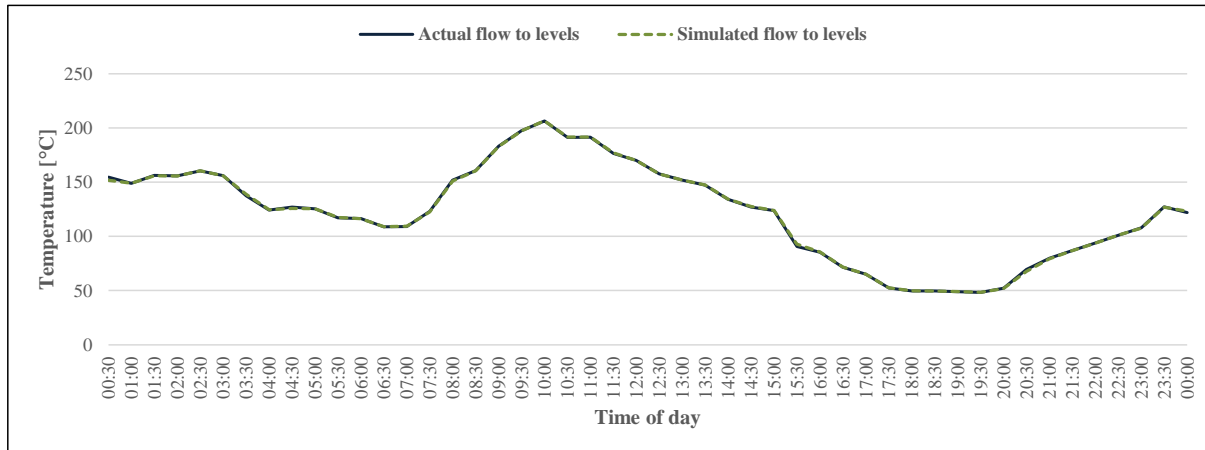


Figure 48: Actual versus simulated flow to mining levels – Mine P

The average daily actual versus simulated flow to mining levels is illustrated in Table 25. The actual and simulated flows to mining levels differed with 0.02% for the selected day. This is a very good accuracy and is crucial for doing informed energy management studies, whilst simulating the water distribution to mining levels accurately.

Table 25: Actual versus simulated flow to mining levels comparison – Mine P

Average 39L temperature	Value
Actual [ℓ/s]	122.75
Simulated [ℓ/s]	122.77
Error [%]	0.02

The actual versus simulated flow and temperature from the 38L hot dam to the surface surge dam is illustrated in Figure 49. As illustrated, the average actual and simulated water flow profiles are similar. However, the actual flow to surface is offset with approximately an hour compared with the simulated flow.

The offset effect is due to the simulated controller of the 38L dewatering pumps, which will be addressed later in this chapter. Additionally, the flow from the mining levels to the settlers in actual applications occurs over a series of days. The water flow from the mining levels is assumed to be at almost the same period as the water that is used.

It should also be noted that the water balance of the system indicated that approximately 16 l/s on average has to be pumped to the gold plant situated near the mine. This water can be defined as groundwater, which is also known as fissure water, and was assumed to be constant. The simulated and actual temperature to surface compared fairly accurately. The simulated temperature increases slightly during the day whereas the actual temperature remains almost constant.

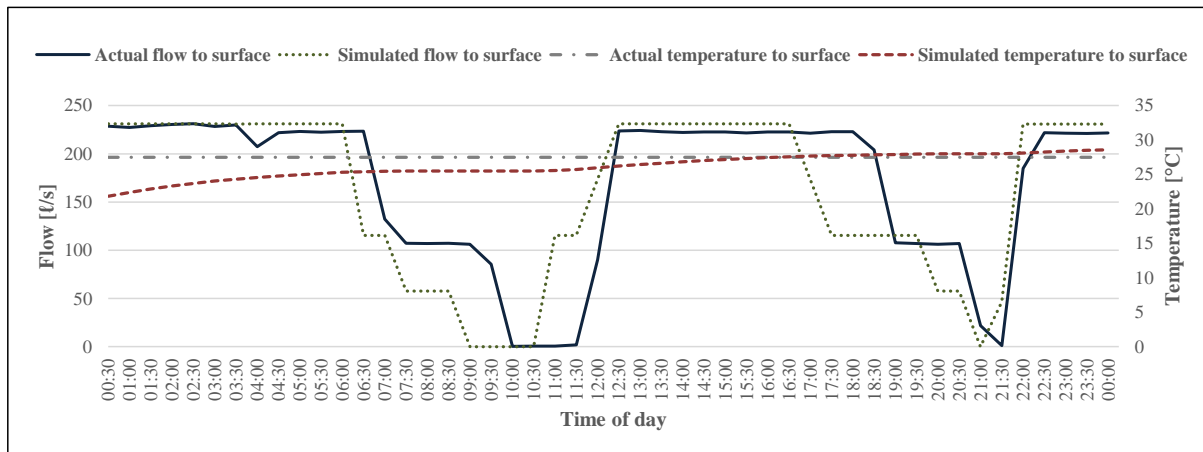


Figure 49: Actual versus simulated flow and temperature from 38L to surface – Mine P

The actual versus simulated flow and temperature from underground comparison is given in Table 26. The average actual flow dewatered to surface is 168 l/s, whereas the simulated water flow was 160.95 l/s. The difference is due to the simulated pumping characteristics that were estimated for the simulation. The percentage error of 4.38% can, however, be reduced by additional calibration of the 38L dewatering pumping sub-system.

The daily average actual temperature was determined as 27.51 °C, whereas the simulated temperature was 26.19 °C. The difference of 4.99% can be attributed to the heat transfer coefficient in the simulated dam not being similar to actual conditions. This is also an effect that needs to be considered throughout the entire system. However, with manual measurements, this effect can be quantified.

Table 26: Actual versus simulated flow and temperature from underground – Mine P

Parameter comparison	Value
Average actual flow [l/s]	168.00
Average simulated flow [l/s]	160.95
Error [%]	4.38
Average actual temperature [°C]	27.51
Average simulated temperature [°C]	26.19
Error [%]	-4.99

The next parameters to consider are the actual flow and air outlet temperature of the BAC. The actual BAC water flow was estimated from the available actual data and used as a constant value for comparison. Comparing the simulated and actual flow, the profiles are similar. The simulated BAC water flow stays fairly constant due to the type of control implemented.

This is also the case for the actual system. Only one BAC was operational during the evaluated day. However, an additional BAC should have been operational due to the air temperature often exceeding the allowable 7 °C dry bulb. When comparing the simulated and actual air outlet temperature, the new simulations predicted the BAC air outlet temperature accurately.

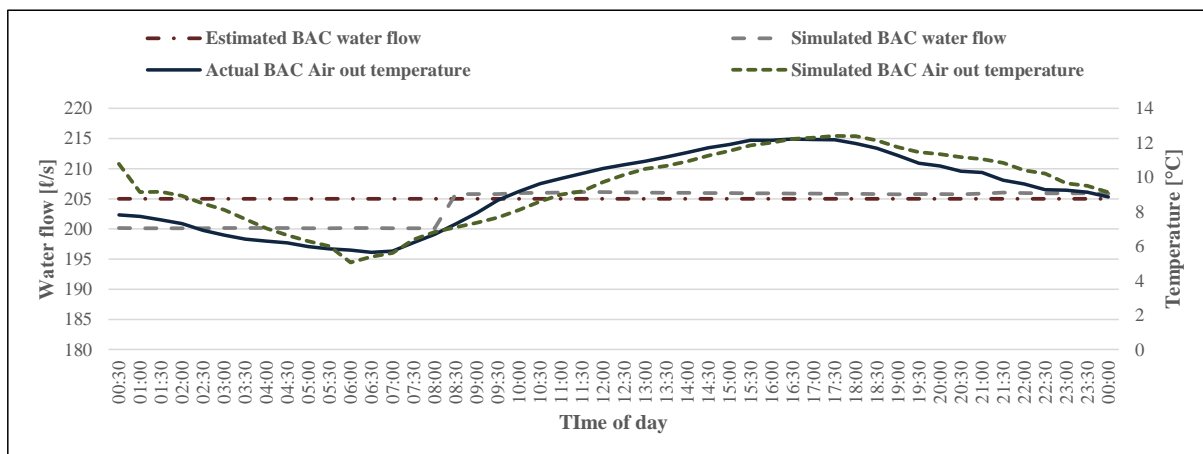


Figure 50: Actual versus simulated BAC flow and temperature – Mine P

The actual versus simulated flow and temperature of the BACs is illustrated in Table 27. By comparing the actual and simulated BAC flow, a 0.5% error is calculated, which is acceptable. By examining the average daily actual temperature and simulated temperature, it is clear that an additional BAC should have been operational. However, by selecting only one BAC to run, the simulated BAC air outlet temperature was accurate with a daily average percentage difference of 2.48%. This is an acceptable error.

Table 27: Actual versus simulated flow and temperature of BACs – Mine P

Parameter comparison	Value
Average actual flow [l/s]	205
Average simulated flow [l/s]	204
Error [%]	0.5
Average actual temperature [°C]	9.16
Average simulated temperature [°C]	9.40
Error [%]	2.48

4.2.4. Summary

This section focused on verifying the new simulation model and approach. A case study mine was selected to verify the models and the approach. Actual and simulated data was compared to verify the model. It was found that the integrated and combined system power can be dynamically simulated with a percentage error difference of approximately 1%.

It was also determined that there was an average difference of 3.2% between all the simulated and actual parameters that were compared. The accuracy of the simulation models can be due to the software that uses explicit models for simulation. Using implicit models will increase the accuracy. However, this will also affect the complexity of the simulations and the simulation time required.

The accuracy of the simulations influences the use of the new models and approach for energy management studies on MCSs. However, an accuracy of 3.2% is accurate enough to do energy management studies such as energy saving measure identification, operational evaluation and suggesting changes, dynamic energy forecasts and M&V studies or assessments.

4.3. Verification of the component control emulation method

The integrated simulation of Mine P's MCS was completed for the previous section. During the simulation process, various control procedures had to be determined, selected and employed in the simulations. The approach developed in Section 3.4 was used to determine the control procedures. The approach and new method for control emulation can now also be verified.

The first step in the control emulation procedure (A.1 to A.4) is to ensure that the simulation process P-1 to P-8 is completed. These processes were already completed for Mine P in the previous section and mainly included the following:

1. Ensuring that the system is calibrated and simulated;
2. Applying existing control philosophy in the simulated system;
3. Simulating data and operation accurately; and
4. Selecting the control emulation application.

For this section, only the control emulation will be verified and the application of the simulation is therefore not relevant. However, the implemented control on the system will be verified by analysing the implemented control of present projects on the MCS of Mine P. The second procedure, which is the control required for the application can therefore also be omitted. However, it will be shortly addressed in the sections to follow.

The next important step is the process definition – procedure C.1 to C.3.

4.3.1. Process boundary definition and selection of equipment to be controlled

The process boundaries (C.1) and equipment to be controlled (C.2) were selected to verify the approach and method, which are illustrated in Table 28 with the controllers relevant to the system. These systems were selected as part of the verification procedure because they represent the most common controllers used on Mine P.

When simulating MCSs, this list will include all equipment that must be controlled, as well as most of the controllers discussed in Section 3.4.

Table 28: Process boundary selection for verifying control emulation – Mine P

Boundary	Controller	Control output
38L dewatering sub-system	Step controller	On/off (1/0)
75L dewatering sub-stem	Step controller	On/off (1/0)
Precooling tower 1 sub-system	PI controller	Frequency (0–50 Hz)

The 38L and 75L dewatering sub-system boundaries are illustrated in the simulation model and in Figure 122. However, for the simulation verification, the control was implemented in the integrated simulation. This was required because of the integrated effect that the control on the dewatering pumps has on the rest of the system.

As illustrated in Table 28, the 38L and 75L pump controllers were simulated with step controllers. The output of these controllers is either an on or off value, depending on the control limits, equipment boundaries and feedback control signal. This will be discussed in more detail in the following section.

The precooling tower 1 sub-system was also selected to verify the control emulation. The precooling motors of the actual system are controlled by VSDs. The variable flow control through a VSD can easily be simulated using the integrated transient simulation of Mine P. A PI controller was selected for simulating the variable flow control due to the applicable controller inputs. This will be discussed in more detail in the section to follow.

4.3.2. Control limit definition and equipment boundaries

The control of the sub-systems was implemented as part of energy management strategies on Mine P. The control on the 38L and 75L dewatering pumps was implemented as part of a load-shifting project. The simulated control inputs are illustrated in Table 29.

As illustrated, the step controller firstly requires a feedback signal, as would an actual PLC. The feedback signal of the actual controller is the upstream dam level, as mentioned in Section 4.2. The feedback signal for the 38L pumps is therefore the 38L hot dam level, whereas the feedback signal for the 75L pumps is the 75L hot dam level.

The number of steps and slope were discussed in the development of the approach to use the controllers in Section 3.4. The number of steps and slope are set to 1 for each of the pump controllers. The start and stop limits are listed in Table 29. However, these limits had to be determined in the calibration process. This was done by analysing the dam storage capacity and selecting the control to match the demand of the surface cooling system for hot water to be cooled.

These limits can, however, still be adjusted to allow for more pumping capacity. The only constraint is that the pumps should not cycle during operation, and should preferably be run throughout the day and only be stopped during Eskom peak periods. The final controller input is the inlet limit. This limit is a safety interlock to prevent the downstream dams from being flooded. The level percentages for the downstream dams of 38L and 75L pumps were set at 90%.

Table 29: 38L and 75L step controller initial inputs – Mine P

Controller property	38L Pump 3	38L Pump-turbine 1	75L Pump 1	75L Pump 2	75L Pump 3
Feedback signal [%]	38L hot dam level	38L hot dam level	75L hot dam	75L hot dam level	75L hot dam level
Number of steps [-]	1	1	1	1	1
Slope [-]	1	1	1	1	1
Start limit 1 [%]	40	35	35	45	35
Stop limit 1 [%]	30	30	30	30	30
Inlet limit [%]	Surface surge dam level – 90%		38L hot dam level – 90%		

The actual 38L dewatering pump control can be verified by comparing the actual flow, dam level and statuses from Mine P's SCADA system with the simulated flow, dam levels and statuses. The actual versus simulated 38L hot dam level and the actual versus simulated flow to surface are illustrated in Figure 51. The flow was already discussed in Section 4.2. However, reference is made to the 38L flow to surface compared with the 38L hot dam level.

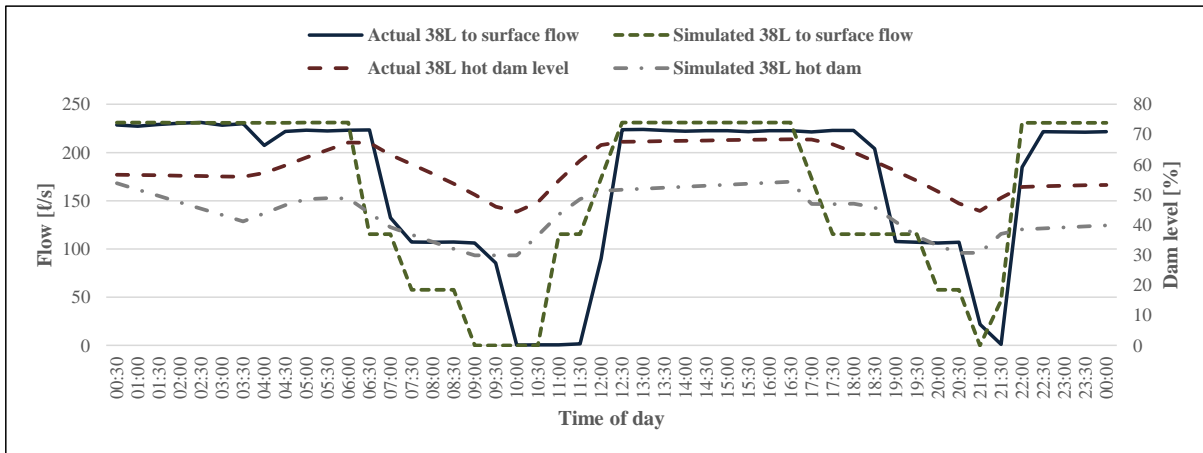


Figure 51: Actual and simulated 38L hot dam level control and flow to surface – Mine P

As seen in Figure 51, the simulated and actual dam levels follow the same profile. However, there is a 35% difference between the simulated and actual dam level. This can be due to the start and stop limits being defined with too little control of the dam capacity. Care should therefore be taken when commissioning the actual system control.

With additional iterations of the simulation, the values can be matched with the actual system. Only one iteration of the simulated calibration procedure was conducted to determine the start and stop limits of the 38L pumps. After doing two more simulation iterations and adjusting the controller inputs, a more accurate simulated dam level was obtained. The simulated versus actual 38L hot dam level after three iterations is illustrated in Figure 52. The percentage error was reduced to 4.29%. This is still an acceptable error.

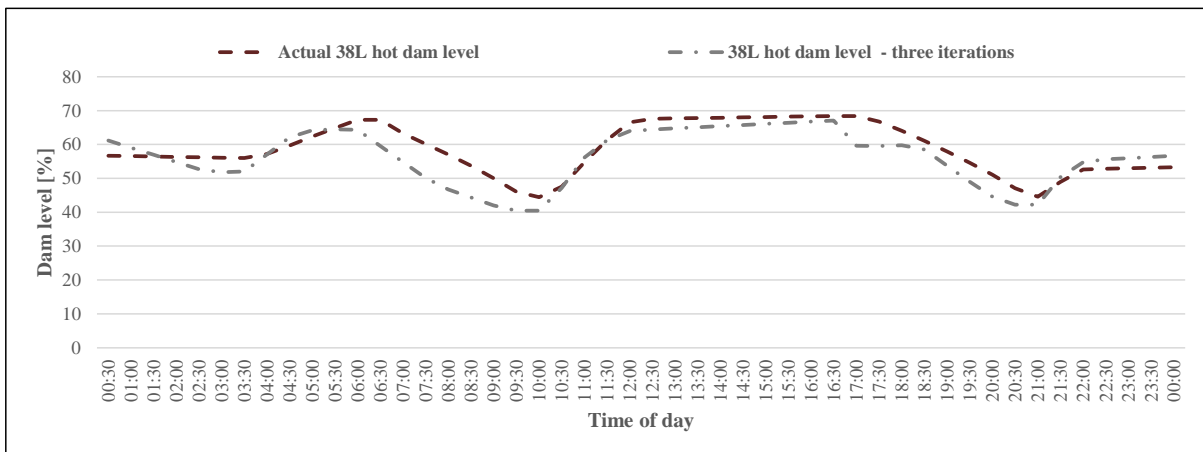


Figure 52: Actual versus simulated 38L hot dam level, three iterations of controller inputs

The final controller inputs for the 38L pumps are shown in Table 30. As discussed, the start and stop limits were updated to represent the actual dam level control more accurately. These values can be used to commission the 38L dewatering pumps in a case where the initial control is unknown.

Table 30: 38L step controller final inputs – Mine P

Controller property	38L Pump 3	38L Pump-turbine 1
Feedback signal [%]	38L hot dam level	38L hot dam level
Number of steps [-]	1	1
Slope [-]	1	1
Start limit 1 [%]	55	50
Stop limit 1 [%]	45	40
Inlet limit [%]	Surface surge dam level – 90%	

Similarly, the actual control output can be compared with the simulated control output. The 38L dewatering actual pump control output versus the simulated control output is illustrated in Figure 53. As shown in the figure, the simulated and actual control output compare favourably.

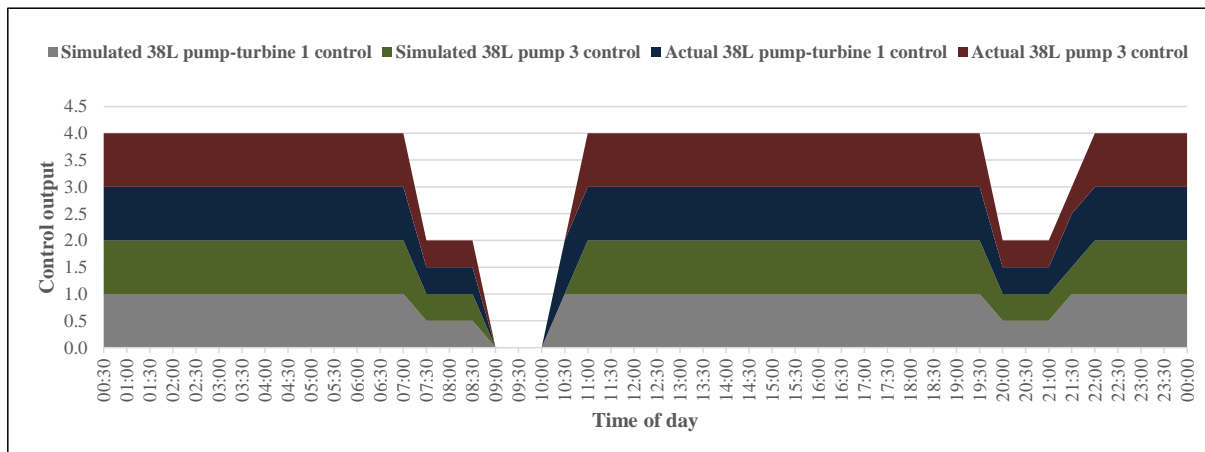


Figure 53: 38L pumps actual versus simulated control output – Mine P

The actual 75L dewatering pump control can be verified by comparing the actual flow, dam level and statuses from Mine P’s SCADA system, with the simulated flow, dam levels and statuses. The actual versus simulated 75L hot dam level and actual versus simulated flow to surface are illustrated in Figure 54. For the flow delivered, the dam level control compares accurately.

The average daily actual flow was 166.37 ℓ/s compared with the average simulated flow of 154.12 ℓ/s. The average difference is 7.95% between these two scenarios. The load shifting on the 75L pumps can clearly be seen between the periods from 06:00 to 10:00 and again

from 18:00 to 21:00. However, the dam level control resulted in a daily average difference of 1.55% between the actual and simulated dam levels.

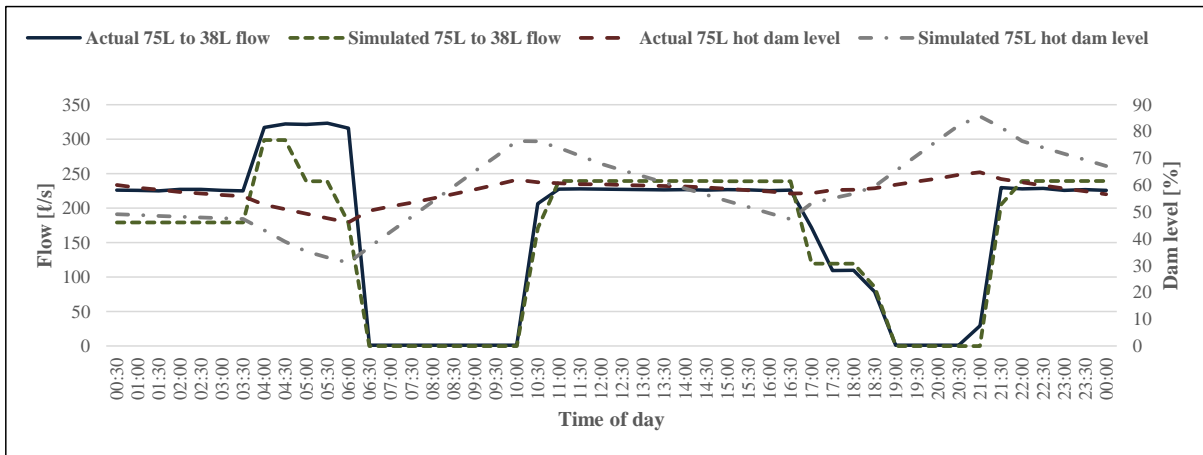


Figure 54: Actual and simulated 75L hot dam level control and flow to surface – Mine P

Similarly, the actual control output can be compared with the simulated control output of the 75L pumps. The 38L dewatering actual pump control output versus the simulated control output is illustrated in Figure 55. As shown in the figure, the simulated and actual control output compare favourably.

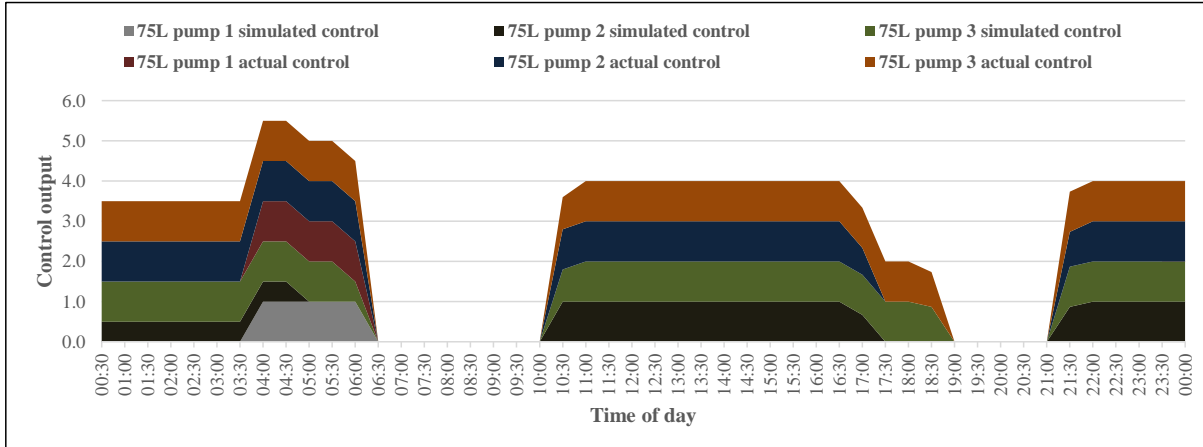


Figure 55: 75L pumps actual versus simulated control output – Mine P

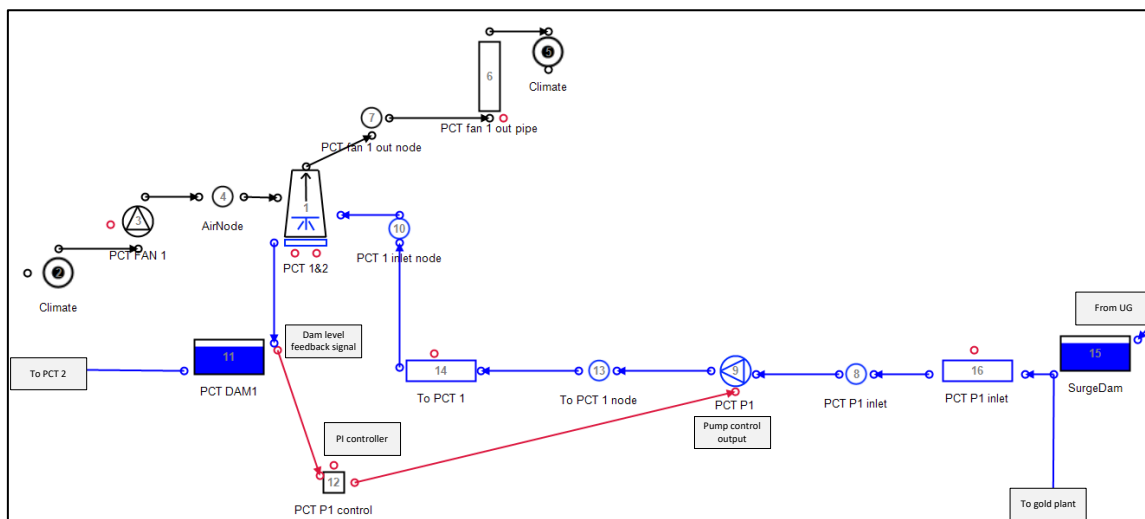
The final control emulation to be verified is the PI controller and variable flow control emulation. The developed control emulation method allows the simulation engineer to experiment and determine the best control variable for the system informatively. In the case of the verification, the parameters have already been defined with the implemented variable flow control strategy. The control of the VSDs installed on precooling tower pump 1 was implemented as part of a variable flow control project. The simulated control inputs are illustrated in Table 31. The actual controller input was shown in Table 17.

Table 31: PCT pump VSD controller inputs versus actual – Mine P

PI controller property	Simulated input	Actual input	Comment
Feedback signal	PCT dam level		Simulated and actual input is similar
Control limit 1 [-]	50	N/A	Actual control limit not applicable – see proportional gain
Control limit 2 [-]	37	N/A	
Proportional gain	0.08	0.8	Factored difference – can be manually determined
Integral gain [-]	0.01	0.1	
Minimum output [-]	0.74	37 Hz	Simulated 0.74 (74%) is equal to 37 Hz ($37 \times 2 = 74$)
Set point [%]	80		Set point is similar in both cases – manually selected
Schedule [-]	1	Surge dam level dependent	The PI controller will always output control – actual system allows for pump stoppage

The PI controller requires a feedback signal to be linked to the controller. This is also the case for PLC control, as illustrated by the process variable input in Figure 125 in Appendix III. In this case, the feedback signal of the PLC and simulated PI controller feedback is the downstream PCT dam level. The simulated PCT sub-system is illustrated in Figure 56.

Control limit 1 and 2 were determined through manual iterations. This was only done to determine the proportional gain of the controller. The proportional gain was determined as 0.08. This differs by an acceptable factor of 10 compared with the actual implemented control. The factor is due to the increments of data used to determine the simulated input and was determined through trial and error. Using smaller increments of data logging will result in improved analyses of the transient response of the system. This will enable the simulation engineer to better predict the proportional gain of the controller.


Figure 56: PCT sub-system controller definition – Mine P

The averages actual versus simulated PCT sump level and actual versus simulated pump frequency are illustrated in Figure 57. As seen in the figure, the actual and simulated dam levels differ significantly. This is due to the actual PCT pump that is stopped automatically when the minimum surge dam level is reached.

The simulated control output is also sensitive as illustrated. However, if the exact pump curves could be obtained for the specific pump, the control output could be more accurate. One of the issues that have been identified is the logging interval of the SCADA data. This is a concern as the comparison of control outputs is limited as only two-minute data is available from the SCADA system.

It is suggested that the mine personnel or simulation engineer proactively set up data loggers to record data in the smallest possible interval. This will ensure that the control output can be compared accurately. The control output emulation is a very strenuous task and needs to be conducted by a relatively experienced system simulator. The results of Figure 57 were obtained after five iterations of the simulation control output. However, more detail of such a system is required to simulate the control response or output at various systems accurately.

