



Integrated dynamic water and cooling simulation planning in deep-level mines

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ABSTRACT

Keywords: Simulation, Integrated, Dynamic, Deep-level mines, Future planning, Water and cooling systems

The deep-level mining process is a dynamic and complex process where mines are getting deeper and new mining areas are constantly being developed. Some of the deep-level mines are reaching record depths of over 4 km with mined-out distances covering more than 200 km. To ensure that mines remain profitable and safe, efficient mine planning is essential, as it has direct implications on the profitability and safety of the mine.

Mine water- and cooling systems (WCS) are essential to cool workplaces and to achieve production targets. Effective WCS planning is important for the success of a mine and its long-term sustainability. However, these systems are complex due to their size and the large number of components involved. To add to the complexity, these components are also integrated with one another and consist of multiple dynamic variables.

A critical literature study shows that mines often neglect the integrated and dynamic aspects of WCS planning. Current methods often lead to wrong decisions that limit productivity and impact the safety of the mine. The large uncertainties associated with current methods require large safety margins that, in turn, lead to capital wastages and unnecessary operational costs. This means the industry requires a method that accurately simulates and predicts the outcome of planning decisions by accounting for the integrated and dynamic nature of the WCS.

In this study, a unique mine WCS planning method was developed. The new method makes use of simulation tools using empirical and dynamic data to predict operating conditions of large integrated mining systems. Applications of the method *inter alia* include life-of-mine planning, safety improvements, and identification of operational improvement opportunities. The new method differs from the old method which is non-integrated, static and uses design variables. The old method also does not make use of simulation tools.

The new method (WCS planning) was applied to a complex deep-level mining operation in South Africa. At this mine, production decreased from maximum to complete closure over a two-year period. The method was used to forecast the effect of the mining changes on the WCS of the mine over the 27 months. As part of the method, an integrated and dynamic model was constructed that makes use of more than 2 000 semi-empirical components to predict future operating conditions. By comparing the predictions with actual results, the new method is shown to be more than 90% accurate.

The new planning method was also tested on other case studies and the results were compared with the current non-integrated, static, and design approach. The new method showed that underground temperatures can be improved by between 16% and 34% compared with the current method. In some instances, the new method also predicted that underground temperatures can be improved by more than 3 °C. These improvements could have significant benefits on safety, production as well as cost. An estimated benefit of R2.2 billion over the life of mine was calculated. Another case study showed that, by implementing changes identified by the new planning method, the predicted time of mine flooding during a total power failure event could be increased by more than 22 hours compared with the current planning method.

The developed method was only applied on deep-level mine water and cooling systems which restricts the method's application to other industries or systems on the mine. However, it is possible to utilise the method for other industries or mining systems with some modification. The method also requires significant data to be accurate which is a challenge in the deep-level mining environment. It is recommended that data accuracy be improved in some instances data collection be automated.

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NOMENCLATURE

Symbol	Description	Units
A	Area	m^2
C_p	Specific heat capacity	$\text{kJ/kg}\cdot^\circ\text{C}$
D	Diameter	m
D_h	Hydraulic diameter	m
f	Friction factor	$\text{kW/m}^2\cdot^\circ\text{C}$
g	Earth gravitational constant	m/s^2
H	Head	m
h	Heat transfer coefficient	$\text{kW/m}^2\cdot^\circ\text{C}$
k_r	Absolute roughness coefficient	mm
k	Thermal conductivity	$\text{kW/m}\cdot^\circ\text{C}$
L	Length	m
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
η	efficiency	$\%$
P	Power	kW
ρ	Density	kg/m^3
p_{abs}	Absolute pressure	kPa
p_{gauge}	Gauge pressure	kPa
Symbol	Description	Units

π	Pi constant	-
Q	Heat load	kW
Re	Reynolds	-
r	Relative roughness	-
t	Time	s
T	Temperature	°C
ΔT	Difference in temperature	°C
UA	Overall heat transfer coefficient	kW/kJ/kg
V	Volume	m ³
$\dot{V}$	Volumetric flow rate	m ³ /s
v	Velocity	m/s
W	Weight	kg

LIST OF ABBREVIATIONS

3 CPFS	3 Chamber Pipe Feeder System
ACU	Air Cooling Unit
AP	Ammonia Plant
BAC	Bulk Air Cooler
CAPEX	Capital Expenditure
CC	Cooling Car
CCT	Condenser Cooling Tower
CCC	Condenser Cooling Coefficient
CCOPC	Condenser Coefficient of Performance Coefficient
COP	Coefficient of Performance
ECC	Evaporator Cooling Coefficient
ECOPC	Evaporator Coefficient of Performance Coefficient
FP	Fridge Plant
KPI	Key Performance Indicator
LOM	Life of Mine
MCS	Mine Cooling System
MHSA	Mine Health and Safety Ac No. 29 of 1996
OPEX	Operating Expenses
PFD	Process Flow Diagram
PI	Proportional Integral

P&ID	Piping and Instrumentation Diagram
PLC	Programmable Logic Controller
PRV	Pressure-Reducing Valve
PTB	Process Toolbox
SCADA	Supervisory Control and Data Acquisition
SF	Safety Factor
WCS	Water and Cooling Systems

DEFINITIONS

Word	Definition	Ref
Boundary conditions	The conditions present on the boundary of the control volume applied to the system.	[1]
Boundary demand	A demand applied to the system outside of the control volume.	[1]
Boundary inputs	Boundary conditions and demands used as inputs to the simulation.	[1]
Digital Twin	A 3D representation of the actual system on an electronic platform or software.	[2], [3], [4]
Dynamic	This term refers to variables that continuously change over a period of time.	[5], [6]
Dynamic boundaries	In this study dynamic boundaries refers to fluctuating boundary conditions because of daily or seasonal changes.	[1]
Integrated	Combining separate components so that it provides an interrelated complete system. The system of components is affected by the individual performance of each component.	[7], [8]
Method	A systematic procedure developed to answer the study's objectives.	[9]
Model	A process that takes certain inputs and based on scientific principal provides outputs.	[9]
Simulation	A software tool that is a mathematical and analytical recreation of a real-world system on a computer. In this study the tool is specifically used to predict the thermohydraulic effect of system changes on large thermohydraulic systems.	[9], [10], [11]
Verification	Comparing predicted results of the proposed method to that of the actual system under actual conditions.	[12]
Validation	Applying the method to other case studies to prove the methods usefulness to the client.	[12]

Chapter 1: Introduction



Surface operations of a deep-level gold mine¹.

Background pertaining to water and cooling system (WCS) planning in deep-level gold mines are given in this chapter.

¹ Retrieved from <http://chriswesselsphotography.blogspot.com/2017/03/> copyright Anglo Gold Ashanti.

CHAPTER 1 INTRODUCTION

1.1 Preamble

This study focuses on water and cooling system (WCS) planning for deep-level mines. Chapter 1 provides a brief overview of the study background, need for the study, objectives, and novel contributions. Firstly, the state of the South African deep-level mining industry is discussed and analysed. The complex integrated and dynamic WCSs required to mine successfully at depths of up to 4 km are also researched. Then available tools such as simulation that are used to assist mines with planning as well as current planning approaches are also investigated.

1.2 Background

1.2.1 Mining industry in South Africa

During the 20th century large capital was made available for new South African mining developments through foreign and governmental investment [13]. The industry has since seen a decline in new investment forcing the industry to mine deeper ore bodies with aged infrastructure [14]. The significant costs involved with sinking a new shaft or deepening old shafts are not feasible because of the marginal nature of deep-level gold mining in South Africa [15], [16]. South Africa has the fourth largest gold deposit in the world and was the largest producer of gold in the world up until 2006 [17]. Therefore, there is a clear trend to continue mining at current operations with deepening projects or closing unprofitable shafts.

For a mine to remain profitable, mines need to continue operating the current mining operations past the established life-of-mine (LOM). The current state of mining operations is summarised in Figure 1. The figure shows the age of several South African deep-level mines and their depth with an average age of mining operations approaching 40 years and average depth of 3.5 km respectively. The trend towards older and deeper mines is evident, that the mine are mining the deeper ore-reserves.

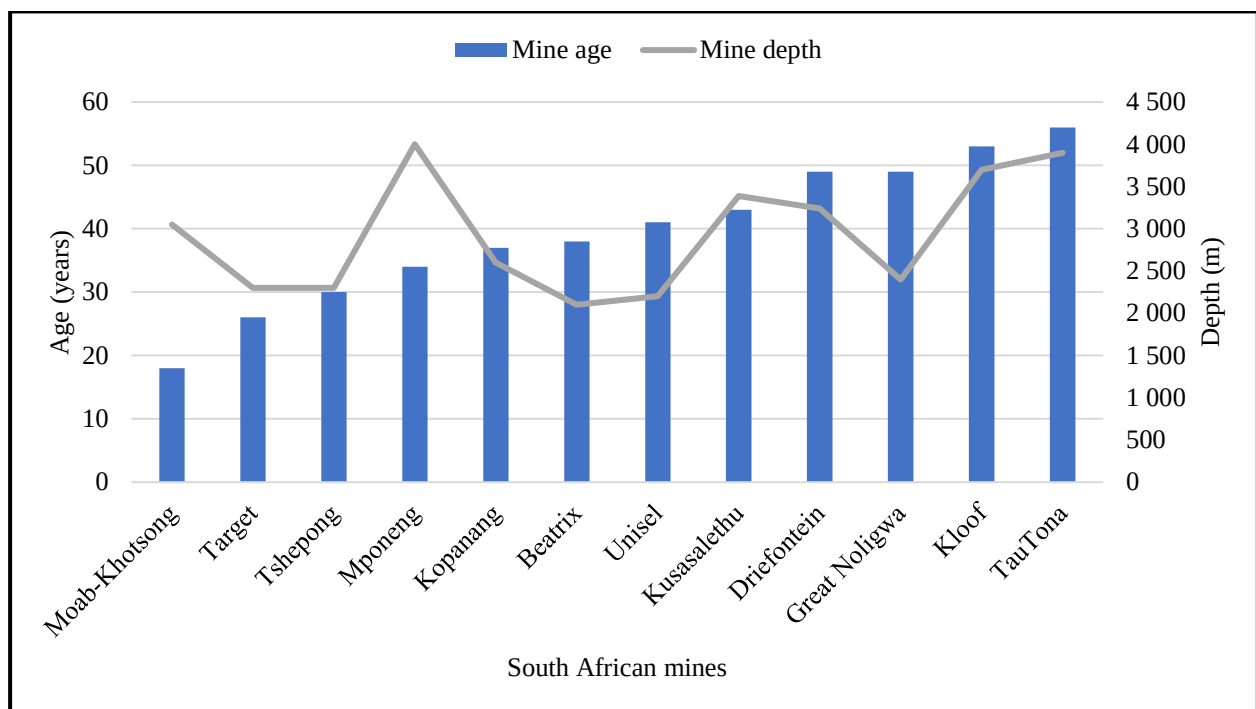


Figure 1. South African deep-level gold mines' ages²

The continuation of mining operations at shafts approaching 40 years of age poses safety and operational challenges [18]. The most important factors for mines to stay profitable are operating costs, gold price, environmental impact, and engineering limitations [19], [20].

1.2.2 Mining systems

The important mining engineering systems required in deep-level mines include compressed air [21], water [22], refrigeration and cooling [23], [24] and ventilation [25], [26]. Each system consists of hundreds to thousands of components integrated with one another. Deep-level mine cooling systems consist of three main elements, namely dewatering, refrigeration and cooling, and water reticulation [11]. Each of these elements (e.g. dams, pumps, chillers, turbines, fans, water pipes and heat exchangers) are connected via kilometres of piping. Each component in the system has a unique dynamic response to environmental changes with a direct effect on components up- or downstream [27], [28]. Figure 2 is a simplified illustration of the integrated elements of a mine cooling system.

² Information retrieved from: <https://www.sibanyestillwater.com/>; <https://miningdataonline.com/>; <https://www.harmony.co.za/>; <https://www.miningreview.com/>; <https://www.miningweekly.com/>; <https://www.mindat.org>

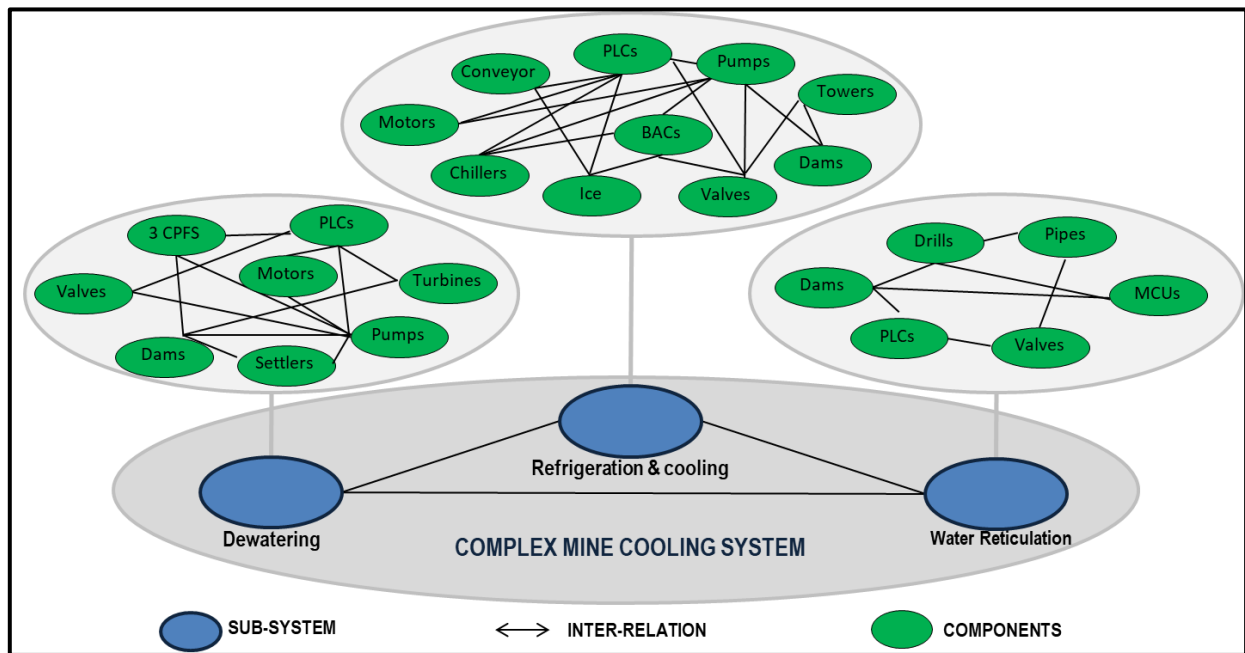


Figure 2. Simplified illustration of a complex mine cooling system (adapted from [11])

The virgin rock temperatures of deep-level mines can reach up to 60 °C [29]. Safety regulations prohibit miners from working in workplaces where wet-bulb temperatures exceed 32.5 °C [25]. It is therefore impossible to mine successfully and safely at extensive depths without the intervention of WCSs [29], [30]. The effective operation of the WCS also has a direct effect on the performance and safety of the mine and its operations [31]. A typical example of a WCS is shown in Figure 3. The main concept of the WCS is to send chilled water underground which removes geothermal heat from underground to ensure safe working conditions. Water is then pumped to surface where the heat collected in the water is removed using ambient conditions and refrigeration.

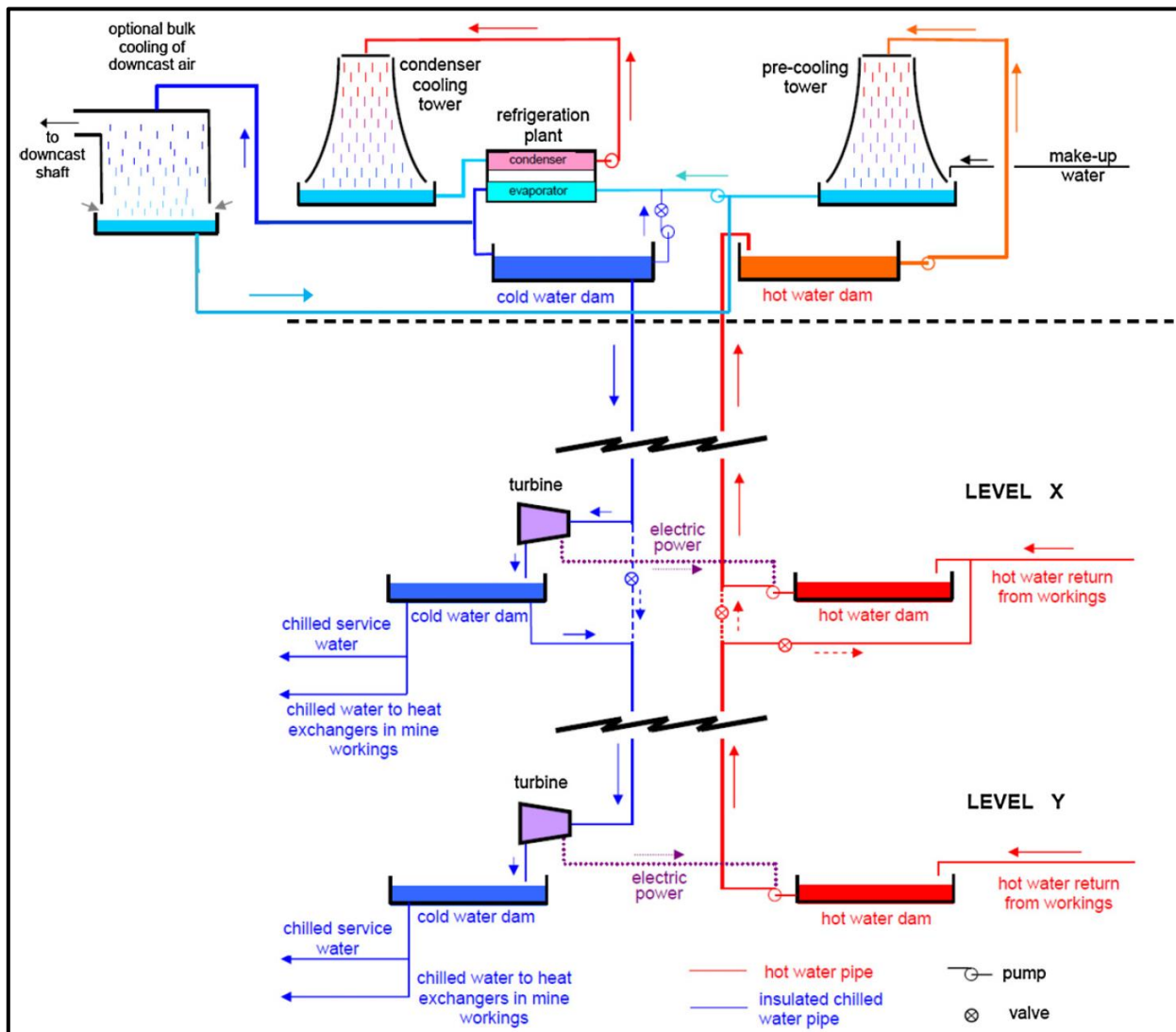


Figure 3. Simplified process flow diagram of a typical WCS (retrieved from [27])

WCS in mines consist of thousands of components on the supply and demand side. They are all connected via thousands of meters of piping. The complexity of the system increases as the depth of the mine and the distance of mining activities from the shaft increase.

The WCS's main purpose is to supply chilled water for mine cooling, drilling, cleaning, and dust suppression [8]. Chilled water is produced using a refrigeration cycle or fridge plant (FP). The FPs feed into a network of piping and dams which leads to several "water users". These users include equipment such as cooling devices (bulk air coolers and cooling cars), mining devices (drills) and cleaning devices (water jets) [32].

After the chilled water has been utilised, the water enters the dewatering system which is integrated into the cooling system. Water is pumped through a multi-stage pumping cycle to surface. The water then follows the same process and is used once again as chilled water and sent down the shaft.

The systems are all integrated. The vertical and horizontal distances at which working places are located from the systems that supply services are vast [33]. Working places can be located up to 4 km down and 7 km to the side from the point of supply. Therefore, it is critical that all systems work effectively to provide the end user (miner) with the right services (water pressure, quantities, and temperature) to mine successfully.

The effective operation of the water and cooling system has a direct effect on the performance and safety of the mine and its operations [34]. These under performing systems mean the miner cannot perform his/her role effectively and safely. This is a concern for the mining industry as stringent safety regulations are put in place for the safe operation of mines.

The South African Department of Mineral Resources (DMR) has certain minimum requirements to be able to mine safely which is established in the Mine Health and Safety Act (MHSA) [35]. Additionally, as mentioned above, the rock drill operator has certain minimum pressure and flow requirements for the pneumatic or hydraulic rock drills to drill and remove ore successfully. An under-supply of cooling to critical areas in the mine can result in unworkable working places. Therefore, accurate future planning is required to ensure that the minimum service requirements are met.

1.2.3 Mine planning

Mining in general is known to be dynamic in nature. This is due to the varying production schedules of different mining stopes (mining areas) located at different parts of a mine [36]. Figure 4 is an example of a medium-term production plan. Each stack represents the production from each stope for a specific month.

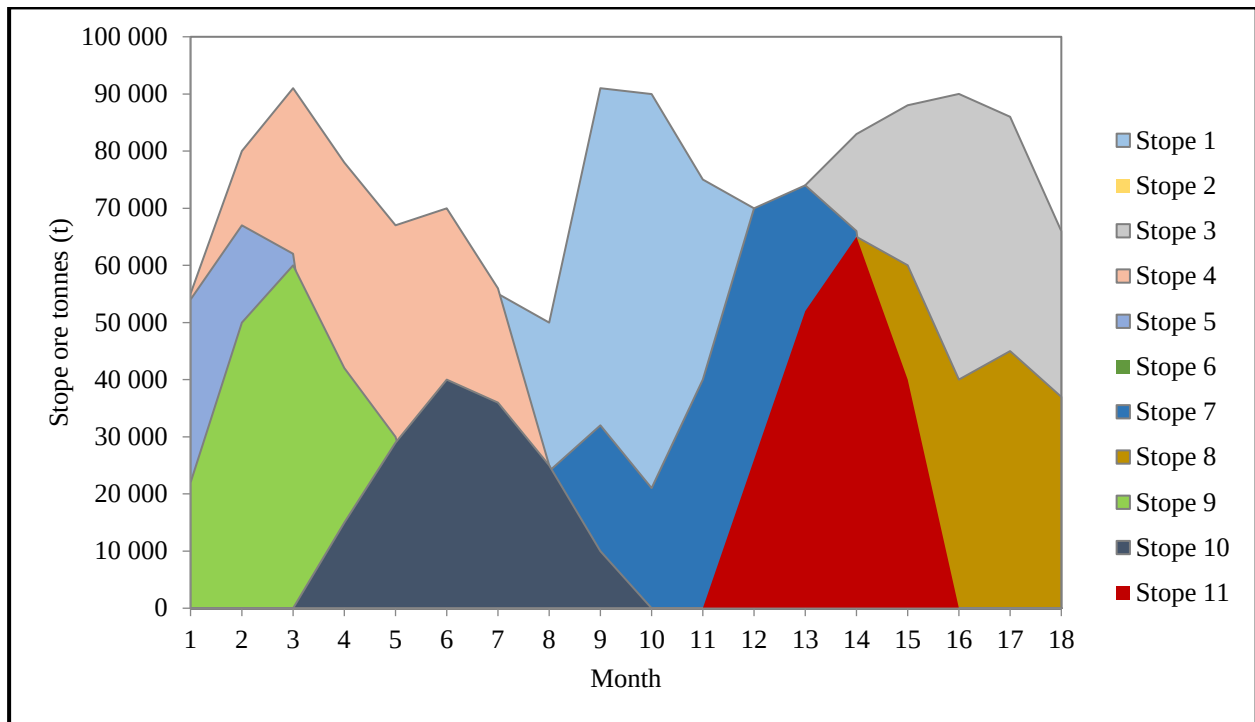


Figure 4. Medium-term production schedule (adapted from [36])

As the production varies for different areas of the mine, the cooling demand at those areas is also affected [37]. To match the cooling demand, the cooling supply needs to be adjusted. This means that operational cooling decisions need to be revised regularly. These decisions *inter alia* include future mine planning needs and continuous system improvements to ensure optimal cooling is supplied at the lowest cost.

As the production varies and the supply requirements change on a medium-term basis, so the demand changes. A short-term example of the dynamic nature of the mining environment is shown in Figure 5. Figure 5 shows the chilled water demand of a typical mine which shows the dynamic nature of production and services.

Typically, two peaks exist, one during the drilling shift where water is used to cool compressed air drills and the other during cleaning and sweeping operation, where water jets are used to clean working places and move ore. There also exists a continuous demand for cooling which is typically active for 24 hours a day without change. The constant cooling chilled water demand is indicated in Figure 5; however, in this example, water is reduced during the blasting period for energy-saving initiatives.

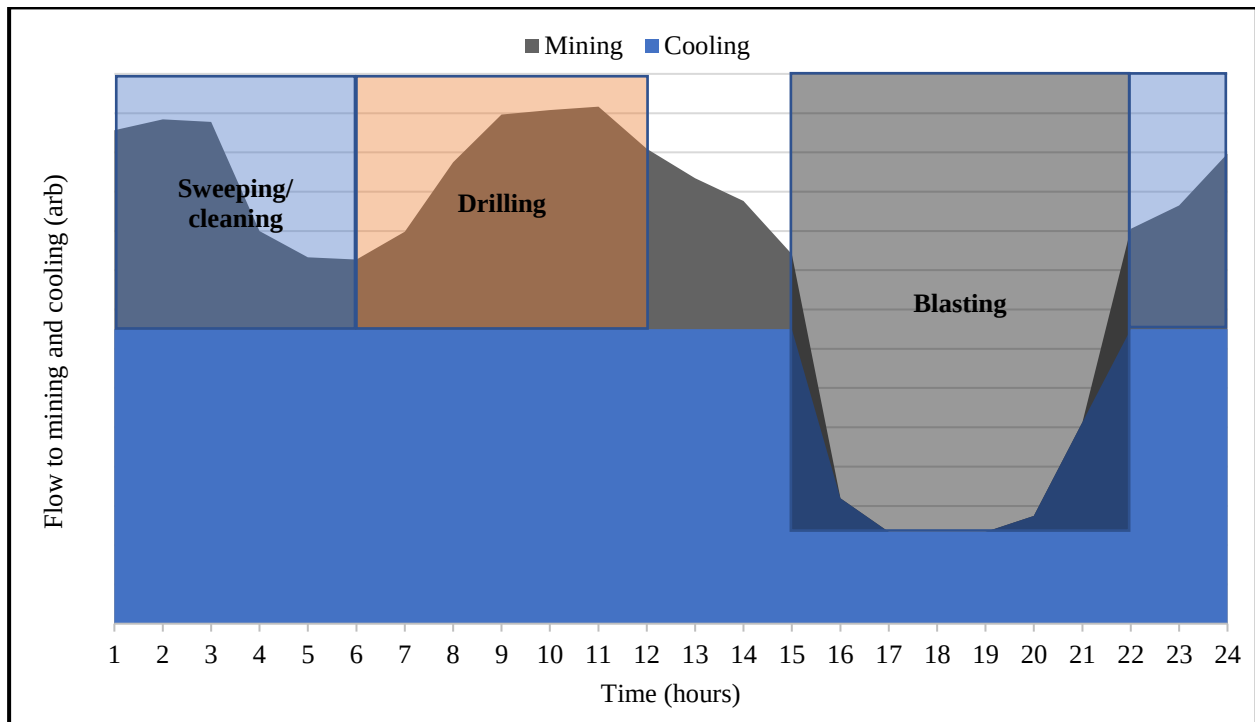


Figure 5. Dynamic demand of a typical mine [27]

Due to the dynamic nature of deep-level mines [25], [11], the cooling demands change all the time [29] and subsequently, system operations need to adapt [6], [38]. This means that decisions need to be made continuously. These decisions include identifying if current infrastructure can meet future production requirements, if current infrastructure can meet the necessary redundancy in an emergency scenario, and if optimisation opportunities on the current operation exist.

An especially important area is emergency response or emergency readiness. Several factors affect the safe working conditions of underground workings such as air quantities and temperature, dust inhalation, harmful gasses, and fire [39]. The thermohydraulic systems used in deep-level mining ensure that the requirements are met through supplying sufficient air and cooling to underground mine employees. Therefore, careful planning is required to ensure all requirements are sufficiently met underground.

Critical equipment failure also needs to be considered whereby requirements need to be met or allow sufficient emergency response time after equipment failure and before repair. Therefore, critical underground systems need to have redundancy or an emergency mitigation plan that allows for sufficient emergency response before working conditions become dangerous. Emergency planning forms an important part of mine planning as it influences the production of the shaft (with possible lost shift time) and more importantly can endanger the lives of underground mine personnel.

1.2.4 Digital twinning and simulation in mining

The adoption of new technologies such as digital twinning with simulation has been slow in the mining industry [31], [3]. The consensus is that the mining industry is accustomed to a certain way of “doing things” due to the high risk of its operations. Therefore, digital twins with simulation are often considered unnecessary and a waste of resources.

Fortunately, the attitude towards new technologies has shifted due to the overwhelming complexity of mining systems and the challenging economic conditions where profitable mining is a direct result of successful planning [31], [40]. This is where digital twinning with simulation can assist the industry in several ways.

Digital twinning is a process whereby an exact three-dimensional (3D) representation is created of a particular system [41]. The simple process of recreating systems in 3D allows users and personnel to visualise large complex systems quickly and easily [2]. This is advantageous to the mining industry where the majority of the systems are several kilometres from the surface and not easily accessible.

Therefore, planning and system discussions can be conducted with a 3D mine available to senior personnel and planners without costly and time-consuming underground visits. Underground visits also lack the ability to see the entire system and the focus of the audit is typically on a single area making strategic planning or decision-making challenging [4].

An example of the complexity of a mine and its numerous components is shown in Figure 6. Figure 6 shows the WCS of a mine represented in 3D. The distance between the farthest working places is more than 14 km. Additionally, the systems contain thousands of components and equipment on a smaller scale which are not visible in Figure 6.

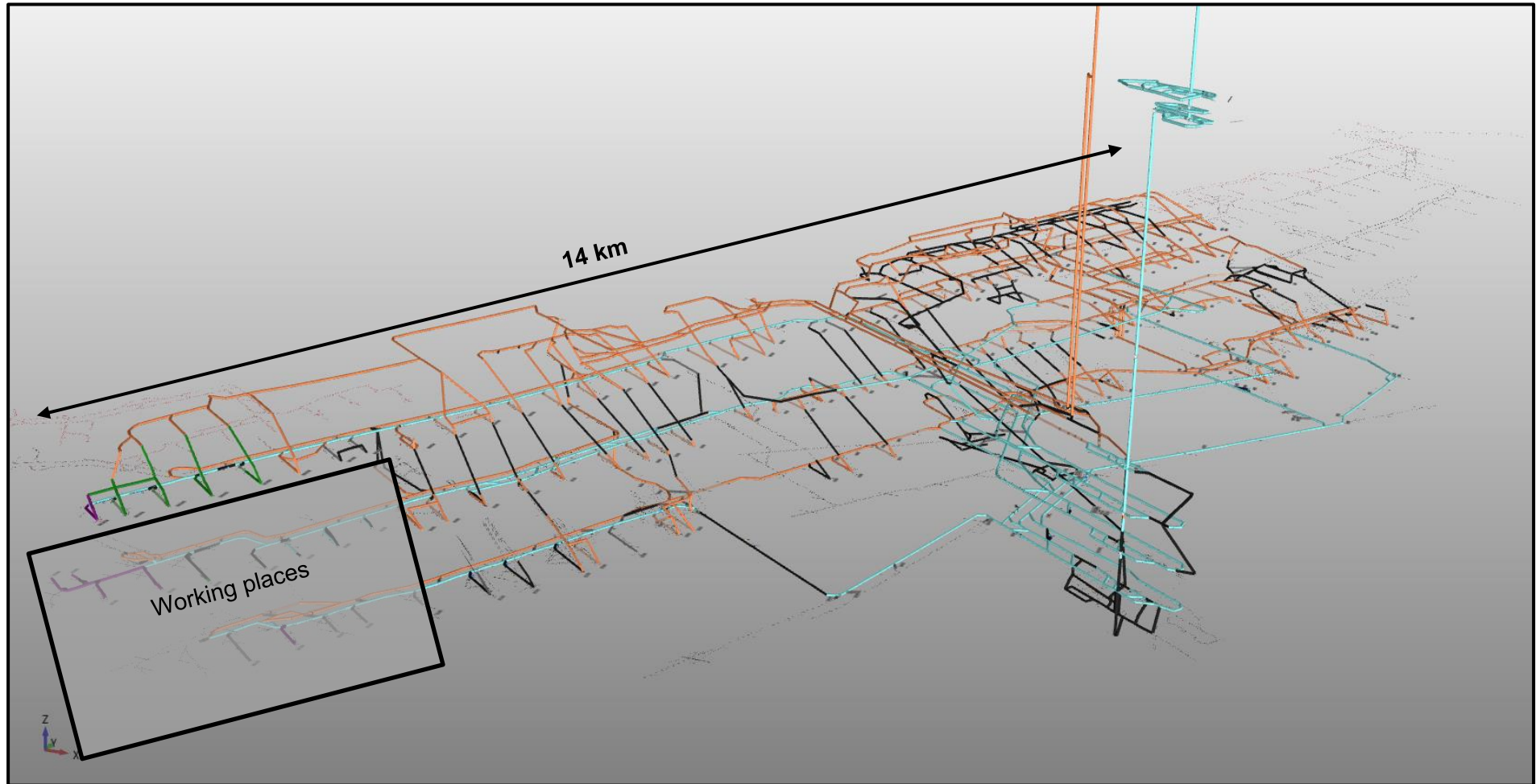


Figure 6. Digital twin with simulation of an entire WCS (Process Toolbox (PTB) simulation software)

Figure 7 shows the complexity of the system on a smaller scale. The figure shows a typical surface refrigeration system which consists of coolers, cooling towers, refrigeration systems, pumps, dams, piping, valves, controllers, actuators, sprays, instrumentation, and several other equipment. Therefore, the ability to “zoom” in and out of a system using digital twins is a new level of visualisation and understanding for the mining industry.

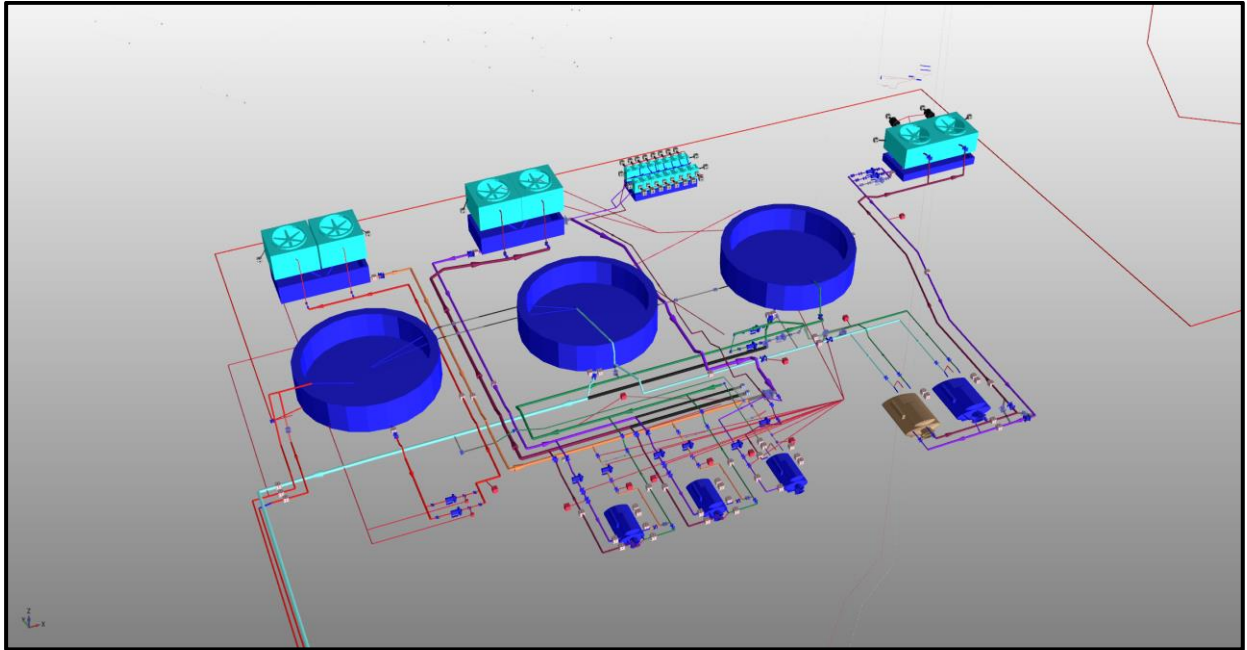


Figure 7. Digital twin with simulation of a surface refrigeration plant which forms part of the integrated WCS (Process Toolbox (PTB) simulation software)

The combination of digital twinning with simulation is new to the mining industry [42]. The addition of simulation allows the industry to visualise and simulate complex thermohydraulic systems. This is a departure from the current method of local characterisation of mining systems [23], [24].

Current methods investigate at a component level and do not integrate between systems and over the entire mining complex, therefore equipment is characterised and investigated individually [25], [26]. The current method is limited by the user as he/she determines the level of integration. Digital twinning with simulation allows the user to integrate all components through connections created in the simulation software. All components can be simulated simultaneously and dynamically which is not possible with current methods. This allows the user to visualise and simulate an entire mining complex simulatively and dynamically whilst integrating all components. The approach described falls under the umbrella of system dynamics (SD) which distances itself from traditional linear isolated models and incorporates a more interconnected approach looking at the system as a whole [43], [44], [45], [46]. Forliano et al., 2024 describes it well as “*Systems dynamics (SD), which is rooted in the broader discipline of systems thinking, offers a powerful lens through which to understand and navigate these complexities.*”

Unlike traditional econometric models, which often rely on linear assumptions and static relationships, SD excels in modeling dynamic systems characterized by feedback loops, time delays, and nonlinear interactions (Woodside, 2013). In response to these analytical shortcomings, there has been a discernible shift toward complexity theories and asymmetrical techniques that better accommodate the intricate dynamics of organisational systems (Misangyi et al., 2017; Kumar et al., 2022). As a foundational component of SD, systems thinking promotes an understanding of organizations and their environments as interconnected wholes, rather than as collections of isolated parts (Ricciardi et al., 2020). This holistic approach is critical for addressing the multifaceted challenges faced by modern organizations, which are often systemic and cannot be effectively understood through reductionist methods (Dentoni et al., 2021; Mair & Seelos, 2021). SD, as an extension of systems thinking, enable the exploration of how various elements within an organization interact over time, thereby providing insights into potential future behaviours and outcomes.” [45]

Dynamic simulation is important as it shows the dynamic effect of any changes made on the system and allows for dynamic boundaries [47]. Dynamic boundaries are a critical part of the mining industry as seen in the previous sections where the dynamic nature of the mine was shown. Therefore, a steady-state simulation falls short in simulating the peak demands which apply certain loads on the system. Steady-state simulation is often used for design purposes, where large safety factors are included [48]. Failure in simulating the peaks could result in an under-design, under-supply, or failure of a system; therefore large safety factors are required.

A dynamic and integrated digital twin with simulation can answer several “what if” scenarios in quick succession without the need for capital expenditure (CAPEX) and real-world testing. The effect of each “what if” scenario to the system can be determined and quantified allowing for improved planning. This reduces guesswork and allows any scenarios which have negative or negligible effect on the overall system to be disregarded. Therefore, a calibrated and verified dynamic and integrated digital twin with simulation provides the ability to apply changes to that system to minimise CAPEX.

The use of digital twins with simulation (hereafter only referred at simulation) in the mining industry is therefore a new and unexplored tool that could assist in solving a larger problem currently faced by deep-level mining operations.

1.3 Problem statement & Need for the study

Problem statement

Underground cooling demands are continuously changing due to the dynamic nature of deep-level mines and, consequently, system operations must adapt by making fast, informed decisions. These decisions include whether current infrastructure can meet future production requirements, if current infrastructure can meet the necessary redundancy in an emergency scenario, and if optimisation opportunities on the current operation exist.

The problem, however, is that current mine WCS planning methods do not account for the inter-linked nature of the dynamic underground water and cooling systems. This means that decision-makers are not fully equipped to make correct decisions for long-term sustainability and preparedness.

Need for the study

The dynamic and integrated nature of components in deep-level mines makes successful and accurate future WCS planning challenging. Therefore, the industry requires a new WCS planning method to accurately show the effect of the dynamic and integrated changes experienced by mines.

This new method will need to aid decision-making and future planning for cooling- and water systems. The method should interlink the two systems, water and cooling, and all their individual components.

The deep-level mining industry needs a method that can address the dynamic and integrated nature of deep-level mining components to assist in more accurate WCS planning.

1.4 Aim and objectives

Satisfying the need can be achieved through new technologies such as digital twinning with simulation (Section 1.2.4). Using a digital twin with simulation, it should be possible to model the integrated system with dynamic boundaries accurately (up to 95% accuracy). This will allow the mine to quantify the effect of system parameter changes quickly and accurately or, alternatively, provide possible solutions to operational concerns.

This study aims to develop a new method to assist with future mine WCS planning that reduces uncertainties and improves accuracy when compared with current methods.

To achieve the aim, this study will:

1. Develop a new WCS planning method that accounts for the dynamic and integrated nature of the WCS systems.
2. Ensure the method's applicability using criteria identified from a literature review.
3. Use the new method to simulate the WCS planning scenarios that are current being investigated by various case study mines in South Africa.
4. Compare the new planning method's results/predictions with current planning methods.
5. Report the new method's improvement over current WCS planning methods in:
 - a) accuracy,
 - b) production, and
 - c) safety.

1.5 Scope

The study will use current planning scenarios being considered by deep-level mining case studies in South Africa. Only water and cooling systems are considered. The study will report on accuracy, production and safety planning aspects only. The method will use simulation as a tool amongst many that will contribute towards solving the problem.

1.6 Research methodology

The case study methodology approach is followed in this study. A study conducted by Teegavarapu [49] showed the advantages of utilising a case study method for design research. The process developed in the study was closely followed in this study and is shown in Figure 8.

The process starts with the problem or need, already defined in Section 1.3. The next step is to consider current literature on the subject to identify important criteria for a successful WCS planning method in mining. With an understanding of the problem and the available methods, a new method will then be developed in Step 3 to address the need.

Once the method is at a satisfactory level it can be applied to case studies to investigate its effectiveness and feasibility (Step 4). It is important to note that the case study results should again be compared with other methods which attempted to achieve the same outcome (if available). If the method is an improvement, it is beneficial to the industry. However, if it is less effective it is suggested that the method is modified to improve the results if possible.



Figure 8. High-level case study methodology (adapted from [49])

1.7 Thesis layout

Ch. 1 | Ch. 2 | Ch. 3 | Ch. 4 | Ch. 5



Chapter 1: Introduction

Chapter 1 focused on the background of the current state of the mining industry, the thermohydraulic systems involved and planning methods used in the industry. The state of the art regarding mine planning, simulation and dynamic boundaries are investigated and discussed. The need is formulated from the state of the art which provides the objective of the study. The novel contributions are briefly discussed and

summarised. The objective is to use digital twinning with simulation to assist with future mine WCS planning.

Chapter 2: Literature Review

Chapter 2 focusses on an in-depth review of the state-of-the-art surrounding mine services planning. Several key areas are investigated namely, future mine planning, production planning, services planning and combined planning. Several approaches are also investigated such as simulation, dynamic boundary values and integrated simulation. The novel contributions of the study are also highlighted and discussed.

Chapter 3: Development of a new simulation-based planning method

A detailed step-by-step guide is provided to formulate a method that satisfies the need of the study. The method is separated into four major steps including data acquisition and quality, digital twin with simulation, dynamic boundaries, and verification and simulation-based planning. Each step is broken down and discussed so that the method is repeatable. The final step is critical to the study and utilises the developed simulation to assist with mine planning. The developed method is a simulation-based tool used for critical decision making and planning on deep-level mine WCSs. However, the approach can be applied to any system.

Chapter 4: Results and discussion

Chapter 4 showcases the use of the model developed in Chapter 3 on several real-world case studies. The method was applied to three case studies, each with a unique requirement and purpose. The method is discussed in detail for the first case study and detailed results shown. The remainder of the case studies are shortened to include only the key results to reduce the length of the document. The method application and results of each case study are discussed and compared with the current method in the industry.

Chapter 5: Conclusions and recommendations

Chapter 5 provides a summary of the study. The summary includes critical outcomes of the study, final discussion regarding the success of the method and future recommendations. Additional work that can be conducted and the application to other industries and systems are also discussed.

Chapter 2: Review of current mine planning solutions



Underground operations of a deep-level gold mine³.

The state of the art regarding water and cooling system (WCS) planning in deep-level gold mines are investigated and discussed in this chapter.

³ Retrieved from <https://www.miningweekly.com/article/modernisation-to-address-safety-efficiency-of-deep-level-mines-2020-04-24>.

CHAPTER 2 REVIEW OF CURRENT MINE PLANNING SOLUTIONS



2.1 Preamble

The dynamic, integrated, and complex nature of mine cooling systems requires that the mining industry adopt Industry 4.0 tools to assist with complex operational questions. One tool that can address this need is simulation. Digital twinning with simulation is an important technology used to improve planning, decision-making and design [50]. Digital twins with simulation are known to assist engineers in solving integrated, dynamic, and complex problems [51].

The purpose of this state-of-the-art review is to identify current methods used for WCS planning, determine their suitability for mining, and discuss the shortcomings of these methods.

2.2 Search strategy

The primary databases used for the literature search are ScienceDirect, SpringerLink, Scopus and Google Scholar. The search terms used in the literature included variations and combinations of the following keywords: water, simulation, cooling, planning, industry 4.0, digital twin and ventilation. Pre- and post-modifiers included deep-level, mine, dynamic, integrated, boundary, inputs, services, production, complex and mining.

The review yielded 39 studies relevant to current mine simulation methods for mine planning and improvements. The next section discusses and focuses in detail on each aspect considering what the current state of the art is regarding mine planning, mine digital twins and simulation and dynamic boundaries.

2.3 Future mine planning

Planning in mines forms an integral part of the success of the mine and long-term sustainability [52], [53]. Therefore, mines require significant time and energy for successful mine planning [54]. The industry's approach to mine planning was evenly split between production planning and services planning. 43% targeted production planning, 54% targeted services planning (comprising ventilation, cooling, compressed air, and water planning) and only a single study considered both. Figure 9 shows a breakdown of

subcategories of production and services planning found in literature. The figure was constructed through analysing and categorising all the relevant studies.

The two sections form an integral part, as services are required for production and make up a large cost component of the mine. Therefore, only after a satisfactory services cost is determined can a successful production plan be completed. Conversely the limitations of equipment and services determines the production plan. Therefore, the two are integrated.

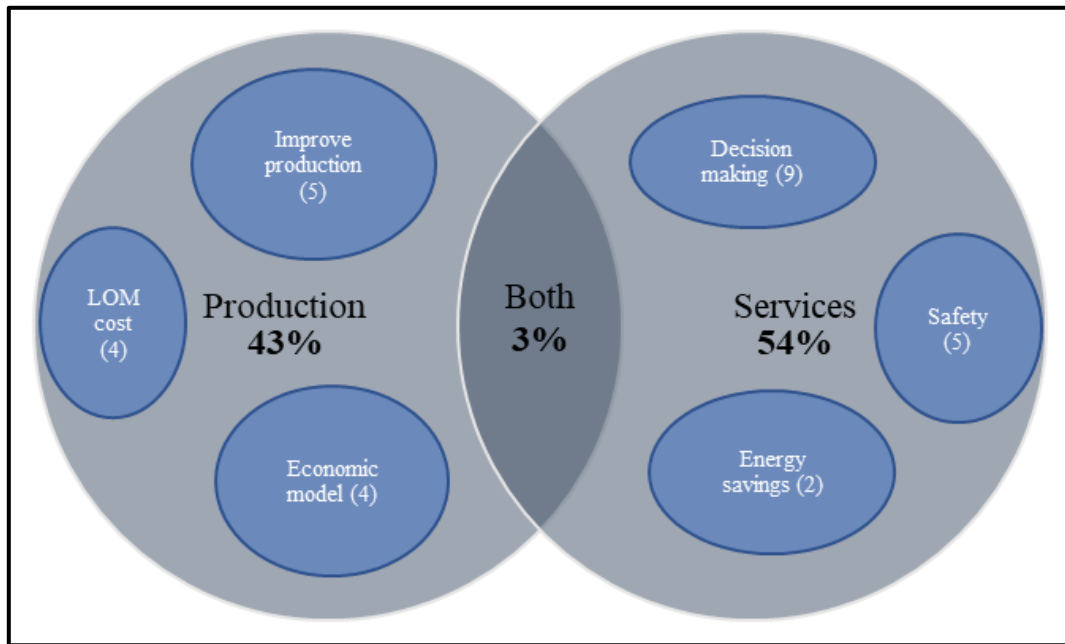


Figure 9. Chart indicating area of focus from mine planning literature study

2.3.1 Production Planning

Production planning in the industry was found to fit into three subcategories, namely economic driven, production improvement driven, and end LOM cost.

Economic production planning methods focus on economic factors to determine the suitability to mine and the quantity of mining required. The industry's major factor that contributes to this type of planning is the ore grade and commodity price. The planning method is typically short-term and changes depending on current economic factors.

Therefore, production planning includes short-term planning (typically months) and long-term planning (typically several years) [54], [55]. A study conducted by Prakash [56] was able to accurately (95%) predict short term production and planning of an open pit mine. The study modelled truck and shovel systems to determine the tonnes per hour and efficiency of the system.

Another notable study was conducted by Del Castillo [57] which determined a production plan based on ore grade and mine scheduling in a copper open pit mine. The method utilised an economic method based on copper price and ore grade to determine the best time to expand. The method predicted when CAPEX projects were viable to maintain or increase production. The method increased the net present value (NPV) of the mine by US \$170 million.

The method is applied and adapted in this study whereby a CAPEX project must significantly increase the NPV of the mine before it is considered feasible. Other studies that considered an economic driven production planning method included:

- Behrang [55] who designed a method for long term production planning based on price uncertainty for open pit mining.
- Sepúlveda [58] who developed an open pit mine planning method to determine remaining LOM based on several mining associated costs.
- Ajaka [59] developed a method to determine a production plan based on predicting iron ore deposits for an iron ore mine.

Several studies focused on improving the production of the mine through various methods. An important study is the one conducted by Paricheh [60] that developed a method to locate surface facilities at an open pit mine to improve production based on a risk management approach. The location of the facilities had a direct effect on the route and distance of all trucks at the mine. A risk management approach was used to determine the optimal location. The risk management method has merit in the deep-level gold mining industry where risks are associated to any form of planning and form a major role in decision making.

Three studies conducted by Chai [61], Muniappen [5] and Ozdemir [62] all focused on improving production by improving mine equipment. The optimised use of equipment resulted in increased production. These studies give an overview of how to improve current systems to boost production without significant CAPEX.

The total cost included in end of LOM activities is extremely important to take note of when planning for mine closure or growth. Four studies considered the total costs involved in LOM closure costs and the economics involved. Nehring [63] and Paricheh [64] determined the cost to close open pit mines through different techniques.

Nehring used an NPV based method to determine the final cost involved and the closure cost as the LOM is extended. Paricheh used simulation to predict the same closure costs. Importantly, both studies saw the benefit of keeping mines operational for as long as possible as LOM closure costs decrease with an increase

in LOM. Riméleá [65] focused on reducing the LOM closure costs after mine closure by disposing of tailings wastage in mined-out sections.

Otto [52] specifically focused on a method to enforce and track LOM planning to ensure that it is followed. The study showed that a mine was able to follow LOM planning to within 3% if tracked and communicated, which resulted in an improved confidence in the LOM plan. This in turn assists services planning. The closely followed LOM plan results in known service requirements which can be planned accordingly.

The above section provides insight into the integrated nature of production and its dependence on successful services planning.

2.3.2 Services planning

Similar to production planning and improvement, it is important to plan for mine services in accordance with the planned production. Services planning was found to fall into three subcategories, namely decision making, energy savings and safety.

Decision making is a vital role in planning. Therefore, developed methods and tools that can assist senior mine personnel in making informed decisions are beneficial to the success of services planning [57].

Eight studies developed methods or simulations to assist mine management with decision making for future planning. 50% of the studies were based on underground mines and 50% on open pit mines.

The studies that focused on underground mining planning considered three systems, namely mine cooling systems, mining methods, and ventilation. A study conducted by Pretorius [25] utilised a data-information-knowledge-wisdom (DIKW) method to provide short term insight to system improvements of mine cooling systems.

The method simplified the vast number of data points collected from underground equipment into an easy-to-digest package. The method removes unnecessary complexity and only provides critical current performance metrics for mine cooling systems (MCS) equipment. The method to simplify the way data is represented to mine personnel so that informed decisions can be made is extremely important for any planning method.

Two studies conducted by Weia [66] and Cheng [67] showed the benefit of providing a 3D to scale representation of the mine ventilation for improved understanding and planning. The simple act of providing a 3D digital twin of the mine's ventilation system allowed planners to visualise production areas, problem areas and distances to working places.

Visualising the mine on a 2D not to scale digital twin misinforms mine management to the actual scale of the mine and possible problems. For example, mining areas can be up to 2 km away from the nearest cooling equipment, therefore positional efficiency can be improved and visualised through the 3D digital twin. An example of the 3D ventilation digital twin created by Weia is shown in Figure 10.

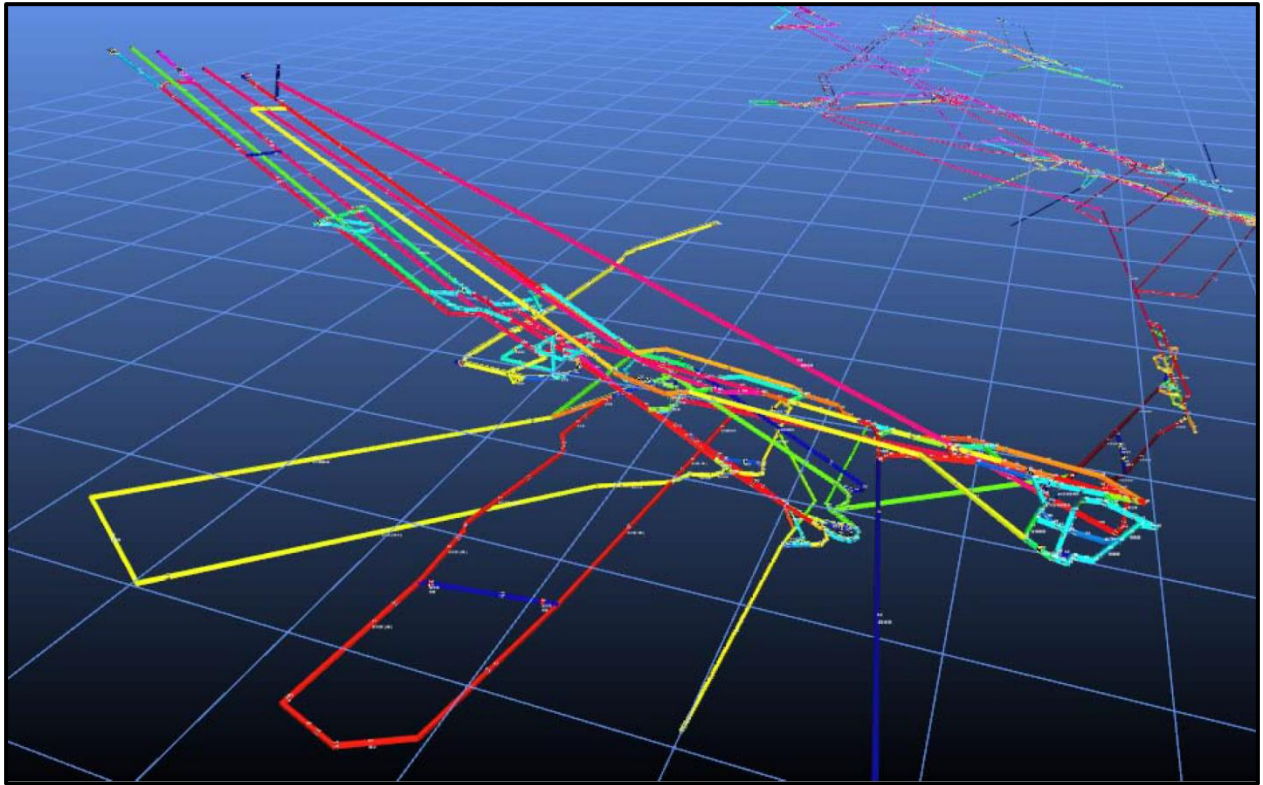


Figure 10. 3D mine ventilation digital twin rendered using Vuma network [66]

A study conducted by Yuna [68] used 3D mine ventilation simulation software to determine the best course of action for optimised cooling. Three possible cooling solutions were investigated using the simulation and the favourable solution that was selected was based on underground temperatures. The study demonstrates the unique ability to test multiple solutions using simulation software to assist with decision making.

A study conducted by Liang [69] developed a model for selecting the best mining method for underground mining based mainly on the technical aspect with economic effects included. The method is specifically suited to new deep-level mines, which is not the current environment in South Africa. However, if new development is planned underground the option to investigate several mining methods is advantageous.

The remaining studies assisted with decision making focused on open pit mining. The studies focused on three systems, namely material handling, dewatering, and predicting blasts.

Studies conducted by Meng [70] and Mia [71] considered material handling systems to assist with decision making. Meng developed a model to characterise material handling systems which could predict production tons and be used to assist with future planning and mining. Mia considered a maintenance model for vertical mills to maintain equipment optimally to improve production.

White [72] conducted a study to model the underground water flow of an open pit gold mine to predict future dewatering requirements. The model assists mine management with proactive solutions to future concerns or problems assisting decision making and future planning.

Bernarda [73] investigated simulating blasts to assist with future production predictions. This provides a picture of the possible production that can be expected, and services can be determined accordingly.

Two studies specifically focused on energy management and savings for future planning. The study conducted by Pelzer [74] developed a method whereby dewatering pumps in deep-level gold mines was scheduled to reduce energy costs. The reduction in energy costs subsequently reduced operating costs and increased LOM prospects.

The remainder of the services planning studies specifically focused on safety. Continuous safety improvements and requirements are extremely important to protect the employees. Therefore, it is important to plan accordingly whilst including safety planning. Most safety scenarios considered were based on underground ventilation systems.

A study conducted by Adjiski [75] used 3D ventilation software to optimise emergency evacuation routes underground. The simulation was used to reduce the time and distance workers would be in contact with dangerous gasses and heat during an underground fire. Similarly, a study by Stefopoulos [76] utilised simulation to determine the best emergency ventilation in case of an underground fire in an underground workplace. Also utilising simulation, Feng [77] developed underground mitigation strategies for gas leaks using a CFD model for underground buildings.

Wua [78] developed a 3D underground simulation and monitoring tool to assist with underground safety in coal mines. The simulation was used to communicate critical underground conditions to mine safety personnel to ensure areas are safe for workers. The model was also used to predict possible problem areas or impending emergencies allowing for improved reaction.

Finally, Tomiyamaa [79] focused on the safety impact of mining on the larger community. The developed method modelled underground water to predict acid mine drainage (AMD). The predictions were used to determine the best course of action to ensure reduced AMD for the future.

The above studies all show the importance of services planning to ensure continuous and safe underground operations, and open cast operations for that matter.

2.3.3 Combine production and services planning

The only study to consider both services and production planning was conducted by Campeau [54]. The study specifically considered short term production planning based on geological, labour- and equipment limitations. The important aspect is the equipment limitations. This is often overlooked by planning strategists in the mining industry.

Production and services, which are subject to equipment limitations, are integrated. Therefore, integrating the two is extremely important. The study investigated four scenarios based on production targets and equipment limitations in an underground coal mine. The model was able to demonstrate the improvement available based on maximising equipment and improving scheduling as a result. The same number of tons was removed in 20% less time as compared with the current method.

It is, however, important to note that the model did not include any simulation software and was purely based on a numerical analysis. Therefore, with the inclusion of mine simulation software that can accurately determine equipment limitations, a more accurate model can be developed. It is clear from the literature that the current planning methods fall short in accurate future planning on mine systems. This will be investigated further in the next sections.

2.4 Simulations

The use of simulation in the mining industry is not new. Simulation has been used in the mining industry for years [24]; however, fully integrated and dynamic thermohydraulic simulations have not been used the industry in its entirety and are not the norm [11].

The importance of integrated and dynamic thermohydraulic simulation cannot be understated. A fully integrated, dynamic, empirical, and verified simulation provides a realistic representation of the actual system [11], [41]. Integrated in this instance refers to the effect a mining system component has on the overall system. A change in one component has a global effect on the system and is therefore integrated in the system. The component's effect cannot be isolated as the global effect will be ignored. This is advantageous in the mining industry due to the complexity of the system. It is not possible for a human

operator, planner, or manager to fully grasp the integrated effect of system changes, mining demand changes and equipment changes [4]. However, a simulation can easily display important results to the operator, planner, or manager that take the integrated effect into account without his/her knowledge. Overlooking the integrated effect of a system can easily result in incorrect conclusions or solutions [11], [30].

