Simulation-based improvement of bulk air heat exchanger efficiency in deep-level gold mines

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

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Graduation: July 2025

ABSTRACT

Title: Simulation-based Improvement of Bulk Air Heat Exchanger Efficiency in Deep-level Gold Mines

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Keywords: “bulk air cooler”, “mine cooling”, “underground ventilation”, “heat exchanger performance”, “simulation-based improvement”, “secondary cooling”, “heat transfer efficiency

One of the primary concerns within deep-level mining is the mitigation of heat, which ensures the health, safety, and productivity of the miners. This is achieved through cooling and ventilation infrastructure which includes finned-tubbed bulk air coolers (BACs) that form part of the secondary cooling systems in mines where working/active levels are at depths that exceed 2 km. Due to “off-design” conditions, which include restricted air flow or water flow, increased inlet temperatures and fouling, the operational performance of the BACs decreases over time, as heat is being transferred between the working fluids.

Previous methods relied on “pre-selected" operating variables, such as fouling, water flow, or geometry for analysing the performance of a BAC, which required extensive monitoring instrumentation or the assumption that the infrastructure had to operate within the design specifications. This resulted in the actual performance being significantly lower than the achievable performance under real mining conditions. The shortfall of the previous literature was then the lack of a systematic method to identify, quantify, and mitigate the influence of operating variables as the BAC operates within the mining conditions.

This study, therefore, developed a simulation-based methodology for determining the achievable performance of the BACs, the limiting operating variable/s, and the recommended corrective measures to increase the actual operational performance and decrease the outlet Wet bulb (WB) temperatures. The method was applied to four BACs within a gold mine, and the results provided insight into the performance restrictions of BACs and potential improvements. After the corrective measures were implemented, the achievable performances were 1156.0 kW, 1157.3 kW, 503.3 kW, and 1423.0 kW for the respective Case Studies 1 through 4 where the re-audit results additionally indicated the following:

- Case Study 1: 44% operational performance increase and a 1.5 °C WB temperature decrease.

- Case Study 2: 26% operational performance increase and a 1.5 °C WB temperature decrease.
- Case Study 3: 28% operational performance increase and no decrease in WB temperature due to an increased thermal and relative humidity load.
- Case Study 4: 13% operational performance increase and a 6.5 °C WB temperature decrease.

Therefore, the mine had increased the available cooling capacity and supplied the working areas with cooler air and was a direct benefit from the increased operational performance of the secondary cooling infrastructure in terms of the BACs on the working levels. The results of the simulations validated the methodology and the respective objectives, and the aim of the study was successfully achieved.

ACKNOWLEDGEMENTS

I want to acknowledge and express my sincere gratitude to a few people and entities who have contributed to the success of this study:

- ETA Operations (Pty) Ltd – for the support, resources, and the relevant training.
- Mine A – for the support, assistance, access, and willingness to implement the study.
- Prof. E.H. Mathews (Managing Director) – for providing the opportunity to pursue a dissertation in the discipline of mine cooling and ventilation.
- Dr J. van Laar (Study leader) – for the continued assistance, guidance, insight, and editing regarding technical writing.
- Dr J. Vosloo (Co-study leader) – for the overall technical insight and guidance regarding the problem and the solution.
- I. Mathews (Mentor) – for the technical assistance and guidance in terms of the simulation software and representation of the data.

The information of this study was concluded while acknowledging sources and referencing the relevant published work. Should any oversights be identified, please inform me so that it can be addressed and rectified.

ABBREVIATIONS & GLOSSARY

ACU	-	Air Cooling Unit
BAC	-	Bulk Air Cooler
CC	-	Cooling Car
CCT	-	Condenser Cooling Tower
CFD	-	Computational Fluid Dynamics
DB	-	Dry Bulb Temperature
FTHX	-	Finned Tubed Heat Exchanger
GDP	-	Gross Domestic Product
HTX	-	Heat Exchanger
LMTD	-	Log Mean Temperature Difference
MS	-	Microsoft
OEL	-	Occupant Exposure Level
OEM	-	Original Engineering Manufacturer
PTB	-	Process Toolbox (Simulation Software)
RAW	-	Return Air Way
RSA	-	Republic of South Africa
SCADA	-	Supervisory Control and Data Acquisition
TEM	-	Tube Element Method
WB	-	Wet Bulb Temperature

NOMENCLATURE

"Baseline"	-	Reference point used for future comparison
"Capex"	-	Capital expenditure
"Down Cast"	-	Mine shaft through which clean ventilation air enters the mine
"Non-selected"	-	Non-bias to/or a prior determination of an object, variable or specification
"Off-design"	-	Conditions that do not conform to the original/ideal testing specifications
"Pre-selected"	-	A prior determined object, variable or specification
"Reworked"	-	Alteration of a verb or noun with the intent of improvement relevant to the specific topic
"UA Factor"	-	Heat transfer coefficient
"Up Cast"	-	Mine shaft through which hot ventilation air is rejected
"Working Level"	-	Any level within a mine where ore is mined, or development is occurring

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CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Preamble

The mining industry in South Africa is a significant contributor to the country's GDP and forms a large part of the economic foundation [1]. As gold reserves deplete, mines are being deepened to extract ore where underground temperatures can exceed 40 °C due to exposure to increasing virgin rock temperatures [2], [3]. This presents significant challenges in deep-level mining.

Bulk Air Coolers (BACs), among other cooling and ventilation infrastructure, are employed to mitigate heat and maintain safe underground environmental conditions [4]. Despite their importance, BAC performance deteriorates over time, reducing safety margins and increasing operational costs [5], [6].

Current simulation software can be used to analyse and improve the performance of a BAC by studying the respective operating variables under various scenarios [4], [7], [8]. Existing research primarily focuses on the thermohydraulic effects on a BAC and not on identifying the root cause of decreasing BAC performance. Therefore, the focus of this chapter will be as follows:

- Defining the operational environment of BACs.
- Clarifying the various types of BACs.
- Describing how the operating variables influence the performance of a BAC.
- Investigating current research and simulation software.
- Identifying the objectives and a problem statement for this study.

1.2 Gold mines in South Africa

Spanning over a century, the Republic of South Africa (RSA) remains one of the top mining countries in the world [9]. The mining sector of the RSA contributed approximately 9% to the Gross Domestic Product (GDP), with an average of R 487.5 billion per annum between 2021 and 2023 [10].

Despite advanced infrastructure and remaining gold reserves, RSA's yearly gold mine production has been declining since the 1990s, resulting in a diminished contribution to the world's gold production [11]. During the 1970s, the RSA contributed more than 20% to global gold production compared to 3% in 2022 [9], [11]. Figure 1 represents the decline in gold production over time for various companies operational in the RSA.