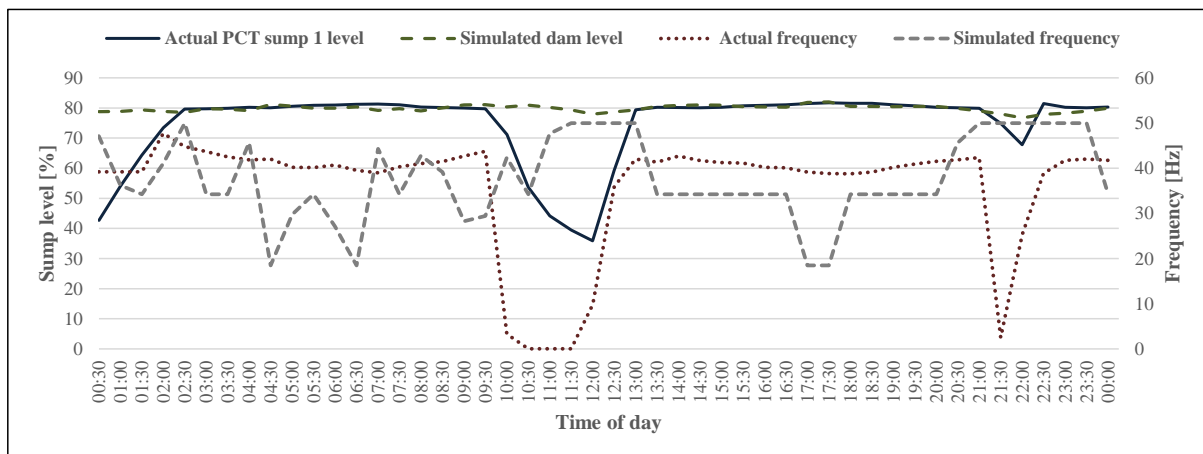


Figure 57: Actual versus simulated PCT sump level and pump frequency – Mine P

The other controllers discussed in Section 3.4 were not verified. These controllers work with a simple average, minimum and maximum function. The functioning of these controllers will be illustrated in Chapter 5. The documentation of the control parameters and the physical implementation of the control are largely sub-system based.

The resources allocated to the control emulation and physical implementation was determined during the implementation of the variable flow case study of Mine P [62]. During this study, variable flow control strategies were recommissioned after being decommissioned by mine personnel due to inadequate process control. The initial recommissioning was based on a trial-and-error approach. However, if the new integrated system simulations could have been used, the initial PLC control values could have been determined in a few iterations of the simulation instead of numerous iterations on the PLCs.

The resources and costs involved in such a process are detailed in Table 32. The table illustrates the hourly tariff for resources as well as the scope of implementing the control on the various systems. This gives a good indication of resources required, but does not validate the study completely. The full validation of the study will be discussed in Chapter 5.

The control emulation method should only be used as a preliminary control definition of the system. Although the integrated system has been modelled, it is difficult to simulate the system response accurately without the required data. Only two-minute intervals were available for the verification, thus making it difficult to predict control outputs that are normally represented in milliseconds.

However, the simulation model can easily be adjusted to include the control emulation in smaller time steps. The inputs of the simulation need to be adjusted as discussed in Section 3.4. The simulation engineer can ensure that the data is logged in the smallest possible interval to ensure that the control outputs can be calibrated and compared.

Table 32: Integrated system simulations resource allocation – Mine P

Scope of work				
Scope		Resource (hours)		
		Simulation engineer	Senior project engineer	Project manager
1	Gather system specifications and compile layouts	8	–	2
2	Acquire and verify data – automatically logged	2	1	–
3	Acquire and verify data – manual measurements	0	0	-
4	Compile sub-system simulations	40	4	–
5	Verify and validate sub-system simulations	2	8	1
6	Compile integrated simulations	8	4	–
7	Verify and validate integrated simulations	2	3	2
8	Consult with mine personnel	–	8	-
9	Consult with mine/energy engineer	2	4	2
10	Update and verify simulations	2	2	1
11	Do documentation and administration	12	10	4
Total hours		80	44	12
Engineering Council of South Africa (ECSA) rate (rand per hour)		670	920	1 550
Total rate (rand value for total hours)		R53 600	R40 480	R18 600
Total		R450 290		

The time taken to compile the simulations is illustrated in the green highlighted cells from Step 4 to Step 7. This is a good indication of the efficacy of the new approach which gives a simulation engineer the correct procedures to follow. The combined time taken was approximately 74 hours.

4.3.3. Summary

After the integrated system has been constructed, calibrated and simulated, the control studies can be concluded. Various control parameters can be determined, equipment control limits can be defined and operational control can be emulated. The control emulation procedure was verified by comparing actual process variable data with simulated control outputs.

The methods developed in Section 3.4 were used as part of the simulation procedures. It was determined that the control emulation method can be used for control prediction and to aid the simulation engineer with practical control commissioning. However, the determined commissioning values should only be used as preliminary inputs to the PLCs.

It should also be kept in mind that the accuracy of the control emulation method is dependent on the data-logging interval. With the control emulation method verified, the new applications verification can now be discussed.

4.4. New application verification

The new simulation model and approach, as well as the control emulation method, have been verified in the previous section. As a result of developing the new models and approach, new applications are possible which aid the energy engineer with energy management of the MCS. Methods for using the simulations for these applications have been developed in Chapter 3.5. The verification of these methods will now be discussed.

As discussed in the dynamic energy forecasting approach (P-11) in Section 3.5, the simulation approach P-1 to P-8 should be completed (procedure A.1 to A.4). This has been discussed in Section 4.2 to Section 4.3. The next procedure is obtaining the mine operational plan. The mining plan for Mine P could not be obtained before completing this thesis. However, this will be discussed in the next chapter.

Procedure C of the P-11 approach shows the possibility of simulating various energy forecasting scenarios. The possibilities/applications include the following:

1. Investigating the addition or expansion of components;
2. Evaluating new configurations;
3. Implementing new equipment and changes to the system feasibility;
4. Testing the replacement of entire systems in the simulation; and

5. Doing other what-if analyses.

As mentioned, the simulation model and approach were verified with actual data in Section 4.2. The new method for energy demand has therefore been verified indirectly. This method is only a preliminary method for quantifying the effect on the system energy consumption and serves as an early indication of the feasibility of any of the scenarios mentioned above. The new method was therefore verified and will be validated with an illustrative example in Chapter 5.

The new applications that were identified in the beginning of this thesis include the dynamic energy forecasting method through simulations, which was verified earlier in this chapter. It was determined that the new applications can be conducted with the newly developed models and approaches.

The next step is to verify whether the integrated transient response simulation meets the requirements as stated earlier in this thesis. This will be discussed in Section 4.5.

4.5. Evaluation of simulation requirements

Although only the simulation approach P-1 was discussed from Section 4.2.1 to Section 4.2.5, it should be noted that the other approaches (P-2 to P-12) were followed in detail to verify the study. Approach P-2 to P-12 are summarised as approach P-1. The final verification of the new integrated transient response model and approach evaluates whether the requirements that have been set out at the start of this thesis have been met.

The requirements of the novel simulations for energy management were identified in Table 3 in Section 2.5.3. The developed models and approach can now be evaluated and the simulation requirements verified. Table 33 illustrates the updated integrated transient response simulation requirements evaluation. As indicated in the previous sections, each of the requirements was evaluated and all the requirements have been satisfied.

Table 33: Evaluation of integrated transient response simulation requirements

Requirement	Result
Transient system simulation	Passed
Accurate simulation of dynamic energy systems	
Ability to integrate systems	
Reduce resource time	
Easy-to-use model	
Simulate MCS control	
Customisable to meet system constraints	

4.6. Conclusion

The novel simulations and approach for energy management of MCSs were verified in this chapter. The new transient response simulations were verified by comparing the simulated results with actual data of an MCS of Mine P. An overall percentage error of 3.2% was determined. An overall combined accuracy of 96.7% was therefore achieved. The simulation model and approach were therefore fairly accurate compared with the actual system. An accuracy of 93% would still have been sufficient considering the size and complexity of the MCSs.

The new component control emulation method was also verified by comparing the simulated output of the controllers with the actual output. However, it was determined that the data-logging intervals of the actual system response play a significant role in the component control emulation.

It was suggested that the relevant energy or simulation engineer ensures that the most critical data is logged in the smallest possible interval to ensure that the system control is calibrated accurately. Mine P's data was available in two-minute intervals, which was not sufficient for predicting the exact accuracy of the control emulation method. However, this method is still sufficient for preliminary control emulation studies and will be reviewed in Chapter 5.

Furthermore, the energy forecasting method was verified in principle by verifying the simulations. The methods developed for these applications were discussed and it was shown that the new simulation models and approach allow the simulation engineer to do dynamic energy forecasting studies of planned energy saving projects. This will also be the case when the system is evaluated. The simulation verification was conducted by using 74 resource hours. This is an indication of the efficacy of the new models and approach.

The verification of the new simulation approach was not illustrated in detail in this chapter. However, by applying the new transient response energy management simulations, the new approach is also validated. This validation will be discussed in the chapter to follow. The validation of the energy management approach, P-9, will also be discussed.

The requirements of the new integrated transient simulations were verified and evaluated. All the relevant requirements were met. Chapter 5 shows the validation of the newly developed models through application in actual case studies.

5

CHAPTER 5

VALIDATION THROUGH A CASE STUDY

“When you want to know how things really work, study them when they're coming apart.”

~ William Gibson (Writer)

5. VALIDATION THROUGH A CASE STUDY

5.1. Preamble

Chapter 4 focused on verifying the methods developed for the contributions of this thesis. The new integrated transient simulation models and approaches were verified by comparing the simulated results with actual data available from a case study mine. The goal of Chapter 5 is to validate the use of the newly developed models and approaches through case study.

A deep-level gold mine in South Africa was selected to validate the case study. The mine accesses ore at depths of up to 3 100 m below surface. The mine will be referred to as Mine A due to confidentiality agreements. The mine produces approximately 7.2 tonnes of gold per annum. Mine A was selected due to the complexity of its MCS. Successful application of the models and approaches developed in this thesis on Mine A will validate the solution, and give an indication of the resources and costs involved with conducting such a study.

Mine A measures most of the critical parameters required to conduct successful integrated transient response simulations. However, the mining areas are not instrumented and manual measurements are required to adequately quantify the service delivery demand from the MCS. This is another reason for selecting Mine A, as it represents most mines in the South African environment. Considering the validation of the new contributions to the field, the following need to be validated through the case study on Mine A:

- Energy management approach developed as part of the new simulation approach;
- Energy management is possible through unique integration of the MCS of Mine A;
- Ease-of-use of the new simulation models and approach;
- Resource time and cost involved with conducting the study; and
- Successfully determine the effect of system changes through MCS integration in transient simulations.

The following section focuses on the description of Mine A and conveys the approach followed to conduct the integrated transient response energy management simulations.

5.2. System description and information

The newly developed procedures were followed while executing the case study. Most of the procedures were discussed in Chapter 3 and Chapter 4, and will only be repeated where necessary.

5.2.1. System overview and control

Mine A's surface refrigeration system is illustrated in Figure 58. The process starts with used mining water pumped from underground entering the three PCTs directly at 22 °C and 660 ℓ/s. The PCT uses ambient air to cool the water to about 17 °C, where after the water is stored in the PCT sump.

From the PCT sump, the water is supplied to an ice plant, where soft ice is made in the ice dam. During Eskom's evening peak period, the ice dam is melted and the water is supplied to underground in a slush form. The water from the PCT sump is also supplied to the five Hitachi chillers, which are configured in parallel. Each chiller operates at approximately 200 ℓ/s.

Water is cooled to about 7 °C and stored in the Hitachi chill dam. The evaporator pumps of the Hitachi chillers have VSDs installed on each of the pumps. The VSDs are controlled according to a low, medium or high water flow rate, depending on the demand for chilled water. The demand for chilled water is reflected by the cold dams underground. The pump speed is determined by the flow rate demand through the 3CPFSs, which will be discussed hereafter.

From the Hitachi chill dam, the water is pumped through six ammonia plants where water is cooled to approximately 1.5 °C at a rate of 130 ℓ/s per plant and stored in the chilled water dam. All six ammonia plants are normally in operation. From the chilled water dam, the BAC feed pumps supply water to the three surface BACs at a flow rate of approximately 340 ℓ/s, depending on the season. The BAC supply valves are manually throttled to match the demand for cold dehumidified air. The chilled water from the chill dam is also fed underground.

The BAC water is collected in the BAC sump, where after the BAC return pumps supply the water back to the PCTs at about 12 °C, depending on the season. The process is repeated. All electric equipment specifications are also illustrated in Figure 58.

Chilled water from the surface chill dam is supplied to underground. The underground water reticulation system of Mine A is illustrated in Figure 59. The chilled water is pumped by the surface booster pumps and passes through 1200L 3CPFS East and West at a flow rate of about 220 ℓ/s and a temperature of 3 °C each. The water is stored in the 1200L chilled water dam. From the 1200L dam, the water is pumped by the 1200L booster pumps and is split into two sections, East and West.

The West water is firstly supplied to mining levels 64L, 70L, 73L and 76L where after the water passes through 77L 3CPFS West and is stored in the 77L chilled dam. The East water passes directly through 77L 3CPFS East. A combined water flow rate of 320 ℓ/s is therefore fed to the 77L chilled dam.

From the 77L chill dam, 77L booster pumps supply water to the remaining mining levels through a high-pressure U-tube system. Most the mining activities take place on these levels. The mining levels are divided into 85L, 95L and 101L. From 85L, water is supplied to 85L and 88L active mining areas. The 95L split supplies water to 92L, 95L and 98L. The 101L split supplies water to 101L and 102L. About 320 ℓ/s is supplied to these levels.

The exact water flow through each of the levels is illustrated in Figure 60 and will be discussed hereafter. After the water passes through the U-tube system on each of the mentioned levels, the MCU water is returned to the 77L hot confluence dam after passing through the settlers. The water used for the drilling and other mining activities is then directed to the 102L hot confluence dam.

From the 102L hot confluence dam, the three 102L Sulzer pumps dewater the water to the 77L hot confluence dam at a flow rate of 180 ℓ/s and a temperature of 26 °C. Normally, only one 102L Sulzer pump is in operation. From the 77L hot confluence dam, most of the water is pumped into the 3CPFS by filler pumps, where after the water is dewatered by the 77L 3CPFSs to the 1200L hot confluence dam. The remaining water is pumped to the 1200L hot confluence by the 77L Sulzer pumps.

The process of dewatering from 77L to 1200L is repeated by the 3CPFSs on 1200L and the water is then supplied to the surface PCTs. The entire process is repeated. It is also important to note the heat exchange in the 3CPFSs. The relevant equipment specifications are illustrated in Figure 59.

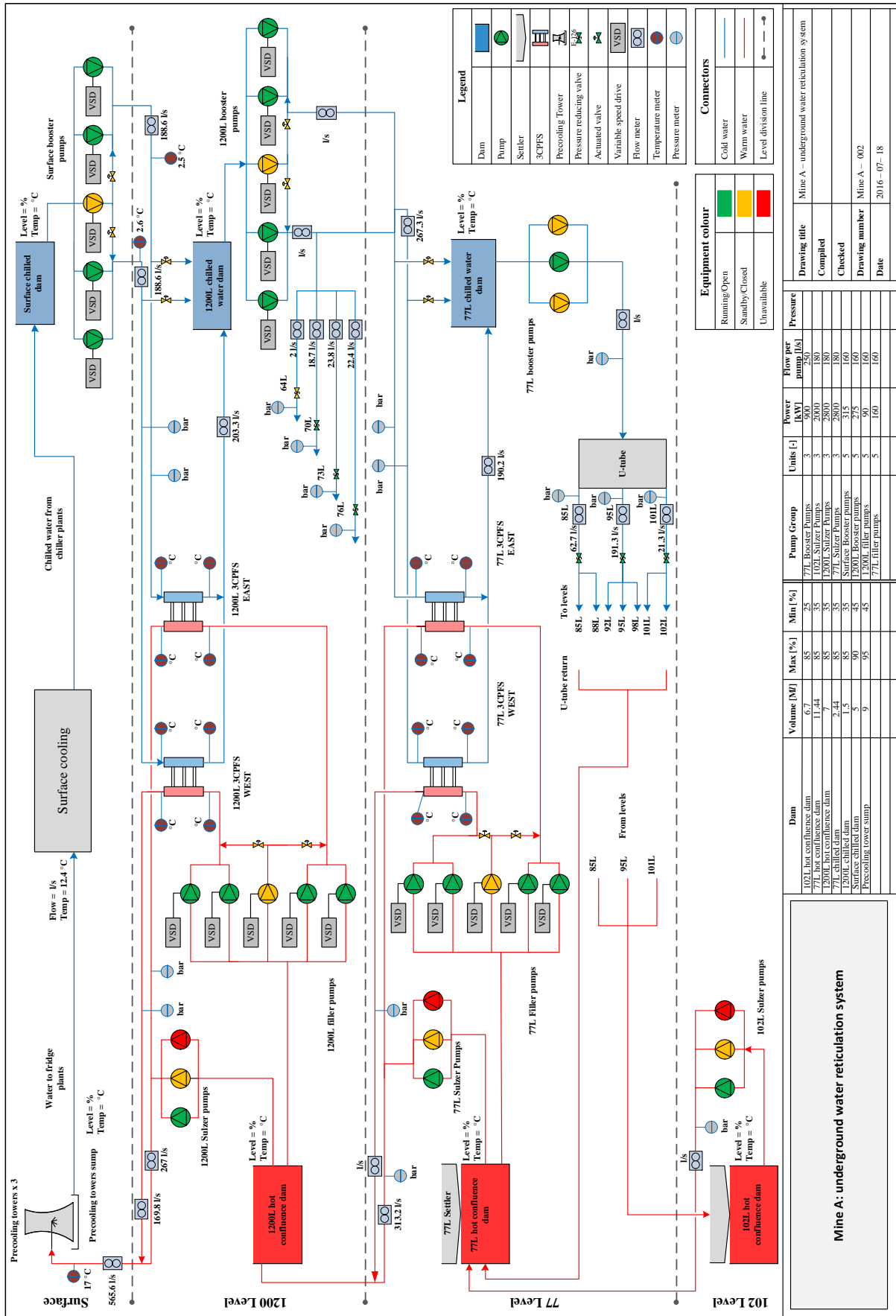


Figure 59: Underground water reticulation system process flow and snapshot – Mine A

The 88L mining layout is illustrated in Figure 60. The water flow from the 77L chill dam and booster pumps is illustrated. The chilled water is supplied from the 85L split to the 88L mining areas through a decline section. The water is transported to each of the active mining areas as illustrated.

As the water arrives at the mining area, it first passes through the MCU. The MCU consists of the unit itself as well as an electric fan with a typical rated capacity of 45 kW. The exact functioning of an MCU is illustrated in Appendix I. The water cools the ventilated air as the air passes through the unit. After passing through the MCU, the water firstly splits to the drill PRVs. The water pressure is regulated to about 16 bar at this stage and is supplied to the drilling areas where mining activities occur.

The water that is not used by the mining activities is circulated back through the high-pressure U-tube system to the 77L hot confluence dam. The process flow of 88L is similar for each of the 85L, 92L, 95L, 98L, 101L and 102L mining levels. The process flow as illustrated in Figure 60 was compiled after conducting manual measurements on the mining levels.

The number of MCUs on each of the mining levels differs depending on the number of active mining areas. These units are also placed in areas where fairly high air temperatures are present. The number of MCUs was determined by a joint effort from mine personnel to include the correct number of units in the simulations.

The drilling water consumption of each section was determined by conducting a mass balance of the water supplied to the section and the water that returns to the 77L hot dam. The return water was also manually measured. The data acquisition will be discussed in the section to follow. The relevant equipment specifications are also illustrated in Figure 60. A typical mining level layout is illustrated in Figure 123.

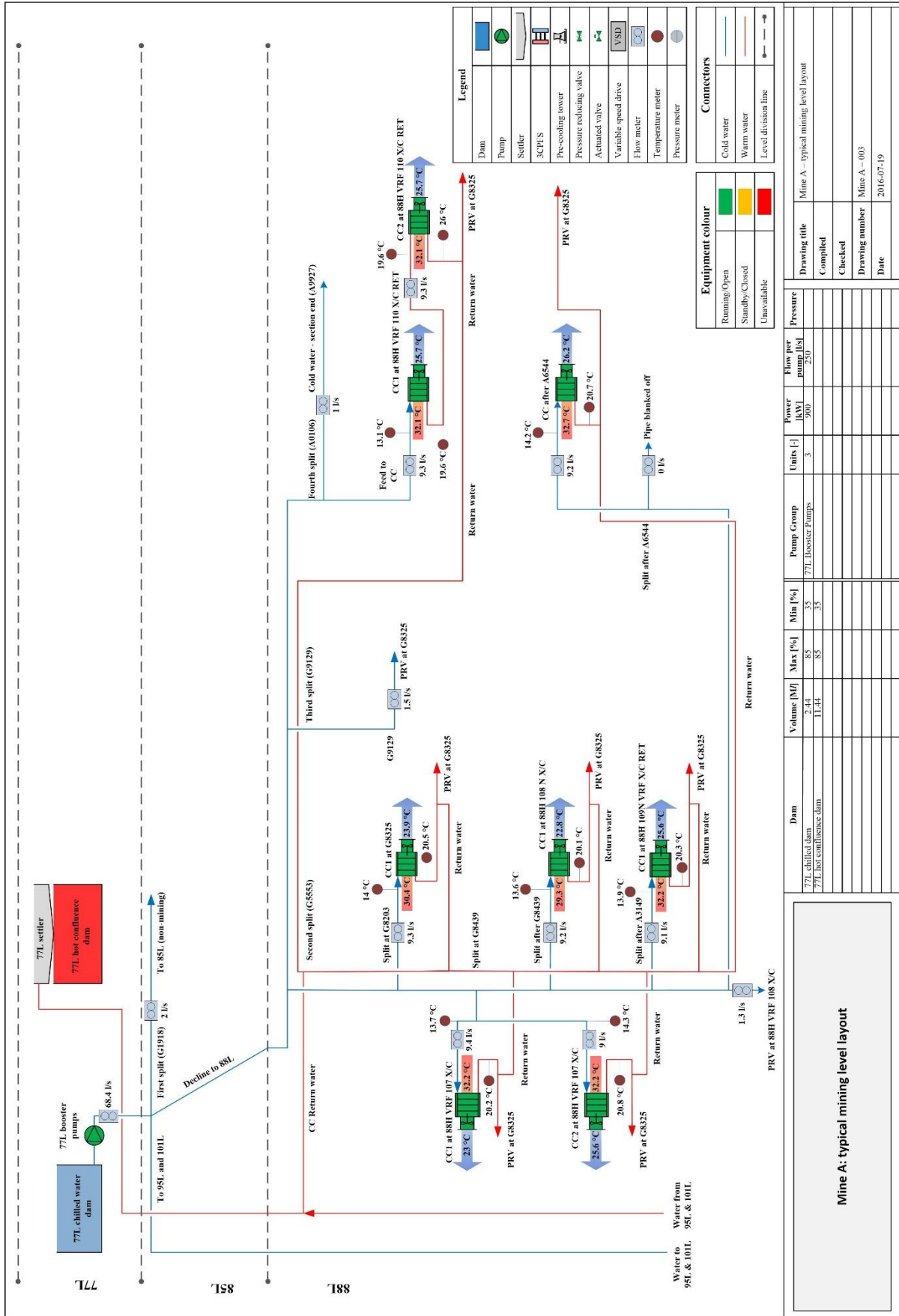


Figure 60: Typical mining level process flow and equipment layout – Mine A

5.2.2. Data acquisition

As previously mentioned, Mine A logs most of the data required for energy management simulations on their SCADA system. However, not all required data sets were available and some of the available data sets needed to be verified. This was done by doing mass and energy balances. The data sets that were automatically logged on the SCADA system are listed in Table 34. The snapshot values in Figure 58 and Figure 59 also illustrate the measurement points.

Table 34: Mine A data set information – automated data logging

No.	Data set	Relevant component	Parameter	Data source	Logging interval	Use
1	Weather data	Climate	$RH_{amb}, T_{DB}, P_{baro}$	Weather station	2 minutes	Simulation input
2	Dams	Dams simulated	L, T_w	PLCs, SCADA	2 minutes	Output verification
3	Chiller statuses	Chillers	S, T_{ei}, T_{ci}	SCADA	2 minutes	Output verification
4	Chiller power	Chillers	\dot{W}_c	Power meters	30 minutes	Output verification
5	Ice plant	Ice-plant model	$\dot{W}_c, T_w, \dot{m}_w$	SCADA, Power	2 or 30 minutes	Output verification
5	Pumps	Pumps	\dot{m}_w	SCADA	2 minutes	Output verification
6	Pump power	Pumps	\dot{W}_p	Power meters	30 minutes	Output verification
7	Towers	Cooling towers	$\dot{m}_{wi}, \dot{m}_{ai}, T_{wi}, T_{ai}$	SCADA	2 minutes	Simulation input
8	Tower fan	Cooling towers	\dot{W}_f	Power meters	30 minutes	Output verification
9	3CPFSs	3CPFS model	T_{wi}, \dot{m}_{wi}	SCADA	2 minutes	Output verification
10	3CPFS power	3CPFS model	\dot{W}_{CPFS}	Power meters	30 minutes	Output verification
11	System power	All	\dot{W}_{total}	Power meter	30 minutes	Output verification

The parameters that were not logged automatically had to be measured manually as part of the investigation. These parameters are listed in Table 35. As illustrated in the table, only the 88L MCUs and PRVs were measured. The rest of the levels were part of an audit to determine the number of units. The water flow recorded on the SCADA system was then used to approximate the consumption per unit. Figure 124 in Appendix IV illustrates some of the manual measurements that were taken on the MCUs and PRVs.

Table 35: Mine A data set information – manual measurements

No.	Component	Variable	Measurement equipment	Logging period
1	77L U-tube return	\dot{m}_w, T_w	Ultrasonic flow meter, temperature loggers	24 hours
2	All 88L MCUs	$\dot{m}_w, T_{wi}, T_{wo}, T_a$	Ultrasonic flow meter, temperature loggers	5 hours per PRV
3	88L PRV water	\dot{m}_w, T_w	Ultrasonic flow meter, temperature loggers	5 hours per PRV
4	95L to 101L MCU	Number of units	Not applicable	Not applicable

The integrated simulations required various assumptions to be made, including:

- Water consumption per MCU and PRV is similar on all levels;
- SCADA data is accurate enough for approximating energy consumption; and
- Heat in mining areas is not accounted for in the simulation.

The data integrity was checked by using the mass and energy balances.

5.2.3. Mine A energy consumption

Energy management of MCSs firstly requires a global scope to be defined, as discussed in the simulation approach for energy management (approach P-9 in Section 3.3.7). As part of this approach (P-9, D.1), it is required to identify the high energy demand systems, which in the case of Mine A are:

- Refrigeration sub-systems (chillers and ice plants);
- Air cooling sub-systems (BACs and auxiliaries); and
- Pumping and dewatering sub-systems (3CPFSs and electrical dewatering pumps).

The next procedure in this approach is to characterise the systems, as developed in the simulation approach P-2 (acquiring system information). This was done by analysing the previously mentioned data sets as well as the power demand of the systems.

The focus of the transient simulations is therefore to dynamically integrate the mentioned systems and to apply the energy management procedure to identify energy saving projects. The system analysis consists of:

1. Identifying operational improvements and analyse the integrated operation;
2. Identifying new projects (energy efficiency, load shifting or peak clipping); and
3. Investigating the improvement of existing projects.

To get an indication of where to start with the system analysis, it is crucial to define the system power consumption. To achieve this goal, the business unit reports were analysed, which contained the year-to-date performances of the actual versus budget of each of the systems. This proved to indicate the areas for improvements. Mine A's pumping budget versus actual, as well as the previous year's consumption are illustrated in Figure 61 as an example of such an analysis.

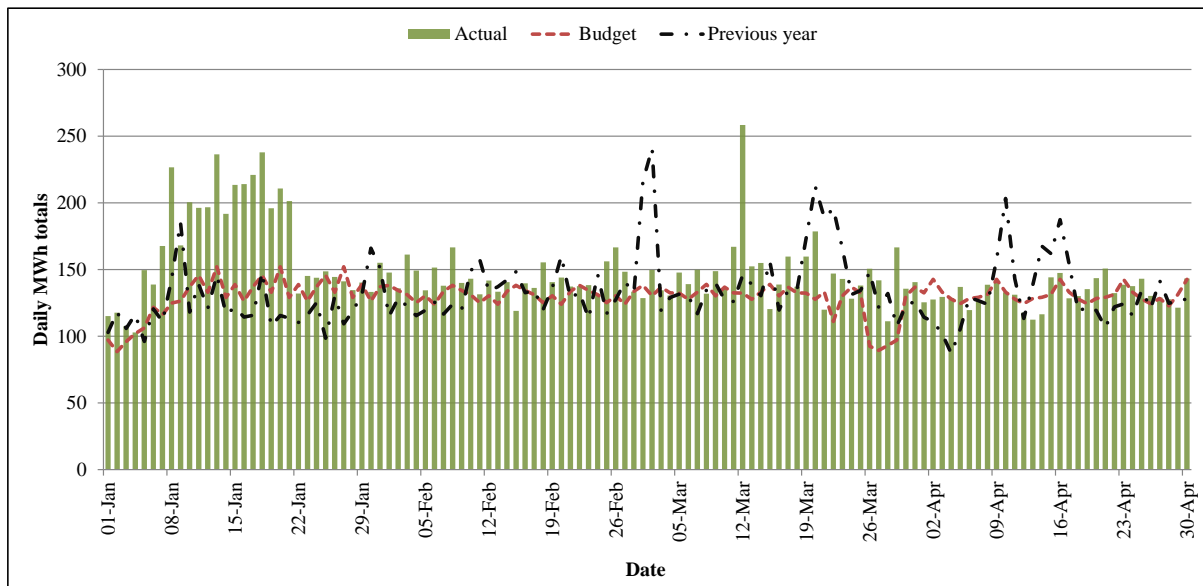


Figure 61: Mine A pumping budget versus actual

5.2.4. Summary

Mine A was selected as the case study mine due to the complexity of its systems. This example gave a good indication of the resources involved when replicating the models and approaches developed in this thesis on various other mines. The system overview and control of Mine A were presented first.

The data acquisition of Mine A was discussed with the emphasis placed on the manual measurements that had to be taken to complete the integrated system simulations. The energy consumption of Mine A was defined, and it was indicated how the system was analysed for effective energy management.

The next section focuses specifically on the simulation approach and configuration as well as the baseline simulations that are required for comparison.

5.3. System simulation approach and configuration

5.3.1. Baseline simulations

The system was described and defined in Section 5.2. The baseline simulations can now be compiled. The baseline simulations were constructed after approach P-2 to P-6 was followed. The simulation inputs are discussed below. The surface refrigeration, pumping and water reticulation, and the mining levels were constructed and simulated in three different models. This was done in accordance with the newly developed approach and models.

Simulation inputs

The simulations were compiled to represent all four seasons of the typical South African climate. The average climate data per season as logged on Mine A's SCADA system was used as inputs for all climate components. The relevant component statuses of all equipment in operation during these seasons were matched with the simulation inputs. A summary of the simulation input data is given in Table 36. Various checks and balances were also indirectly used for calibration.

Table 36: Simulation input summary – Mine A

	Summer	Autumn	Winter	Spring
Equipment specification	As per tables in Figure 58 to Figure 60			
Ambient conditions	Seasonal climate data (relative humidity and dry bulb temperature)			
PCTs and pumps	3	3	1	3
BAC towers and pumps	3	2	0	2
Condenser towers in operation	4	3	2	3
Ice plant in operation	1			
Hitachi chillers	4	3	2	3
Ammonia plants	6	5	4	5
3CPFSs	4	4	4	4
3CPFS booster and filler pump schedules	4	4	4	4
77L booster pumps	1			
1200L Sulzer pumps	1			
77L Sulzer pumps	1			
102L Sulzer pumps	1			
MCU and PRVs	Always operational			

Sub-system construction

After the relevant simulation procedures were followed (P-2 to P-6), the baseline simulations were obtained. The baseline simulations were constructed by using the various models developed in Chapter 3 to save resource time. The sub-systems were evaluated for accuracy by comparing them with actual data. The inputs were used in the simulation as indicated in Table 36. The simulations were then compiled and the calibration process was started.