A study conducted by Maré [11] developed an integrated simulation-based method to determine the best course of action for deep-level mine cooling system energy management. Maré used an integrated and dynamic simulation model to simulate the current underground MCS and its inefficiencies. The model was then used to determine possible energy saving initiatives and tested using the simulation. The method assists with determining possible future energy costs and savings for the MCS. This dissertation focused on future planning for WCS infrastructure requirements and is not focused on energy savings. The use of simulation is also investigated for future planning.

The study conducted by Maré [11] clearly showed a lack of integrated and dynamic simulation in the mining industry. The study showed that 50% of all published work only considered steady-state simulations. Of the steady-state studies 50% focused on an integrated system, and 25% of studies focused on transient (dynamic) simulation. Of the transient studies, only 10% focused on the integrated system. Figure 11 was adapted from Maré [11] and shows the percentage of mine simulations that included transient (dynamic) simulation.

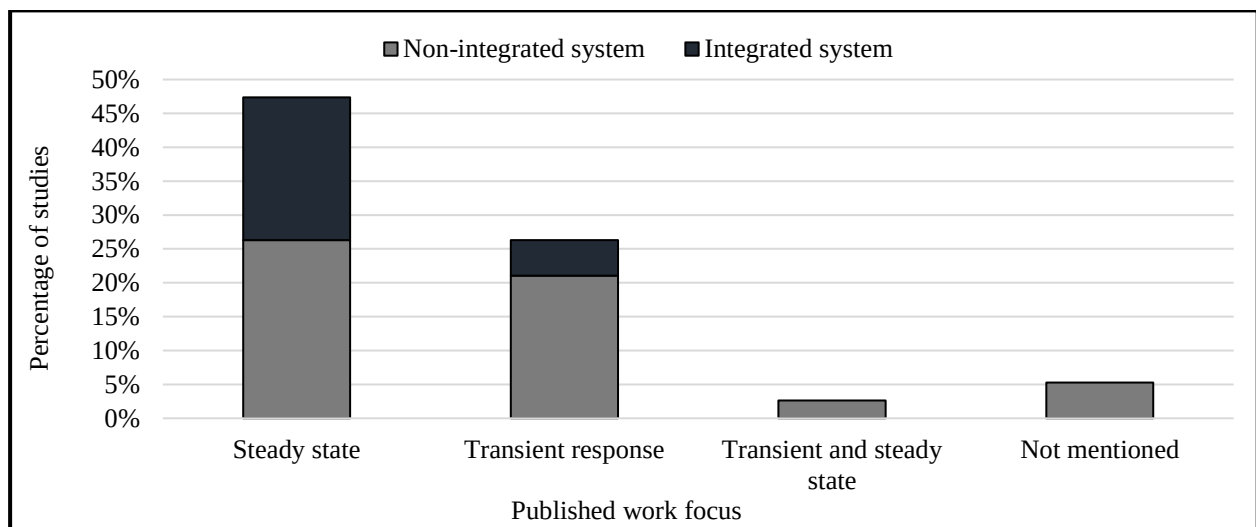


Figure 11. Percentage of studies focusing on transient response simulations in mining, adapted from [11]

The same breakdown was conducted for this study. It was found that only 20% of the studies focused on an integrated and verified models. Of those studies 60% focused on mine planning. Therefore 13% (5 studies) of all 39 studies used an integrated and verified model for mine planning. 45% of the studies

realised the importance of verification, but the majority were not integrated models. The breakdown is shown in Figure 12.

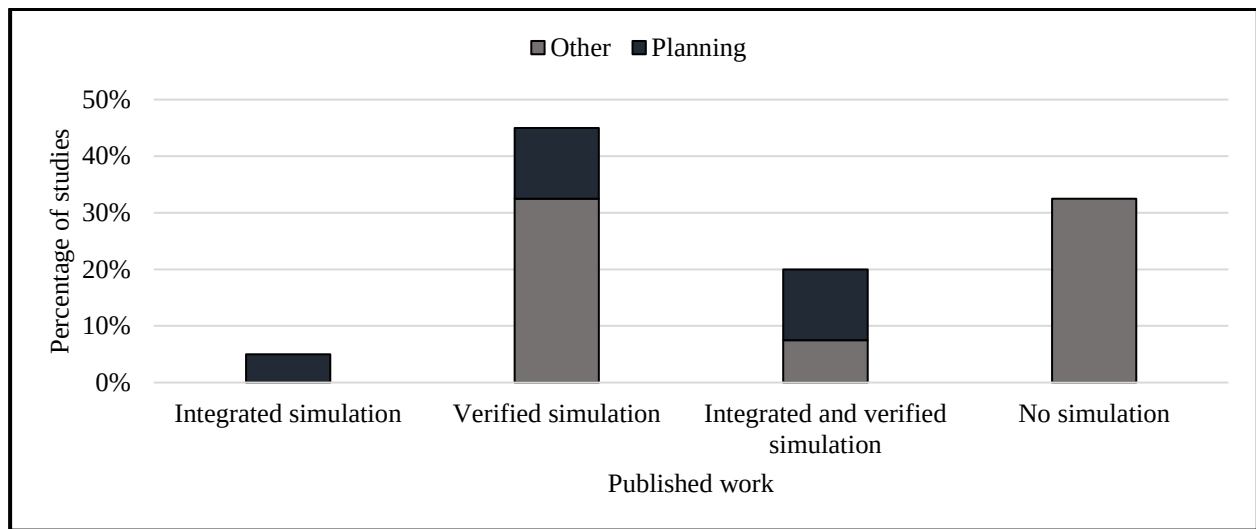


Figure 12. Percentage of 39 studies using simulation for mine planning

The four studies that made use of integrated simulation all focused on different areas and none were concerned with future mine infrastructure planning. The studies conducted by Pelzer [74] and Maré [11] both focused on energy savings management to reduce operational costs on deep-level mines. The study conducted by Mathews [80] focused on a simulation-based maintenance model to improve maintenance scheduling. The scheduling tool took several costs, equipment limitations and production into consideration. The model was applied to a coal-fired power station.

The last of the four studies conducted by Stefopoulos [76] used an integrated and verified ventilation simulation to determine the best ventilation for an underground emergency. The simulation was applied to an underground workplace facility.

A study conducted by Fair [81] showed the importance of accurate simulation for mine ventilation planning. He investigated the use of a new simulation method for ventilation planning and compared it with the current method. The simulation-based method showed a clear accuracy improvement over the current outdated heat load method. He, however, did not consider the WCS in his study which was focused only on ventilation of deep-level mines.

The above section shows there are no studies that use simulations to determine the integrated effect of components for future WCS planning which this study attempts to achieve.

2.5 Dynamic boundary values

The dynamic nature of the mining environment, with changing conditions, demand, and supply, requires certain dynamic boundary inputs and demands. The systems and components found in a deep-level mine are all integrated and therefore react to these dynamic boundaries. The dynamic boundaries are out of the mine's control or subject to certain fixed parameters.

An example of this is the environmental conditions on surface or underground. These are dependent on the atmospheric conditions and are constantly changing as seasons change. This is seen as a dynamic input to the simulation. The simulation will subsequently react to the input [81].

Alternatively, a dynamic boundary demand is dependent on several factors, most commonly human factors. An example is the water demand on a system. This demand roughly follows the work shift; however, it is unique to each mine and is highly dependent on mine management, mine technique, mining schedule, underground etiquette, and discipline. A simplified schematic description of dynamic boundaries is shown in Figure 13.

In Figure 13 dynamic boundaries are shown to include model inputs in the form of dynamic boundary conditions and dynamic demands. For example, ambient temperatures and temperatures are a dynamic boundary condition and mine water usage is a dynamic demand. Both are inserted into the models as dynamic inputs.

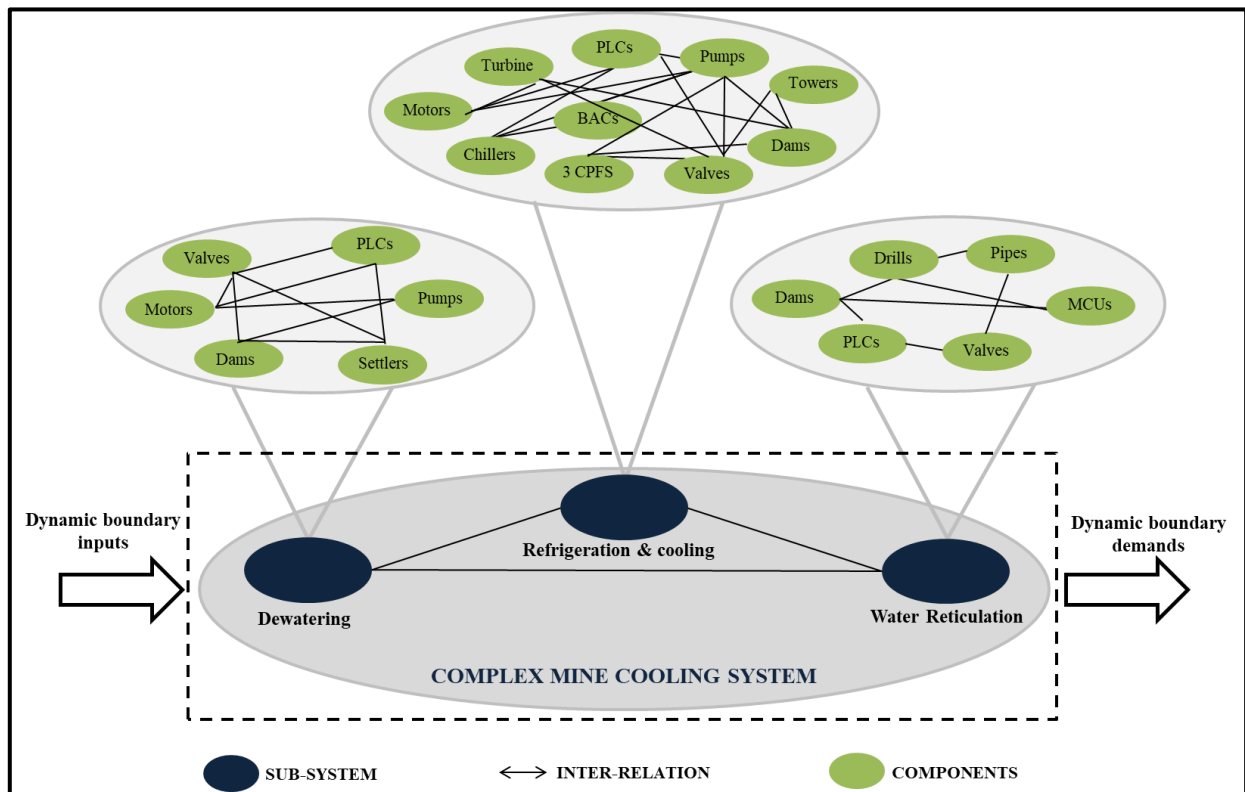


Figure 13. Simplified layout of dynamic boundaries in an integrated mine system (adapted from [11])

Dynamic boundaries significantly improve the accuracy of the simulation and form part of a dynamic simulation. The dynamic boundary provides an input or a demand on the system which the system must react to. The peaks and troughs of the boundary affect the operation of the entire system.

An example of a dynamic boundary is the ambient conditions which are constantly changing daily and on a seasonal basis. The input for a steady-state simulation or a transient simulation without dynamic boundaries would be a fixed value over the entire 24-hour period. Such an input or demand will not show the effect of the peaks and troughs in the demand, providing a less accurate result.

Of the 39 studies considered in the state of the art, only two studies contained dynamic boundaries. The study conducted by Du Plessis [8] constructed a mine cooling system simulation to reduce energy costs in deep-level mines. The simulation included dynamic water temperatures from underground, air conditions, and a dynamic water demand to underground. The simulation was, however, focused on energy savings and not specifically on planning. Therefore the 24-hour profiles were of less importance than the average monthly savings.

The second study considered ambient conditions for the use of developing cooling strategies for long wall coal mining. The developed method was a mathematical method without simulation capabilities, hindering

the turnaround time of the model. However, Belle [82] showed that utilising the dynamic boundary, in this case ambient conditions, the model could accurately determine underground temperatures with various cooling solutions applied. This shows the benefit of utilising dynamic boundaries.

2.6 Findings from the state-of-the-art review

The summary of the findings from the investigation showed some studies considered planning items such as hoist scheduling [83], mathematical models of sub-sea gold mining planning [69], predictive maintenance for vertical mills [71], or modelling groundwater [79], [84]. All these studies were focused on a single system within an integrated model. Most of these planning methods are for open pit-, coal- and shallow mining [78], all of which are a simpler form of mining with far fewer complexities than deep-level mine cooling systems.

The literature study also found several simulation studies on deep-level mine ventilation systems [31]. Most of these studies focus on ventilation-related challenges. Only a few of the studies recognise the importance of water and cooling systems. However, the few studies that included cooling systems did not address the integrated effects of all the various components of mine cooling [28].

A study done by Maré [11] also indicated that most simulation studies conducted in mine cooling systems only focus on a specific system in isolation, and do not consider the integrated effect of all components of the mine cooling systems. Most of the simulation methods only considered steady-state conditions, rather than dynamic conditions. Steady-state simulation is often used for design purposes, where large safety factors are included [48].

Maré [11] also aimed to address the integrate and dynamic simulation need associated with deep-level mine cooling. However, the method used by Maré focused on energy management and energy savings. Maré did not consider the challenges associated with future planning or water and cooling service improvements. The same applies for studies [27], [8], [6], [74].

From this review, several key criteria arose as requirements for a successful mine planning method.

These criteria are used as a reference point for comparing various studies, summarised in Table 1 and graphically shown in Figure 14.

1. Planning:

- a) Did the study use the developed model to predict future demands (e.g. temperatures, pressures, conditions)?
- b) Did the study use these results to plan for future expansion, system changes, closures or emergencies?
- c) Were the study's results/model implemented in a working mine? Building, calibrating, and verifying a model of a large complex system is time consuming [11]. Therefore, it is important that the results can be used in real-life applications. The implementation of these changes or simulation results is the final step in the validation process.

2. Digital twin:

- a) Did the study create an exact digital representation of the mine?
- b) Did the study use software that allows for 3D simulation and models?

3. Fully integrated and verified simulation:

- a) Did the study use a form of simulation software to model the thermohydraulic system for future production and emergency planning? Indicated as "Yes" in Table 1 if the study used an integrated and verified simulation model.
- b) Did the study model the fully integrated system? Fully integrated simulation models simulate the effect that one system parameter change has on all the components of the system (indicated as "I" in Table 1).
- c) Did the study compare simulated or model results with actual data verifying the model? Verification is an important step to determine the validity of the model/simulation. Without verification it is difficult to determine if the simulations results can be trusted (indicated as "V" in Table 1).

4. Dynamic boundaries:

- 1. Did the study include dynamic boundaries? These typically include dynamic underground temperatures, surface temperatures, chilled water demand/flows, dewatering demand/flows and thermal storage. The use of dynamic boundaries is unique and improves the accuracy of the simulation model which better represents the actual system.

Table 1. State of the art for mine planning and simulation

No.	Author	System	Application	Planning	Digital twin	Integrated (I) verified (V) simulation	Dynamic boundaries	Main task	Main finding	Cit.
1	J. Vosloo	Dewatering	Energy savings	No	No	Yes	No	Use integrated simulation to reduce water reticulation costs.	Simulation assisted control strategy reduced costs by 13%.	[27]
2	G.E. du Plessis	Refrigeration	Energy savings	No	No	Yes	Yes	Use integrated simulation to reduce cooling costs.	Simulation assisted strategy reduced costs by 33%.	[8]
3	R. Pelzer	Dewatering	Energy savings	Yes	No	Yes	No	Use simulation to reduce peak energy loads of pump systems.	Simulated assisted load reduction of 113 MW over 33 shafts.	[74]
4	Y. Wua	Monitoring	Planning	Yes	Yes	V	No	3D underground simulation allowing decision making capabilities.	Use of 3D simulation assists with underground safety.	[78]
5	J. Cheng	Ventilation	Planning	Yes	Yes	No	No	Develop integrated mine ventilation model for coal mines.	High level model developed to assist with future planning.	[67]
6	M. Paricheh	Locating facilities	Planning	Yes	Yes	V	No	Simulation to predict best location for surface facilities to ensure least distance for trucks.	Economical model to determine ideal locations of facilities, applied to mine in Iran.	[60]
7	C. Meng	Material handling	Planning	Yes	No	V	No	Develop material handling simulation model for open pit mines.	Simulation assist decision making in material handling systems and improve efficiency.	[70]
8	M. Paricheh	Open pit	Planning	Yes	No	No	No	Develop model to predict open pit mine closure time and cost.	95% confidence level model in determining time and cost of mine closure.	[64]
9	T. Chai	Ore grinding	Planning	Yes	No	No	No	Develop economic model to optimise grinding process.	Improved costs and grinding capacity by 40%.	[61]
10	B. Belle	Ventilation & refrigeration	Modelling	No	No	V	Yes	Develop cooling strategies for longwall coal mining.	Investigated and proposed several strategies to cooling Australian mines.	[82]
11	K. Muniappen	Open pit coal	Planning	Yes	No	V	No	Use dynamic material handling system simulation to assist with LOM planning.	Simulation validated on new opencast coal mine.	[5]
12	B. Ozdemir	Multi-pit	Planning	Yes	Yes	V	No	Use of simulation to improve material handling systems at open pit mines.	Simulation assisted strategy increased production by 9.4%.	[62]
13	M.F. Del Castillo	Open pit	Planning	Yes	No	No	No	Economic model to optimise production scheduling in open pit mine complexes.	Simulation assisted strategy resulted in a US\$170 million increased net present value.	[57]
14	G. Danko	Ventilation	Modelling	No	No	V	No	Thermodynamic model for mine ventilation.	Verified thermodynamic ventilation model.	[31]
15	S.P. White	Open pit	Planning	Yes	No	V	No	Underground water flow model to predict future dewatering demands.	Verified model used to predict underground water quantities.	[72]
16	W. Badenhurst	Hoisting	Scheduling	No	No	V	No	Develop model for hoist scheduling during peak load.	Model assisted strategy reduced costs by 31%.	[83]

No.	Author	System	Application	Planning	Digital twin	Integrated (I) verified (V) simulation	Dynamic boundaries	Main task	Main finding	Cit.
17	T. Bernarda	Blasting	Blasting	Yes	No	No	No	Develop simulation for blasting.	Blasting model accurately simulates several scenarios to within 85%.	[73]
18	W. Liang	Sub-sea gold mine	Planning	Yes	No	No	No	Model to determine best mining method for deep level mines.	Best mining method selected for new mine in China.	[69]
19	S. Mia	Vertical mills	Maintenance	Yes	No	V	No	Predictive maintenance model for vertical mills.	Best solution selected from several for best maintenance.	[71]
20	W. Bornman	Cooling system	Modelling	No	Yes	Yes	No	Developing mine cooling simulation.	Simulation verified to 97% accuracy.	[28]
21	S. Tomiyamaa	Groundwater	Planning	Yes	No	No	No	Numerical model to predict acid mine drainage.	Model showed backfilling could red AMD by 61%.	[79]
22	S.P. Upadhyay	Open pit	Planning	Yes	Yes	V	No	Mine planning simulation for open-pit mines.	Verified to within 95% confidence interval.	[56]
23	M.A Riméla	Open pit	Planning	Yes	No	V	No	Modelling tailings storage in mine pit with focus on life-of-mine planning.	Successful in pit waste management is possible and reduces environmental impact.	[65]
24	J.A. Crawford	Cooling system	Energy savings	No	No	V	No	Model and control strategy to improve energy efficiency of cooling system.	Control strategy resulted in USD\$83k and 2 MW peak savings.	[6]
25	M. Nehring	Costing	Planning	Yes	No	No	No	Life-of-mine planning using an optimised NPV model.	Determined mine closure cost for several LOM scenarios.	[63]
26	G.F. Sepúlveda	Production	Planning	Yes	No	No	No	Open pit mine planning model.	Applied to case study which gave 15 years LOM.	[57]
27	F. Weia	Ventilation	Planning	Yes	Yes	I	No	Use of 3D mine ventilation software for mine management.	Provided improved vision to mine planners who could visualise underground ventilation.	[66]
28	P. Maré	Refrigeration and cooling	Energy management	Yes	No	Yes	No	Integrated simulation model used for energy savings of mine cooling systems.	Integrated simulation assisted with R31 million energy savings.	[11]
29	I. Mathews	Power station	Maintenance planning	Yes	Yes	Yes	No	Integrated simulation of a coal fire power station.	Simulation used to predict best time to maintain CFPS condenser.	[80] [85]
30	K. Behrang	Production	Planning	Yes	No	No	No	Life-of-mine planning using a model based on price uncertainty.	Model compared and used on a case study which yielded a LOM NPV of USD\$2.4B.	[55]
31	S. Yuna	Ventilation	Decision making	Yes	Yes	V	No	Use of 3D mine ventilation software for mine management.	Simulation assisted with best solution for three options available to the mine.	[68]
32	T.J. Otto	Open pit production	Planning	Yes	No	No	No	Method to track and enforce life-of-mine planning execution.	An open pit mine that followed method was 90% in line with LOM planning.	[52]

No.	Author	System	Application	Planning	Digital twin	Integrated (I) verified (V) simulation	Dynamic boundaries	Main task	Main finding	Cit.
33	A.D. Ajaka	Geological	Production planning	Yes	No	No	No	Method to determine risk of clay uncertainty in iron ore deposits.	Method was 79% accurate in predicting clay and resulted in 12 - 21% increased NPV.	[59]
34	L. Campeau	Production	Planning	Yes	No	V	No	Short term mine planning method for underground mines.	Determines best areas to mine according to several user and geological inputs.	[54]
35	C. Loredó	Underground water	Modelling	No	No	V	No	Thermodynamic underground water model.	Used to determine feasibility of using flooded mines for geothermal energy.	[84]
36	E.K. Stefopoulos	Ventilation	Safety	Yes	No	Yes	No	Utilise simulation to determine best emergency ventilation in case of fire.	Simulation used to determine best flow rates and equipment to ensure safety during an underground fire.	[76]
37	J.G. Pretorius	Refrigeration and cooling	System improvement	Yes	No	I	No	Developed a DIKW model for mine cooling systems.	Implemented model resulted in a system improvement of 5.3MW or 55%.	[25]
38	J.R. Feng	Ventilation	Safety	Yes	No	V	No	CFD model used for underground gas leaks and mitigation strategies.	Modelled resulted in 20% reduced time in contact with gas.	[77]
39	V. Adjiski	Ventilation	Safety	Yes	Yes	V	No	3D underground ventilation simulation of underground fire.	Simulation used to optimise evacuation routes for a simulated fire.	[75]

	Included in reference
	Not fully included in reference
	Not included in reference

Table 1 shows none of the studies utilised a fully integrated simulation with dynamic boundaries⁴ to assist with future production and emergency planning. 69% of the mine planning studies had no simulation or dynamic boundaries and only 10% used simulation. Of the simulation-based tools only 3% contained dynamic boundaries. Very few studies had dynamic boundaries included in their model, this is because the search was narrowed down to only include sources that were within the mining industry. If the search was to be extended outside of the mining industry several more studies would have been relevant. It is also important to note that several keywords were used for dynamic boundaries such as dynamic boundary, dynamic boundaries, dynamic inputs, dynamic control volume and dynamic model inputs.

Therefore, from the literature review the mining industry lacks an integrated and dynamic mine cooling simulation method to address future planning and service improvement. This is surprising as the mining environment is constantly changing, dynamic and integrated.

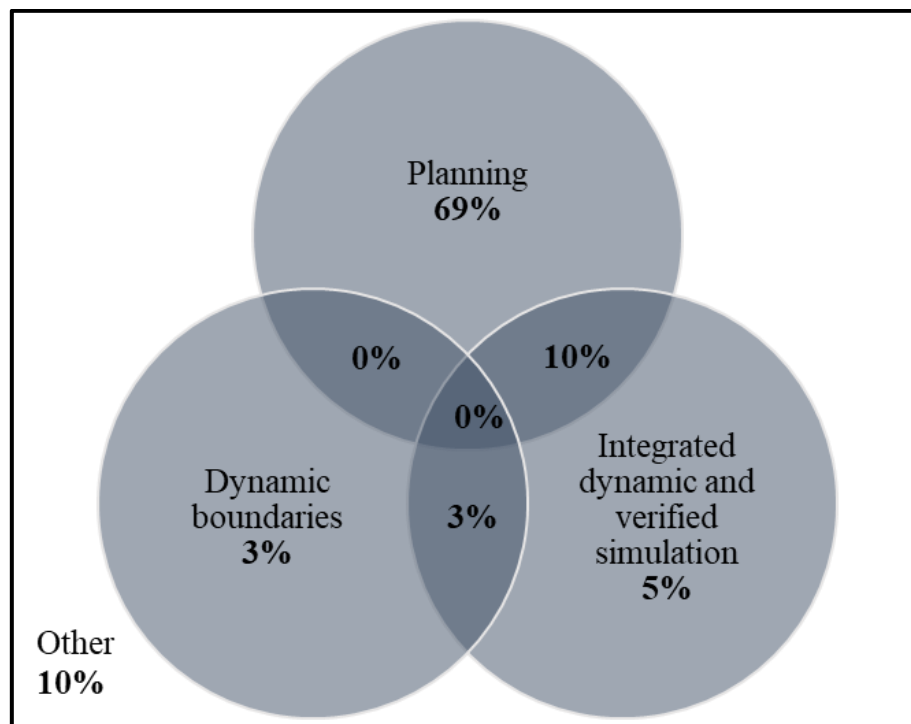


Figure 14. Breakdown of studies focusing on planning, simulation, and dynamic boundaries

The investigation showed a clear lack of mine WCS planning that incorporates integrated simulation and dynamic boundaries into the mine planning method.

⁴ Several other keywords were also included such as dynamic boundary, dynamic boundaries, dynamic inputs, dynamic control volume and dynamic model inputs.

2.7 Expected novel contribution

The success of the new WCS planning method will assist the mining industry with improving WCS. The drawbacks of using current methods will be compared in the results chapter of this thesis. The main expected contribution of the study is therefore summarised as:

A new planning method for deep-level mine WCS which accounts for the integrated and dynamic nature of the WCS components for improved accuracy, production and safety.

Current method or approach

Section 2.3 show that the current approach to mine WCS planning focuses on production planning using static mathematical models and not simulation models [54], [69], [79], [83], [84]. The current approach uses mathematical models that are based on:

1. Design parameters and exclude the dynamic effects (e.g. ambient conditions and, variable water and heat storage) associated with complex WCS. [25], [69], [70], [71].
2. Equipment and systems are also considered in isolation. The current approach does not consider the integrated effects that the different equipment and even systems have on each other.

Shortcomings of current method

The industry's reluctance to adopt simulation for future mine planning has several shortcomings. Without the use of accurate thermohydraulic simulation, the future demand and changes are not visible to mine planners. Therefore, it is difficult to plan services according to future production requirements accurately. Most of the work only considered economic factors and ignored planning for services [5], [52], [55], [58], [59], [60], [61], [62], [63], [64], [65]. The few methods that did focus on services did not take production into consideration and integrated effects of the different systems and equipment were not considered [66], [67], [69], [72], [73], [74], [75], [76], [78], [79].

Contribution of this study

The use of integrated and dynamic models in this study will greatly improve the accuracy to which production and WCS planning can be conducted. The components that will be integrated include water supply (e.g. pipes, turbines, dissipators, valves, dams and pumps), dewatering (e.g. pipes, valves, dams and pumps), and cooling (e.g. pipes, chillers, valves, bulk-air-cooling, heat exchangers, cooling cars). The condition of future underground services can be accurately simulated and matched according to the required

production planning. The output variables that will be considered include, water pressure, water flow, energy consumption, water temperature and air temperature). The method will allow several scenarios or solutions to be investigated to allow for the planned production in the future. This will reduce any uncertainty with the limitations and requirements of services.

The contribution of this study can be summarised as:

- Accurate thermohydraulic simulation of integrated mine water and cooling systems.
- Improved future services prediction accuracy for deep-level mines.
- Improved future services planning accuracy for deep-level mines.
- Ease of testing several services configurations for future planning without any infrastructure or capital expenditure.

2.8 Conclusion

Chapter 2 investigated and discussed the current state of the art of mine production and services planning. The state of the art showed a clear lack in the use of modern tools such as integrated simulation for planning. The gap in literature led to the novel contributions and the focus of this study. The next chapter will discuss the proposed method using dynamic, integrated simulation for mine services planning.

Chapter 3: Development of a new simulation-based planning method



An underground refrigeration plant used to chill water⁵.

The development of a new novel method for WCS planning is discussed in this chapter.

⁵ Retrieved from <http://chegepublishing.net/wp-content/uploads/2016/03/14MW-Underground-Refrigeration-Plant.jpg>

CHAPTER 3 DEVELOPMENT OF A NEW WCS PLANNING METHOD



3.1 Preamble

As discussed in Chapter 1, the dynamic and integrated nature of mining environment necessitates a systematic approach to water- and cooling systems planning. The method developed here in Chapter 3 will address the need and criteria identified in Chapter 1. This method is adapted from a study conducted by Teegavarapu [49] which makes use of a four-step process that takes the information and data from the case studies and transforms them into an integrated simulation planning method for the respective mine(s).

The newly developed method furthermore makes use of empirical measurements (based on current conditions) and takes the integrated and dynamic effects of the mine's WCS into account. The method can be used for numerous mining planning applications e.g. mine development, safety and emergencies.

3.2 Method requirements and construction

This chapter is focused on the "Develop Solution" step of Figure 8. The key learnings (criteria) from the literature will be used to determine and construct the key steps of the new method.

3.3 Step 1: Data acquisition and quality

3.3.1 Preamble

The first step is to collect significant amounts of data and information to understand the system completely before a detailed simulation and planning method can be developed. The mine has significant data available due to modern technologies such as sensors and supervisory control and data acquisition (SCADA) systems which record and display measured parameters [86]. Therefore, with the significant data available a good understanding of the system as well as an accurate digital twin with simulation is possible. The process is shown in Figure 15.

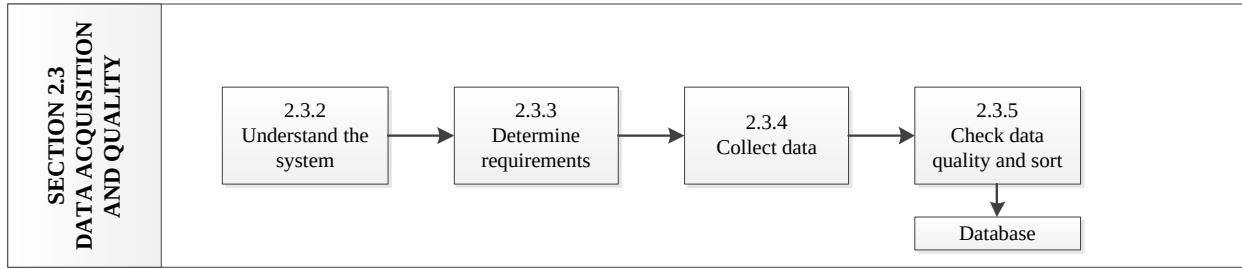


Figure 15. Extract from development of solution (Step 1: Data) [7]

3.3.2 Understand the system

The first step in data acquisition and data quality is to understand the system. This is critical as it allows for deeper knowledge of the system and allows for discernment between useful information and noise. To understand the system, it is important to investigate all the components in the system and their interaction with other components [87]. The mine services systems are separated into four main systems: cooling, ventilation, water, and compressed air [21]. It is important to understand what the system looks like, what the major systems are and what the major components in the system are. This step requires significant literature review of the system to be investigated and planned.

3.3.3 Determine requirements

Determining the requirements of a system is critical to the success of the simulation [88]. It is vital to construct the model according to the requirements. The requirements also determine the detail and complexity to which the digital twin needs to be simulated. For example, if a study is required on shaft A, B and C water handling systems, it is unnecessary to model shaft D. This adds unnecessary complexity and simulation time.

The simulation requirements are determined from current and future system requirements to ensure production is not affected and they allow for expansion or reduction in production. A certain production plan is drafted by the production planners from which the required services can be determined. This is done by using a specific service value per ton of ore that is to be mined. From this, the required air, chilled water, and compressed air can be determined.

An example of a production plan was shown in Figure 4 in Section 1. This figure shows the planned production for a mine complex which includes several levels of production with increases and reductions in mining. The data can be used to determine the future required services which subsequently can be planned for using the digital twin with simulation.

Alternative requirements could be for safety to ensure production is not hindered. An example of this is power failure whereby all mine systems lose power. The danger with a power failure event is those essential systems which are required for safe conditions underground are not available anymore. Therefore, contingencies are required to ensure emergency systems are available and that mine personnel can safely exit after a power failure event. These contingency requirements are critical for the safety of a mine.

Studies [89] and [90] showed that projects that do not have clear requirements have a higher possibility of failure as compared with projects with clearly defined requirements. The studies highlighted the importance of determining the requirements early in the project and ensuring the requirements are sensible.

It is also important to note that the requirements can and possibly will change. A study conducted by Ochodek [91] showed that projects that have detailed but fixed requirements also tend to underperform. The study showed the importance of continuously checking the requirements and ensuring that they are justifiable and attainable. The study also showed that certain requirements were not well thought out and therefore large amounts of manpower were invested in a requirement that was unnecessary or unachievable [90].

3.3.4 Collect data

Once a good understanding of the system has been reached and the requirements determined, it is important to gather information and data on all WCS components to model the system accurately and correctly.

Data is the fundamental driving force behind Industry 4.0 tools and modern systems [92]. Without sufficient data, these systems are as accurate as the user's best guess [93]. Therefore, obtaining significant amounts of data on the system to be digitalised is of high importance. Typical data required includes water- and air flow rates, temperatures, energy consumption, valve statuses, and pressures. Many different platforms are available for data acquisition. The most common in the mining industry include supervisory control and data acquisition (SCADA) systems and paper logs [25].

A SCADA system displays and gathers information from several sensors. These sensors are installed underground or on surface [86], [94]. The system consists of several physical pieces of equipment and software.

Study [94] has shown that incomplete data sets or missing information can decrease the accuracy of the model by up to 10%. Therefore, it is critical to ensure good datasets before attempting to construct a digital twin with simulation.

In an ideal case, the SCADA data will be sufficient to characterise a system correctly. However, it is extremely difficult and not feasible to add sensors to the entire mining operation. The mines consist of kilometres of tunnels, pipes, and cabling [11]. Therefore, it will be difficult to instrument every working place, pipe, piece of equipment and haulage [25], [30].

The gap in SCADA and instrumentation is bridged through paperwork, paper trails, specification sheets and personal communication [25], [86]. If the equipment cannot be measured or is not measured the next best option is to make use of the original equipment manufacturer (OEM) specifications. Most equipment installed in the mine is tested before delivery and OEM specifications are provided with the equipment. The specifications include certain limits and performance curves under changing operating conditions. The OEM specifications indicate the equipment's intended purpose and requirements for correct operation.

The final step is to conduct equipment (underground or surface) audits. This process comes in handy especially if no SCADA or paper-based information is available. Equipment audits have a two-fold purpose. The first is to understand and visually inspect the system. This gives the user a better understanding of the system, how it operates and how the process flows [25].

The second purpose is to gather data on the system where there was none. The audit provides sizes, locations, manufacture plates and measurements of the key parameters. The data obtained from an audit can be used to characterise the system to its current specification and running conditions. A study conducted by Rodriguez [95] showed the importance of physical audits where data was not available resulting in an improved understanding of the system and improved accuracy. Lastly, audits are an important process to verify existing data and information.

3.3.5 Check data quality and sort

The data collection process produces thousands of data points. This is overwhelming for the user; therefore, it is necessary to formulate a process whereby the data is filtered, sorted, averaged, checked for limits, and stored. This process reduces the size of the database into manageable amounts that can be effectively used for simulation input and calibration [11]. An example of the significant data which is collected from the SCADA is shown in Appendix B.

The process to reduce the size of the data found in Figure 16 to something more manageable was adapted from studies [96] and [97] and resulted in a four-step process.

The data can be extracted from the SCADA through the internet. Therefore, it is possible to extract SCADA data remotely [86]. The database is accessed, and the requested interval of data is extracted. In this step, it is important to decide upon the interval of the data. This is dependent on the purpose of the model or model

input. A study conducted by Zhai [98] showed a significant increase in the model accuracy when more data is used to calibrate the model. A year data set allows for sufficient data to track the performance of equipment during winter and summer months as well as major holidays and unexpected breakdowns. This provides a spectrum of operations over a long period which results in an accurate model [25], [85].

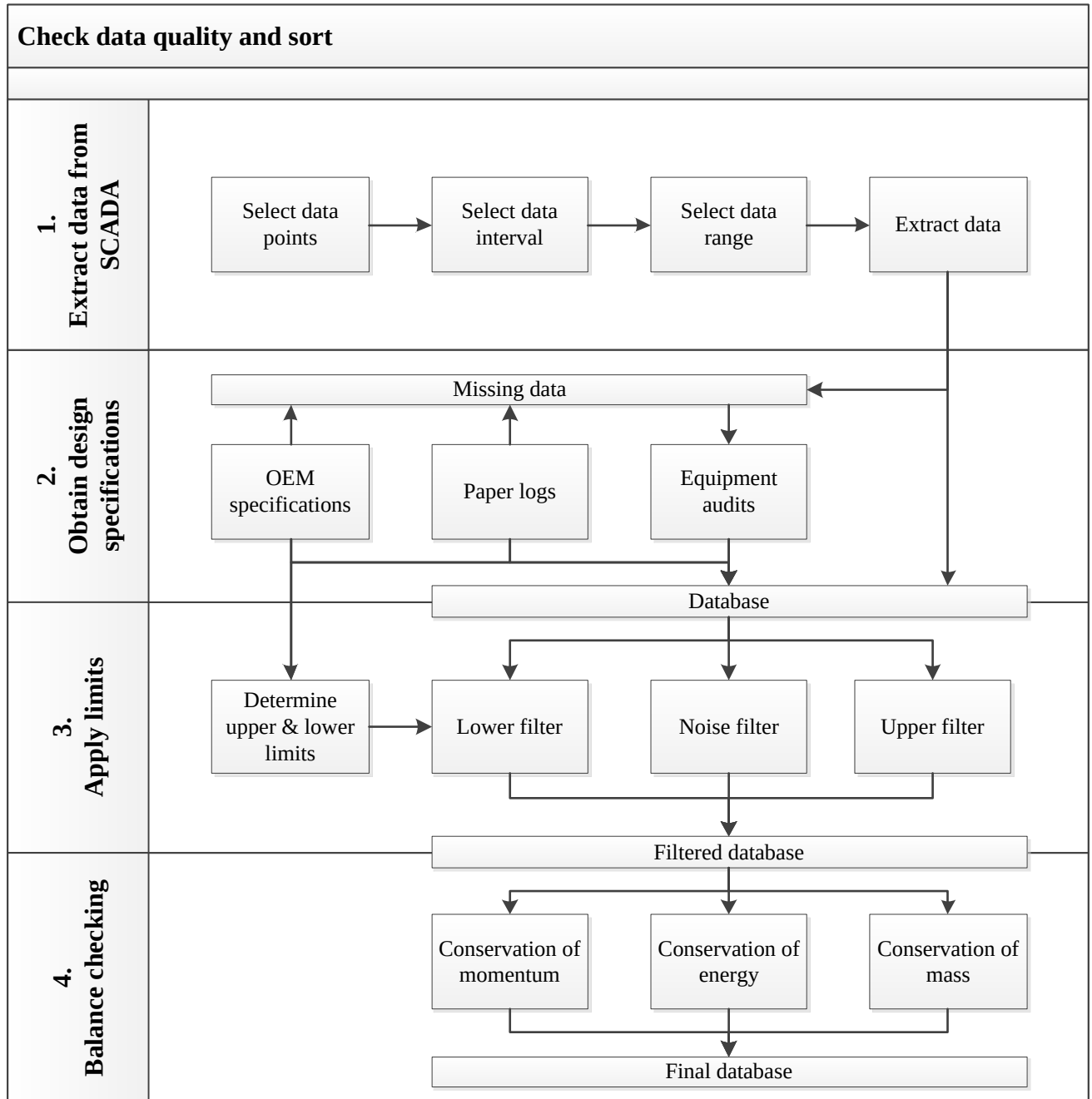


Figure 16. Data collection and quality checking process to reduce the size of data

The final step is to check the data quality and remove any outliers, missing data, or erroneous data. An example of a filtering process to obtain relevant and accurate data is shown in Figure 17.

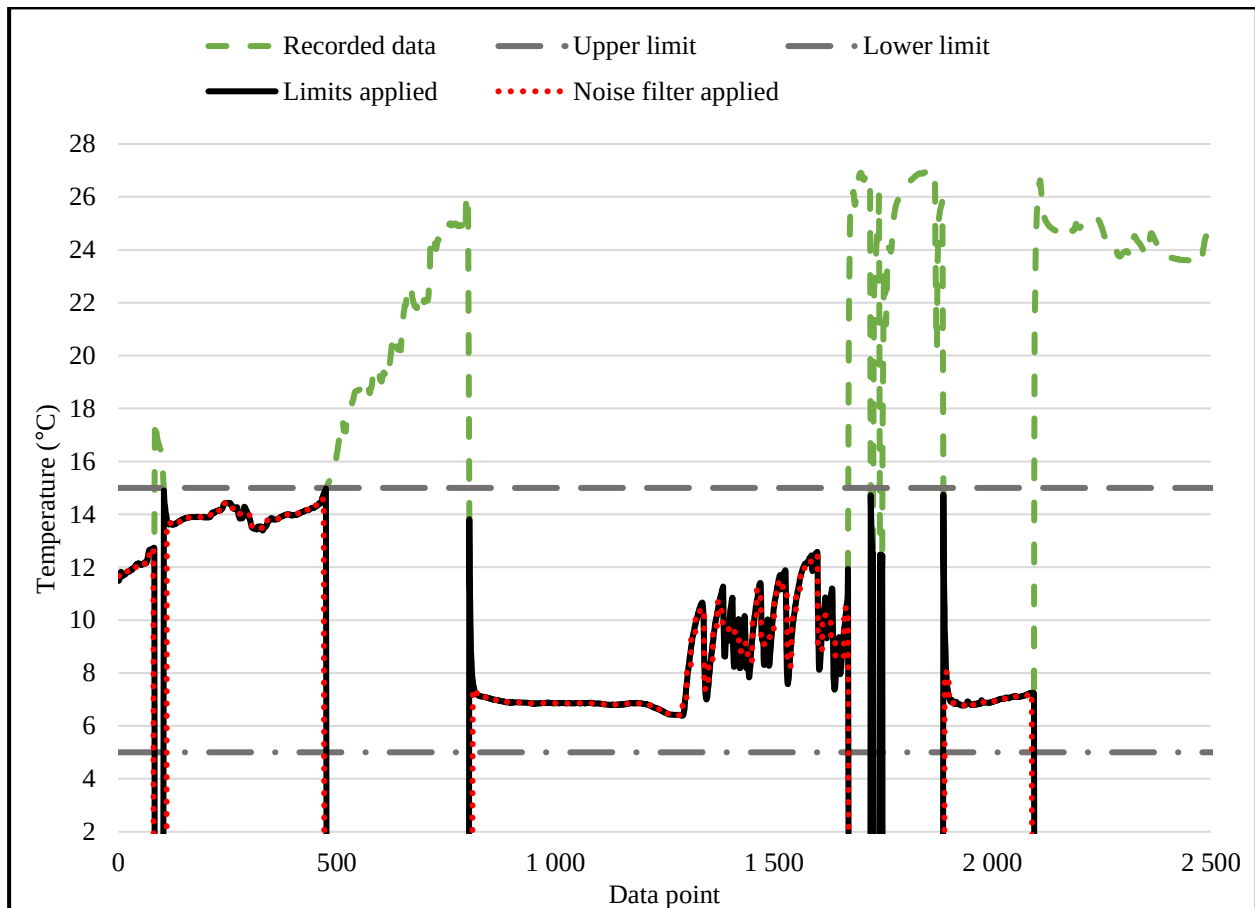


Figure 17. Recommended filtering and data quality checking methods [25], [99], [100]

Figure 17 shows several techniques to filter and check data quality. The methods were adapted from studies [25], [99] and [100]. Using the four data filtering and checking methods, a data set containing only usable data is created. The data set can then be used to construct the model.

The techniques used to ensure a useable dataset is created that can be used to successfully create an accurate simulation are:

- **Setting limits:** Upper and lower limits were set on all data points within reasonable boundaries. A good understanding of the system is required to set boundaries. An example is the guide vane percentage of a fridge plant. Anything above 100% is not possible and anything below 95% does not show a clear representation of the machine's performance. [101]
- **Averaging:** The data points are measured and logged at different intervals which require standardisation. Data is averaged in bins of desired intervals to match the simulation time period (any interval is possible as long as it is larger than the logged data). The data is backward averaged. Therefore, time period 11:00 is an average of the data from 10:01 – 11:00. [102]

- **Noise filtering:** Where data had excessive noise a rolling average technique was used to smooth the data. The rolling average data points was determined by the severity of the noise. [103]

Data capture and quality was not the focus of this study (Section 2.7), but it is still important to consider other data capture- and quality techniques for more complex data sets.

3.4 Step 2: Digital twin with simulation

3.4.1 Preamble

The significant amount of data and components found in a deep-level mine is overwhelming [25], [11]. Modern technologies such as 3D simulation and digital twinning allow the user to have an unprecedented understanding of the system [2], [50], [66]. The digital twin with simulation can be used to any level of detail depending on the requirements of the user. A digital twin with simulation contains all the information of the entire system in an easy-to-understand and easy-to-digest 3D visual representation.

Therefore, a correctly calibrated digital twin with simulation is an exact representation of the actual system [41], [104]. This is a powerful tool where the user can quickly and easily make changes to the system and determine the resultant effect [11]. The steps are outlined in Figure 18.

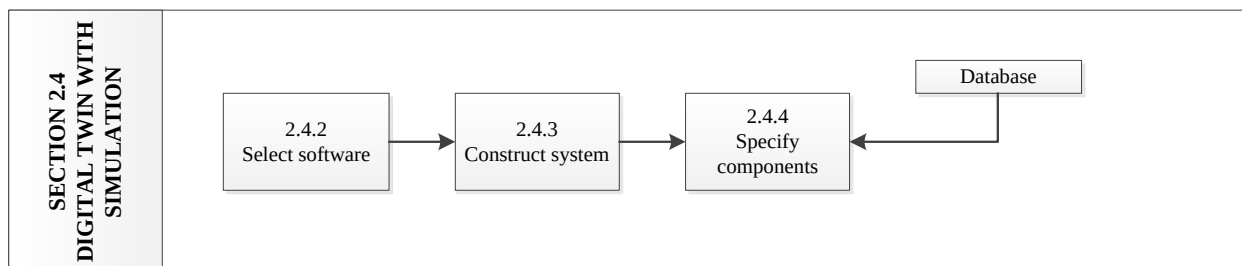


Figure 18. Extract from the development of solution (Step 2: Digital twin with simulation) [7]

3.4.2 Select software

Selecting the correct simulation software is a critical step which requires significant consideration and investigation. It is important to select a software package that satisfies the requirements.

Many different software simulation packages are available for use in WCS in mines. These are summarised in Table 2 along with each software package's focus area(s).

Investigating each software package we discovery the following:

- **Process Toolbox:** PTB is a one-dimensional computational fluid dynamics (CFD) code for solving complex thermohydraulic networks, such as the case study presented in this paper [80], [85], [105]. The code includes incompressible (water), compressible (air), and two-phase fluids (steam and other). Air and water components are present in a WCS; however, two-phase fluid components are not used in this study.⁶
- **Vuma Network:** VUMA-network 5.0 is an interactive network simulation programme developed to assist mine-ventilation engineers and practitioners to plan, design, operate and control the ventilation and cooling systems of underground mines.⁷
- **Ventsim:** Ventsim is an underground mine ventilation 3D simulation software package designed to model and simulate ventilation, airflows, pressures, heat, gases, financials, radon, fire and many other types of ventilation data from a model of tunnels and shafts.⁸
- **VNet (MVS):** It provides numerical simulations of subsurface ventilation networks based on mine layouts, airway dimensions or measured resistances, and the location and characteristic curves of fans. The results are provided in graphical and tabular format.⁹
- **Ventgraph:** Ventgraph software provides a dynamic representation of the fire's progress (in real-time) and utilises a colour graphic visualisation of the spread of combustion products throughout the ventilation system. During the simulation session the user can interact with the ventilation system, introduce inert gases and change fan characteristics. These changes can be simulated quickly allowing for the testing of various fire-control and suppression strategies.¹⁰
- **VenPri:** A discontinued mine ventilation software that quickly solve the networks once the resistance parameters of each branch of the network have been provided.
- **3D-Canvent:** 3D-CANVENT is a software package that integrates advanced computer aided design (ACAD) true 3D graphics with a mine ventilation simulator. It is composed of two primary modules: DMVENT and MINEDESIGNER. DMVENT is a traditional Fortran coded Hardy-Cross iterative ventilation network solver written in 1980 with thermodynamic capabilities. MINEDESIGNER is the graphics engine that optimizes the ventilation design process.¹¹
- **FlowNex:** Flownex® SE determines pressure drop [flow] and heat transfer [temperature] for the connected components of a complete system in steady state and transient, e.g. pumps or compressors, pipes, valves, tanks and heat exchangers.¹²

⁶ Flow resistance, heat transfer, mass transfer and work on fluids are all determined by components added to the system.

⁷ Retrieved from <https://www.vuma3d.com/vuma-network/>

⁸ Retrieved from <https://ventsim.com/ventsim-design/>

⁹ Retrieved from <https://www.srk.com/en/products/vnet-ventilation-network-simulator>

¹⁰ Retrieved from <https://www.gwmt.com.au/fire.html>

¹¹ Retrieved from <https://www.osti.gov/biblio/269265>

¹² Retrieved from <https://flownex.com/industries/general/>

- **SimMine:** SimMine is a world-class specialist mining simulation and optimisation software package. Development (Orebody Access), Mine Production (Stoping / Caving Operations) and Equipment Optimisation (e.g. LHDs, Trucks, Conveyors, Bins / Silos, Crushers).¹³
- **OptiSlot:** Advanced applied mathematics in warehouse slotting strategy, including deterministic algorithms paired with patented optimization processes yield optimal client solutions.¹⁴
- **Pumpsim:** Pumpsim design is a tool that can be used to accurately model, simulate and optimise pump and pipe fluid reticulation systems for safe supply of gases, liquids, slurries and many other fluids.¹⁵
- **EDEM:** EDEM is high-performance software for bulk material simulation. Powered by state-of-the-art Discrete Element Method (DEM) technology, EDEM quickly and accurately simulates and analyses the behavior of bulk materials such as coal, mined ores, soil, tablet, and powders.¹⁶
- **Simscape:** Simscape enables you to rapidly create models of physical systems within the Simulink environment. With Simscape, you build physical component models based on physical connections that directly integrate with block diagrams and other modeling paradigms. The software models systems such as electric motors, bridge rectifiers, hydraulic actuators, and refrigeration systems, by assembling fundamental components into a schematic. Simscape add-on products provide more complex components and analysis capabilities.¹⁷

For this study, the important aspects considered were whether the simulation software (“Sim.”) package complies with the identified criteria (from Section 2.6) i.e. can the software package model the dynamic (“Dyn.”) and integrated (“Int.”) nature of a mine’s water- and cooling system?

Table 2 shows that simulation software that models the ventilation of a deep-level mine is by far the most popular. This is a result of the focus that is placed on ventilation in the mining industry. It is a system that causes concern for the mines as it is not well understood, and it is the only system with a fixed government standard (MHSA) required to mine safely [37] and [67].

¹³ Retrieved from <https://simmine.com/features/>

¹⁴ Retrieved from <https://www.fortna.com/software/fortna-optislot-dc/>

¹⁵ Retrieved from <https://pumpsim.com/description/>

¹⁶ Retrieved from <https://www.ansys.com/partner-ecosystem/technology-partners/edem>

¹⁷ Retrieved from <https://www.mathworks.com/products/simscape.html>

Table 2. Mine simulation software comparison table

No.	Software	Cit.	Water				Cooling				Ventilation			
			Sim.	Dyn.	Int.	Dig. Twin	Sim.	Dyn.	Int.	Dig. Twin	Sim.	Dyn.	Int.	Dig. Twin
1	Process Toolbox	[85], [11]	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
2	Vuma Network	[106]									✓			✓
3	Ventsim	[66]									✓	✓		
4	VNet (MVS)	[107]									✓			
5	VentGraph	[108], [109]									✓			
6	VenPri	[110]									✓			
7	3D-Canvent	[104]									✓			
8	FlowNex	[111], [112]	✓				✓				✓			
9	SimMine	[113]												
10	OptiSlot	[114]												
11	Pumpsim	[115], [116]	✓	✓		✓								
12	EDEM	[117]												
13	Simscape	[118], [119]	✓											

This study considers the WCS of a mine. Although this does not require certain ventilation components, to model the integrated nature of the WCS successfully a software package is required that can model all three systems (water, cooling, and ventilation).

In this study, PTB will be utilised due to its theoretical compliance with all criteria [80], as well as its accessibility throughout the study. The inclusion of all major systems into the simulation software allows for easy integration across all the systems and approaches a true representation. This makes PTB a good choice to model mine cooling systems accurately and successfully. However, when applying the new proposed method, a user might not necessarily have access to PTB and might consider a different simulation package that can comply with the specific user/mine's requirements.

The purpose of the study was to utilise simulation software for planning. PTB was most suitable and therefore used. The software itself was not the main contributing factor of the thesis. It was the use of the simulation software as a tool. Other software could also be used, however not as efficiently as PTB. Several software packages would be required to achieve the same outcome.

3.4.3 Construct system

In this section, only the high-level approach to constructing the model on the simulation package is explained. A dewatering system will be used as an example. More detail on PTB is given in references [77], [115], [116], [120]. To construct the digital twin with simulation, the first step is to import the mining levels to the simulation software. PTB allows for mine-level layouts or computer-aided drawings (CAD) to be imported into the work environment. The level layouts contain exact coordinates (including elevation) of

the mine and are therefore a one-to-one representation of the underground areas. An imported level layout of a mine complex is shown in Figure 19.

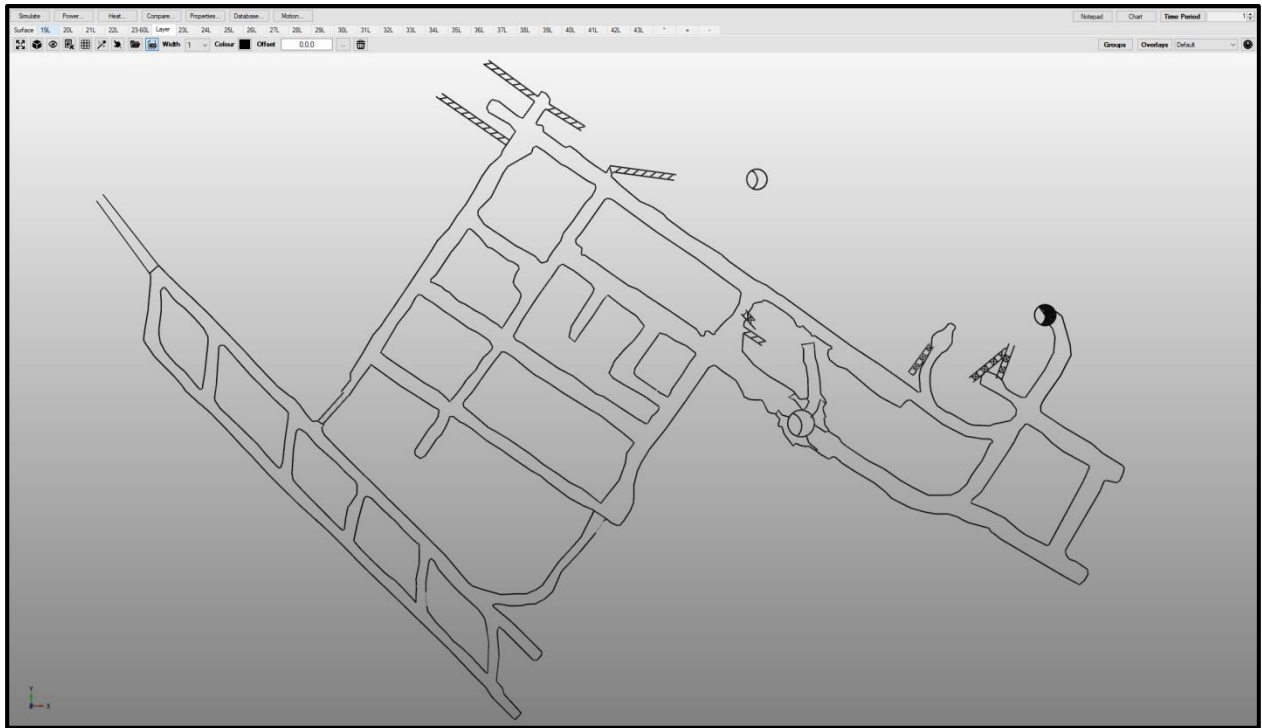


Figure 19. An underground mining level layout imported to PTB

The components can then be placed on the level layout in their exact locations. The location of components is obtained from the data and acquisition step, specifically underground audits. Once all the components for a specific system have been placed the components are connected. Figure 20 shows an example of a pumping level with all components placed in their relevant locations and connected according to the flows.

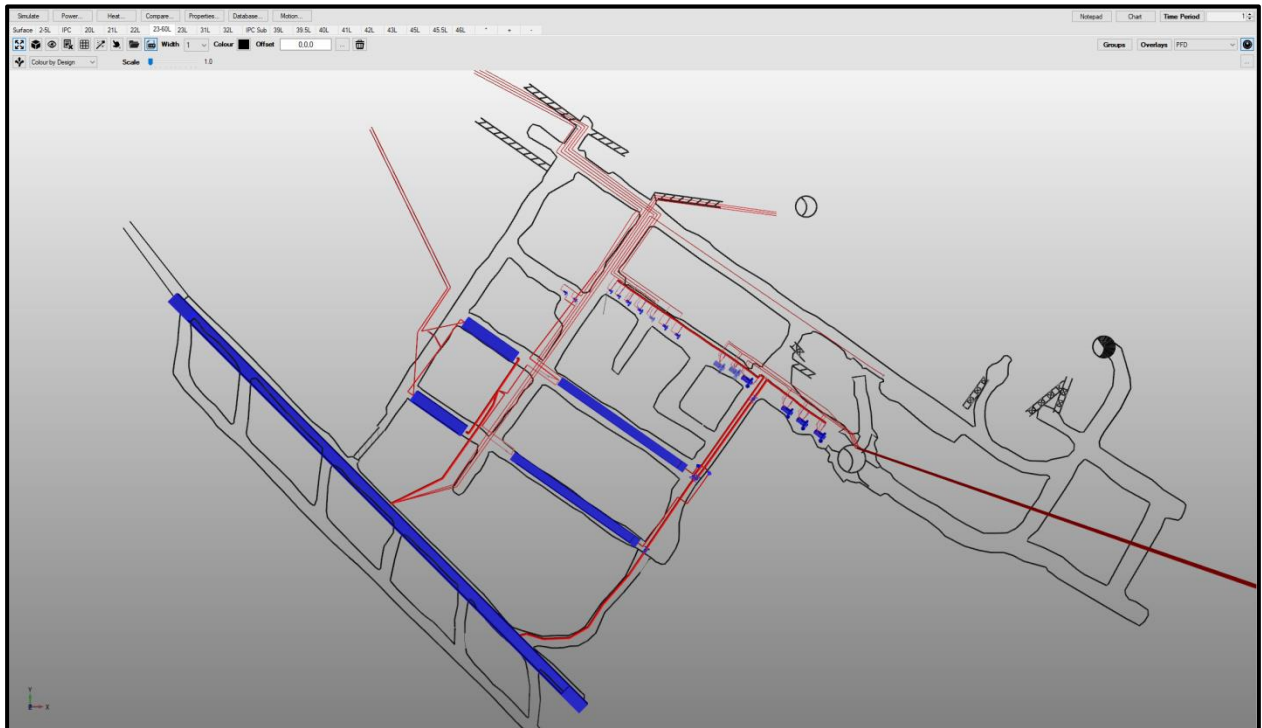


Figure 20. Underground pumping level showing dams, pipes and pumps

A mine consists of several levels, therefore PTB allows the user to add several layers each representing a mining level. The user can import a level layout to each layer giving the model elevation which is important in a deep-level mining simulation. The components between levels can be connected through a global view in PTB. Once connected, the two levels are connected with one another, and their subsequent elevations are linked. The difference in elevation results in pressure changes in the connections which are calculated in the node component. Figure 21 shows two connected pumping levels that clearly show the large elevation change.