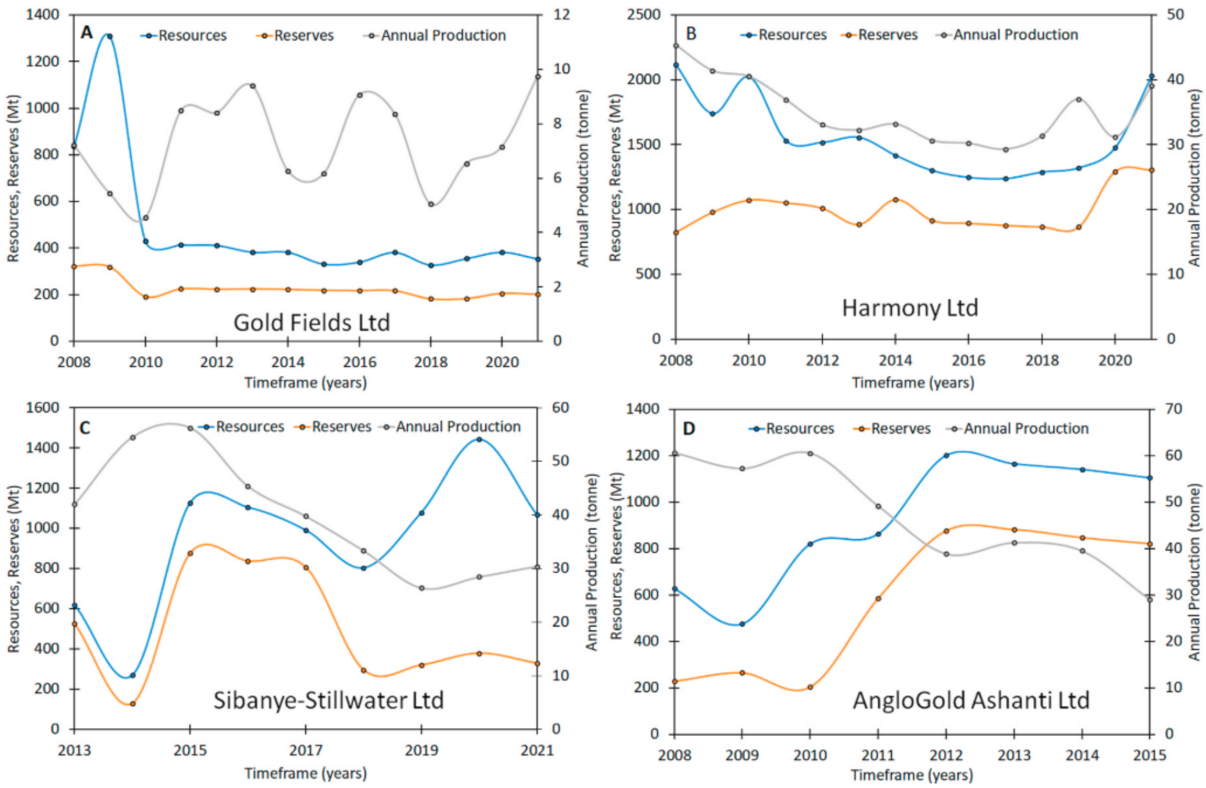


Figure 1: Declining Gold Production in South Africa [3]

A study done by Szczygielski *et al.* [11] investigated the relationship between the gold price, the South African Rand–US Dollar exchange rate, and gold production. It was concluded that the return on gold is strongly influenced by the gold price and the exchange rate, allowing mining companies to remain economically viable during lower production phases [12]. Despite the long history of gold mining history and commodity sales in RSA, the country's contribution to the global exploration budget was less than 1%, which indicates limited investment towards discovering new reserves [10].

In 2018, it was estimated that South Africa had 125.31 tonnes of gold reserves left, resulting in approximately 39 years of mining [13], [14]. To access these reserves, mines need to go deeper [15]. South Africa also has seven of the world's ten deepest gold mines, operating at a depth exceeding 2 500 m [16]. As the mines increase in depth, so does the complexity of the thermohydraulic systems, operational costs, technical challenges, and increased heat exposure [17].

The increase in mining depth limits the capacity for maintaining the correct working environment for miners. Factors such as dust, fumes, gasses, humidity, and virgin rock temperatures negatively impacts the design and operating conditions of the cooling and ventilation infrastructure [18]. Previous studies investigated the effect of the environmental conditions on the productivity of miners, and the results indicated that improved environmental conditions enhance production and productivity [19], [20].

Miners' productivity can be defined as the efficiency by which the labour tasks are performed. Otherwise known as the metabolic rate, it is typically measured by output per unit of labour. The main categories of labour include ore extraction (efficiency of ore extraction productivity), development (efficiency in preparing infrastructure), and support productivity (efficiency of logistical and maintenance tasks) [21]. Figure 2 illustrates the relationship between indices for hot working environments and the Wet bulb (WB) temperature [22].

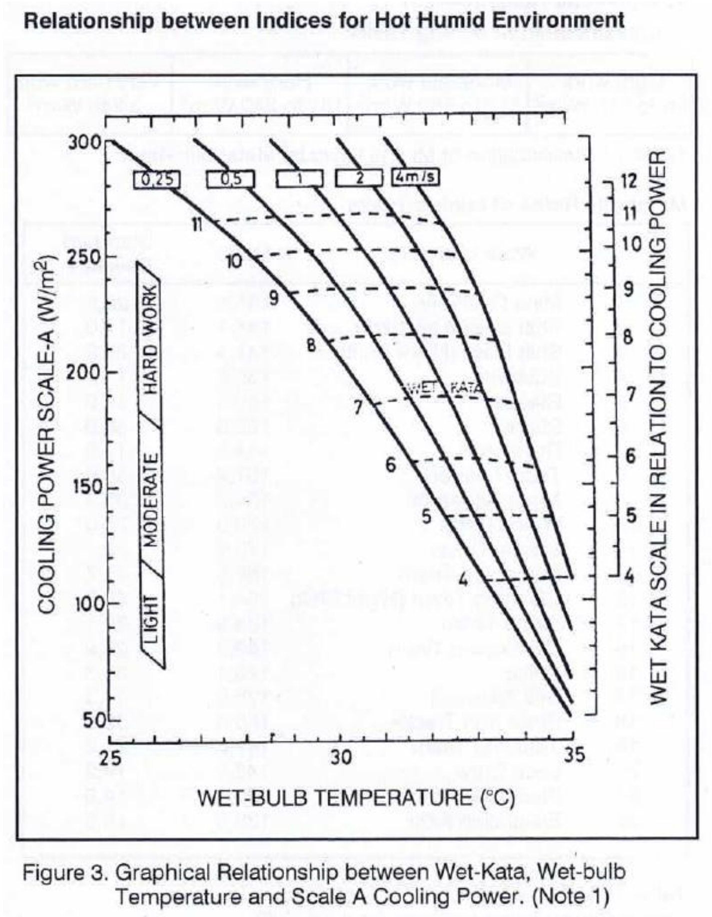


Figure 2: Relationship Between Wet-Kata, Wet bulb, Temperature, and Scale A Cooling Power [22]

As shown in Figure 2, metabolic rates decrease as the WB temperature increases during a constant velocity of air flow; therefore, the productivity of the miners decreases as the WB temperature increases. The relationship between the effectiveness of the mine workers and the WB temperature is summarised in Table 1.