Simulation calibration

The simulation calibration was a timeous process due to the complexity of Mine A's operations. The simulations were calibrated per the actual power, mass flows, running schedules and equipment specifications. Care was taken with the data sets to prevent irregularities in the simulations. This was done in accordance with standard M&V protocols.

Only weekdays were considered for the simulation calibration as they reflected the normal mining operation the most accurately. The simulations were then calibrated successfully. The simulation outputs are discussed in the next section.

Simulation models

The simulation model for the integrated surface refrigeration system is illustrated in Figure 62. The systems were isolated to show the simulated sub-systems and components.

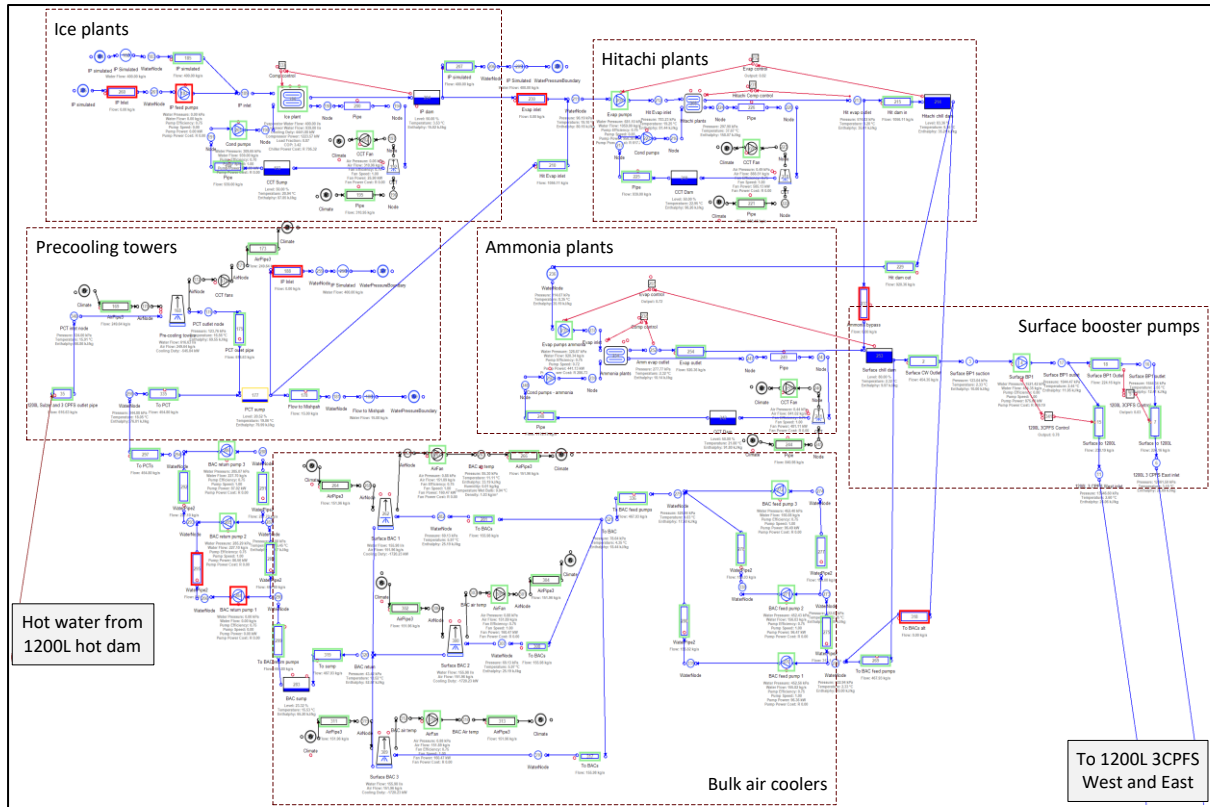


Figure 62: Integrated system simulation – Mine A surface system

The simulation model for the integrated dewatering and water reticulation system is illustrated in Figure 63. The 1200L 3CPFSs to the 77L chill dam are shown, as well as the dewatering pumps and mining level consumption.

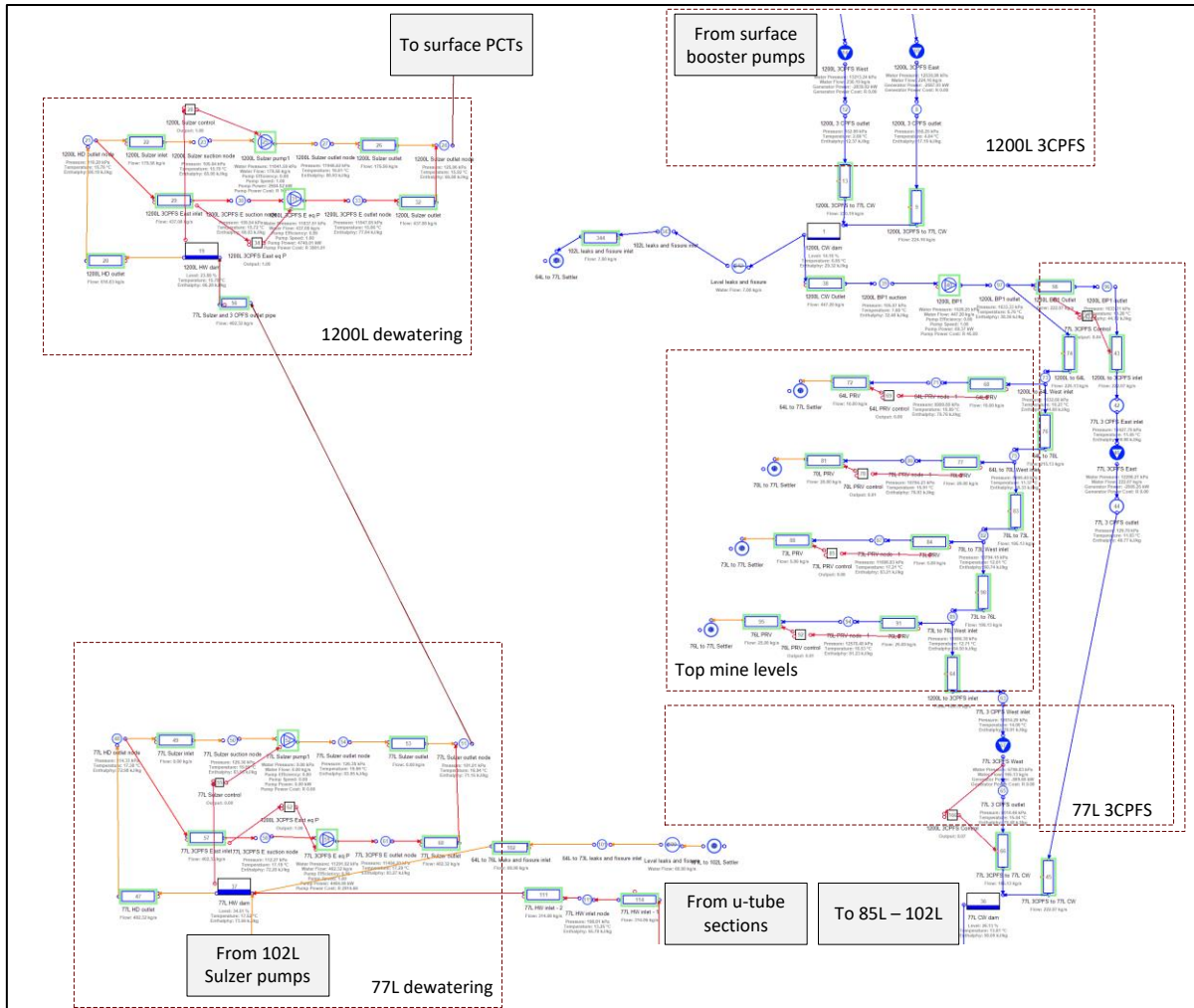


Figure 63: Integrated system simulation – Mine A 1200L to 77L

The simulation model for the integrated dewatering and water reticulation system for 77L to 102L is illustrated in Figure 64. It is important to note that the mining activities were excluded from this screenshot. The detailed mining activity simulation is illustrated in Figure 65.

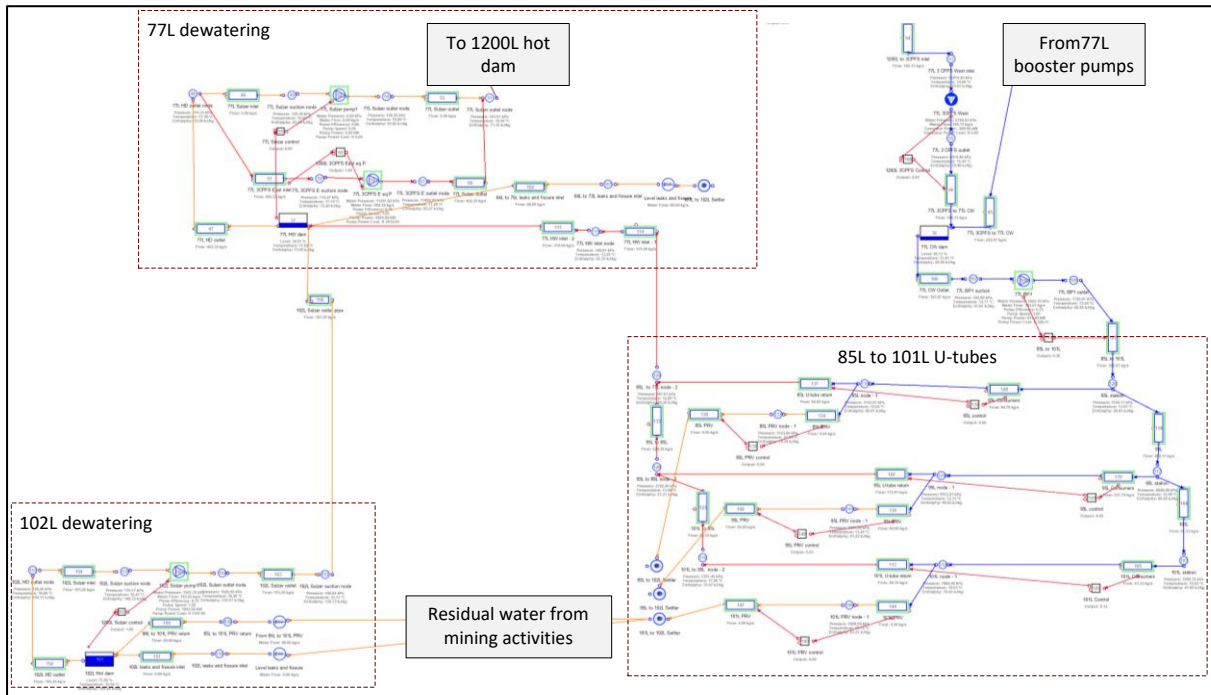


Figure 64: Integrated system simulation – Mine A 77L to 102L

The simulation model for the integrated water reticulation system for 88L mining activities is illustrated in Figure 65. The water inlet to the level as well as the return through the high-pressure U-tube system was simulated. The supply of chilled water to the other high-pressure systems from 95L to 102L was also included.

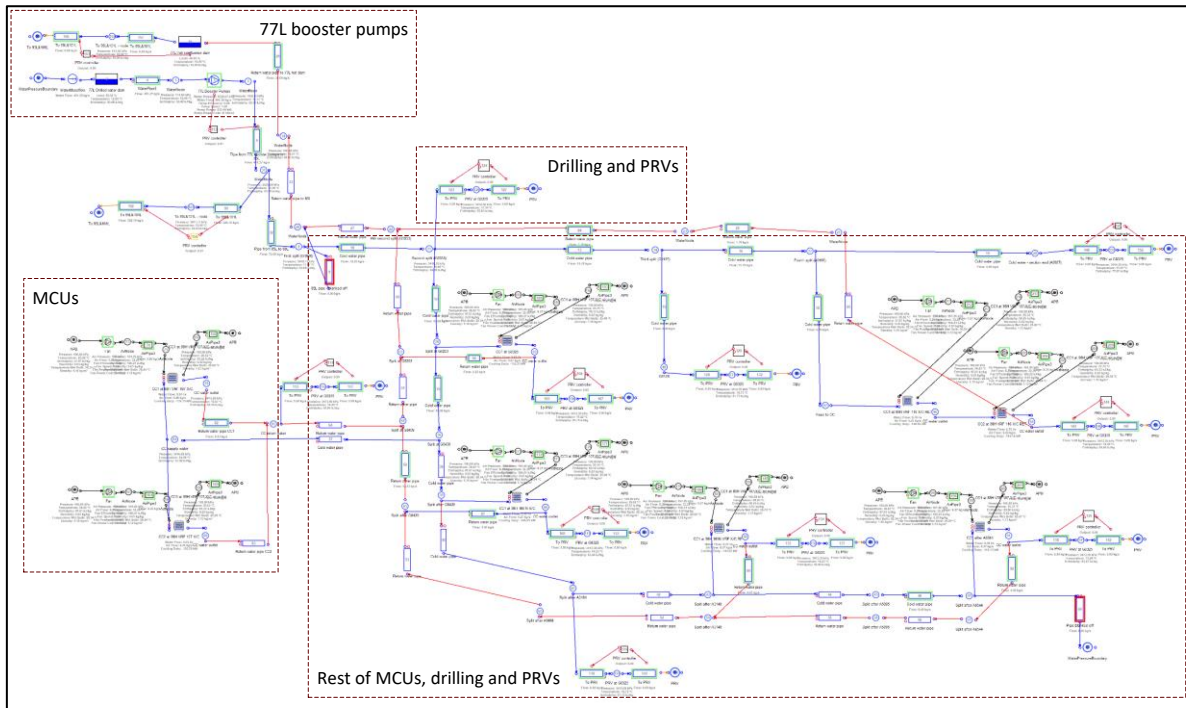


Figure 65: Integrated system simulation – Mine A 88L mining activities

The complete integrated simulated system is illustrated in Figure 66.

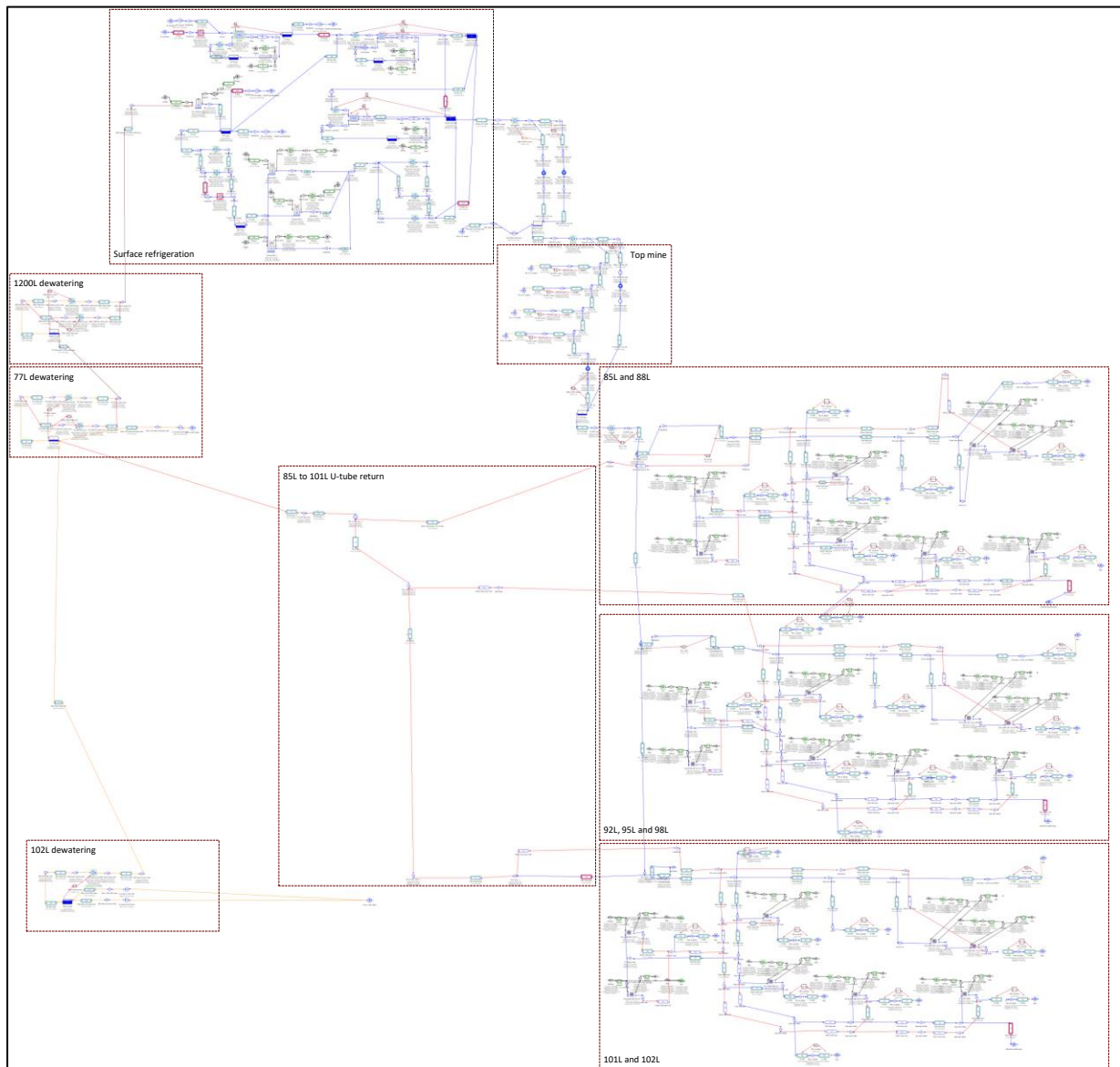


Figure 66: Complete transient integrated simulated system

5.3.2. Baseline simulation analyses

The simulation outputs needed to be verified to ensure simulation accuracy. The simulated versus actual surface refrigeration system daily power profiles for each season are illustrated from Figure 67 to Figure 70. It is important to note the effect that the melting of ice in the ice plant has in the evening peak period, which is from 17:00 to 21:00.

During this period, most of the running equipment is switched off to enable load shifting on the system. The chilled water is then supplied to underground by the ice plant.

Surface refrigeration system power comparison

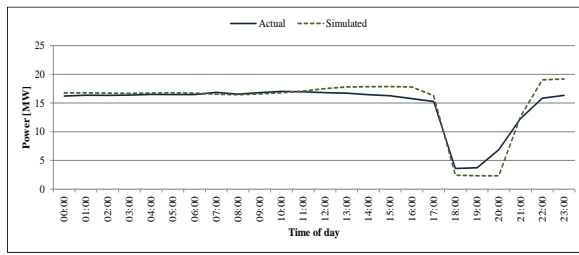


Figure 67: Summer actual versus simulated power – Mine A

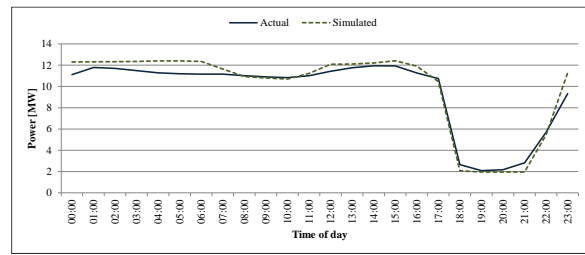


Figure 69: Winter actual versus simulated power – Mine A

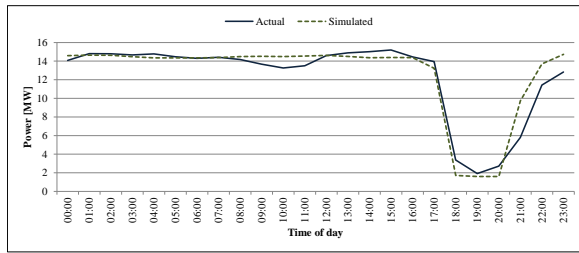


Figure 68: Autumn actual versus simulated power – Mine A

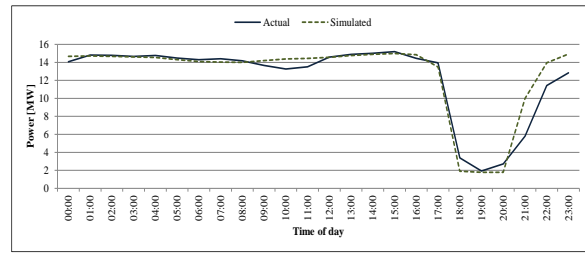


Figure 70: Spring actual versus simulated power – Mine A

The average accuracy between the simulated and actual power demand was approximately 97%. It is therefore clear that the baseline power of the operation of Mine A’s surface refrigeration system was simulated accurately. The baseline simulation can thus be used for the simulation applications that will be discussed in Section 5.4.

The simulated versus actual underground reticulation system daily power profiles for each season are illustrated in Figure 71 to Figure 74. It is important to note the load-shifting effect during the morning and evening Eskom peak periods in winter compared with only the evening peaks in summer, autumn and spring. This is mainly due to a load-shifting initiative employed by the mine to gain the maximum benefit from electricity tariff savings in winter when the tariffs are more expensive (see Appendix VII).

Underground reticulation system power comparison

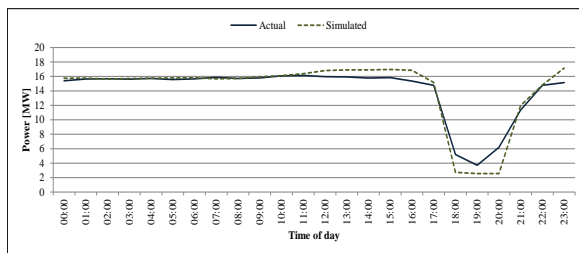


Figure 71: Summer actual versus simulated power – Mine A

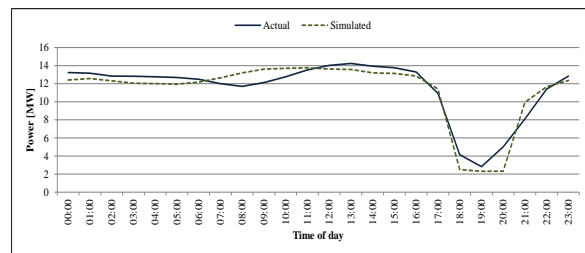


Figure 72: Autumn actual versus simulated power – Mine A

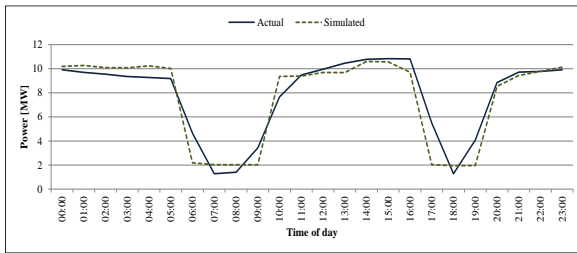


Figure 73: Winter actual versus simulated power – Mine A

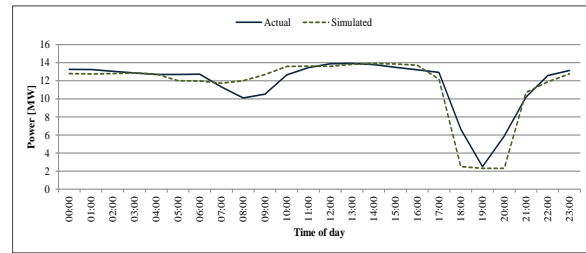


Figure 74: Spring actual versus simulated power – Mine A

The average accuracy between the simulated and actual power demand was approximately 98%. It is therefore clear that the baseline power of the underground operation of Mine A's system was simulated accurately. The baseline simulation of the process parameters is discussed in the following section. The integrated system power was simulated with a combined accuracy of 97.5% compared with the actual system power consumption. This is an acceptable accuracy.

5.3.3. Dynamic simulation of the integrated system

The power comparison done in the previous section illustrated that the integrated system can be simulated accurately. However, the process parameters need to be compared to validate the simulation model and approaches. The spring/autumn process parameters will be analysed in detail. However, the summer and winter profiles were analysed using a similar approach.

Figure 75 to Figure 78 compare the BAC system parameters between the actual and simulated values for spring/autumn. The evening load shifting was simulated accurately, as can be seen in Figure 75 and Figure 76 in the periods from 17:00 to 21:00. The simulated and actual values for the supply flow and BAC air outlet temperatures compare favourably.

The average BAC supply flow for the simulated day was 252 ℓ/s where the actual flow was 220 ℓ/s . This is due to the manual BAC flow control philosophy employed by mine personnel. An average flow was therefore simulated as these values differ intermittently. The simulated BAC water inlet temperature was 2.88 $^{\circ}C$ compared with the actual daily average of 2.36 $^{\circ}C$. There was an actual versus simulated difference of 0.74 $^{\circ}C$ of the BAC outlet duct temperature.

The BAC water inlet temperature differs slightly, but is sufficient to determine the effect of any system changes. The profiles for the BAC water outlet temperature also compare

favourably, with a slightly higher simulated value. The combined simulation accuracy for the four BAC parameters was 90%.

BAC system actual versus simulated comparison – spring/autumn

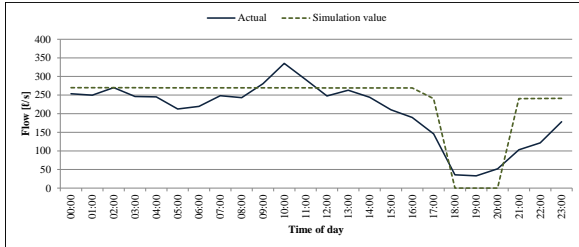


Figure 75: BAC supply flow – Mine A

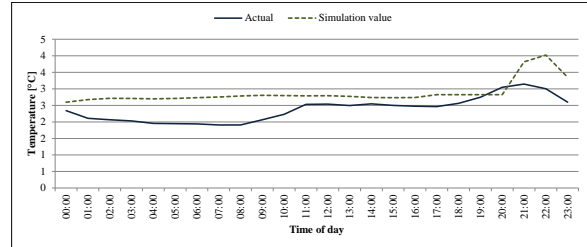


Figure 77: BAC water inlet temperature – Mine A

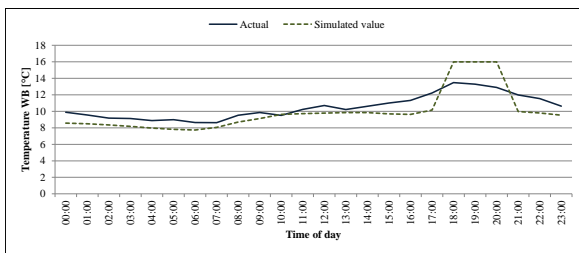


Figure 76: BAC air outlet temperature – Mine A

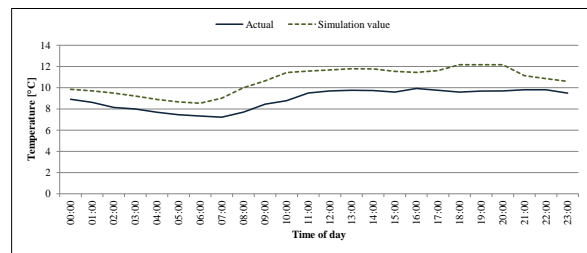


Figure 78: BAC water outlet temperature – Mine A

The service delivery of chilled water is the next comparison required to ensure the baseline simulation reflects the actual operation. The actual and simulated chilled water from the Hitachi and ammonia plants are compared. The chilled water flow and temperatures for spring/autumn are illustrated from Figure 79 to Figure 82.

Chiller and ammonia system actual versus simulated comparison – spring/autumn

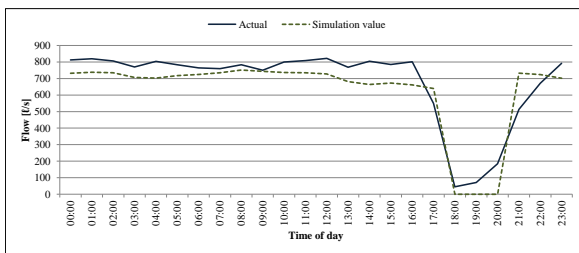


Figure 79: Water flow to Hitachi dam – Mine A

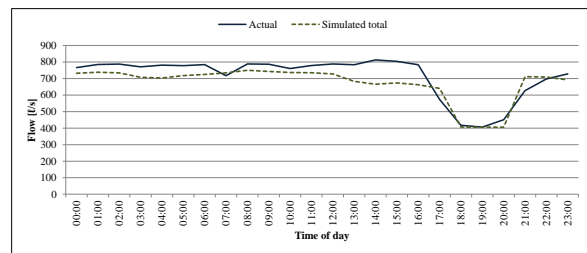


Figure 81: Water flow to surface chill dam – Mine A

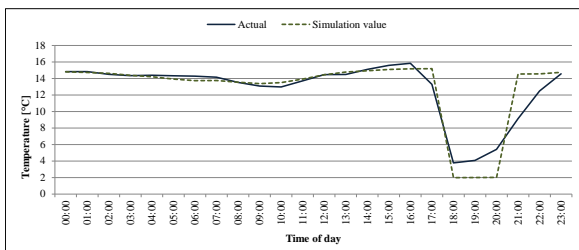


Figure 80: Hitachi water temperature in – Mine A

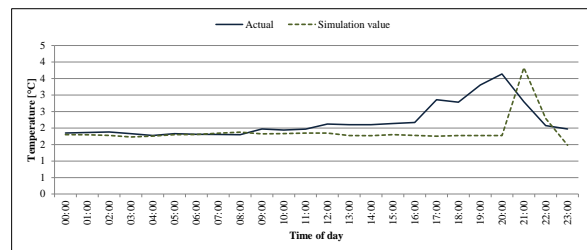


Figure 82: Ammonia water outlet temperature – Mine A

The combined simulation accuracy for the four parameters illustrated in Figure 79 to Figure 82 was 92%. The water flow to the Hitachi dam indicates the load shifting of the surface refrigeration system due to using the ice plant. The water from the ice plant flows through the Hitachi plants before being stored in the Hitachi chill dam.

The temperature can clearly be seen in the period from 17:00 to 21:00. The simulated water flow was approximately 623 ℓ/s and the actual daily average flow was 677 ℓ/s . The simulated underground water reticulation accuracy was verified similarly. The combined simulation accuracy of the entire integrated system was determined as 94%.

The accuracy is sufficient for conducting the simulation applications. The simulation applications will be discussed in Section 5.4.

5.3.4. Summary

The accuracy of the new simulation models and approaches have already been verified in Chapter 4. However, to simulate energy management of MCSs, the accuracy of the actual and simulated baseline had to be compared. The calibration procedure in the new approach also indicates this step.

With the accuracy of the simulated baseline determined, the new simulations can therefore be used as intended for energy management. The integrated system simulation accuracy was determined as 94%.

5.4. Simulation applications on Mine A

The baseline simulations for Mine A were shown to be accurate. The overall integrated system simulation accuracy was determined to be 94%. The new applications were therefore executed by following the relevant approaches as developed in Chapter 3. The focus is specifically on the simulation approach of application selection. The newly developed models were therefore applied as indicated in approach P-3. The applications include:

- Identifying energy saving measures on MCSs;
- Evaluating operation and changes of the MCSs; and
- Forecasting dynamic energy of integrated systems.

The applications and relevancy to Mine A will be discussed in the sections to follow. The control emulation strategy also had to be applied to determine the control of the initiatives identified.

5.4.1. Energy saving measure identification

As indicated in approach P-3, energy saving measure identification requires project investigation procedures as well. A summarised project investigation procedure is given in Appendix V [62]. The simulation models and procedures are applied in combination with these procedures. However, the simulation formed the most important part of the energy saving measure identification on Mine A.