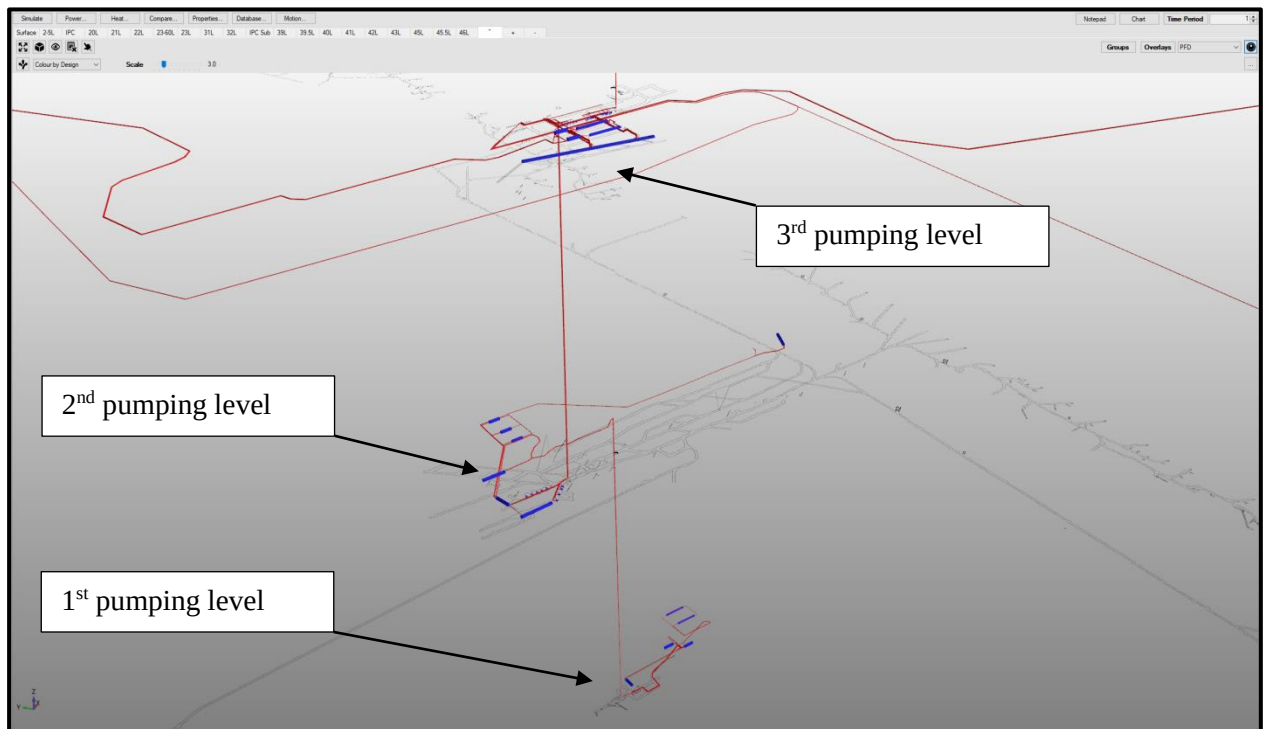


Figure 21. Three connected underground pumping stations

The process is then followed for all the levels and detail is added as necessary according to user requirements. The final model includes several levels with thousands of components. An example is seen in Figure 22.

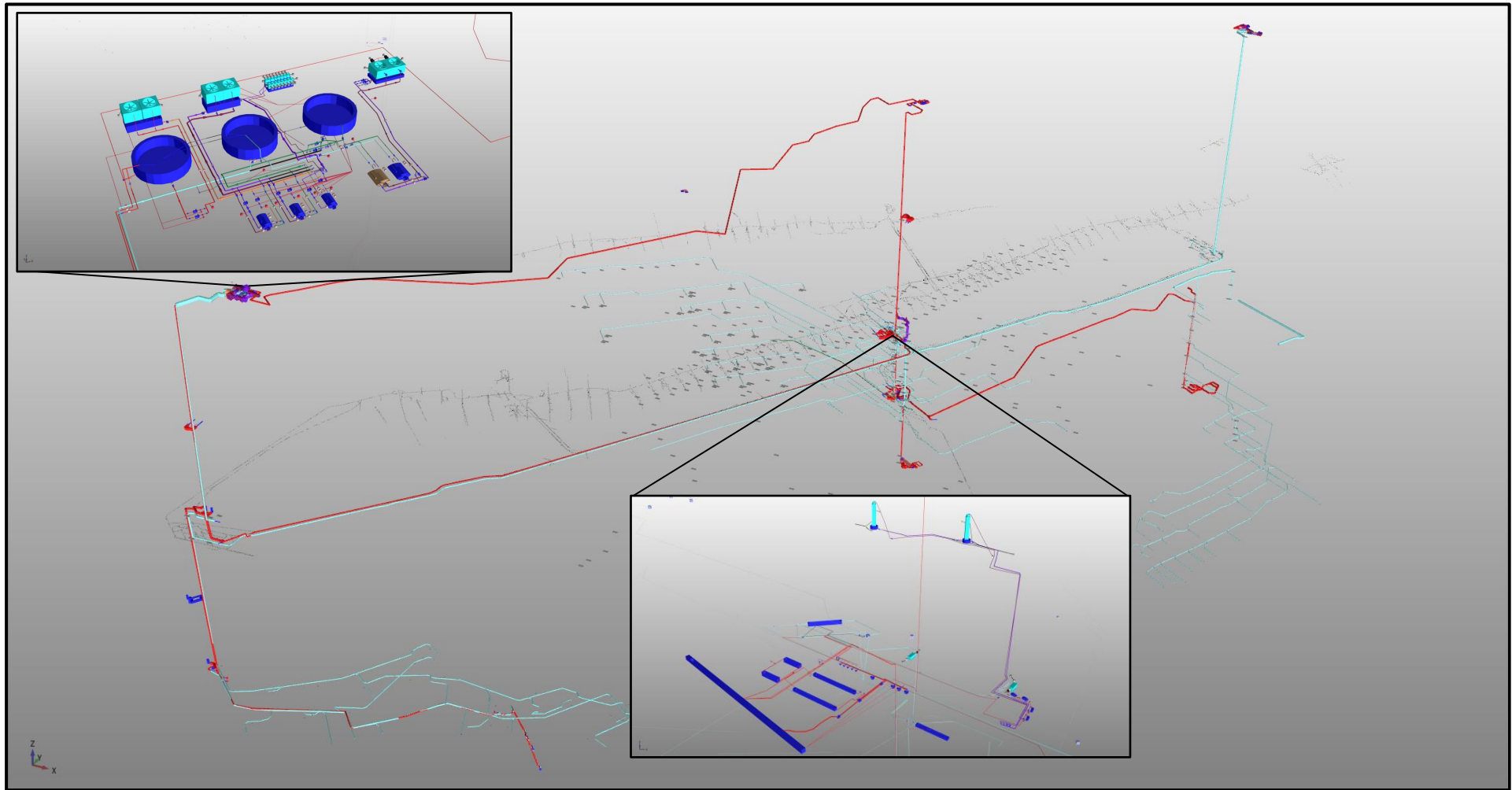


Figure 22. Example of the final model of a WCS on PTB

It is important to note that the model is only an accurate visual representation of the system in its current state. The model is not in a state where it can be simulated and provide results. Therefore, the next step is to configure each individual component of the model.

3.4.4 Specify components

The visual model contains only default components. Therefore, all components will not be specified correctly and the model is a misrepresentation of the actual equipment. To specify equipment PTB uses an input interface of the major inputs required to characterise a piece of equipment successfully. The process was adapted from the study conducted by Mathews which explained the process in detail [85]. An example of the inputs to a water pump is shown in Figure 23.

WaterPump 1,1

Name: WaterPump

Inputs Outputs References Notes

Inputs

- Specification
- Coordinate
- Size
- Orientation
- Offset

Properties

Name	Unit	Initial
Pressure 1	kPa	400.000
Pressure 2	kPa	300.000
Pressure 3	kPa	0.000
Flow 1	l/s	0.000
Flow 2	l/s	100.000
Flow 3	l/s	200.000
Efficiency Rating 1		0.750
Efficiency Rating 2		0.750
Efficiency Rating 3		0.750
Motor Efficiency Rating		0.950
VSD Efficiency Rating		1.000
Speed Fraction		...
Pressure Factor		1.000
Flow Factor		1.000
Efficiency Factor		1.000
Energy Tariff	R/kWh	...

Calculate Import... Export...

Accept Cancel Help

Figure 23. Water pump inputs in PTB

The inputs are all determined from the data and acquisition stage. Therefore, for example, a water pump can be specified exactly as it is in real life using the inputs. If the detailed inputs are not available PTB has a calculate function. This function allows the user to provide inputs that are easier to obtain and measure and the software calculates the detailed inputs.

The water pump example is a simpler piece of equipment. A more complicated component such as a chiller (FP or AP) is slightly more tedious but follows the same principal. Several components require significant measurements or data to characterise accurately. The process is the same for all components in PTB. This step is repeated for all the components which give a solid foundation for the model and the next step which is verification.

3.5 Step 3: Dynamic boundaries and verification

3.5.1 Preamble

Each component in the model is isolated and compared with actual data to be calibrated. Once the component reaches the satisfactory accuracy of 95% it is added back to the larger model including all components. Once the step has been completed for the entire model KPIs need to be determined. The KPIs and the stipulated requirements for future LOM planning are determined by mine personnel.

Once the KPIs are determined the entire model is then compared with actual data using the KPIs and calibrated to within 95% of the actual system. Calibrating the model to 95% accuracy is sufficient to provide a representative model [11], [50], [85]. The calibrated model is then modified to represent system changes and predict the outcome of several scenarios. These outcomes are then used for decision-making purposes.

The verification step is the final step in creating an accurate digital twin with simulation which is capable of being used as a tool for accurate future mine planning. The step is extremely important as it provides confidence in the accuracy of the model [80], [111], [121]. It is also a necessary step before the model can be applied to real-world scenarios where the results can be trusted with confidence. Once a fully verified model has been confirmed the model can be used for several applications including future planning with a good level of confidence. The steps are outlined in Figure 24.

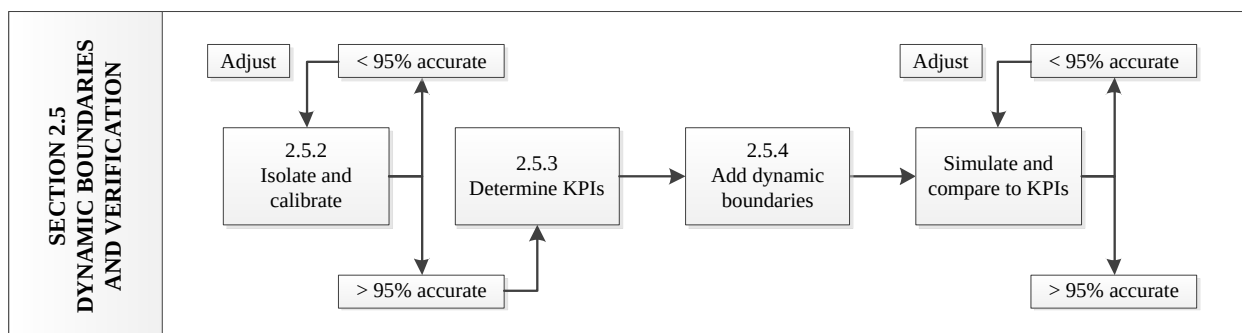


Figure 24. Extract from development of solution (Step 3: Dynamic boundaries and verification) [7]

3.5.2 Isolate and calibrate

The calibration of the model is extremely important. If the model is not correctly calibrated an accurate representation of the actual system will not be possible [85]. The aim of the calibration step is to approach the 95% accuracy requirement for all the components. There exist several methods of calibration. The most effective was found to be the isolation method which was adapted from studies conducted by Maré [11], Kunwar [122] and Tardioli [123].

Each major section or component of the system is isolated, given fixed boundary conditions and calibrated. This approach allows the user only to focus on a single piece of equipment at a time with fixed inputs obtained from the data and acquisition stage. Therefore, if the isolated equipment is calibrated correctly when it is added back to the larger model it is assumed to provide the correct output given the right boundary conditions. If the equipment is not performing as expected, we can isolate it to a boundary condition input that is not within specification. An example of the process is shown in Figure 25.

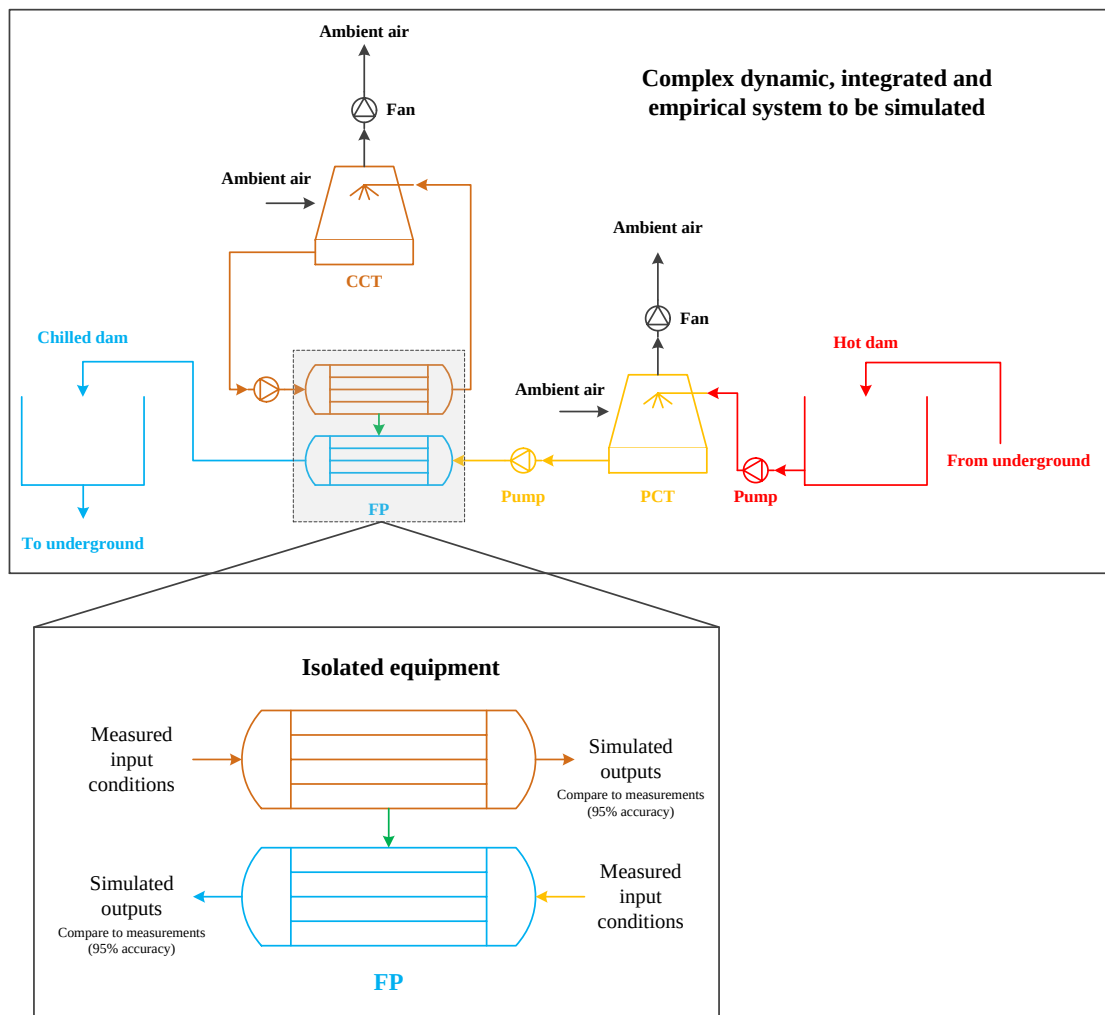


Figure 25. Isolate and calibrate example

The result is a calibrated piece of equipment that will respond in the same way as the actual equipment. It is important to note that the calibration process uses current operating conditions and not design conditions. Therefore, the response will be the same as the actual current equipment. The benefit of this approach is highlighted in a study conducted by [11] which showed the large deviation of mine equipment from design specifications. A calibration tool was developed in the study and is shown in Appendix D.

An example of the outcome of isolation and equipment calibration is shown in Figure 26. Figure 26 shows the response of an FP to dynamic ambient and input conditions.

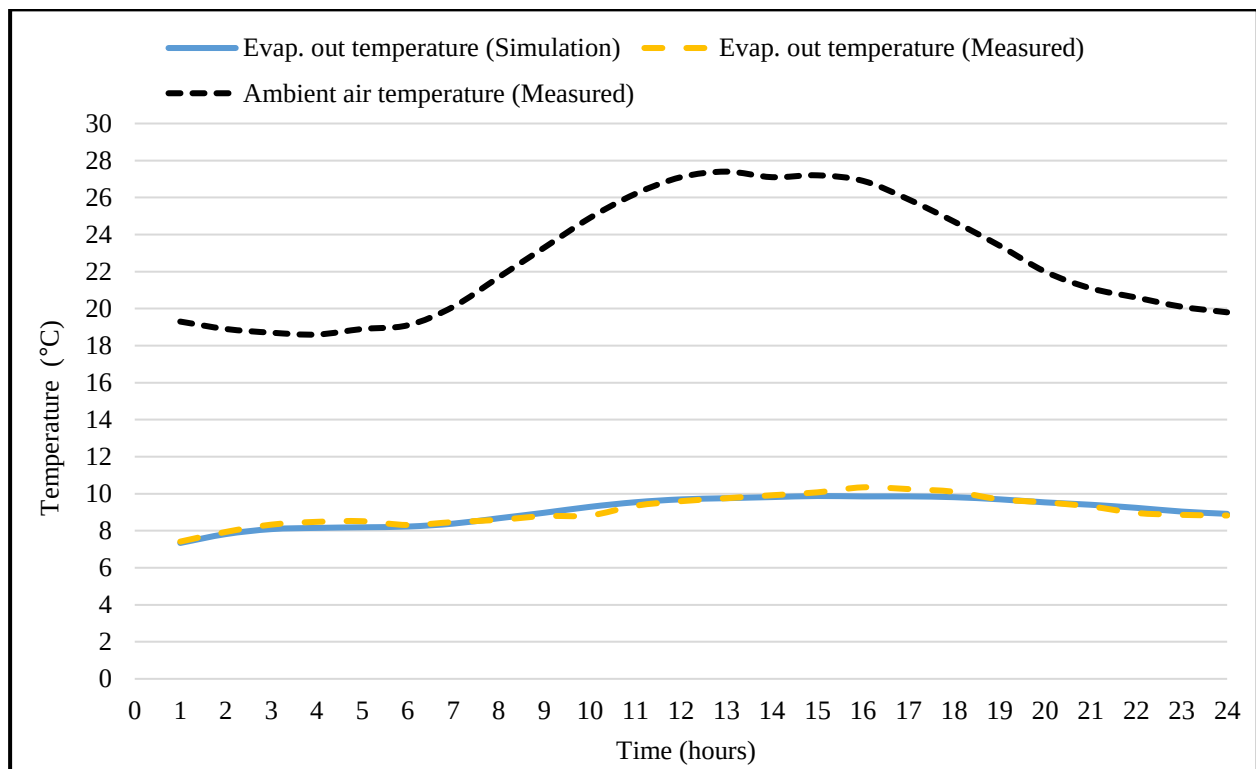


Figure 26. Dynamic fridge plant response to multiple dynamic input boundaries

Figure 26 shows a simulated evaporator outlet temperature profile like that of the actual recorded data. This indicates that the equipment has been correctly calibrated and follows the same performance curve as the installed equipment. It can therefore confidently rely on the simulated results as they closely match actuals. The accuracy is quantitatively determined by two values. Firstly, the overall average accuracy is calculated by averaging the measured and simulated data. Then the two averages are compared and must fall within 95% accuracy. Satisfied with the average accuracy, each simulated data point is compared with the subsequent measured data point to obtain an accuracy per data point. The total average accuracy of all data points must be above 95%.

Once all the components have been isolated and calibrated the calibrated equipment is added back to the model. The assumption, therefore, is that the entire system should react as required given certain dynamic boundary input values. These dynamic boundaries are measurable values that can be added to the bigger model and the expected response is compared with the actual response from the system. This is the final verification step. However, first certain key performance indicators of the system need to be determined to streamline the process as thousands of data outputs are available for comparison which is tedious. The KPI method is adapted from several studies.

3.5.3 Determine KPIs

A digital twin with simulation is only as good as its accuracy. Therefore, it is extremely important to verify the model against actual data. Large integrated models can have upwards of 1 000 dynamic profile inputs and 2 000 dynamic outputs [11], [85]. It is therefore important to decide upon certain key areas to focus on and compare with the actual system to confirm the validity of the entire model [85]. These focus areas are called key performance indicators (KPIs). Determining the KPIs of a system is extremely important for simplicity and determining the accuracy of the model and its response to inputs.

The first KPIs come from the requirements. In the step where the requirements are defined certain key temperatures, flows or pressures are required for a successful project. These are the most important KPIs. If the model does not accurately simulate the requirement KPIs, the model cannot be used to determine future solutions.

The second set of KPIs is a little more obscure. The majority of KPIs are based on user discretion. However, a good process to decide upon KPIs was discussed in studies [124], [125], [126]. The studies' methods were adapted to form a simple five-step check process for determining KPIs as shown in Figure 27.

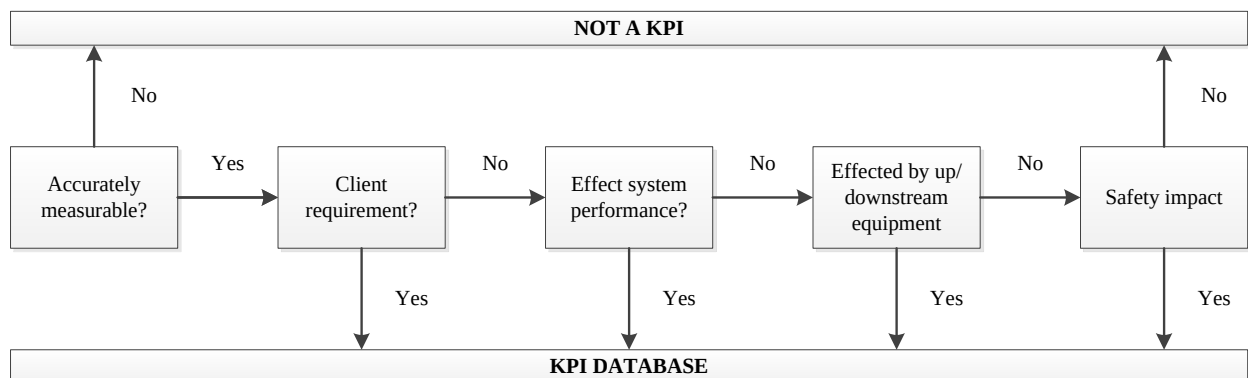


Figure 27. Simple four-step process in determining KPIs (adapted from [29], [127], [128])

Once the KPI checking method has been applied to all measurable items in the system a table of KPIs can be determined. An example of such a table is shown in Table 3. The table highlights all the KPIs for a typical WCS model of a deep-level mine.

Table 3. Typical KPIs used in mining water- and cooling systems

No.	Area	Equipment	Measurement	Unit	Actual	Simulation	% Error
1	Surface/Underground	Hot dam	Inlet/outlet flow	(L/s)			
2			Level	(%)			
3			Temperature	(°C)			
4		FP evaporator	Inlet temp	(°C)			
5			Inlet flow	(L/s)			
6			Outlet temp	(°C)			
7			Outlet flow	(L/s)			
8			Cooling duty	(kW)			
9			Compressor power	(kW)			
10		Chilled dam	Inlet/outlet flow	(L/s)			
11			Level	(%)			
12			Temperature	(°C)			
13		...	Flow	(L/s)			
14			Pressure	(kPa)			
15			Temperature	(°C)			
16			...	(...)			

The table is used to record hourly, daily or monthly actual values and simulated values. They are compared and the accuracy determined. The target error is less than 5%. This ensures the simulation is 95% accurate which falls within the accuracy of typical measuring equipment. Therefore, further calibration to achieve better results does not necessarily result in a more accurate model [85], [129].

The next step is to add all the boundary conditions to the model and to simulate. The simulation results are then added to Table 3 and compared with actuals for accuracy.

3.5.4 Add boundaries and verify model/simulation

The verification phase is separated into a five-step process adapted from studies [11], [28], [121]. The process is shown in Figure 28 and can be applied to static or dynamic simulations.

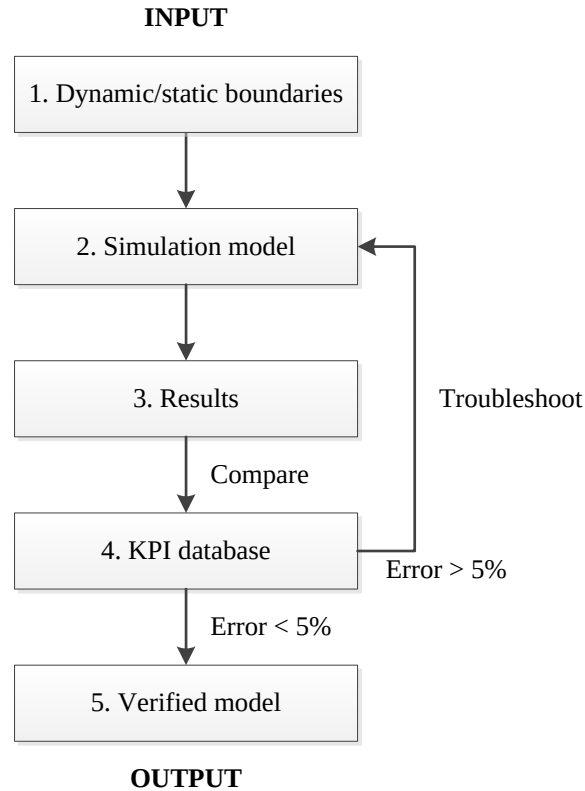


Figure 28. Model verification steps flow diagram (adapted from [11], [28], [121])

Verification is initially conducted using steady-state values [11] to simplify the process [25]. Adding dynamic boundaries and transient changes for the initial verification step adds complexity and increases the difficulty to reach a verified model. Once this has been completed the next step is to add dynamic boundaries and to do a final verification step.

Therefore, the first step is to obtain monthly averages for the boundary value inputs and KPIs. The monthly average values are used as steady-state inputs and steady-state results to compare. The purpose of a monthly average is that it includes several days' worth of operation which provides an accurate picture of the boundary values [8]. These values are obtained during the data acquisition and data quality step.

Once all boundaries have been calculated and added to their respective boundary input components in the simulation software, the model can be simulated. The simulated results are recorded and averaged. The averaged results are added to the KPI table where the accuracy of the model is determined. If the average error falls below 5% the model is assumed verified and accurate to real life [85], [129]. An example of such a KPI table with inputs was shown in Table 3.

If the model does not fall below 5% error, re-calibration is required. The key areas where the error does not meet 5% are listed and only re-calibration in those areas is required. It is important to note that certain

equipment has a knock-on effect. Therefore, it is beneficial to determine the faulty or incorrectly specified equipment and to focus calibration attention on that specific area. The next step is to transform the model from a simple steady-state, to transient.

The dynamic boundary inputs are the same as the steady-state boundary inputs. The important difference is that a profile of the average pressure, flow, temperature and any other boundaries must be used. This takes the model from a steady-state model to a dynamic model with dynamic boundaries. The benefit of simulating dynamically is clearly shown in a study conducted by Maré [11] and Crawford [6]. The study showed the benefit of simulating dynamically with improved accuracy.

The boundary profile is obtained from the data acquisition step [85]. Figure 29 shows an example of a typical 24-hour profile of the temperature and flow from underground to surface.

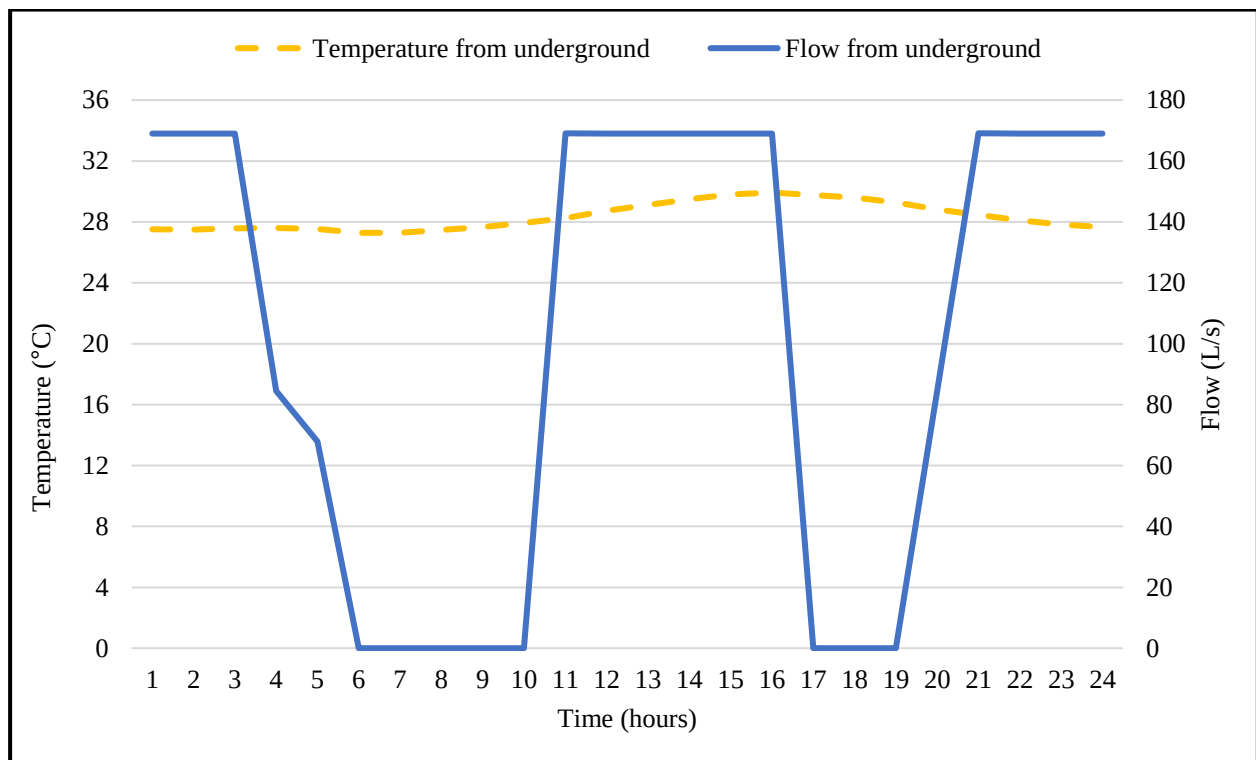


Figure 29. 24-hour profile of hot dam inflow and temperature

Once all dynamic boundaries have been captured for a 24-hour profile, the steady-state boundaries need to be replaced in the model. The model will then respond dynamically to the dynamic boundary value inputs.

The model is refined until a 95% accuracy¹⁸ is achieved using Table 3 KPI comparison. This, however, only confirms correct daily averages and not dynamic profiles. Once satisfied with accurate static averages the model is deemed accurate. The final step is to confirm the dynamic response of the KPIs which are accurately measured. An example of a dynamic comparison is shown in Figure 30.

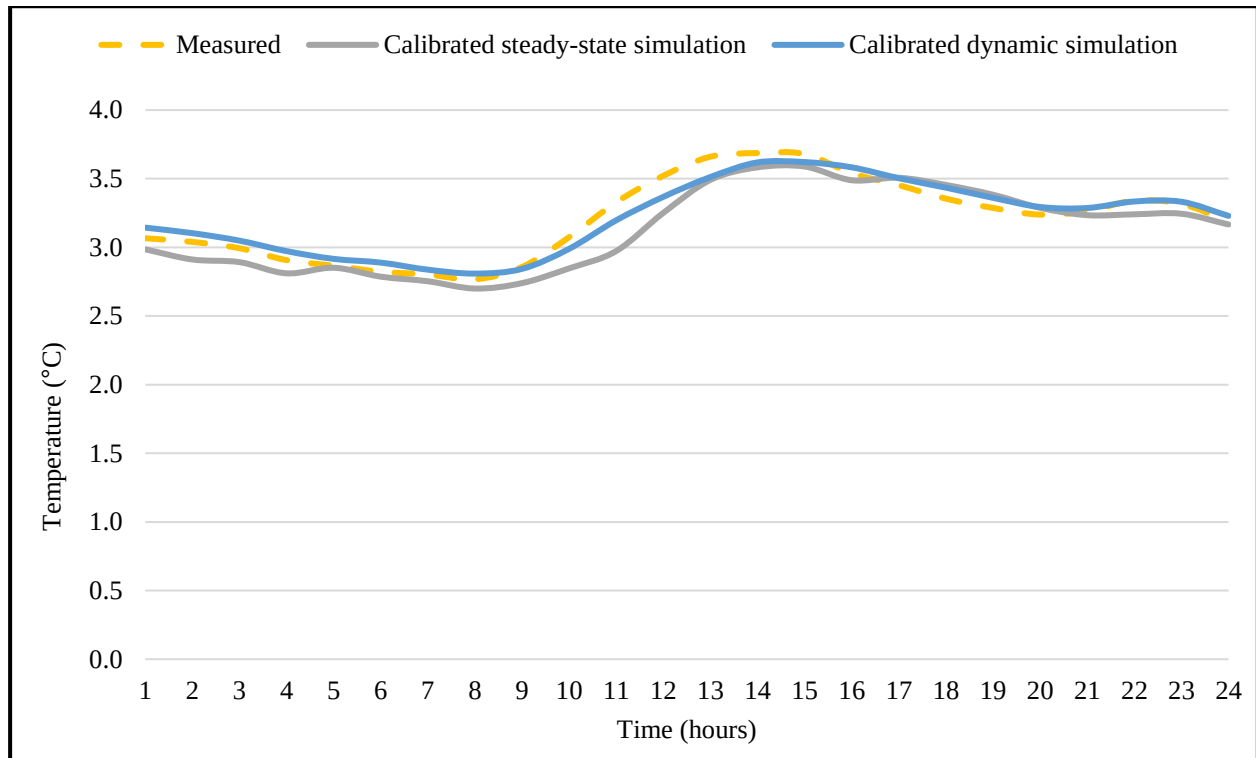


Figure 30. Example of simulated vs actual surface chilled dam temperature

Figure 30 shows a clear correlation between the simulated and recorded temperature profiles. Therefore, the simulation is providing the correct response to dynamic inputs.

A final step of verification is to conduct equipment tests at simulated configurations not used for calibration. An example of this is simulating equipment at off-design or current operating conditions and comparing the real-world test results with simulation results. If the simulation is accurate the response should be the same as in the real world. An example set of results is shown in Figure 31.

Figure 31 shows over a large range of evaporator temperatures that the simulation accurately predicts the actual measured cooling duty. The simulation predicted trend is slightly lower than the measured actual

¹⁸ Accuracy is calculated as one minus the average error of each time period.

duty, the reason may be due to the simulation being trained on older data before the machine was maintained. The error is still within the targeted 95% accuracy.

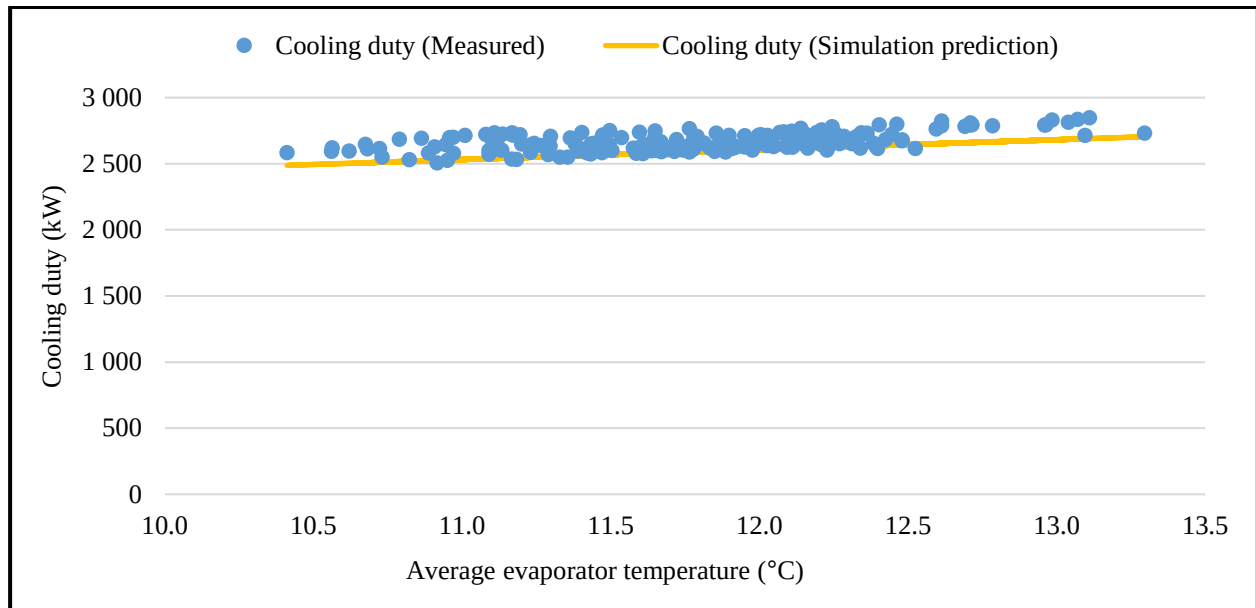


Figure 31. Example of test results versus model prediction

Once a satisfactory simulation has been created and calibrated, the simulation can be used for several applications where configuration changes can be made, and the response recorded. Due to the detailed nature of calibration and verification, it can be assumed that the model will react similarly, if not the same, as the actual system [11], [85].

Therefore, the next step is to utilise the model as an accurate tool to predict future requirements, system changes, mining and more.

3.6 Step 4: Dynamic, integrated, and empirical design

3.6.1 Preamble

Once a 95% accurate model is achieved, it is possible to apply the model to several scenarios (initiatives). The first step is to define the scope and identify any issues or problem areas. This step is critical and requires significant research and data gathering.

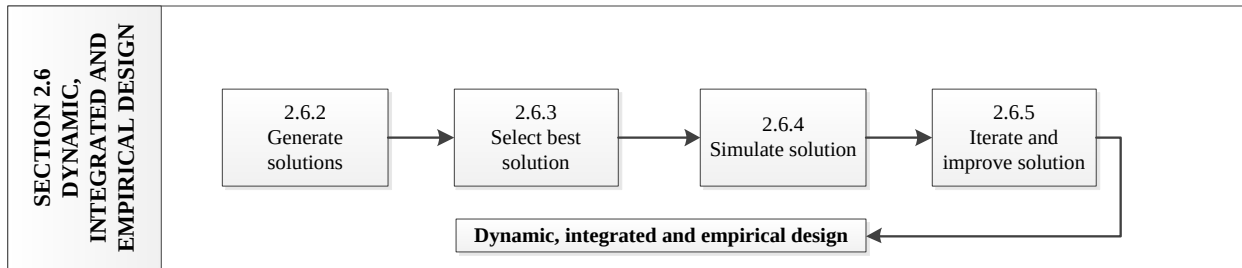


Figure 32. Extract from development of solution (Step 4: Simulate solutions) [7]

From the investigation, a scope can be defined, and the requirements identified [89], [90]. Several simulation solutions can then be developed. The solutions can include *inter alia* simple infrastructure changes, changes to control philosophies, a complete redesign, or installation of new infrastructure. Now solutions can be applied in the virtual environment, their effect on the system quantified, and their feasibility determined quickly, and without significant cost.

Once a satisfactory solution has been identified through several iterations it can be implemented. The solution can consist of either a single change to the system or a combination of solutions. The final step is to define the solution in depth, listing each component or system change and associating a cost to each item as well as its LOM benefit.

The process followed for generating feasible solutions is shown in Figure 33 and adapted from [130], [131], [132], [133], [134], [135].

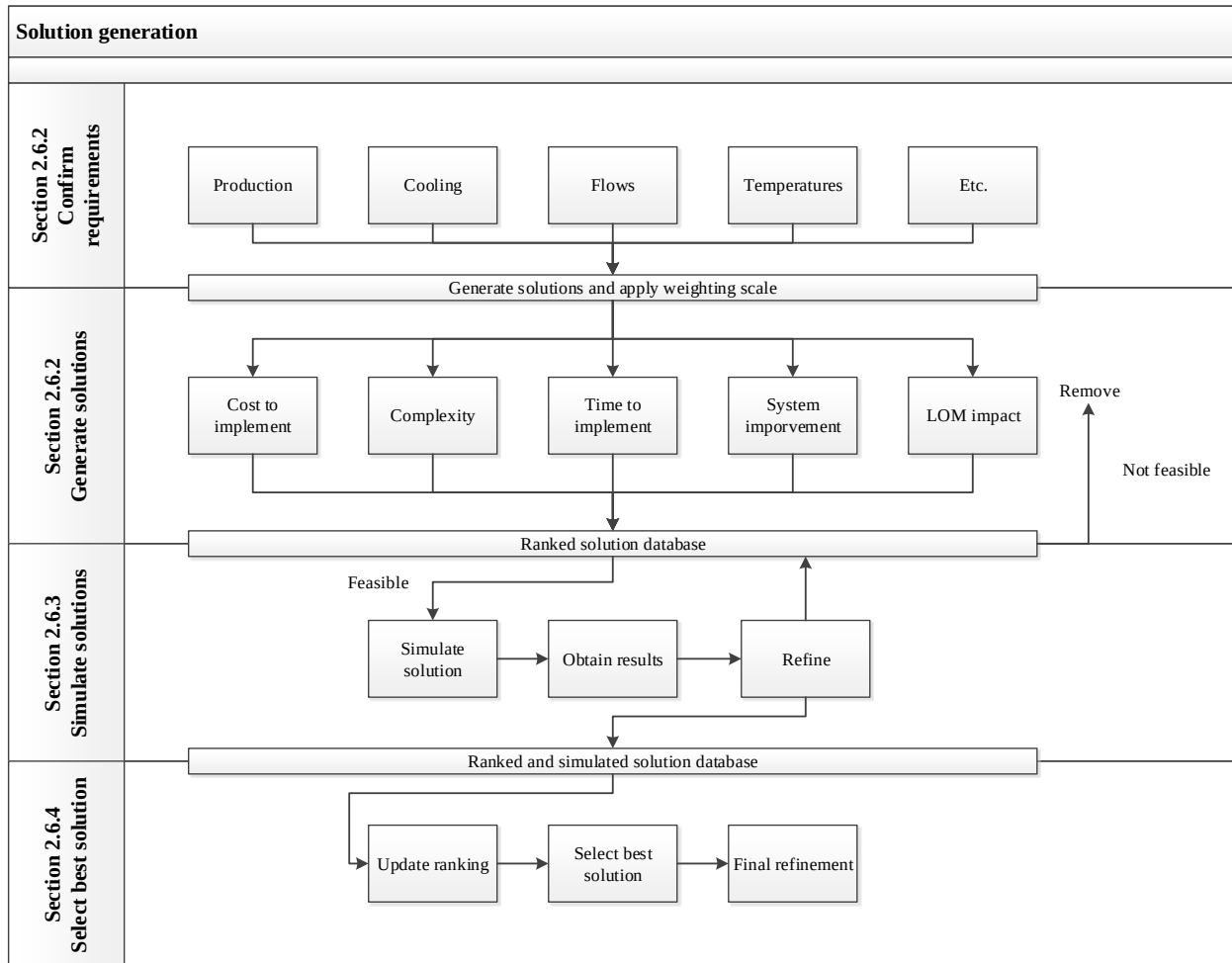


Figure 33. Process for generating WCS-related solutions and testing their feasibility

3.6.2 Generate solutions to meet requirements

This is a critical step that starts with confirming the requirements as prescribed by the client. It is important to reaffirm what is required from the method, and what the solution is attempting to solve, optimise and improve. Here production tons or planned mining is considered which will have a direct effect on the required future planning of the required services. The requirements may include tons of ore removed from certain levels which require services at specified flow rates, pressures, and temperatures.

Once the requirements are clearly defined, several solutions can be developed to optimise the system. The solutions are investigated according to six key factors adapted from studies [130], [131], [136] and through extensive talks with mine personnel:

- **Cost to implement:** What is the estimated cost of the proposed solution? It is important to understand what the cost of a proposed solution will be. The cost assists in determining the

economic effect of the solution and if it can fit in with the current business plan. Rough quotations or costing from simple internet research, previous projects, or word of mouth should be obtained.

- **Complexity:** What is the complexity of the proposed solution? The solution should not be so complex that it is extremely difficult to implement or not practical. It is also important to understand the client or area where the solution will be applied. An example is in the mining industry where equipment is placed in adverse conditions with high humidity, temperatures, and prone to damage from mining equipment.
- **Time to implement:** What is the required time to implement? The proposed solution must stay within time constraints. For example, if production requires a solution to be implemented and operational within a month a solution that takes three months to implement will not suffice or will pose a risk to the production schedule.
- **System improvement:** What is the thermohydraulic effect of the solution and what is the system improvement possible from implementing the solution? The proposed solution should ultimately satisfy a single requirement or combination of requirements regarding temperature, flow, pressure, cooling and so on. Therefore, the solution should be tested for its system improvement, as a proposed solution that does not provide any system improvement or system improvement of any value should be disregarded.
- **Life-of-mine impact:** What is the life-of-mine benefit from implementing the proposed solution? The proposed solution should provide a net benefit towards the mine to ensure it is a viable business case. This is a combination of the initial cost to implement and the overall benefit if the full life-of-mine is considered.
- **Safety:** What impact does the proposed solution have on safety? Does the solution increase safety and redundancy? The proposed solution should not negatively impact the safety of operations. An improvement in safety and system redundancy is beneficial and counts in favour of the proposed solution.

A study conducted by Rojanamon [137] showed the integrated effect of system changes and their effect on the business plan and economic benefits. The study communicated the fact that mechanical or system improvements should always consider the economic benefit.

Each solution is discussed with engineering mine personnel in an open forum. The benefit of each solution and possible negative impacts are discussed, and new solutions are added as seen fit. The six key factors are always considered. The process results in a list of possible solutions which is tabulated as shown in Table 4.

Table 4. Example of solution generation and weighting process

Solution no.	Description	Comment
1	Replace equipment	Expensive but shows clear improvement
2	Upgrade equipment	Expensive without improvement
3	Change configuration	Inexpensive and significant improvement
...	-	
n	-	

3.6.3 Select best solution

Once all solutions have been tabulated a mini feasibility study is conducted by mine personnel. The feasibility takes the six aspects into account and includes:

- **Cost to implement:** Initial estimate quotes of the work required to implement a solution. A final value to implement the solution is given which is substantiated by quotations from suppliers.
- **Complexity:** Initial infrastructure estimates and contact with suppliers will provide a better idea of the actual complexity of the proposed solution and its robustness in the mining environment.
- **Time to implement:** Interaction with suppliers and mine personnel provides a better idea of the actual time required to complete the work required for the proposed solution. Here an estimated schedule can be set up and an actual timeframe provided in days, months, or years.
- **System improvement:** The improvement on the overall system is initially estimated with hand calculations. A model will, however, assist at a later stage with increased accuracy. The simulation results will provide an accurate value of the actual system improvement regarding temperatures, cooling duties, flows, pressures, power usage and working conditions. This is easily comparable and quantifiable for accurate decision making.
- **Life-of-mine impact:** The life-of-mine impact is calculated from using a net present value (NPV) method. This is an initial calculation using the estimated costs and estimated cost savings over the entire LOM. The impact is then quantified, and the economic success can be determined. An expensive solution might have a poor economic score; however, the long-term LOM impact outweighs the initial capital expenditure required and therefore it might be a feasible option.
- **Safety:** The model and initial infrastructure can determine estimates of the safety impact of the proposed solution. Improvement in safety will significantly favour the solution as it is a critical aspect of the mining industry.

After each solution is investigated in more detail a final solution comparison table is determined by mine personnel and provided. An example for the case study discussed is shown in Table 5.

Table 5. Example of the final solution comparison and decision-making

Solution no.	Description	Rank	Comment
1	Replace equipment	2	Expensive but shows clear improvement
2	Upgrade equipment	3	Expensive without improvement
3	Change configuration	1	Inexpensive and significant improvement
...	-	-	
n	-	-	

Table 5 works as a complete comparison of all the aspects regarding each solution and provides an overview of each solution's advantage. This will provide a clear guideline for decision making allowing informed decisions to be taken. Here, solution 3 is deemed as the best solution and will be used as an example to be investigated further through the next sub-step, namely simulation.

3.6.4 Simulate solution

Once the feasible solutions have been determined and a preferred solution selected, the solution is added to the model and simulated. It is important to note the simulation includes all the previous infrastructure, dynamic boundaries, calibrated equipment, and dynamic demands.

Therefore, the effect of the proposed solution will be visible on the entire system. It may be possible that the proposed solution changes the system significantly to where other areas are no longer within specification. An example of this is increasing water demand on the current system which applies an additional load on the refrigeration system and pumping system which might not be able to cope with the additional load.

The simulation provides feedback on the thermohydraulic success of the proposed solution using the critical requirements discussed in the previous section. It also gives feedback on the entire mining complex which was not previously available.

The simulation also provides feedback on the complexity of the proposed solution. During the construction of the model and simulation of the proposed solution, certain complexities are highlighted. Due to the exact representation of the model issues such as space restrictions, actual distances required and distance from the shaft are easily visualised and realised.

The simulation results from the proposed solutions are added to a visual representation that includes all important components, temperatures, flows, pressures, cooling duties, and requirements. An example of what these visual simulation results would entail is shown in Figure 34.

The critical requirement areas or requirement KPIs are investigated further to ensure they are within specification. The 24-hour profile can be extracted from the simulation model and displayed to show the dynamic change and effect of the proposed solution. An example of such an area of concern or KPI is shown in Figure 35.

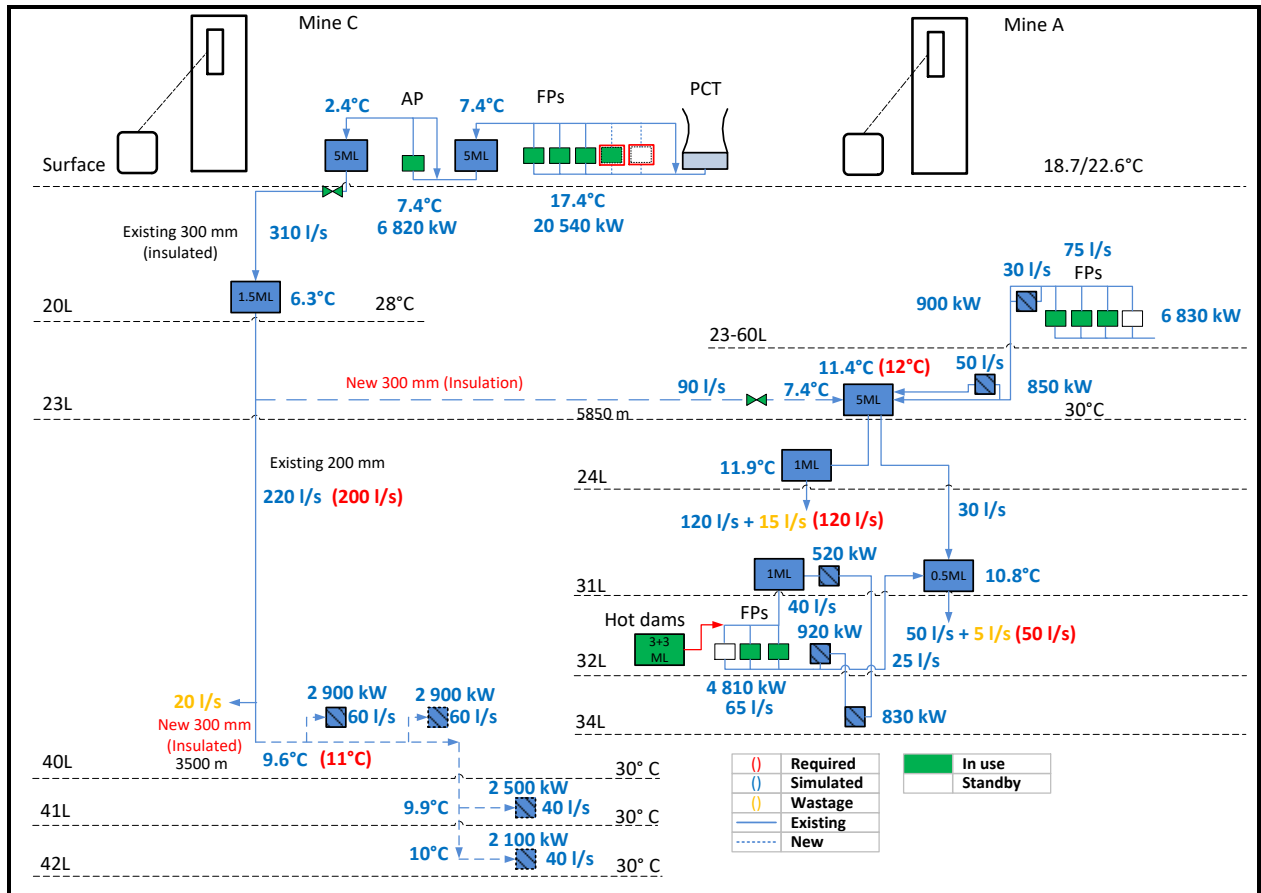


Figure 34. Example simulation results from solution 1 implementation

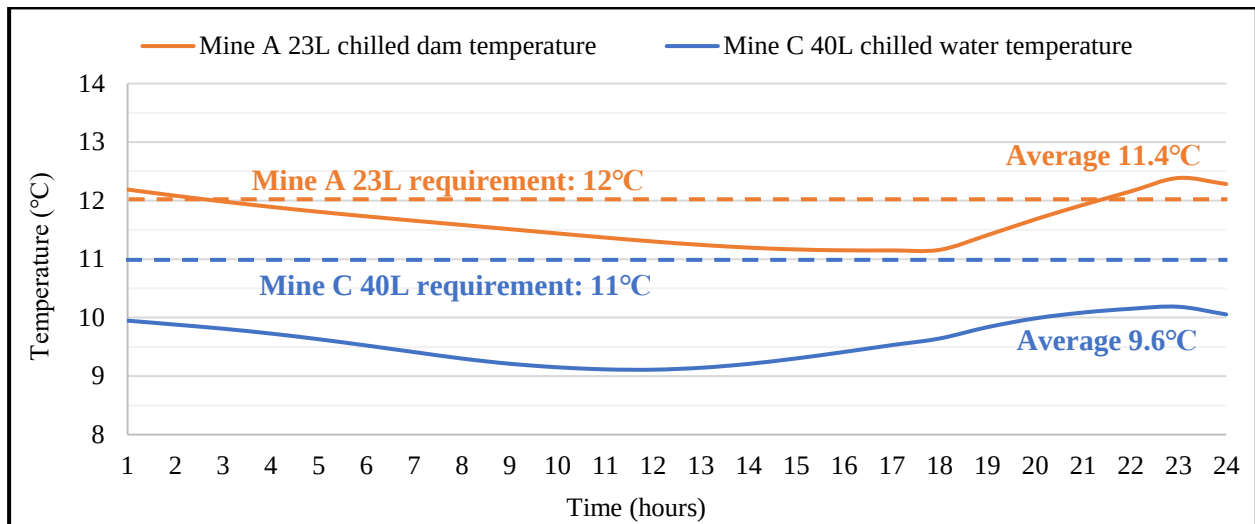


Figure 35. KPI 24-hour profile after implementation of solution 1

If the solution does not yield favourable results the solution must be revisited and simulated again with the required additional changes or equipment to meet all requirements.

3.6.5 Iterate and improve solution

The same process is followed for the revisited simulation, and iteration is required until a favourable solution that meets the client's requirements is obtained.

Once the additional simulations have been completed, if required, the solution can be further investigated. The required changes and updated information might affect the rank given to the solution because the integrated effect on the entire system could be determined. For example, if additional refrigeration is required, it will severely increase the costs, complexity, and the time to complete the solution, and decrease the LOM net benefit due to the factors described.

At this step, the solution can either be removed or investigated further according to the information available. If the solution is feasible a cost and scheduling analysis can be done to further update the cost, complexity, and time to implement scores. The required infrastructure and changes are determined from the simulation. Therefore, quotes can be requested for the required work and scheduling conducted around the available down-time of the shaft and haulages.

The entire process is followed for all iterations and the results tabulated. An example is shown in Table 6.

Table 6. Example of updated solution weighting after simulations

Iteration	Description	KPI 1	KPI 2	OPEX (LOM)	CAPEX
		(°C)	(°C)	(R million)	(R million)
1	Change config	15	11	R2 400	R23
2	Iter. 1 + insulation	14.5	10.5	R2 350	R27
3	Iter. 1 + 2 + additional refrigeration	12.0	10.1	R2 320	R120
4	Iter. 1 + 2 + 3 + new BAC	11.3	9.2	R2 200	R170

Table 6 shows how each iteration improves the system. However, the changes might add cost and complexity that will need to be considered. The simulation shows a clear improvement and is an accurate representation of the actual system improvement. This provides further insight on the benefit of utilising the simulation model which provides an integrated view of the entire system and the effect of the proposed solution on the entire system. This improves the accuracy to which planning can be conducted avoiding guesswork and estimations which were incorrect without the simulation model.

3.7 Verification and validation of proposed method

Verification of proposed method

To verify that the new proposed method (Figure 15) can achieve the aim of the study (i.e. whether it is applicable to the problem), it must comply with the criteria identified from the literature (Section 2.6) and objectives (Section 2.7). Table 7 below supports the suitability and applicability of the new proposed method.

Table 7: Proposed method applicability determination

Steps in method	Criteria for a suitable mine WCS planning method (Section 2.6)				Objectives of the study (Section 2.7)			
	Planning	Digital twin	Integrated (I) verified (V) sim.	Dynamic boundaries	1	2	3	4
Step 1	X						X	
Step 2		X				X		
Step 3			X					X
Step 4				X			X	

It is also important to verify whether the new proposed method (Figure 15) accurately predicts changes to a system. Therefore, actual results should be compared with a prediction made by the new proposed method. This will be addressed in Section 4.2.

Validation of proposed method

Once the method has been verified, it can be applied to several case studies to validate the effectiveness of the method. Validation compares the new method with the old static and non-integrated methods. Both scenarios are simulated, and the results are compared. Due to the size, cost, and timelines of implementing the different scenarios, the results are simulated rather than physically implemented and measured. This approach is feasible because the model used have been proven to be accurate (similar to studies: [8], [10], [11], [25], [81], [138]). The new method must ensure that the objectives of each case study are always met when solutions are offered through the new method. Most importantly is whether the need is satisfied that was stated in the introduction (Section 2.7).

3.8 Conclusion

Chapter 2 presented and discussed the new method to assist with effective future mine planning. The steps required for the new method are summarised in Figure 36.

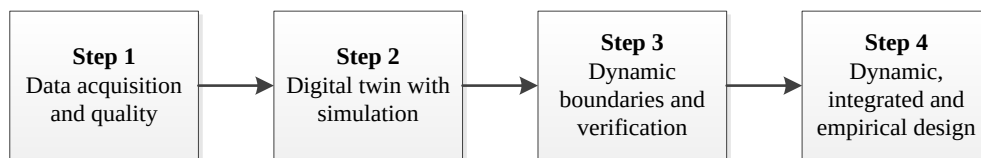


Figure 36. Summary of new four-step planning method

The developed solution is visually shown in Figure 37. This method was also published in the conference proceedings of the 32nd annual Southern African Institute for Industrial Engineering Conference (SAIIE32), seen in Appendix A.