Table 1: Relationship Between Worker Efficiency and WB Temperature [23]

Worker Efficiency	Wet Bulb Temperature
100% Efficiency	WB < 27 °C
Economic Efficiency	27 °C ≤ WB < 29 °C
Corrective measures are required	29 °C ≤ WB < 33 °C
Short period of exposure	33 °C ≤ WB

1.3 Cooling and ventilation

From a secondary perspective on the deepening of gold mines, the cooling power of the cooling infrastructure decreases as the temperature difference of the latent heat transfer increases, resulting in increased miner fatigue. This effect highlights the importance of ensuring the operational capacity of the cooling infrastructure to mitigate heat within a mine effectively.

When mine depths started increasing, a simple framework for implementing cooling methods was developed [24]. This framework is illustrated in Figure 3; starting with ventilation only, it steadily progresses towards surface-bulk air cooling, underground air cooling, and finally, ice-from-surface for mines deeper than 2 250 m.

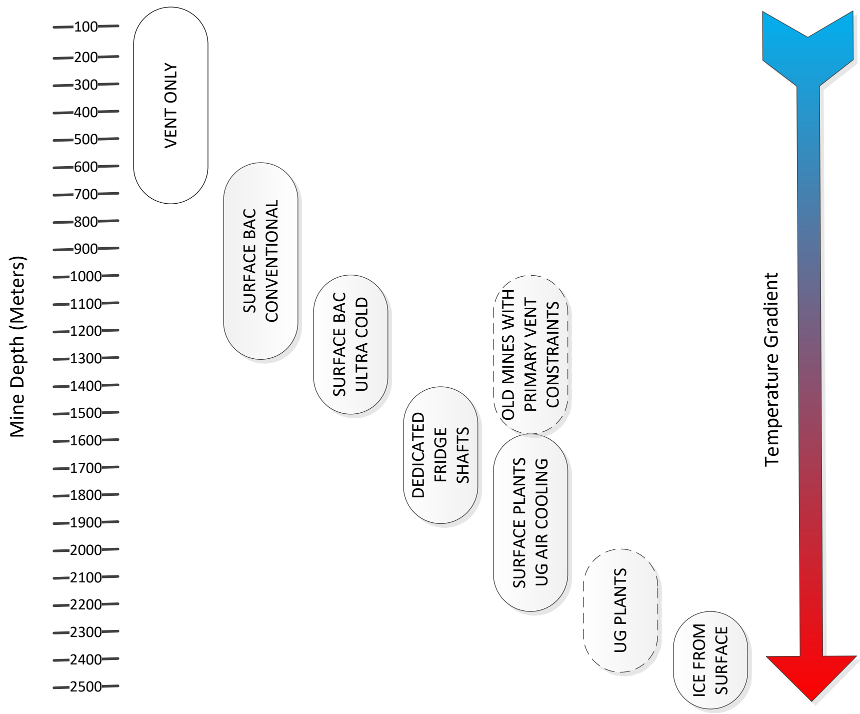


Figure 3: Hierarchy-with-depth and Phase-in of Refrigeration Modes (Adapted From [24])

The ventilation system of a mine is responsible for maintaining safe working conditions as well as economical operations in an underground environment. National mining laws and regulations are enforced by governments, as the role of ventilation in mine safety is well documented. The regulations set the minimum safety and environmental standards of an operational mine. The Mine Health and Safety Act 29 of 1996 of South Africa requires that the WB and DB temperatures may not exceed 32.5 °C and 37.0 °C respectively. In addition to the thermal environmental conditions, Regulation 22.9(2)(a) state the permissible levels of pollutants in the air such as dust, diesel particulate matter, and gases [25].

It is, therefore, important to provide a sufficient supply of fresh air to dilute the mine pollutants to the required occupational exposure level (OELs) and to ensure the removal of dust, fumes, and gasses. Additionally, the fresh-air supply must have sufficient cooling power at the respective working areas/environment to counteract heat loads and benefit the evaporative cooling from the miners' bodies [26].

According to Figure 3, the ability of the ventilation to maintain the underground temperatures becomes insufficient when mining depths exceed 750 m. This is caused by the increased geothermal gradient, resulting in increased cooling demand. When the mining depths exceed 600 m, additional cooling infrastructure is employed to assist the fresh-air supply in maintaining the required cooling power. The cooling infrastructure includes BACs, closed-loop Air Cooler Units (ACUs), and Cooling Cars (CCs) [27], [28]. Although implementing this infrastructure requires capital and operational costs, they are ultimately required to ensure suitable environmental conditions for the miners [28].

Cooling infrastructure can be divided into different categories based on the scale of the system, namely centralised cooling systems, spot cooling systems, and micro-climate cooling systems.

1.3.1 Centralised cooling systems

Centralised cooling systems, also known as primary or bulk cooling, are used by mines where the strata-heat is widespread [17]. These systems usually contain two heat exchanger sub-systems. The first system is a BAC, which operates as an evaporator to cool the air, and the second system is a refrigeration plant, which operates as a condenser to release heat into the environment through water and/or air [29]. Should the heat be rejected using water, a Condenser Cooling Tower (CCT) is required, which transfers the heat from the water to the air [30].

A centralised cooling system can be divided into two types based on the location of the BAC, namely Surface and Underground BACs. While both types share design features, they can differ in configuration due to site-specific factors that may include available Capex, haulage area and available infrastructure, and cooling requirements [28].

1.3.2 Spot cooling systems

Spot cooling systems are used where heat is localised in remote locations far from the main airways. Also known as decentralised, in-stope, tertiary, and face cooling systems [5], [17], these systems are usually positioned at active mine panels, development areas, and main haulages where the air temperature is no longer sufficient [5]. Despite their limited cooling capacity due to their physical size, spot coolers' mobility can provide high positional efficiency.

Spot cooling systems are commonly used in conjunction with centralised cooling systems, but where the heat load is low and concentrated at a specific area, they can be used independently [5]. CCs and ACUs form part of this category.

1.3.3 Micro-climate cooling systems

Micro-climate cooling systems refer to the cooling of the area directly surrounding the miner, resulting in the most efficient method for mitigating heat and cooling miners in underground environments and is cooling system can achieve 100% efficiency in positional cooling [31]. This system includes air-conditioned cabins for mining equipment, resulting in reduced heat-related injuries and increased productivity. However, not all mining activities can be conducted inside an air-conditioned cabin, as not all mines are mechanised; as such, heat stress remains an issue [28].

A secondary method of micro-climate cooling involves providing miners with cooling clothes such as ice-cooled vests and liquid-cooled garments [32]. Originally utilised by the U.S. Bureau of Mines in the 1970s, modern variations of this method include air cooling, water circulation, and gas expansion. A study done by Sajjad *et al.* [32] and Hallé *et al.* [33] concluded that while cooling clothes mitigate heat stress significantly, they cannot safeguard miners against heat exposure in an underground environment entirely.

A direct comparison of the various cooling systems can be challenging due to their respective operating principles and performance. Each cooling system's capacity, operational costs, capital investment, and efficiency differ. The efficiency of these systems can vary in terms of mine design, mining methods, environment, and headloads as well as the area of application. Furthermore, these factors also affect the efficiency of these systems over time, resulting in insufficient cooling that does not meet the cooling requirements [27], [28].