As part of the integrated system simulation, it was identified that there were four sub-systems with potential energy or cost savings. The integrated system simulations were used to identify any inefficiency that exists in the system. The projects were then determined from the industry best practice. These projects/measures will now be discussed.

Install VSDs on BAC feed and return pumps

The BAC sub-system was identified as the first potential inefficient system. It was known that mine personnel manually control the flow through the BACs. However, this is an inefficient process. From industrial projects previously implemented, it was recommended to install VSDs on both the BAC feed and return pumps.

This will allow the BAC water supply to be controlled per the 8 °C wet-bulb temperature as recommended by mine personnel. The BAC return water pumps will then be controlled per the PCT sump level. Although this measure was simulated in the integrated transient simulation model, it would have been possible to draw a boundary around the system. However, the heat transfer in the PCT sump needed to be determined. This was an advantage of the integrated simulation. The effect on the refrigeration machines was also defined in the integrated simulation.

The average daily simulated baseline as well as the simulated effect of the VSD installation is illustrated in Figure 83. Only the surface refrigeration power is presented. These profiles include the average effect over all four seasons of the year. The clear energy efficiency impact can be seen between 00:00 and 17:00. Thereafter, the melting of the ice plant ice is

initiated. The BACs are used again from 21:00 to 00:00. An average daily energy saving of approximately 12 MWh was determined. This is the average daily saving for all seasons.

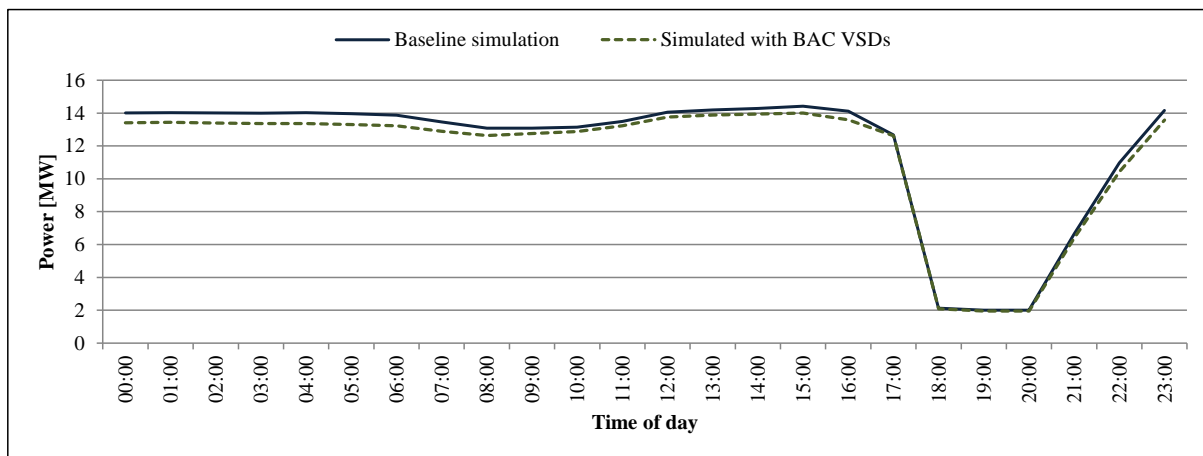


Figure 83: VSD installation on BAC feed and return pumps – Mine A

The project costing and infrastructure also needed to be quantified to justify the identified measure. A summary of the equipment required for the initiative is illustrated in Table 37. Table 37 furthermore illustrates the annual cost savings and the payback period without contractor costing. A payback period of 10.1 months is possible.

Table 37: Mine A energy saving measure – BAC VSDs costing

BAC VSD installation	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
VSDs	12 MWh	R2 442 908	R2 893 391	10.1
PLCs and instrumentation				
Cables and cable racking				
Control installation				
Commissioning of equipment				
Contingencies				

The equipment costing is a predicted figure and only refers to an indication to determine the payback of the project. The predicted costing was determined from analysing previous projects requiring similar equipment.

An analysis of the BAC system was required to determine the effect on the sub-system after installing the VSDs on the BAC feed and return water pumps. This effect is illustrated in Figure 84. The BAC supply flow and air outlet temperature were simulated.

The new control of the VSDs on the pumps can clearly be seen as the pump speed increases as the outlet air temperature increases. The effect of load shifting on the system can also clearly be seen. It is also clear that better service delivery can be obtained by controlling the BAC feed pumps automatically.

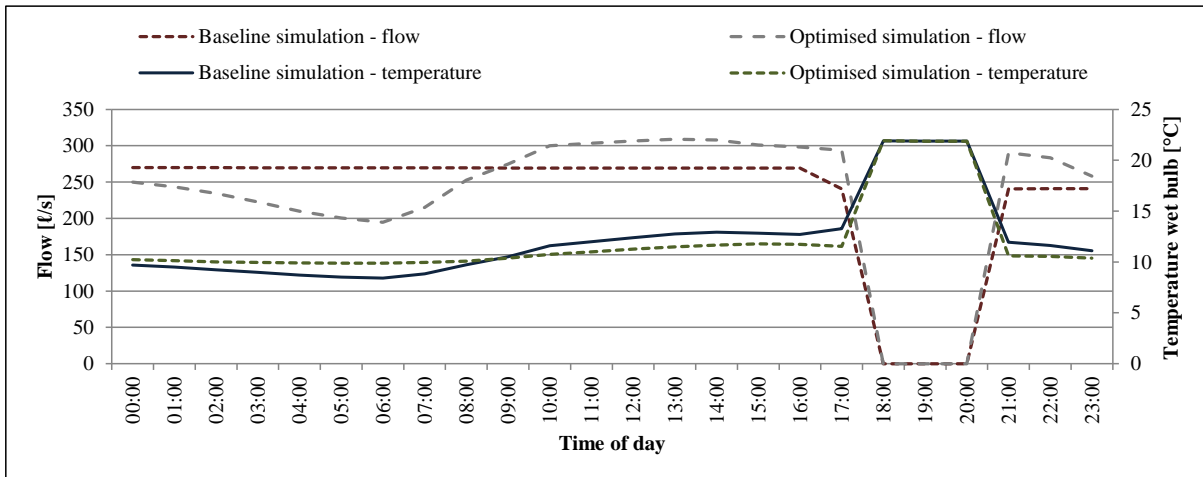


Figure 84: BAC supply water flow and outlet air outlet temperature – VSD installation

The proposed control for the VSDs on the BAC supply pumps is illustrated in Figure 85. The control feedback of the controller was the ambient wet-bulb temperature and the set point was selected as 9 °C for the controller inputs. The required control limits were determined and the control was emulated.

The controller adjusted the control output per the change in ambient wet-bulb temperature. This is expected as the measured variable will change as the temperature changes. It is also illustrated that the actual temperature stays on the selected set point. However, the effect of ice-plant load shifting can clearly be seen between 17:00 and 21:00.

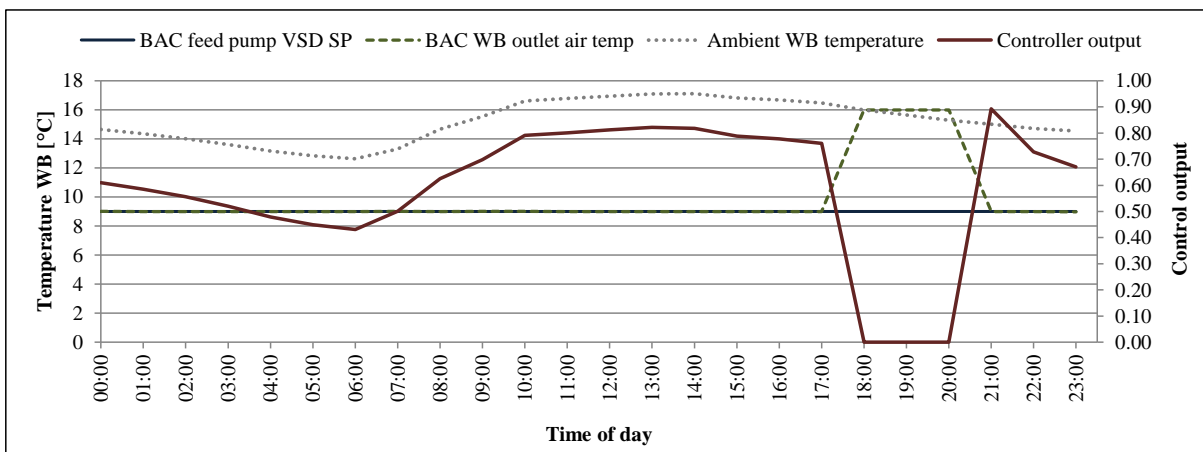


Figure 85: Proposed BAC feed pump control

The proposed control for the VSDs on the BAC return pumps is illustrated in Figure 86. The VSDs were simulated to control the BAC sump level at a set point of 50%. This value can be adjusted as required. The control feedback signal will therefore be the BAC sump level. The control response illustrated a profile similar to that of the VSDs on the feed pumps. This can

be expected because the sump level is a function of the supply flow from the feed pumps. The effect of the ice-plant load shifting is also visible from 18:00 to 20:00 in Figure 86.

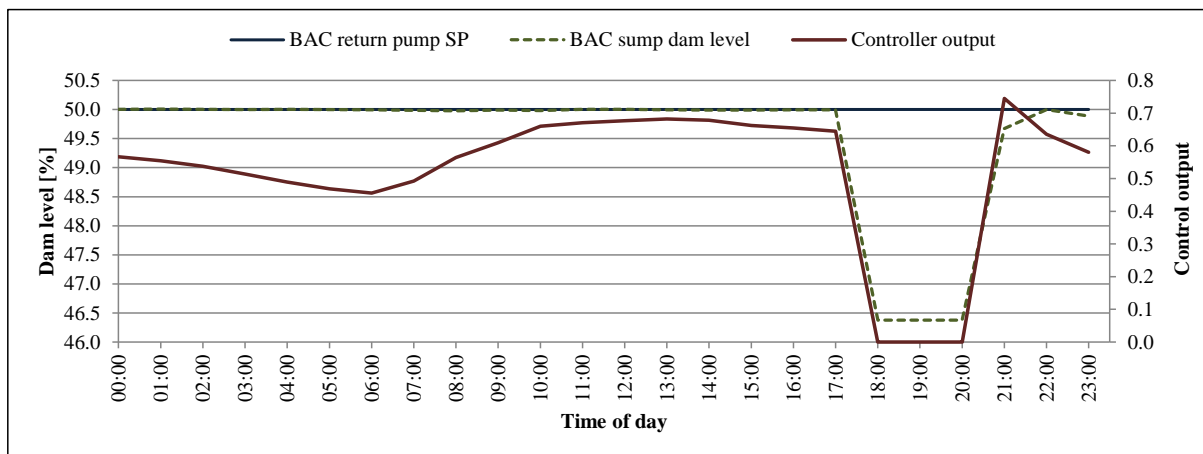


Figure 86: BAC return pump VSD control

The payback associated with the suggested energy saving measure is 10.1 months. An alternative measure to BAC optimisation is installing valve control on the BAC feed and return pipelines.

Install valve control on BAC feed and return pipelines

Installing valves on the BAC feed and return pipelines can also reduce flow through the BACs. This will result in a reduced power consumption of the surface chillers. The control parameters will be similar to the VSD installation. The average daily simulated baseline and the simulated effect of the VSD installation are illustrated in Figure 87. The results are similar to the VSD installation on the BAC feed and return pumps. However, the potential energy savings are reduced due to pump savings that are no longer included. The control valve installation on the supply and return lines can potentially result in an energy saving of about 9.6 MWh.

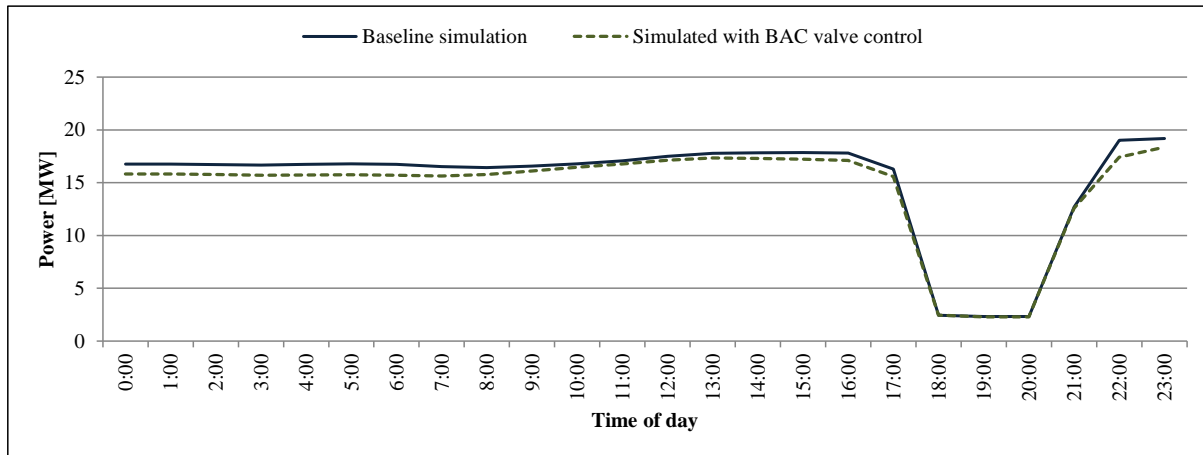


Figure 87: Control valve installation on BAC feed and return pipelines – Mine A

Although the energy savings are less than for the VSD installation, the project payback is reduced significantly. A summary of the equipment required for the initiative is illustrated in Table 38. Table 38 also illustrates the annual cost savings and the payback period excluding contractor costing. A payback period of 6.3 months is possible.

Table 38: Mine A energy saving measure – BAC control valve costing

BAC control valve installation	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
Valves and actuators	9.6 MWh	R1 215 000	R2 300 000	6.3
PLCs and instrumentation				
Cables and cable racking				
Control installation				
Commissioning of equipment				
Contingencies				

The control associated with the valve control on the BACs was similar to that of installing VSDs. The above-mentioned initiatives can now be presented to the mine engineer to request capital to implement either one of the two projects. Additional projects are also possible and will be mentioned in later sections.

Implement 77L booster pump control or install WCSs on lower levels

The 77L booster pumps were also identified as a potential sub-system for applying energy saving measures. The sub-system was inspected through the simulation and manual measurements that were done. It was found that the chilled water is not controlled or used efficiently in the MCUs.

It was determined that the water supply to the levels can be controlled during other periods of the day. To determine the effect on service delivery, the integrated simulations were used to investigate the system. It was found that the water flow to these periods can be reduced by

approximately 98 ℓ/s. A potential average daily energy reduction of 26.4 MWh was determined through the simulations.

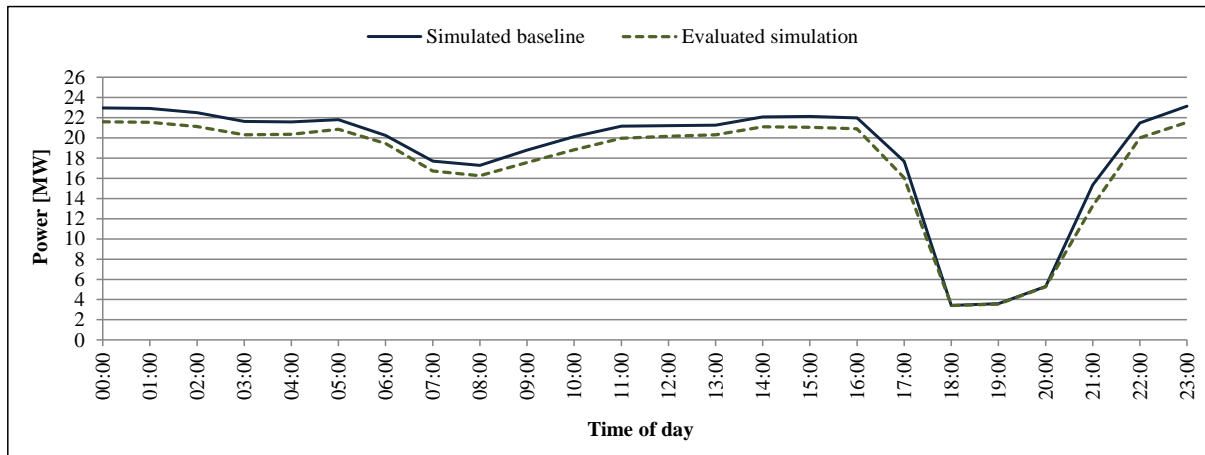


Figure 88: Simulated power – water flow control on 85L to 101L

However, two methods can achieve the savings. The first is installing VSDs on the 77L booster pumps. This would entail a more detailed study on the dynamic reaction of the system. However, the preliminary studies through the simulation indicated that the control would be possible and that the service delivery requirements would still be met. The second option is installing WCSs on each of the mining levels from 85L to 101L. This will ensure that mine personnel have optimal control of water to the levels at any time of the day.

Both options are expensive but have favourable payback periods. The WCS installation costing, annual cost saving and payback period are illustrated in Table 39.

Table 39: Mine A energy saving measure – water control on 85L to 101L costing

Flow control 85L to 101L	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
Valves and actuators	26.4	R3 861 984	R4 875 198	9.5
PLCs and instrumentation				
Cables and cable racking				
Piping and infrastructure				
Control installation				
Commissioning of equipment				
Contingencies				

Similarly, the MCUs on the upper mine levels (64L to 76L) can also be optimised by installing flow-regulating valves on the inlet pipelines. This has been proven to effectively reduce the consumption of chilled water by MCUs. This will result in less pumping and less refrigeration required. The costing involved with the upper mine MCUs is illustrated in Table 40.

Table 40: Mine A energy saving measure – MCU control on upper mine costing

Upper mine MCU flow control	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
Valves and actuators	12 MWh	R410 850	R2 893 391	1.7
Piping and infrastructure				
Commissioning of equipment				
Contingencies				

Optimising the upper mine MCUs has a very fast payback. This initiative will be the easiest to install and maintain the predicted savings. In such a scenario, the energy or mine engineer can now make an informed decision and prioritise the energy saving measures that have been identified.

The energy saving measures mentioned are only some of the identified projects that are possible for Mine A. Additional measures to be investigated include the following:

- Optimising additional Hitachi chillers which includes evaluation of VSD control;
- Implementing automatic integrated control of the 3CPFSs, Hitachi and ammonia plants; and
- Decommissioning the ice plant.

The measures have been identified with the easy-to-use models. This statement can be made due to the simplicity of easily switching off a chiller due to lowered chilled water demand and almost instantaneously being able to predict system impact. This is true for all the identified energy saving measures.

The resource cost involved with completing this study will be discussed in Section 5.4.4 to validate how easy the models and approaches are to use. The energy or mine engineer can therefore make informed decisions regarding equipment procurement, project payback and implementation time involved with energy saving measures.

5.4.2. Operational evaluation and changes and energy forecasting

The operational evaluation approach as well as the energy forecasting procedure form part of the simulation approach (P-3). The operational evaluation approach (B.1 to B.4) involves investigating potential operational changes. These investigations would not be feasible or would be limited without the newly developed models and approaches. The transient effect of system changes must be considered in such a case.

With this new approach, what-if analyses can be conducted easily. The findings can then be evaluated and the feasibility of implementation can be determined. The effect on the budgets as well as predicted energy consumption for each month of the year can be determined. Various factors can therefore be analysed and considered by applying these procedures.

Use alternate underground system feed from Hitachi plants

The first operational evaluation that was conducted with the completed models was the supply of chilled water to underground. It was noted that the water exiting the mining levels through the high-pressure sections is frequently overcooled. The simulation engineer therefore investigated the potential of supplying chilled water to underground, not only from the surface chill dam, but also directly from the Hitachi dam as well.

It was determined that this is indeed feasible. However, when ambient conditions are not sufficient, the ammonia plants must be used as the system is constrained by increased ambient conditions. In effect, water from 6 °C would then be supplied underground during the autumn, winter and spring periods. This can potentially result in significant energy and cost savings.

The effect of the alternate water supply to underground was evaluated using the developed simulations. The effect on the PCT inlet temperature is clearly seen in Figure 89. There is an approximate temperature increase of 1.5 °C during a typical simulated day. It was also determined that there is no residual effect on service delivery.

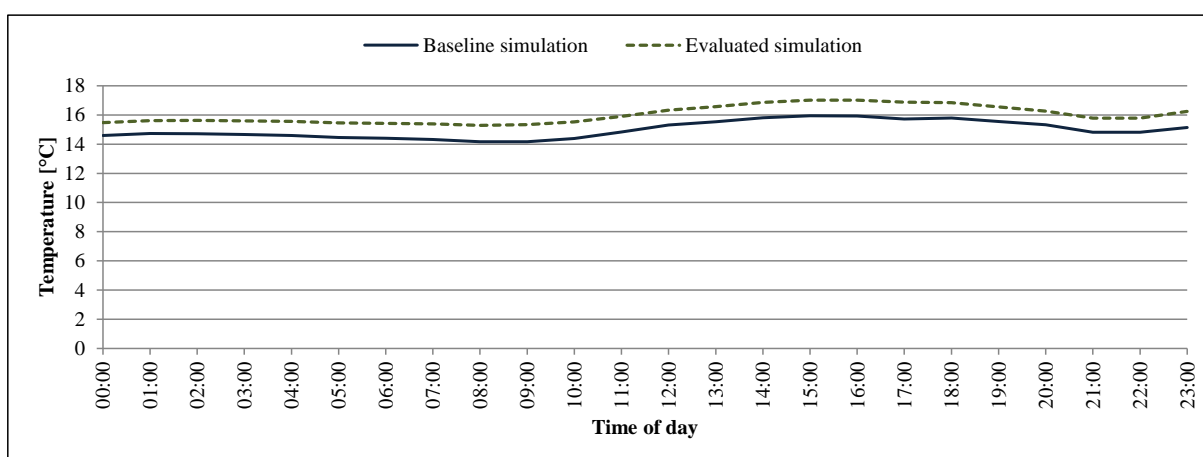


Figure 89: Effect on used water due to alternate water supply to underground – Mine A

The combined surface and underground system was analysed with the integrated simulation. The baseline versus evaluated simulation power consumption is illustrated are Figure 90. The effect of supplying water from the Hitachi chill dam can clearly be seen. Such an operational

change can result in a potential daily energy saving of approximately 34.8 MWh during the autumn, winter and spring seasons.

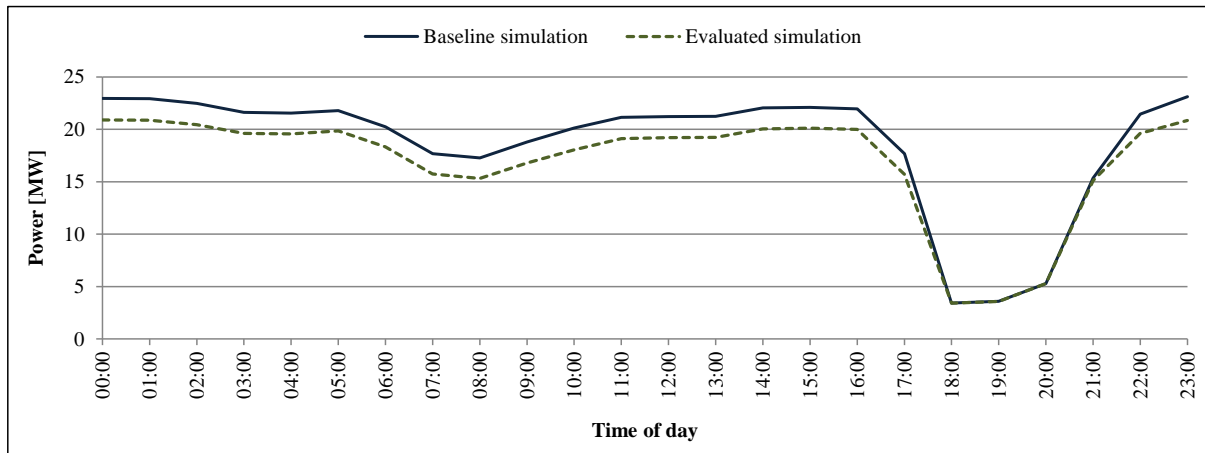


Figure 90: Baseline versus evaluated power consumption of water supply to underground

The summarised equipment costing of using the Hitachi chill dam water for underground operations is illustrated in Table 41. The costing, however, does not include any contractor costing. These types of project can be implemented by the mine with limited assistance from contractors.

The physical system was also investigated. It was determined that only some automation of existing valves was required to automatically switch between supplying water from the surface chill dam or from the Hitachi chill dam. Some additional instrumentation such as temperature transmitters may also be required to efficiently monitor the water temperatures to underground. A favourable payback of 1.2 months was determined.

Table 41: Hitachi utilisation for water supply to underground – Mine A

Underground feed from Hitachi's	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
Valves and actuators	34.8 MWh	R788 850	R7 733 334	1.2
Piping and infrastructure				
Commissioning of equipment				
PLCs and instrumentation				
Contingencies				

Feed BAC water from the Hitachi dam

Similarly, the BAC feed from the Hitachi dam was also investigated. Currently the BAC is supplied with water at 2 °C whereas a supply from the Hitachi dam could also be feasible during autumn and spring periods. The operational change was evaluated. The simulated baseline and evaluated simulation power consumption are illustrated in Figure 91.

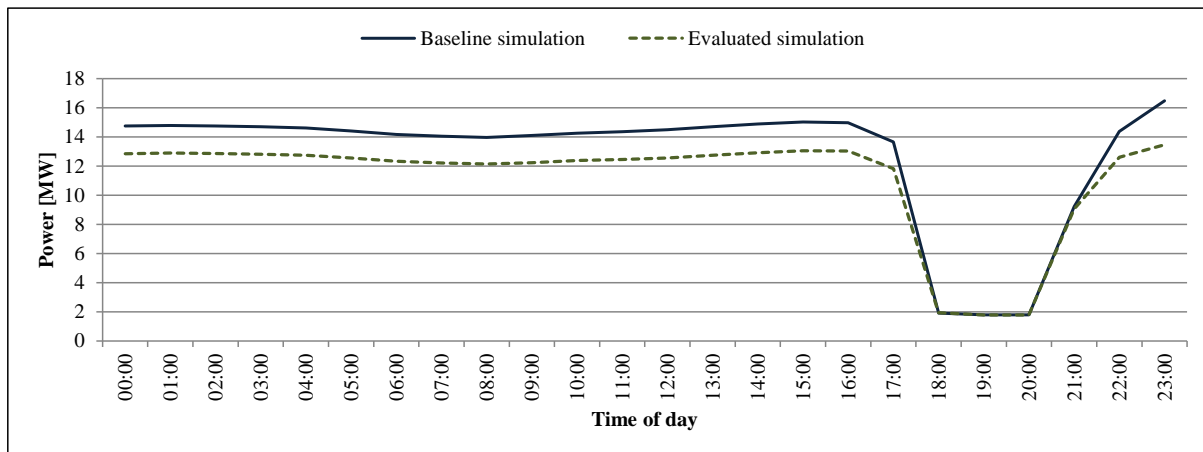


Figure 91: Baseline versus evaluated power consumption of BAC water from Hitachi's

A possible 21 MWh daily energy saving is possible during the autumn and spring months. The project costing for such an operational change was also considered. The costing is illustrated in Table 42. A project payback of 0.9 months is possible. The short payback is attributed to the fact that only the BAC supply line must be automated to feed the water automatically from either the Hitachi dam or the surface chill dam. In the case where the BAC water is fed from the Hitachi chill dam, the BAC outlet air temperature will reach peaks of approximately 10.1 °C.

Table 42: Hitachi-ammonia BAC supply optimisation – Mine A

Hitachi-ammonia BAC supply	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
Valves and actuators	21 MWh	R378 000	R5 063 445	0.9
Piping and infrastructure				
PLCs and instrumentation				
Commissioning of equipment				
Contingencies				

Analysing the effect of water temperatures during summer periods proved that such a change would affect the mining and ventilation conditions adversely. The potential effect of the configurational change on the BACs is illustrated in Figure 92. The allowable limit, as indicated by mine personnel, is exceeded.

A schedule should therefore be developed to ensure that the proposed configurational change does not affect the BAC air outlet temperature adversely. Further investigation is proposed to determine the efficacy of the cold BAC air supplied to the mining areas. This was not investigated in these analyses.

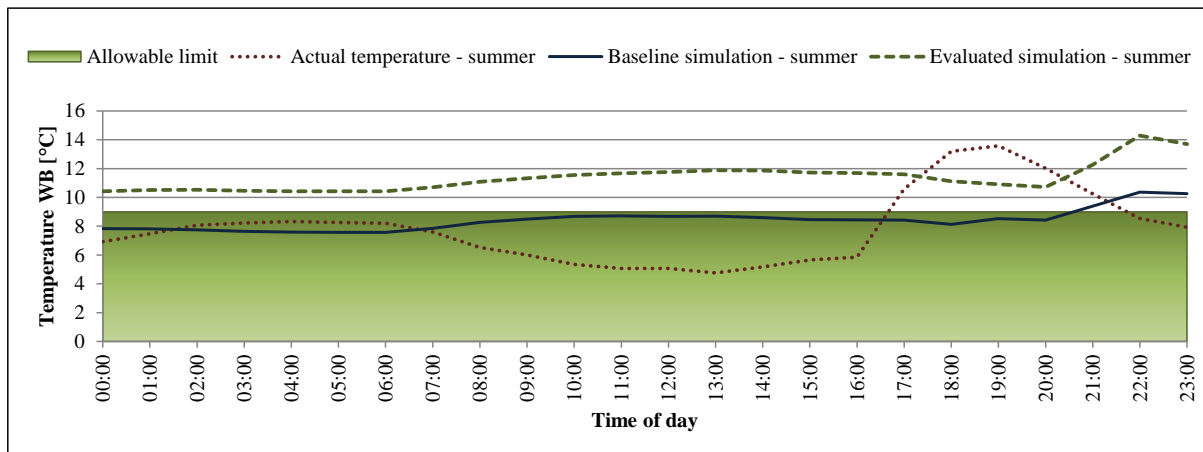


Figure 92: Limitation of feeding Hitachi plant feed to underground – BAC limit exceeded

The potential of the evaluated operational change can be considered due to the favourable energy savings. The costing involved with such an operational change was also investigated. Previous projects requiring similar equipment specifications were used to forecast the expenses related to this change.

Switch off ammonia plants when possible

Ammonia plants are typically overused during the transition of seasons – from autumn to winter, and from winter to spring. The cooler ambient temperatures can be used optimally to control the number of ammonia plants in operation. An operational evaluation was conducted where the potential of switching off ammonia plants during these seasons was investigated. It was found that the surface chill dam reaches temperatures of about 4 °C. This in turn influences the service delivery to mining levels and the cold water supply to the BACs.

However, it was determined that half the plants that are normally in operation can be operated in such a manner that the risk of too hot water can be avoided by running the plants during cooler periods of the day. The average daily power consumption over the autumn, spring and cooler summer days is illustrated in Figure 93. The power consumption is displayed for the entire integrated system.