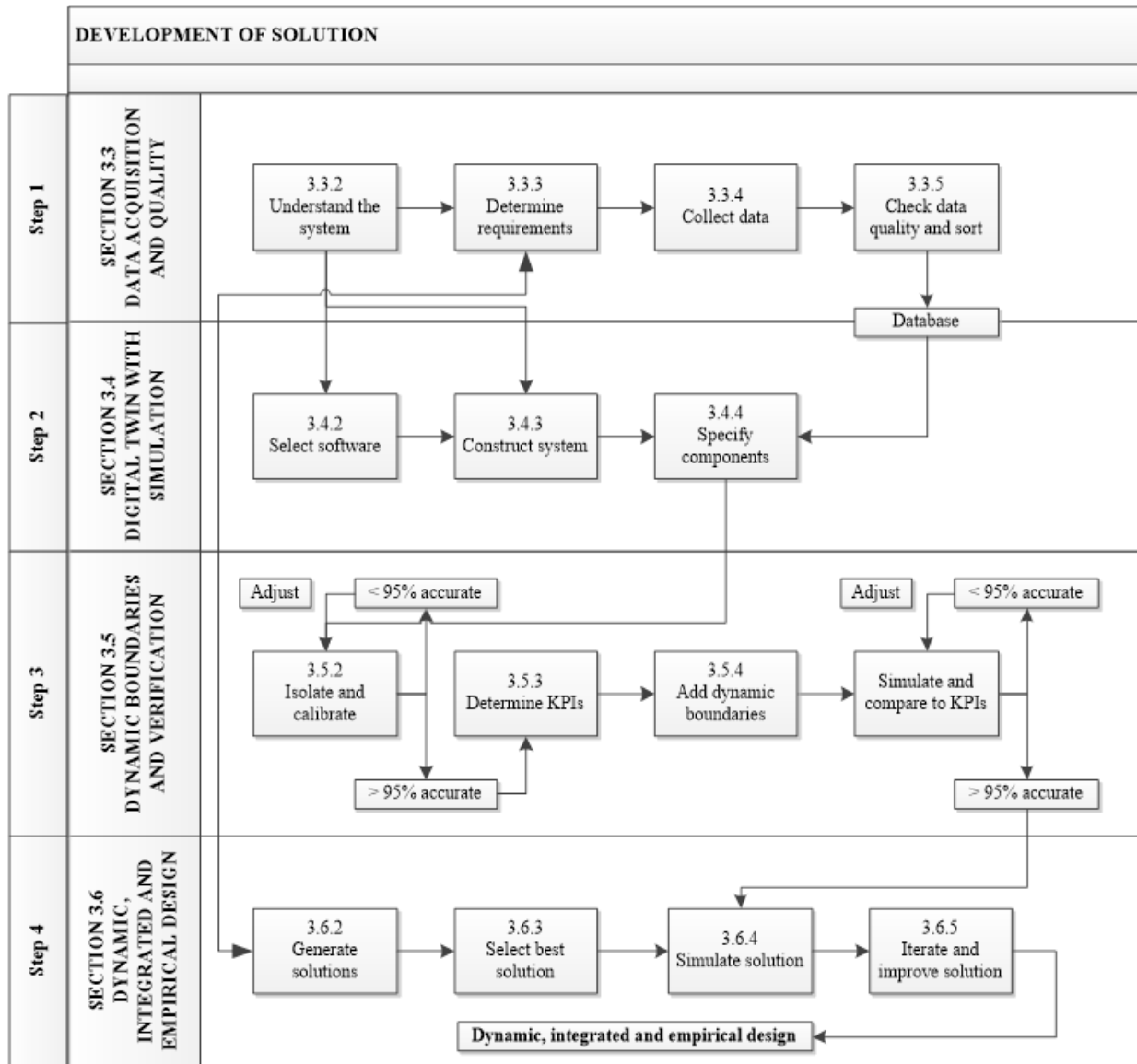


Figure 37. New four-step method for integrated and dynamic WCS planning [7]

The new method consists of four main steps with several sub-steps. The first step is the “data acquisition and quality” step which is broken into four sub-steps:

1. **Understand the system (e.g. information acquisition and audits)**
2. **Determine the requirements**
3. **Collect data**
4. **Check data quality and sort**

The second step is constructing the digital twin with simulation which is separated into three steps:

1. **Selecting the best software**

2. **Constructing the system**
3. **Specifying components**

The third step is modelling, adding dynamic boundaries, and verifying the model which consists of three steps:

1. **Isolate and calibrate**
2. **Determine KPIs**
3. **Add dynamic boundaries and verify**

The final step is generating and simulating solutions to the requirements determined in the first step and is done using a four-step process:

1. **Generate solutions**
2. **Compare solutions and select best option/solution**
3. **Simulate chosen solution**
4. **Iterate and improve solution using simulation**

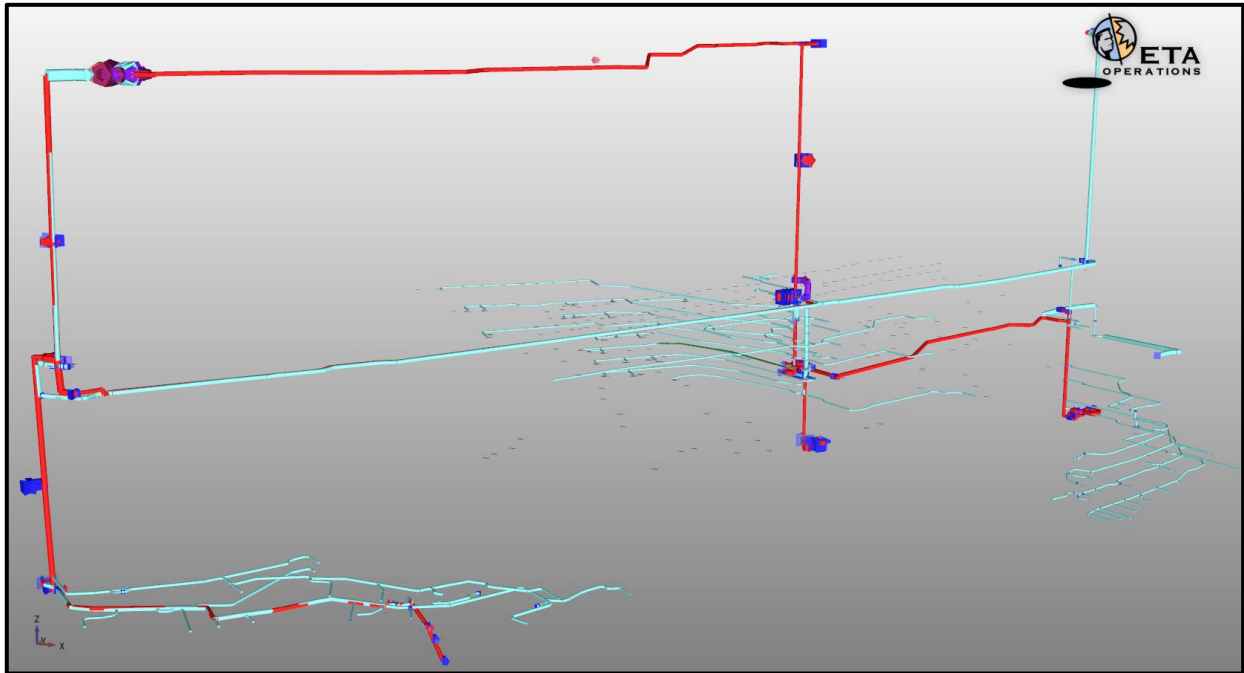
The construction of Figure 37 is discussed in further detail in the following sections.

The method uses significant data obtained from the system and incorporated into the digital twin with simulation to characterise each piece of equipment effectively as it is currently installed. This results in a fully integrated and dynamic model that is a to-scale representation of the actual system and is accurate to within 95%.

The digital twin with simulation is then used to test several solutions to production and services planning requirements. The solutions are accurately tested using the simulation model which assists with rapid planning. Each solution can be tested for several key factors using the model to determine its success and net benefit to the mining complex and improved safety.

The method allows solutions which have a negative or neutral benefit to be removed early in the project life. The remaining solutions are further investigated, and the final LOM, safety and complex benefit are determined. This is used to make a final decision on the best solution for the required future production.

Chapter 4: Results and discussion



Full 3D simulation model of a deep-level mine WCS¹⁹.

This chapter verifies and validates the method through applying the new novel method to several case studies.

¹⁹ Screenshot obtained from PTB.

CHAPTER 4 RESULTS AND DISCUSSION



4.1 Preamble

This chapter applies the new simulation-based planning method to several case studies to verify and validate the method, and to showcase the effectiveness and accuracy of the model. The approach followed for each case study was based on the method described in Chapter 3. A summary of each of the four case studies investigated are listed below.

Case study 1 (Method verification [139]): The first case study is used as a verification tool for the proposed method. The method is applied to a shaft that reduced mining from full production to complete closure. The shaft, however, still supplies a neighbouring shaft with chilled water underground. The method determines the temperature, flow and power required during the drastic production change during shaft closure.

Case study 2 (Production planning, cost avoidance and method validation [12], [111]): The second case study considers a six-shaft complex that is fully integrated. The shafts are dependent on each other for services and have individual production plans and LOMs. The simulation method was used to determine the best course of action for future planning to ensure all shafts continue with their planned production schedules at the optimal cost for the entire complex. The simulation allowed several solutions to be investigated in quick succession which resulted in an optimised solution.

Case study 3 (Emergency planning, production loss avoidance and method validation [12], [111]): The third case study considers a surface chiller failure on the integrated four-shaft complex. The simulation model is used to determine the effect of the loss of critical equipment on underground temperatures. The effect is clearly seen from simulations and a subsequent risk analysis conducted.

Case study 4 (Emergency planning, production loss avoidance and method validation [12], [111]): The fourth case study considers a serious power failure of the entire mine. A power failure of all systems is simulated. The focus was placed on the water system and ensuring the mine does not flood within 48 hours. Several options are simulated to meet the requirement of when no electricity is available.

After each case study, the new method's solutions are compared with those of the current methods used in the mining industry. This comparison will highlight the benefits of the new method. As explained in Chapter 1, the current methods make use of static and non-integrated models as well as design parameters that influence the accuracy of the results.

4.2 Case study 1: Shaft closure WCS planning

4.2.1 Background

Overview

A South African mine complex consisting of six integrated active shafts is considering closing one of the shafts. The reason for the closure is that the shaft is reaching its end of LOM and the costs involved with keeping the mine in care and maintenance are significant. Therefore, the successful closure of the shaft will reduce operating costs and result in the improved economic performance of the remaining shafts. The estimated savings from the closure of Mine B are shown in Figure 38, which shows an estimated savings of R2.2 billion over 12 years with LOM continuing past 2033 for Mines A and D.

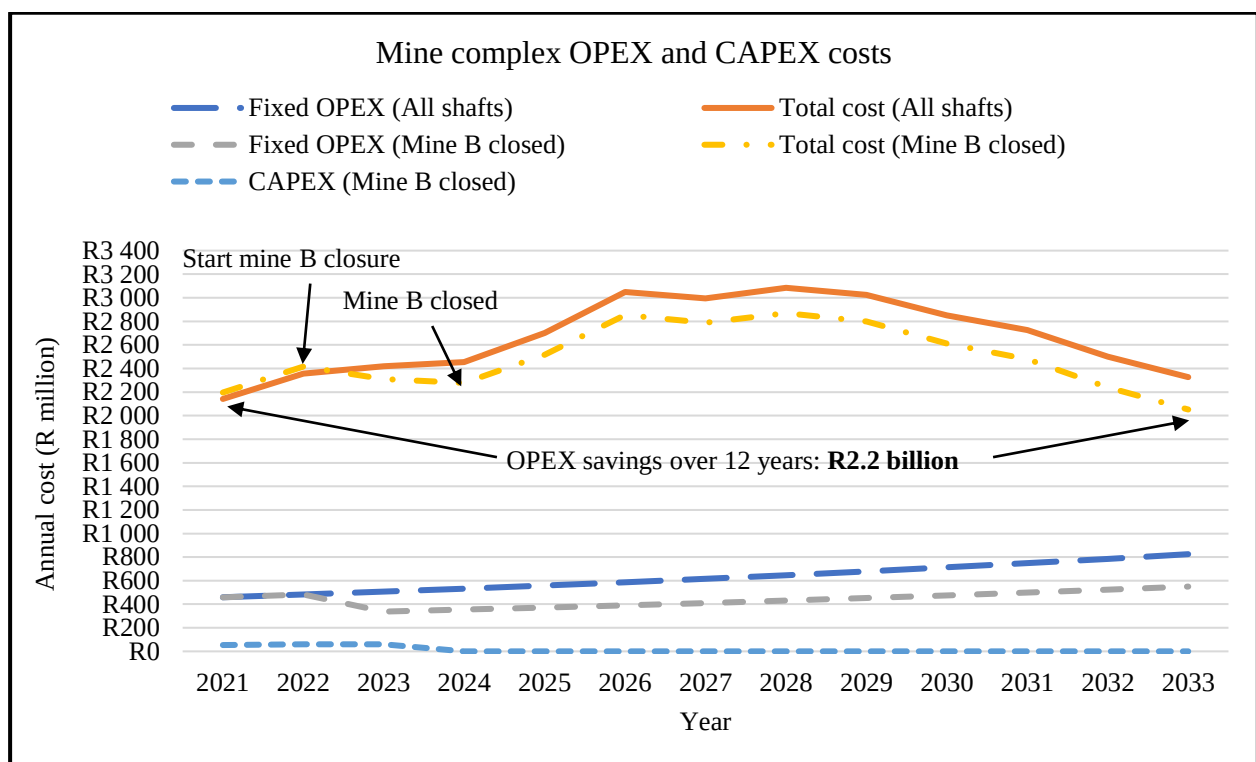


Figure 38. Potential benefit of Mine B closure over complex LOM

The closure of Mine B is estimated to include a total CAPEX of R170 million over three years. Once Mine B closure has been achieved a yearly OPEX saving is estimated at R80 million. This results in a net benefit

over the 12 years of all shafts of R2.2 billion assuming 5% inflation per year. Therefore, on an economic basis the project seems feasible.

The future life-of-mine and production of each shaft is shown in Figure 39. The figure shows the total expected mining of each shaft averaged over a year from 2022 to 2030. Mine A and Mine D have the longest LOM plans with Mine B and C end of LOM approaching in 2022 and 2023 respectively. Mine E is on a low production plan with end of LOM approaching in 2025 and Mine F operating on care and maintenance.

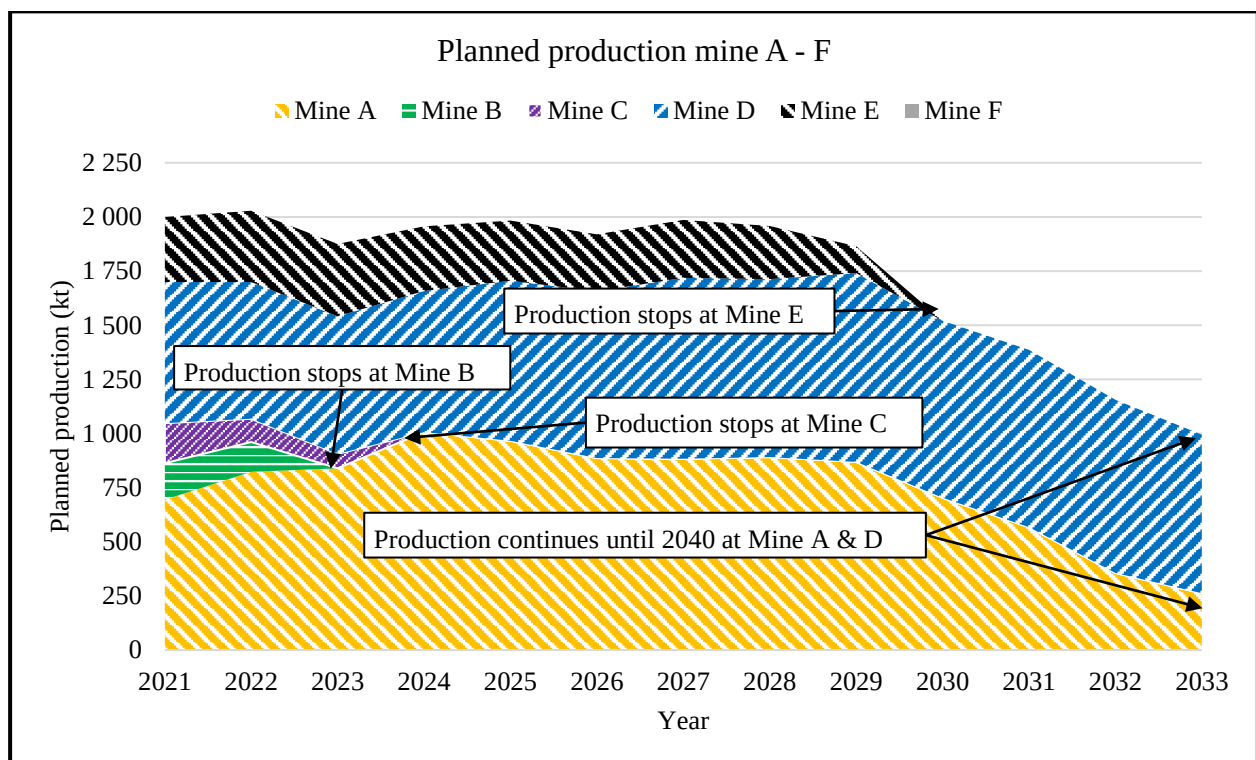


Figure 39. LOM of interconnected shafts at a large mining complex

The closure of Mine B seems straightforward; however, Mine B is a significant supplier of services to Mine A due to the integrated nature of the mining complex. Mine B supplies service water underground to Mine A; this water is used and returned to Mine B for cooling on surface. The future situation of the chilled water system is schematically shown in Figure 40²⁰. The figure shows a decommissioned Mine B with no service water to Mine A. Figure 40 also indicates the future required demands and available cooling for Mine A.

²⁰ All dewatering systems are not shown in Figure 57 for simplification purposes, for example the column from Mine A to mine B on surface.

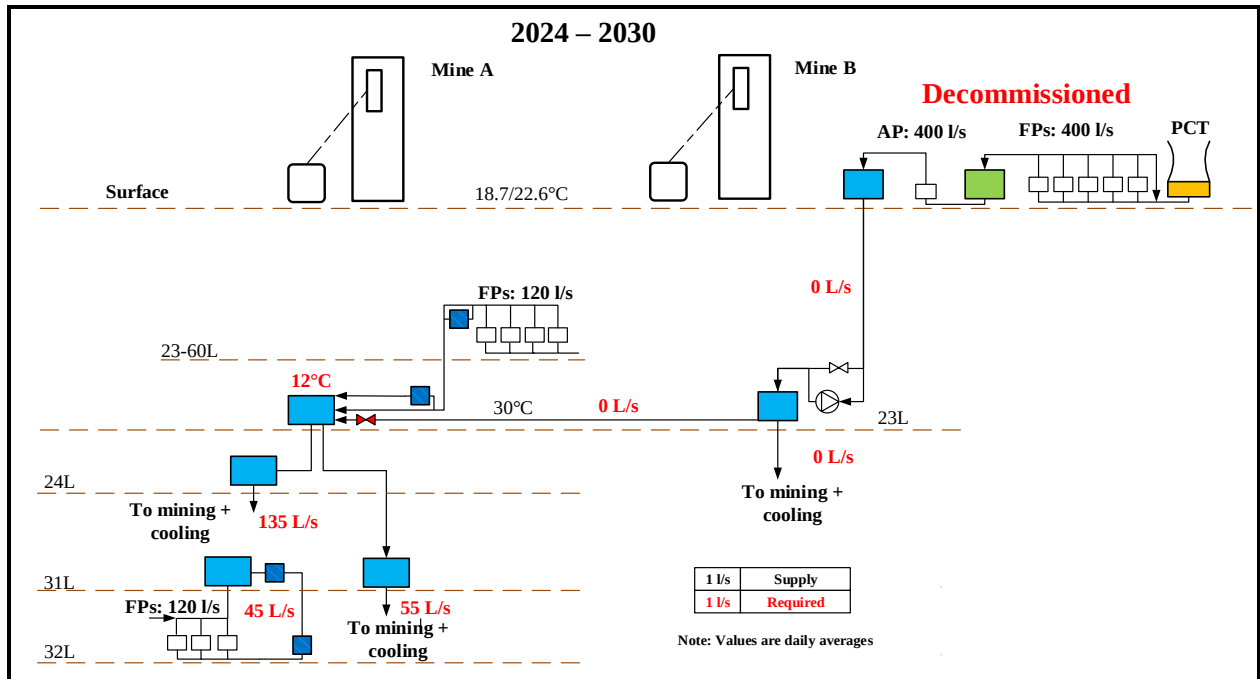


Figure 40. Case study A system overview and requirements 2024 – 2030

The focus of this case study is to predict the conditions of the system during the decommissioning process and to verify the proposed novel method.

Case Study Objective

Verify the new proposed method through comparison with actual data.

4.2.2 Step 1: Data acquisition and quality

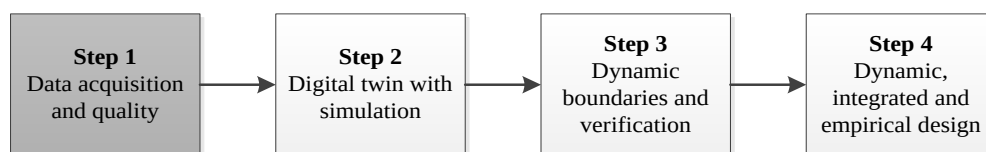


Figure 41. Step 1 of new four-step method in case study 1

Detailed audits of the system were conducted as a starting point and critical items noticed. The current system uses surface FPs and APs situated at Mine B in conjunction with underground FPs situated at Mine A to supply both Mine A and Mine B with chilled water. The simplified layout of the system is shown in Figure 40. The refrigeration plant receives hot return water from underground via mine A (a neighbouring shaft) through a surface pipeline. The water is sent through a pre-cooling tower that reduces the water temperature using ambient conditions (this step provides significant cooling).

Afterwards the water is chilled further by five FPs (not all running concurrently, and this depends on the load) and then two APs (not all running concurrently, which also depends on the load). The final chilled water is sent to the chilled dam which supplies water to underground users. The underground users depend on mining and cooling for Mine B as well as mining and cooling for Mine A.

Mine B is set to close in two years' time from the current configuration seen in Figure 40. The closure of Mine B poses a threat to the production of Mine A if sufficient water at the correct temperature is not available. Case study 2 predicts the required refrigeration including temperatures, flows and power over the two-year decommissioning period.

The timeline from reducing mining to completely stopping at Mine B is as follows:

- **Month 1 – 8:** Normal operation
- **Month 8 – 17:** Normal mining and reclamation
- **Month 17 – 22:** Only reclamation
- **Month 22 – 27:** Care and maintenance only supplying Mine A until supply change

All the required data was collected over a year period before the closure start to characterise the system completely and to do sufficient future planning. The data was filtered and checked for quality. Any data that was required but not measured was measured using portable flow and temperature measurement devices. The resulting database was used to calibrate the model and then applied to the future production plan.

The future production plan was obtained from the mine which included planned number of crews, location of crews and tons per month for stoping and meters for development. This was used to determine a water usage per crew based on the current usage per stoping crew and development crew.

The culmination of the data and information gathered was then used to create the digital twin with simulation.

4.2.3 Step 2: Digital twin with simulation

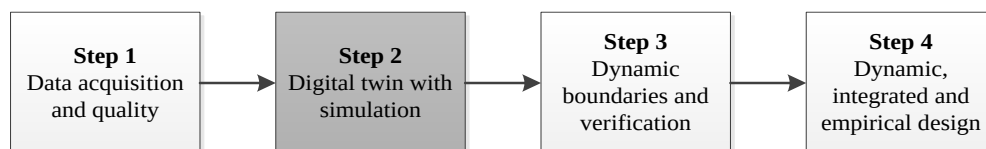


Figure 42. Step 2 of new four-step method in case study 1

The system was constructed in PTB which is shown in Figure 44. The simulation included the entire mining complex including all refrigeration equipment and underground users. The model is created to an exact representation of the actual system including all major working levels and equipment. The model includes refrigeration systems as well as dewatering equipment.

4.2.4 Step 3: Dynamic boundaries and verification

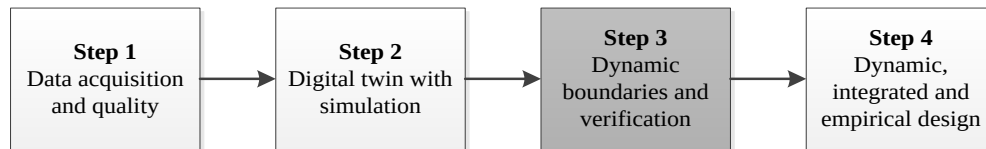


Figure 43. Step 3 of new four-step method in case study 1

The simulation model in Figure 44 shows the integrated systems and level of detail simulated. All the data collected in step one is added to the simulation to characterise the model empirically. One such input is the dynamic boundaries which takes the simulation from static to dynamic. In this instance a 24-hour daily profile was modelled. An example of a dynamic boundary is the ambient conditions over the 24-hour period. An example of a typical summer's day conditions is shown in Figure 45. The figure shows the daily ambient temperatures for a typical summer's day. The dynamic boundary condition is used as a simulation input resulting in a dynamic simulation. Other dynamic boundary condition simulation inputs include:

- Ambient air conditions
 - Dry bulb temperature
 - Wet bulb temperature
 - Relative humidity
 - Air pressure
- Chilled water demand to underground
- Hot mine return water temperature
- Hot mine return water flows

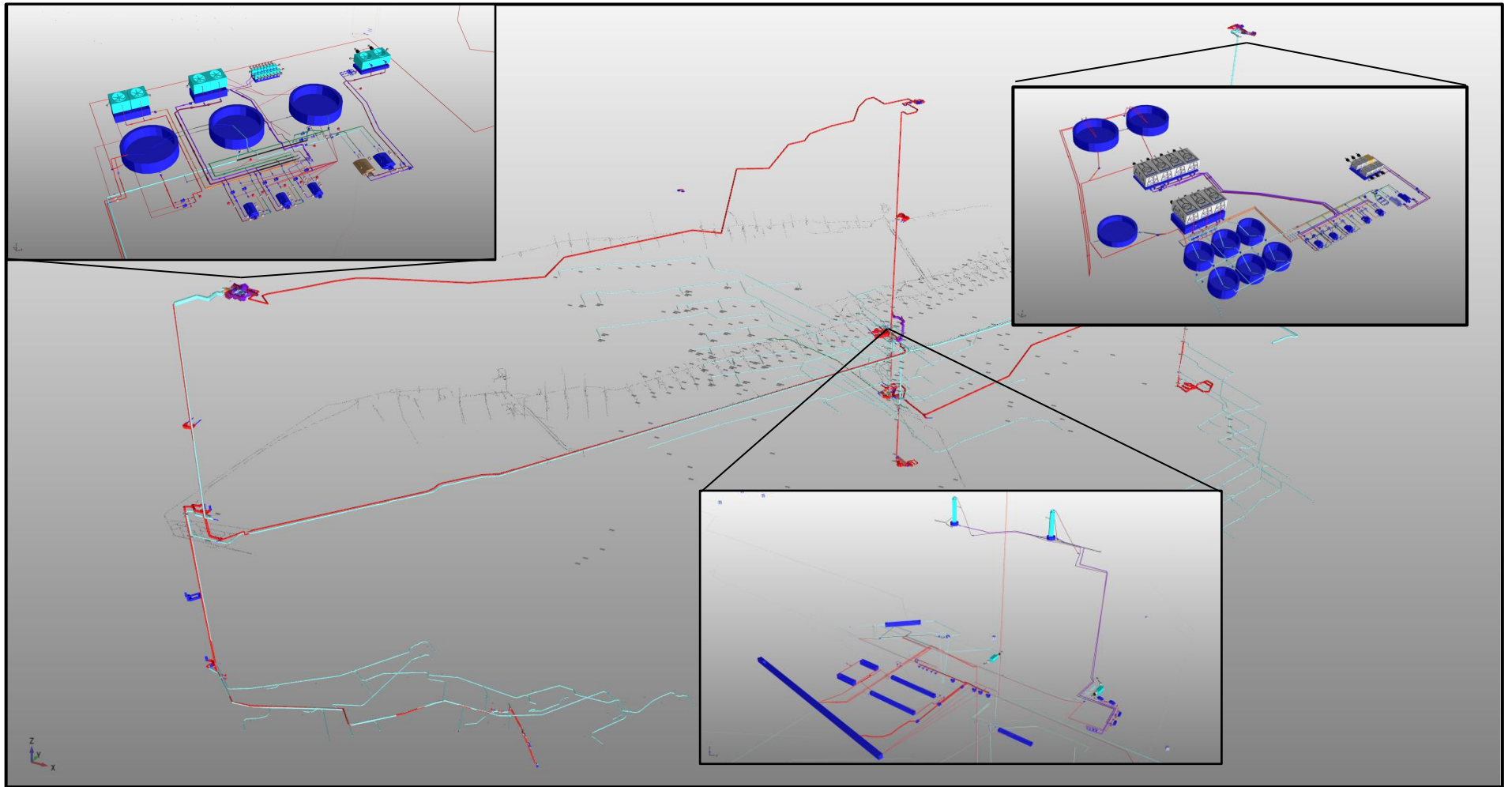


Figure 44. Fully integrated and dynamic simulation of Mine A, B, C & D (Process Toolbox (PTB) simulation software)

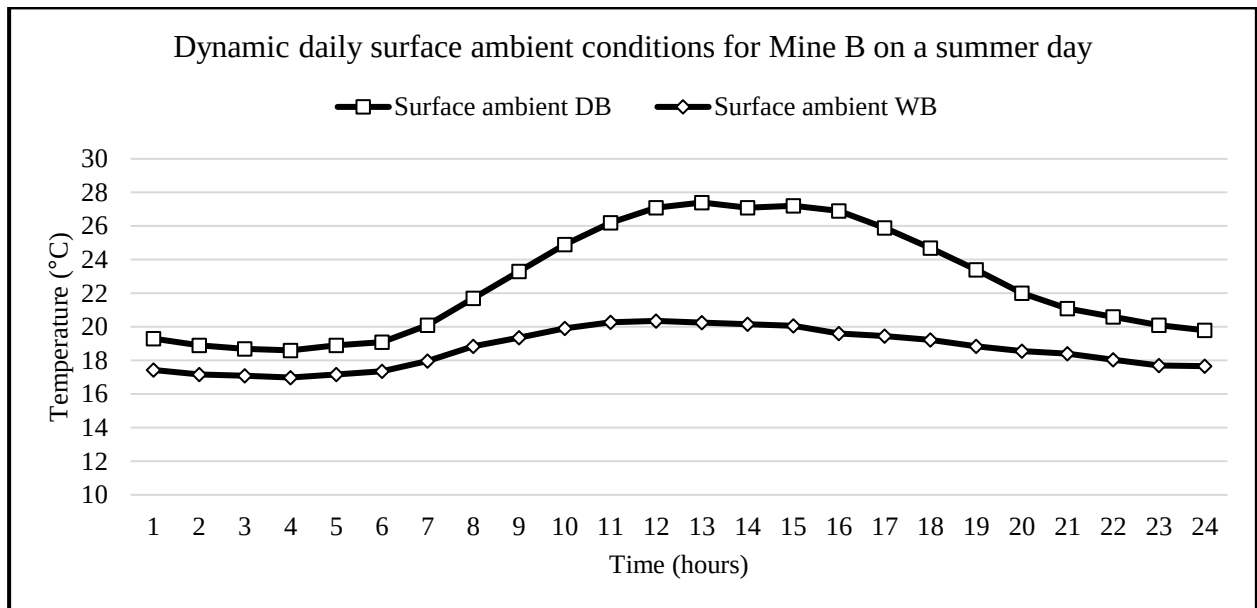


Figure 45. Daily dynamic air boundary condition

The daily dynamic boundary conditions are monthly averages converted to a dynamic daily profile. The closure of Mine B requires simulation over several months. Therefore, the average dynamic profiles needed to be determined for several months. The average of the surface temperatures is shown in Figure 46. The air temperature changes significantly over the months of the year which in turn changes the cooling load on the system and outlet temperatures of the refrigeration machines.

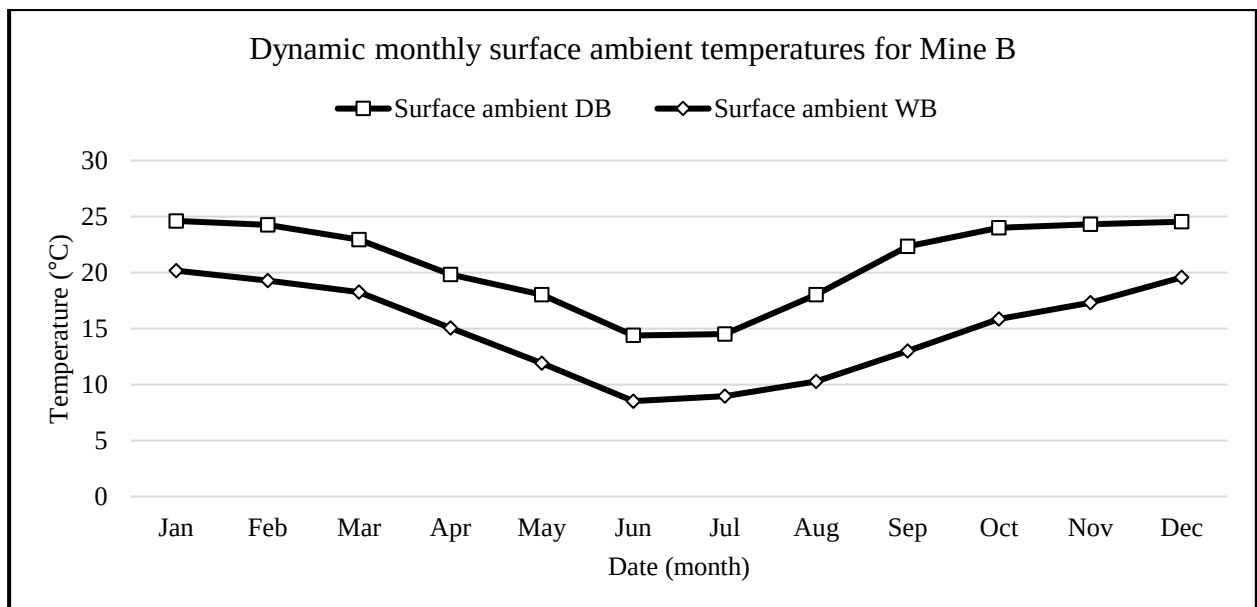


Figure 46. Monthly dynamic air boundary condition

Once a typical day's boundary conditions are entered as simulation inputs, the simulation is run and certain KPIs compared with measured values. The simulation is calibrated to within 5% of the measured KPIs through the method described in section 3.5.4. The outcome of the calibration exercise is shown in Figure 47. The figure shows a good match between the simulated and actual surface chilled dam temperature. Once this is confirmed it can be assumed that the simulation is accurate and can be used for future predictions. This is the next step in the method.

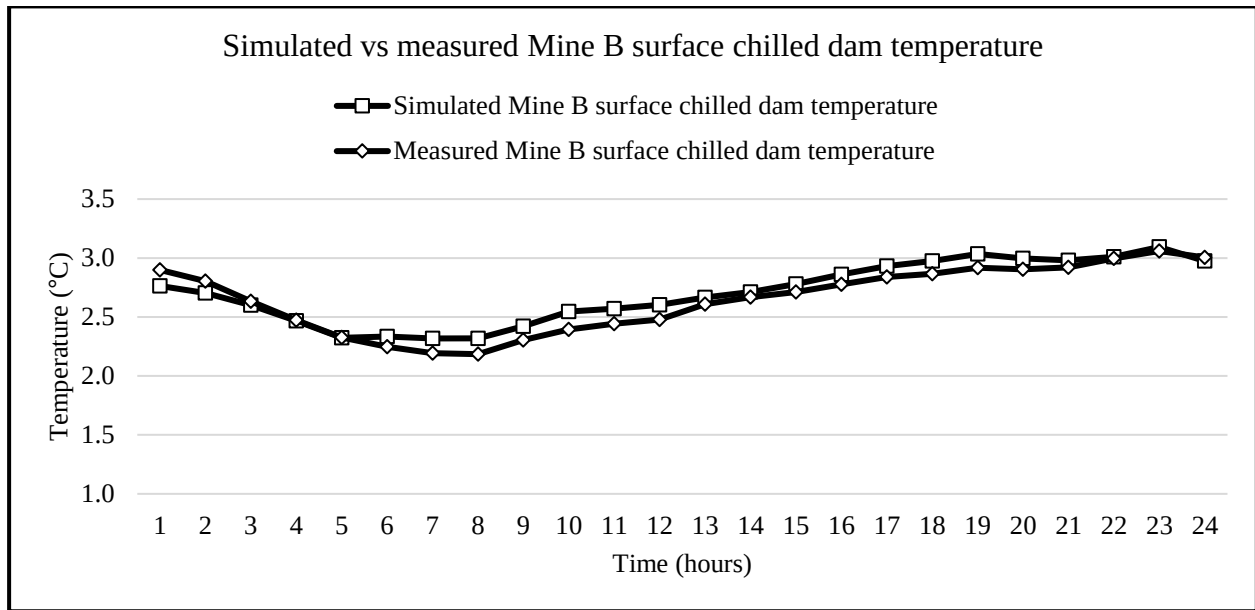


Figure 47. Simulated versus actual temperatures for a single known day

4.2.5 Step 4: Dynamic, integrated, and empirical design

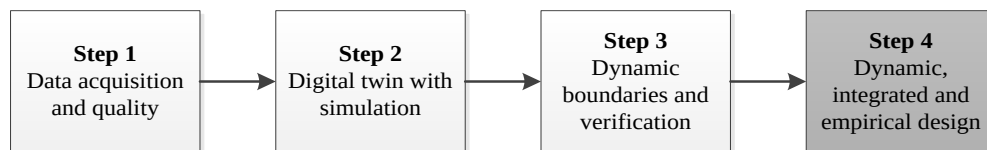


Figure 48. Step 4 of new four-step method in case study 1

The primary inputs to the model for each month that needs to be simulated from start of closure to complete closure are:

1. Surface air wet bulb temperature
2. Surface air dry bulb temperature
3. Surface air pressure
4. Hot dam return water temperature
5. Hot dam return water flow
6. Predicted chilled water demand to underground

Items one to five are obtained from historical data whereas item six requires future prediction. The chilled water demand is determined from the tonnes planned, crews underground and type of work being conducted (stopping, development, or reclamation). The entire process from ramping down to reclamation to closure was predicted using the above-mentioned method. The final required chilled water demand to underground is shown in Figure 49.

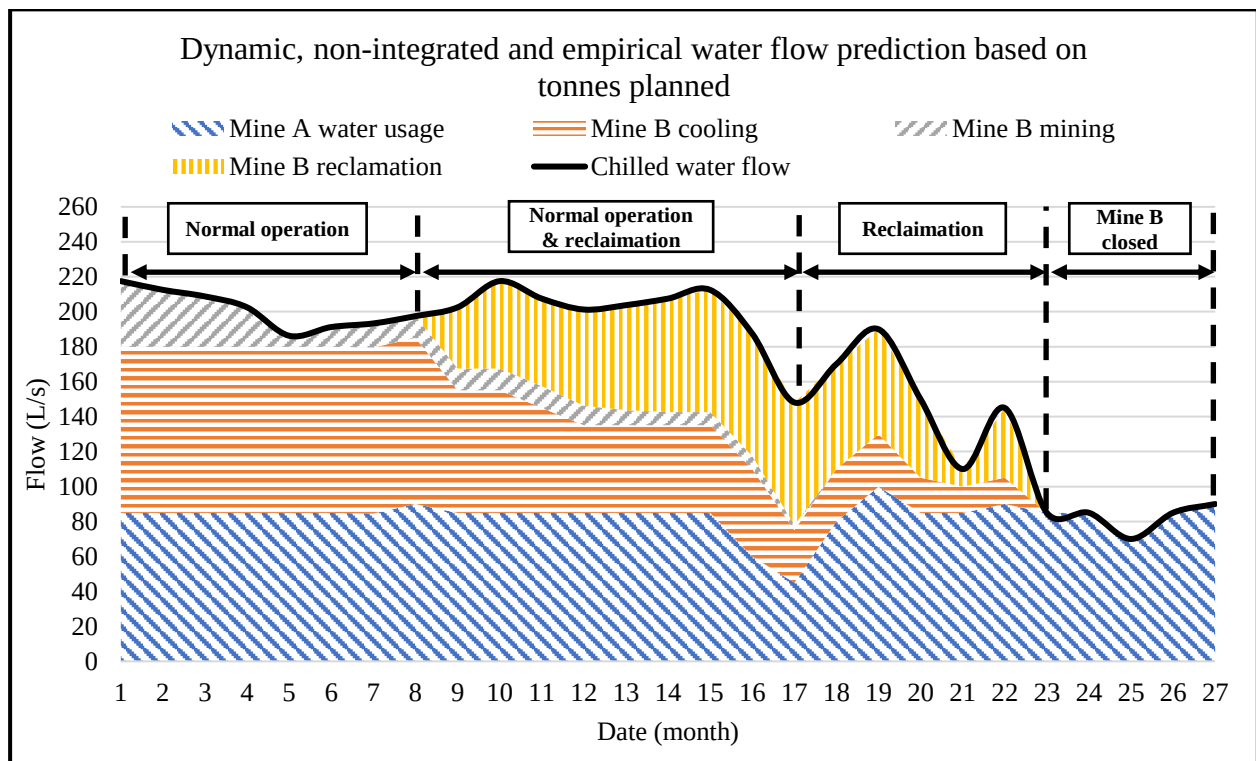


Figure 49. Mine B predicted chilled water flow rate to underground

Each month was simulated with the average dynamic daily boundary conditions entered as a boundary condition. The simulation was then used to predict the temperatures, flows and power consumption for the

entire complex during the simulated month. The results of the simulations for the 27-month period are shown in Figure 50 to 54.

Figure 50 shows the surface dam temperature for Mine B and the underground dam temperature for Mine A. The figure shows relatively constant dam temperatures except for two spikes in temperature. These spikes fall over December when production is reduced significantly with several days where no refrigeration occurs increasing the average temperature during the month.

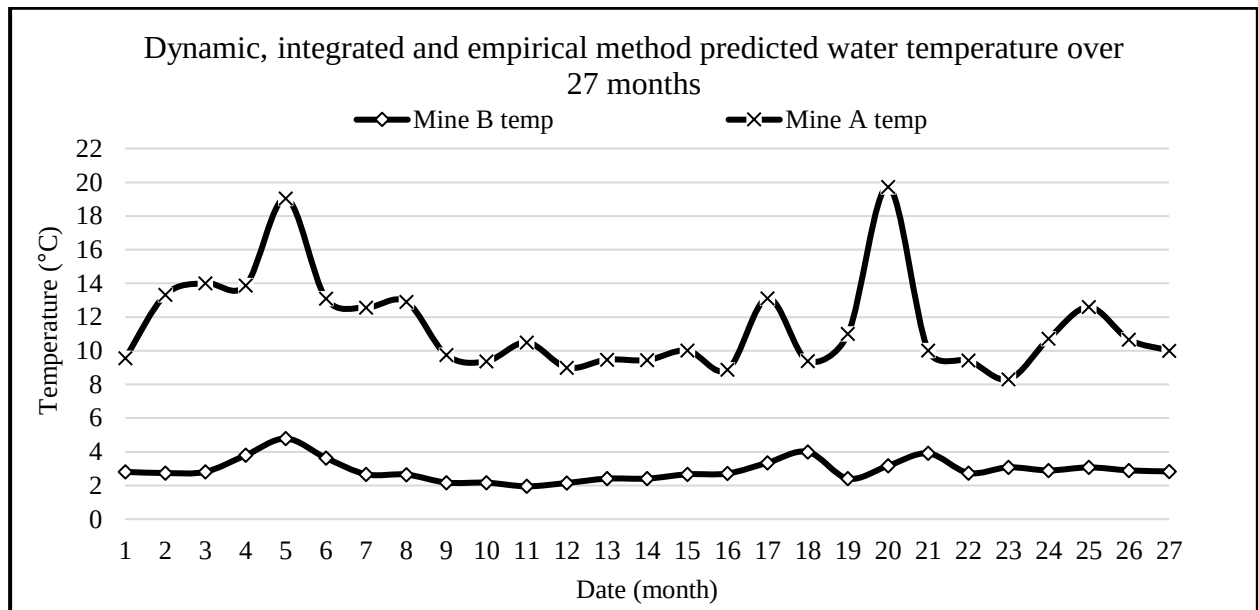


Figure 50. Simulated chilled water temperature for 27-month period

Figure 51 shows the predicted flow to underground from Mine B and Mine A. Mine B produces significantly more water due to Mine B supplying its own activities and Mine A. However, the supply from Mine B reduces as suspected due to reduced production. Mine A's water supply remains relatively constant during the 27-month period.

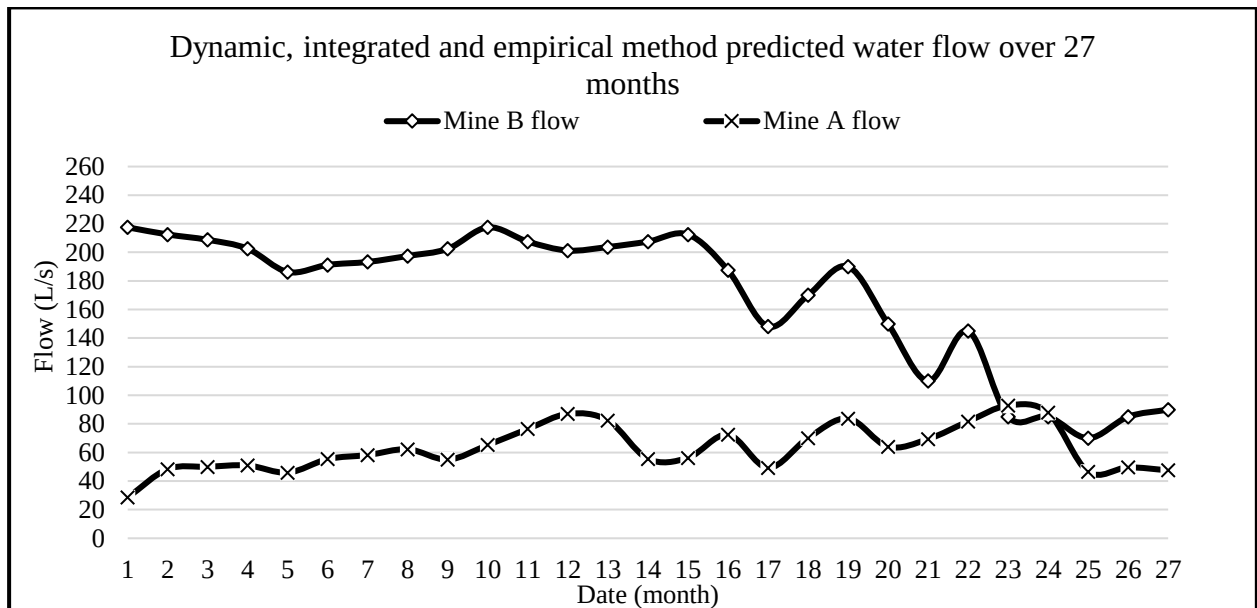


Figure 51. Simulated chilled water flow for 27-month period

Figure 52 shows the predicted power consumption for the refrigeration system for Mine B and Mine A. The power consumption follows a similar trend to the water flow profile. This is expected as the energy required to refrigerate water is a function of the flow rate. There are also seasonal changes in the required power due to increased refrigeration demand in summer months versus winter months.

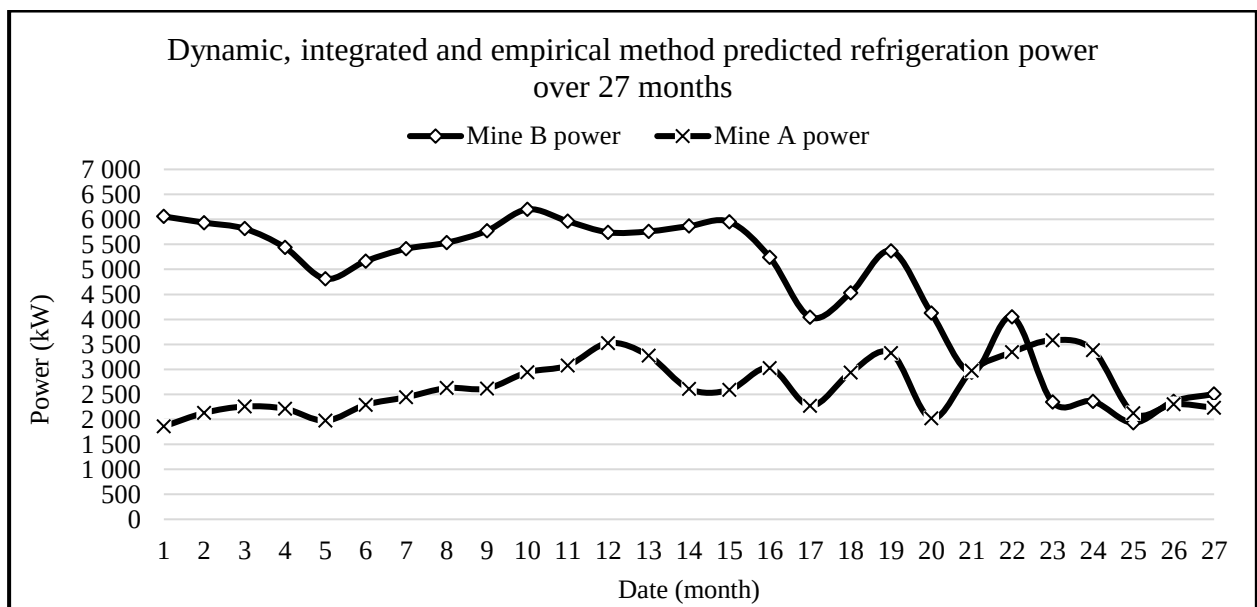


Figure 52. Simulated refrigeration power for 27-month period

4.2.6 Verification of new method

Finally, the results from the simulation could be matched to the actual data. The 27-month period passed, and Mine B is currently under care-and-maintenance, only supplying chilled water to Mine A. The surface and underground dam temperatures, flow rates to underground and power consumption were compared with the actual values shown in Figure 53, Figure 54 and Figure 55.

Figure 53, 54 and 55 show that the novel method predicted the parameters with some accuracy whilst also following the seasonal and yearly trend of the 27-month period, indicating that applying the novel method to the system yielded positive results.

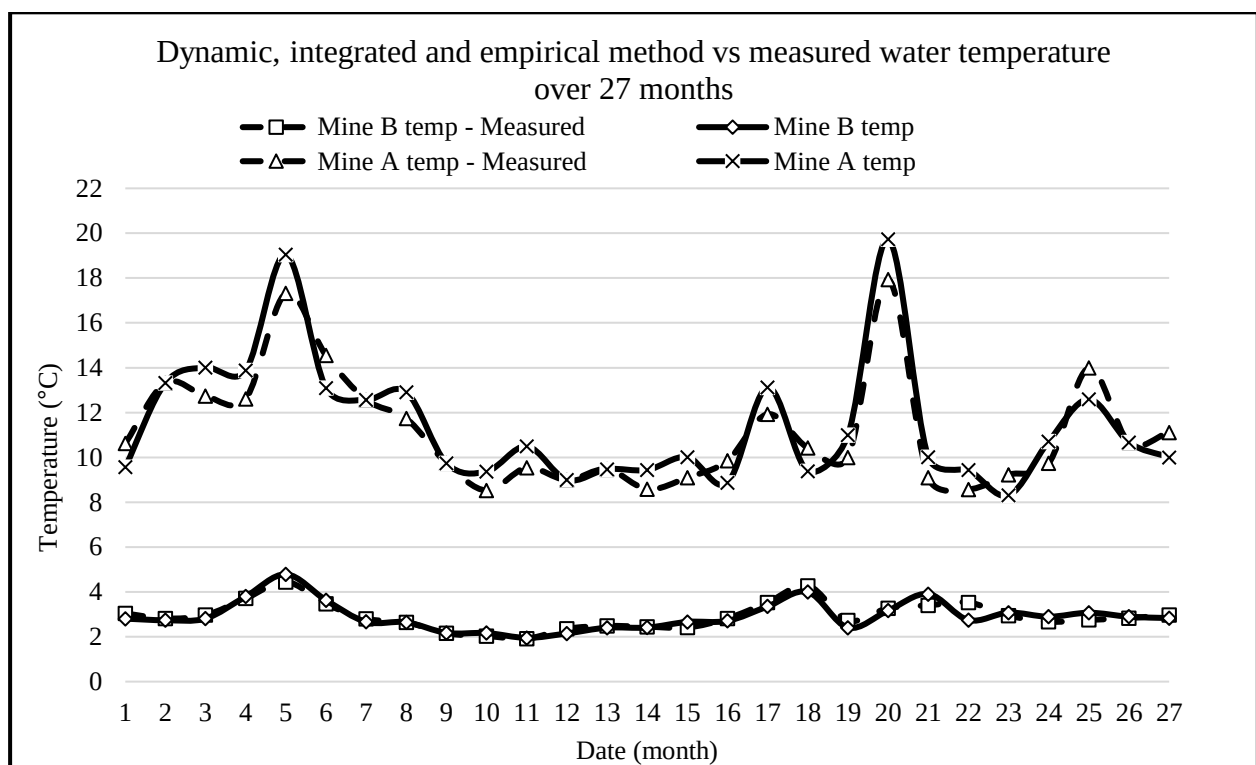


Figure 53. Verification: Predicted temperature results compared with actual values over 27-month period

Figure 53 shows the predicted temperature for the surface chilled dam at Mine B and underground dam at Mine A versus the actual data. Each month's predicted temperature was compared with the actual data and an error calculated for each month. The method shows accurate prediction capabilities with an average error of 6% and 5% for Mine B and Mine A chilled water temperatures respectively. Some outliers are noted; these typically fell on months with significant off days where the data was skewed, such as the December break period and April holidays. The error was calculated as:

$$Error (\%) = \frac{abs(simulated - actual)}{actual} \times 100$$

A similar trend is seen for the flow error to underground as seen in Figure 54. The average error for the flow prediction was 4% and 27% for Mine B and Mine A respectively. The high error for Mine A was due to unforeseen circumstances where operations were not business as usual (BAU). Business not as usual includes labour strikes, equipment failure, unplanned shutdowns and safety stoppages. The worst period was in months 16 to 20 where errors as high as 400% were seen. For the remainder of the months the method predicted the flows with an error of 14%. If the months where business was not as usual are removed the error reduces to 9%.

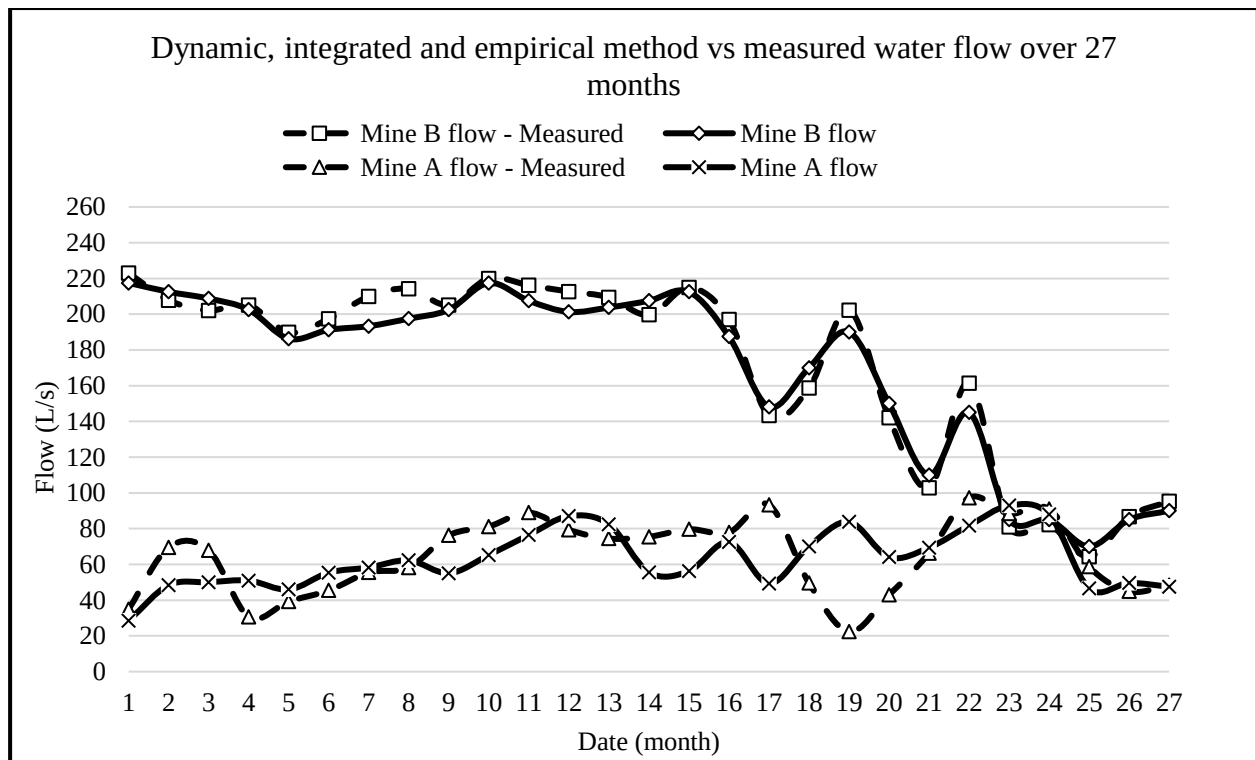


Figure 54. Verification: Predicted flow results compared with actual values over 27-month period

Figure 55 shows the predicted power consumption for refrigeration over the 27-month period. The power consumption follows a similar trend as the water flow due to the power required to cool water being most sensitive to flow rate (temperature plays a smaller role). The power consumption for Mine B and Mine A refrigeration was predicted with an error of 4% and 13% respectively. The same problem exists with Mine A not operating business as usual in certain months. If business as usual was maintained the error would reduce to 5%. The accuracy of the method on power prediction makes it a powerful tool for future energy cost planning and budgeting.

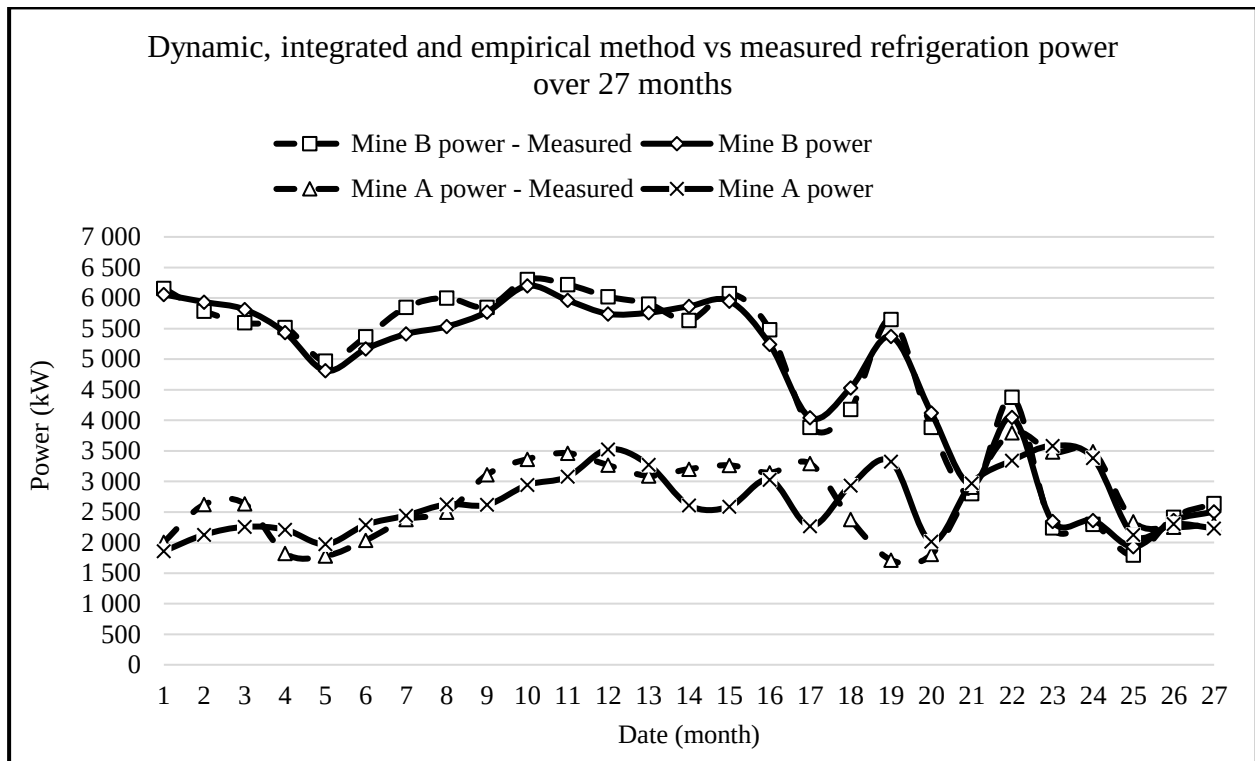


Figure 55. Verification: Predicted temperature results compared with actual values over 27-month period

4.2.7 Conclusion

Case study 1 considered the interim system during decommissioning and closure of Mine B. Critically, as the closure is conducted two FPs needed to be moved from Mine B to Mine C. The case study required that the refrigeration demand and supply be predicted to ensure Mine B is not negatively affected by the moving of the FPs and subsequent reduction in refrigeration.

The new method successfully predicted the refrigeration demand and supply.