Mines must, therefore, constantly improve or maintain underground environmental conditions to comply with the necessary specifications and requirements. This can be achieved by establishing the achievable performance within the operational environment and identifying the factors that hinder this performance, ensuring they are addressed, changed, or fixed to ensure a satisfactory working environment [22], [25], [34], [35].

1.4 Bulk air coolers

1.4.1 Position and utilisation

Cooling systems rely on water as a primary cooling medium, and the water temperature used in underground mining operations is optimised by water chiller and ice plants. This infrastructure is of great importance to the operations of a mine [36], [37]. The water supply process centres on two factors: controlling the temperature and managing the flow of the water within the system to meet the underground demand [38].

Temperature control ensures the water is at a predetermined temperature before reaching the working areas. This temperature is crucial, as it directly impacts the cooling efficiency and the ability of the cooling infrastructure to maintain a safe working environment. As previously mentioned, the cooling system involves transferring the cooling effect of the water--which was cooled by the water chiller or ice plants--to the air within a mine, a process achieved by using BACs.

Flow management focuses on maintaining constant pressure and sufficient water distribution throughout the mine Correct control of these variables is crucial to the overall efficiency of the cooling systems [39], [40]. Figure 4 illustrates a flow diagram of a typical water reticulation for a gold mine.

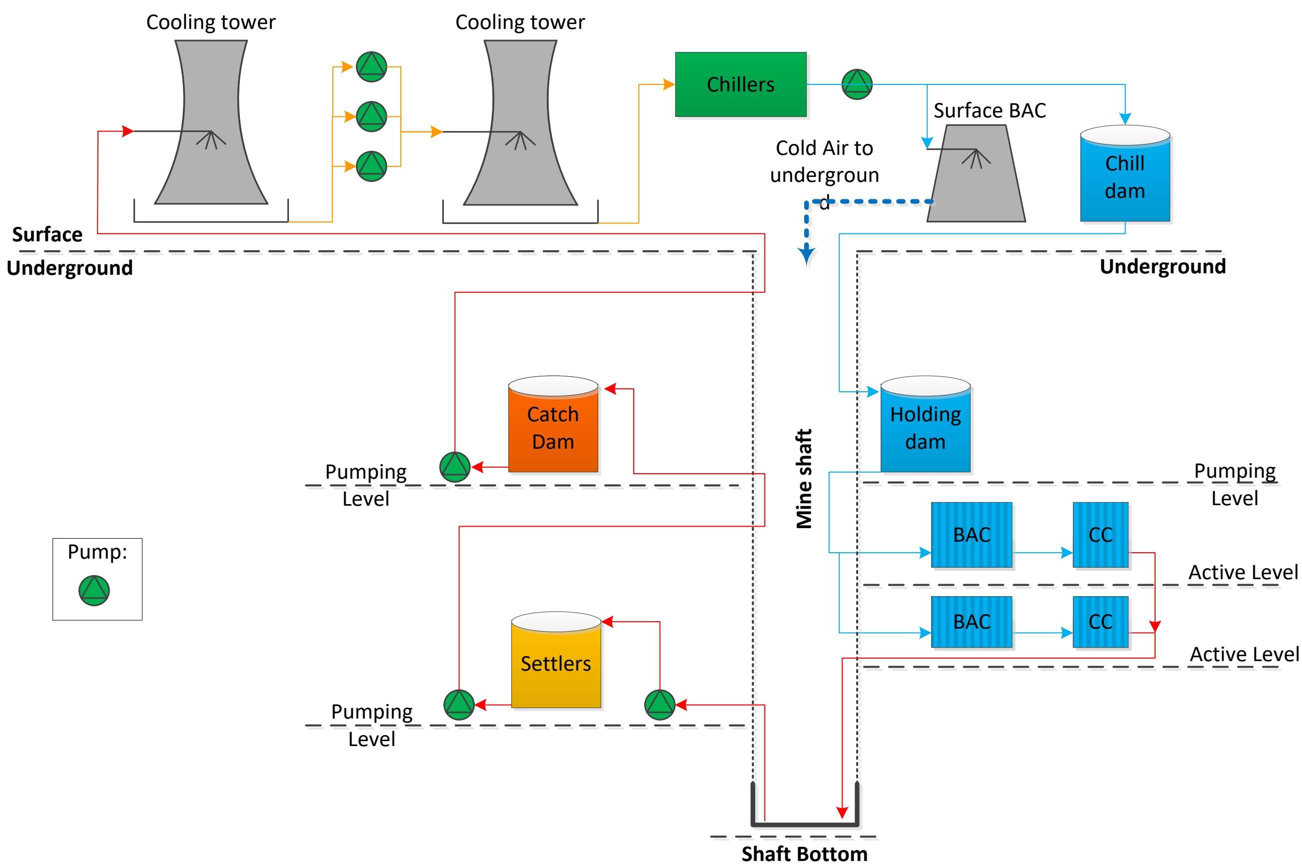


Figure 4: Underground: Typical Water Reticulation of a Mine (Adapted From [5])

The flow diagram shows the water reticulation in the shaft. The water is then pumped to the settlers to separate the mud and water, following which the water is then pumped to a catch dam, where it receives additional treatment to achieve water reclamation for recirculation [41]. This water is then supplied to cooling towers to decrease the temperature before entering the chillers.

The chillers then cool the water to a predetermined temperature and send it to the surface BAC and chilled water dam. The chilled water dam is a storage facility that ensures continuous and uninterrupted water supply for the respective mining activities and services. The surface BAC uses the chilled water to cool the primary ventilation air before it enters the mine shaft. The water is usually gravity-fed towards the holding dam from the chilled water dam. From the holding dam, the water is then distributed to various working/active levels as required. After the mining activities have used the water, it is directed and drained towards the shaft bottom, where the reticulation is reinitiated [40], [41], [42], [43].

The ventilation system of a mine is directly connected and dependent on the water reticulation system. Figure 5 illustrates a flow diagram of a typical ventilation system used by gold mines in South Africa.