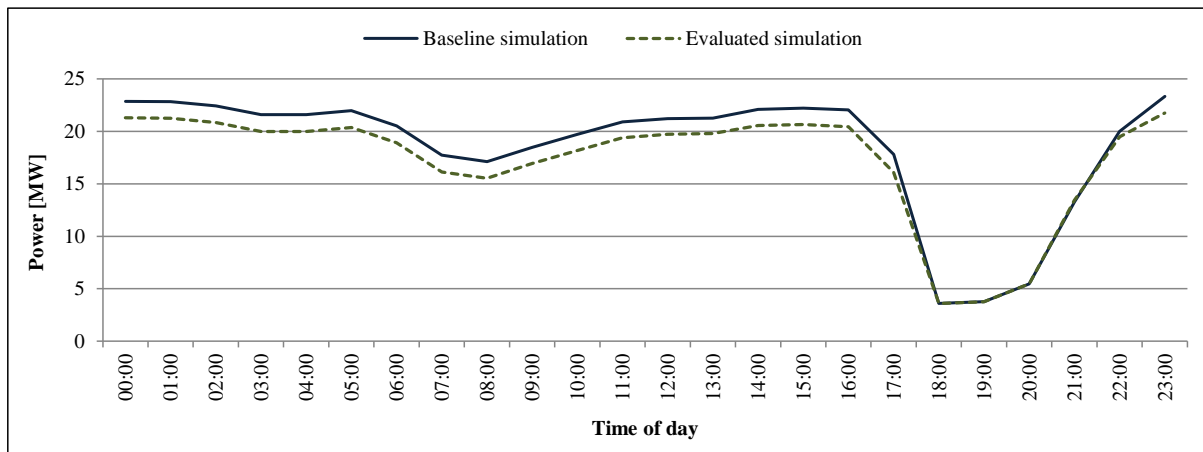


Figure 93: Baseline versus evaluated power consumption of reduced ammonia operation

As mentioned, the effect on the surface BACs should be considered if such an operational change were to be implemented. The BAC wet-bulb air outlet temperature between the baseline and evaluated simulations is illustrated in Figure 94.

As can clearly be seen, there is an adverse effect on the BAC. However, the outlet temperature should be evaluated on each of the mining areas. When the effect of the increased temperature is quantified on the underground mining areas, it should be determined if the operational change can be made. Mine health and safety personnel have to be consulted in such a case.

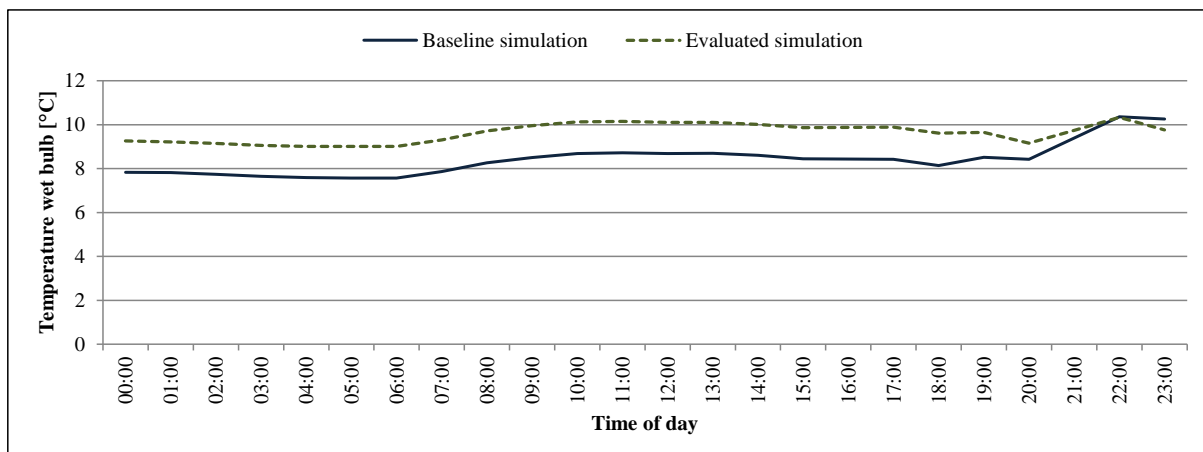


Figure 94: Reduced ammonia plant operation effect on BAC air outlet – Mine A

The influence that fewer plants in operation have on water temperature also needs to be considered. The effect on the outlet surface chill dam temperature is illustrated in Figure 95. The dam temperature increases to approximately 4 °C on average. However, this is suitable for the cooler months of the year.

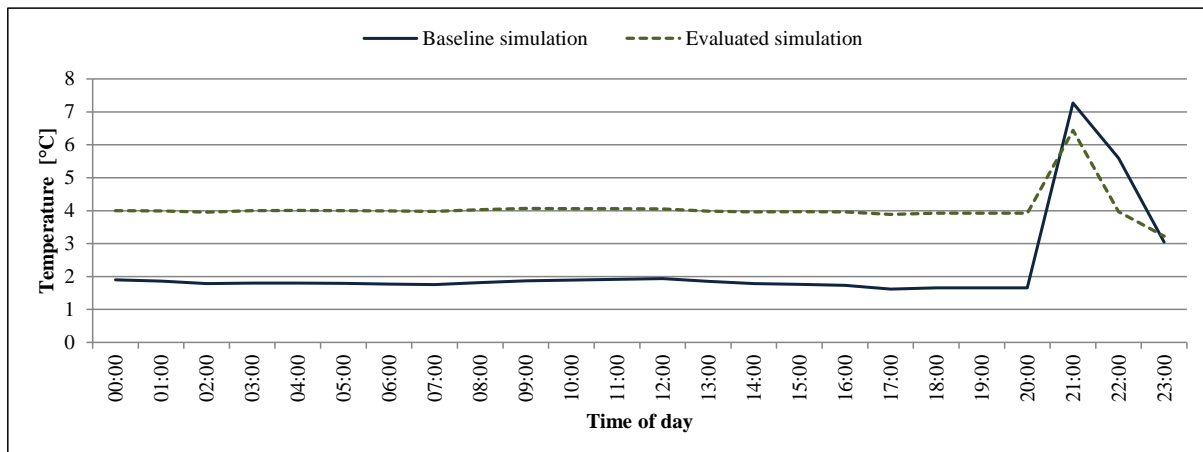


Figure 95: Reduced ammonia plant operation effect on temperature – Mine A

The costing involved with the reduced ammonia operation is illustrated in Table 43. As illustrated, no additional infrastructure is required for the operational change. The payback is therefore immediate.

Table 43: Reduced ammonia plant operation – Mine A

Reduced ammonia operation	Average daily energy saving	Estimated equipment cost	Annual cost saving	Payback period [months]
No equipment required	29.6 MWh	–	R6 586 667	Immediate

The operational evaluation conducted was limited. The limitation was partly imposed by Mine A's target for energy savings as well as cost savings compared with capital expenditure. However, the completed integrated transient simulations can be used to identify further operational changes. Some of the additional systems that can be investigated for thorough operational evaluation are the following:

- Using a high-pressure system on the top mine;
- Installing chillers underground instead of using all chillers on surface;
- Evaluating the effect of ventilation on the integrated MCS and the placement of MCUs.

5.4.3. Validation of the study

Energy management through dynamic integrated simulations

As mentioned in Chapter 1, MCSs are energy intensive and complex systems. Compiling integrated dynamic simulations for an MCS allows the energy engineer to understand, quantify and improve the relevant system. The simulations enable the engineer to identify energy saving measures, evaluate the effectiveness of the existing operation, do dynamic energy forecasts and conduct control emulation studies.

These studies would be limited if transient simulation models were not developed. Similar studies have been conducted before, but the effect on the integrated system could not be completely quantified. By applying the new models and approaches, various energy saving measures were identified. A summary of the identified potential energy saving measures as well as the cost savings are listed in Table 44.

Table 44: Summary of identified energy saving measures – Mine A

Energy saving measure	Average daily energy saving	Annual cost saving
BAC VSD installation	12.0 MWh	R2 893 391
Automated valve control on BACs	9.6 MWh	R2 300 000
Water control on 85L to 101L	26.4 MWh	R4 875 198
MCU water flow control (64L to 76L)	12.0 MWh	R2 893 391
Total (including VSDs)	50.4 MWh	R 10 661 980
Total (including valves)	48 MWh	R 10 068 589

Applying the new models and approaches also allowed for the existing system control and operation to be evaluated operationally. A summary of the identified potential operational changes and the cost savings are listed in Table 45.

Table 45: Summary of identified potential operational changes – Mine A

Potential operational changes	Average daily energy saving	Annual cost saving
Underground feed from Hitachi's	34.8 MWh	R7 733 334
BAC feed from Hitachi dam	21.0 MWh	R5 063 445
Reduced ammonia operation	29.6 MWh	R6 586 667
Total	85.4 MWh	R 19 383 446

The identified energy saving measure and the operational changes can enable Mine A to stay competitive in the gold mining market. However, the potential constraint of the identified improvements will be the mine personnel who are not proactively ensuring energy savings. A behavioural change is as important as the energy and cost savings for Mine A to stay competitive.

The newly developed models used in the simulation aided the successful simulation, analyses and predictions of the case study on Mine A and the verification of Mine P. The newly developed and adapted models included:

- Precooling, BAC and condenser circuits and sub-systems;
- Chillers and ice-plant sub-systems;
- Dewatering, turbine and 3CPFS sub-systems;
- MCUs; and
- Drilling PRVs.

These models also enabled the simulations to be conducted faster due to the preconstructed calibrated systems. Although these models are unique in the software, similar models can also be constructed in other applications. The new control emulation method was also successfully used to emulate the control of the system and to predict the impact of the control of the planned initiatives in a transient fashion.

Discussion of the validation

To validate this study, a practical evaluation of the newly developed models and approaches was done. The following was validated:

Energy management approach developed as part of the new simulation approach and unique integration of MCSs:

It was shown that the newly developed models can be used for energy management of MCSs by doing accurate baseline simulations, and manipulating the verified simulations to determine new energy saving projects. This was verified in Chapter 4 and validated by the case study on Mine A. However, this would not have been possible without the unique ability of the simulations to integrate the MCSs.

Ease-of-use of the new models, and approach and costs involved with conducting energy management studies on MCSs:

From literature, it was determined that conducting transient simulations of basic systems requires significant resources and between 10 and 20 iterations. It is difficult to compare this with the new models and approach, as the only literature found did not conduct similar studies to those done on Mine P and Mine A.

However, the resources and the number of iterations involved with the transient integrated simulations with this study were well documented. The number of iterations was mentioned in the verification and validation sections. The resources involved with conducting the case study on Mine A are illustrated in Table 46.

Table 46 illustrates that three different types of resource were used to conduct the study. These resources may vary in different companies. However, at least a project engineer with some simulation background is required. A senior project engineer is required for verification and validation purposes. The resources used in this case were an engineer, senior project engineer and project manager.

It should be noted that the ease-of-use of the new models enables mine personnel with some mining background to evaluate the simulations and use them to some extent that can still add value. As illustrated in Table 46, a total of 368 hours was used by the simulation engineer, 149 hours by the senior project engineer and 43 hours by the project manager. The hourly tariff for professional engineers operating in South Africa during 2010 was used [89].

It should be noted that the combined resources spent a total of 144 hours on the simulations, as highlighted by Step 4 to Step 7 in the green area. This is approximately 25% of the total hours spent on the study. This validates the model as being easy to use because the simulation engineer was relatively inexperienced with the relevant mining system and has only been exposed to simulations for a period of two months prior to conducting the study.

Conducting this study without the developed approach and models would have been a tedious task. The models are specifically developed for deep-level gold mining operations and allow the mine, simulation or energy engineer to conduct the studies quickly and effectively if information is available. In the case of limited information, industry averages or appropriate estimates can be used.

Table 46: Integrated system simulations resource allocation – Mine A

Scope of work				
Scope		Resource (hours)		
		Simulation engineer	Senior project engineer	Project manager
1	Gather system specifications and compile layouts	48	–	8
2	Acquire and verify data – automatically logged	20	4	–
3	Acquire and verify data – manual measurements	120	24	2
4	Compile sub-system simulations	96	6	–
5	Verify and validate sub-system simulations	2	16	1
6	Compile integrated simulations	8	8	–
7	Verify and validate integrated simulations	2	4	2
8	Consult with mine personnel	–	16	8
9	Conduct system investigations through simulations	16	12	2
10	Conduct operational evaluations through simulations	13	6	2
11	Consult with mine/energy engineer	8	12	4
12	Update and verify simulations	8	7	2
13	Do final review and present findings	4	16	4
14	Do documentation and administration	24	18	8
Total hours		368	149	43
Engineering Council of South Africa (ECSA) rate (R per hour)		670	920	1 550
Total rate (R total hours)		R246 560	R137 080	R66 650
Total		R450 290		

Successfully determine the effect of system changes through MCS integration in transient simulations:

It was shown that the simulations aided the engineer to evaluate certain system changes to achieve energy savings or to increase service delivery. This option is not limited and can be continued on Mine A. Although control emulation is possible with the new approach, in-depth knowledge of the functioning and operation of MCSs is still required.

5.4.4. Summary

The applications discussed in this section were very limited. Numerous other applications can also be considered as the energy engineer identifies and implements projects. The new models are not constrained in this sense. It is recommended that the integrated system simulations be updated continuously to ensure continual improvement by applying the procedures and approaches developed.

The requirements and solution to the defined problem were validated in the case study on Mine A. It was proven that successful energy management is possible by the applications as specified earlier in this thesis. The time taken to conduct the study validates that the model is easy to use.

5.5. Conclusion

The goal of Chapter 5 was to validate the use of the newly developed models and approaches by applying them on a case study mine. A deep-level gold mine in South Africa was selected as the validation case study. Mine A was selected due to the complexity of the MCS employed by the mine.

The solutions were validated by applying the models and approaches on Mine A successfully. Furthermore, it gave an indication of the resources and costs involved with conducting a similar study. The system was modelled by following the newly developed approach.

The energy consumption of Mine A was defined, and it was indicated how the system was analysed to do effective energy management through simulations. The combined simulation accuracy of the entire integrated system of Mine A was 94%. This accuracy is sufficient for conducting the simulation applications. The simulation applications consisted of the energy saving measure identification, operational evaluations and energy forecasting.

Potential energy saving measures of approximately R12 million per annum were determined with the simulation. Through the operational evaluation, potential system changes can result in approximately R19 million should the changes be implemented. This results in a combined potential cost saving of R31 million. These improvements could not have been evaluated to such an extent without the newly developed models and approaches. The study was validated in the chapter.



CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes this thesis and recommendations for future studies are discussed.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

Chapter 1 highlighted the existing state and importance of energy sources worldwide. It was found that energy and water efficiency is crucial to sustainable development. The focus of this study was on energy management of deep-level gold mines in the South African environment. These mines were defined as significant energy consumers that purchased a total of 13.8% of the electricity supplied. Thus, it was decided to focus efforts on reducing the energy demand in this industry.

MCSs consume approximately 41% of the electricity supplied to a typical deep-level gold mine. Deep-level gold mines in South Africa require MCSs to operate safely at increasing depths and extreme underground temperatures associated with deep-level mining operations. MCSs were collectively defined as the refrigeration, pumping and air cooling systems.

Various previous studies aimed at efficiently integrating the MCSs which resulted in significant energy savings. Chapter 1 also focused on reviewing the shortcomings of these previous studies that conducted energy management of MCSs with simulations through a critical evaluation.

It was found that there is a need for new dynamic integration models and simulations to efficiently integrate the mine cooling, water reticulation and ventilation systems of deep-level mines. The advantage of system integration was presented and proved beneficial to energy management.

It was determined that limited studies have been published that consider dynamic system integration through simulations. It was also determined that a new approach is required to efficiently integrate the MCS with simulations. The objective of this study was also defined in Chapter 1. The contributions of this study were defined in detail from the findings presented in the chapter.

Chapter 2 focused on a comprehensive review of published literature. Deep-level gold mines were reviewed to give the reader a background and basic understanding of MCSs on deep-level gold mines. The existing work on energy and cost savings through an integrative

approach was reviewed and it was found that additional savings could be achieved by implementing the measures identified through integrated transient simulations.

Through the comprehensive literature review it was also found that a trial-and-error approach was the alternative to integrated simulations. The review involved an in-depth analysis of the models currently employed in industry through which novel simulations can be conducted. The benefits of system integration were again proven by literature. It was found that the existing approaches and models in industry do not supply a sufficient solution to the objectives of this thesis.

Chapter 3 therefore focused on developing the new transient response simulation model and approach to achieve the objective of the study. The transient response simulation model was firstly developed with the focus on integrated transient response simulations. To make the model easier to use, various sub-systems for the integrated system simulations had to be developed. Significant focus was placed on reducing the time to conduct the simulation to save resources.

The new simulation approach for using simulations for energy management of MCSs was developed. The approach was developed into various separate approaches consisting of multiple procedures to achieve the goal of conducting energy management studies through simulations. This new approach is unique because no integrated transient simulations have been conducted in previous work. The simulation approach was therefore also determined to be unique.

A need was also identified for a control emulation method for simulating the control on actual systems. The control emulation method that was developed allows engineers to emulate the control of various applications on the MCSs to determine the effect on the process and energy consumption. These effects ultimately influence energy management of the MCS. This method also ensures reduced implementation time for projects. New applications for prefeasibility studies were also developed which consisted of operational evaluations and energy forecasts for the MCSs.

Chapter 4 focused on verifying the new simulations and approach for energy management of MCSs. The new transient response simulations were verified by comparing the simulated results with actual data of an MCS on Mine P. An overall simulation accuracy of 96.8% was

determined. The simulation model and approach was therefore fairly accurate compared with the actual system operation and power consumption. The integrated system was therefore successfully simulated.

The new component control emulation approach was also verified by comparing the simulated output of the controllers with the actual output. However, it was determined that the data-logging intervals of actual system response play a significant role in the component control emulation. This method was still deemed sufficient for preliminary control emulation studies. The control was accurately predicted; however, this requires data in smaller intervals for sufficient comparison.

Furthermore, the applications were also verified in principle by using the simulations. The methods developed for these applications were discussed and it was shown that the new simulation models and approach allow the simulation engineer to do operational evaluations and dynamic energy forecasting studies for potential projects. The new approach allowed an in-depth simulation study to be conducted with a resource cost of approximately 74 hours for the verification simulations alone. This was achieved due to the new approach.

The study was validated in Chapter 5. The goal of this chapter was to validate the use of the newly developed models and approaches through a case study application on Mine A. A deep-level gold mine in South Africa was selected as the validation case study. Mine A was selected due to the complexity of the MCS used on the mine.

The models and approaches developed in Chapter 3 were applied on the case study mine and the solution was validated. An indication of resources and costs involved were also given. The ease-of-use of the model was also discussed. It was shown that an inexperienced team can replicate a similar study with a resource cost of 368 hours for a simulation engineer, 149 hours for a senior project engineer and 43 hours for a project manager.

The newly developed approach therefore aided in an effective study with a significant time constraint. The new approach allowed the simulations part of the study to be conducted with a resource cost of 144 hours. This was the case for Mine A due to the complexity of the system and gives an indication of the simulation time required for 24 iterations of the transient simulations.

The combined simulation accuracy of the entire integrated system of Mine A was 94%. The accuracy was deemed sufficient for conducting the simulation studies. The simulation applications consisted of the energy saving measure identification, operational evaluations and energy forecasting.

Potential energy saving measures of R12 million per annum were determined with the integrated transient simulations. Through the operational evaluation, considering the transient effect of system changes, potential system changes can result in approximately R19 million should the changes be implemented. These improvements could not have been evaluated to such an extent without the newly developed models and approaches. The study was fully verified and validated in the chapter. At a total resource cost of approximately R0.45 million, potential savings projects of R31 million were identified with the simulations.

As stated in Chapter 1, the objectives of the study firstly involved selecting appropriate models for conducting novel transient simulations of the integrated cooling system. The models that were selected formed part of the PTB software, with adaptations that were made in the model development in Chapter 3. The models were validated through the case study on Mine A.

The second objective was to develop a new transient response simulation procedure for simulating MCS energy consumption. These models were developed and validated in Chapter 4 and Chapter 5 respectively by applying the new simulation models. A new component control emulation method for energy saving project commissioning and simulation was the third objective.

This method was verified by comparing control outputs with actual control system outputs. The method was also validated by simulating the operation of Mine A's integrated cooling system accurately. The fourth objective was to ensure that the developed models were verified and validated, as previously discussed.

6.2. Contributions to the field

The contributions as set out in the start of this thesis are listed below. The contributions were developed, evaluated, verified and validated throughout the course of this thesis.

1. Transient response simulations to integrate MCSs for energy management.

2. New control emulation method with integrated transient response simulations for energy saving measures on MCSs.
3. Dynamic energy forecasting of MCSs through transient response simulations.
4. New transient response simulation approach for integration of MCSs.

From the outcomes of the contributions, a unique approach was followed and it was proven that the new simulations and approach can be used for energy management of MCSs. The widespread adoption of the newly developed models and approach can potentially lead to significant energy and cost savings in this industry. It can also contribute significantly towards national and energy efficiency targets.

6.3. Limits of this study and further recommendations

At the start of this thesis, an MCS was defined as the refrigeration, pumping and water reticulation systems of a deep-level gold mine. However, these systems have a significant impact on the ventilation of a deep-level gold mine. The effect on the ventilation system needs to be considered in future studies.

A separate study should also consider the dynamic integration of the MCS with the deep-level mine ventilation system. It is suggested that this must be investigated through new ventilation simulations, as there are no present models to help with this dynamic integration. Although the BACs have been optimised in previous studies, there is still scope for integrating the BACs with the ventilation system. Ventilation on demand is becoming the state of the art, and should be considered with such integration.

A future study should also determine the efficacy of surface BACs on deep-level gold mines. Although this thesis was not specifically aimed at integrating BACs with mine ventilation, there seems to be significant scope for future optimisation studies to completely re-evaluate using surface BACs.

The models used and developed in this thesis still require empirical models to be developed for the 3CPFSs, soft ice, and hard ice plants. It is suggested that these models must be developed as part of PTB. This will make the simulations even faster and may also reduce the required iterations.

It was further identified that the existing International Performance Measurement and Verification Protocol is not sufficient for the mining or industrial industry in terms of calibrated simulations. This was determined when examining the existing approach to calibrated simulations for the building environment. The approach developed in this thesis can aid in developing a new protocol to measure and verify energy saving projects. It is therefore suggested that a separate study should focus on developing such a protocol.



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CITED LITERATURE AND BIBLIOGRAPHY

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APPENDIX I – MCS COMPONENTS

A simplified MCS is illustrated in Figure 96. Reference is made to MCSs throughout this thesis. In these instances, the referral is made to Figure 96.

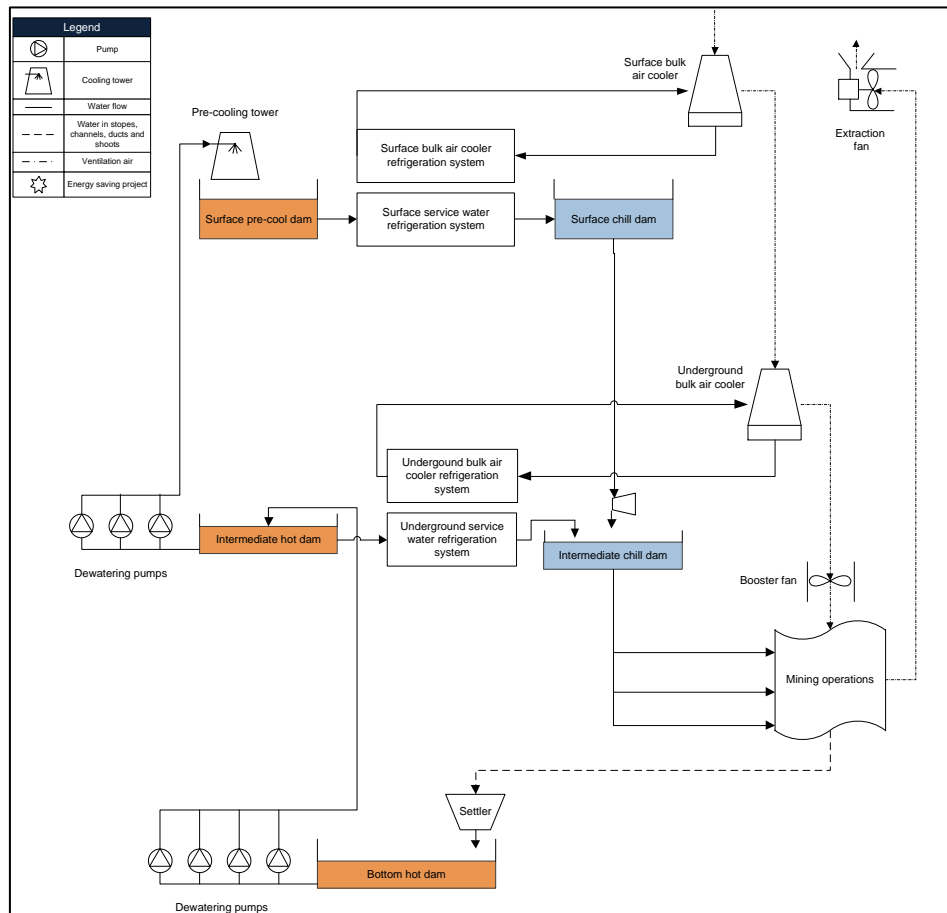


Figure 96: Simplified MCS

Cooling system components

The various key components that make up the sub-system configuration of an MCS will now be reviewed. These components form part of the integrated system that was optimised in this thesis. It is crucial to understand the fundamental principles of their operation before considering any alteration for improved energy efficiency.

1. Cooling towers

Mine cooling is categorised as direct heat exchangers due to their fundamental operation principles. There are two processes that involve cooling towers in a typical MCS, namely, the precooling and condenser cooling processes. The precooling process involves cooling the

water before it enters the evaporator circuit. The condenser cooling process involves the rejection of heat to the atmosphere to cool condenser water.

In both processes, a combination of convection and evaporation causes heat to be removed from the water, and thus transferred to the ambient air [90]. Nozzles are used in mechanical draft cooling towers to disperse the inlet water, resulting in droplets forming. The pressure drop in the nozzles, as well as the presence of packing or cooling tower fill, determines the radii of the water droplets. The water flow rate and temperature also determine the size of droplets, which in turn influences the heat rejection to atmosphere [91].

A schematic drawing of a mechanical draft cooling tower is illustrated in Figure 97. Mechanical draft cooling towers are most commonly used on surface of deep-level mines [57]. The cooling towers are used to cool the water to within approximately 3–6 °C of the ambient air temperature [30]. Warm process water enters the cooling tower and flows through the spray nozzles that disperse the water. As the water is dispersed, the ambient air is sucked through the inlet louvres where after the water and air mix.

The warm air is extracted to the ambient surroundings. The air velocities in these types of cooling tower are in the range of 1.5–3.6 m/s. After the water is cooled, it is collected in the sump to be cooled by the chiller plant. The COP of a mechanical draft cooling tower is approximately 30 [23]. Only the pumping of reticulation water, the motors of the axial fans and the replacement of the evaporated water can be identified as energy consumers on these towers. However, changing the operational parameters of cooling towers can have a significant effect on their performance.

Scaling and fouling of the cooling tower fill should be considered when altering the inlet flow and temperature. Scaling and fouling is the build-up of sedimentation and impurities on the tower components, such as the tower full and air inlet louvres.

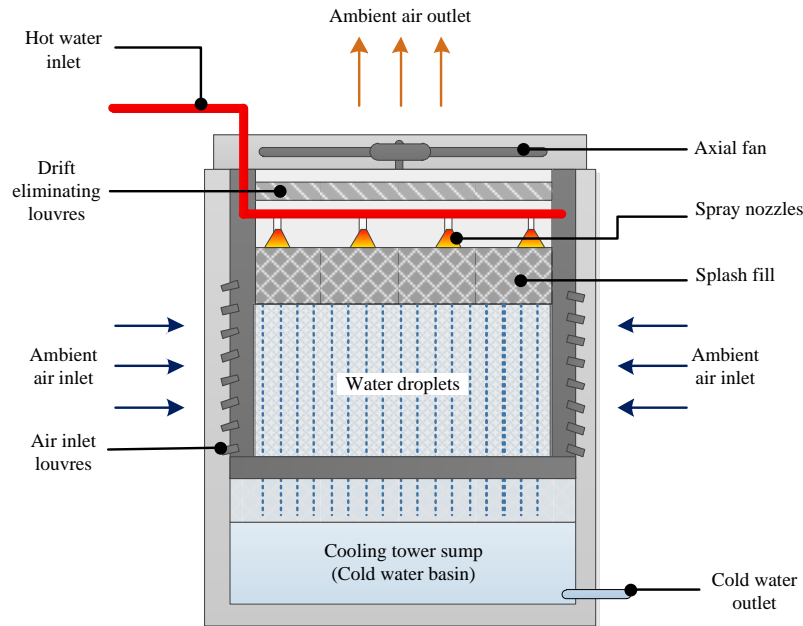


Figure 97: Typical cooling tower schematic drawing(adapted from [62])

The OEM specifications must always be considered when optimising the flow and temperature through the tower. A decrease in COP can be a result of inadequate flow rates and temperatures. From a maintenance aspect, the treatment of water becomes important to ensure effective heat transfer in the tower [92].

2. BAC towers

BACs are used as centralised units, situated underground or on surface, to cool and dehumidify the air entering the mine or a mining level. BACs use the chilled water from chillers to cool the ambient air to the required temperature for circulation underground [62]. BACs are similar to cooling towers as described in the previous section, except for the heat transfer direction [93].

BACs, which are installed on surface, are normally situated near the ventilation or services shaft with the cold air being sent underground by ducting into the shaft. During colder seasons in South Africa, the surface BACs are not required due to the ambient air being sufficiently cold and dry during these months. Maintenance on these towers are normally conducted during these months, which include months between June and August [23].

BACs used underground operate in a similar fashion, except that there is an added benefit for mine ventilation and cooling, as these BACs act as dust suppressors while cooling the air [13]. However, the operational costs associated with using BACs underground increase

with mining depth and pumping distance. A solution to this is to install the chiller plants underground to shorten the distance in which chilled water, and therefore air, travels [21].

The COP of the chiller and the entire cooling system is dependent on the performance of the BACs. The cooling range of the chillers can be affected by inefficient cooling towers that can cause a gradual temperature rise throughout the system [90]. The water-side efficiency of the cooling tower can be calculated using Equation 9 [74].

$$\eta_W = \frac{T_{wo} - T_{wi}}{T_{ai(WB)} - T_{wi}} \quad \text{Equation 9}$$

Where:

η_W	=	water-side efficiency (%)
T_{wo}	=	water out temperature (°C)
T_{wi}	=	water inlet temperature (°C)
$T_{ai(WB)}$	=	air inlet wet-bulb temperature (°C)

The range of the BAC is the delta of the water inlet and outlet temperature as given by $-(T_{wo} - T_{wi})$. The approach of the cooling tower is the difference of the water outflow and wet-bulb temperature of the airflow as given by $-(T_{ai(WB)} - T_{wi})$. The performance indicators of BACs are similar to those of cooling towers.

3. Storage dams

MCSs require storage capacity for hot water, dewatered from underground, and chilled water for storage on surface and underground [94]. Chilled water demand varies daily, resulting in a variation of chilled water use and hot water from underground pumped to surface. Variations in chilled water demand also occur due to seasonal effects; this in turn governs the number of chillers required for operation [59].

Chillers are used to supply a constant temperature to the chilled water dams, maintaining a set temperature throughout a typical day. When the chilled water dam is full, water is recirculated to the precooling or hot dam. Some mines control chilled water dams on a specified level by throttling valves to avoid unnecessary cooling by matching the demand. However, controlling water flow by throttling valves is an inefficient process [95]. Implementing variable flow strategies is therefore more efficient [96].