The novel method met the objectives set for case study 1 being described as:

- 1. Predict required refrigeration demand and supply:** The required chilled water temperature, water flow, and refrigeration power were predicted using the integrated, dynamic, and empirical method.
- 2. Verify the method through comparison with actual data:** The method yielded an accuracy²¹ of 95%, 94% and 95% for temperature, flow, and power prediction respectively if business as usual was maintained. The actual accuracy if unforeseen circumstances were included was 94%, 84%

²¹ Accuracy was calculated by comparing actual data to simulated/predicted data and dividing by the actual data.

and 95% for temperature, flow, and power prediction respectively. The summary is shown in Table 8. The method is therefore verified. The accuracy was calculated using the formula below:

$$Accuracy (\%) = \left(1 - \frac{abs(simulated - actual)}{actual} \right) \times 100$$

Table 8. Case study 1 prediction error summary based on actual and business as usual

No.	Description	Error (predicted vs actual)	Error (predicted vs BAU)
1	Mine B temp	6%	5%
2	Mine A temp	5%	4%
3	Mine B flow	4%	3%
4	Mine A flow	27%	9%
5	Mine B refrigeration power	4%	4%
6	Mine A refrigeration power	14%	5%

4.3 Case study 2: Six-shaft WCS integration

4.3.1 Background

Step 1: Data acquisition and quality (Section 3.3)

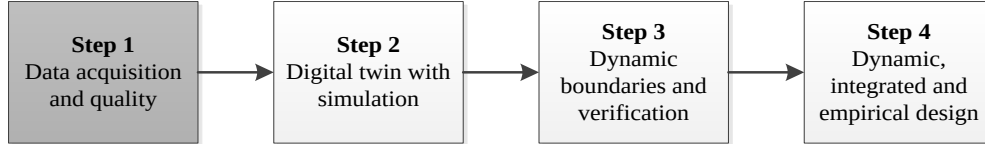


Figure 56. Step 1 of new four-step method in case study 2

Overview

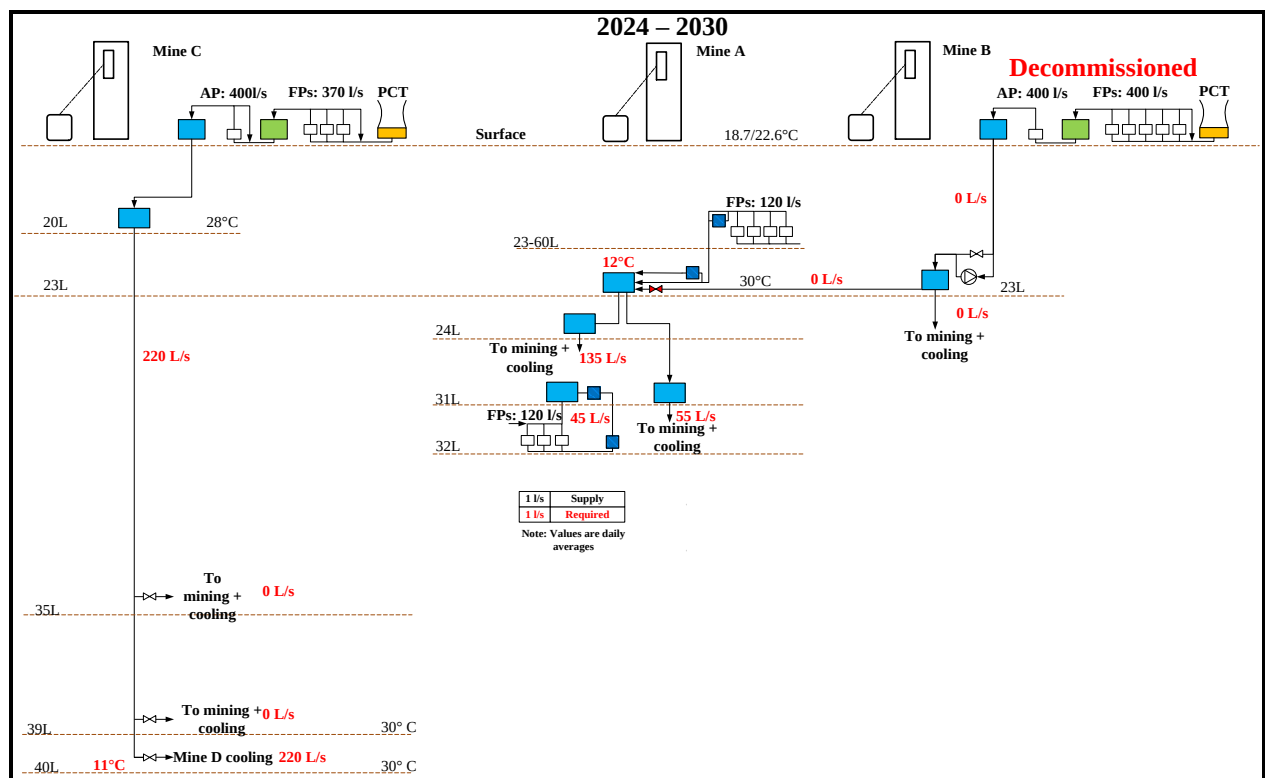
Case study 2 uses the same model developed in case study 1. However, case study 2 considers the system after the decommissioning and closure of Mine B during the 2024 – 2030 period.

The future system configuration and demands are shown in Figure 57. Mine A has a chilled water flow demand of 190 L/s with a 70 L/s chilled water deficit if all cooling is to be used at Mine A. Additionally two KPIs were provided by the mine. One is the chilled water temperature at Mine D on 40L after the dissipator valve, and the other one is Mine A's chilled dam temperature on 23L. The required temperatures for the KPIs were 11 °C and 12 °C, respectively. Therefore, a solution is required to supplement the deficit in cooling due to the decommissioning of Mine B and to ensure the KPIs are met.

For clarity in the document, the number (1) is used to represent the static, non-integrated and design results with (2) representing the dynamic, integrated, and empirical results. The number (3) indicates the novel dynamic, integrated and empirical design method.

The objective of the case study is to determine the required infrastructure to close Mine B:

1. Using the verified novel method
2. Showing clear improvement over the current method
3. Without affecting current and future operations or production
4. Ensuring underground temperature requirements are met



90

4.3.2 Static, non-integrated, and design approach (Result 1)²²

The current static, non-integrated and design approach used by the industry is based on isolated calculations in steady (average) conditions using design specifications obtained from suppliers [24], [140], [141], [142], [143], [144]. The typical equations used are those for heat transfer in pipes, heat gain due to pressure dissipation, and cooling duty.

The method follows four major steps which are described in Figure 58 and are based on industry-standard practices and general thermohydraulic equations obtained from literature [140]:

1. **Demand:** The cooling demands are calculated using average underground temperatures, flows and required chilled water temperatures. The results are given in cooling power (Watts).
2. **Losses:** Losses include heat gain due to heat transfer into pipes and dams and pressure dissipation. The results are also given in Watts.
3. **Supply:** The supply is obtained from the design specifications of the cooling equipment available. The results are given in Watts.
4. **Redundancy:** The redundancy is the difference between the supply and total demand including all losses. The results are given in Watts. Once all four steps are completed a final temperature is calculated for the KPIs.

The steps were followed for the case study using static and average demands as well as supply and losses. It is important to note that real-world conditions are dynamic with fluctuating ambient and underground conditions as well as demands. The chillers were specified at design values and assumed non-integrated, i.e. the performance of each piece of equipment operates independently of the other. The results are shown in Table 9 with the KPIs shown in Figure 59 and Figure 60. The equations used in the method are all based on basic thermodynamic equations found in thermodynamic textbooks [140], [141], [143].

²² The result in brackets is used as an indicator for comparison between the current and new method.

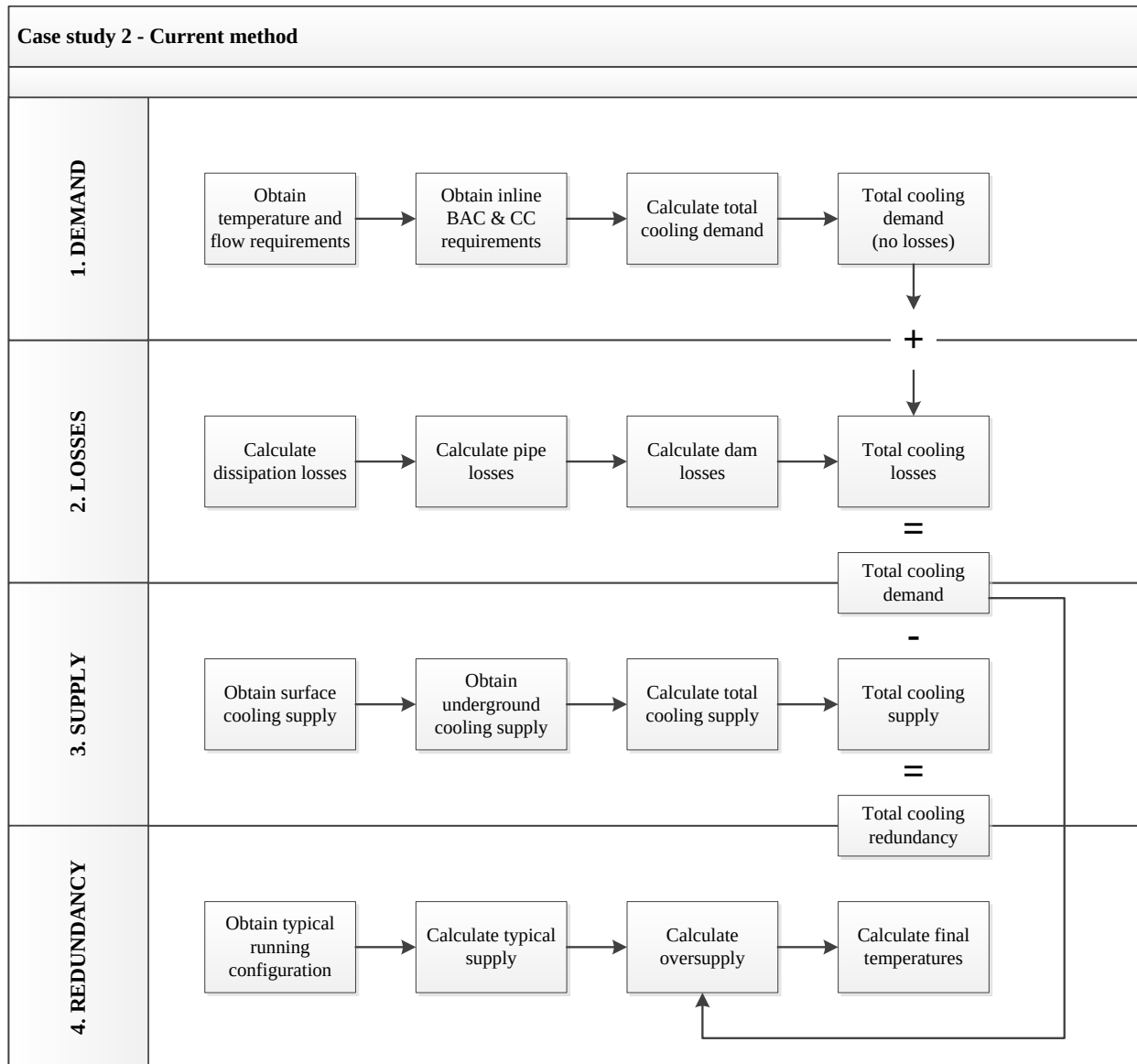


Figure 58. Static, non-integrated and design method flow diagram for determining refrigeration supply, demand, and redundancy (current method)

Table 9 clearly shows favourable results. The current method indicates that with the current infrastructure there is a 12 MW (No. 43) redundancy in cooling. Running the refrigeration machines in their typical configuration results in a cooling oversupply of 5.7 MW (No. 42). The results show that an underground column from Mine C to Mine A is sufficient to supply the mining complex and meet the KPIs.

The oversupply of 5.7 MW (No. 42) results in KPI temperatures below the requirements. KPI 1 (Mine C 40L chilled water temperature) is 1.7 °C (No. 45) below the required 11 °C and KPI 2 (Mine A 23L chilled dam temperature) is 0.3 °C (No. 46) below the requirement. The KPIs are plotted in Figure 59 and Figure 60.

Table 9. Static, non-integrated and design method calculation and results

No.	Step	Description	Unit	Value
System demand				
1	1	Mine C 40L temperature requirement	(°C)	11.0
2		Mine C 40L flow requirement	(L/s)	220.0
6		Mine C demand without losses	(kW)	15 708.0
3		Mine A 23L dam temperature requirement	(°C)	12.0
4		Mine A 23L flow requirement	(L/s)	190.0
7		23-60L inline BACs	(kW)	1 750.0
5		Mine A demand without losses	(kW)	14 518.0
8	Total cooling demand (no losses)		(kW)	30 226.0
System losses				
8	2	Mine C dissipation heat (Surface-20L)	(kW)	3 166.8
10		Mine C dissipation heat (20L-40L)	(kW)	2 402.4
14		Mine C pipe heat (Surface-20L)	(kW)	730.8
16		Mine C pipe heat (20L-40L)	(kW)	1 570.8
20		Mine C dam heat	(kW)	1 339.8
12		Mine A dissipation heat	(kW)	119.7
18		Mine A pipe heat	(kW)	239.4
22		Mine A dam heat	(kW)	478.8
24	Total cooling losses		(kW)	10 048.5
26	Total cooling demand		(kW)	40 274.5
System available supply				
27	3	Mine C PCT cooling	(kW)	6 510.0
28		Mine C FP1 cooling	(kW)	8 500.0
29		Mine C FP2 cooling	(kW)	8 500.0
30		Mine C FP3 cooling	(kW)	8 500.0
31		Mine C AP1 cooling	(kW)	6 000.0
32		Mine C AP2 cooling	(kW)	6 000.0
33		Mine A FP1 cooling	(kW)	3 500.0
34		Mine A FP2 cooling	(kW)	3 500.0
35		Mine A FP3 cooling	(kW)	3 500.0
36		Mine A FP4 cooling	(kW)	3 500.0
37	Total supply		(kW)	58 010.0
System redundancy				
38	4	Total cooling redundancy	(kW)	17 735.5
39		Typical supply Mine C	(kW)	35 510.0
40		Typical supply Mine A	(kW)	10 500.0
41		Total supply	(kW)	46 010.0
42		Oversupply	(kW)	5 735.5
43		Redundancy	(kW)	12 000.0
Final temperatures				
45	5	Mine C 40L calculated temperature	(°C)	9.3
46		Mine A 23L calculated dam temperature	(°C)	11.7

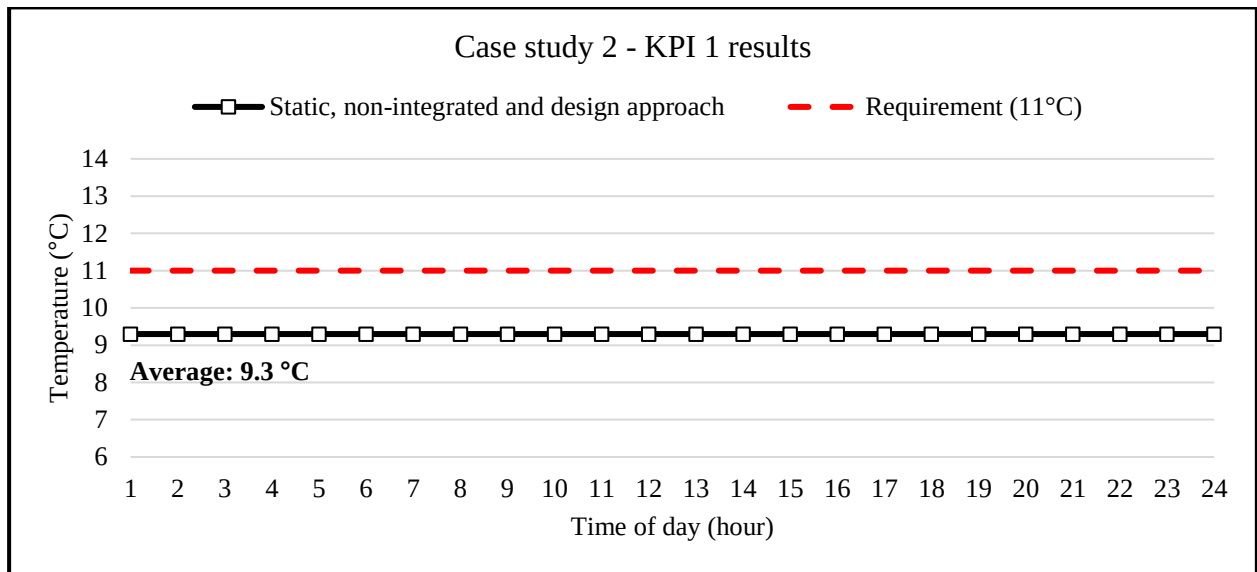


Figure 59. Static, non-integrated and design method: Mine C 40L temperature results

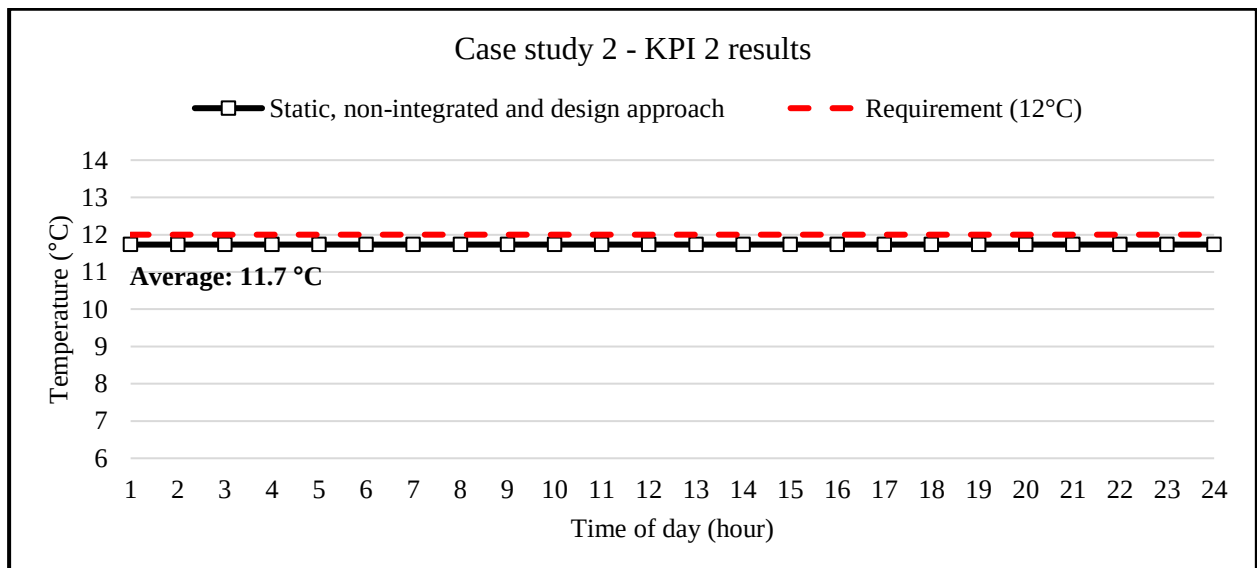


Figure 60. Static, non-integrated and design method: Mine A 23L dam temperature results

4.3.3 Dynamic, integrated, and empirical approach (Result 2)²³

Steps 2 & 3: Digital twin with simulation & dynamic boundaries and verification (Section 3.4 & 3.5)

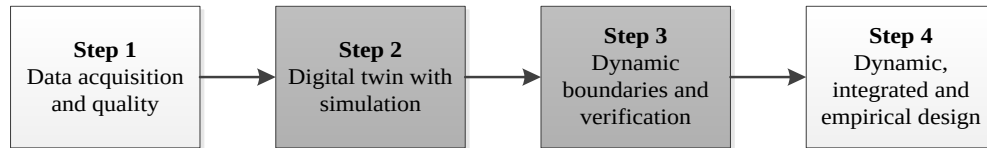


Figure 61. Steps 2 & 3 of new four-step method in case study 2

The current approach is simple and quick. However, it is not dynamic, integrated or based on actual operating conditions (empirical) which reduces accuracy.

The dynamic, integrated, and empirical approach discussed in Chapter 3 is applied to the solution provided in section 4.2.3 of a simple underground column from Mine C to Mine A.

The first difference between the current and proposed methods is the use of dynamic boundaries. One such boundary for this case study is the chilled water demand for Mine A which is shown in Figure 62. Using dynamic simulation increases accuracy and shows peaks and troughs that have an impact on underground conditions.

²³ The result in brackets is used as an indicator for comparison between the current and new method.

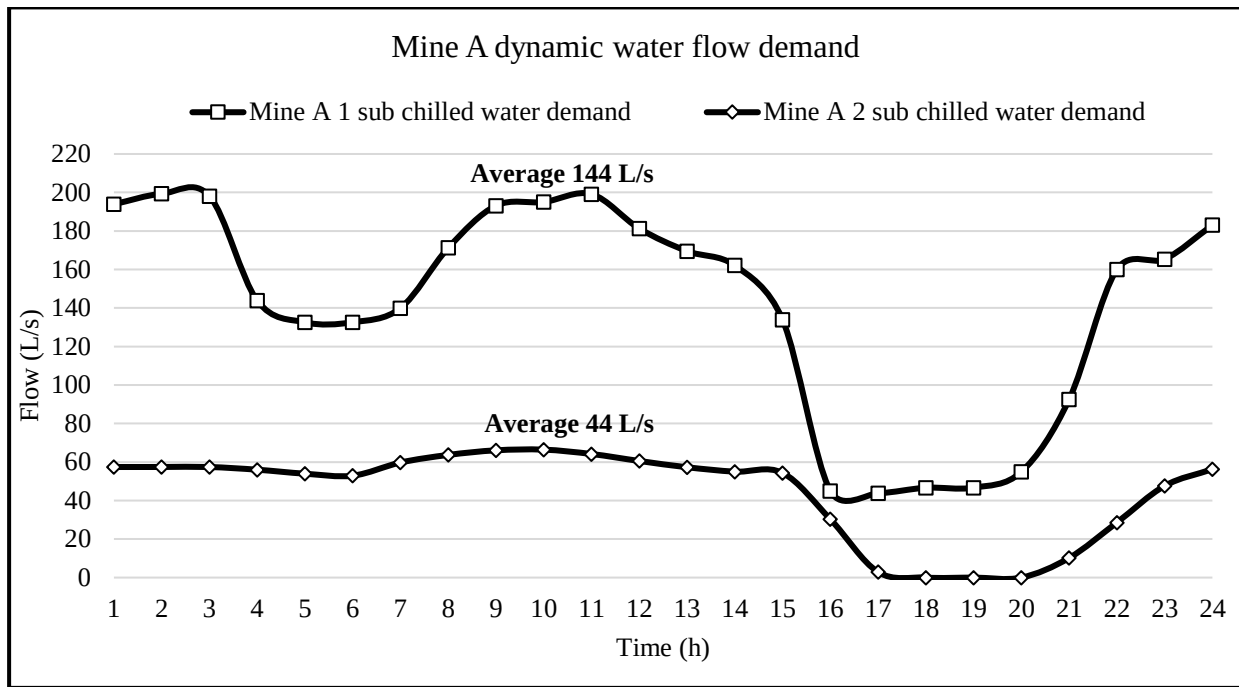


Figure 62. Dynamic flow requirements added to simulation

The dynamic boundaries are added to the integrated digital twin with simulation WCS of the four-shaft complex that includes all required equipment such as pumps, pipes, dams, cooling towers, fridge plants, BACs, and drills. The final integrated model is shown in Figure 63.

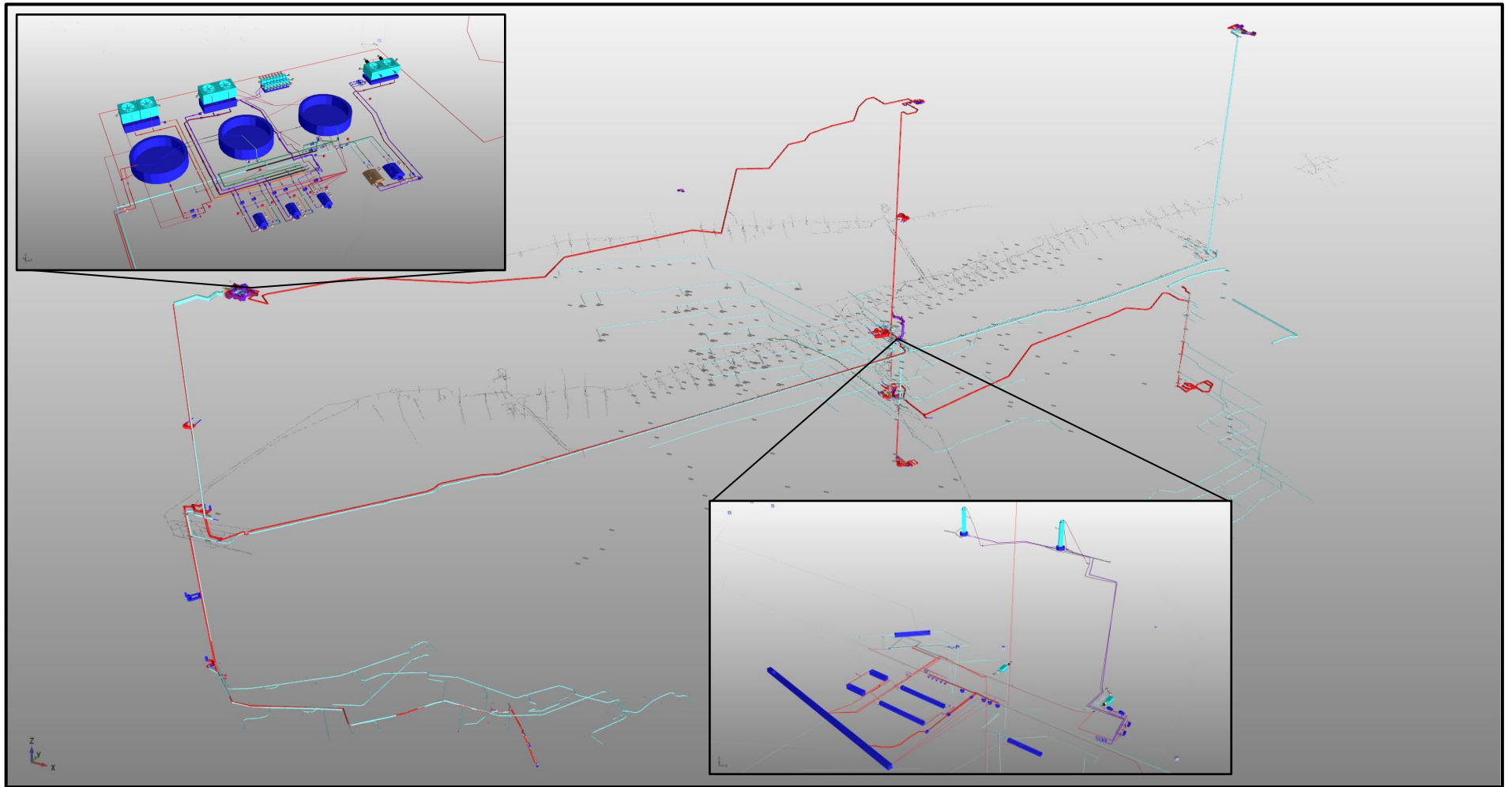


Figure 63. Fully integrated and dynamic simulation of Mine A, B, C & D

The model is calibrated using actual data obtained from measurements taken underground and SCADA systems. As an example, a fridge plant has 20 sensors measuring several operating parameters. The data for the entire complex was extracted in hourly intervals for an entire year.

After the data was retrieved, it was then sorted, filtered, and tested for quality using the techniques described in section 3.3.5. The limits and expected performance numbers were obtained from the collection of mine documentation which gave a broad overview of the operating limits which can be expected. An example of the operating parameters used for Mine A's underground FPs is shown in Figure 64 which utilised the filtering and data quality checking techniques discussed in Chapter 2.

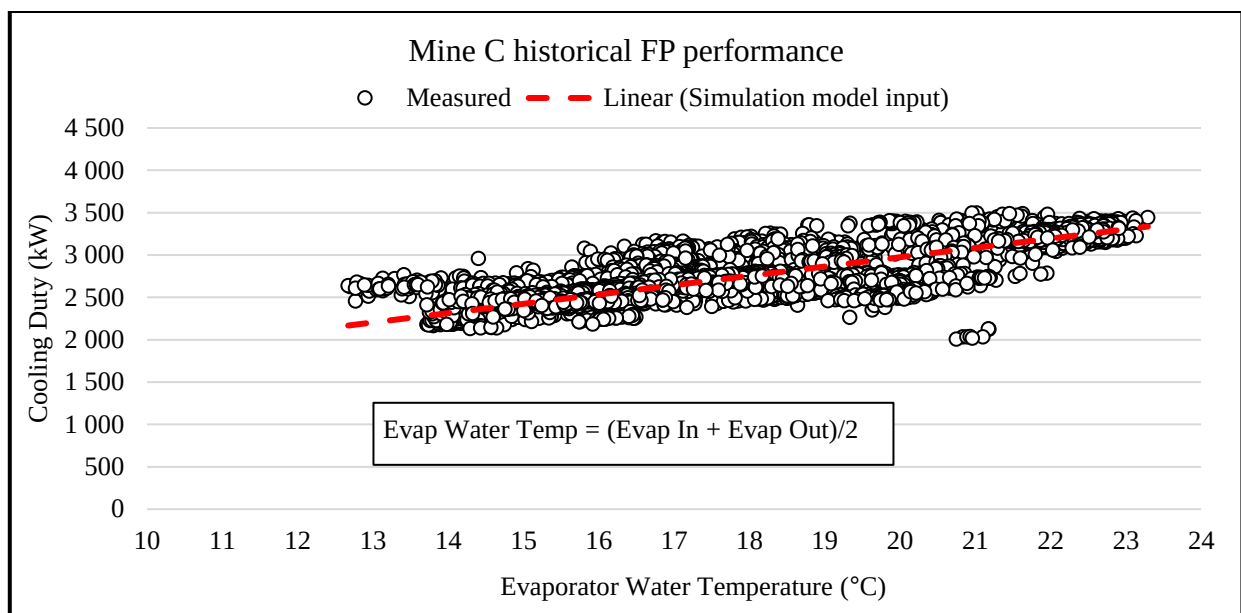


Figure 64. Empirical FP performance data used for model calibration

Once all components have been specified according to the techniques described in Chapter 2, the model can be verified. In this case, several verification KPIs were considered and compared. The actual versus simulated results of the model for Mine C can be seen in Table 10. Note that Mine A's KPIs are not included to reduce the size of the table. As seen from the results, 95% accuracy (less than 5% error) was achieved.

Table 10. Verified simulation results comparing all KPIs

No.	Area	Equipment	Measurement	Unit	Actual	Simulation	% Error
1	Surface	Hot dam	Inlet/outlet flow	(L/s)	145	142	2%
2			Level	(%)	70	67	4%
3			Temperature	(°C)	27	27.3	1%
4		FP evaporator	Inlet temp	(°C)	18	17.6	2%
5			Inlet flow	(L/s)	260	258	1%
6			Outlet temp	(°C)	5.5	5.3	4%
7			Outlet flow	(L/s)	260	258	1%
8			Cooling duty	(kW)	17 000	16 500	3%
9			Compressor power	(kW)	3 400	3 355	1%
10		Intermediate dam	Inlet/outlet flow	(L/s)	260	258	1%
11			Level	(%)	65	68	5%
12			Temperature	(°C)	5.6	5.4	4%
13		AP evaporator	Inlet temp	(°C)	5.6	5.4	4%
14			Inlet flow	(L/s)	260	255	2%
15			Outlet temp	(°C)	2	2.1	5%
16			Outlet flow	(L/s)	260	255	2%
17			Cooling duty	(kW)	8 000	7 950	1%
18			Compressor power	(kW)	2 000	1 967	2%
19		Chilled dam	Inlet/outlet flow	(L/s)	145	143	1%
20			Level	(%)	66	67	2%
21			Temperature	(°C)	3.1	3.2	5%
22	Underground	20L chilled dam	Inlet/outlet flow	(L/s)	145	143	1%
23			Level	(%)	66	64	3%
24			Temperature	(°C)	6.2	5.9	5%
27		39L	Flow	(L/s)	80	79	1%
28			Temperature	(°C)	10.2	10.1	1%
29			Pressure	(kPa)	1 750	1 730	1%
30		40L	Flow	(L/s)	65	64	2%
31			Temperature	(°C)	10.5	10.3	2%
32			Pressure	(kPa)	1 650	1 630	1%

The final verification step is to check for dynamic accuracy and to do real-world tests. The temperature of Mine C surface chilled dam was compared with the simulation model over a 24-hour period. The results are shown in Figure 65 with an overall error of 2% and a clear common profile which indicates the system is responding as required.

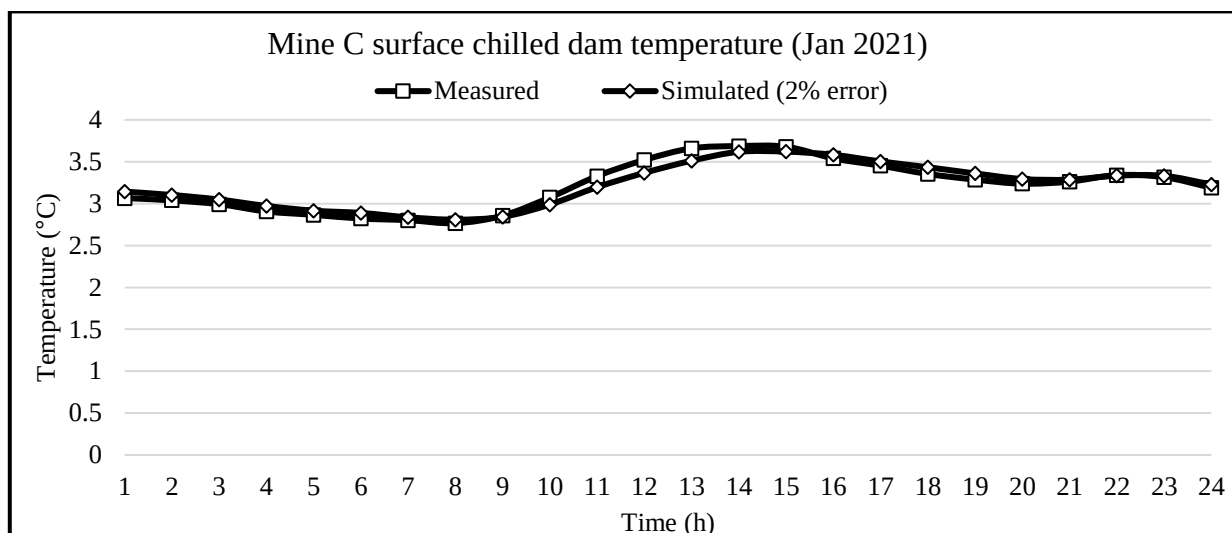


Figure 65. Verified dynamic simulation result for Mine C surface chilled dam temperature

A tool was developed to assist with verification and tracking down problem areas, as simple errors that are easily fixed were discovered during the study. The process is shown in Appendix D.

Using the troubleshooting process and verification process a 95% accurate steady-state simulation model is possible.

A real-world test was also conducted on all fridge plants. For the sake of the study, only the results of Mine C surface FP1 are shown in Figure 66. The test results are plotted on a 50% and 90% simulation model prediction of the FPs' performance. The test clearly shows a common profile between the simulation model and actual performance. The 50% model is the average performance of the FP whereas the 90% model is the 10th percentile model. Therefore, using the 50% model the simulation model will over- or underperform 50% of the time, whereas the 90% model will underperform 90% of the time (in other words the real-world FP will provide better results 90% of the time as compared with the simulation model).

The test showed that at lower evaporator temperatures the data tends to curve below the 50% and 90% model regression line. This is due to instrumentation accuracy that reduces at lower temperatures which skews the data giving the shape seen in Figure 65. The high-water flow rates mean that a small temperature inaccuracy has a large effect. Once adjusted for errors the test data follows the simulation model regression with a 95% confidence level.

The results were adjusted through linear interpolation. It was assumed that at lower flows and temperatures the measuring equipment went "out of range" of the OEM specification. Therefore, the OEM cannot guarantee sensor accuracy outside of the measuring range. Instead of removing the data which fell below the OEM measuring range the data was adjusted to follow the predicted linear line.

The adjustment took the form of:

$$Adjusted = actual_x \times \left(\frac{predicted_x}{\sum_x^{x+5} actual_x} \right)$$

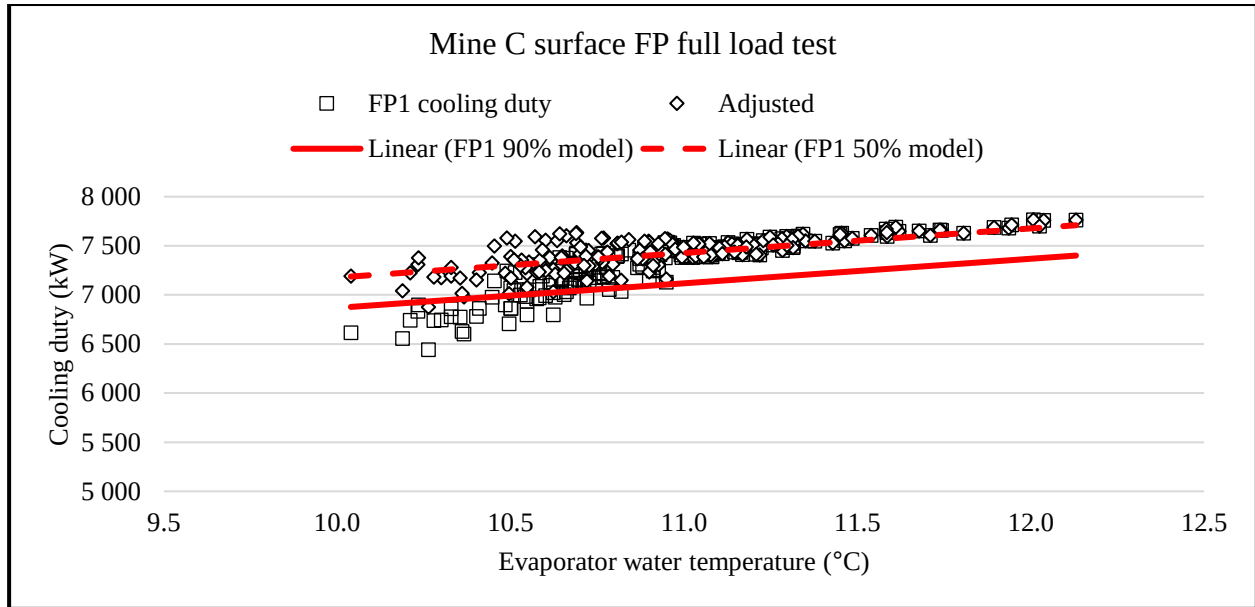


Figure 66. Mine C full load test validating accuracy of the model

The dynamic, integrated, and empirical simulation model was then used to simulate the solution obtained from the static, non-integrated and design method provided in section 4.2.3. Due to the accuracy of the digital twin with simulation, the results of the simulation are assumed to be an accurate representation of the actual system.

The results of the two KPIs of the static, non-integrated and design methods are shown in Figure 67.

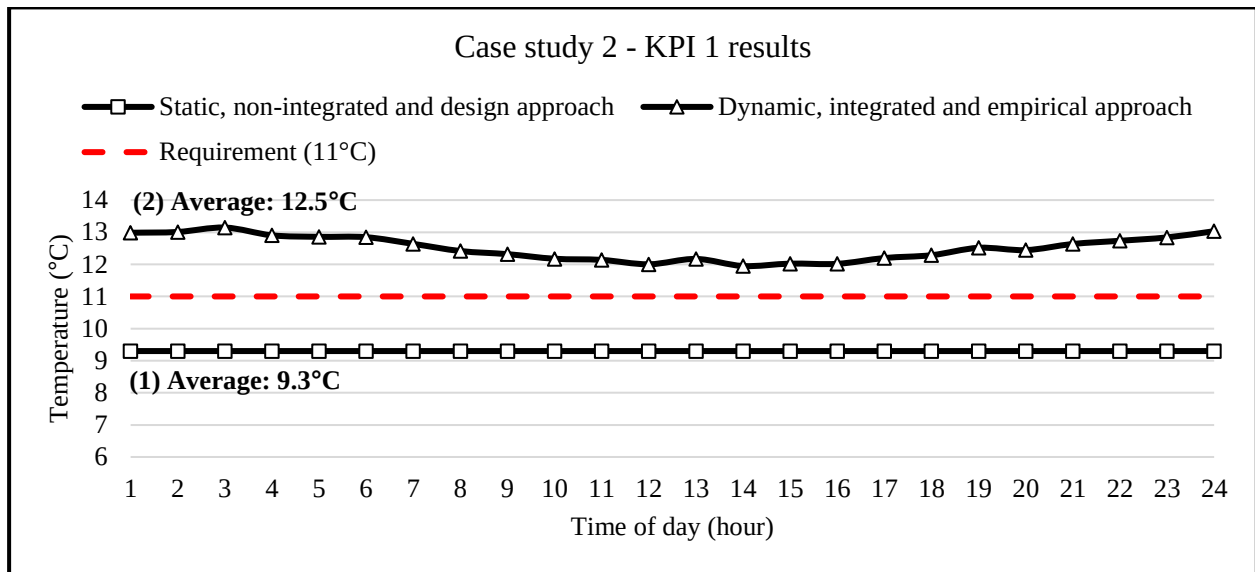


Figure 67. KPI 1 results (1) and (2)

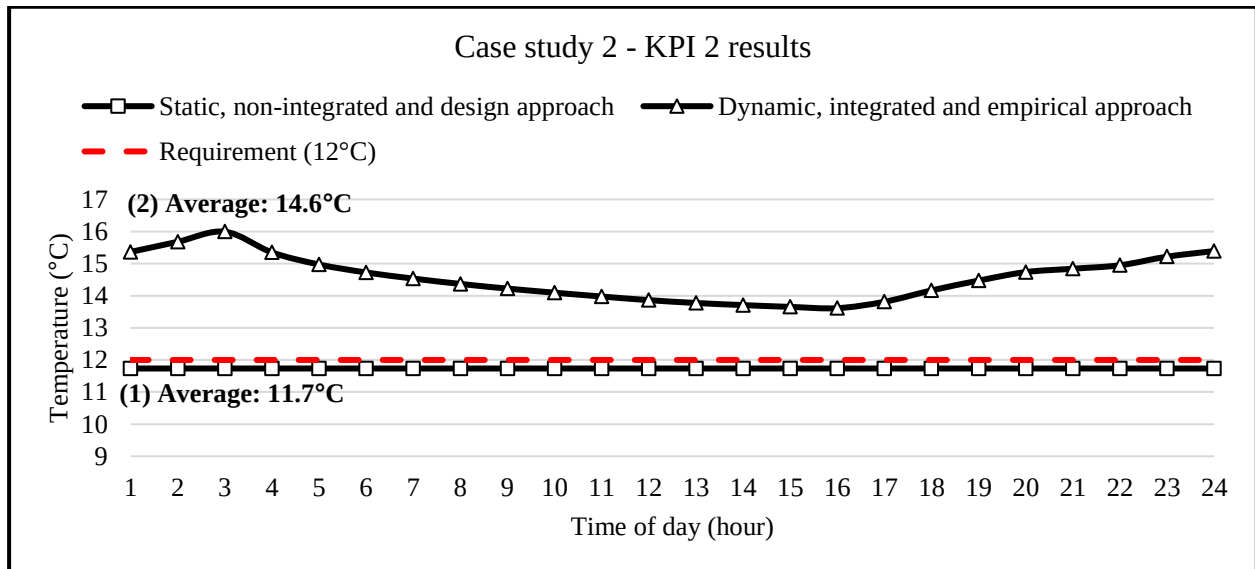


Figure 68. KPI 2 results (1) and (2)

Figure 67 and Figure 68 show a clear discrepancy between the results obtained from the static, non-integrated and design approach. The dynamic, integrated, and empirical approach reveals that the solution obtained using the current method (1) would lead to a system that does not meet the requirements and an error of 30% in the results. The new approach shows dynamic temperatures reaching 13.2 °C and 16 °C for KPI 1 and 2 respectively with average temperatures of 1.5 °C and 2.6 °C above the requirements. This is well above the requirements and therefore will result in an under supply of cooling.

4.3.4 Dynamic, integrated, and empirical design (Result 3)²⁴

Step 4: Dynamic, integrated, and empirical design (Section 3.6)

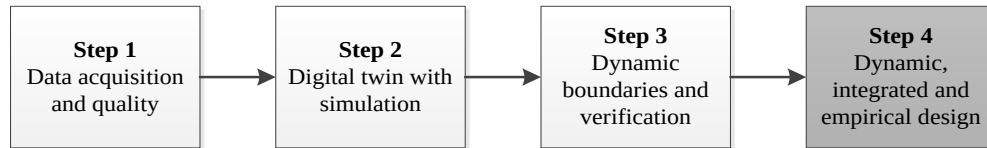


Figure 69. Step 4 of new four-step method in case study 2

The results obtained from simulating the current solution approach using the dynamic, integrated, and empirical approach showed a need to increase available cooling to reduce the two KPI temperatures to meet requirements.

The first step was to investigate several solutions to increase available cooling. Several solutions were considered with the top five shown in Table 11. Note that the selection process is not part of the scope of this study and therefore the process is not explained in detail. Solution 4 was deemed the most favourable as it requires the least amount of capital and time to implement. Solution 4 is like the solution obtained by the current method. However, the simulation allows iteration and improvement of the chosen solution.

Table 11. Top solutions for Mine B closure

Solution no.	Description	Comment
1	Install surface refrigeration at Mine A	Not enough space for new column in shaft. Expensive to install
2	Keep Mine B open under care and maintenance	OPEX for C&M is costly
3	Additional underground refrigeration at Mine A	Requires significant underground development
4	Utilise and upgrade Mine C surface refrigeration	Requires underground and surface column
5	Utilise decommissioned Mine E refrigeration	Mine E chillers in a very poor condition

With the solution selected it was simulated using PTB to obtain results. The solution was simulated and iterated hundreds of times as discussed in Section 3.6.5. The major iterations which led to a final solution are shown in Table 12. As can be seen in the table the initial solution (current method used in industry) does not yield favourable results. Therefore, it was improved and iterated through five steps. The philosophy followed for changes included considering all the factors discussed in Chapter 2 with a major

²⁴ The result in brackets is used as an indicator for comparison between the current and new method.

factor being the time to implement and cost. A solution that is simple and easy to achieve was simulated first to quantify the impact. The major changes include:

1. New underground column from Mine C to Mine A on 23L
2. Starting an additional FP at Mine A on 23-60L
3. Insulating the column from Mine C to Mine A on 23L
4. Integrating Mine A 32L FPs into the chilled water system (currently Mine A 32L FPs are only used to supply BACs with chilled water)
5. Moving two machines from Mine B to Mine C on surface to assist with redundancy and cooling

Table 12. Summary of simulation iterations

Iter.	Mine C FP supply	Mine A FP supply	Configuration	Mine C 40L (11°C)	Mine A 23L chilled dam (12°C)
	L/s	L/s		°C	°C
1	350	60	New Mine C to Mine A 23L column	12.8	13.4
2	320	90	Iter. 1 + 3x Mine A 23-60L FP	11.6	13.2
3	320	90	Iter. 1 + 2 + insulated Mine C – Mine A column	11.6	12.3
4	315	95	Iter. 1 + 2 + 3 + integrate Mine A 32L FPs	11.1	12.6
5	315	95	Iter. 1 + 2 + 3 + 4 + move 2x Mine B FPs to Mine C	11.0	11.9

The final iteration included all five improvements and resulted in a favourable outcome meeting all the KPI requirements and flows. The final solution results are schematically shown in Figure 70. The results are daily averages with the changes and new infrastructure shown using dashed lines. The requirements are shown in red, simulated values in blue and wastage shown in yellow. Wastage is added to the simulation and planning as an additional safety factor.

The dynamic results are shown in Figure 71 and Figure 72. Using the simulation model iteration was possible until the optimal design was reached. This is shown in the results where iteration was stopped once all requirements were reached. It is important to note that the simulation model included several safety factors requested by the mine, which included:

1. All service flows are to be increased by 10% above the required flow.
2. All FPs are to operate at a 90% confidence level (ensuring the results shown in the simulation will be met 90% of the time).

The safety factors “decrease” the cooling performance of the FPs and APs and increase the required cooling. Therefore, the results obtained from the simulation model provide increased confidence that the actual system can meet future system requirements.

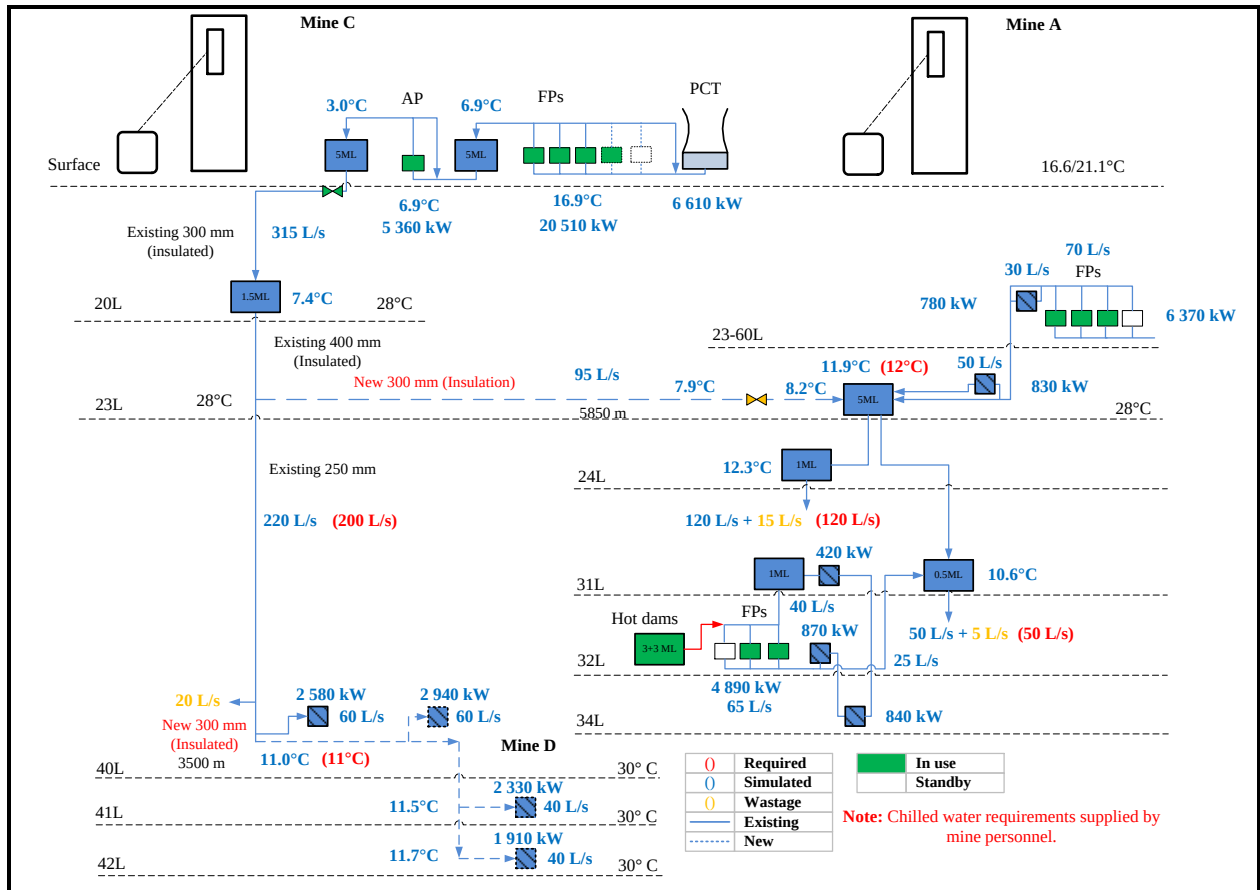


Figure 70. Final solution results (case study 2)

The dynamic KPI 1 and 2 results, shown in Figure 71 and Figure 72, indicate favourable temperatures for both KPIs. The dynamic nature of the simulation shows that for certain hours of the day the temperature is slightly above the requirement with the average being below or the same as the requirement. This insight is not possible with static models and provides a more accurate answer that can be monitored on a 24-hour basis.

For example, low temperatures are important between 6am and 12pm on weekdays (drilling shift) when most human activity takes place underground. Therefore, the temperature during that time has the largest effect on the perceived temperature of the miner. In this case, both KPIs are at their lowest temperatures during the drilling shift showing dynamic optimisation.

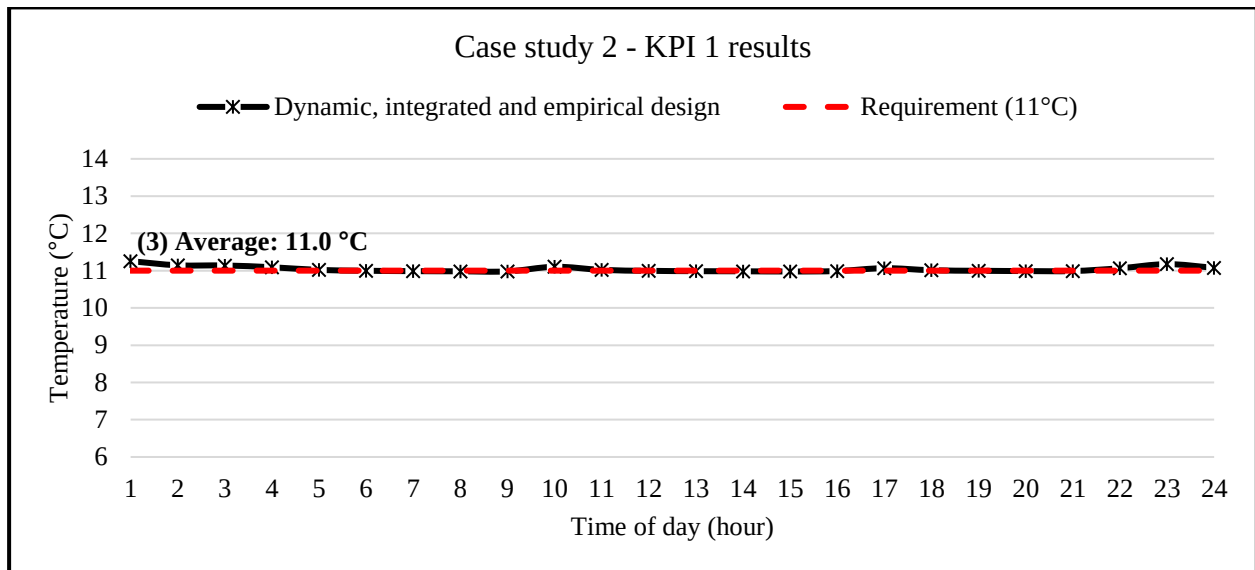


Figure 71. KPI 1 results for the dynamic, integrated, and empirical design (3)

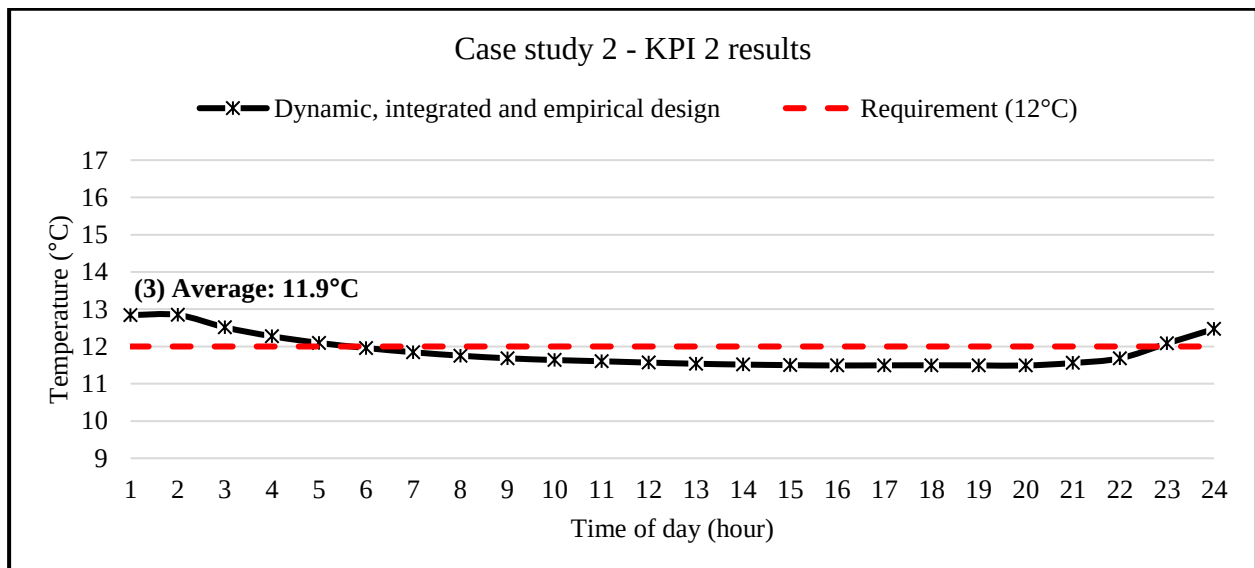


Figure 72. KPI 1 results for the dynamic, integrated, and empirical design (3)

The results show that the proposed solution meets the requirements. The proposed solution has several infrastructure changes that need to be considered. Therefore, the final step is to investigate if the solution remains economical. The total costs to implement the infrastructure changes are shown in Table 13. The table shows the major infrastructure costs which amount to roughly R97 million.

Table 13. Cost to implement the iterated solution on case study 2

No.	Description	Cost
1	Mine C surface FP critical spares	R14 640 000
2	Moving 2x Mine B FPs to Mine C	R45 580 000
3	Mine C – Mine A underground column	R26 820 000
4	Mine A – Mine C overland column	R9 450 000
Total		R96 490 000

With the project costs estimated, an LOM benefit can be conducted. The costs to close Mine B are R97 million; however, the costs to keep Mine B operational as a care and maintenance shaft are shown in Table 14. The cost saving therefore for closing Mine B is roughly R73 million per annum.

Assuming an LOM for Mine A of 16 years²⁵ (2024 – 2030) the total cost savings at an annual inflation rate of 5% are R2.4 billion.

Table 14. Cost savings per year from Mine B closure

No.	Description	Cost (R/year)
1	Payroll 1	R18 600 000
2	Payroll 2	R10 200 000
3	Contractors	R7 700 000
4	Water	R320 000
5	Stores	R24 600 000
6	Electrical energy	R11 200 000
Yearly cost saving (2020 tariffs)		R72 620 000
LOM net benefit (16 years at 5% inflation)		R2 413 100 000

The total cost savings and cost to close Mine B show that closing Mine B does not pose an economic risk. The novel approach used to develop a solution shows that closing Mine B with the required infrastructure does not pose a safety or production risk as sufficient mine cooling will be available into the future.

4.3.5 Validation

The final results for the three result cases are shown in Figure 73 for KPI 1 and Figure 74 for KPI 2. The results for KPI 1 in Figure 73 show a clear underestimation of the temperature (9.3 °C) for the static, non-

²⁵ The LOM of Mine A is only calculated to 2033; however, Mine A is likely to be open far beyond 2033 increasing the total savings.

integrated and design method (1) in the current configuration. The same configuration was modelled using the dynamic, integrated, and empirical method (2) which showed an actual average simulated temperature for KPI 1 of 12.5 °C with peak temperatures above 13 °C with a requirement of 11 °C.

Therefore, the current method severely underestimates the actual underground temperatures and therefore allows for a negative safety margin, with a total error of 3.2 °C or 34%. The major reason is the lack of integration and the assumption that the equipment operates at design conditions, whereas most of mine equipment operates at off-design conditions. Off-design operation is because of maintenance neglect and changes to the system which it was not designed for. The simulation method is integrated and takes the current off-design operating conditions into account and any degradation of equipment performance due to calibration by empirical data.

The system configuration was then adapted and designed using the dynamic, integrated, and empirical design approach which led to a system that meets the required temperature of 11 °C and includes redundancy with a safety margin of 10% on flow requirements and utilising a 95% confident simulation model.

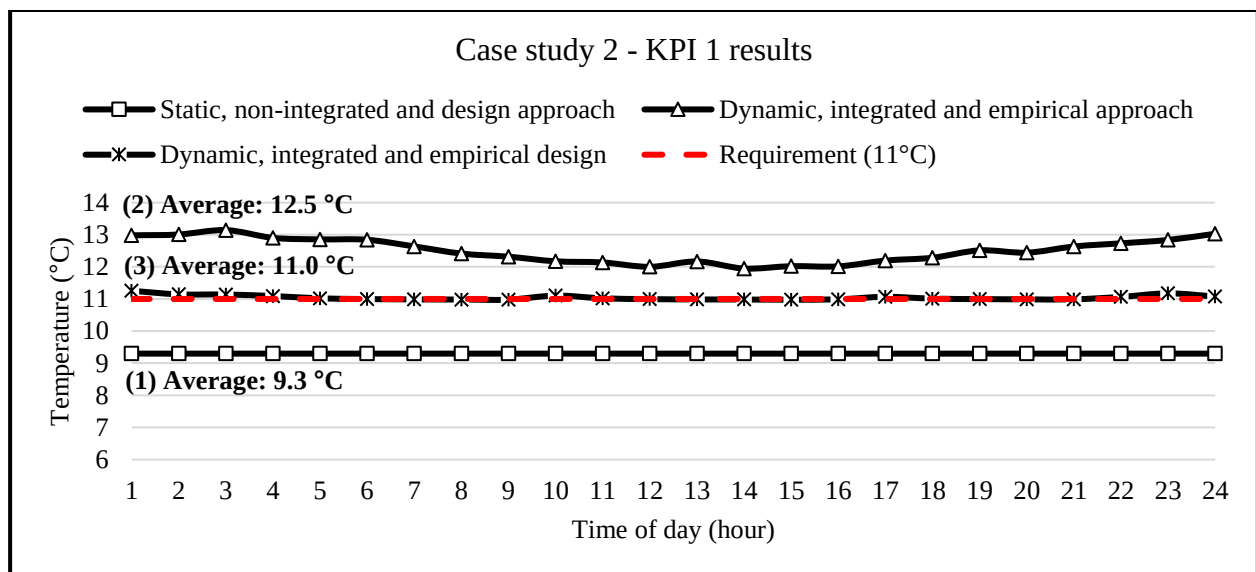


Figure 73. KPI 1 results (1), (2) and (3)

The same results apply for KPI 2 where the static, non-integrated and design approach underestimates the actual underground temperatures by 2.9 °C with an error of 25%. The current configuration results using the dynamic, integrated, and empirical method show an average temperature of 14.6 °C with a requirement of 12 °C and peaks of above 16 °C.