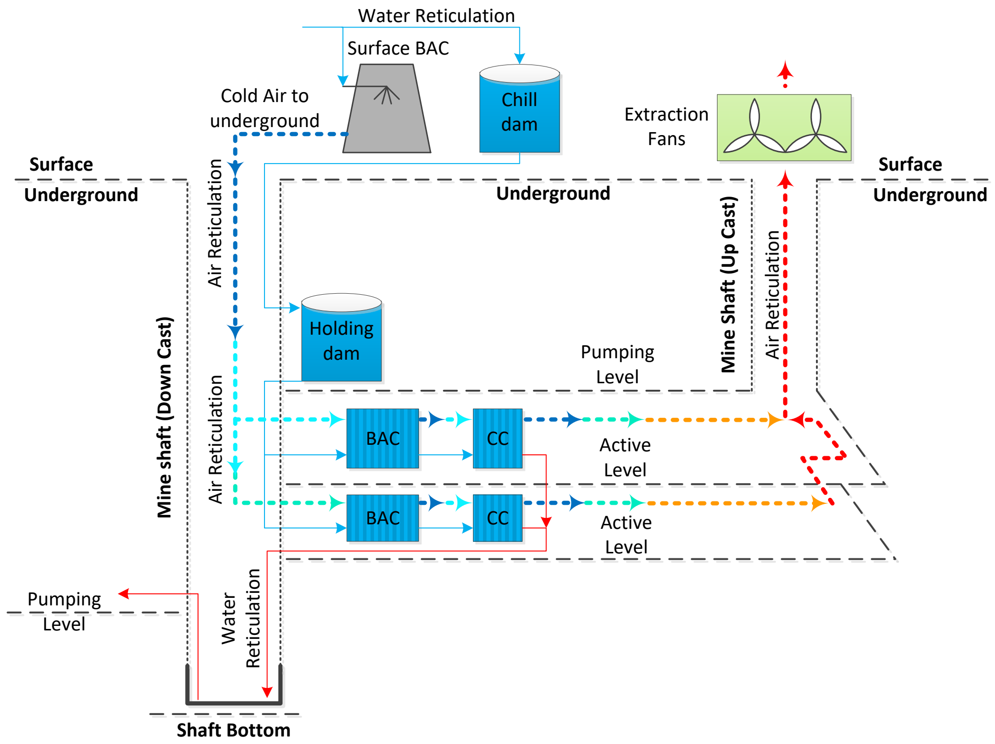


Figure 5: Typical Ventilation Reticulation of a Mine (Adapted From [5], [44])

Figure 5 highlights the ventilation system's dependence on the water system. The ventilation system's intake draws air directly from the ambient environment at the surface. Most of the ventilation air is cooled by the surface BAC before it is sent underground. Cool ventilation air travels via the down cast shaft towards the active/working levels.

As the ventilation air travels through the down cast shaft, the temperature increases considerably due to the geothermal heat flow and auto-compression. This effect is amplified as the cool air absorbs heat from the surrounding rock strata. These challenges are partially overcome due to the ability of the surface BAC to cool large volumes of air, as no limitations are placed on the geometric size of the cooler. Several surface BACs can also be placed in various configurations at the exact location to increase the cooling efficiency [45].

However, the control setpoints of the surface BACs are limited since the ventilation air temperature within the down cast shaft cannot be lowered too substantially, as the shaft is also used for personnel transport and hoisting. Additionally, the surface BAC will become cost ineffective at a certain point as the mining depth increases. This critical depth depends on the location of the mine and the specific heat load at a given depth. Beyond this depth, additional cooling, in terms of underground BACs, becomes necessary to effectively maintain the heat load of the mine [45], [46].

When the ventilation air enters the active working levels, it is cooled once more by passing through BACs located relatively close to the shaft entrance to the active levels. As the air continues through the mine, additional infrastructure—such as ventilation doors, fans, and ducts— is used to regulate pressure differences and ensure adequate air distribution. However, as the air moves through the working/active levels, its temperature increases due to blasting, fissure water, oxidation, machinery, and human metabolism [22], [24], [39], [44].

As such, the air is passed through CCs to maintain suitable temperatures in the working areas. After serving its purpose, extraction fans reject the ventilation air from the mine through the "Up Cast" or Return Air Way (RAW). The ventilation system is thus the backbone of mining operations, ensuring the supply of fresh air, the removal of dangerous gases and dust, and maintaining acceptable temperatures in the working areas for both equipment and personnel [47], [48].

Figure 4 and Figure 5 illustrate the relative positions of the centralised cooling systems, showcasing both surface and underground BACs, which are crucial for regulating the overall temperature of the ventilation air.

1.4.2 Surface BAC

Due to the complexity and cost associated with implementing underground cooling systems on a large scale, conventional direct-contact BACs are implemented to cool the ventilation air artificially [42]. However, the positional efficiency of the surface BAC is lower than that of other methods because they are located far from the mine's active/working levels.

A conventional direct-contact BAC can be categorised into two types, namely horizontal and vertical forced-draft BACs. Horizontal force-draft BACs can be located on the surface and underground, however, they are predominantly implemented underground [47]. As such, horizontal force-draft BACs will be discussed in Section 1.4.3.

Vertical force-draft BACs use mechanical fans to pull the ambient air through the cooling chamber, where chilled water is sprayed in a fine mist at the top of the BAC. The heated water flows by gravity into a sump, from where it is pumped back to the chillers, cooling towers, or a pre-cooling dam. The ambient air is pushed through the chilled water mist to maximise the heat transfer between the mist and air. The mist then absorbs the heat as the air flows upwards, producing artificially cooled air. The cooled air then passes through a mist eliminator to remove excess residual moisture before continuing underground. Vertical force-draft BACs are the most cost-effective method for cooling the ventilation air of a mine [49]. Figure 6 indicates a vertical force-draft BAC as implemented on surface at a mine in South Africa.

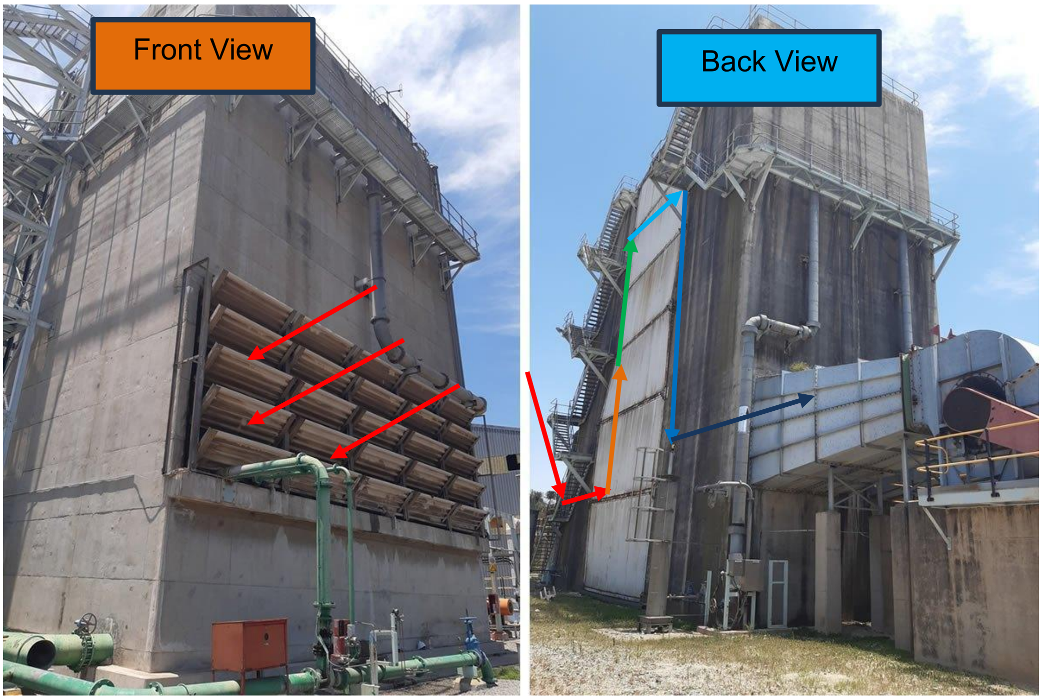


Figure 6: Vertical Force-draft Surface BAC [50]

1.4.3 Underground BAC

Underground BACs are strategically placed to allow large volumes of intake air, from the down cast shaft, to pass through them. Auxiliary fans are often used to assist this process [51]. The conventional implementation involves placing a primary underground BAC in the main air intake, while secondary BACs or CCs are placed deeper into the working levels, such as to re-cool fresh or recirculated air. Horizontal, multi-staged force-draft BACs are commonly used underground due to the minimal excavation required to accommodate the infrastructure [47].