Some mines suffer from poor water quality; sediment build-up is thus a frequent occurrence. Sediment build-up can restrict dam level limits and, therefore, control on storage dams due to the reduced capacity. Mines experience these constraints when production surpasses the settler operating capacity [97]. Figure 98 illustrates a typical settler used for separating mud from service water. Mining water used on a typical mining level, as well as fissure water, flows down the shaft to the next levels in a drain system that accumulates at shaft bottom. The water and mud is then separated other using settlers.



Figure 98: Mine settlers used for separating mud from service water [13]

Poor water quality and sedimentation build-up result in more frequent maintenance on all system components. The increased maintenance can lead to increased operational and labour costs [23].

4. Chillers

A simplified mine refrigeration system is illustrated in Figure 99. Reference is made to refrigeration systems throughout this thesis. The process flow and basic operation of mine refrigeration systems are illustrated with referral made to Figure 99.

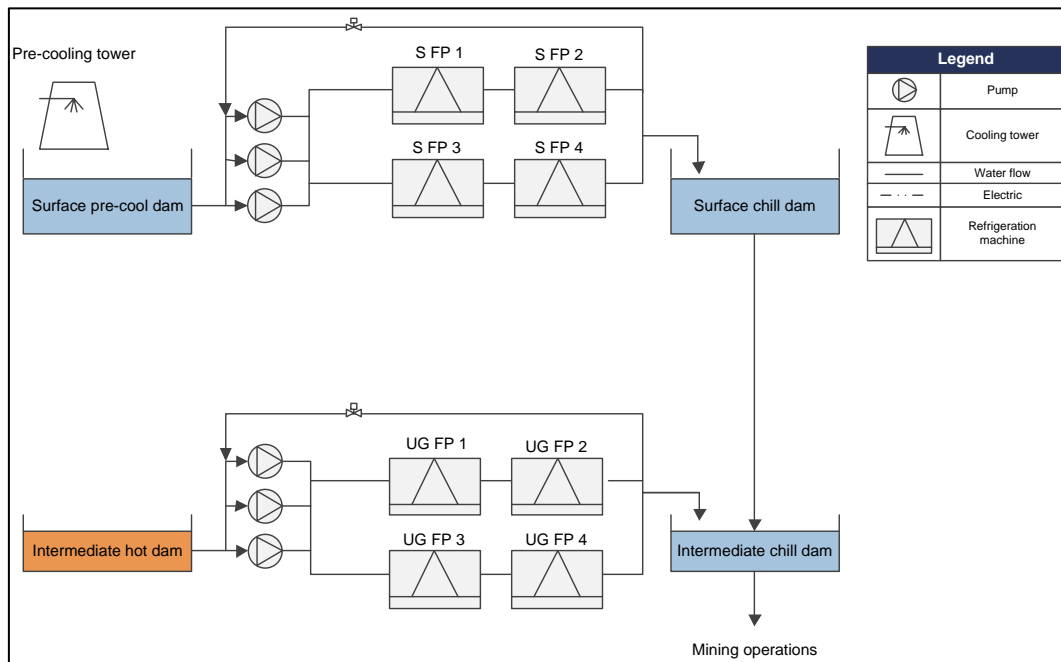


Figure 99: Simplified mine refrigeration system

A typical MCS can consist of one or more chillers arranged in three different configurations. The arrangement is mostly dependent on the requirements of the specific mine. Chillers are designed to handle variations in the thermal loads. Different chiller loads are catered for by the different arrangements. Figure 100 illustrates the three different chiller configurations typically found on deep-level mines.

The variations in chiller configurations can be [81]:

1. Parallel configuration – used for variable flow requirements;
2. Series configuration – used for variations in temperature; and
3. Series-parallel configuration – variable flow and variable temperature requirements.

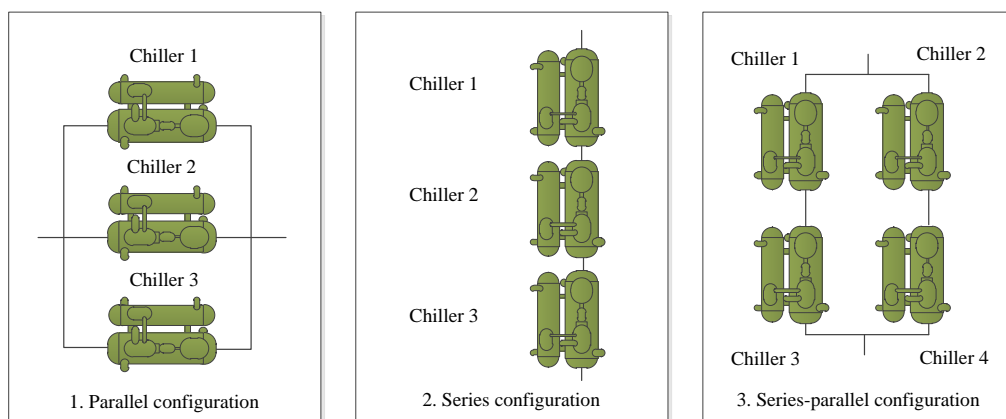


Figure 100: Chiller configurations used in industry(adapted from [62])

Surface and underground chillers are used to cool mining water for the mine cooling and water reticulation systems, and provide cold air to workplaces by using spot coolers. Chiller plants situated underground are constrained due to the limited availability of exhaust air, where surface chillers use atmospheric air [23]. Chillers plants can cool water to between 1.5 °C and 6 °C, depending on the specific mine's requirements [30]. Typical deep-level mine chillers have individual cooling capacities to the order of 6 MW [98].

Chillers use shell-in-tube heat exchangers that use screw and centrifugal type compressors [99]. The main refrigeration cycles used in industry are vapour-compression and ammonia-absorption cycles. The specific mine's standards and requirements normally determine the required refrigeration cycle [100].

The vapour-compression cycle used in most mine chillers is illustrated in Figure 101. The water flows through the tubes as the refrigerant flows in the shell. The latent heat of evaporation in the refrigerant is used to chill the water in the evaporator. Heat rejection in the process is absorbed by the condenser water [100].

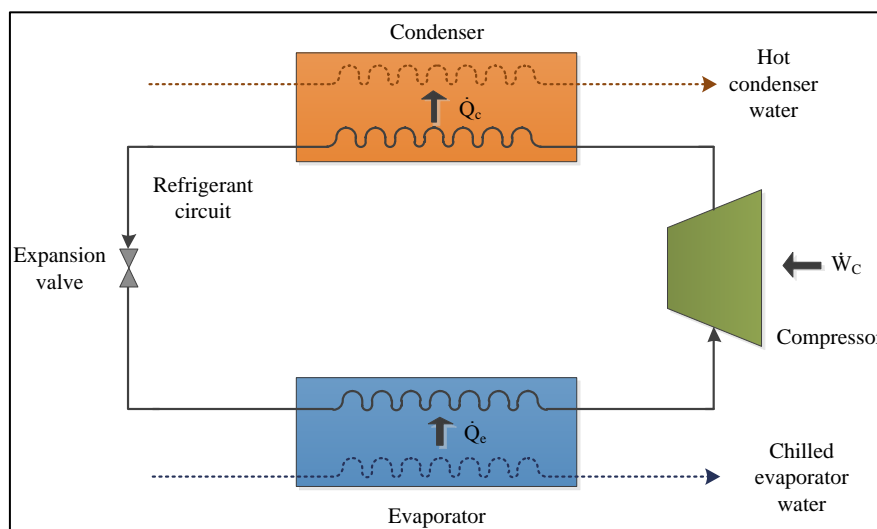


Figure 101: Vapour-compression cycle used in mine chillers(adapted from [62])

The compressor of a chiller has guide vanes (for centrifugal compressors) or slide valves (for screw compressors). The cooling load required is controlled by the guide vanes or slide valves, depending on the type of compressor used [101]. The system-specific pressures and specific volume requirements govern the type of compressor to be used [99].

The compressor is the main power consumer on a chiller. The COP reflects the efficiency of the chiller, which is largely dependent on the compressor power consumption. The COP of the chiller can be calculated using Equation 10 [38].

$$COP = \frac{Q_{evaporator}}{P_{ref}} \quad \text{Equation 10}$$

Where:

COP	=	coefficient of performance (–)
$Q_{evaporator}$	=	refrigeration rate (kW)
P_{ref}	=	compressor motor power (kW)

A high COP value, typically between 6.0 and 6.5, indicates an efficient chiller. The cooling load changes and compressor power input affect the COP of the chillers. A set water outlet temperature in the evaporator circuit is achieved by compressor-capacity control systems. The equation used to calculate the refrigeration rate of the evaporator is given by Equation 11.

$$Q_{evaporator} = \dot{m}_{water} C_p (T_{out} - T_{in}) \quad \text{Equation 11}$$

The equation used to calculate compressor three-phase motor power is given by Equation 12.

$$P_{ref} = \sqrt{3}VIpf \quad \text{Equation 12}$$

Where:

P_{ref}	=	motor power (kW)
V	=	volt (V)
I	=	ampere (A)
pf	=	power factor (–)

From Equation 11 and Equation 12, a change in evaporator flow rate and temperature can affect the refrigeration rate, and therefore influence the COP of the chiller plant.

5. Ice plants

Ice is produced in one of two forms in current ice installations, namely, “slush” ice (having 70–75% of ice by mass) and irregular “hard” particulate ice [102]. Slush ice is produced by dewatering a dilute ice slurry and hard ice is made with extensive freezing surfaces. It was found that the cost of owning and operating the two types of system seem to be comparable for a depth of 3 km [103]. A simplified mine thermal ice storage system is illustrated in Figure 102.

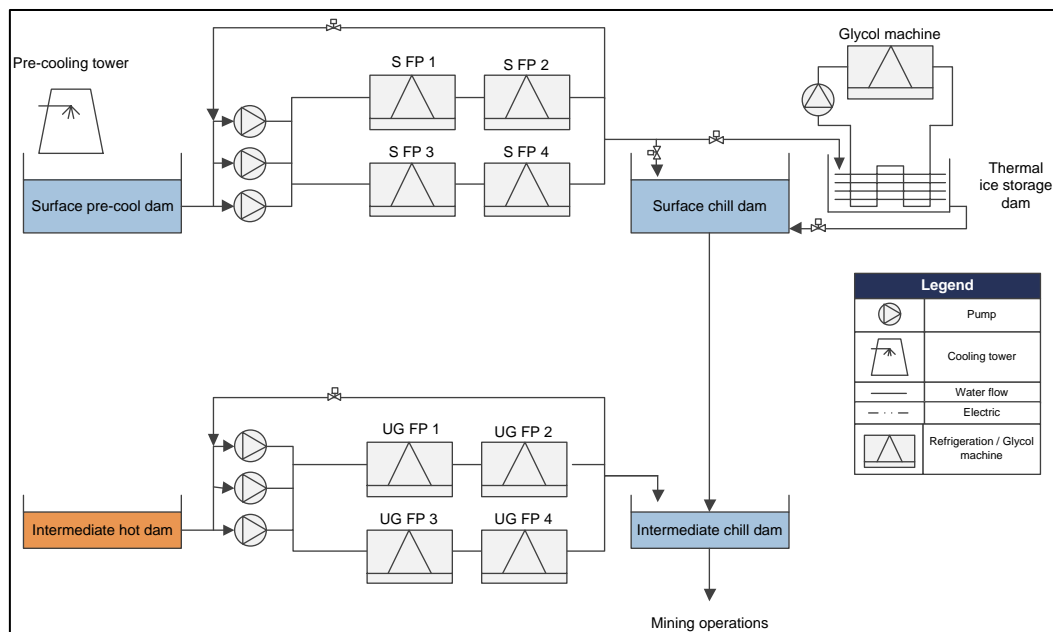


Figure 102: Thermal ice storage system

Slush ice plants have higher COPs but these plants incur higher water pumping costs due to the wetness fraction of ice sent underground. More conventional installations are used to make hard ice with extensive freezing surfaces, using defrosting cycles for harvesting the ice. Most of these installations use screw compressors with ammonia refrigeration cycles. Water quality and brine management are some of the main concerns of using vacuum ice machines, due to the risk of corrosion of the freezing surfaces. A simplified ice system is illustrated in Figure 103.

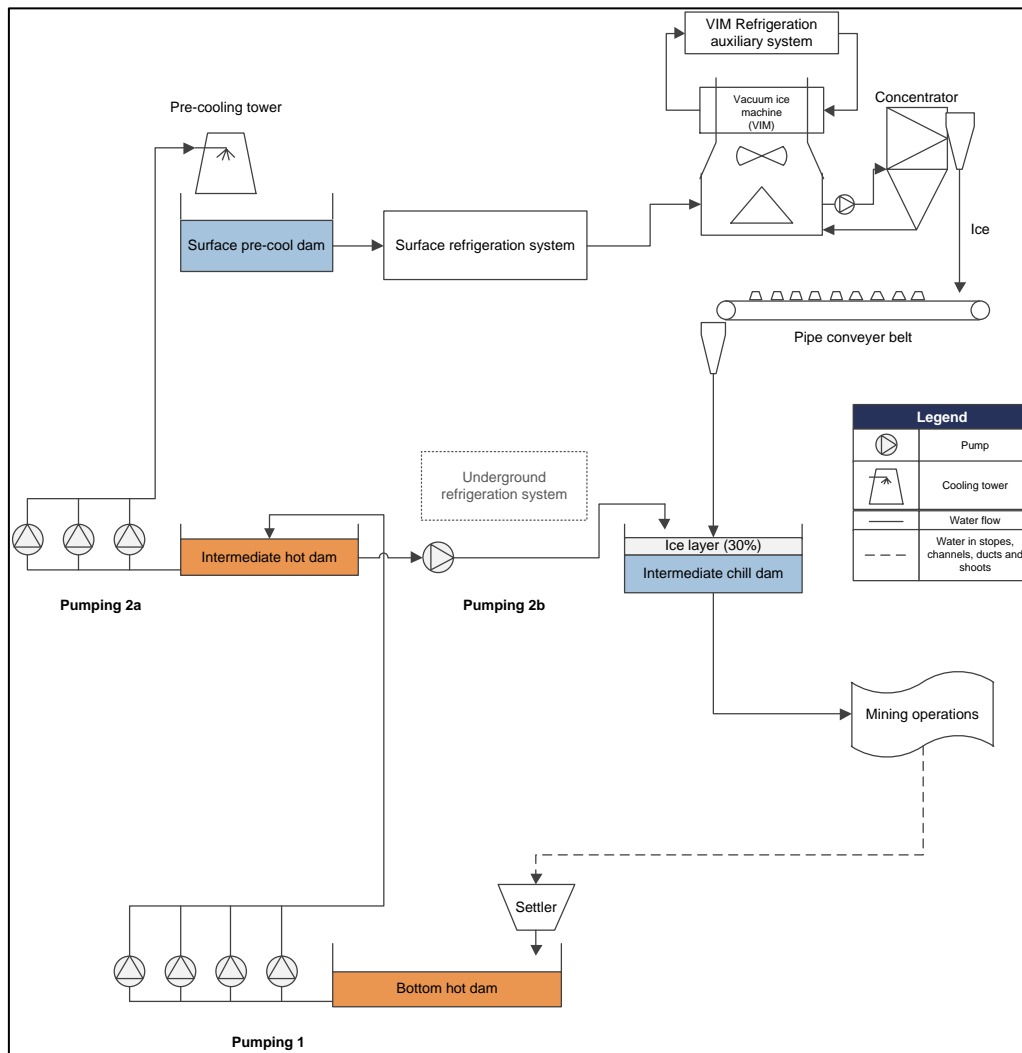


Figure 103: Ice system layout

Ice can provide the same cooling capacity as normal chilled water, with 70% less mass flow rate. However, the initial maintenance and operating costs of ice plants are high. In the case of South African mines, the costs associated with running ice plants are less than the burdens when pumping heads of 2 500 m are reached. As indicated in literature, water being pumped underground can experience an increase of 2.4 °C per kilometre of pipe run [21]. Ice only becomes a viable alternative for underground cooling where depths exceed 1 900 m [13].

Mines therefore use ice as an energy saving strategy to reduce the amount of water that is circulated through mining operations, therefore reducing the pumping energy required. Transporting hard ice to working areas is not feasible, but mines implement a conveyor system to transport hard ice to the chilled dams where the ice melts to decrease the water temperature to approximately 1 °C [13].

It should be noted that ice systems also enable other energy and cost saving initiatives, especially in a country such as South Africa where variable power tariffs are imposed. These initiatives include thermal energy storage and load-shifting capabilities. However, the effectiveness of these initiatives still have to be tested fully.

Literature on the use of ice in the mining industry is about ice being an alternative to underground chiller plants, or reducing the amount of water circulated, or ice storage. An ice water mixture is always used irrespective of the sort of ice cooling method.

The specific heat of ice (C_p) is at 2.04 kJ/kg.K, and it is not an advantage to the 4.18 kJ/kg.K specific heat of water [13]. Ice below 0 °C blocks pipes because the inside of the pipe wall freezes. Therefore, ice below freezing point is rarely used [100].

6. Turbines

A simplified mine turbine system is illustrated in Figure 105. Companies like Sulzer promote products such as turbine-pump configurations, where dewatering pumps are used as turbines. However, the Pelton wheel is the most popular turbine used in South African mines [13]. A Pelton wheel turbine is illustrated in Figure 104.



Figure 104: Pelton wheel turbine – front view[13]



Figure 106: Pressure-reducing station situated on a mining level

Most mines have poor water quality that affects the turbine availability due to the sensitivity of the equipment of a turbine. The dissipating valves are used in conjunction with the turbines to supply the required flow to mining sections. The dissipating valves are usually on a common supply manifold with the turbine. However, operating the dissipating valve while running the turbine reduces the supply pressure to the turbine. The turbine will then operate below the capacity due to the reduced pressure differential [13].

7. Pumps and motors

MCSs use pumps as part of the water reticulation network. These pumps supply various system components with process water, such as the condenser and evaporator water circuits. These pumps, including the cooling tower fans, are termed the “auxiliary equipment” of the cooling system. The auxiliary pumps operate separately from the chillers and can be controlled individually [73].

Auxiliary pumps can be configured in various configurations when applied to chillers, namely, parallel or direct-inline. Figure 107 illustrates the inline pump and chiller configuration, and the parallel pump-set configuration. Configuration 1 is applied to individual chillers arranged in parallel, whereas Configuration 2 is used in common manifolds to supply a network of chillers [62].

These configurations are important when considering pump speed control. Parallel pump sets require valves on the inlet chillers to control the flow through the chiller according to the design flow. Common manifolds complicate the control of auxiliary pumps due to the pressure drops experienced. Inline pumps, however, are suitable configurations for controlling pump speed effectively due to only the one chiller being affected.

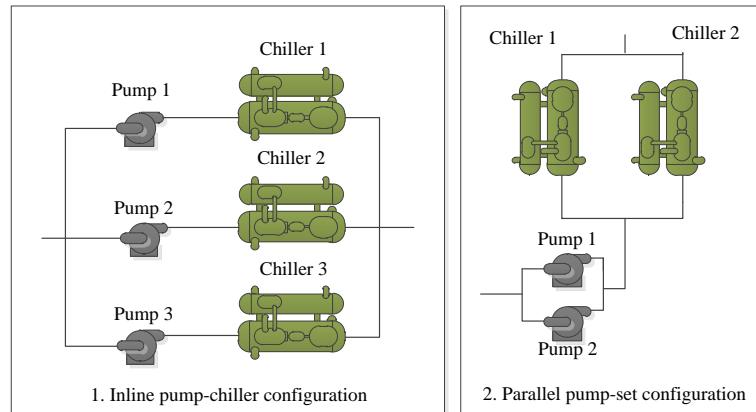


Figure 107: Chiller-pump configurations used in industry(adapted from [62])

Centrifugal pumps are most commonly used in these applications due to the pump size varieties that are available [105]. Positive displacement pumps with higher efficiencies are also available, but are limited in size. The impeller and casing shape design govern the efficiency of producing the required pump pressure. The pressure produced by a centrifugal pump is due to a rotating impeller accelerating the passing liquid circumferentially [23].

Pump selection for these cooling systems require matching the system characteristics curve with the characteristics of the pump. The system curve reflects the positive static head and friction of the relevant system, whereas the pump curve shows the designed performance of the pump [106]. Numerous influencing factors need to be considered when controlling the speed of centrifugal pumps due to their influence on the pumping efficiency.

Pressure control on these pumps is therefore limited by the fact that the efficiency of the pump is changed due to the speed change. Affinity laws can be reviewed to determine the effects that flow rate reductions can have on the characteristic curve of the pump [107]. The affinity laws are illustrated from Equation 13 to Equation 16 [108].

$$\frac{Q_1}{Q_2} = \frac{D_1}{D_2} \quad \text{Equation 13}$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \quad \text{Equation 14}$$

$$\frac{H_1}{H_2} = \left(\frac{Q_1}{Q_2}\right)^2 \quad \text{Equation 15}$$

$$\frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^3 \quad \text{Equation 16}$$

Where:

D	=	impeller diameter (m ²)
Q	=	water flow rate (ℓ/s)
H	=	pressure head (m)
N	=	rotational speed (rpm)
P	=	pump input power (kW)

When reviewing the affinity laws, the flow rate (Q) is directly proportional to the speed of rotation (N). The increase in pressure head (H) is directly proportional to the square of the flow rate and, lastly, the input power is proportional to the cube of the speed of rotation [109].

The region of optimal pump efficiency on the pump characteristic curve should generally correspond with the operating point of the pump. This region is called the best efficiency point. System changes, such as discharge valve adjustments, have the effect of changing system resistance, therefore affecting the flow rate and pressure of the pump.

These factors are important to consider due to the use of VSDs on pumps in the mining industry [96]. Systems that are mainly dominated by friction losses are beneficial for variable flow or pressure control. However, system characterised by significant static pressure heads have limited speed range for control. These systems therefore suffer significant efficiency losses under variable flow control [64].

Consider the operating points and efficiencies of a system- and pump characteristics curve, as illustrated in Figure 108. The pump efficiency can be maintained while the required input power is significant [64]. This case is true due to the speed reduction causing the pump operation point to move down along the iso-efficiency line. Therefore, small static heads and significant friction in MCS applications are therefore suitable for the control [81].

Further inspection of Figure 108 clearly indicates that for a system with no static head, the operating point at A at a rotational speed of N_1 translates to A' due to the speed reduction N_2 . The same iso-efficiency is therefore maintained from A to A'. In contrast, in a system with a

large static head, the operating point at the reduced speed B' will translate to an efficiency lower than that of operating point B at a nominal speed of N_1 [64].

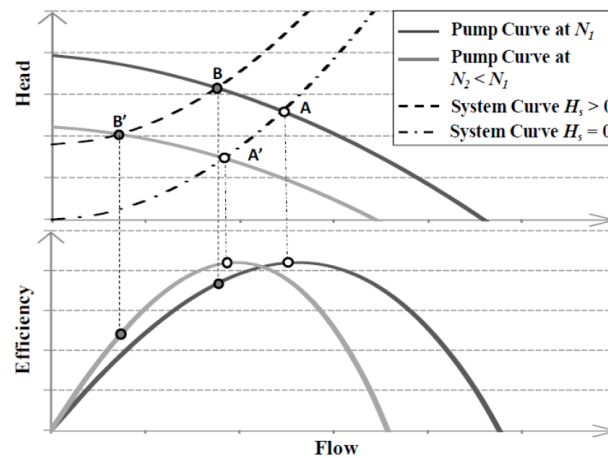


Figure 108: Typical pump efficiency and system curve[62]

It is therefore clear that sustainable pump efficiencies are proportional to electricity savings and possibly prolongs the life of the pump [107]. However, the type of control has to be considered in an integrated strategy, which will be discussed in later sections.

The motors that are connected to the pumps deliver the required input power to drive the pumps in a specific application and are sized accordingly. Pump motor speed can be altered by either changing the number of poles of the pumps or by altering the incoming frequency. Altering poles requires physical changes to the motor, whereas changing the frequency can easily be achieved by installing a VSD.

Applying VSDs results in lower current drawn by the motor, which directly influences the power consumption of the motor [110]. Several studies concluded that installing VSDs lead to significant power savings when applied to MCSs [111]. Mine personnel raised concerns regarding motor speeds causing operating temperatures to be detrimental to the motor. Electric motors in variable torque applications can have a speed reduction of approximately 50% without adversely affecting the motor.

The pump motor applications of MCSs operate in variable torque configurations, thus further improving the viability of VSD use on pumps. Other unwanted effects of applying VSD control are harmonics and bearing pitting. However, VSD manufacturers have developed harmonic filters to counter system harmonics. Bearing pitting has also been prevented by

replacing the existing bearings with isolated bearings, and installing shaft-grounding brushes [111].

Dewatering pumps make up the bulk of the water reticulation system and therefore forms part of the MCS as it completes the reticulation process. Multistage, high-pressure pumps are used for pumping hot water from shaft bottom between cascading dams to surface.

There are multiple dewatering pumps installed per pumping station. These pumps are critical to ensure that the water is pumped from the mine to prevent the lower levels from flooding. Dewatering pumps have to pump against significant pressure heads, which is typically between the first mining level and surface due to the depths of South African mines [13]. The theoretical equation used for pumping and turbines is shown in Equation 17 below.

$$P_H = \rho g Q H \quad \text{Equation 17}$$

Where:

P_H	=	pump power required (kW)
Q	=	flow capacity (ℓ/s or kg/s)
ρ	=	fluid density (kg/m ³)
g	=	gravitational acceleration (m/s ²)
H	=	differential head (m)

Mine dewatering systems are influenced by several factors, which include [39]:

- Water inflow quantities from mining areas;
- Centralised pumping or small pump stations that pump directly to surface;
- Location and number of pumps;
- Pump delivery pressure requirements;
- Amount of water to be pumped;
- Fluid friction losses versus cost to reduce losses; and
- Dam capacities required to reduce pump operation in peak times.

These factors must be considered when integrating the pumping system into a new integration method.

8. 3CPFS

A simplified 3CPFS is illustrated in Figure 109. The 3CPFS consists of horizontally placed pipes situated underground that are used to convert kinetic energy from the high-pressure vertical shaft pipe system to a low-pressure system. The 3CPFS was identified as a system or mechanism to reduce electricity costs associated with pumping.

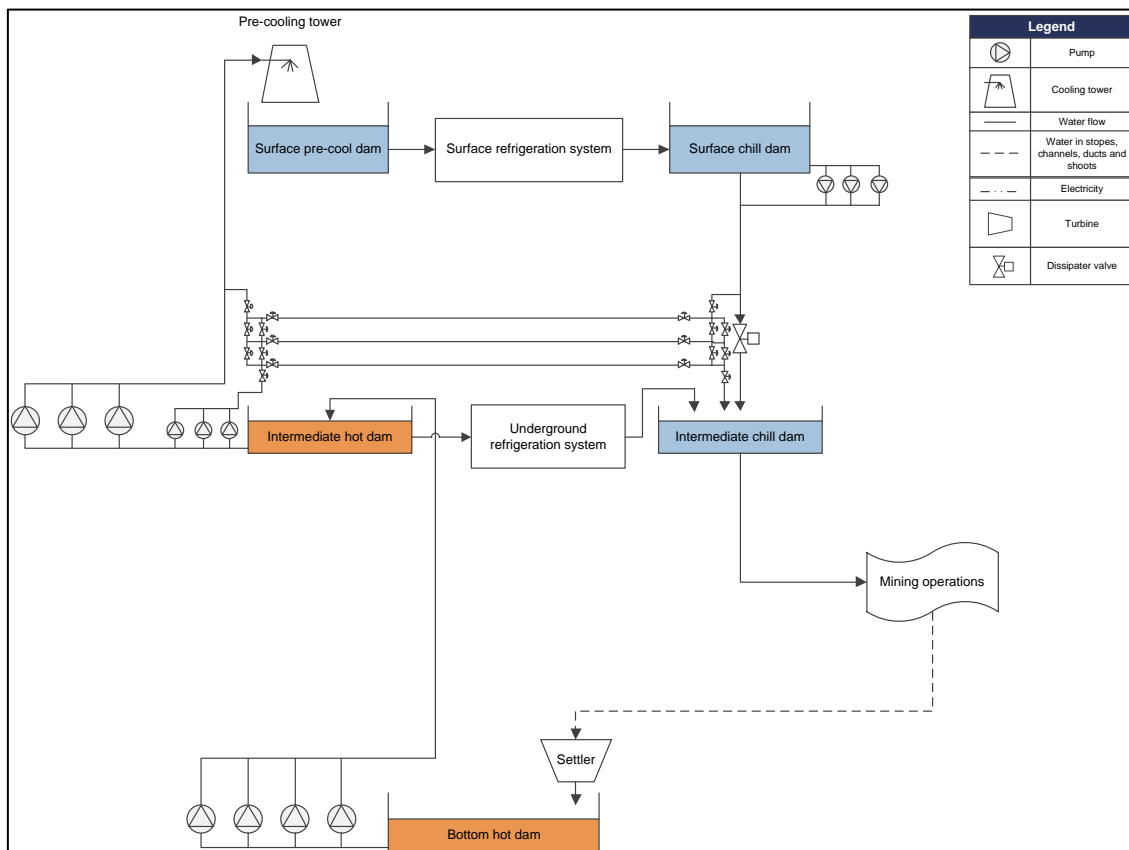


Figure 109: Mine 3CPFS layout

These systems are used to pump the hot used water from the mine back to the surface by using smart valve control. The advantage of such a system is that it can easily be designed to handle pressures of up to 160 bar [39]. However, these systems are expensive, as they contain a series of complex valves and a large installation area.

Some 3CPFS systems have been noted to have efficiencies of up to 98%. However, these systems can have low utilisation percentages due to water quality [39]. Normally, all excess water at shaft bottom have to be dewatered with conventional pumping, but the 3CPFSs can be used to pump most of the water to surface. Standard dewatering pumps can then dewater the excess.

3CPFSs work on the U-tube principle, where certain amounts of chilled water sent underground is used to pump hot water from underground. The resultant head and friction losses, however, still need to be overcome by small booster pumps. Filler pumps are also used to fill the three chambers when emptied [13]. The three chambers are charged alternately with a low-pressure and high-pressure medium, which results in a continuous flow in the high and low-pressure circuits [39].

3CPFSs can be used to increase the efficiency of the dewatering system. The system acts as the interface between the water sent underground and the used water sent to surface. This therefore reduces the need for conventional pumping requirements, resulting in less power required for dewatering. However, the use of 3CPFSs on some mines must be improved to realise its full potential [54].

9. Water control, spot coolers and MCUs

A typical hard rock mining schedule is illustrated in Figure 110.