Therefore, the current system and approach would lead to an under supply of chilled water and increased underground temperatures above the required limit. The dynamic, integrated, and empirical design approach led to a system that meets the required 12 °C target at an average of 11.9 °C.

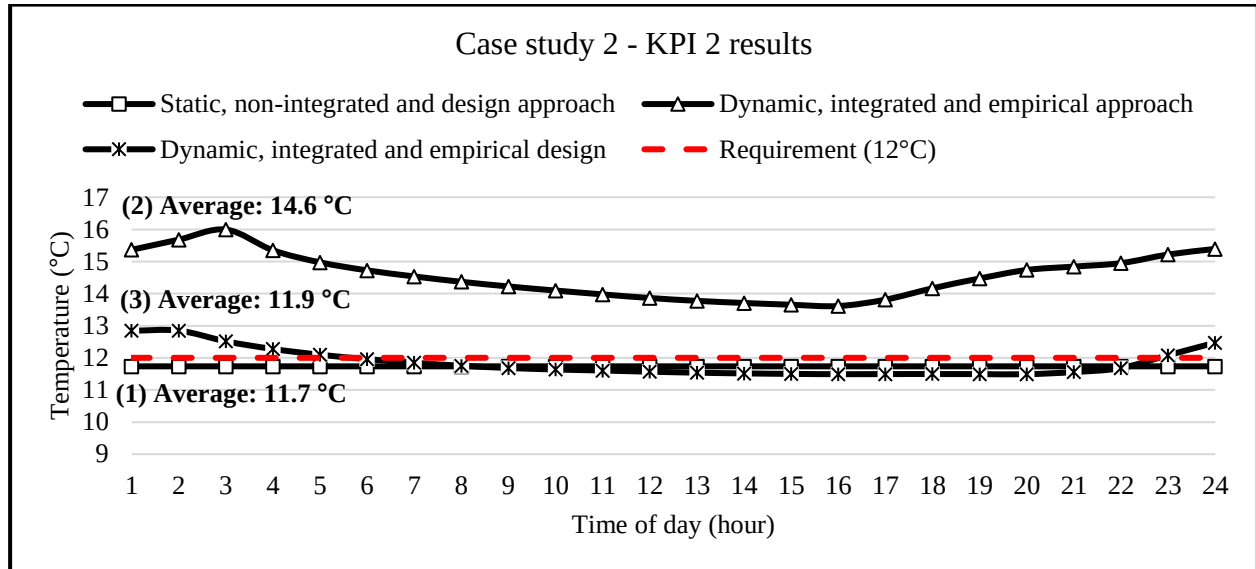


Figure 74. KPI 2 results (1), (2) and (3)

4.3.6 Conclusion

The novel dynamic, integrated, and empirical approach described in this case study was used to generate a solution that ensured a safe closure of Mine B in an integrated mining complex. The closure is estimated to result in significant LOM cost savings while ensuring safe working conditions underground.

The current method was compared with the novel method and showed a clear under-design of the system with a 30% error as compared with the novel method. The novel method met the objectives set for case study 2 being described as:

1. **Using the proposed novel method:** The proposed method was applied to the case study and showed successful results.
2. **Show clear improvement over the current method:** The current method was compared with the novel method with an improvement of 30% in accuracy.
3. **Without affecting current and future operations or production:** The method showed that current and future underground temperatures and operations will not be affected by the closure of Mine B if the required infrastructure is installed.

4. **Ensuring underground temperatures requirements are met:** The novel approach led to a solution which met the required underground temperatures using a 95% accurate simulation calibrated to 90% percentile confidence level and 10% wastage added.

4.4 Case study 3: Surface equipment breakdown

4.4.1 Background

Step 1: Data acquisition and quality (Section 3.3)

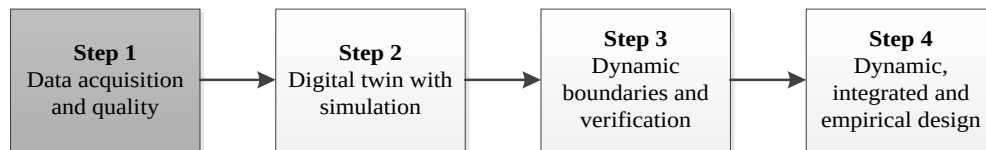


Figure 75. Step 1 of new four-step method in case study 3

Overview

Case study 3 considers the same system as described in case study 2. However, in this case study, the focus is on unplanned and unforeseen FP or AP breakdowns or failures. The failure of any refrigeration machine poses a major risk to the conditions underground, safety of the miner and production. Reduced refrigeration results in reduced cooling or under-supply resulting in increasing temperatures underground or complete lack of chilled water flow stopping underground operations. The most critical time to encounter a failure is in the drilling shift between 6am and 12pm (on weekdays) when most activity takes place underground.

The case study investigates a power failure of the FP and AP on surface at Mine C. There is a redundant FP available; however, both the APs are operational and therefore have no redundancy. The FPs and APs at Mine C were deemed most critical due to their significant effect on the system supplying most of the cooling for the system. The schematic of the failure scenario is shown in Figure 76.

For clarity in the document, the number (1) is used to represent the static, non-integrated and design results with (2) representing the novel dynamic, integrated and empirical design method.

Case Study Objective

The objective of this case study is to develop a mitigation plan to avoid production loss due to unsafe underground working conditions using the solution proposed in case study 2. The failure scenarios will include a short-, medium- and long-term failure for the surface FP and AP at Mine C. Short-, medium- and long-term failures are divided into 4 hours, 24 hours, and 72 hours, respectively. The hours were obtained from mine personnel relating to typical surface breakdowns and their subsequent repair times.

The current method will be used and compared with the novel method that makes use of a dynamic, integrated, and empirical simulation approach.

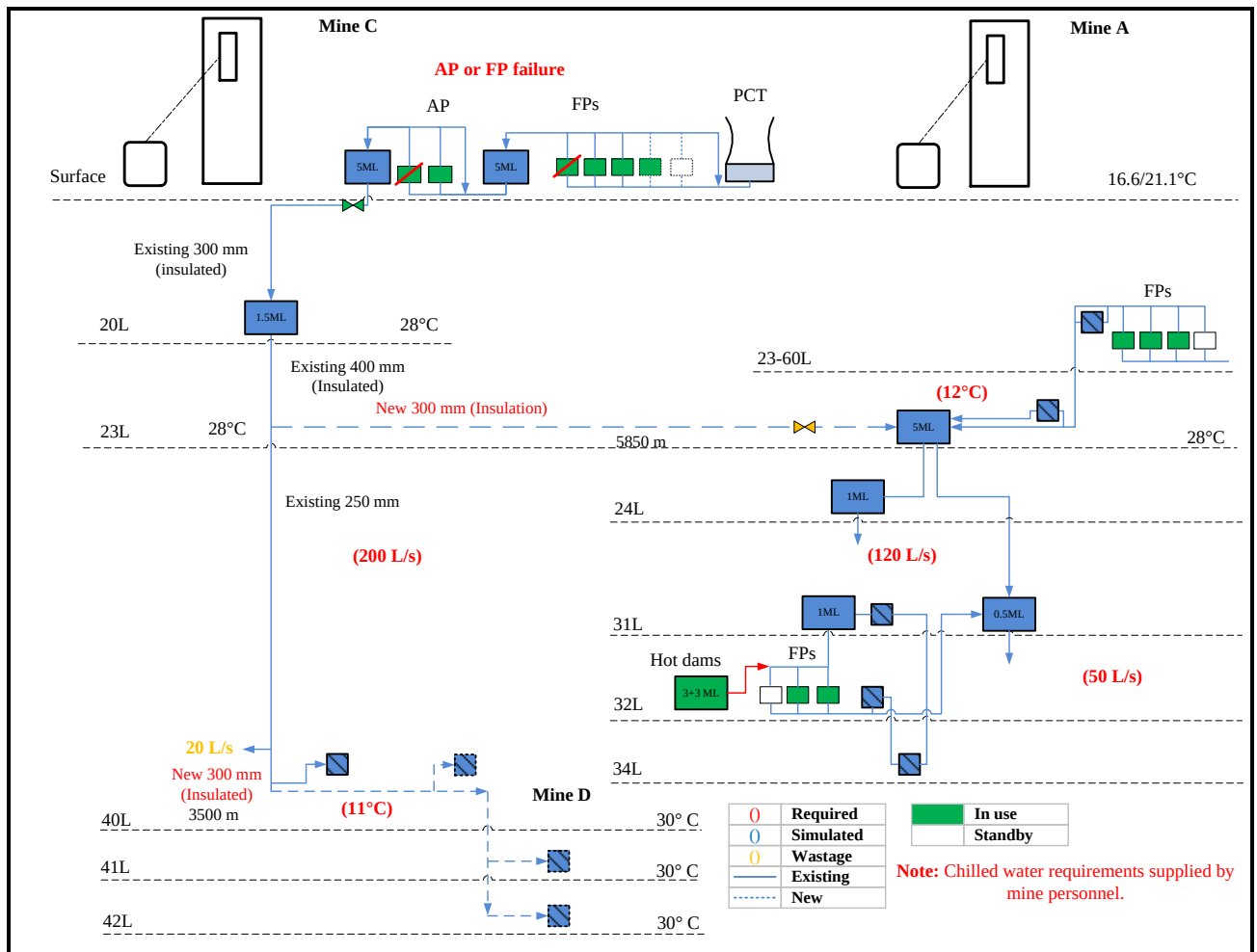


Figure 76. Schematic layout of AP or FP failure

The objective of the case study is to determine the effect of a refrigeration failure at Mine C:

1. Using the proposed novel method
2. Showing clear improvement over the current method
3. Without affecting current and future operations or production
4. Ensuring underground temperatures are kept below safe limits

4.4.2 Static, non-integrated, and design approach (Result 1)²⁶

As discussed earlier, the static, non-integrated and design method is the current approach used in the mining industry and is based on typical cooling duty equations obtained from [140], [141], [142], [143], [144]. The loss of cooling duty is replaced by available redundant machines without regard to the dynamic and integrated effects of the change between machines. The method, therefore, uses design and static values to determine the effect of a breakdown. The method cannot determine the real-time dynamic effect that a failure has on the overall system and therefore cannot provide insight on the effect of short-, medium- or long-term failures. Additionally, peak demands from underground workings cannot be factored in and only average values can be used. The method is described schematically in Figure 77.

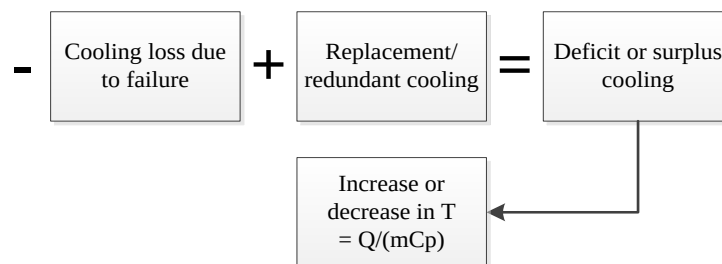


Figure 77. Simple method to determine underground temperatures after failure

The figure shows that the design loss in cooling is subtracted from the available redundant cooling. This provides a static, non-integrated, and designed cooling surplus or deficit value. The deficit or surplus is used to calculate the decrease or increase in temperature through the cooling duty calculation. The final answer is a static estimation of the chilled water temperature after failure of the respective refrigeration equipment. The calculation and method are quite simple and therefore severely lacking in accuracy and insight into the effect of a power failure. The results of the method applied on a surface FP and AP failure for Mine C are shown Table 15.

Table 15. Results of applying static, non-integrated and design method

No.	Failure	Cooling loss	Redundant cooling	Cooling deficit	Mine C FP supply	Mine C 40L (11 °C)		Mine A 23L (12 °C)	
		(kW)	(kW)	(kW)		Std. (°C)	SOA (°C)	Std. (°C)	SOA (°C)
1	Mine C FP1	8 500	5 000	3 500	315	11.0	12.8	11.9	12.7
2	Mine C AP1	6 000	5 000	1 000	315	11.0	11.5	11.9	12.1

²⁶ The result in brackets is used as an indicator for comparison between the current and new method.

The first scenario considers the failure of FP1 that is located on surface. The design duty of the FP1 is 8.5 MW with a 5 MW redundant machine being available on the same circuit. Therefore, a deficit of 3.5 MW is calculated due to the failure of FP1. This increases the surface chilled water temperature at Mine C which in turn increases both Mine C 40L chilled water (KPI 1) and Mine A 23L chilled dam (KPI 2) temperatures. KPI 1 and KPI 2's temperature increases by 1.8 °C and 0.8 °C, respectively. The failure has a larger effect on KPI 1 due to increased water flow to KPI 1 and KPI 2 temperature is a combination of Mine A and Mine C chilled water.

The same was done for a failure of AP1 which results in a cooling loss of 6 MW with the redundant FP supplying 5 MW. Therefore, a theoretical deficit of 1 MW exists. The cooling loss results in increased temperatures of 0.8 °C for KPI 1 and KPI 2. Similar to the previous study, the results are shown in Figure 78 and Figure 79 and denoted as the static, non-integrated and design method by the number (1).

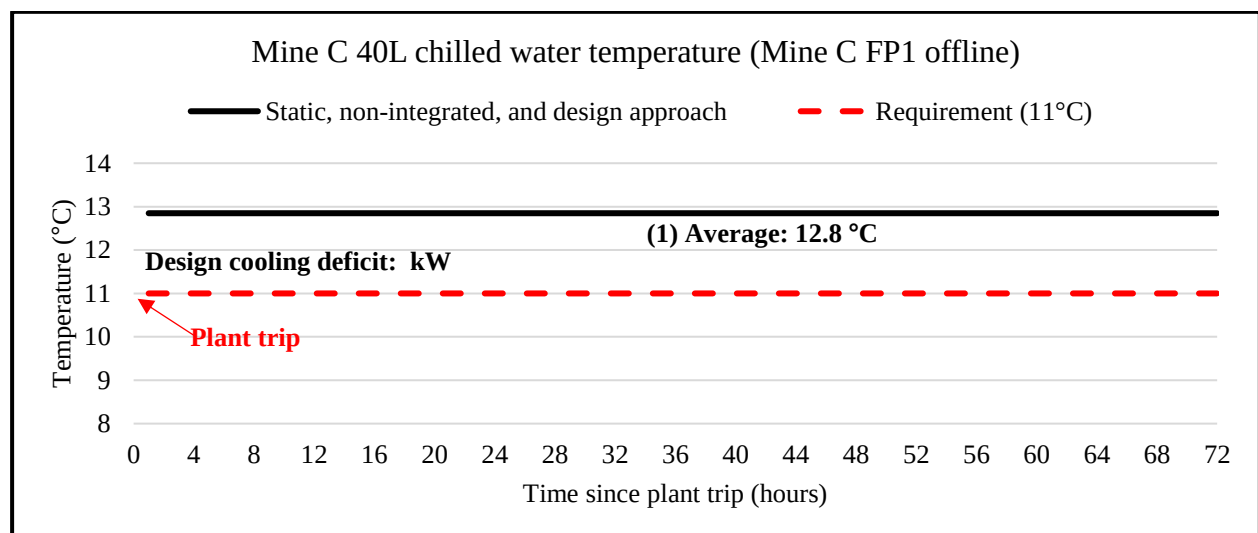


Figure 78. Static, non-integrated, and design approach FP failure results for KPI 1

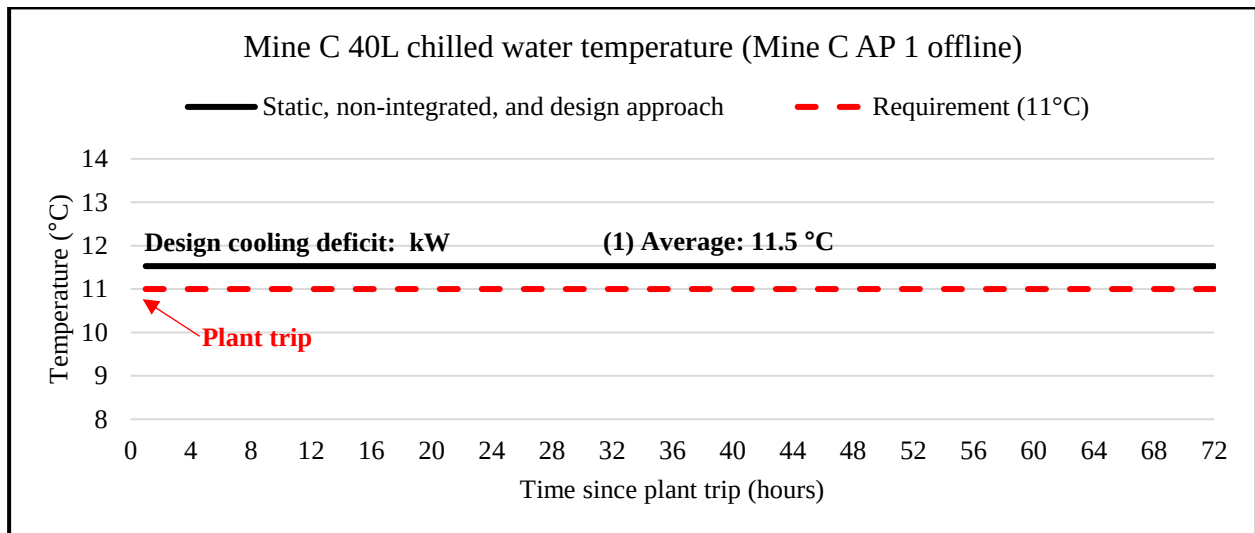


Figure 79. Static, non-integrated, and design approach AP failure results for KPI 1

Both KPIs show a static value above the required temperature for safe underground working conditions. However, due to the cooling capacity of the mine, short-term “spikes” at these temperatures are acceptable as long as the average temperature remains close to the requirement.

4.4.3 Dynamic, integrated, and empirical design (Result 2)²⁷

Steps 2 – 4: Digital twin with simulation, dynamic boundaries, and verification & Dynamic, integrated, and empirical design (Section 3.4 – 3.6)

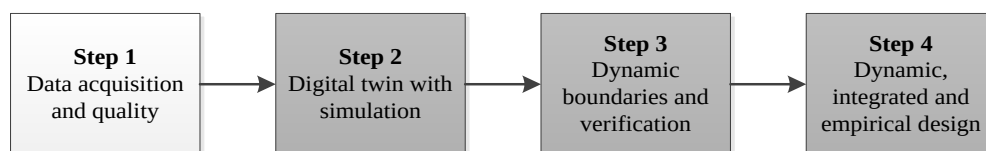


Figure 80. Steps 2 – 4 of new four-step method in case study 3

The scenarios calculated in the previous section (4.3.3) were simulated using the dynamic, integrated, and empirical model. The same model that was developed in the first case study in section 4.2 was used. Several mitigation strategies for the loss of a refrigeration machine were investigated as the best option. The chosen mitigation strategy was to utilise the redundancy available on surface. A notable consideration includes the use of redundant refrigeration at Mine A; however, it was not deemed necessary after simulation and discussion with mine management.

²⁷ The result in brackets is used as an indicator for comparison between the current and new method.

Each failure was simulated hundreds of times for short-, medium- and long-term failures which resulted in a simulation database of approximately 500 simulations. The iterations led to the best mitigation strategy for which the results are shown in Figure 81 to Figure 84.

Mine C surface FP failure

The first set of results is for FP1 failure at Mine C's surface FPs. The simulation model was used to apply the mitigation strategy and simulate the results for short- (4 hours), medium- (24 hours) and long-term failure (72 hours). The results are shown in Figure 81 and Figure 82.

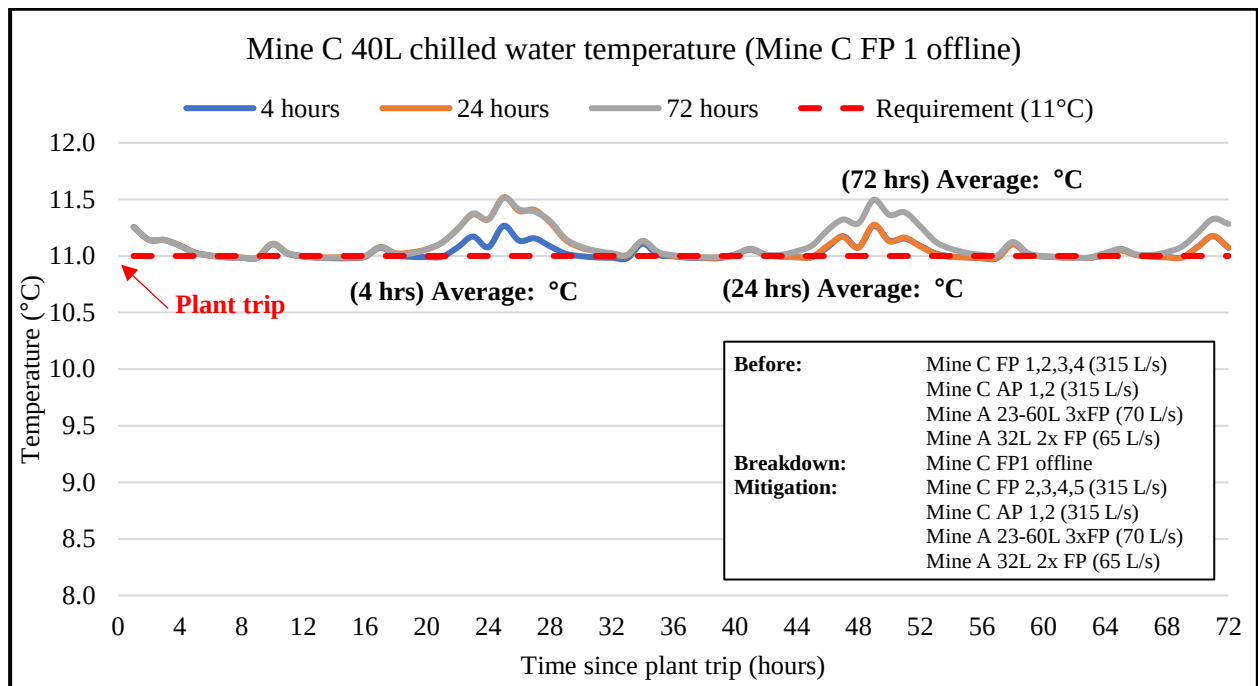


Figure 81. Dynamic, integrated, and empirical approach FP failure results for KPI 1

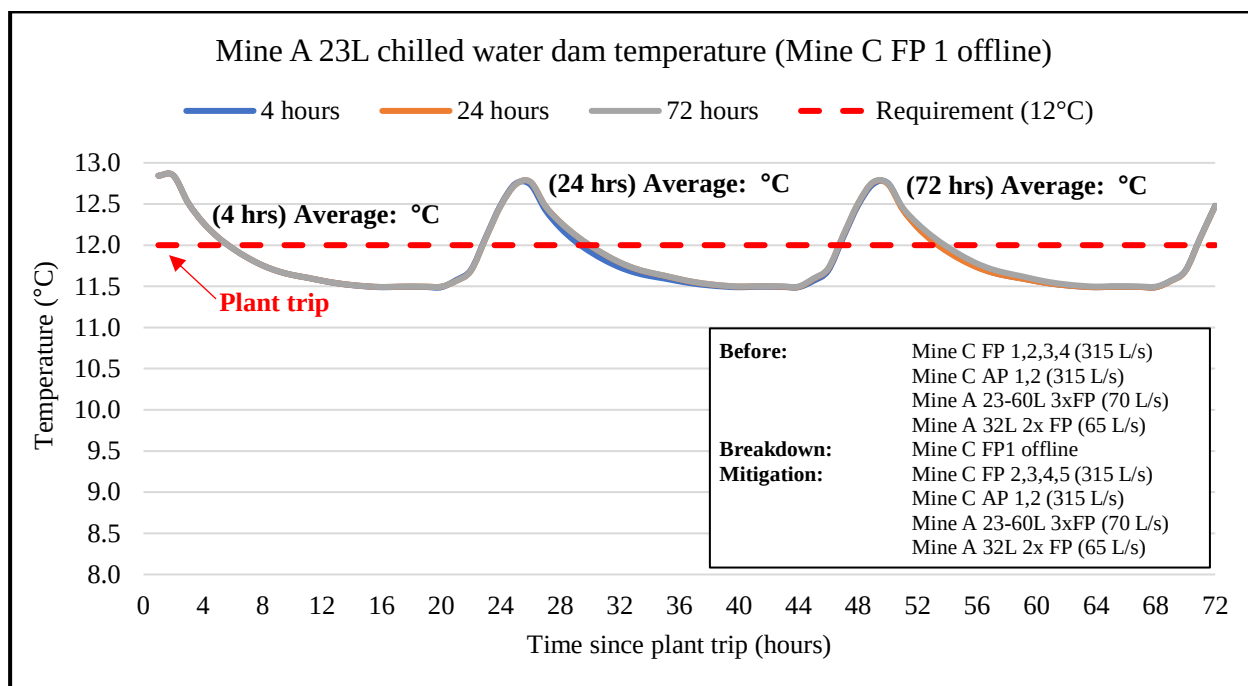


Figure 82. Dynamic, integrated, and empirical approach FP failure results for KPI 2

Figure 81 shows the results for KPI 1 and the impact the failure has on the temperature. The simulation provides significant insight into the effect of the three types of failures. The short-term failure has almost no effect on the underground temperatures for KPI 1. However, the medium- and long-term failures have an effect, which in the case of a FP1 failure, is insignificant with a temperature increase of only 0.1 °C for KPI 1.

The effect on KPI 2 is even smaller as Mine A refrigeration also plays a role in the temperature at 23L chilled dam. Again, the dynamic and integrated effect of the failure can only be seen using simulation. Additionally, the model is based on empirical data which results in a smaller effect than that which was calculated in the current method.

The small temperature increase of the FP1 failure is due to the redundant machine assisting with the cooling loss, but also the APs being able to increase duty due to the increased inlet temperatures because of the overall reduced FP cooling duty, offsetting the effect of the failure.

From Figure 81 and Figure 82 it is clear that the FP failure has a larger effect on Mine C 40L chilled water temperature and almost no effect on Mine A 23L chilled dam temperature. The reason is that Mine A 23L chilled dam has two incoming streams of chilled water, one from Mine C surface and one from Mine A 23-60L. Therefore, the increase in temperature on surface at Mine C has a much smaller effect than Mine C 40L chilled water temperature which is directly and exclusively supplied from Mine C surface FPs.

Mine C surface AP failure

The same process was followed for the AP failure. The results of the failure and its effect on KPI 1 and 2 are shown in Figure 83 and Figure 84. The results immediately showed the larger effect that an AP failure has on the overall system. The reason is that the AP is used to lower temperatures below the typical 6 °C possible with conventional FPs using R134a. APs can lower chilled water temperatures to below freezing or close to freezing due to ammonia gas having a lower boiling and freezing point.

Therefore, the final cooling from 6 °C to 1 °C must be done with the ammonia plant. It is therefore not possible to make up for lost cooling from an AP with a FP due to the temperature differences. The redundant FP stops contributing to the overall cooling duty once the FP outlet reaches the set limit of the machine which is typically 6 °C. Therefore, the redundant FP cannot fully reduce the temperatures to what was possible with both APs running.

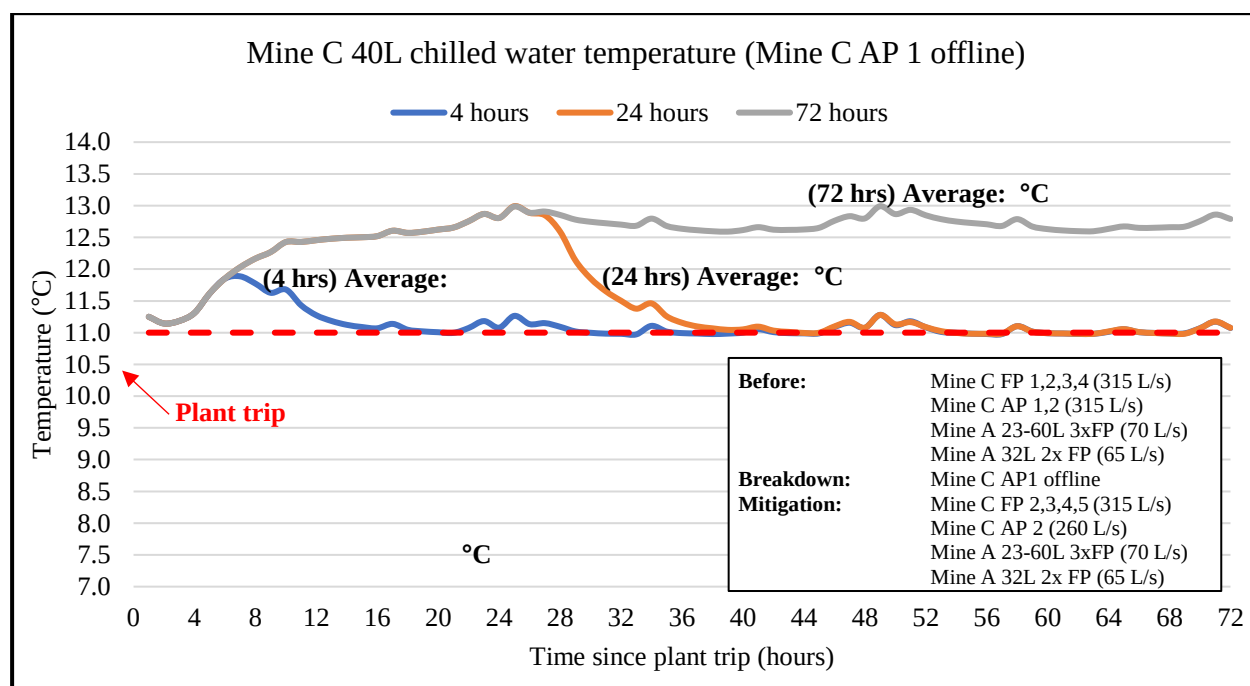


Figure 83. Dynamic, integrated, and empirical approach AP failure results for KPI 1

Figure 83 shows an immediate and dramatic increase in temperature for KPI 1 as the AP failure occurs. The short-, medium- and long-term failure influences underground temperatures with a 0.1 °C, 0.6 °C and 1.6 °C increase for 4-hour, 24-hour and 72-hour failures respectively. The same effect is seen for KPI 2; however, it is slightly dampened due to the integration of the Mine A underground FPs also supplying the 23L chilled dam. The AP failure results in an increase of 0.2 °C and 0.7 °C for 24-hour and 72-hour failures, respectively.

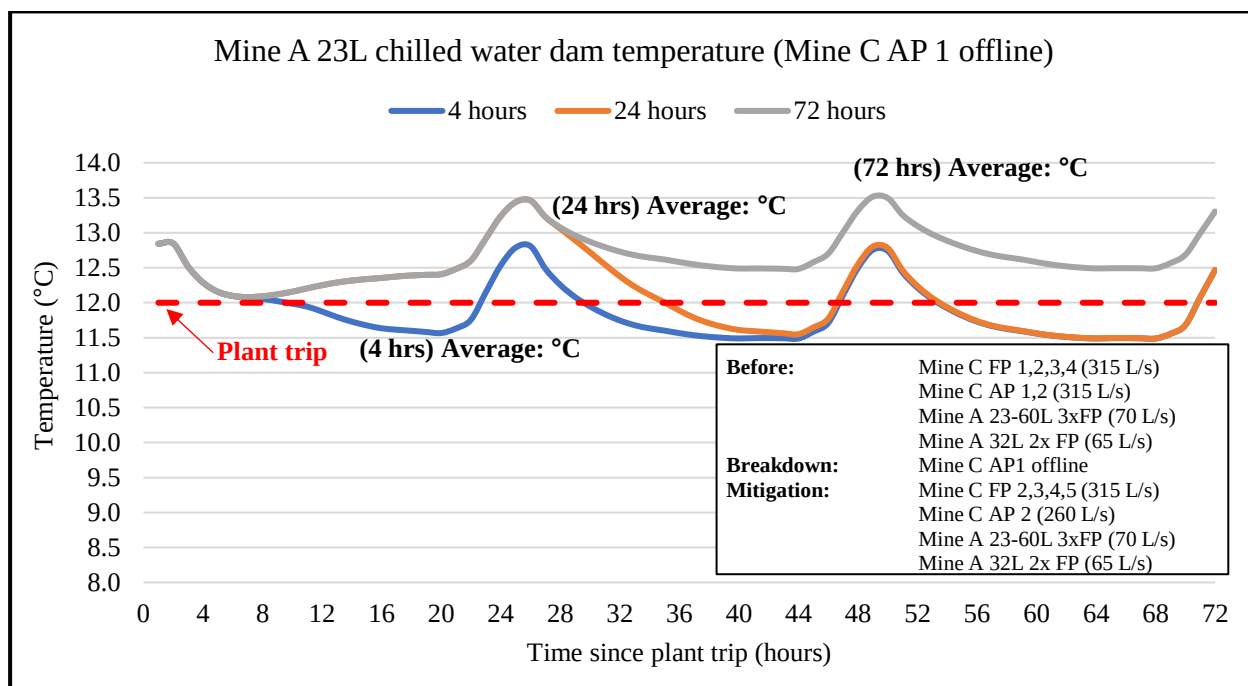


Figure 84. Dynamic, integrated, and empirical approach AP failure results for KPI 2

The results obtained from the FP and AP failure and the effect on KPI 1 and KPI 2 for the system are summarised in Table 16. The table shows a clear increase in underground temperatures over the different duration failures. However, the increase is mitigated due to redundant surface equipment being available.

Table 16. Method 2 results summary (case study 3)

No.	Failure	Mine C FP supply		Mine C 40L (11 °C)				Mine A 23L (12 °C)		
			Std.	4hrs	24hrs	72hrs	Std.	4hrs	24hrs	72hrs
		(L/s)	(°C)			(°C)				
1	Mine C FP1	315	11.0	11.0	11.1	11.1	11.9	11.8	11.8	11.9
2	Mine C AP1	315	11.0	11.1	11.6	12.6	11.9	11.9	12.2	12.7

The method shows a clear benefit in that the dynamic and integrated effect of failures can be visualised. This data can be used to predict future underground temperatures in the event of a failure and provide a response time. Limits can be imposed on maximum underground supply temperatures whereby miners are requested to stop production and return to surface for safety.

Using this, an emergency response procedure can be determined in the event of a failure and guidance to surface personnel can be given as to the importance of getting the refrigeration machines operational again.

4.4.4 Validation

As a final comparison between the current and novel method the combined results for KPI 1 are shown in Figure 85 and Figure 86 over a long-duration failure.

Figure 85 shows an FP failure for both methods. The current method incorrectly predicts the cooling deficit as the AP is capable of improved cooling duty due to the increased inlet temperature. This cannot be determined from the current method and shows the impact the novel method has on the results.

The static, non-integrated and design approach calculated a temperature increase of 1.8 °C for an FP failure as compared with the dynamic, integrated, and empirical approach which simulated only a 0.1 °C temperature increase, leading to an inaccuracy of 1.7 °C or 16%.

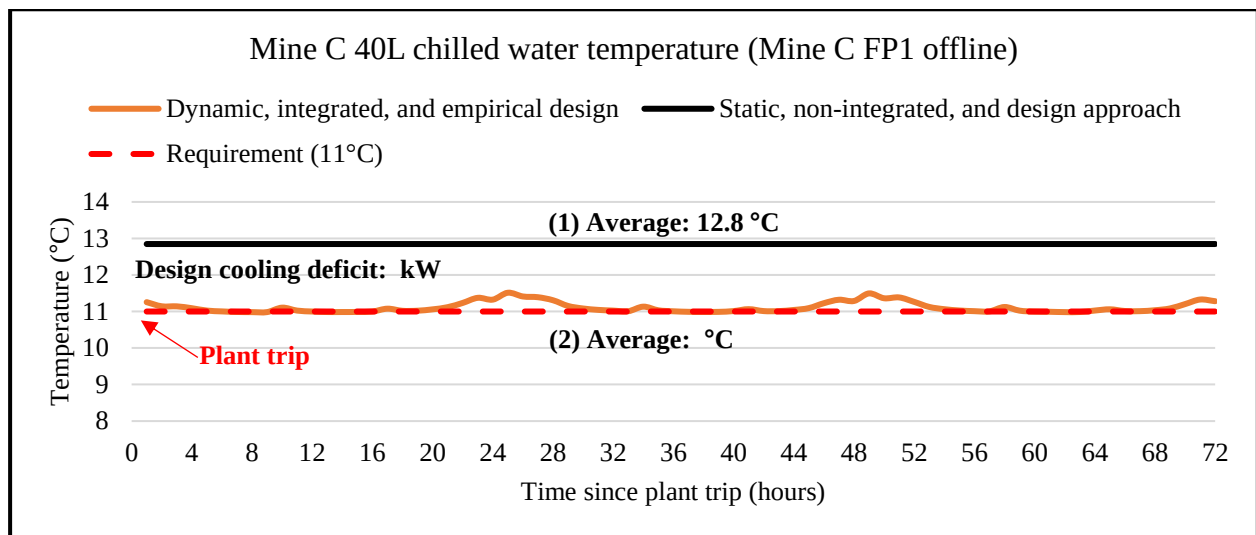


Figure 85. KPI 1 FP1 failure results for results (1) and (2)

Similarly, the results for an AP failure are shown in Figure 86. Here the effect is underestimated as the FP reaches the limits of their design due to the refrigeration gas being used. The current method incorrectly diminishes the effect of an AP failure which is clear has a larger effect as seen by the novel method. Therefore, the focus should be made to ensure the APs are in a good working order to reduce failures as far as possible.

The static, non-integrated and design approach calculated a temperature increase of 1.6 °C for an AP failure as compared with the dynamic, integrated, and empirical approach which simulated a 0.5 °C temperature increase. This led to an inaccuracy of 1.1 °C or 10%. The static, non-integrated and design approach, therefore, underestimates the effect of an AP failure and incorrectly shows it as a lower priority than an FP

failure, whereas the simulations show that the FP failure has almost no effect and the AP failure has a larger effect on underground temperatures.

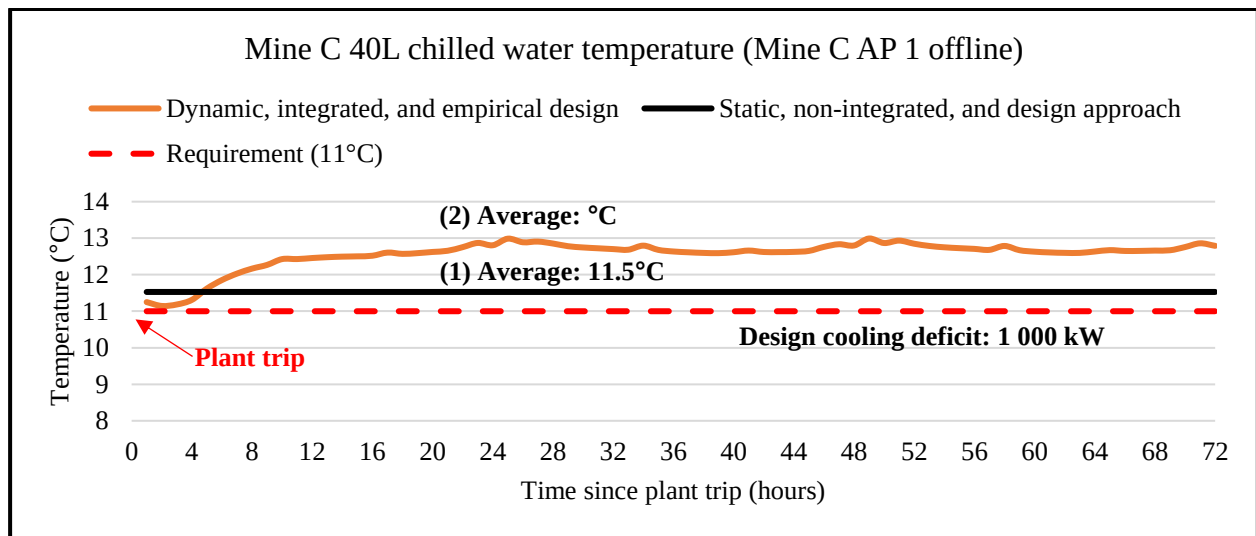


Figure 86. KPI 1 AP1 failure results for results (1) and (2)

The results for the standard operation (no failure), current method and novel method are summarised in Table 17. The table shows the overestimation of an FP failure and the underestimation of an AP failure. The focus, therefore, using the current method is on the incorrect equipment with the AP being the limiting equipment in a failure.

Table 17. Result summary of results (1) and (2) compared with standard operation (no failure)

No.	Failure	Cooling loss (kW)	Redundant cooling (kW)	Cooling deficit (kW)	Mine C FP supply (L/s)	Mine C 40L (11 °C)			Mine A 23L (12 °C)		
						Std. (°C)	(1) (°C)	(2) (°C)	Std. (°C)	(1) (°C)	(2) (°C)
1	Mine C FP1	8 500	5 000	3 500	315	11.0	12.8	11.1	11.9	12.7	11.9
2	Mine C AP1	6 000	5 000	1 000	315	11.0	11.5	12.6	11.9	12.1	12.7

4.4.5 Conclusion

Case study 3 investigated a power failure on the surface FP1 and AP1 at Mine C. The current method was used and compared with the novel method using a dynamic, integrated, and empirical approach. The objectives for case study 3 were met whereby the novel method showed insight into the effect of a short-, medium- or long-term failure of the FP and AP which was not possible with the current method. The detailed results are used to provide real-time response to a power failure and can be used to determine the best course of action in the event of a failure.

The current method was more than 1.8 °C above (16%) and 1.5 °C below (14%) the novel approach in certain instances for up to 14 and 10 hours, respectively. This results in incorrect planning and a false sense of safety.

The objective set out for the case study were met and are summarised below:

1. **Using the proposed novel method:** The proposed method was successfully applied to the case study and yielded accurate results assisting with future planning and emergency readiness.
2. **Showing clear improvement over the current method:** The novel method showed an average improvement of 15% over the current method indicating an improvement prediction of underground temperatures. Additionally, the novel method shows a dynamic profile which is not possible with the current state of the art.
3. **Without affecting current and future operations or production:** The novel method assisted with designing mitigation strategies which ensure that production can continue during a refrigeration failure.
4. **Ensuring underground temperatures are kept below safe limits:** The novel method showed that with the mitigation strategies in place underground temperatures will remain within a margin of safety of the design requirements.

4.5 Case study 4: Total power failure

4.5.1 Background

Step 1: Data acquisition and quality (Section 3.3)

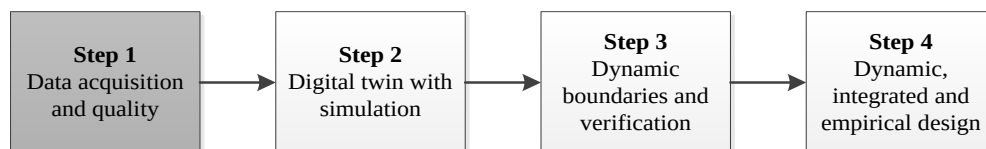


Figure 87. Step 1 of new four-step method in case study 4

Overview

Case study 4 considers a mine shaft consisting of several levels with a multistage pumping system. The pumping system is responsible for dewatering the mine and avoiding flooding. Several fissure water sources and service water sources make up the dewatering demand on the pumping system. The shaft has a total of 106 L/s of fissure water which was verified as constant over 24 hours and 105 L/s of service water which is dynamic over 24 hours.

The fissure water consists of four major sources all arriving at the lowest level for pumping to surface. The sources all originate below the 21L pumping station. Similarly, the service water is piped and drained to the lowest pumping level using holes blasted between levels called annex holes and piping on levels. The total dewatering demand is pumped from 25L to 21L to 5L then surface. The layout of the pumping system is shown in Figure 88.

For clarity in the document, the number (1) is used to represent the static, non-integrated and design results with (2) representing the dynamic, integrated, and empirical results. The number (3) indicates the novel dynamic, integrated and empirical design method.

Case Study Objective

The objective of the case study is to investigate the effect of a total power failure on the pumping system. This is not uncommon and has occurred in the past [145]. When this occurs, there is no pumping and water needs to be stored underground. Therefore, the system needs to be designed in such a way that a total power failure does not flood critical systems and endanger the shaft's operations and more importantly human life.

Therefore, the requirement is to be able to store all water sources underground for 48 hours without flooding the lowest pumping level which will render the shaft inoperable and dangerous. This case study will investigate the current method used to determine the mine's emergency capacity and response time and apply the novel method to determine the current risk levels and if the 48-hour requirement is met.

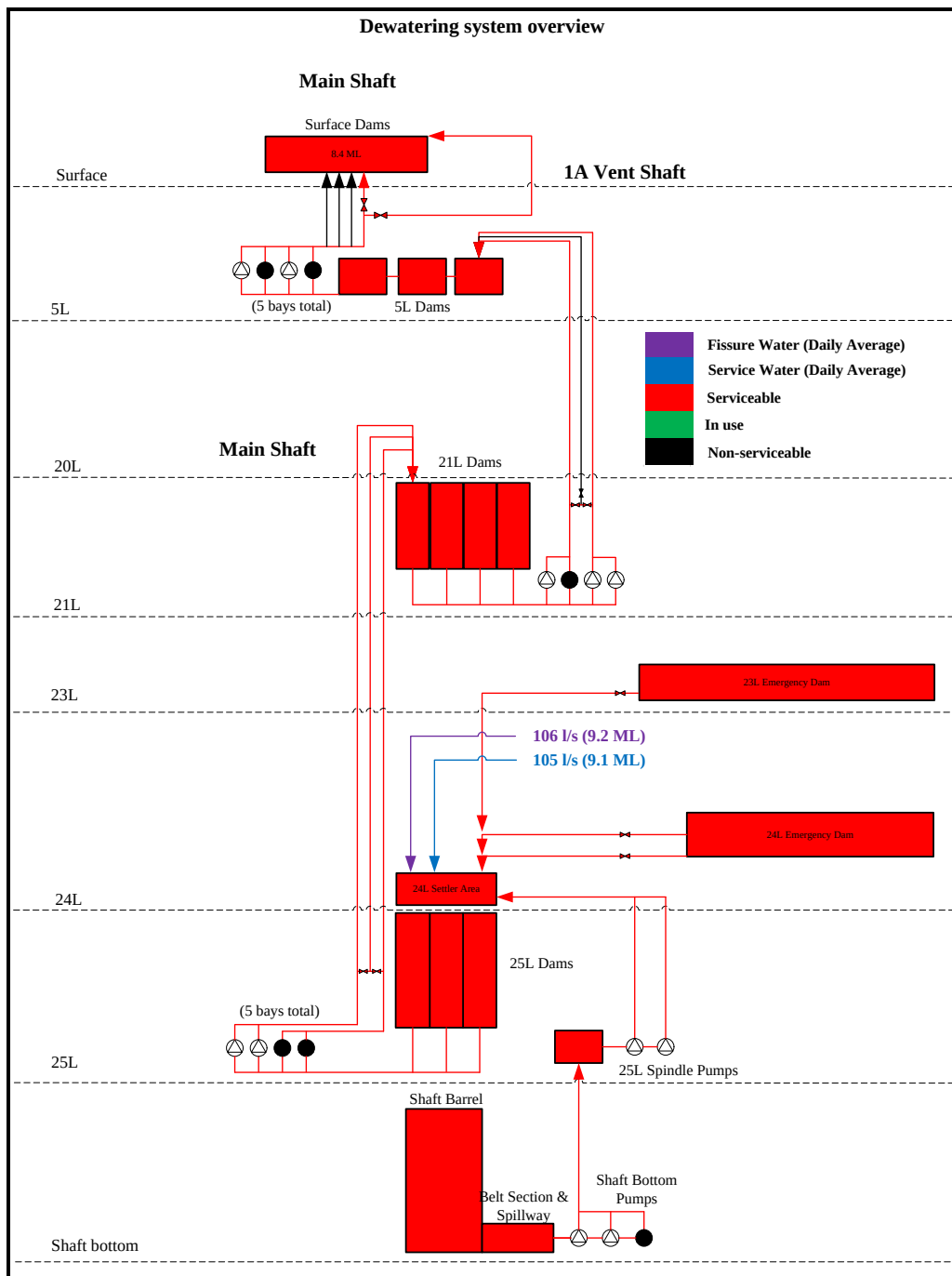


Figure 88. Schematic overview of dewatering system (case study 4)

The objective of the case study is to determine the required infrastructure to ensure the mine does not flood within 48 hours:

1. Using the proposed novel method
2. Showing clear improvement over the current method
3. Without affecting current and future operations or production
4. Ensuring the 48-hour power failure rule is met

4.5.2 Static, non-integrated and design approach (Result 1)²⁸

The current method used to determine the emergency capacity and emergency response time is a spreadsheet type approach [143], [144], [146]. Design dam capacities are used to determine a total emergency capacity available, and it is assumed that each dam capacity is used in series and not integrated. Additionally, the flows are all assumed to be static. The method is schematically shown in Figure 89.

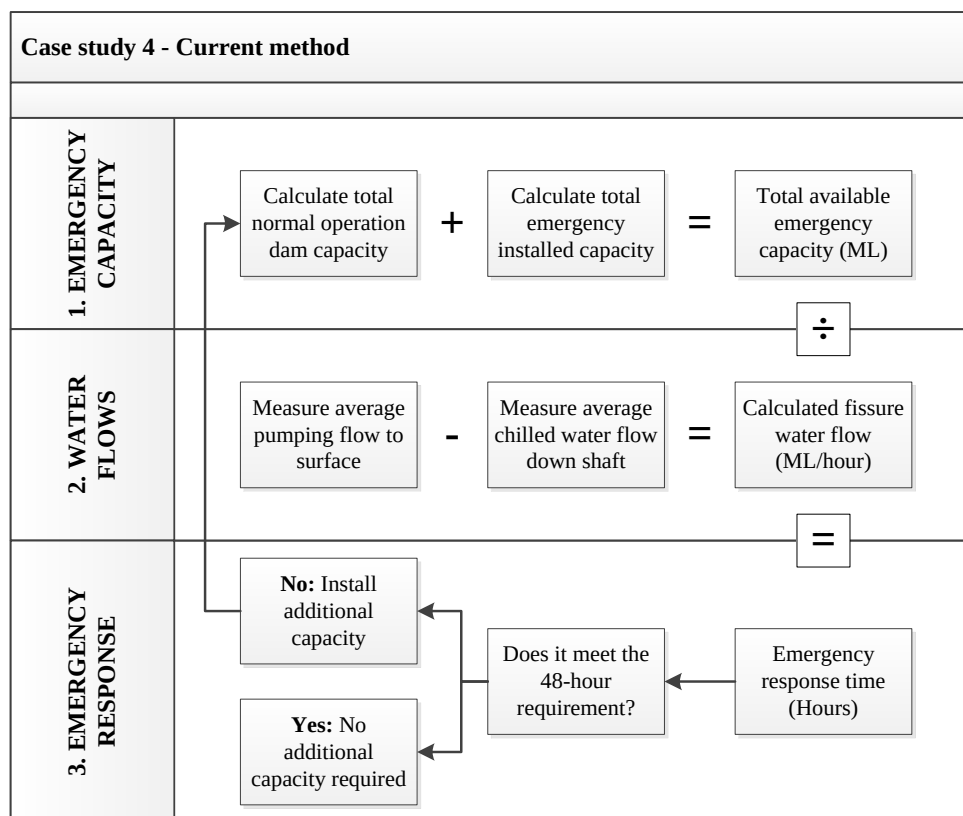


Figure 89. Static, non-integrated and design approach flow diagram (current/old method)

²⁸ The result in brackets is used as an indicator for comparison between the current and new method.

The method shown in Figure 89 shows schematically the current approach followed. The approach is simple, and does not take any integrated or dynamic effects into account, and follows five simple steps:

1. **Emergency capacity:** The total emergency capacity is calculated and determined from design values or estimates. The total emergency capacity is made up of two capacities, one being the normal operational redundant capacity which is unused capacity in the operational dams. The second is emergency capacity which is dams that are only used in case of emergencies.
2. **Water flows:** The water flows are separated into two categories, service water and fissure water. Service water is sent underground for cooling and drilling and fissure water is underground water flows from faults in the rock underground. Service water flow is determined by underground mining activities where fissure water is not controllable and is typically constant throughout the year. Here the fissure water flow is calculated as the service water flow is known from SCADA and the water pumped to surface is also known from SCADA. The remainder is therefore the constant fissure water flow and used for the calculation of the emergency response.
3. **Emergency response:** Once the total fissure water flows are known in ML/hour the emergency response can be calculated. This is a simple calculation of the total available emergency capacity divided by the ML/hour fissure water flow. The calculation is made for each emergency capacity and the hours to flood each capacity are determined. This is then shown graphically on a timeline.

The service water flow was determined from SCADA data using the flow meter found on surface, and the average flow over 24 hours was determined as 105 L/s. The fissure water flow was determined using SCADA and the flow meter on surface measuring water was pumped from 5L. The surface flow meter measured an average flow of 211 L/s over 24 hours. Therefore, an additional 106 L/s of water was pumped from underground which accounts for fissure water.

The available emergency capacity was calculated using design dam specifications and the typical operating capacity was obtained from SCADA data. The data showed that 25L hot dams operated between 30% and 60% capacity. Therefore 40% of the capacity is use-able for emergencies. The total capacities of all dams, shaft barrels and spillways are shown in Table 18.

Table 18. Calculated emergency water capacities of various levels

No.	Description	Capacity	Normal operation	Emergency capacity
		ML	%	ML
1	25L hot dams (3x2 ML)	6.00	60%	2.40
2	Spare settler	3.58	0%	3.58
3	Area above settlers	1.98	0%	1.98
4	Shaft bottom	0.47	0%	0.47
5	Belt section and shaft barrel	4.35	0%	4.35
6	23L emergency dam	8.75	0%	8.75
7	24L emergency dam	6.00	0%	6.00
Total emergency capacity				27.53

The total emergency capacity is 27.53 ML. Therefore, the next step according to the current method is quite simple. The time is calculated to fill each dam capacity in series. The results thereof are shown in Figure 90. The current approach assumes service water does not influence the flow during a power failure as the chilled water valve is closed immediately.

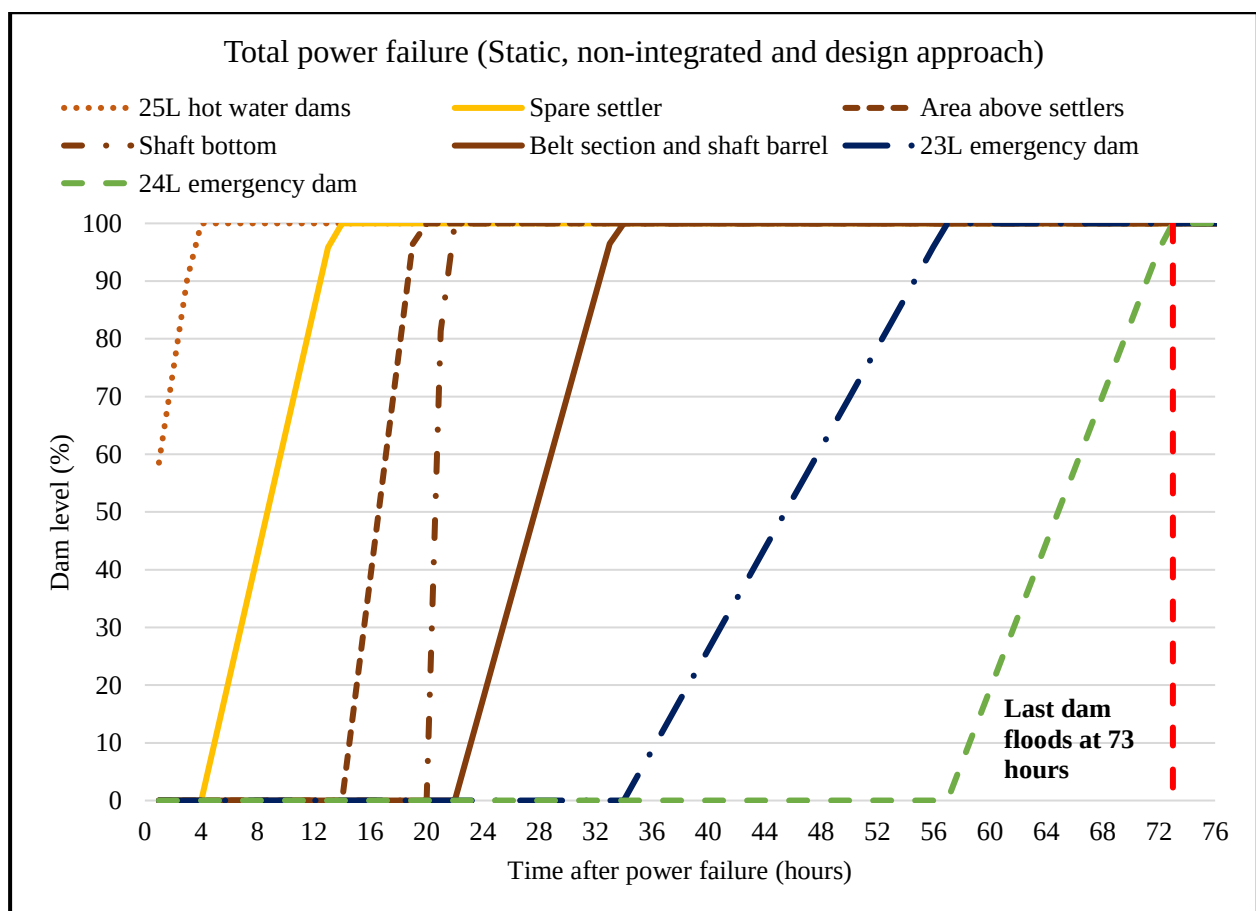


Figure 90. Static, non-integrated and design approach total power failure results

The current method shows a total emergency response time of 73 hours when the last of the emergency dams flood and subsequently flood the shaft barrel and 25L. The sequence of flooding is determined by the user of the current method. Therefore, shaft bottom floods before the 24L emergency dam which is not logical.

It was determined that the current method assumes an emergency pump is available to pump water from shaft bottom to the emergency dams. However, in a total power failure scenario it is not suggested practice to assume power, even emergency power, will be available before 48 hours,. Therefore, according to the current method, the system meets the required 48-hour power failure rule.

4.5.3 Dynamic, integrated, and empirical approach (Result 2)²⁹

Steps 2 & 3: Digital twin with simulation & dynamic boundaries and verification (Section 3.4 & 3.5)

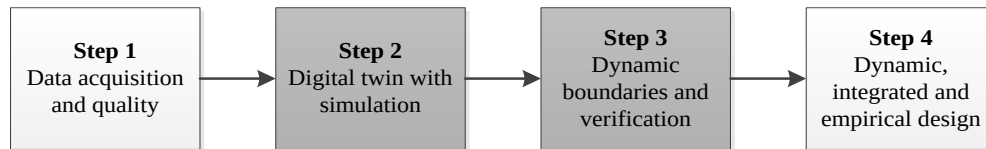


Figure 91. Steps 2 & 3 of new four-step method in case study 4

The current approach is not dynamic or integrated, using static water flows and assuming the emergency capacities are used in series. Additionally, the dam capacities are based on design values and not empirical audited values.

The dynamic, integrated, and empirical approach attempts to reduce the assumptions through detailed audits, dynamic and integrated simulation.

The first step is to determine the inputs into the model. The service water and fissure water flows were audited and confirmed using underground audits and SCADA data. The water flows are shown in Figure 92.

²⁹ The result in brackets is used as an indicator for comparison between the current and new method.