In a similar operational philosophy to vertical force-draft BACs, horizontal force-draft BACs push the intake air horizontally, instead of vertically, through a water mist to ensure maximum heat transfer. The cooled ventilation air is then directed through the working/active level. Water sprays at the top and bottom of the vertical force-draft BAC are used to create a mist that cools the air as it flows through the BAC. The chilled water from the respective stages falls back into a sump, from where it is pumped through the sprays of the sequential stage [52]. Figure 7 indicates an underground horizontal force draft/direct-contact BAC.

Figure 7: Horizontal force-draft BAC (Personal Picture)

As a substitution for underground direct-contact BACs, cooling-coil BACs—such as finned-tube heat exchangers (FTHX)—can be used. This type of BAC has been steadily implemented due to its ability to provide increased heat transfer efficiencies while maintaining a relatively compact size while adhering to service delivery demand of the mining operations [25], [48], [49]. The heat transfer area of the coil-cooling BACs, also known as indirect-contact BACs, increases efficiency. Figure 8 indicates an underground coil-cooling BAC.

Figure 8: Cooling-coil BAC (Personal Picture)

The operation of an underground cooling-coil BAC relies on chilled water flowing within the tubes, which then indirectly interacts with the ventilation air flowing externally across the tubes in a perpendicular direction [53], [54]. This method allows for successful heat rejection from the ventilation air before it enters the active/working level. The heat capacity of the chilled water is approximately four times that of the ventilation air, which means water can transfer heat four times faster than air [55]. A limitation for the heat transfer is created as the coil separates and prevents direct contact between the water and the air. This limitation is overcome by extending the surfaces on the air side to increase the contact area and induce turbulent air flow [7], [56]. Figure 9 illustrates the working principle of an FTHX.

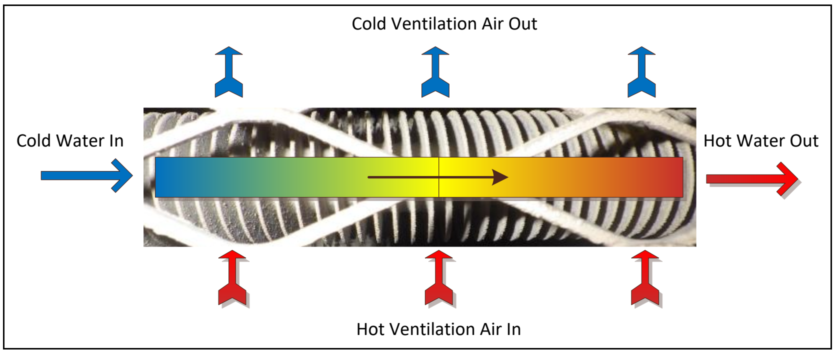


Figure 9: Cooling-coil Operation (Adapted From [6])

Despite these design conditions, the performance of all BACs deteriorates over time when operating under "real-world/off-design'' conditions. Reduced heat transfer occurs as a result of this degradation, resulting in decreased overall efficiency [57]. The "off-design" conditions are a combination of the operating variables required by a BAC and are discussed in the following sections.

- **Fouling**

Fouling is a phenomenon in finned-tube heat exchangers that has two key negative impacts on performance. First, the thermal efficiency is reduced due to increased thermal resistance, and second, a degraded hydraulic performance is caused by an increased pressure drop that impacts the fluid flow [58], [59]. This occurrence is particularly problematic within the mining sector as it leads to increased energy consumption, maintenance costs, and unexpected shutdowns [60].

Internal fouling, also known as scaling or precipitation, occurs when reverse solubility salts—such as calcium carbonate ($Ca\text{-}CO_3$)—and other impurities, precipitate out of the water due to temperature differences. These salts form solid deposits on the inside of the HTX tubes and require chemical flushing for cleaning [6], [61].

External fouling is when sedimentation on the heat transfer surfaces occurs due to particles and impurities in the ventilation air. The sedimentation deposits can become solid over time and can be removed through chemical cleaning or rinsing [34], [62]. Figure 10 and Figure 11 indicate external and internal fouling respectively.

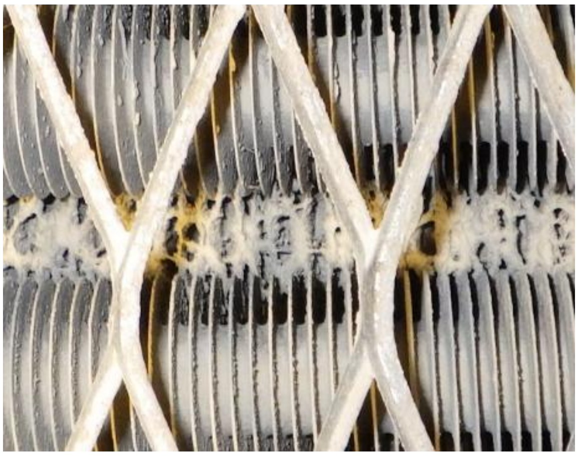


Figure 10: External Fouling (Photograph taken by author)

Figure 11: Internal Fouling [5]

- **Water flow**

The chilled water in an underground BAC act as the cooling liquid. By reducing the flow of this cooling liquid, it negatively impacts the overall performance and operational efficiency of the BAC. The heat transfer efficiency is also influenced by a decreased flow rate, which increases the outlet temperature of the ventilation air. The increase in the BAC's outlet temperature reduces the ventilation air's cooling power, which negatively impacts the working/active areas in the mine, as the environment may no longer be sufficiently cooled.

An increase in pressure-drop across the BAC occurs due to a lower cooling liquid flow rate. This effect increases the energy consumption and decreases the overall performance as the BAC compensates for the reduced efficiency. Additionally, the reduced flow rate also increases the time of the chilled liquid within the cooling-coils, which increases the risk of impurities settling on the inside of the HTX tubes and contributing to internal fouling.

In cases where multiple FTHXs are used in tandem, which is often the case for underground BACs, a restricted water flow through a single unit can affect the performance of the entire BAC. This effect causes uneven ventilation air cooling, which may necessitate adjustments or an entire re-design of the BAC. The combined impact of reduced water flow can also lead to a reduction in lifespan and, therefore, could be mitigated by ensuring the correct water flow [54], [63], [64].

- **Water temperature**

Similar to the water flow operating variable, restrictions on the temperature of the cooling liquid can negatively impact the overall performance and operational efficiency of a BAC. Should the cooling liquid be insufficiently cooled, it absorbs less heat from the ventilation air, resulting in increased outlet air temperatures of the BAC. To mitigate this and maintain optimal performance, the correct water temperatures must be supplied.