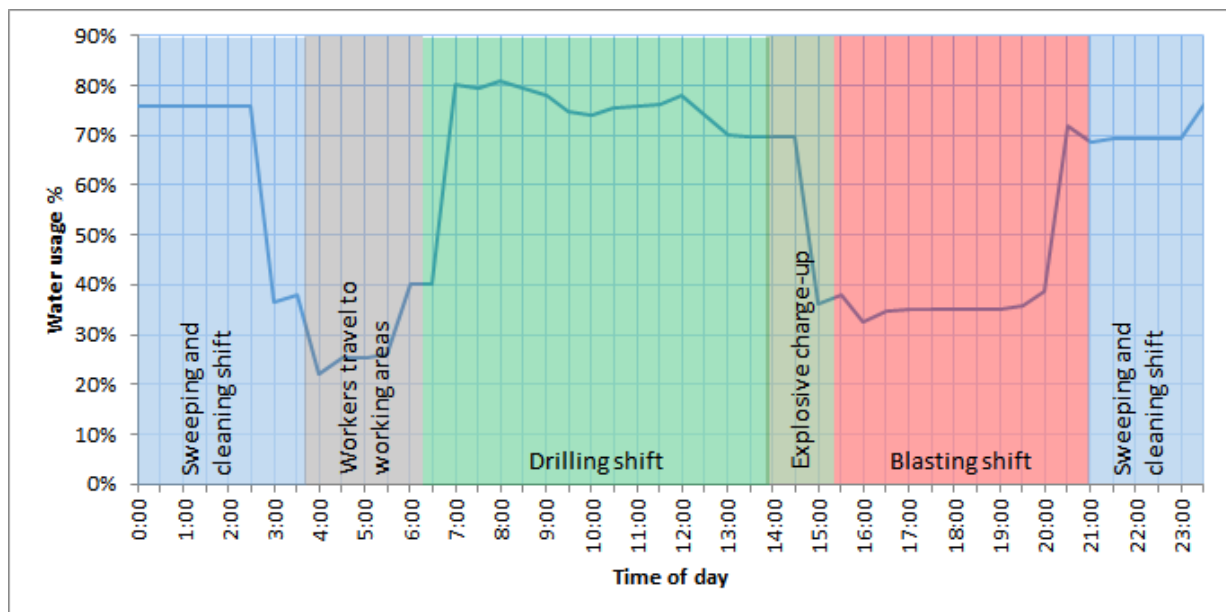


Figure 110: Typical hard rock mining schedule(adapted from [112])

A typical WCS is illustrated in Figure 111.



Figure 111: WCS installed at a deep-level gold mine – 2 km deep

There are numerous cooling equipment and methods that can be used for cooling underground work areas to acceptable temperatures. As mentioned previously, artificial cooling is required when the average temperature of a working area exceeds 32 °C wet bulb. The equipment that can be used include the following:

- Surface or underground BACs;
- MCUs; and
- Spray chambers.

A typical mine layout showing the process flow of water to and from an MCU is illustrated in Figure 112. From the main shaft column, the water is sent to the mining levels. The water is typically split between the inlet of the MCU and flow to the working areas. In some cases, mines utilise the outlet water from the MCU for mining purposes, while others dump the water on the floor after it passed through the MCU [60].

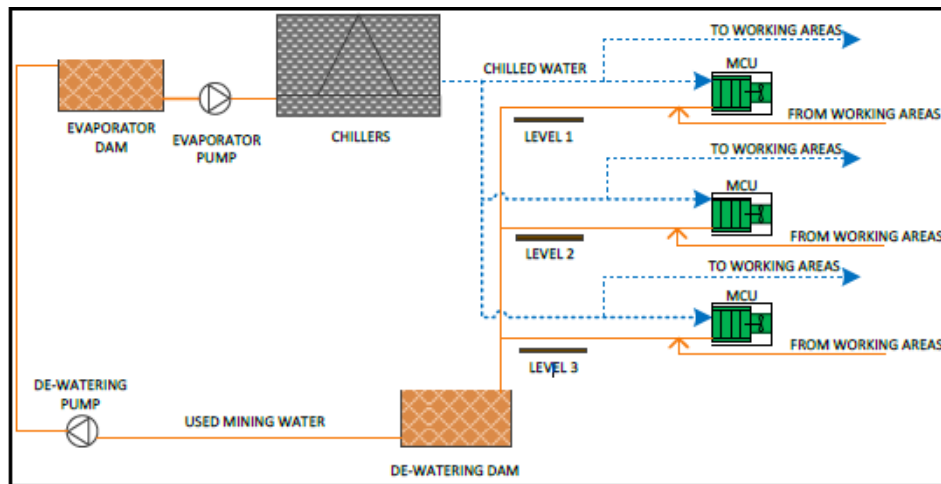


Figure 112: General process flow and MCU configuration in a typical deep-level mine[60]

The cooling method used in most MCUs is based on convection and conduction heat transfer between cold water and warm ventilation air [113]. Cold water is pumped through the tube and fin heat exchanger inside the cooling unit. Electric fans, typically 22 kW rated, are used to vent the ambient air through the MCU to produce cold air. A typical MCU or spot cooler situated underground is illustrated in Figure 113.



Figure 113: Mobile spot cooler situated underground

Some studies aimed to utilise MCUs efficiently to reduce the overall dewatering pumping costs associated with operating MCUs [60, 113]. The aim was to control the flow rate through the cooling units by using flow-regulating valves. The reduced flow results in reduced pumping costs.

District or spot-cooling has been used since the 1950s with typical capacities ranging from 100 kW to 500 kW [21]. Horizontal spray chambers are also used and are designed to cool

incoming ventilation air. These spray chambers should preferably be multistage arrangements in which water is resprayed several times to ensure effective contact between air and water.

The sequence of these spray chambers is arranged to produce a counterflow effect. A significant amount of heat can be removed with a certain flow of cold water. This means that a smaller amount of chilled water is required and circulated back to the chiller plants [114].

10. Ventilation fans

The mine main fans are found on surface, with booster fans and other smaller fans situated underground. Additionally, a BAC fan can be seen as a booster fan as it assists with the translation of air into the mineshaft. The mine main fans extract air from the mine at an approximate rate of $560 \text{ m}^3/\text{s}$, depending on the depth and size of the mine [13].

Ventilation can be divided into two parts, namely, flow-through ventilation and auxiliary ventilation. Flow-through ventilation is the main circuit of mine ventilation. The atmospheric air enters the shaft through a shaft, adit or ventilation raise. The flow of air is then distributed through internal ventilation raises, with the flow being governed mainly by the main ventilation fans on surface.

Auxiliary ventilation takes the air from the flow-through system and ensures distribution to the working areas. Mine booster fans and other auxiliary fans cause the airflow. The air is then pushed into mine headings, or exhaust systems that draw out contaminated air. These ventilation systems are required to supply a sufficient volume to dilute and remove dust particles and gases. These gases typically include NO_x , SO_2 , CH_4 , CO_2 and CO .

Airflow is also required to regulate air temperature of working areas. The mine ventilation and cooling components are the largest part of the operating cost. Optimisation strategies to improve these services can result in significant electricity cost and energy savings [115].

11. Control and instrumentation

The control and instrumentation on mines are required to manage and control equipment discussed in this section. The control and instrumentation on MCSs require live and dynamic connections between the SCADA system and the PLC to perform control procedures.

Interaction among field instrumentation, PLCs and the SCADA system requires connections such as open platform communications to communicate efficiently. Although the focus of this thesis is not on improving the instrumentation, the control of equipment can be altered, and the use of the mine instrumentation will be critical to manage MCSs efficiently.

Altering or implementing any optimisation strategies or aiming to dynamically integrate these systems requires the control and instrumentation network [55]. The control of MCSs requires accurate and calibrated measuring devices. Although potential measuring errors may exist, these should be minimised by regular calibration. The instrumentation on any deep-level MCS should thus be sufficient to perform control, monitoring and reporting of the systems.

APPENDIX II – SIMULATION MODEL

The one-dimensional differential equations governing transient flow through a variable pipe area are illustrated from Equation 18 to Equation 20.

$$\text{Continuity} \quad \frac{\partial P}{\partial t} + \frac{\partial(\rho VA)}{A \partial x} = 0 \quad \text{Equation 18}$$

$$\text{Momentum} \quad \frac{\partial(\rho V)}{\partial t} + \frac{\partial(\rho V^2 A)}{A \partial x} + \frac{\partial P}{\partial x} + \rho g \cos \theta + \frac{f \rho V |V|}{2D} = 0 \quad \text{Equation 19}$$

$$\text{Energy} \quad \frac{\partial}{\partial t}(\rho u_o) + \frac{\partial\{(h_o + gz)\rho VA\}}{A \partial x} - \dot{q} = 0 \quad \text{Equation 20}$$

Simulation model equations

Simulation models can be compiled by using the software described in this thesis. Some of the equations used are illustrated below [62, 36].

Equations used for simulations:

Direct contact heat exchangers (BACs, PCTs and CCTs):

$$h_{ao} = \frac{(1-r)}{(\tau-r)} h_{ai} + \frac{(\tau-1)}{(\tau-r)} \varphi T_{wi} \quad \text{Equation 21}$$

$$T_{wo} = \left[\frac{(\tau-1)r}{(\tau-r)} h_{ai} \right] / \varphi + \frac{(1-r)\tau}{(\tau-r)} T_{wi} \quad \text{Equation 22}$$

$$r = \frac{C_a}{C_w} \quad \text{Equation 23}$$

$$\tau = \exp[-UA \left(\frac{1}{C_w} - \frac{1}{C_a} \right)] \quad \text{Equation 24}$$

$$C_a = m_a \quad \text{Equation 25}$$

$$C_w = \frac{c_{pw} m_w}{\varphi} \quad \text{Equation 26}$$

Where:

h_{ai}	=	air inlet enthalpy
h_{ao}	=	air outlet enthalpy
T_{wi}	=	water inlet temperature
T_{wo}	=	water outlet temperature
m_a	=	mass flow rate of air
m_w	=	mass flow rate of water
c_{pw}	=	water specific heat
Φ	=	saturation enthalpy/water temperature ratio
UA	=	heat transfer coefficient

The equation below can be used to calculate the chiller cooling capacity:

$$C = C_{ref}[(T_{evap} - T_{evap}^{ref})(0.03) + 1][(T_{cond}^{ref} - T_{cond})(0.03) + 1] \quad \text{Equation 27}$$

Where:

C	=	cooling capacity
C_{ref}	=	full-load cooling capacity at design conditions
T_{evap}	=	average evaporator temperature
T_{evap}^{ref}	=	average evaporator temperature at design conditions
T_{cond}	=	average condenser temperature
T_{cond}^{ref}	=	average condenser temperature at design conditions

The following equation calculates the chiller electric power:

$$P_{wr} = \frac{C}{COP} \quad \text{Equation 28}$$

Where:

P_{wr}	=	chiller electric power
C	=	cooling load
COP	=	coefficient of performance

The following equation calculates variable pump pressure difference:

$$P = \frac{F^2}{\rho A} \quad \text{Equation 29}$$

Where:

- P = pump pressure difference
- F = pump mass flow
- ρ = water density
- A = flow admittance

The following equation calculates the pump electric power:

$$P_{wr} = \frac{PF}{\rho\eta} \quad \text{Equation 30}$$

With

- P_{wr} = chiller electric power
- P = pump pressure difference
- F = pump mass flow
- ρ = water density
- η = pump and motor efficiency

Simulation approach P-2 layouts

An example of an electrical reticulation layout is illustrated in Figure 114.

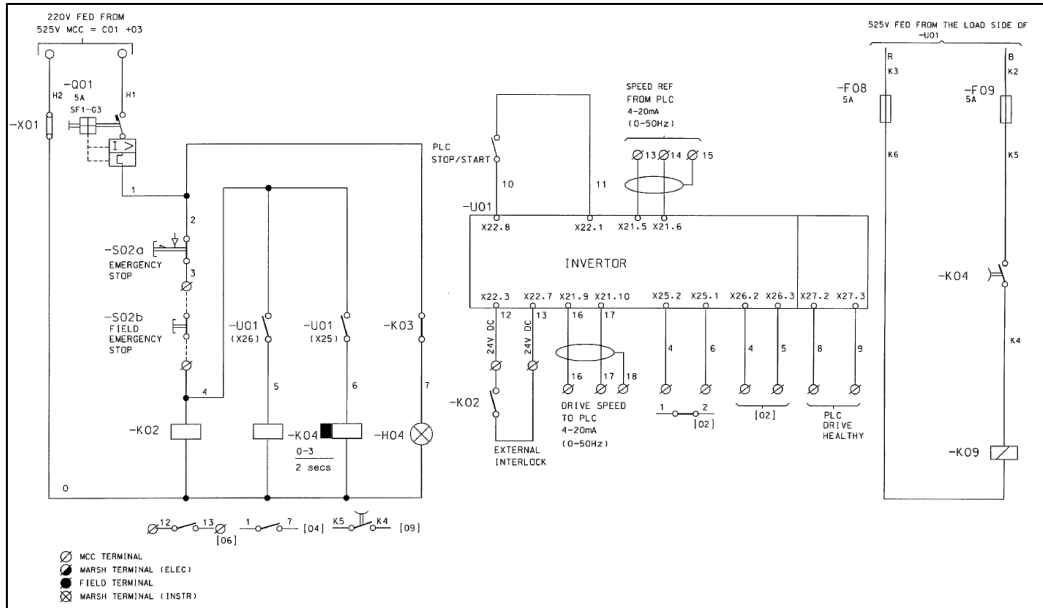


Figure 114: Electrical reticulation drawing

An example of a PID diagram is illustrated in Figure 115.

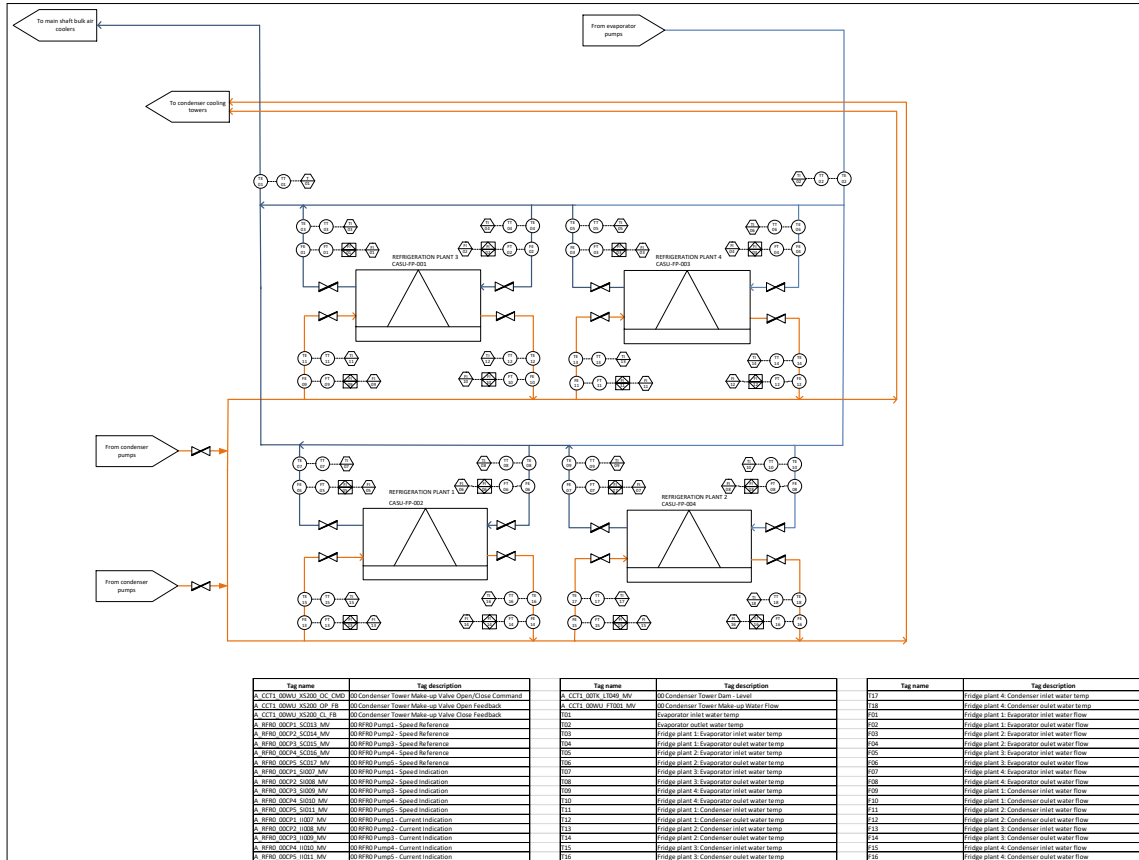


Figure 115: PID diagram

APPENDIX III – VERIFICATION APPENDIX

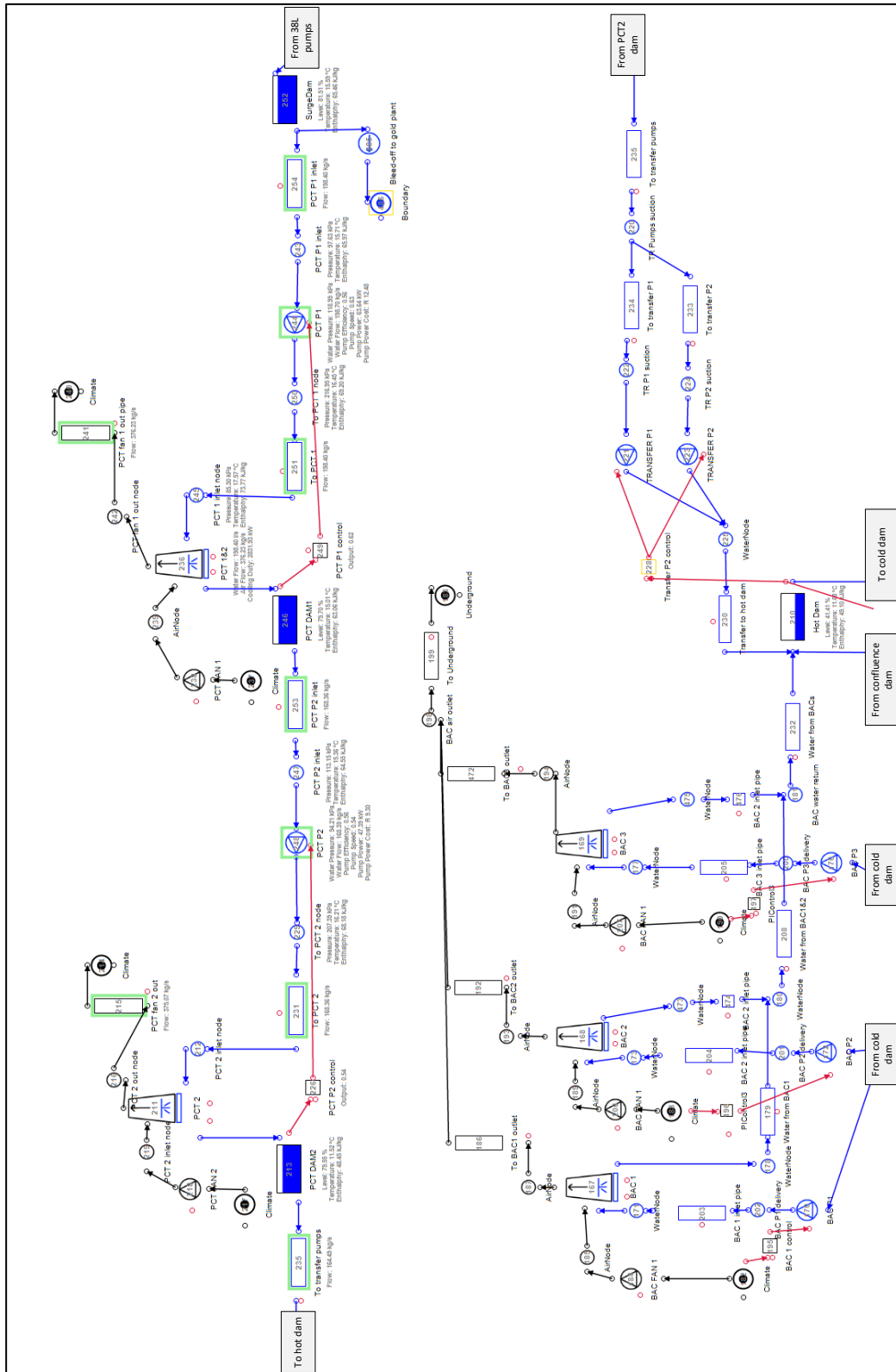


Figure 116: Mine P – simulation section of precooling and bulk air cooling

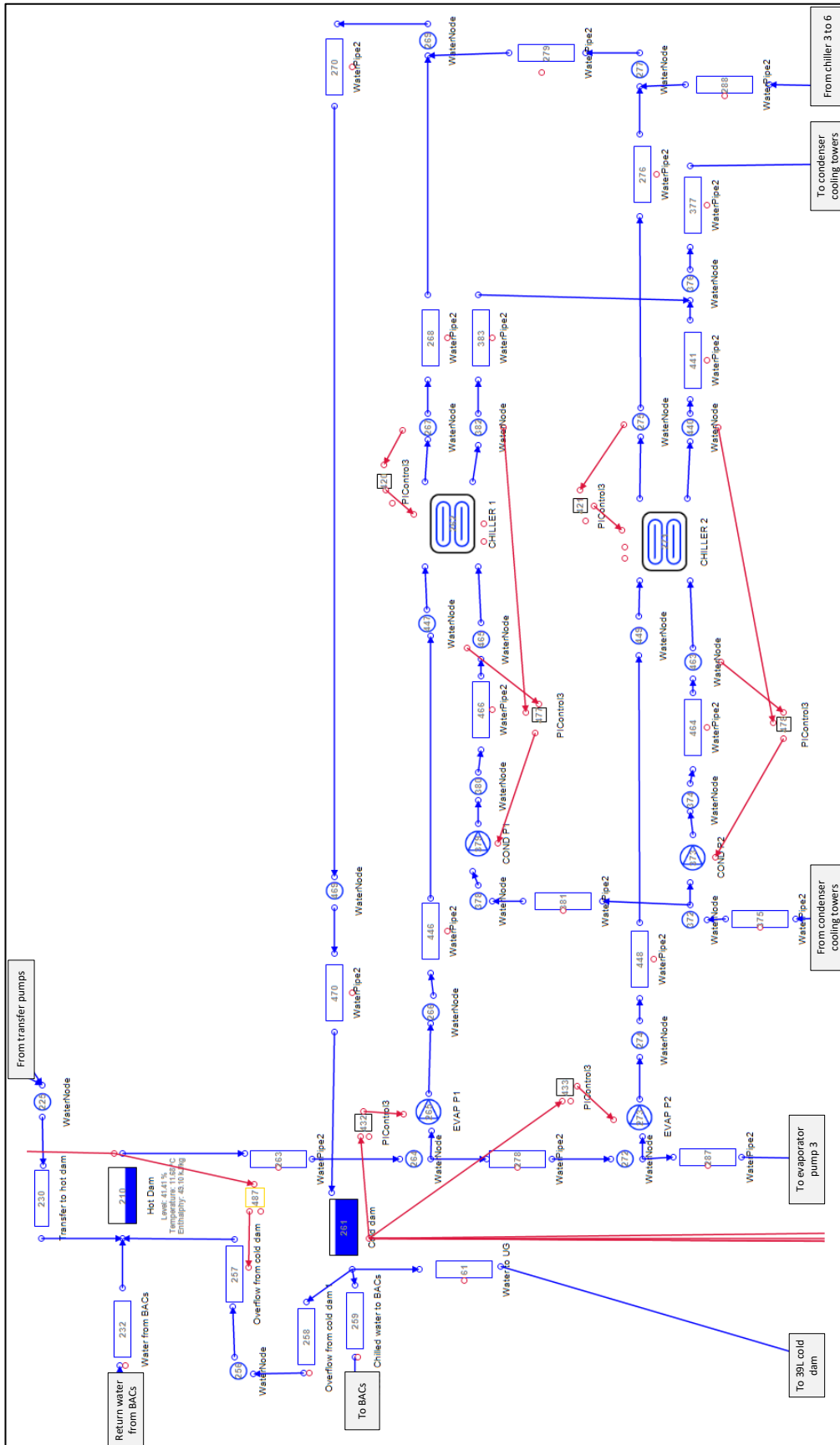


Figure 117: Mine P – simulation section of chiller 1 and chiller 2

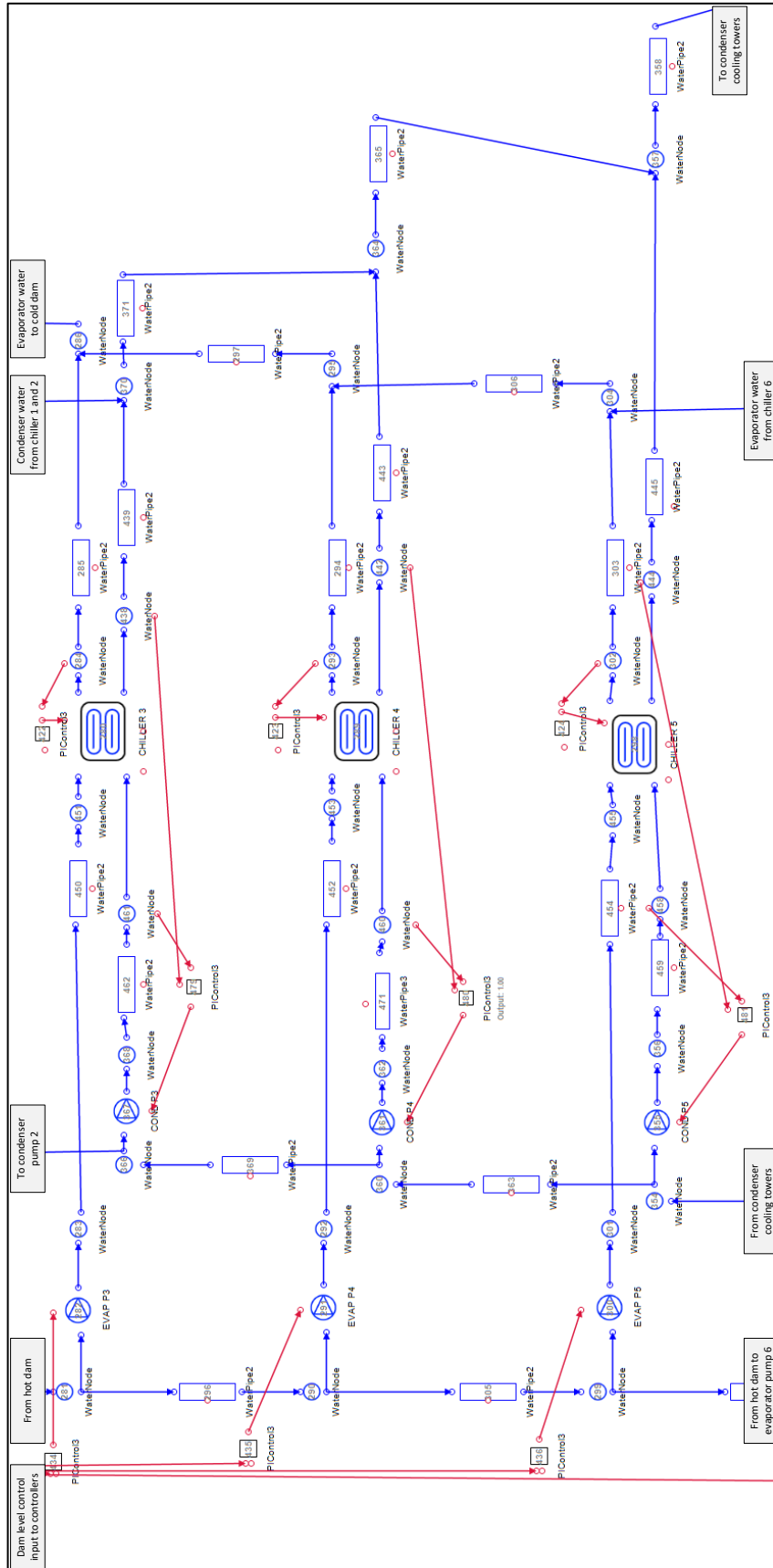


Figure 118: Mine P – simulation section of chiller 3 to chiller 5

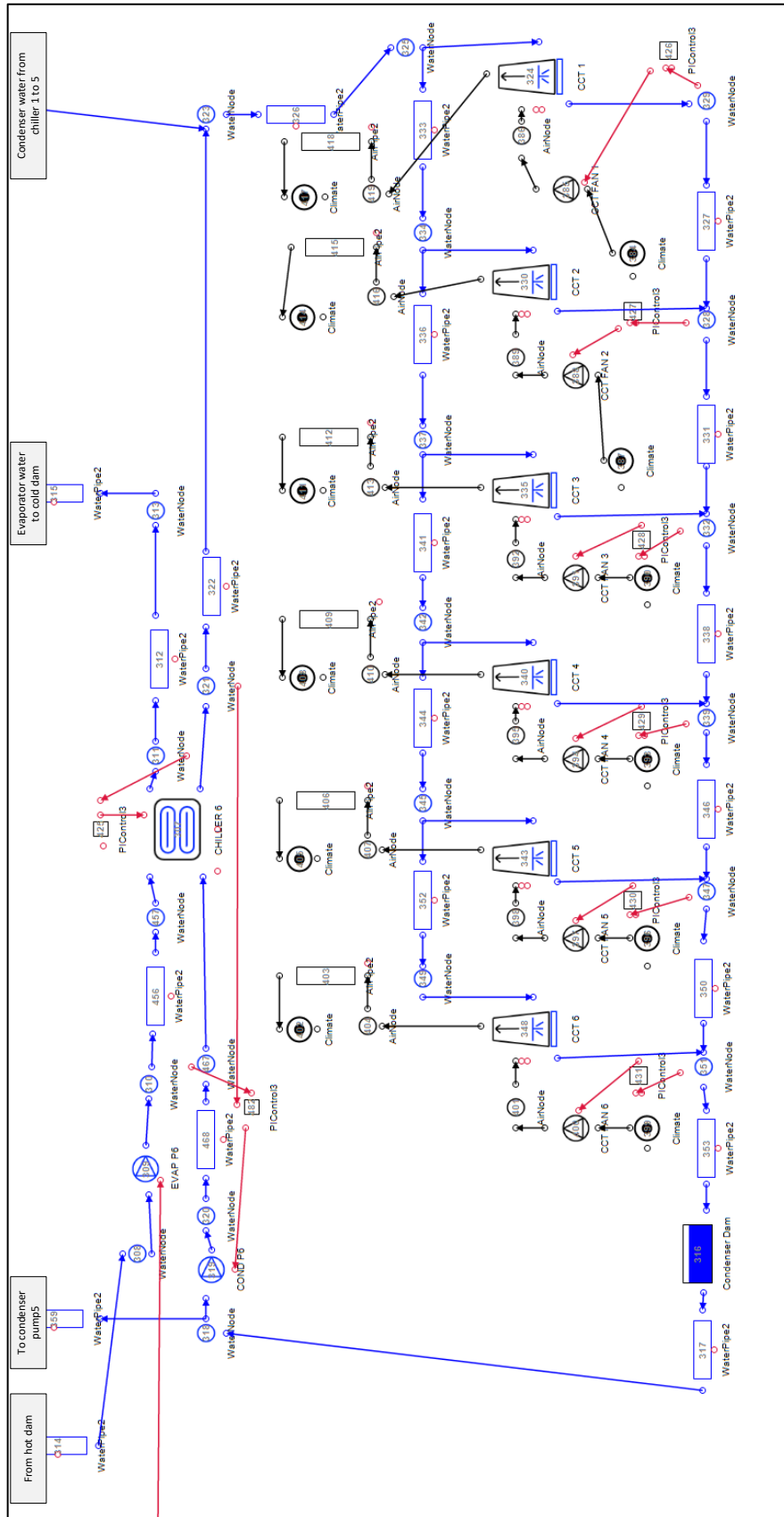
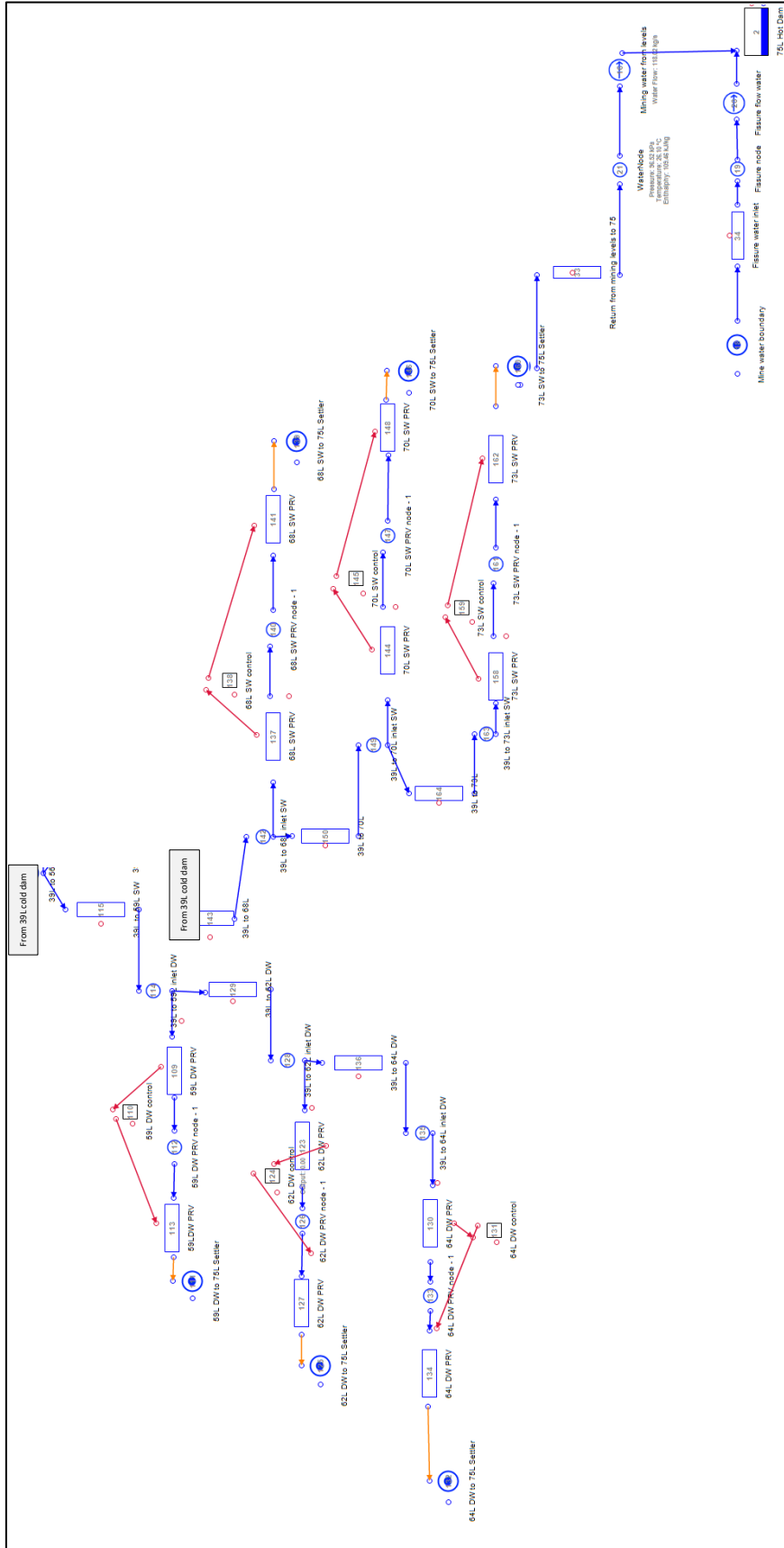