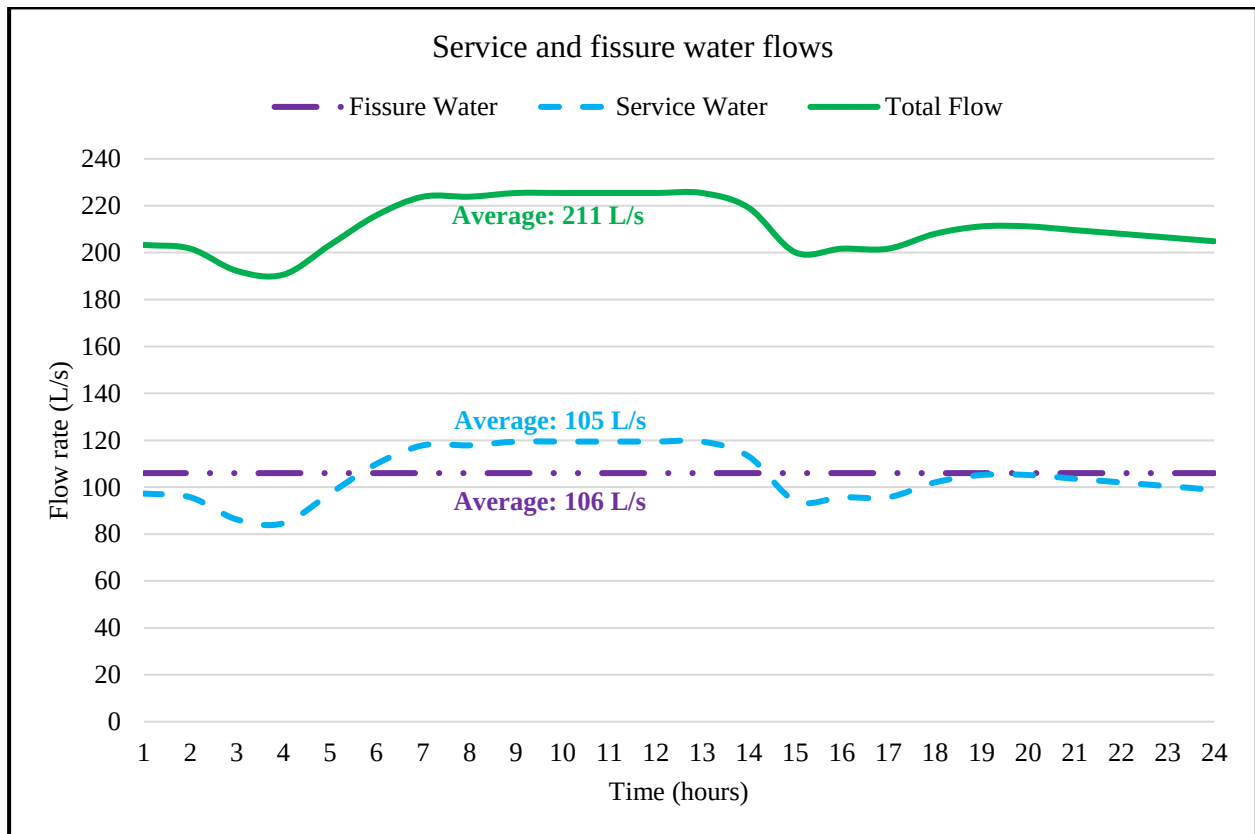


Figure 92. Verified fissure and service water flows

The flows were added to the calibrated and verified model which is shown in Figure 93. Figure 93 shows the integrated nature of the mine water system and includes all emergency capacities, pumping infrastructure, water flows and routes.

The model was calibrated to 95% accuracy and includes all pumping levels, emergency dams and service and fissure flows. The model also includes updated capacities after detailed audits and measurements of all dam and emergency dam capacities were conducted. Additionally, the exact location of fissure water sources, annex holes and infrastructure were investigated and added to the model. A simplified schematic of the entire system with flow inputs is shown in Figure 94.

The figure indicates several fissure sources that travel to 25L through different paths. Most important is the 39 L/s that bypasses all emergency dams and continues straight to the settlers, and the 2 L/s which goes directly to the shaft bottom and which cannot be pumped once power failure occurs. The service water flow is a dynamic input and follows the profile showed in Figure 92 with an average daily flow of 105 L/s.

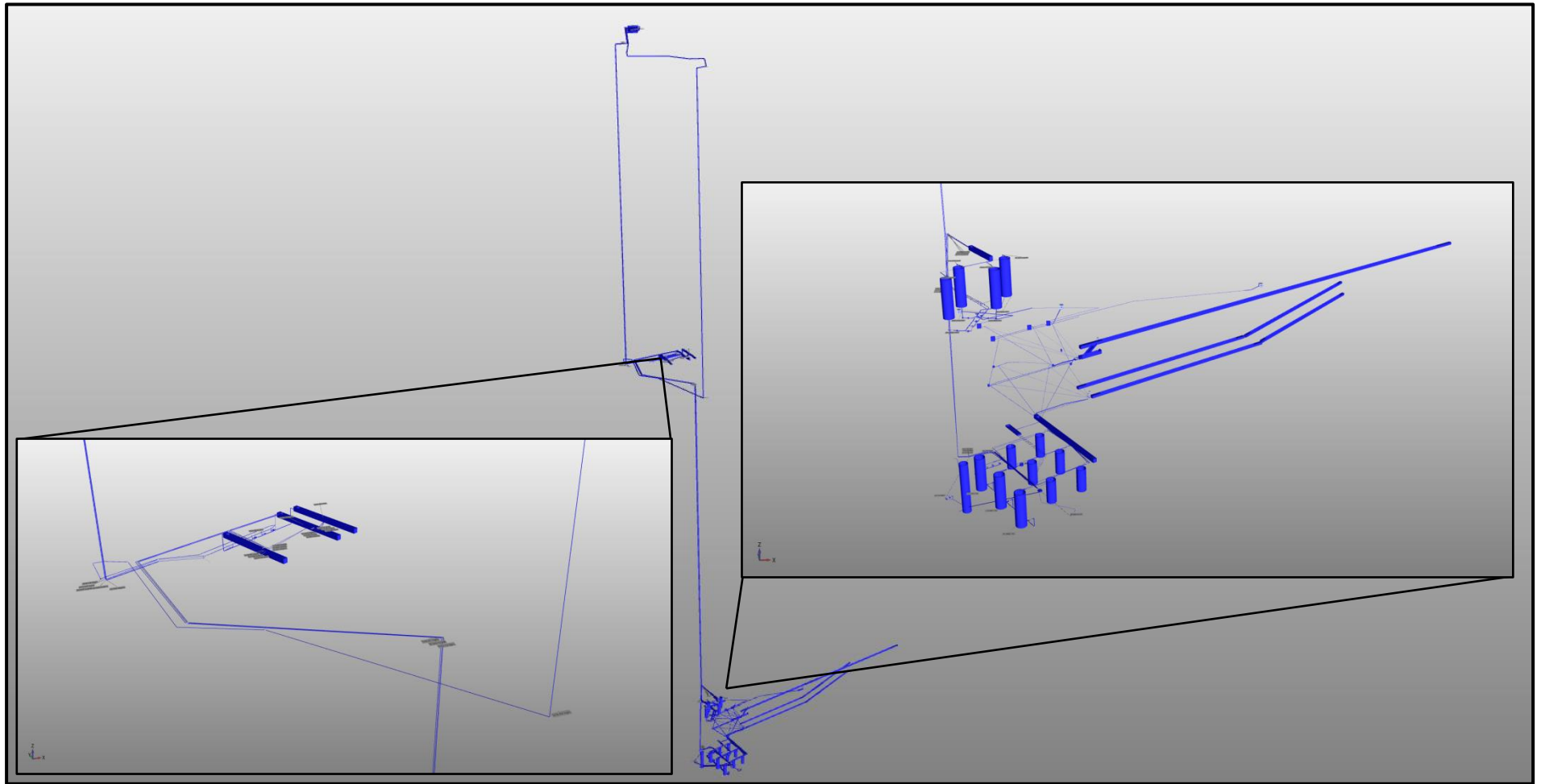


Figure 93. Fully integrated simulation of dewatering system and emergency stores

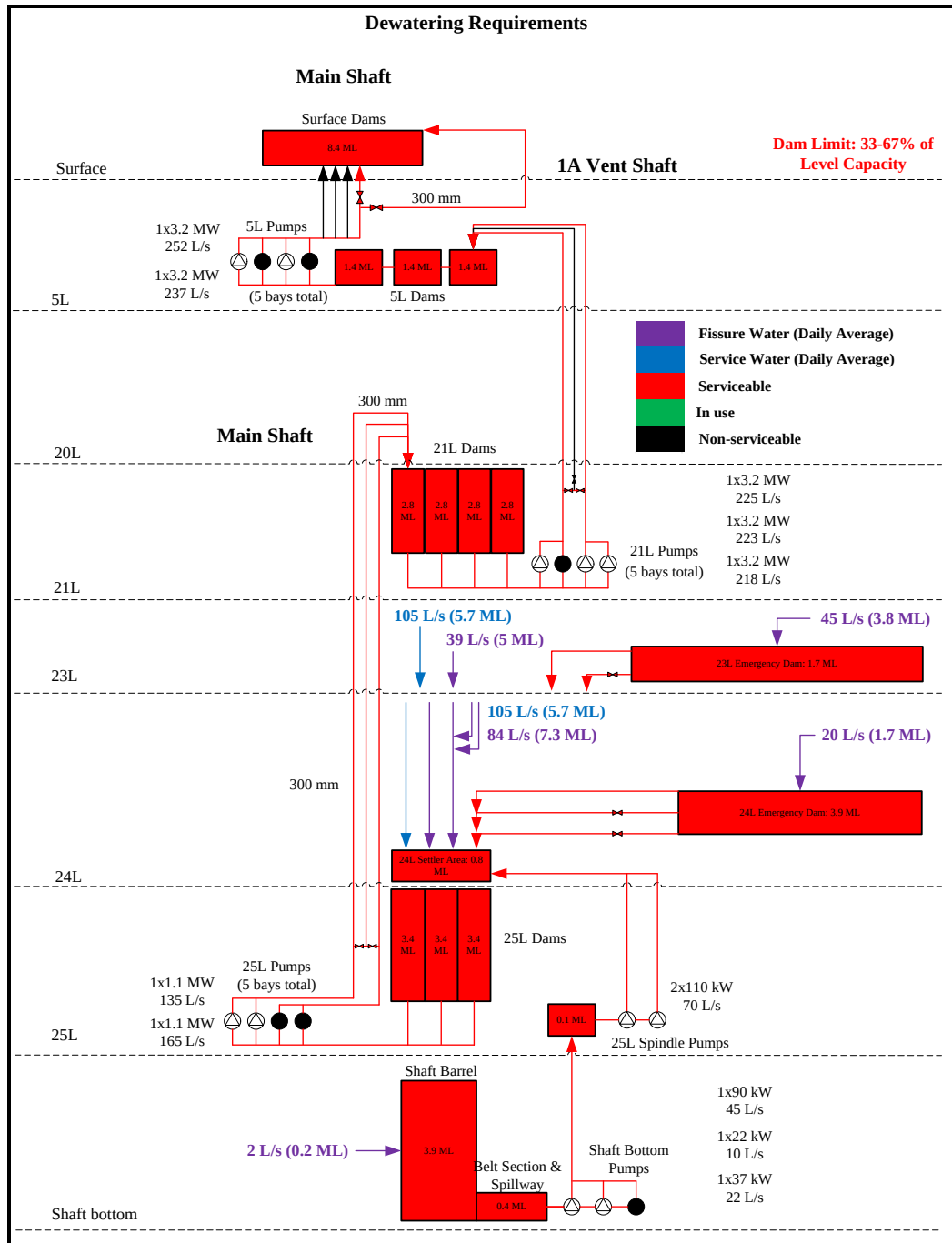


Figure 94. Dewatering system including fissure flows and locations

The power failure event was then simulated using the current layout and assuming service water flow is only closed after one hour and takes approximately seven hours to completely drain columns and reduce to 0 L/s. The time taken to drain the columns was calculated from the total capacity in the columns, pressure, and audited leaks in the system. The reduction in service water flow was verified using SCADA data in COVID-19 lockdown where the surface chilled water valve was closed at the stop of production. The power failure fissure and service flow inputs are indicated in Figure 95.

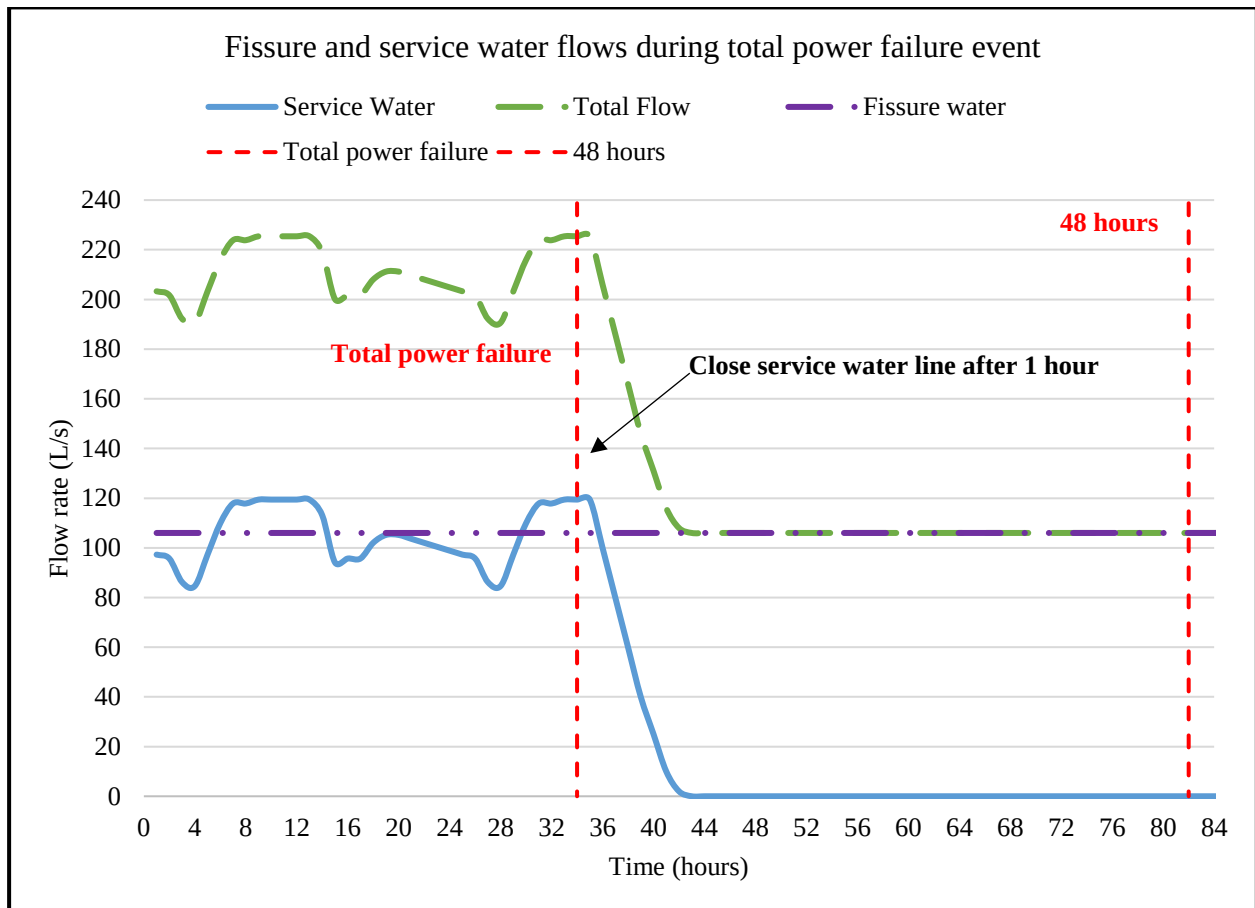


Figure 95. Verified fissure and service water flows during power failure

Figure 95 shows that power failure was simulated at a worst-case flow rate for the shaft during peak production and peak service water flow. The power failure occurs at hour 34 with the service water valve being closed at hour 35. The purpose of simulating a full 24-hour production shift before power failure is to ensure all dams and emergency dams are at their operational levels before power failure. The available dam capacities and flows before power failure and during normal operation is shown in Figure 96.

The simulation was run in the current configuration with a power failure occurring at hour 34 and continued for 48 hours after power failure. The simulation showed if the current system could retain the service and fissure water flows underground without pumping for 48-hours. The results thereof are shown in Figure 97.

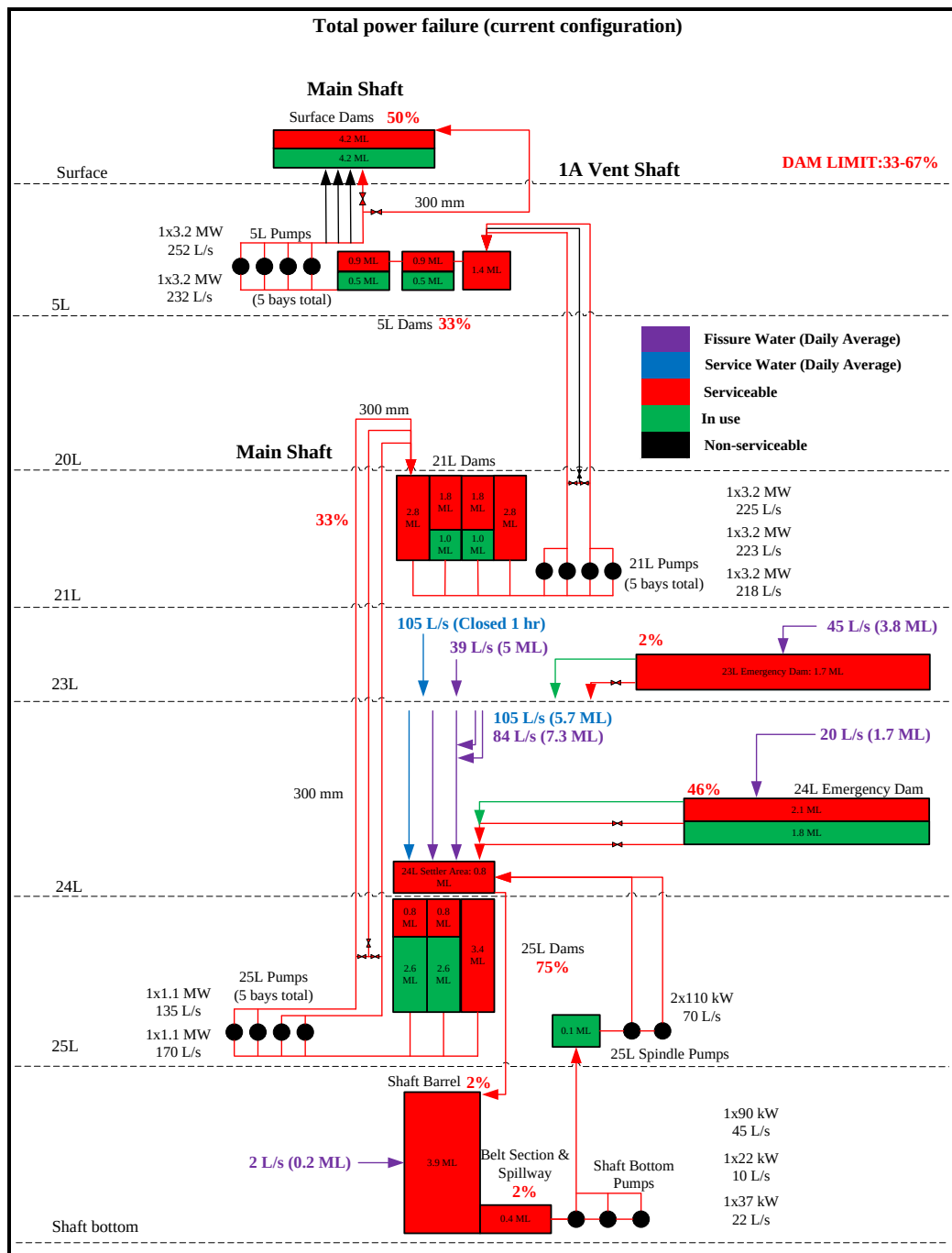


Figure 96. Total power failure – current configuration

Figure 97 shows the simulation results for the current configuration. The figure indicates a total available emergency response time of 31 hours before shaft bottom floods, rendering 25L pumping unusable in the current configuration. The major contributing factor is the reduced emergency dam capacities due to water building up behind 24L emergency dam and the reduction in capacity for both 23L and 24L emergency dams after detailed audits and measurements. Additionally, the sequence in which capacities are filled is parallel and integrated and not in series as assumed in the current method.

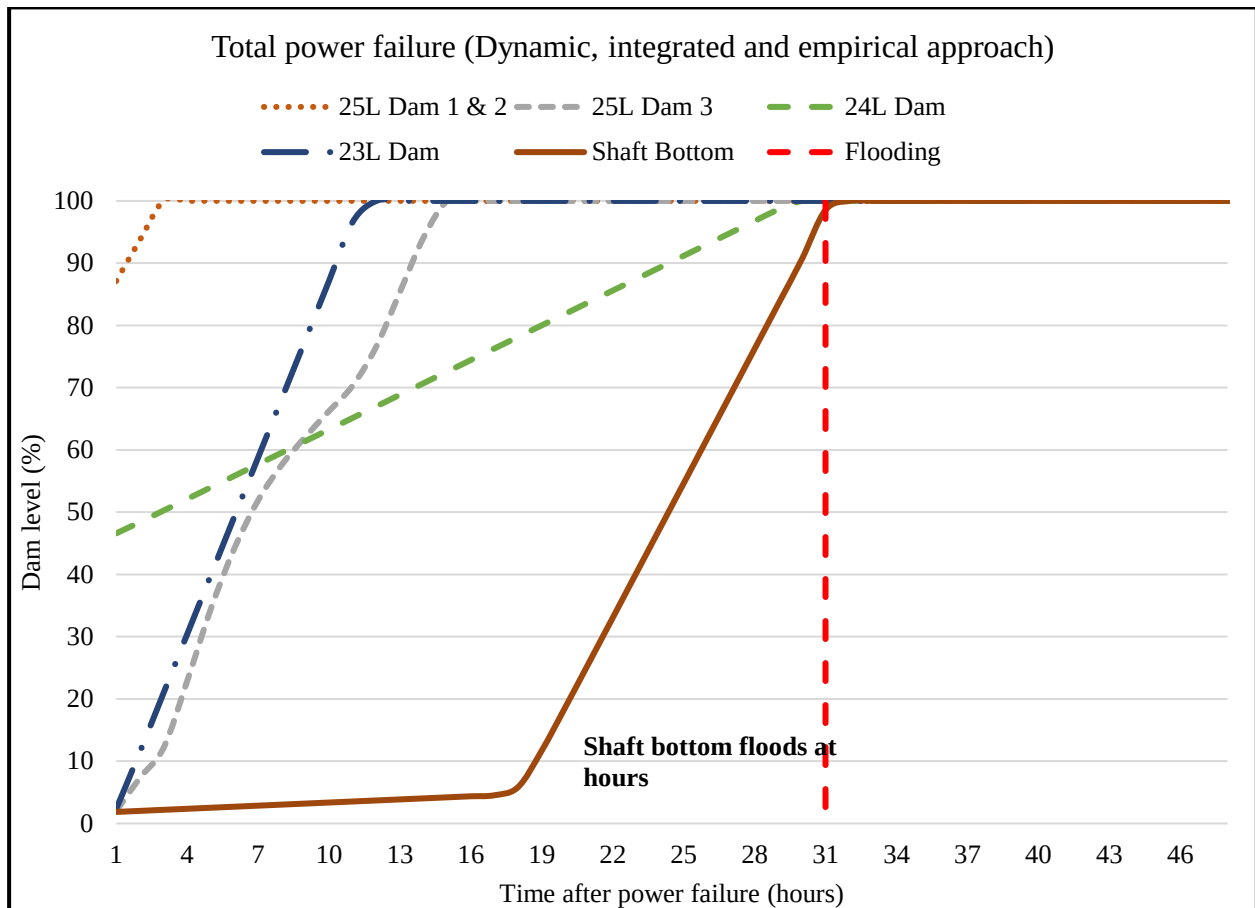


Figure 97. Dynamic, integrated, and empirical approach total power failure results

The dynamic integrated and empirical method applied in this case study shows an error of more than 100% as compared with the current method indicating a total time of 73 hours before shaft bottom floods. The next section attempts to use dynamic, integrated, and empirical design method to reach the required 48 hours.

4.5.4 Dynamic, integrated, and empirical design (Result 3)³⁰

Step 4: Dynamic, integrated, and empirical design (Section 3.6)

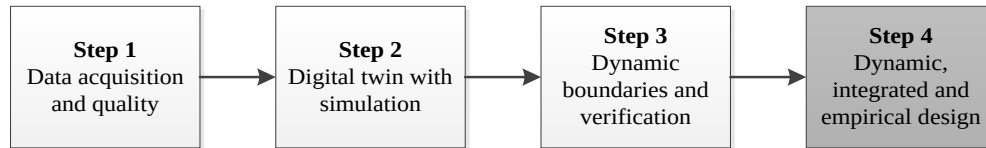


Figure 98. Step 4 of new four-step method in case study 4

The previous section indicated that the current system does not support a 48-hour requirement for a total power failure. Therefore, changes to the system are needed to meet the requirements. The simulation is a powerful tool whereby several solutions can be quickly and accurately tested without need for infrastructure. Several solutions, which are shown in Table 19, were considered.

Table 19. Top solutions for total power failure

Solution no.	Description	Comment
1	Direct all water to 20L	Will not solve lower fissure sources
2	Build water door on 25L	Will affect ventilation
3	Increase wall height of emergency dams	Inexpensive, simple, will affect ventilation and does not capture all water sources.
4	Reroute all water to 23L emergency dam	Feasible, will require larger 23L dam
5	Install surface backup generator	Expensive, not immediately useable if shaft electrical infrastructure fails

The solutions were discussed with mine personnel which led to a final accepted combined approach. The combined approach was planned in such a way that the solution that was easiest to implement was simulated first and then iterated on, the reason being that the lack of 48-hours response time in a power failure scenario is a major concern and needs to be rectified as soon as possible.

After several simulations (more than 100 scenarios) the steps to reach the 48-hour emergency response during a total power failure were achieved. The results and iterations are shown in Table 20.

³⁰ The result in brackets is used as an indicator for comparison between the current and new method.

Table 20: Summary of simulation iterations

Iteration	Description	Total hours	Additional hours
0	Current Configuration	31	-
1	Empty 24L Emergency Dam	31	0
2	Iteration 1 + T-piece into 24L Dam	36	5
3	Iteration 1 + 2 + Increase 23L Dam Walls to 3.5m & 24L Dam Walls to 3m	53	22

Only three iterations were necessary to achieve an emergency response time of more than 48 hours. The first attempt was to ensure the emergency dams are empty before power failure. 23L emergency dam is always empty as the drain valves are piped directly into a drain hole going to 24L. However, the 24L emergency dam is approximately 50% full during normal operations as the piping leading from the dam to the settlers is small in diameter (100 mm) and does not have enough head to completely empty the dam. Therefore, the first solution was to pump the 24L emergency dam empty during normal operation.

The emptying of the 24L emergency dam had no effect on the total time to flood shaft bottom, the reason being that some of the fissure water flows bypass the emergency dams. This means the shaft bottom floods before the emergency dams are filled.

Therefore, the next iteration was to redirect all the water to 24L emergency dam using a T-piece in the annex holes coming from 23L. This allows all the flow to be redirected into either the 23L dam or the 25L dam. The implementation of the T-pieces only improved the total time by 5 hours indicating the empty 24L capacity is not sufficient.

The final iteration included increasing the 24L dam walls to 3.5m and 3m for 23L and 24L dams respectively. The dam heights were determined by ventilation constraints. This increase in dam height significantly increased the total capacity which resulted in a total emergency response time of 53 hours.

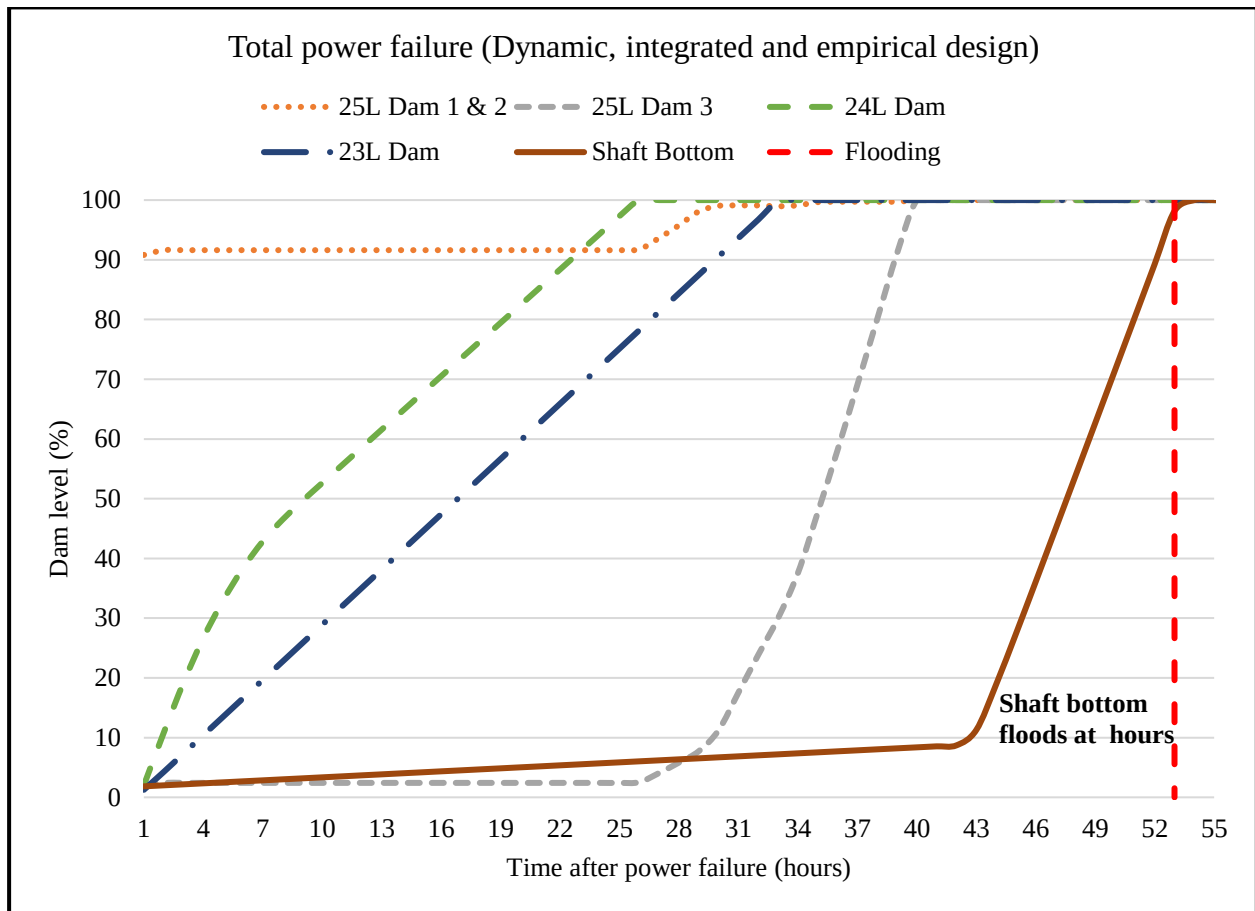


Figure 99. Dynamic, integrated, and empirical design total power failure results

The proposed configuration is shown in Figure 100 with the dam level results shown in Figure 99. The results show a clear improvement over the current system with minimal changes. The ability to investigate several solutions quickly for their feasibility led to a satisfactory outcome with clear actions required to reach the set requirements for a total power failure scenario. The novel approach increased accuracy and ensured a safe mitigation solution was developed.

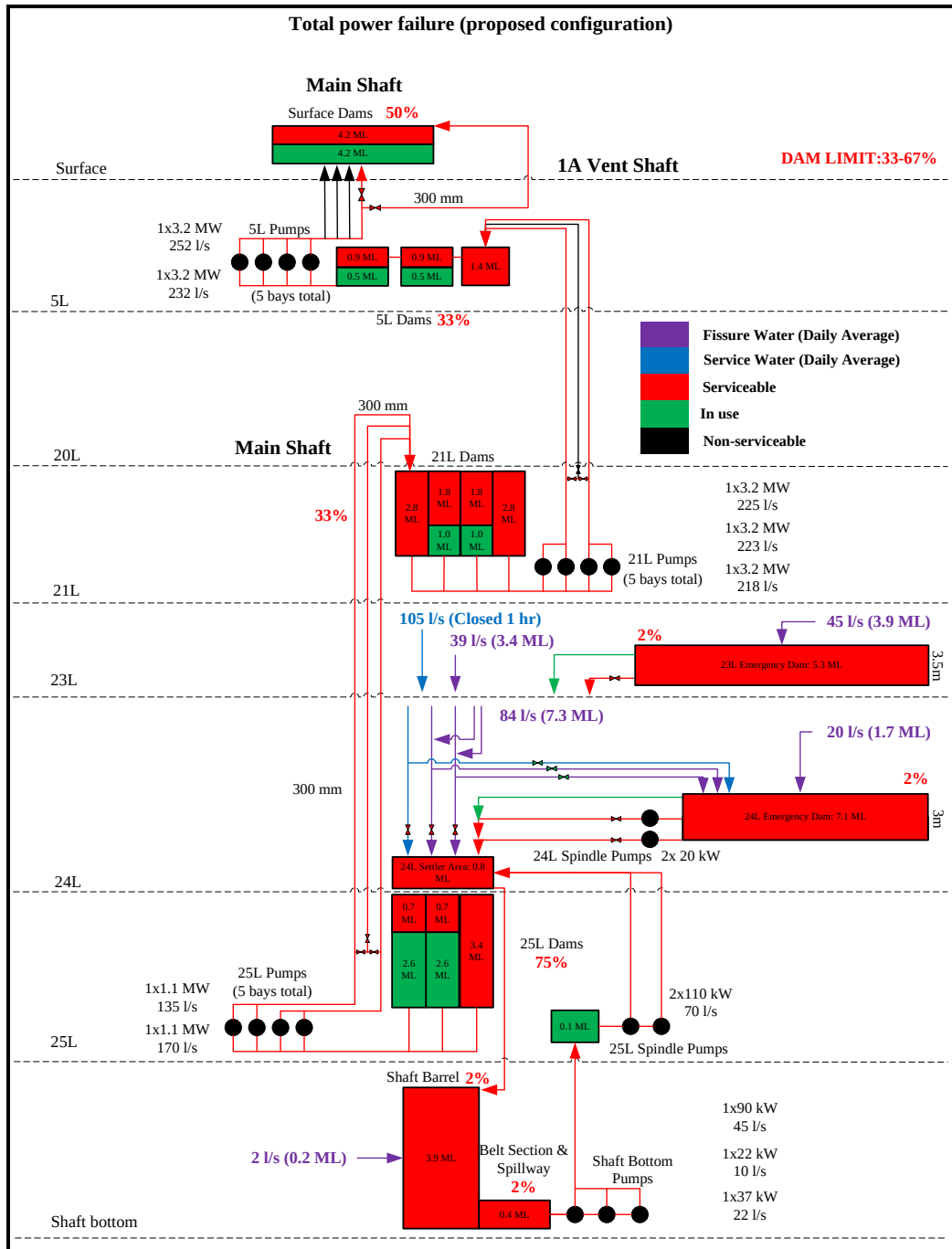


Figure 100. Total power failure – proposed configuration

4.5.5 Validation

The results for the static, non-integrated and design method is shown Figure 101 and compared with the dynamic, integrated, and empirical approach as well as the simulated assisted design result. The figure clearly shows that the static, non-integrated and design method underestimates the severity of the situation during a total power failure. The current system and current approach show a total emergency response time of 73 hours which is far above the required 48 hours. The dynamic integrated and empirical approach

shows an actual emergency response time of 31 hours during a total power failure which is 42 hours less than what was calculated using the current method. Therefore, the current method has an error of 135% and severely compromises the operations underground and provides a false sense of security.

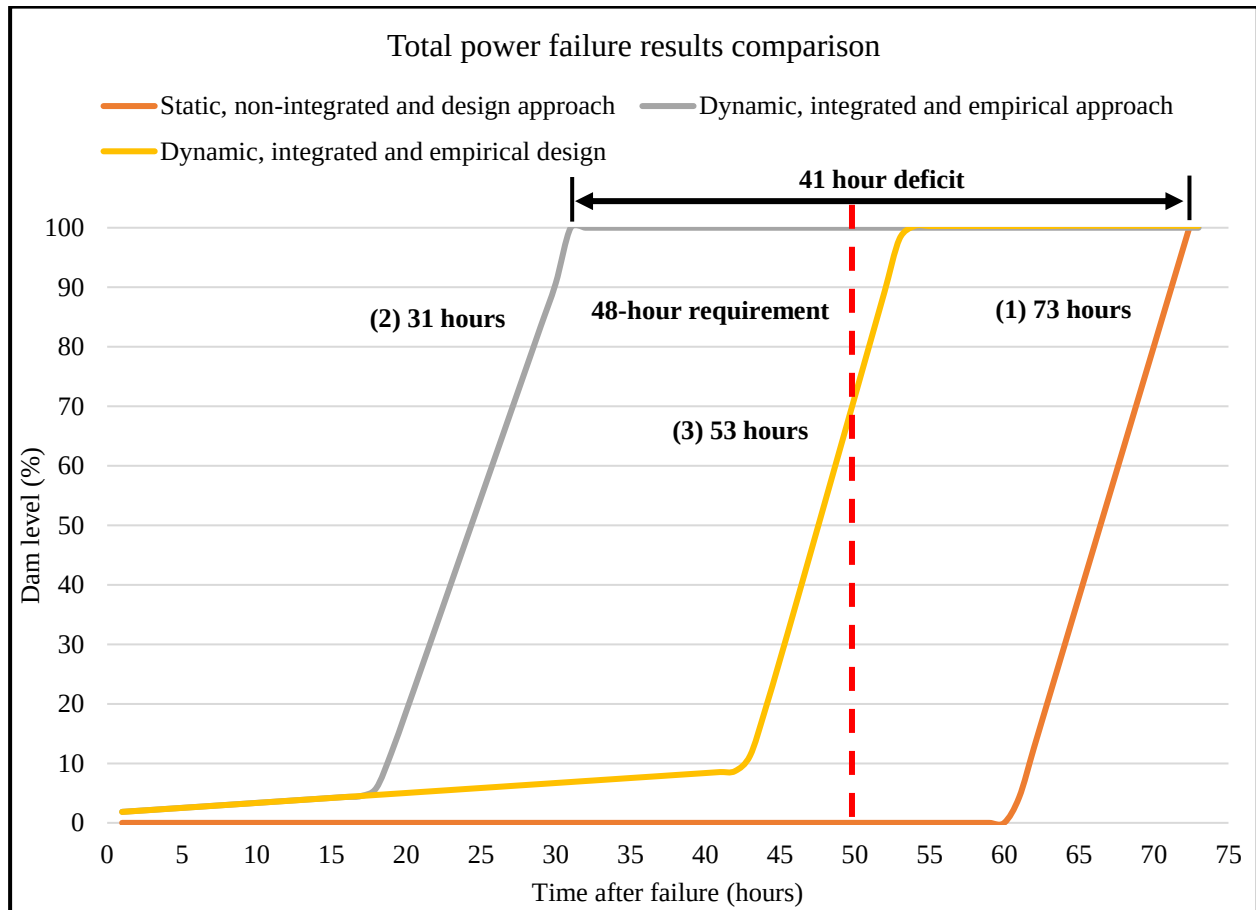


Figure 101. Total power failure results for results (1), (2) and (3)

The dynamic, integrated, and empirical design method led to the design of a system with configuration changes leading to an increase of 22 hours to a total of 53 hours response time. The simulation assisted with a successful design that allows for more than the required 48 hours after power failure.

4.5.6 Conclusion

Case study 4 showcased the novel dynamic, integrated and empirical design method being applied to a total power failure scenario. The objectives of the case study were met, and the method showed shortcomings in the current method applied which does not incorporate simulation and is based on a static, non-integrated and design method.

The novel approach showed improvements in the accuracy of more than 100% which led to further investigation regarding the total power failure readiness of the mine. The novel method was then applied

to the current configuration where it was shown that the system underperforms and does not meet the requirements. The method was then used to design a configuration that meets the requirements with optimal changes.

The proposed changes and final system after the use of the integrated, dynamic, and empirical design approach resulted in a system that meets the requirements with only minor changes. The approach allowed several configuration changes to be tested which was not possible with the current method. The final solution showed an improvement of 71% over the current system's emergency response time.

The objective of the case study is to determine the required infrastructure to ensure the mine does not flood within 48 hours:

1. **Using the proposed novel method:** The novel method was successfully used to determine the required infrastructure to reach the 48-hour power failure requirement.
2. **Showing clear improvement over the current method:** The novel method showed an improvement of 135% over the current state of the art.
3. **Without affecting current and future operations or production:** The proposed changes to reach the 48-hour requirement do not affect operations or production and ensure that the shaft will remain open in the case of a power failure.
4. **Ensuring the 48-hour power failure rule is met:** The novel method was used to design a system that meets the 48-hour rule. The final flooding time with all changes implemented is 53 hours, 5 hours above the requirement.

4.6 Cross-case conclusion



Case studies 1 to 4 showcased the use of a novel dynamic, integrated and empirical design method on real-world applications and applied in industry. Each case study was investigated using the current method and the proposed novel approach to indicate if the proposed solution improves on the current approach and provides benefit to the industry.

The results of the KPIs for each case study are summarised in Table 21. The table shows each case study's KPI result for the three approaches followed, namely:

- Static, non-integrated and design (1)
- Dynamic, integrated, and empirical (2)
- Dynamic, integrated, and empirical design (3)

Table 21. Case study 1 – 4 result summary

Case study	Case study requirement/objective (KPIs)	Unit	Sta. N-Int. Des. (1)	Dyn. Int. Emp. (2)	Dyn. Int. Emp. Des. (3)	Improvement over current method (%)	Comment
1	Temperature prediction	(°C)	NA	NA	NA	95% accurate	Aim was to verify novel method. Was not to compare with current method. An overall accuracy of 90% was achieved.
	Flow prediction	(L/s)	NA	NA	NA	94% accurate	
	Power prediction	(kW)	NA	NA	NA	95% accurate	
2	Mine C 40L temperature	(°C)	9.3	12.5	11.0	34%	Underestimation of temperatures would result in undersupply and lead to high underground temperatures.
	Mine A 23L chilled dam temperature	(°C)	11.7	14.6	11.9	25%	
3	Mine C 40L temperature FP1 offline	(°C)	11.0	12.8	11.1	16%	Over-estimation of temperature increase after failure which leads to a misrepresentation of the issue.
	Mine C 40L temperature AP1 offline	(°C)	11.0	11.5	12.6	14%	Underestimation of temperature increase after failure which shows the APs are the critical surface machinery and not the FPs as the current method suggests.
4	Shaft bottom at 100%	(hrs)	73	31	53	135%	Gross overestimation which leads to a false sense of security and emergency response time which is limited in the current configuration.

Table 21 shows the results for each case study. Case study 1 verified that the new method can accurately predict the drastic mining changes over a long period. For case studies 2 to 4, the percentage improvement in accuracy by comparing the current and novel method with one another is also listed.

Case study 2 indicates a 30% average error comparing the current method with the proposed approach. Therefore, in case study 2, a 30% under-design system configuration would be approved and result in underground temperatures higher than what is required when using the current approach. This runs the risk of production stoppages due to heat-related incidents underground due to under-supplied cooling underground because of the increased actual temperatures. Additionally, the current method provides no safety margin due to the overestimated time to flooding. Therefore, there exists no redundancy if the current approach is followed and the mine will flood before the required 48 hours.

Case study 3 shows a similar trend with an over-estimation of 16% for KPI 1 which indicates that an FP failure is a priority and should be rectified immediately. However, the novel approach indicates that an FP failure poses almost no immediate risk. The results for KPI 2 show a 14% underestimation for an AP failure which directs attention to the FPs in error. The APs are a higher priority during a breakdown as compared with the FP when using the novel approach. This leads to decreased awareness and reduced safety factors from the current method which is avoided using the novel approach.

Case study 4 has the worst over-estimation of the performance of the system with an error of 135%. The current method incorrectly determines the time for the shaft to flood by a factor of two which is concerning. The total time available after a power failure is extremely important to ensure the shaft restores power before critical components are flooded underground and a risk is posed to personnel. Therefore, the application of the novel approach improved accuracy and allowed for an updated configuration which, through minor changes, increases the emergency capacity by 71% over the 48-hour requirement.

4.7 Validation of new method



The results and comparisons from the case studies show a requirement for accurate planning and design in the mining industry. The application of the dynamic, integrated, and empirical design approach resulted in accurate planning which in turn resulted in system configuration changes that met or exceeded the clients' requirements.

The final study objectives (Section 2.7) are summarised in Table 22 showing whether the objectives of the study were met or not. Objectives 1 – 4 were described as:

1. Make use of semi-empirical models instead of design parameters to improve accuracy.
2. Account for the integrated effects of the WCS components.
3. Simulate the dynamic effects of mine WCS.
4. Improve WCS planning.

Table 22. Case study 1 – 4 objectives

Case study	Obj. 1		Obj. 2		Obj. 3		Obj. 4	
1	✓	Semi-empirical model created in PTB	✓	Several shafts and thousands of WCS integrated in the model. Included all refrigeration and water components.	✓	Simulation included dynamic boundaries and provided a dynamic response over a 24-hour period per month.	✓	Accurately predicted WCS response over 27 months of operation. Current method unable to predict WCS parameters.
2	✓	Same model used as in case study 1	✓	Closure of shaft in multi shaft complex could be simulated and the integrated effect predicted.	✓	Simulation included dynamic boundaries and provided a dynamic response over a 24-hour period for peak demand in a 6-year period.	✓	30% accuracy improvement as compared with the current method.
3	✓	Same model used as in case study 1	✓	Failure of refrigeration equipment could be simulated and the integrated effect was predicted.	✓	Simulation included dynamic boundaries and provided a dynamic response over a 24-hour period.	✓	15% accuracy improvement as compared with the current method.
4	✓	Semi-empirical model created in PTB	✓	Included all dewatering equipment and emergency capacity for a multi-level deep shaft.	✓	Simulation included dynamic boundaries and provided a dynamic response over a 72-hour period.	✓	135% accuracy improvement as compared with the current method.

Chapter 5: Conclusion and recommendations



A typical deep-level gold mine stope face (narrow reef mining)³¹.

The final remarks, conclusion and recommendations are given in this chapter.

³¹ Retrieved from <https://www.moneyweb.co.za/news-fast-news/how-technology-is-going-to-impact-on-deep-level-mining-in-sa/>

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS



5.1 Study overview

This study discussed and described a shortcoming in the mining industry and then provided a novel approach to solving the problem. The problem was described in the introduction (Chapter 1) where it was shown there is a shortcoming in planning with a specific focus on mine cooling- and water systems in deep-level mines. This is due to the complexity of mine cooling- and water systems and the difficulty in accurate planning with current tools and methods. The shortcomings of the current methods were summarised in a state-of-the-art matrix, leading to the following criteria for a successful method:

1. Planning
2. Digital twin with simulation
3. Integrated and verified simulation
4. Dynamic boundaries

Of the 39 relevant studies considered, none complied with all four criteria. Therefore, a need for successful planning WCS system planning was identified that utilises digital twinning, integrated, verified (empiric) and dynamic simulation.

A dynamic, integrated, and empirical approach was then drawn up in the development of a new simulation-based planning method (Chapter 2). The method considered the state-of-the-art methods and new simulation tools available to the industry. A method was then developed that applies an accurate dynamic and integrated model which is calibrated using empirical data.

The method results in a 95% accurate model that is used for future planning in the mining industry. The method can test several solutions to future requirements which is not possible with current methods. The method follows four major steps, namely:

1. Data acquisition and quality
2. Digital twin with simulation
3. Dynamic boundaries and verification
4. Dynamic, integrated, and empirical design

The method was applied to four case studies, each with unique requirements. Case study 1 was used as a verification of the method. The case study considered a transition period whereby mining would be reduced to zero mining at a single shaft in a mining complex with shared services. The focus was the reduction in demand as well as the reduction in refrigeration capacity as machines are to be moved to another shaft in the same complex. The method was applied and verified to be accurate over a 27-month period in predicting the water flow and temperatures.

Case study 2 focused on investigating several solutions for the closure of the shaft without interrupting or reducing production at the entire complex after closure. The method was applied, and a successful solution was developed and is in the process of being implemented. The new method was then compared with the current method. The new novel method showed clear accuracy and planning benefits over the current method.

Case study 3 showed similar improvement over the current method with the study investigating surface refrigeration loss due to breakdowns. The novel method was applied, and a mitigation strategy could be determined for the loss of cooling over three critical periods namely 4 hours (short-term), 24 hours (medium term) and 72 hours (long term). The method successfully showed the dynamic effect of loss of cooling on underground temperatures. The current method under- or overestimated the effect of cooling loss and cannot show the dynamic effect which is important when considering underground temperatures during drilling shifts.

Case study 4 considered emergency planning for a total power failure underground. All pumping activities stop during a total power failure which means the mine is at risk of flooding, losing critical infrastructure, and possibly human life. Therefore, the mine requires at least a 48-hour emergency response time before critical systems start flooding. The novel method was applied to the case study and several solutions could be tested using simulation. The method resulted in a successful emergency plan that ensures the 48-hour requirement is met. The novel method was compared with the current method which showed a major over-estimation of the available emergency response time.

The implementation of a dynamic, integrated, and empirical design method resulted in four successful solutions to the four case studies. The results are summarised in Table 23. The approach improved on the current method's accuracy and, most importantly, met the clients' requirements (KPIs).

Table 23. Summary of significant results of study

Case study	Result description	Improvement (%)
1	KPI 1 (Temperature)	94% accurate
	KPI 2 (Flow)	84% accurate
	KPI 3 (Power)	95% accurate
2	KPI 1 (Temperature)	34%
	KPI 2 (Temperature)	25%
3	KPI 1 (Temperature)	16%
	KPI 2 (Temperature)	14%
4	KPI 1 (Time)	135%

Table 23 shows the current methods as compared with the new method for their respective KPIs. The new novel planning method developed in this study provides improved accuracy in mine planning, requires smaller safety factors, and reduces unnecessary expenditure.

Whereas the current methods are rigid and lack robustness, the new method is dynamic, meaning changes are easily added to the model and its effects predicted and quantified accurately.

5.2 Revisiting the novelty contribution

A new planning method for deep-level mine WCS which accounts for the interlinked and dynamic nature of the WCS systems for improved accuracy, production and safety.

The contributions of this study were originally stated as:

- Accurate thermohydraulic simulation of integrated mine water and cooling systems.
- Improved future services prediction accuracy for deep-level mines.
- Improved future services planning accuracy for deep-level mines.
- Ease of testing several services configurations for future planning without any infrastructure or capital expenditure.

Responding to the four objectives:

- All case study simulations were calibrated to 95% accuracy as compared to current operating conditions.
- Case study 1 predicted services to an accuracy of 84 – 95% for three key areas.
- Case study 2 – 4 improved current services planning accuracy by 14 – 135%.
- Each case study could test several services configurations without any infrastructure or capital expenditure.

- A bonus objective included improved safety which was evident in case studies 3 and 4. Case study 3 showed the effect of equipment breakdown on underground temperatures and case study 4 indicated mining operations would have flooded before the required time.

The study met and exceeded all the study objectives.

5.3 Study limitations and recommendations

The study attempted to cover all possible aspects as far as possible; however, as with any study, some shortcomings exist. Some shortcomings were identified which are discussed below and recommendations for future work are provided.

Limitation 1: Only applied to WCSs

The study only focused on the water and cooling systems of the mine without considering the entire mine ventilation system and compressed air (some ventilation components were included such as BACs, CCs and CCTs used for the WCS simulation.) Incorporating the ventilation and compressed air systems will create a method that can be used for entire mine services planning based on required production targets. Additionally, safety concerns such as power failures, equipment breakdowns and underground fires can be added to the method. The resulting method will be an all-encompassing tool that can be used to plan underground and surface mine services accurately.

Recommendation 1: Apply to compressed air and ventilation system

The recommendation therefore is to expand on the current method whilst including the compressed air and ventilation systems. The proposed approach would be to separate the mine into levels and only simulate the integrated systems per level. This approach will reduce simulation time and complexity which may become too much for the user. Once each level has been simulated and confirmed to be within the requirements, a complete integrated model is suggested which can be used for scenarios and planning.

Limitation 2: Model requires significant data to be accurate

The current approach using semi-empirical model requires significant data to be accurate within the suggested 95% accuracy range. Due to the nature of underground operations, typically data loggers and sensors are subject to interference, damage, and malfunction due to the conditions and therefore have reliability issues. The accuracy of these loggers and sensors determines the accuracy of the model and subsequently the accuracy of the planning. Therefore, a shortcoming of the method is the reliance on data collected from underground sensors which may be subject to data loss, damage, incorrect readings, and

complete loss. The alternative is underground audits; however, this method of data collection is tedious, time consuming and only retrieves instantaneous data.

Recommendation 2: Automate data collection

Due to the reliance of significant data for the success of the current method, it is recommend investigating alternative methods of data collection that can improve data quality. Recommendations include installing redundant sensors, more robust sensors with higher ingress protection (IP) ratings and increasing the frequency of regular maintenance and calibration. Additionally, a task team can be created that is responsible for the accuracy of all underground sensors. If sensors have data loss or it is seen that mass and energy balances do not match, troublesome sensors can be pinpointed through intelligent software doing continuous data checking in real-time. Once the software picks up a faulty sensor an underground task team is notified to rectify the issue.

If improvement of data capture is not possible, the reliance of the approach on data can be reduced. This can be achieved through using industry standards for underground operations that are adjusted to each unique mine. The standards are either already well-understood standards found in the industry or standards developed through experience and knowledge of the mine systems at a specific mine.

Limitation 3: Only applied on deep-level mining

The approach developed in this study was intended for application on deep-level mines. However, the method should be robust enough to be applied on any thermohydraulic system. Unfortunately, it was not possible to test the method on other industries. Therefore, the robustness of the system could not be tested.

Recommendation 3: Apply method to other industries

The recommendation is to apply the approach to other thermohydraulic systems such as energy generation, opencast mining, shallow and medium level mining (platinum, coal, steel etc.). The approach will need to be adjusted slightly for other industries, but the overall principals and guidelines outlined in this study should still apply. The success of the method on other systems will indicate a robust approach that is generic and accurate over several thermohydraulic systems and industries.

Limitation 4: Not directly integrated with production planning tools

The study utilised PTB as the main simulation software which includes all required components for simulating WCS. Production data and production planning was conducted using a separate piece of

software. Therefore, time is required to obtain an answer in the production planning software before the change can be applied to PTB.

Recommendation 4: Integrated production planning and WCS software suite

An integrated production planning and WCS software suite will allow rapid response time in simulating changing environments underground. It is recommended that an integrated software suite is developed or at the least a in between solution is developed which automates the data transfer from the production planning software and WCS simulation software.

Limitation 5: Period of study too short for long term effectiveness and results

The study period was only for two years, which is relatively short in terms of the typical mine's LOM. Therefore, a conclusive result cannot be determined for longer planning periods ranging more than two years.

Recommendation 5: Continue study for 10 years

The continuation of the study for at least 10 years will assist with determining the effectiveness and accuracy of the method over the typical LOM planning period.

Limitation 6: Method and simulation require extensive WCS and mining knowledge from user

The setup and execution of the method requires a good understanding of the thermohydraulic systems and of the mining environment. The method is restrictive in its use to advanced users with prior knowledge of the system being modelled.

Recommendation 6: Utilise new machine learning techniques to lighten the load on the user

The use of machine learning for simulation is not a new practice and therefore is easily applied to the method. Machine learning could assist with calibrating the model, seeing trends that require WCS knowledge, assisting with data capture and handling and reducing the time to check and verify the method.

5.4 Concluding remarks

The literature survey and background showed a clear need for an improved approach to mine planning for services, emergencies, and equipment failure. The method developed for the need described a novel approach whereby dynamic, integrated, and empirical model was used as a powerful planning tool. The

novel approach was applied to three real-world case studies which showed a clear improvement over current methods in use in the industry.

The hope is that the new method developed in this study (Figure 15) becomes the norm in the industry and that modern technologies, such as digital twinning with simulation, are integrated into an industry which is falling behind the current pace of 4th Industrial Revolution technologies.

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APPENDIX A: ARTICLE [7]

INTEGRATED DYNAMIC SIMULATION METHOD FOR DEEP-LEVEL MINE COOLING SYSTEM PLANNING

ABSTRACT

South African gold mines are reaching record depths of over 4 km. At these depths, several key systems, such as water and cooling, are required to operate successfully and efficiently. However, the complexity of these systems increases exponentially with depth due to their dynamic and integrated nature.

A critical literature study found that current methods used to solve complex water and cooling problems exclude their integrated and dynamic aspects. These methods often lead to wrong decisions that limit productivity and safety, while wasting capital. The industry requires a model that accurately simulates and predicts the outcome of decisions by taking the integrated and dynamic effects into account.

This study considers a unique Industry 4.0 approach by applying simulation software to model the complex and integrated systems with dynamic boundaries.

The model was then applied to a multi-shaft mining complex that is facing the closure of a shaft reaching the end of its Life of Mine (LOM). The closing shaft is integral to the complex's cooling needs but, if left open solely for this reason, significant costs will be incurred. The simulation approach was used to identify several solutions to closing the shaft in question without affecting cooling on the complex. A favourable combination of solutions was selected resulting in a LOM benefit of R2.4 billion.

Keywords: Industry 4.0, Simulations, Integrated, Dynamic, Deep-level mines, Future planning, Water and cooling system improvements

1. INTRODUCTION

During the 20th century large capital was made available for new South African mining developments through foreign and government investment [1]. The industry has since seen a decline in new investment forcing the industry to go deeper with aged infrastructure [2]. Current mining operations are reaching record depths of over 4 km which poses some interesting safety and operational challenges [3].

At the abovementioned depths, the mine virgin rock temperature can reach up to 60°C [4]. Safety regulations prohibit miners from working in workplaces where wet-bulb temperatures exceed 32.5°C [5]. It is therefore impossible to mine successfully and safely at extensive depths without the intervention of

mine cooling systems [4,6]. The effective operation of the cooling- and water system also has a direct effect on the performance and safety of the mine and its operations [7].

Deep-level mine cooling systems consist of three main elements, namely dewatering, refrigeration and cooling, and water reticulation [8]. Each of these elements consists of thousands of components (e.g. dams, pumps, chillers, turbines, fans, heat exchangers, etc.) connected via kilometres of piping. Each component in the system has a unique dynamic response to environmental changes with a direct effect on components up- or downstream [9],[10]. Figure 1 is a simplified illustration of the integrated elements of the mine cooling system.

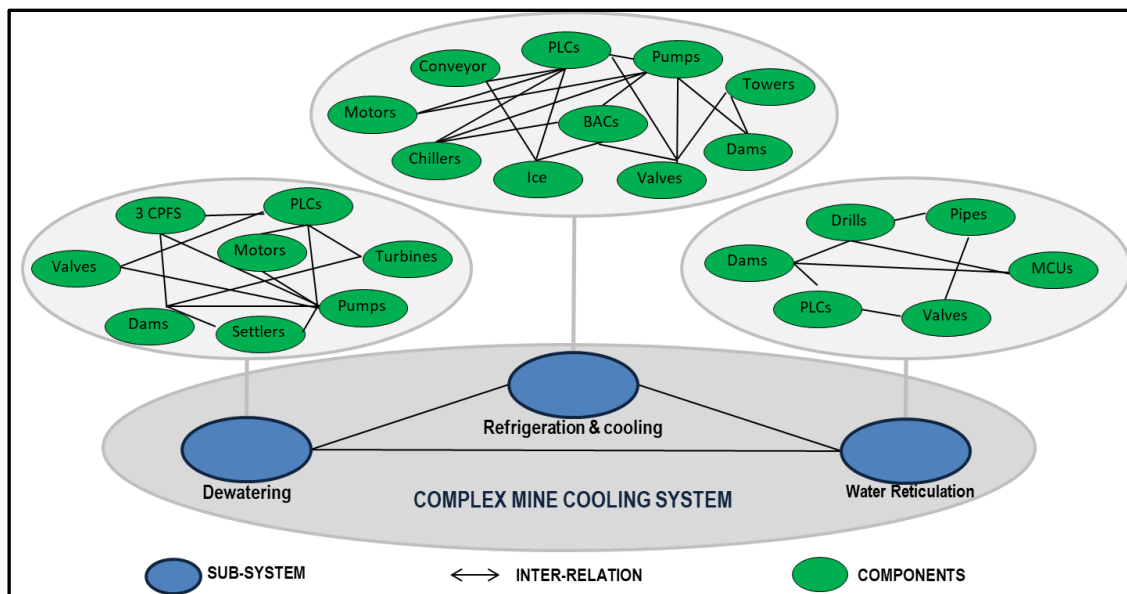


Figure 1. Simplified illustration of a complex mine cooling system (adapted from [8])

Mining in general is also known to be dynamic in nature. This is due to the varying production schedules of different mining stopes (mining areas) located at different parts of a mine [11]. Figure 2 is an example of a medium-term production plan. Each stack represents the production from each stope for a specific month.