This reduction in overall efficiency leads to an increased temperature difference between the working fluids of the BAC. The cooling power of the ventilation air is then further compromised, resulting in inadequate temperatures in the working/active areas. This may lead to the system being operated for extended periods at higher capacities to compensate for the insufficient cooling, resulting in escalated energy consumption. Operation at higher capacities can strain the HTX and related components due to increased wear and tear. Furthermore, internal fouling may increase as higher fluid temperatures can promote the deposition of the chemicals and impurities in the cooling liquid [64], [65], [66].

- **Air flow**

The ventilation air that passes through an underground BAC is the process liquid. If the air flow across the coils is restricted, performance and efficiency will decrease significantly, leading to additional operational issues. These issues include a reduced heat transfer rate, increased air temperatures, and less effective ventilation air cooling.

Similar to a reduced flow of the cooling liquid, a reduced/restricted process liquid will negatively impact the cooling power of the ventilation air, leading to increased operational intensities over prolonged periods and increased component wear [67], [68], [69].

- **Air temperature**

If the temperature of the incoming air increases, a reduced temperature gradient between the incoming air and the outgoing ventilation air will occur, resulting in diminished operational efficiency of the BAC due to a lack of heat transfer rate. Similar to an increase in water temperature, an increase in inlet air temperature will negatively affect the cooling power of the ventilation air, leading to increased operational intensities over prolonged periods and increased component wear.

Due to the reduced cooling power of the ventilation air, a redesign of the BAC may be required. This could involve increasing the surface area of the cooling-coil by implementing larger coils. However, this could complicate the implementation and capital expenditure (Capex) of the project [54], [68], [70].

- **Geometry and design of fins**

Geometry—specifically the fin shape and general design—can significantly affect a BAC's operational efficiency and thermal performance when considered from the perspective of the process liquid. By altering the fin geometry, such as using circular fins on the tubes and gradually transitioning to elliptical fins in the following rows, a significant increase in overall heat transfer rates is possible whilst minimising the pressure drop on the ventilation air. This design is more efficient and achieves an increased balance between effective heat transfer and reduced material costs.

Additionally, tube shape and size further increase the efficiency of the BAC when considered from the perspective of a cooling liquid. Replacing circular tubes with elliptical tubes can ensure decreased internal drag and pressure drops. Additionally, implementing vortex generators in configurations that pair wavy fins with elliptical tubes increases the flow patterns of the process liquid, leading to enhanced performance and efficiency of the BAC [7], [53].

However, the harsh underground environment of gold mines where these BACs operate limits the type of coil geometry to circular fins and tubes, as they offer improved robustness and prolonged operations requiring limited maintenance intervals.

1.5 Problem statement

The operational performance of finned-tube BACs in deep-level gold mines deteriorates over time due to prolonged use and neglect of the operating variables. These variables include air flow restrictions, water flow limitations, incorrect supply temperatures of working fluids (air and water), and fouling caused by impurities in the working fluids.

The decline in operational performance affects the efficiency of the secondary cooling infrastructure, which in turn impacts the health, safety, and productivity of the mines at depths which exceed 2 km.

1.6 Literature review of previous research

Based on the problem statement, a literature review was conducted to examine previous research on the specific methods used to analyse and quantify the impact of the operating variables on the performance of a BAC.

Additionally, the literature review will determine whether existing methods can effectively identify the primary cause of the performance decline, and whether a validated, simulation-based methodology exists to systematically identify and correct performance issues. Therefore, the literature review aims to determine whether a solution to the problem is currently available or if a more comprehensive method is required.

1.6.1 Search strategy

For this study, a systematic scoping review was undertaken to examine previous studies on improving the performance of underground BACs through simulation-based methods. A scoping review was chosen over the traditional systematic review due to the complex, interdisciplinary nature of mine cooling, which spans both thermodynamics and mine ventilation. Work done by Arksey and O'Mally [71] and Munn *et al*. [72] indicated that scoping reviews are most applicable when:

- The area of research is multidisciplinary, complex, and constantly updated, which requires an approach that indicates key concepts and trends.
- An overall assessment of the current methods is required regarding available and used solutions, along with determining the potential gap in previous literature.
- A systematic review is too fixed regarding strict compliance or inclusion requirements when previous research could be considered, which could lead to overlooking insights relevant to the current study.

The scoping review, allowed for a structured yet flexible approach to analysing the previous research. This ensured that the most relevant studies and the respective methodologies were considered while identifying the research restrictions with regard to service delivery. Based on the work of Foo *et al*. [73], the review was additionally guided by a selection process to obtain the relevant literature.

- **Search methodology**

The literature survey was done using academic databases to ensure a comprehensive selection of peer-reviewed studies that were available at the time. The different databases that were used included ProQuest Dissertations & Theses (ProQuest | Better research, better learning, better insights.), SAIMM Journal (SAIMM - The Southern African Institute of Mining and Metallurgy), IEEE Xplore (IEEE Xplore), Scopus (scopus.com/home.uri), Google Scholar (Google Scholar), ScienceDirect (ScienceDirect.com | Science, health and medical journals, full text articles and books.), and ResearchGate (ResearchGate | Find and share research).

An integral part of the search through the various databases, based on the method proposed by Siddiqi *et al*. [74], involved identifying a range of keywords that were used to refine the search. Given the problem statement and the aim of the review, “primary”, “secondary”, and “Boolean” terms were incorporated such that the studies relevant to the performance of a BAC and mine cooling systems could be identified. The keywords are indicated in Table 2.

Table 2: Keywords Used for Research

Primary keywords	**Secondary keywords**	**Boolean operators (AND/OR)**
“bulk air cooler”, “mine cooling”, “underground ventilation”, “heat exchanger performance”, “simulation-based improvement”, “secondary cooling”, “heat transfer efficiency”	“off-design conditions”, “operating variables”, “performance decrease”, “fouling effects”, “water flow effects”, “air flow effects”, “water temperature effects”, “air temperature effects”, “latent- and sensible cooling”, “cooling coil efficiency”, “bulk air cooler modelling”	Examples include: “bulk air cooler” *AND* “fouling effects” *AND* “simulation” or “heat exchanger” *OR* “cooling coil” *AND* “operating variables”

- **Filtering and selection**

The keywords provided relevant studies during the literature search. Due to the large amount of relevant literature available in the different databases, an additional filtering process based on the work of Foo *et al*. [73], was implemented. As such, a two-phase filtering process was implemented as follows:

- **Phase 1: Primary guideline questions**

To reduce the initial number of relevant studies and maintain a focus on BAC performance, the first-level filter applied the following questions:

1. Was the research done in the mining sector/environment?
2. What was the focus of the research
3. How was the research performed?
4. What was the conclusion of the research?

The implementation of these questions significantly reduced the research results and removed studies that focused on unrelated Heating, Ventilation, and Air Conditioning (HVAC) applications and general heat exchangers and did not apply to BACs within a mining environment.