Figure 119: Mine P – simulation section of chiller 6 and the condenser towers



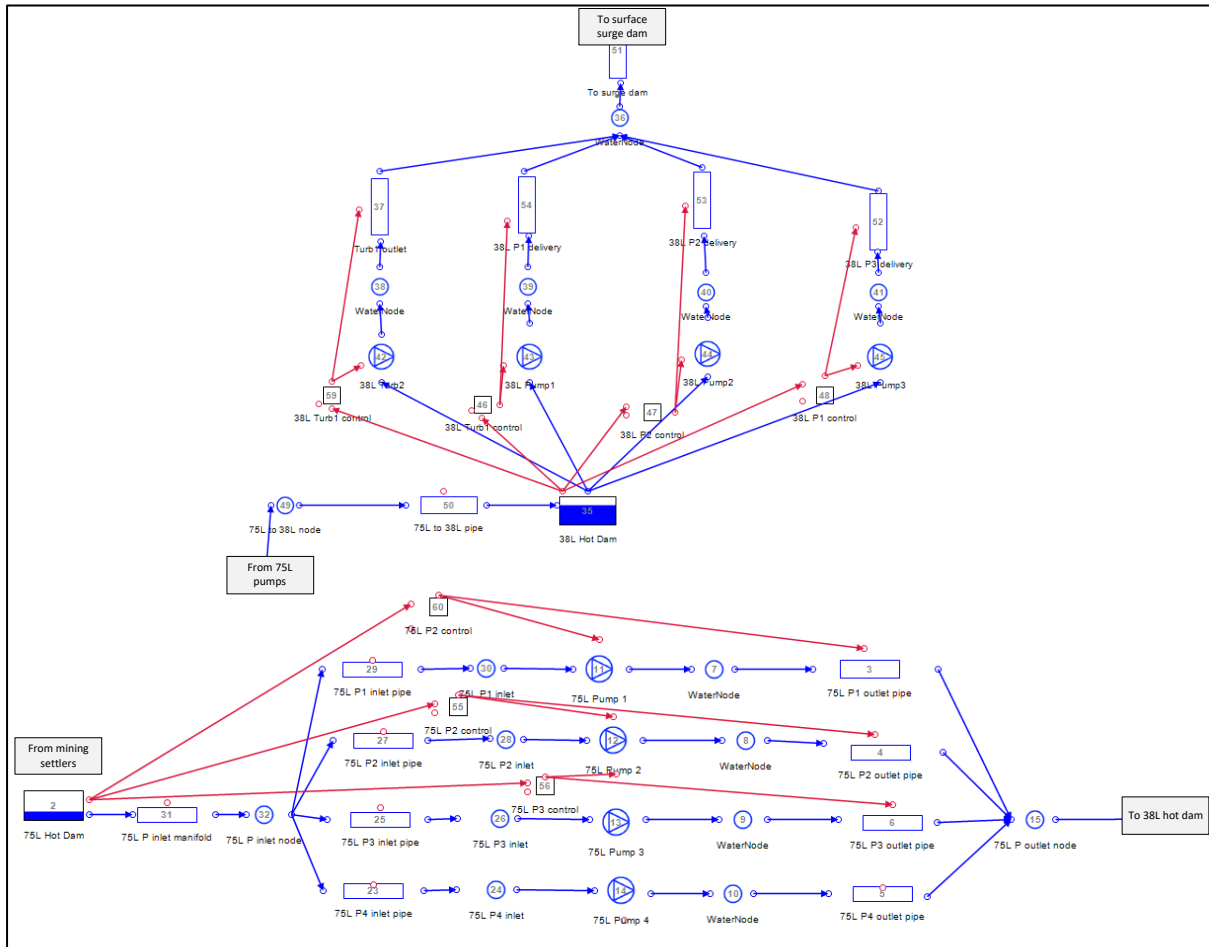


Figure 122: Mine P – simulation section of 75L hot dam to 38L hot dam and surge dam

Table 47: Simulation inputs of Mine P – water flow to mining levels

Time of day	44L flow	47L flow	50L flow	53L flow	56L flow	59L DW flow	59L SW flow	62L DW flow	62L SW flow	64L DW flow	64L SW flow	68L flow	70L flow	73L flow
00:30:00	24.3	5.7	0.0	36.6	10.5	8.5	19.0	0.1	25.1	5.7	0.9	6.4	0.0	11.7
01:00:00	24.1	7.3	0.0	24.0	10.8	8.5	19.5	0.1	29.4	4.6	2.2	6.4	0.0	12.3
01:30:00	24.8	8.2	0.0	24.1	14.6	8.3	20.8	0.1	28.5	4.3	4.0	6.5	0.0	12.1
02:00:00	24.9	8.9	0.0	25.1	14.8	8.3	20.8	2.6	28.8	4.1	0.1	6.6	0.0	10.7
02:30:00	24.0	8.3	0.0	25.4	15.7	8.3	21.0	7.5	27.7	4.9	0.1	6.9	0.0	10.6
03:00:00	24.8	8.2	0.0	26.8	15.4	6.5	18.7	6.0	27.7	5.5	0.1	6.1	0.0	10.2
03:30:00	10.5	8.7	0.0	23.7	14.8	6.5	18.3	5.4	27.2	5.2	0.1	6.6	0.0	10.3
04:00:00	11.6	6.9	0.0	21.8	11.9	4.5	17.2	3.3	25.5	4.0	0.1	6.4	0.0	11.2
04:30:00	26.2	5.8	0.0	18.2	10.6	3.9	13.5	2.8	23.9	4.0	0.1	6.4	0.0	11.5
05:00:00	25.7	5.7	0.0	19.0	10.6	3.6	13.1	1.3	23.0	5.6	0.1	6.4	0.0	11.4
05:30:00	21.7	6.0	0.0	19.1	10.6	3.6	12.6	0.1	20.8	5.4	0.1	6.1	0.0	11.0
06:00:00	21.4	8.2	0.0	17.3	10.7	3.9	12.9	0.1	18.6	5.4	0.1	5.9	0.0	11.8
06:30:00	21.1	10.6	0.0	16.0	10.0	3.6	13.2	0.1	15.1	5.0	0.1	5.4	0.0	8.6
07:00:00	21.1	4.8	0.0	19.5	8.2	4.0	14.4	0.1	15.1	5.3	0.1	8.0	0.0	8.6
07:30:00	23.7	10.2	0.0	19.0	8.7	5.0	14.1	0.1	19.5	5.9	0.1	7.7	0.0	8.9
08:00:00	27.0	12.3	0.0	22.9	12.1	3.6	17.2	7.9	22.3	7.2	2.6	8.2	0.0	8.7
08:30:00	26.9	12.7	0.0	23.9	14.5	2.5	19.8	9.2	25.4	5.6	2.8	8.2	0.0	9.1
09:00:00	27.2	16.7	0.0	32.2	17.4	5.8	19.7	7.5	27.1	7.0	3.3	8.8	0.0	10.7
09:30:00	27.2	16.7	0.0	35.9	20.2	7.3	17.8	9.6	29.5	10.1	3.1	8.7	0.0	11.4
10:00:00	26.8	16.6	0.0	32.7	22.1	6.5	19.5	16.0	28.4	12.7	5.3	9.2	0.0	10.7
10:30:00	23.5	19.4	0.0	29.1	18.4	7.2	19.3	15.3	25.3	12.3	2.2	8.9	0.0	10.5
11:00:00	22.7	20.5	0.0	27.1	17.7	7.9	20.0	16.2	24.1	10.5	4.6	9.8	0.0	10.4
11:30:00	21.6	13.0	0.0	25.7	13.6	9.7	20.8	13.9	26.7	8.8	4.0	7.8	0.0	10.9
12:00:00	24.1	11.3	0.0	22.9	13.6	9.2	17.2	13.9	25.7	8.6	6.1	7.3	0.0	10.3
12:30:00	24.7	9.6	0.0	24.6	10.9	9.7	14.7	11.1	23.5	6.4	4.6	7.4	0.0	10.2
13:00:00	24.7	8.4	0.0	18.5	11.8	9.5	14.3	13.3	23.4	6.8	3.5	7.5	0.0	10.3
13:30:00	25.0	5.7	0.0	18.4	10.4	11.3	13.3	11.5	22.3	6.9	5.3	6.6	0.0	10.6
14:00:00	24.2	4.8	0.0	15.6	8.1	11.3	13.2	9.5	20.4	6.0	4.9	5.9	0.0	10.2
14:30:00	20.7	6.2	0.0	14.6	7.3	5.4	13.1	10.1	20.5	6.5	5.6	6.4	0.0	10.5
15:00:00	20.9	4.6	0.0	14.1	7.5	4.4	13.8	10.0	20.5	6.0	5.0	6.1	0.0	10.9
15:30:00	1.8	4.1	0.0	9.2	7.2	3.6	0.4	15.1	20.8	5.8	4.9	6.4	0.0	11.1
16:00:00	1.1	4.2	0.0	9.4	6.8	3.3	0.4	14.6	20.1	4.6	3.9	6.2	0.0	10.8
16:30:00	0.3	3.8	0.0	9.6	5.7	2.3	0.4	13.1	16.7	0.1	1.4	6.8	0.0	11.3
17:00:00	1.1	0.9	0.0	8.7	5.7	2.0	0.4	10.5	16.0	1.2	1.9	6.0	0.0	10.6
17:30:00	0.8	1.1	0.0	8.7	5.7	2.1	0.4	6.4	14.0	1.4	1.0	0.4	0.0	10.5
18:00:00	0.7	0.2	0.0	8.6	5.7	1.7	0.4	5.0	13.9	0.9	1.3	0.4	0.0	10.7
18:30:00	0.6	0.1	0.0	8.7	5.7	2.2	0.4	6.0	13.9	0.6	0.6	0.4	0.0	10.3
19:00:00	0.6	0.1	0.0	8.7	5.7	1.8	0.4	6.1	13.9	1.3	1.0	0.4	0.0	8.9
19:30:00	0.7	0.1	0.0	8.7	5.7	2.3	0.4	6.0	13.8	0.4	0.8	0.4	0.0	8.9
20:00:00	4.6	0.1	0.0	8.7	5.7	1.8	0.4	6.0	13.9	0.8	1.4	0.4	0.0	8.3
20:30:00	20.8	0.1	0.0	10.1	5.7	3.1	0.4	6.0	13.8	0.5	0.5	0.4	0.0	8.1
21:00:00	24.2	1.3	0.0	10.2	5.7	3.5	0.4	6.0	13.8	0.3	0.8	5.3	0.0	8.1
21:30:00	24.2	2.9	0.0	12.3	7.0	3.3	0.4	6.0	15.1	1.9	1.0	2.8	0.0	10.1
22:00:00	24.4	4.3	0.0	13.3	8.3	3.6	0.4	6.0	15.6	1.5	1.0	5.4	0.0	10.2
22:30:00	21.4	4.4	0.0	14.1	8.9	3.1	0.4	8.0	14.3	5.8	3.2	6.0	0.0	11.3
23:00:00	21.6	7.8	0.0	17.4	8.9	3.8	0.4	10.5	14.1	3.2	3.0	6.1	0.0	11.2
23:30:00	21.0	9.5	0.0	25.5	8.9	4.2	0.4	12.0	17.5	4.9	5.4	6.3	0.0	11.6
00:00:00	8.4	9.6	0.0	26.0	10.8	5.5	0.4	12.5	22.1	4.9	4.6	5.7	0.0	11.6
Average [l/s]	18.2	7.2	0.0	19.0	10.6	5.2	10.6	7.5	20.9	4.9	2.3	5.8	0.0	10.4
MI/day	1.6	0.6	0.0	1.6	0.9	0.5	0.9	0.6	1.8	0.4	0.2	0.5	0.0	0.9

APPENDIX IV – VALIDATION APPENDIX

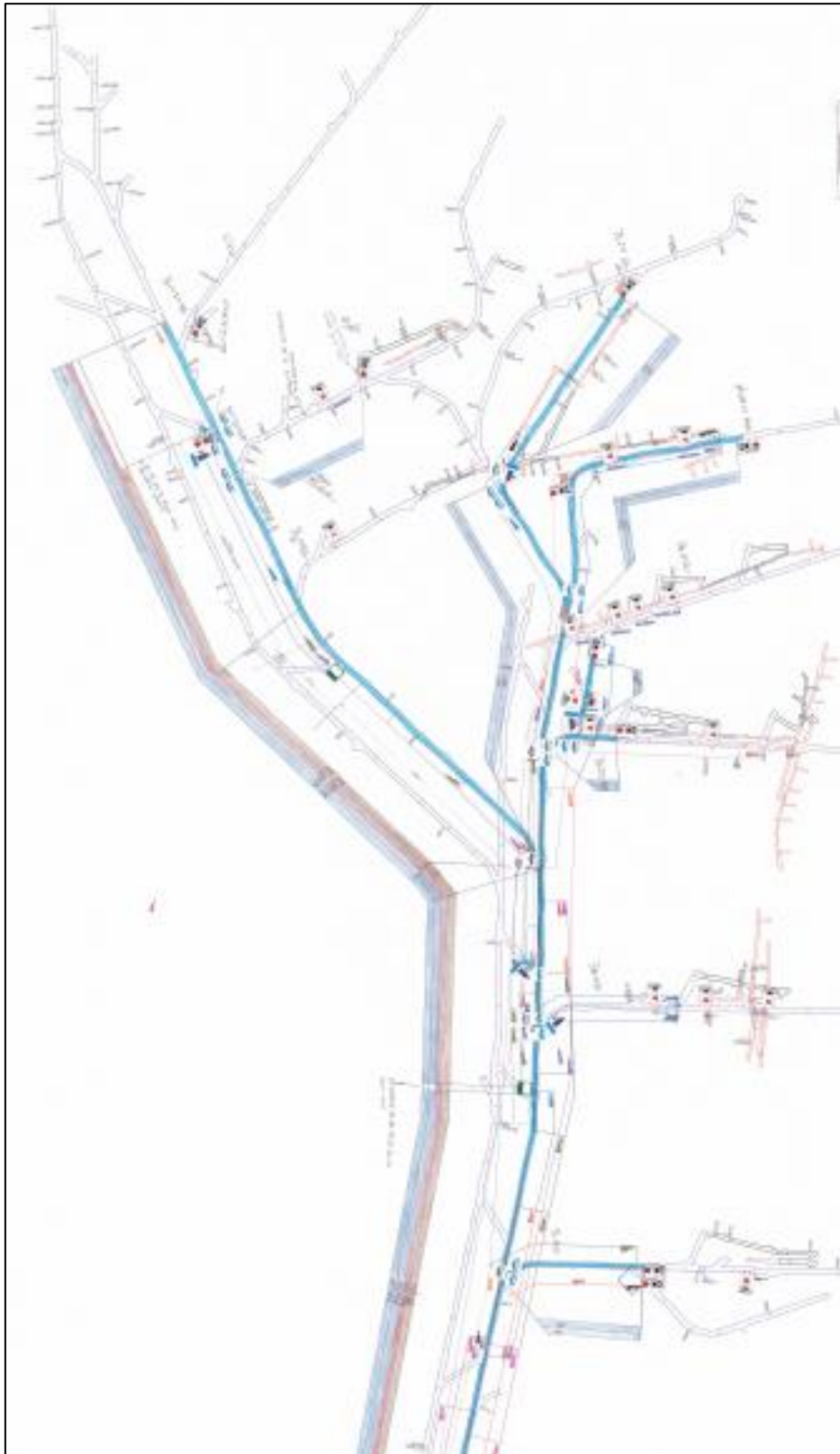


Figure 123: Typical mine plan indicating mining sections – Mine A



Figure 124: Manual measurements on MCUs and PRVs – Mine A

APPENDIX V – SUMMARISED INVESTIGATION METHODOLOGY

Investigation methodology [62]

The investigation methodology requires firstly that the layout and data collection of the system are investigated. The cooling system layout, configuration and data collection involve the following:

1. Obtaining system layouts to understand process flow and interaction between the different components in the MCS.
2. Ensuring that detailed system specifications and limitations are measured on-site to ensure the accurate development of the system baseline.
3. Logging important data and operational trends to obtain system control to develop a relevant baseline as reference to any operational or energy savings.

PFDs may include information regarding process piping, major equipment symbols, names and identification numbers, valves or valve-sets that may affect system operation, interconnection with systems, major bypass and circulation lines, operational flow values such as minimum, maximum and normal flow conditions, and fluid compositions.

An accurate baseline simulation model must be configured as reference. This process involves the following:

1. Configuring energy and mass balances of the system for a set period.
2. Configuring models to profiles to ensure correct daily system response.
3. Conducting baseline simulations by simulating a typical year to serve as reference to future energy savings.

The investigation process can also be summarised as follows:

1. Project investigation:
 - a. Obtain client approval and go-ahead.
 - b. Obtain layouts, operational data, system specifications and constraints.
 - c. Identify possible improvement strategies or operational changes.
 - d. Obtain project baseline data and baseline profiles.
 - e. Compile detailed simulation models.

- f. Verify simulation models before doing any studies.
 - g. Simulate project impact for proposed strategies.
2. Compile preliminary scope of work:
- a. Compile the concept design from the simulations.
 - b. Determine equipment upgrades or process changes required.
 - c. Costing analysis and payback period.
 - d. Compile preliminary project plan.

APPENDIX VI – PRACTICAL CONTROL EMULATION

Figure 125 illustrates an example of PLC function block programming for the control of VSDs on BAC return pumps as implemented on a case study. The blue highlighted section illustrates the dam level set point (SP) and the actual measured variable (PV). The maroon highlighted block illustrates the respective P, I and D values for the controller. The green highlighted blocks indicate the maximum (YMAX) and minimum (YMIN) controller outputs as well as the manual setting (YMAN).

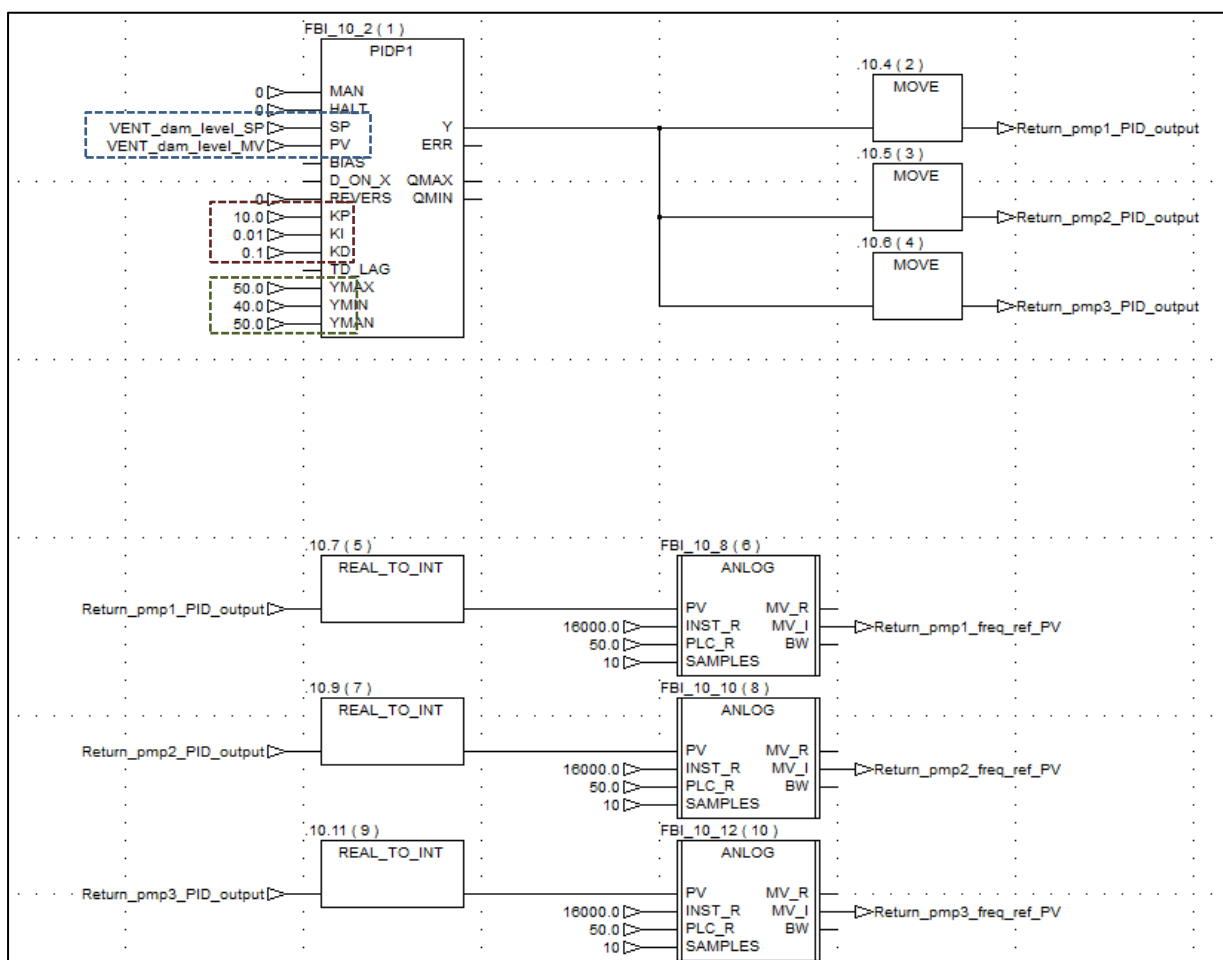


Figure 125: Example of a PLC function block programming – control emulation studies

A typical example of a control specification of the commissioning of VSDs on surface BAC return water pumps is illustrated in Table 48. These values are normally determined during the commissioning phase of a project. However, with the new control emulation method, preliminary values can be established for initial control implementation. The values in Table 48 can then be programmed onto the PLCs.

Table 48: Surface return water pumps control parameters

Control	Closed-loop PID
Feedback signal (Control variable)	Ventilation shaft BAC sump level
Set point	70%
Ventilation shaft BAC sump high-level stop limit 1	98%
Ventilation shaft BAC sump high-level stop limit 2	98%
Ventilation shaft BAC sump high-level stop limit 3	98%
Ventilation shaft BAC sump low level start limit 1	90%
Ventilation shaft BAC sump low level start limit 2	90%
Ventilation shaft BAC sump low level start limit 3	90%
Main shaft BAC sump low level stop limit 1	50%
Main shaft BAC sump low level start limit 1	35%
Main shaft BAC sump low level stop limit 2	50%
Main shaft BAC sump low level start limit 2	35%
Main shaft BAC sump low level stop limit 3	60%
Main shaft BAC sump low level start limit 3	50%
Maximum pump speed	50 Hz
Minimum pump speed	40 Hz
Proportional	10
Integral	0.01
Derivative	0.1

Figure 126 illustrates the control specification of a BAC return water pump. The control specification is derived from the new control emulation method and is presented in this format to the PLC programmer.

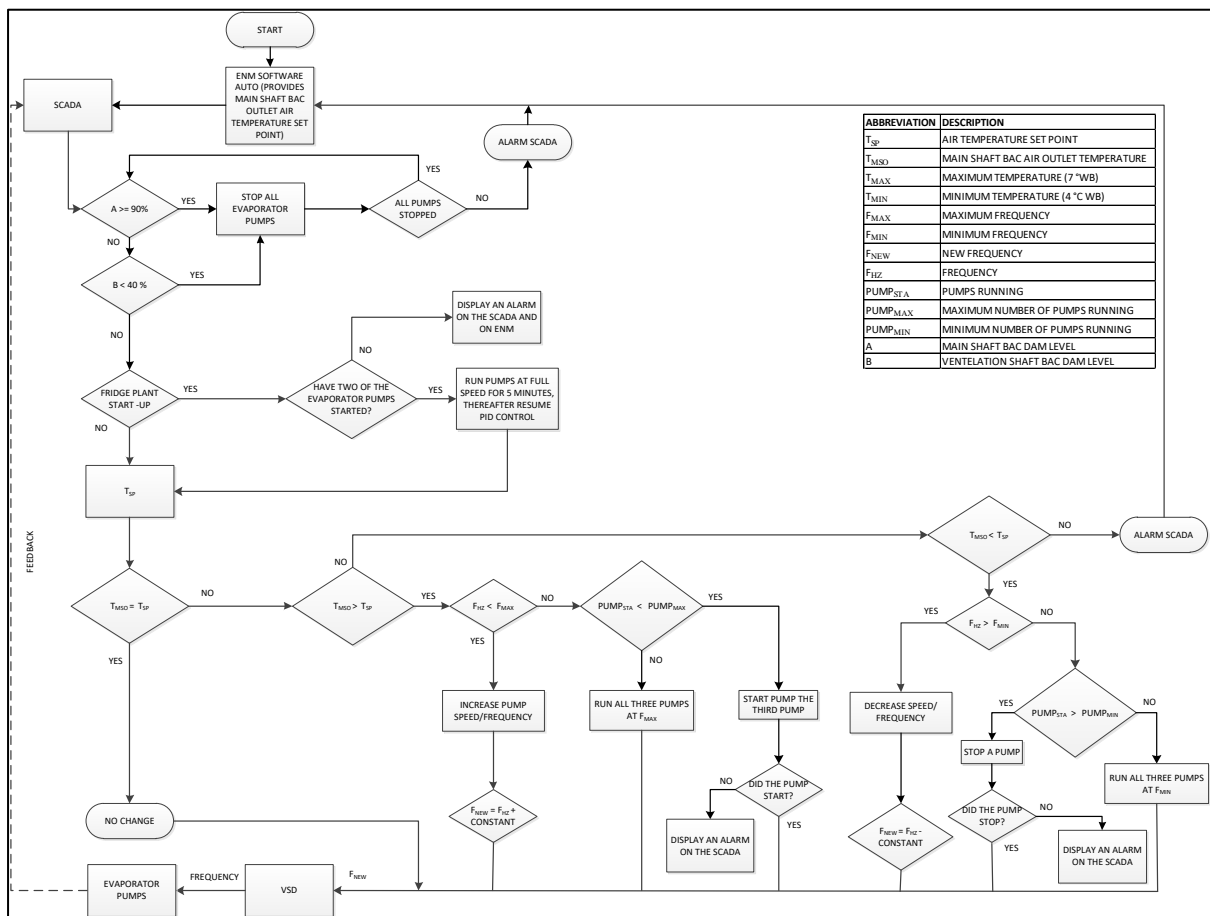


Figure 126: Control specification example – practical control emulation

An additional example of control valve P, I and D values is illustrated in Table 49.

Table 49: Control parameters of globe control valves – practical parameters

Globe control valves	
P	0.8
I	0.01
D	0.0

APPENDIX VII – ESKOM TOU TARIFF STRUCTURE

Table 50 illustrates the Eskom 2016/2017 Megaflex tariff structure and TOU tariffs. The tariff structure is based on the distance of the transmission zone to the closest substation (< 300 km for the case studies in this thesis) and the voltage (> 500 V and < 66 kV).

Table 50: Eskom 2016/2017 Megaflex tariff structure and TOU tariffs

Time of day	Period	c/kWh	
		Low demand season tarrif	High demand season tarrif
0:00	Off peak	0.39	0.45
1:00	Off peak	0.39	0.45
2:00	Off peak	0.39	0.45
3:00	Off peak	0.39	0.45
4:00	Off peak	0.39	0.45
5:00	Off peak	0.39	0.45
6:00	Standard	0.62	0.83
7:00	Peak	0.89	2.72
8:00	Peak	0.89	2.72
9:00	Peak	0.89	2.72
10:00	Standard	0.62	0.83
11:00	Standard	0.62	0.83
12:00	Standard	0.62	0.83
13:00	Standard	0.62	0.83
14:00	Standard	0.62	0.83
15:00	Standard	0.62	0.83
16:00	Standard	0.62	0.83
17:00	Standard	0.62	0.83
18:00	Peak	0.89	2.72
19:00	Peak	0.89	2.72
20:00	Standard	0.62	0.83
21:00	Standard	0.62	0.83
22:00	Off peak	0.39	0.45
23:00	Off peak	0.39	0.45