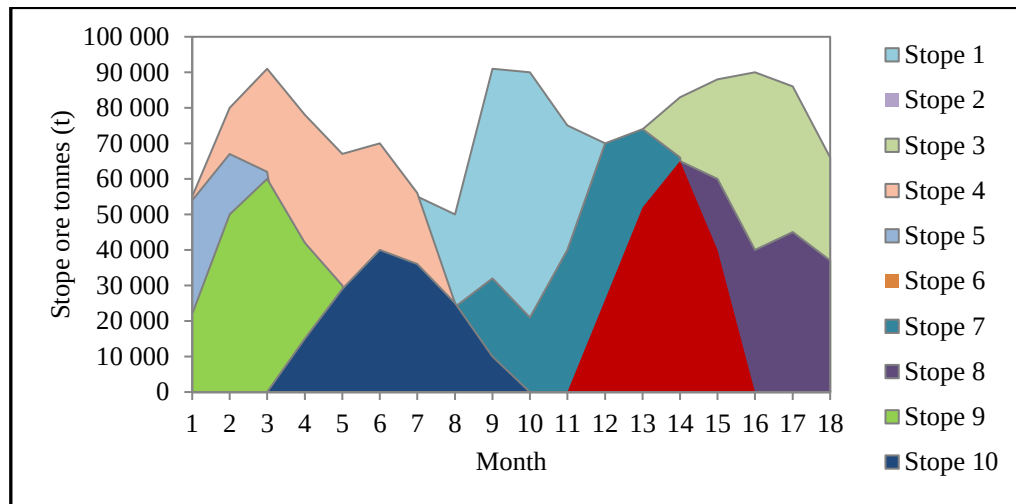


Figure 2. Medium-term production schedule (adapted from [11])

As the production varies for different areas of the mine, the cooling demand at those areas is also affected [12]. To match the cooling demand, the cooling supply needs to be adjusted. This means that operational cooling decisions need to be revised regularly. These decisions *inter alia*, include future mine planning needs and continuous system improvements to ensure optimal cooling is supplied at the lowest cost.

The dynamic, integrated, and complex nature of mine cooling systems requires that the mining industry adopt new Industry 4.0 tools to assist with complex operational questions. One tool that can address this need is simulation. Simulation is an important technology used to improve planning, decision-making and design [13]. Simulation technologies are known to assist engineers in solving integrated, dynamic, and complex problems [14].

An investigation was done into the current mine modelling and simulation methods for mine planning and improvements. Some studies considered planning items such as hoist scheduling [15], mathematical models of subsea gold mining planning [16], predictive maintenance for vertical mills [17], or modelling groundwater [18]. All of these studies were focused on a single system within an integrated model. Most planning methods are for open pit, coal, and shallow mining [19-32], all of which are a simpler form of mining with far fewer complexities than deep-level mine cooling systems.

The literature study also found several simulation studies on deep-level mine ventilation systems [7,33-39]. Most of these studies focus on ventilation-related challenges. Only a few of the studies recognise the importance of cooling systems. However, the few studies that included cooling systems did not address the integrated effects of the various components of mine cooling [10,36,40-42].

A study done by Mare [8] also indicated that the majority of simulation studies conducted in mine cooling systems only focus on a specific system in isolation, and do not consider the integrated effect of all components of the mine cooling systems. Most of the simulation methods also only considered steady state conditions, rather than dynamic conditions. Steady state simulation is often used for design purposes, where large safety factors are included [43].

Mare [8] also aimed to address the integrated and dynamic simulation need associated with deep-level mine cooling. However, the method used by Mare focused on energy management and energy savings. He did not consider the challenges associated with future planning and cooling service improvements. The same applies for studies [9,40,41,44].

From the literature review it is clear that the mining industry lacks an integrated and dynamic mine cooling simulation method to address future planning and service improvement. This is surprising as the mining environment is constantly changing, dynamic and extremely integrated.

2. METHODOLOGY

The constantly changing, dynamic and integrated nature of the mining environment, along with the quick turnaround times, necessitated a simplified method. The method was developed into a four-step process that takes information and data and transforms them into an integrated simulation model of the mine.

The simulation model is used as a tool to “implement” several solutions virtually, and to run “what-if” scenarios to determine the outcome of the solutions. The four-step process is shown in Figure 3.

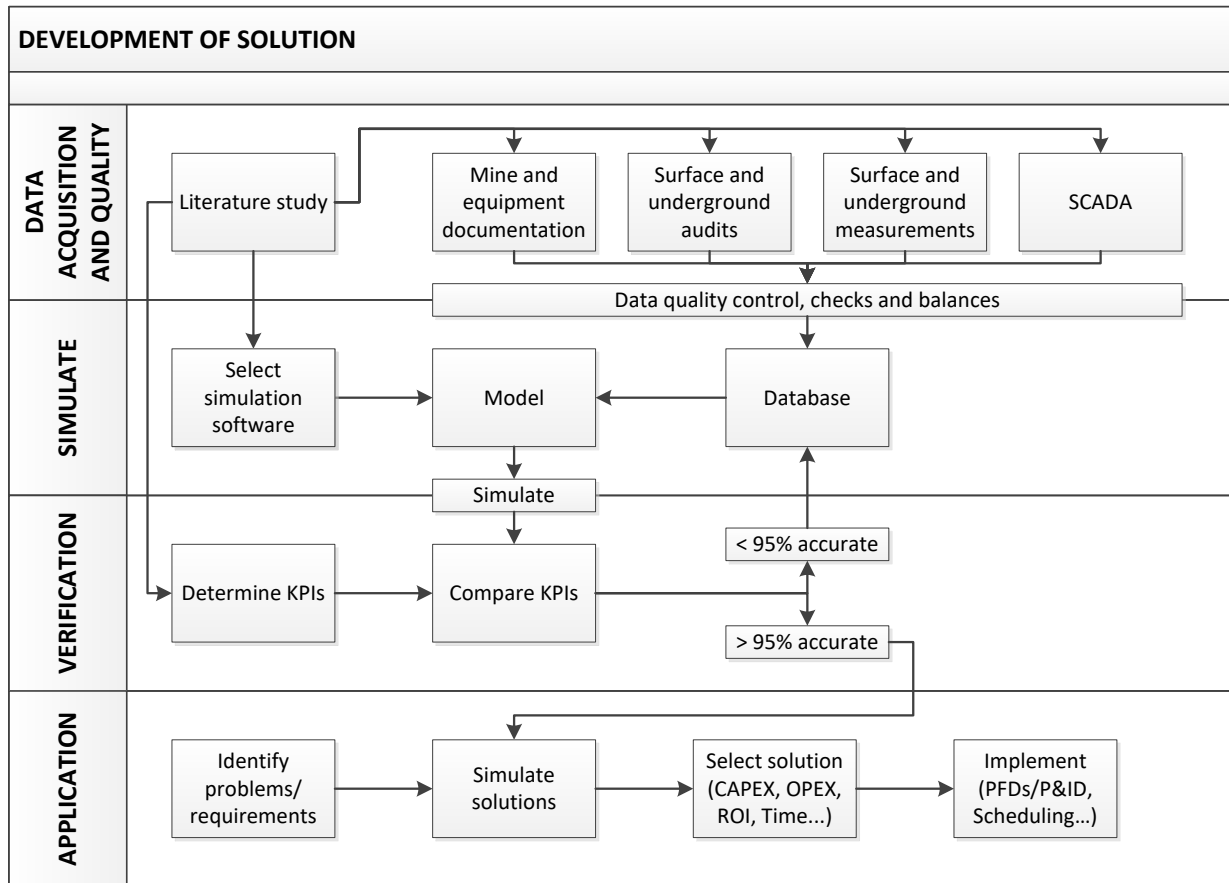


Figure 3. Four-step process flow diagram for developing an integrated and dynamic mine planning decision-making tool.

The method results in a fully integrated and dynamic simulation tool that is an exact replica of the actual system and can be used for several decision-making applications.

2.1 Data acquisition and data quality

Data is the fundamental driving force behind Industry 4.0 tools and modern systems [45]. Without sufficient data, these systems are as accurate as the user's best guess [46]. Therefore, obtaining significant amounts of data on the system to be digitalised is of high importance. Typical data required includes water- and air flow rates, temperatures, energy consumption, valve statuses, and pressures. Many different platforms are available for data acquisition. The most common in the mining industry include supervisory control and data acquisition (SCADA) systems, manual measurements (audits), and paper logs.

Once data has been collected, the quality of the data needs to be determined. Checks used include maximum and minimum limits, standard deviation limits, and balance checking. With sufficient data available it is possible to construct a digital twin of the system.

The final step is underground auditing. Underground audits provide a visual perspective not achievable with documentation and SCADA data. The exact locations, sizes, specifications, and conditions are obtained from audits. Additionally, measuring equipment is used to confirm SCADA data or obtain measurements not found on the SCADA system.

2.2 Digital twin with simulation

The first step after data acquisition and quality control is to decide upon a simulation tool. In the case of mine cooling systems, Process Toolbox (PTB) is the only software able to simulate all integrated and dynamic mining systems fully [47]. The inclusion of all major systems into the simulation software allows for easy integration across all the systems and approaches a true representation. This makes it an obvious choice to model the mine cooling system accurately and successfully.

The PTB software is a semi-empirical thermohydraulic simulation tool that requires prior knowledge of the systems and significant data [47]. The cooling system consists of thousands of components that are added to the simulation model in steps. Once all components are added to the simulation, it is an exact digital representation of the water- and cooling system. An integrated and dynamic simulation can consist of thousands of components and several dynamic boundaries.

Each component requires an input or specification to calibrate it according to the actual equipment. This is achieved through using the acquired data as inputs to the components. The semi-empirical nature of the software then specifies the equipment according to the data. This ensures that components or equipment are modelled exactly as they are in the mine. Once all components have been calibrated or specified the model needs to be verified.

2.3 Verification

A digital twin is only as good as its accuracy. Therefore, it is extremely important to verify the simulation model against actual data. Large integrated models can have upwards of 1 000 dynamic profile inputs and 2 000 dynamic outputs. It is therefore important to decide upon certain key areas to focus on and compare with the actual system to confirm the validity of the entire model. These focus areas are called key performance indicators (KPIs).

The model is then compared with actual data using the KPIs and calibrated to within 95% of the actual system. Calibrating the model to 95% accuracy is sufficient to provide a representative model. This falls within the typical accuracy of measuring equipment [48]. The calibrated model is then modified to represent system changes and predict the outcome of several scenarios. These outcomes are then used for decision-making purposes.

2.4 Application

Once a 95% accurate model has been achieved, it is possible to apply the model to several scenarios (initiatives). The first step is to define the scope and identify any issues or problem areas. This step is critical and requires significant research and data gathering.

From the investigation, a scope can be defined and the requirements identified. Several simulation solutions can then be developed. The solutions can include *inter alia* simple infrastructure changes, changes to control philosophies, complete redesign, or installation of new infrastructure. Now solutions can be applied in the virtual environment, their effect on the system quantified, their feasibility determined quickly and without significant cost.

Once a satisfactory solution has been identified through several iterations it can be implemented. The solution can consist of either a single change to the system or a combination of solutions. The final step is to define the solution in depth, listing each component or system change and associating a cost to each item as well as its LOM benefit.

3. RESULTS AND DISCUSSION

The approach was applied to model a three-shaft mining complex using PTB. Mine A is connected underground and on surface to Mine B and Mine C. The total complex is 15 km wide and 3.6 km deep. All three shafts are operational and require cooling. A schematic layout of the three-shaft cooling system is shown in Figure 4.

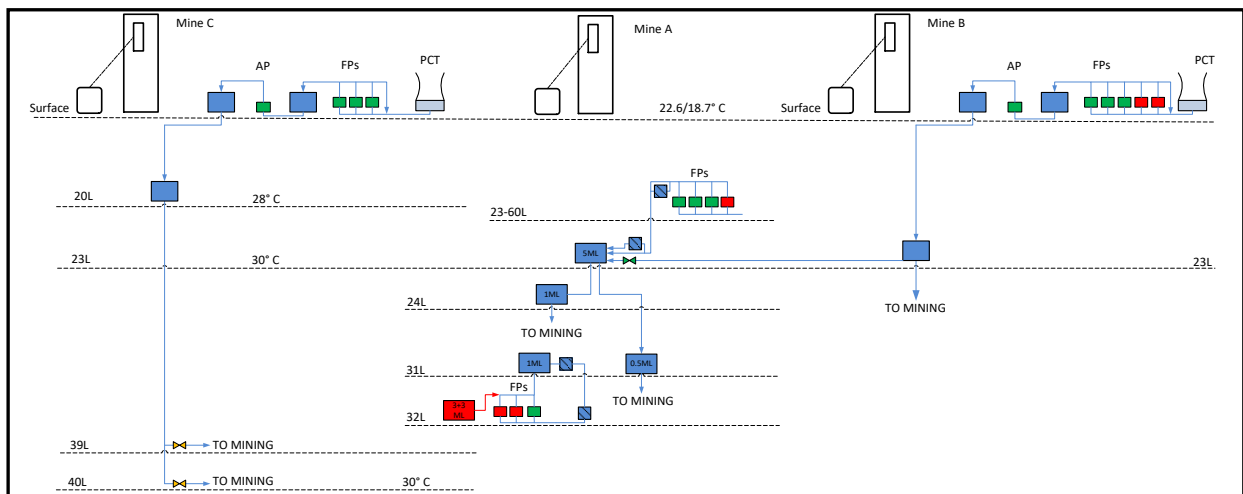


Figure 4. Simplified schematic layout of three-shaft complex cooling supply.

Mines B and C supply chilled water on surface using a two-stage refrigeration system. The system's main purpose is to supply chilled water for mine cooling, drilling, cleaning, and dust suppression [40]. Chilled water is produced using a refrigeration cycle or fridge plant (FP). The FPs feed into a network of piping and dams which leads to several "water users". These users include equipment such as cooling devices (bulk air coolers and cooling cars), mining devices (drills) and cleaning devices (water jets) [8]. The annual electricity cost on this system alone is in excess of R200 million.

3.1 Data acquisition

Data for the three shafts was obtained from the SCADA system, mine documentation, and surface and underground audits. The data was combined, checked for quality, and processed. The first step is mine documentation: this might include items such as pump motor plates, pump curves, piping layouts and diagrams etc.

The second step uses the mines' SCADA system. An example of the calibration data used for the surface fridge plants at Mine A is shown in Figure 5.

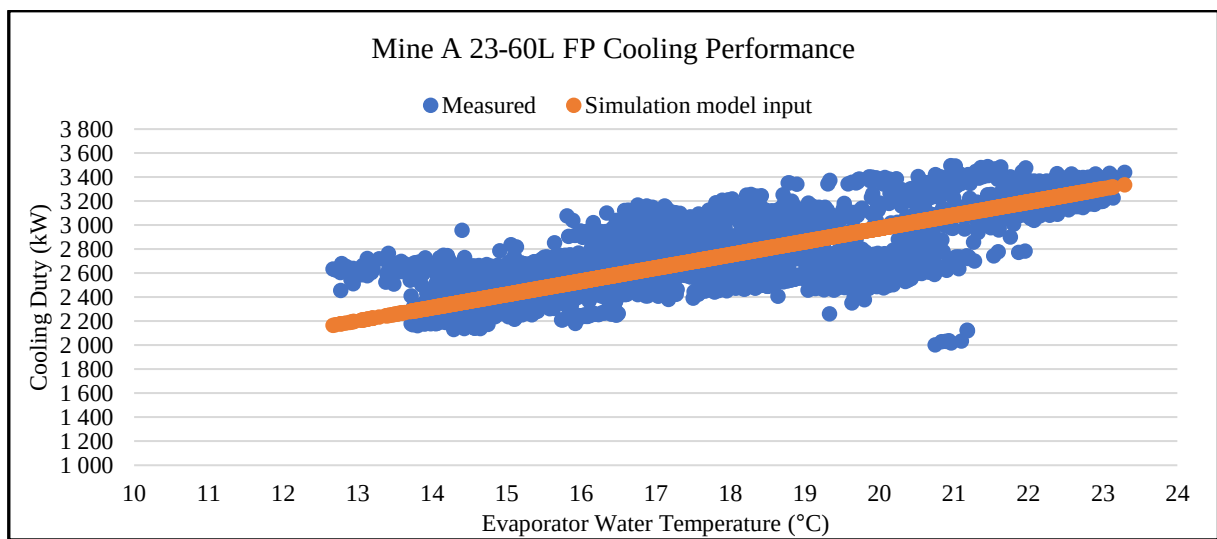


Figure 5. Mine A underground FP calibration data.

The data is detailed and provides an exact map of the operational performance of the machine over a wide spectrum of operating conditions.

In addition to calibrating the equipment, dynamic boundaries also need to be considered. These include surface and underground atmospheric conditions, water temperatures, dam levels and water flows. An example of a dynamic boundary is shown in Figure 6.

Figure 6 shows the dynamic profile for chilled water used underground at Mine A. The profile is determined using underground flow sensors, dam level indicators and mass balance checks, using an average demand profile over an entire operational month.

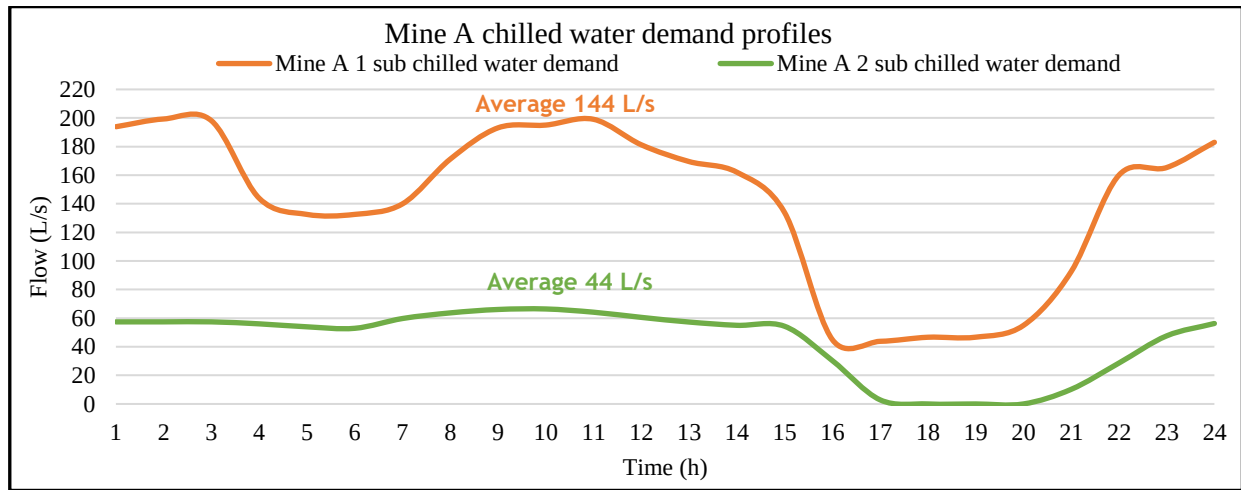


Figure 6. Mine A's dynamic underground chilled water demand.

3.2 Model

The final model consists of more than 2 500 integrated components and 10 dynamic boundaries. A snapshot of the 3D integrated mine cooling simulation for the mining complex is shown in Figure 7.

The model includes all critical cooling systems found in Mines A, B and C. The three shafts are all connected underground and on surface. Mine A is connected to Mines B and C on 23L (1 800 m underground), and Mines B and C are connected on 40L (3 600 m underground). The three shafts are all reliant on each other (integrated), therefore each system is of importance for the entire complex.

The model is separated into two major systems, dewatering and cooling supply systems. The cooling supply provides chilled water to underground equipment to ensure correct working place conditions and assist with drilling operations. The dewatering systems ensure the chilled water is sent down from surface and the underground fissure water is pumped to surface avoiding flooding underground. The two systems are then combined to form a complete digital twin of the water- and cooling system. The enlarged section in Figure 7 shows the level of detail modelled in the simulation. The figure also shows the surface FPs of Mine B.

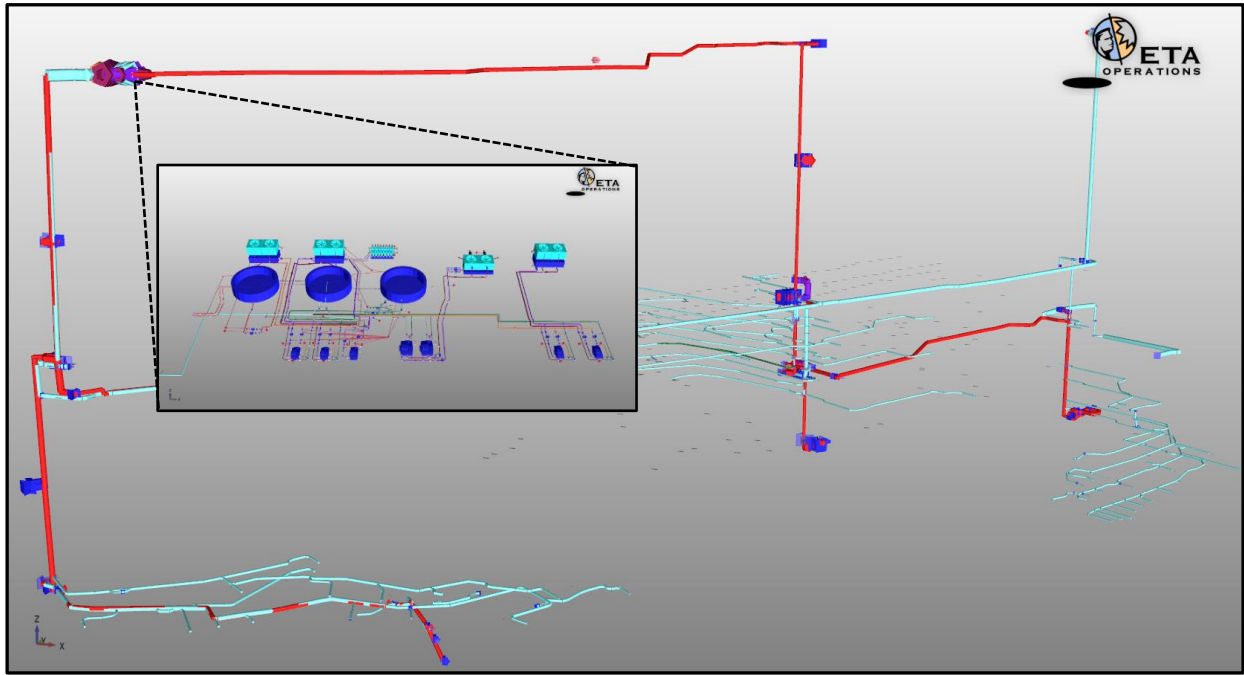


Figure 7. Mines A, B and C simulation model.

3.3 Verification

Table 1 shows the KPI comparison for several key points found in the three-shaft water- and cooling system. The model is refined until a 95% accuracy is achieved. The calibration stage is most time-consuming, requiring significant iterations. However once 95% accuracy has been achieved the model is deemed an accurate representation of the actual system [48].

Table 1 shows an overall calibration accuracy of less than 5%. The next step compares the dynamic profiles of the KPIs. One such example is shown in Figure 8.

Table 1. Three shafts complex KPI comparison of simulation with actual.

MINE C CHILLED WATER							
No.	Area	Equipment	Measurement	Unit	Actual	Simulation	% Error
1	Surface	Hot dam	Inlet/outlet flow	[L/s]	145	142	2%
2			Level	[%]	70	67	4%
3			Temperature	[°C]	27	27.3	1%
4		FP evaporator	Inlet temp	[°C]	18	17.6	2%
5			Inlet flow	[L/s]	260	258	1%
6			Outlet temp	[°C]	5.5	5.3	4%
7			Outlet flow	[L/s]	260	258	1%
8			Cooling duty	[kW]	17 000	16 500	3%
9			Compressor power	[kW]	3 400	3 355	1%
10		Intermediate dam	Inlet/outlet flow	[L/s]	260	258	1%
11			Level	[%]	65	68	5%
12			Temperature	[°C]	5.6	5.4	4%
13		AP evaporator	Inlet temp	[°C]	5.6	5.4	4%
14			Inlet flow	[L/s]	260	255	2%
15			Outlet temp	[°C]	2	2.1	5%
16			Outlet flow	[L/s]	260	255	2%
17			Cooling duty	[kW]	8 000	7 950	1%
18			Compressor power	[kW]	2 000	1 967	2%
19		Chilled dam	Inlet/outlet flow	[L/s]	145	143	1%
20			Level	[%]	66	67	2%
21			Temperature	[°C]	2.1	2.2	5%
22	Underground	20L chilled dam	Inlet/outlet flow	[L/s]	145	143	1%
23			Level	[%]	66	64	3%
24			Temperature	[°C]	6.2	5.9	5%
27		39L	Flow	[L/s]	80	79	1%
28			Temperature	[°C]	10.2	10.1	1%
29			Pressure	[kPa]	1 750	1 730	1%
30		40L	Flow	[L/s]	65	64	2%
31			Temperature	[°C]	10.5	10.3	2%
32			Pressure	[kPa]	1 650	1 630	1%

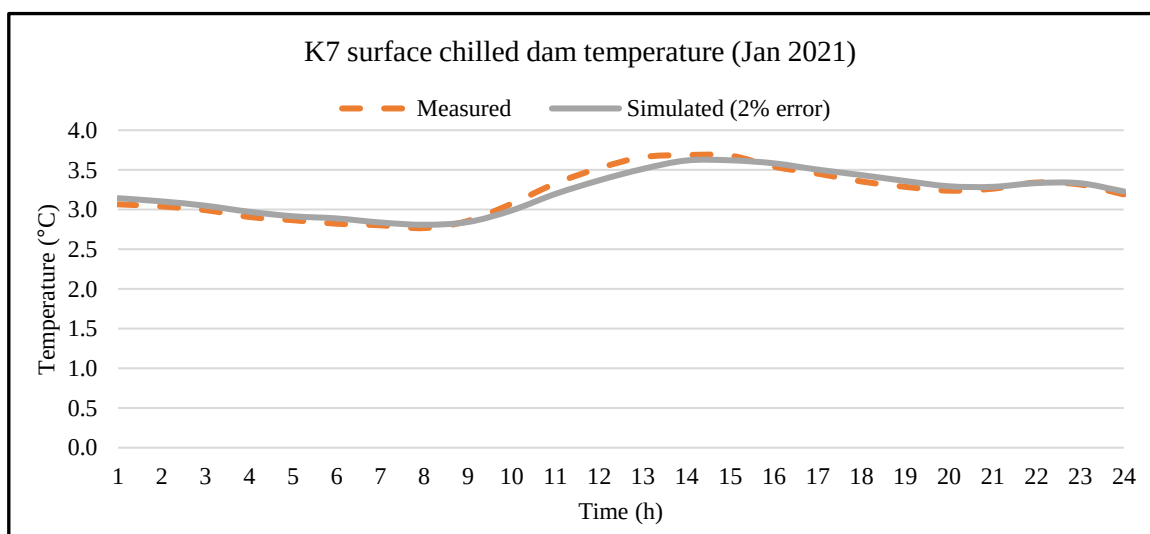


Figure 8. Simulated vs actual Mine C surface chilled dam temperature.

3.4 Application

The case study considers the closure of Mine B in 2022. The care and maintenance costs of keeping Mine B operational to ensure chilled water supply to Mine A is significant (approximately R70 million per annum). Therefore, it is beneficial for long-term planning to consider an alternative solution to supply Mine A with chilled water.

To close Mine B successfully, underground water temperatures should not be affected. Therefore, two key underground temperatures had to be considered for a successful solution.

The two key performance indicators (KPIs) were:

1. Mine C 40L chilled water temperature, and
2. Mine A 23L chilled dam temperature.

The requirements were set at 11°C and 12°C respectively, shown in Figure 9 as an orange and blue box. The underground water flows were also considered, and the solution had to meet current demands with a 10% safety factor. The requirements are summarised in Figure 9.

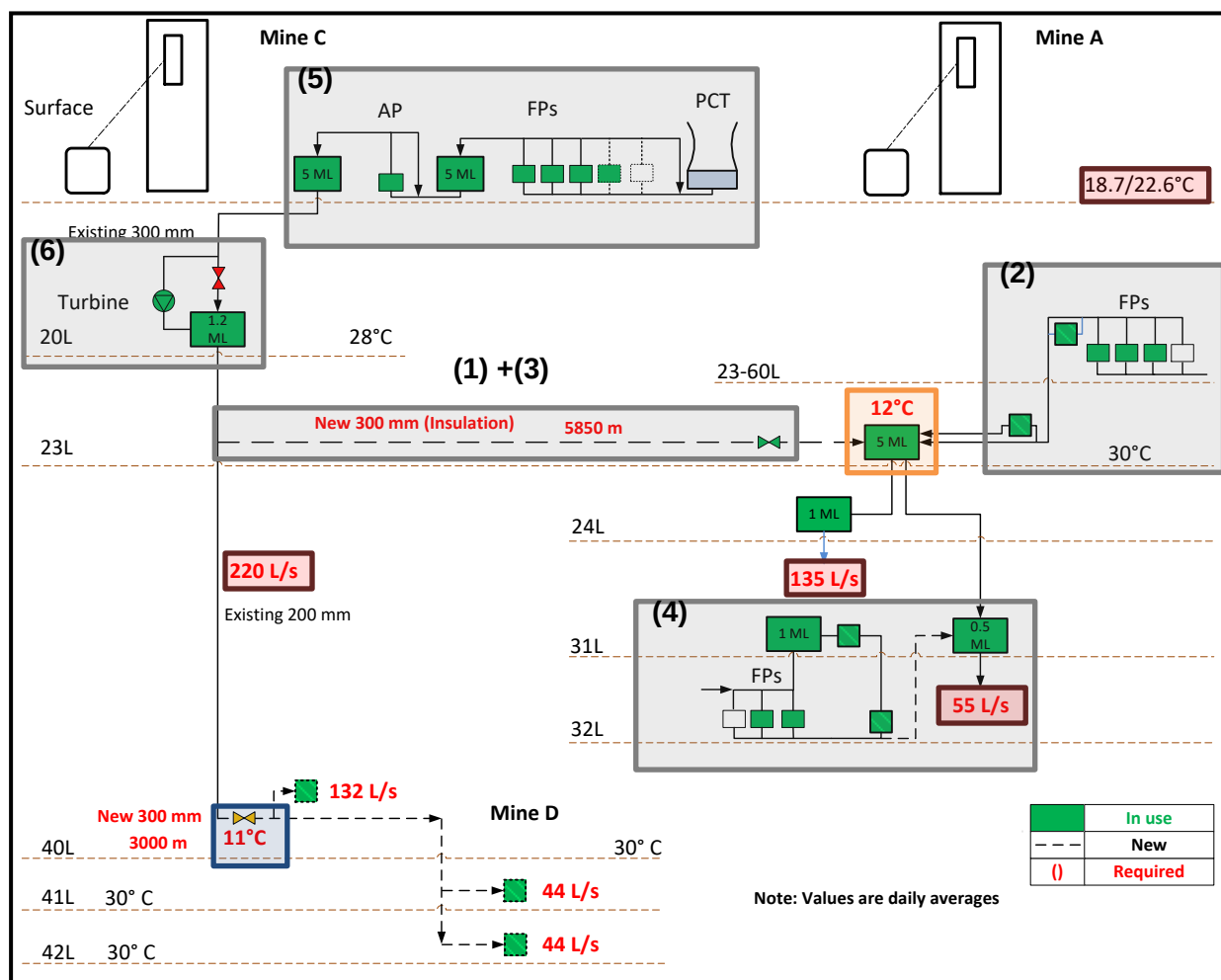


Figure 9. Possible Mine B closure solutions.

The simulation tool was then used to investigate several solutions to close Mine B and meet the requirements. The solutions each considered a system change which affected underground temperatures. More than 50 possible solutions (system changes) were evaluated. However, for simplification purposes, only six are considered in this study. The system change areas are shown in grey on Figure 9 and their impact on the two KPIs are summarised in Table 2.

Table 2. Integration scenario results.

Solution	Mine C FP supply [L/s]	Mine A FP supply [L/s]	Configuration	KPI 1 [°C]	KPI 2 [°C]
			-		
1	350	60	New K7 – K1 column	13.2	13.8
2	320	90	Soln 1 + K1 23-60L FP	12.1	13.4
3	320	90	Soln 1 + 2 + Insulated K7 - K1 column	12.1	12.9
4	310	100	Soln 1 + 2 + 3 + Utilise 32L FPs	11.8	12.5
5	310	100	Soln 1 + 2 + 3 + 4 + Move 2x K3 FPs to K7	9.3	11.5
6	310	100	Soln 1 + 2 + 3 + 4 + 5 + K7 20L turbine	7.4	10.4

The iterative approach led to a combination of several possible solutions to maintain Mine A's chilled water supply. Solution 5 met the criteria without the use of a water turbine as it was part of the scope not to rely on a single piece of machinery to achieve chilled water temperatures. However, the addition of the water turbine further reduces underground water temperatures and generates power.

The final results for the two key requirements areas are shown in Figure 10 which clearly indicates that the mine's requirements were met and exceeded. The average daily temperature of 23L chilled dam and 40L chilled water was 0.4°C and 1.4°C below their temperature requirements of 12°C and 11°C respectively.

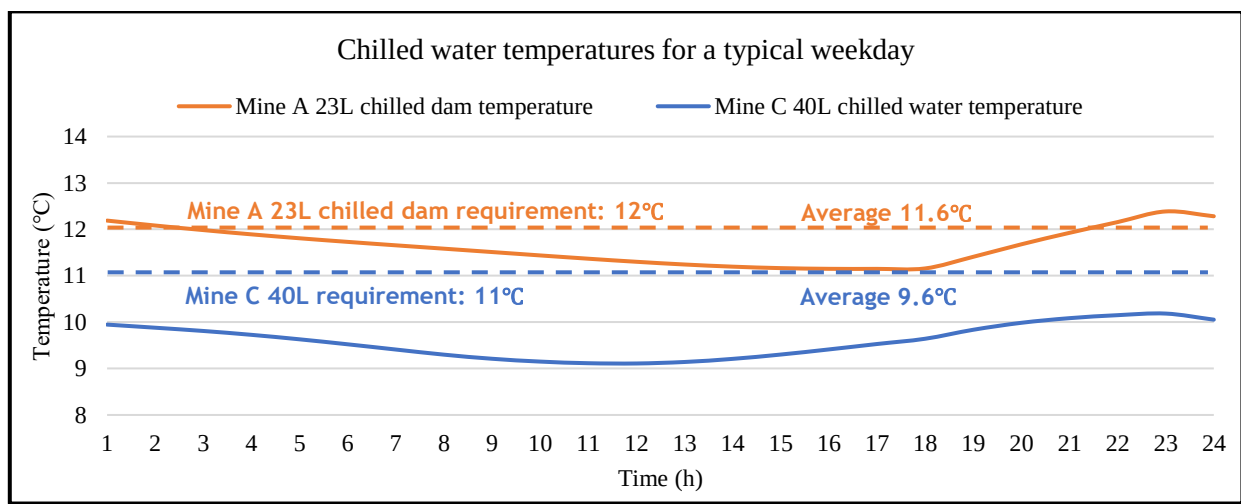


Figure 10. Mine A 23L chilled dam and Mine C 40L chilled water temperatures.

The feasibility of the project was then considered using several factors, most important of which was the cost and LOM benefit. The project costs to close Mine B completely amounted to R97 million, broken down in Table 3.

Table 3. Total cost required to close Mine B.

No.	Description	Cost
1	K7 surface FP critical spares	R14 640 000
2	Moving 2x K3 FP to K7	R45 580 000
3	K7 - K1 underground column	R26 820 000
4	K7 - K1 overland column	R9 450 000
Total		R96 490 000

The cost to implement Solution 5 was then compared with the estimated cost savings of closing Mine B (Table 5). This was done by estimating the cost of care and maintenance of Mine B if it were to remain open to supply chilled water to Mine A. The total cost savings per year from care and maintenance costs were calculated at approximately R73 million.

Table 4. LOM benefit from Mine B closure.

No.	Description	Cost [R/yr.]
1	Payroll 1	R18 600 000
2	Payroll 2	R10 200 000
3	Contractors	R7 700 000
4	Water	R320 000
5	Stores	R24 600 000
6	Electrical energy	R11 200 000
Yearly cost saving (2020 tariffs)		R72 620 000
LOM net benefit (16 years at 5% inflation)		R2 413 100 000

The calculated total LOM benefit over 16 years amounts to R2.4 billion, including inflation. The significant cost savings over the 16-year period assists in the decision-making process.

4. CONCLUSION

This paper discussed a process to successfully create a dynamic and integrated simulation of a deep-level mine cooling system. The process was then applied to a three-shaft integrated mining complex with over 2 000 integrated cooling components. Several dynamic boundaries were quantified and applied to the simulation. The model was then verified to within 95% of the actual system to create a near exact model of the water- and cooling system.

The simulation was then applied for decision-making regarding the future planning of a three-shaft mining complex. A critical cooling supply shaft is approaching its end of LOM and the effective closure of the shaft could result in a significant benefit over the entire future LOM.

The use of modelling helped generate several possible solutions for the successful closure of Mine B. The process, and resulting digital twin, produced a final solution suggesting R97 million expenditure in new infrastructure at current shafts to achieve a grand total LOM benefit of R2.4 billion.

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APPENDIX B: DATA EXTRACTED FROM SCADA SYSTEM

2020/08/01 01:00	88.7	60.1	26.4	13.2	315.2	2.2	109.7	14.6	17.8	10.1	4.1	217.7	56.2	814.9	320.7	67.6	0.0	63.2	824.2	320.5	68.1	0.2	74.6	93.6	27.617293	12.8685806	4.13493836	6.980462002	52.79794377	19.3897242	22.9120997		
2020/08/01 03:00	3.1	-84.1	26.4	13.2	315.0	2.2	109.6	14.8	18.0	10.0	4.1	216.0	56.5	822.0	319.9	68.1	0.2	64.8	802	319.9	68.1	0.2	75.1	94.2	26.5192041	12.84869102	4.91224888	52.7978027	19.38776241	22.91776241			
2020/08/01 05:00	3.0	-38.8	26.2	12.5	313.7	2.3	265.5	14.6	17.7	9.7	3.9	212.7	55.1	814.5	320.1	67.7	0.2	63.6	59.0	319.5	67.9	0.2	73.6	158.1	26.18213921	13.11700722	29.70004289	2.459714642	51.67477751	19.33084623	22.73528437		
2020/08/01 04:00	119.9	81.6	25.9	13.2	312.7	2.5	277.2	14.5	17.7	10.0	4.0	229.8	56.1	813.7	319.7	67.6	0.2	64.8	59.8	319.6	67.8	0.2	74.1	178.5	27.11513188	13.38122098	30.20955151	2.886316466	51.81305151	19.3931434	24.76516044		
2020/08/01 06:00	179.2	157.7	25.5	11.5	318.1	2.5	276.7	14.1	16.9	8.4	3.2	271.1	51.4	791.1	319.1	66.7	0.2	55.5	54.4	787.8	318.5	68.0	0.2	61.5	282.9	21.91118185	13.48454502	30.75960207	12.95053071	19.23426605	23.84715217		
2020/08/01 07:00	168.9	155.6	25.4	10.7	314.7	2.5	275.2	13.1	15.0	7.4	2.6	240.7	48.6	764.4	319.0	65.1	0.2	50.2	50.3	752.2	319.0	66.8	0.2	52.9	283.6	29.45465451	13.48566908	30.8592275	6.348747878	53.91571614	19.34015467	23.9271208	
2020/08/01 08:00	2.4	-32.3	25.4	10.5	315.4	2.4	271.7	13.6	17.1	10.0	4.3	245.6	47.3	754.1	319.4	64.7	0.2	48.7	48.9	741.0	319.8	66.2	0.2	50.8	282.7	28.95717611	13.48683889	30.7966991	6.78869723	53.64680219	19.4283752	24.02269667	
2020/08/01 09:00	2.5	-32.2	25.2	11.3	316.4	2.5	270.6	13.8	17.1	10.4	4.5	250.0	56.0	799.1	320.8	65.5	0.2	66.3	59.1	830.5	320.0	68.3	0.2	74.3	282.6	28.97660289	13.46117895	30.57797481	6.04714387	51.53257307	19.45447701	24.00591455	
2020/08/01 09:00	50.0	-0.4	25.1	11.2	315.4	2.5	267.0	14.6	17.4	8.4	3.2	258.0	51.7	805.8	320.4	67.4	0.2	54.8	54.5	803.1	319.2	68.1	0.2	60.3	282.4	29.01937403	13.6564638	30.65850273	6.05941842	53.52788254	19.4996512	23.85525402	
2020/08/01 10:00	143.0	51.9	25.1	11.0	314.4	2.5	242.8	14.9	17.7	8.5	3.2	255.1	52.4	815.8	319.7	67.9	0.2	54.8	54.5	803.7	320.7	68.3	0.2	59.2	284.9	31.28645213	13.59284515	13.59589776	5.75911299	54.96117169	19.82624718	25.1126973	
2020/08/01 11:00	144.1	66.3	25.4	11.3	314.1	2.7	77.1	15.5	18.4	9.0	3.6	253.3	54.3	835.9	320.3	68.4	0.2	57.6	57.1	830.4	320.8	69.2	0.2	60.5	0.3	30.78251225	12.76972021	13.59347142	11.35729513	53.83412648	19.42929813	24.26488426	
2020/08/01 12:00	139.4	88.3	26.7	14.2	314.7	3.6	77.7	16.6	20.3	11.7	5.0	252.3	63.8	897.2	319.3	70.6	0.2	78.1	68.7	903.4	320.3	71.6	0.2	80.9	0.3	29.01937403	13.6564638	30.65850273	6.05941842	53.52788254	19.4996512	23.85525402	
2020/08/01 13:00	128.1	107.3	27.4	11.3	302.0	4.1	78.5	17.6	21.0	11.3	4.1	172.0	61.5	967.6	320.7	72.8	0.2	69.3	65.1	914.4	320.2	72.9	0.2	72.8	0.3	29.47031034	13.48439954	31.03921975	5.148102318	53.82073961	19.51321229	24.40570888	
2020/08/01 14:00	122.0	116.9	27.9	9.4	298.4	4.0	89.2	15.9	18.5	7.3	2.4	144.5	51.5	852.1	319.2	71.0	0.2	49.8	52.2	830.4	319.3	69.9	0.2	49.4	13.6	29.65880816	13.61032704	31.07067696	11.23617394	53.38468351	19.44227209	25.91354174	
2020/08/01 15:00	124.1	121.6	28.3	9.9	288.6	3.8	156.1	14.8	17.2	6.9	2.1	154.4	49.2	818.3	320.4	68.6	0.2	45.4	48.9	793.0	320.4	68.3	0.1	45.4	110.4	29.40524827	13.8505935	32.122941	6.126478524	53.91571614	19.34015467	24.16222153	
2020/08/01 16:00	122.4	121.1	28.4	10.7	289.7	3.5	156.1	14.9	17.6	8.1	2.9	231	50.7	51.2	820.2	320.3	68.5	0.2	49.1	52.9	803.4	321.1	68.5	0.1	52.6	131.1	32.6172359	16.21278364	33.0397481	6.33381065	54.79819048	19.9012863	24.86904607
2020/08/01 17:00	88.7	71.9	28.4	9.9	290.0	3.4	156.3	15.1	17.8	7.8	2.7	164.4	50.7	822.4	319.3	68.8	0.2	49.7	52.4	819.2	319.4	68.6	0.2	52.1	155.2	31.20170218	13.58181515	13.61706511	7.25307382	53.88772387	19.7680849	24.46120959	
2020/08/01 18:00	-0.1	-27.1	27.6	8.5	288.2	3.0	157.1	14.3	16.6	6.0	1.7	158.3	46.8	794.4	318.9	69.1	0.2	41.3	47.0	771.5	318.6	68.2	0.2	40.8	172.2	31.09645075	13.63876569	31.43717163	52.6560507	19.80022882	23.2364231	24.93010987	
2020/08/01 19:00	1.8	-30.8	26.7	8.7	298.4	2.7	158.7	13.5	15.9	7.2	2.3	159.5	47.1	775.0	321.0	66.6	0.2	45.2	48.9	761.7	320.8	68.0	0.2	48.4	188.7	28.15445929	13.52138082	30.45881284	6.138001324	53.23180804	19.21545605	22.73010987	
2020/08/01 20:00	2.6	-31.0	26.8	9.8	298.4	2.5	159.5	13.2	15.7	7.6	2.6	174.2	47.4	769.1	321.6	66.2	0.2	45.5	48.5	755.4	321.8	66.8	0.2	49.8	195.3	27.00540407	13.11818622	29.87057378	5.53494488	51.09947626	19.94117285	24.41581731	
2020/08/01 21:00	98.6	17.8	26.6	11.6	299.9	3.7	160.2	14.9	16.9	9.5	3.7	160.2	52.2	797.3	321.5	66.3	0.2	56.2	54.0	795.0	321.3	68.9	0.2	60.4	221.9	26.75995086	13.46881346	30.0318092	6.52739245	51.53645313	19.38776241	24.6673088	
2020/08/01 22:00	148.0	43.8	26.3	11.5	281.5	2.5	63.1	14.7	17.7	9.5	3.6	175.5	53.3	815.5	319.1	67.7	0.2	59.5	57.5	738.8	319.1	68.4	0.2	68.9	27.5	28.1346068	13.29533039	30.2160823	5.82851033	53.21946079	19.80521011	23.864948	
2020/08/01 23:00	144.2	58.6	26.0	9.5	197.8	2.5	77.1	14.3	16.2	8.6	4.8	117.8	32.4	736.5	321.3	65.5	7.2	39.7	33.7	732.5	435.0	66.8	8.2	40.2	0.3	28.2831997	13.3608943	30.7979352	8.89184672	53.2462808	19.878024	23.6138152	
2020/08/02 00:00	7.3	-33.1	25.4	17.3	6.8	2.6	78.1	14.1	14.4	8.4	7.7	0.1	0.3	477.6	472.0	48.1	23.7	12.4	0.3	566.2	51.7	25.2	3.9	0.3	11.76252093	14.2088659	31.8899646	6.274142035	54.08948784	19.20181847	24.49719144		
2020/08/02 01:00	3.5	-35.3	24.1	17.8	6.8	2.6	76.0	14.1	14.5	8.4	7.7	0.1	0.3	453.1	447.6	35.7	24.8	12.3	0.3	546.0	54.7	38.9	26.2	1.9	0.3	29.1480671	13.89773867	30.67991373	6.27264252	52.39704684	19.8391573	22.58620498	
2020/08/02 02:00	3.4	-35.5	22.8	17.8	6.8	2.5	75.8	13.9	14.5	8.4	7.7	0.1	0.3	445.5	440.1	28.7	24.8	12.4	0.3	529.5	52.7	31.6	26.2	1.9	0.3	26.01339791	13.66659594	30.19681486	6.6103342	51.78251159	19.93041313	22.30120082	
2020/08/02 03:00	3.5	-35.7	21.7	17.5	6.8	2.5	75.6	13.7	14.4	8.4	7.7	0.1	0.3	442.6	437.2	24.3	24.2	12.4	0.3	517.4	51.7	24.9	25.8	4.0	0.2	25.1179474	13.5104376	29.91314508	20.476149	51.36981265	19.99988899	21.56782456	
2020/08/02 04:00	3.5	-36.3	21.0	17.2	6.8	2.4	75.7	13.5	14.2	8.4	7.7	0.1	0.3	441.1	436.3	21.3	23.5	12.4	0.3	508.5	50.4	23.5	24.9	4.0	0.3	25.0178096	13.14525054	29.63661603	52.08199813	52.0857959	19.7078837	22.75177998	
2020/08/02 05:00	3.7	-35.9	20.7	16.9	6.8	2.4	75.2	13.2	14.1	8.4	7.7	0.1	0.3	441.0	436.3	20.2	22.7	12.4	0.3	502.1	499.1	21.0	23.9	4.0	0.2	26.7532622	11.034097	30.6141322	5.81420254	53.7244991	19.78474265	24.0780047	
2020/08/02 06:00	3.4	-35.7	20.7	16.6	6.8	2.4	75.2	13.0	13.9	8.4	7.7	0.1	0.3	442.3	436.9	17.9	23.8	12.4	0.3	499.2	496.2	20.8	23.0	4.0	0.2	27.9884799	13.246754	30.7340448	5.73454487	53.67579791	19.81277289	24.0776241	
2020/08/02 07:00	0.8	-36.2	20.5	16.8	6.8	2.4	74.5	12.7	13.7	8.4	7.7	0.1	0.3	443.2	436.9	17.4	20.9	12.4	0.3	495.2	491.2	20.6	22.2	4.0	0.2	27.84654779	13.2113002	30.7389422	5.73454487	53.67579791	19.81277289	24.0776241	
2020/08/02 08:00	-2.6	-33.0	24.2	12.3	218.6	2.5	72.4	12.6	13.5	8.7	8.2	138.1	0.3	477.3	472.7	17.7	19.8	12.4	0.3	494.8	491.8	20.2	21.1	4.0	0.3	24.2027412	11.208312	30.389451	5.59405781	54.5427551	53.04206263	24.0776241	
2020/08/02 09:00	1.7	-26.3	25.4	12.0	218.6	2.2	68.9	12.6	13.6	10.1	9.6	140.4	0.3	473.4	473.5	18.2	19.4	12.4	0.3	491.6	497.8	20.9	20.5	4.0	0.3	23.51512254	11.208312	30.389451	5.59405781	54.5427551	53.04206263	24.0776241	
2020/08/02 10:00	0.1	-21.7	25.6	18.2	7.7	3.4	61.8	13.3	14.2	10.5	11.7	102.1	0.3	473.4	473.5	18.2	19.4	12.4	0.3	491.6	497.8	20.9	20.5	4.0	0.3	23.51512254	11.208312	30.389451	5.59405781	54.5427551	53.04206263	24.0776241	
2020/08/02 11:00	0.1	-17.9	25.8	18.1	7.8	3.6	68.6	14.1	15.0	10.5	10.2	102.2	0.3	473.4	473.5	18.2	19.4																

Figure 103. Extracted data for dewatering system

Figure 104. Extracted data for chilled water system

APPENDIX C: PROCESS TOOLBOX SOFTWARE

The PTB software is a semi-empirical thermohydraulic simulation tool that requires prior knowledge of the systems and significant data [80]. The semi-empirical nature of software means a best initial guess of the system parameters is required. The closer the initial guess the quicker the model reaches equilibrium.

“The code solves energy-, mass- and momentum balances for steady-state and transient solutions for any number of time periods and period sizes. Transient flow is solved with a quasi-steady-state semi-implicit algorithm where the pressure matrix is linearised to guarantee convergence for every time step. This means that no iterations are required which is valuable in a truly industrial scenario.

This method improves simulation stability and reduces simulation time which makes simulations in real-time practical. Energy is solved for each time step with transient explicit functions which means that no iterations and matrix solver are required. This also improves stability and decreases simulation time, again valuable in a practical industrial set-up as described in this paper.

All the thermohydraulic properties (pressure, temperature, enthalpy, quality) in the network are calculated in the pressure nodes and pressure boundaries. The component models are responsible for flow resistance, heat transfer, mass transfer and work calculations on the fluids. The component models receive fluid inlet conditions from the upstream nodes, execute the required calculations and transfer the outlet conditions to the downstream nodes.

Each component and node/boundary have a user input interface to specify its operational envelope and a user output interface to view the calculated outputs.

The code of all the component models are a combination of fundamental principles and empirical parameters. The empirical parameters, taken from system measurements, allow for accurate component characterisation and therefore improve simulation results. All the component models utilise explicit functions, therefore no iterations are required during component calculations. All these issues are important in a practical industrial scenario.”

PTB uses an intuitive drag-and-drop 3-dimensional (3D) graphical user interface (GUI) to add and connect several components to configure large networks such as are found in WCS networks. The 3D interface allows the user to configure networks to scale in three dimensions. Pre-defined components are available in a component library for easy configuration. PTB has a large component database of 75 main components with a library of several hundred sub-components (for example pipe sizes and schedules) making it possible to model complex systems [80].

The software uses a quasi-steady-state semi-implicit algorithm with a linearised pressure matrix to guarantee convergence. Therefore, iterations are not required, improving stability and reducing simulation time which is valuable in an industrial scenario. All thermohydraulic properties (pressure, temperature, enthalpy, quality) are calculated in the pressure nodes and pressure boundaries. Flow resistance, heat transfer, mass transfer and work on fluids are all determined by components added to the system.

Each component has user specific inputs which describe the operational envelope and determine the calculations which occur between upstream nodes and outputs to downstream nodes. The components are specified according to empirical values, improving simulation accuracy with each component utilising explicit calculations to remove the necessity for iterations, which is truly beneficial to an industrial application. With the above background, the different systems of the network are developed.

The package uses a graphical drag and drop interface to construct simulation models. The interface makes it easy to add, remove and connect components in a 3D environment. A screenshot of the PTB interface and 3D work environment is shown in Figure 105.

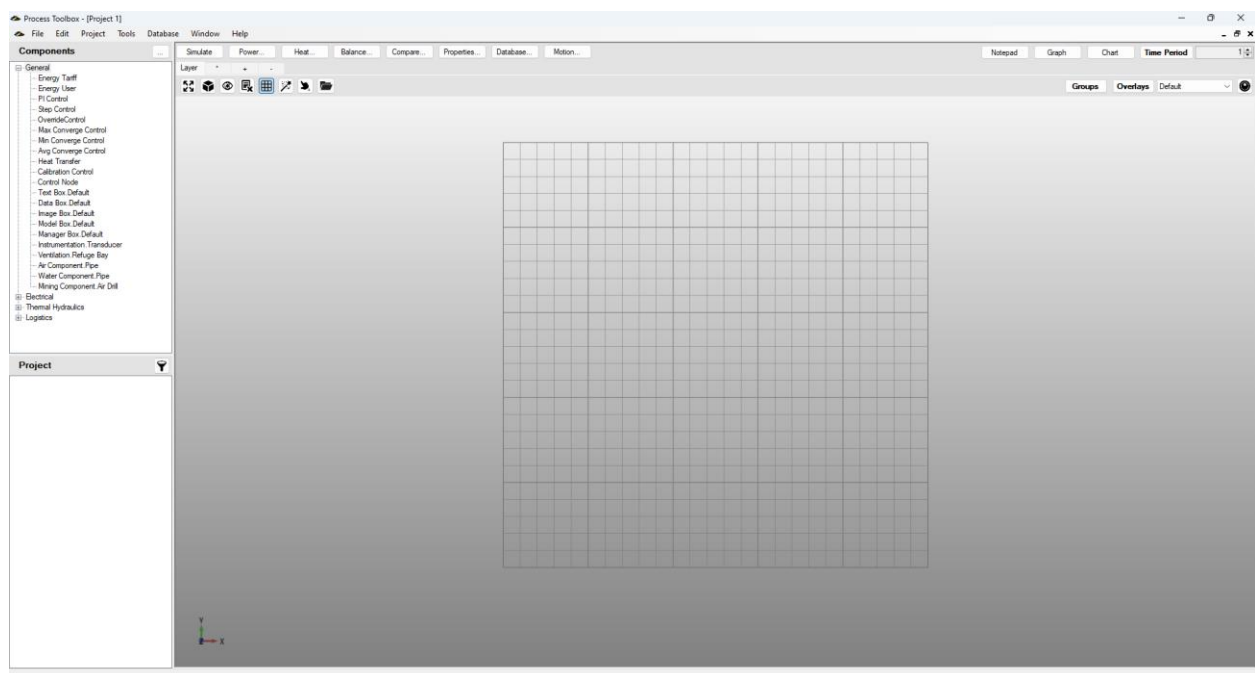


Figure 105. PTB user interface and 3D work environment

Table 24 shows pre-defined components available in PTB

Table 24. Process Toolbox (PTB) - Available components

Water components	Air components	Water/Air components	Steam components	Two phase components	General components
Water Pressure Boundary	Air Pressure Boundary	Water Air Cooling Tower	Steam Pressure Boundary	TwoPhase Pressure Boundary	Energy Tariff
Water Node	Air Node	Water Air Heat Exchanger	Steam Pipe	TwoPhase Pipe	Energy User
Water Pipe Pipe	Air Pipe.Pipe		Steam Node	TwoPhase Node	PI Control
Water Demand	Air Tunnel. Tunnel		Steam Turbine	TwoPhase Turbine	Step Control
Water Pump	Air Fan		Steam Pump	TwoPhase Pump	OverrideControl
Water Dam. Round	Air Fan Curve Fit		Steam Mass Flow	TwoPhase Mass Flow	Max Converge Control
Water Water Chiller	Air Fan Inlet Guide Vanes				Min Converge Control
Water Mass Flow	Air Compressor				Avg Converge Control
Water Mining Demand	Air Demand				Heat Transfer
Water Turbine	Air Water Drill				Calibration Control
Water Water Heat Exchanger	Air Dynamic Compressor				Control Node
Water Water 3 Chamber Pipe System	Air Positive Displacement Compressor				Text Box
Water Soft Ice Dam. Round	Air Mass Flow				Data Box
Water Hard Ice Dam Round	Air Mining Demand				Image Box
	Air Coal Burner				Model Box
					Manager Box
					Instrumentation
					Ventilation Refuge Bay
					Air Component Pipe
					Water Component Pipe
					Mining Component Air Drill

The components are individually placed in the building environment where they are independent from all other components. The components are easily connected with one another through dragging from one component to the other. Several connections between multiple components can be achieved depending on the nature of the component. An example is shown in Figure 106.

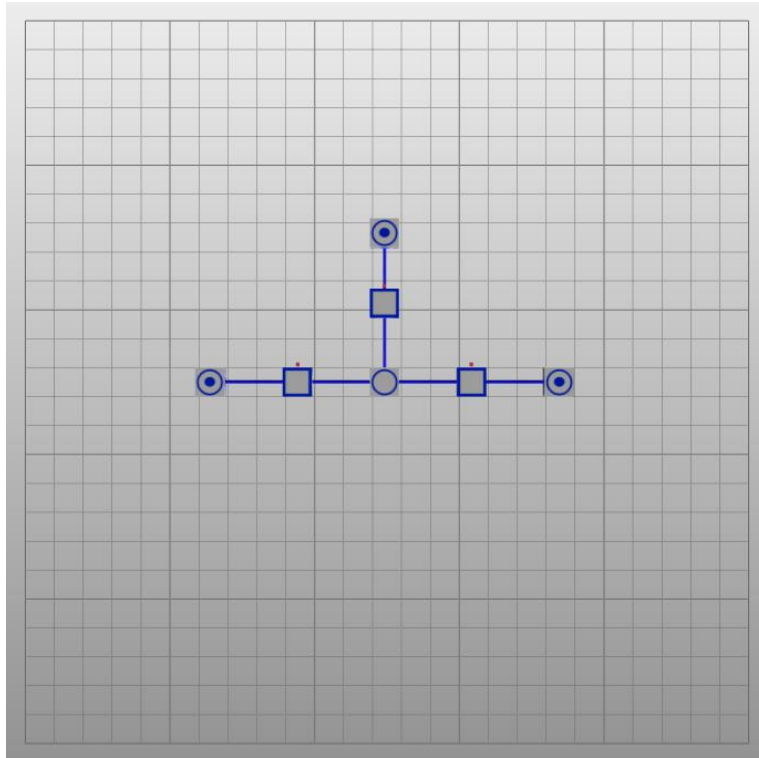


Figure 106. Example of a PTB component connected with several other components

Certain components have several connections points such as a water to air heat exchanger which requires both water and air links. The next step is to construct the system in the virtual environment as an exact copy of the actual system.

APPENDIX D: CALIBRATION TROUBLESHOOTING

No.	System	Issue	Common fault	Solution
1	Water	Incorrect flow	Pipe throttled or open in system	Open or close pipe
			Pipe not specified to correct diameter	Specify pipe to correct size
			Water pump not correctly specified	Specify pump according to performance curve
			Actual flow measured incorrectly	Re-measure flow
			PI controller closing valve	Check PI controller inputs
		Low pressure or vacuum	Not enough head	Increase head (water pump or elevation)
			No backpressure	Throttle valve upstream
			Syphon higher than 10m	Lower column, add pump or increase head
		Negative flow	Pipe connected incorrectly	Swop pipe connection
			Water pump not correctly specified	Specify pump according to performance curve
Water head too great	Increase pump size or decrease head			
2	Cooling	FP evap outlet too high or low	FP not specified correctly	Use calculate function and defaults
			Evap inlet too high or low	Check upstream temps or increase or decrease FP mixing
			Condenser circuit underperforming	Check and calibrate CCT
		FP condenser outlet too high	FP not specified correctly	Use calculate function and defaults
			Condenser inlet too high	Improve CCT performance
			Ambient temperatures too high	Get latest ambient temperatures
		FP flow too high	FP mixing	Increase mixing flow
			FP pressure drop too low	Increase FP pressure drop
		FP flow too low	FP mixing	Decrease mixing flow
			FP pressure too high	Decrease FP pressure drop
		Incorrect BAC/CC duty	BAC not specified correctly	Use calculate function and defaults
			Air flow too low/high	Reduce/increase pressure drop or increase/reduce fan curve
			Water flow too low/high	Reduce/increase pressure drop or increase/reduce pump curve
			Air inlet temperature too low/high	Recheck ambient conditions
			Water inlet temperature too low/high	Recheck water conditions
		Incorrect BAC/CC water flow	Water pump not correctly specified	Specify pump according to performance curve
			Pressure drop too large or small	Decrease or increase water pressure drop over coil
		Incorrect BAC/CC air flow	Air fan not correctly specified	Specify air fan according to performance curve
			Pressure drop too large or small	Decrease or increase air pressure drop over coil