- **Phase 2: Secondary guideline questions**

A secondary filter, established in Phase 1, was then applied to determine the depth, applicability, and shortcomings of the study in terms of improving the BAC performance using simulations:

1. What type of mine-cooling infrastructure was investigated? – (*Infrastructure)*
2. Was the temperature, quantities, and the relevant effect of the operational fluids, in terms of air and water, investigated? – (*Quantity and Temperature)*
3. Was the effect of internal and external fouling on the UA factor of a cooling-coil investigated? – (*Fouling*)
4. Was simulation software used to provide and predict the result? – (*Simulated)*
5. Were the results of the previous studies tested and implemented? – (*Implemented)*
6. Were the results of the previous studies verified through measurements after implementation? – (*Verified)*
7. Did the previous research identify "pre-selected" operating variables through research to investigate and improve, or did the study investigate the cause of the lack of performance without a bias towards a specific operating variable? – (*Emergent causal operation variable)*

The **Phase 1** and **Phase 2** guideline questions identified twelve previous research papers directly correlating to this study. Although not all the guideline questions could be answered through the literature review, valuable insight was provided in terms of the impact of the operating variables on the performance of a BAC, the use of simulation software in the pursuit of improving the operational performance, validation and verification methodologies, and the respective effect of fouling, flow rates, and temperature on the BAC efficiency.

1.6.2 Review of previous research

A literature review of the relevant previous studies is summarised as follows:

1. "Performance and fouling prediction model for finned-tube heat exchangers" by B. van Rooyen [6]:

In reference to the primary guideline questions:

The research focused on the performance improvement the of FTHXs implemented as BACs within deep-level mines. The primary objective of the research was to develop a maintenance model to predict and prevent performance loss due to fouling. The operational efficiency of these types of BACs is greatly influenced by the internal and external fouling phenomenon, which leads to a need to focus on addressing the performance deterioration.

This research was implemented on nine case studies using an empirical model based on the first-principles of heat transfer and psychometry. By using these case studies, key performance losses and effective maintenance schedules were successfully identified. This research led to an empirical model that can accurately predict the loss in performance and maintenance schedules, thereby indicating that the methodology enhanced the performance and prevented future inefficiencies of a BAC.

In reference to the secondary guideline questions:

The research of van Rooyen [6] indicated that FTHXs are a critical component when considering the cooling infrastructure within a mine. The study thoroughly investigated the effect of fouling on the operational fluids by quantifying the performance decline in the air-cooling and outlet temperatures. The primary outcome of this research was the effect of internal and external fouling on the UA factor.

The research relied on testing and implementing an empirical model; as such, no simulation software was used. The accuracy and effectiveness of the predictions made by the empirical model were validated through actual measurement after implementation. Initially, the study focused on a "pre-selected" variable; but the scope of the research was steadily increased to better understand the performance of a BAC due to the effects of fouling.

Final analysis of the research:

The research focuses on predicting and improving the performance of fouling-affected FTHXs used as BACs in the mining industry. It created an empirical model to estimate maintenance schedules and performance losses and prevent additional degradation. The combined effect of internal and external fouling was identified as an operational variable with a significant influence on the outlet air temperatures and the cooling efficiency of BACs. By implementing and validating various case studies, the research validated the effectiveness of maintenance interventions.

In contrast to a simulation-based approach, this research implemented the first-principles to create a dynamic methodology. This methodology was validated after the scope was expanded. The research successfully met the objectives and provided insight into optimising mine cooling infrastructure.

2. “High-pressure water supply strategy for mine bulk air coolers” by E. G. Jordaan [42]:

In reference to the primary guideline questions:

The research focused on increasing the production of South African gold mines by improving the cooling efficiency of indirect-contact BACs used on active/working levels. While this research was implemented in the mining sector, particular focus was placed on optimising the high-pressure water supply towards the BACs to increase operational efficiency without increasing operational costs. The increase in mining depths furthered emphasised the need for effective cooling solutions to address rising production and energy costs.

This research used simulation software to predict improved performance based on water flow optimisation for cooling-coil BACs. This research was implemented and validated in two case studies, which showed increased BAC performance when the water flow was increased, provided energy costs were maintained. The research concluded that focusing on a “pre-selected” water supply variable increased the operational efficiency of indirect-contact BACs.

In reference to the secondary guideline questions:

The research focused on the water pressure of the chilled water being supplied to the individual coils of a BAC. The research concluded that a BAC's performance increased as the water flow through the coils increased. This effect was analysed alongside water temperature, leading to a reduction in the average daily temperature, thereby increasing the cooling power of the ventilation air. While the research increased the BAC performance, the effect of fouling was not addressed.

The results were predicted through the implementation of simulation software and validated according to actual implementation. The research methodology can be implemented on other mines with a focus on water flow through the respective infrastructure. This research identified the effects of a single operating variable; however, a broader investigation is required to determine the effects of the other operating variables on the performance of a cooling-coil BAC.

Final analysis of the research:

The main focus of the research was to increase the efficiency of a BAC by optimising the pressure of the chilled water being supplied towards and through the BAC. The research implemented simulation software in order to predict the results should the relevant changes be implemented. While the research focused on optimising a “pre-selected” operating variable, the immediate need to increase the operating efficiency of the BACs was successfully achieved.

The successful implementation and validation of the research highlight the importance of targeted improvements. These improvements could be enhanced by including the other operating variables of an indirect-contact BAC. This method could contribute to this study's overall methodology; however, it would need significant modifications to include the effect of other operating variables on a BAC's performance.

3. “A decision analysis guideline for underground bulk air heat exchanger design specifications” by M. Hooman, R.C.W Webber-Youngman, J.J.L. du Plessis, and W.M. Marx [75]:

In reference to the primary guideline questions:

The research consists of an analysis framework for enhancing the design process of BACs within the mining sector while considering the original equipment manufacturer (OEM) specification and the operational environment, heat load, capital expenditures, and operating expenses. The lack of comprehensive design criteria for BACs led to the need for this research, resulting in the development of a tool to guide users in creating more efficient BAC designs.

The research employs a decision analysis approach rather than a simulation-based approach. This could lead to potential overestimations of the BAC performance when operating at “off-design” conditions within a deep-level gold mine. The decision analysis framework of this research was validated through implementation at a copper mine.

In reference to the secondary guideline questions:

This research's decision analysis framework applies to direct- and indirect-contact bulk air heat exchangers. The technical specifications for creating the analysis tool includes the effect of various operating variables on the design of an efficient BAC. The tool incorporated a set range for the operating variables and excluded the possibility of misuse or lack of maintenance. This also contributes to the overestimation of BAC performance under real-world conditions.

While the capacity of the tool was verified and implemented in a copper mine, the environment in a gold mine is considered to be more demanding due to increased mining depths. As a result, additional safety measures are required when intending to use the tool to develop the thermohydraulic system of a gold mine.

Final analysis of the research:

The research aimed to provide engineers with a decisional analysis to effectively design BACs while considering cost, location, size, and heat load. Its consideration was justified by its contribution to this study in potentially establishing the design requirements per the OEM specifications of the BACs, thereby enabling a more accurate performance benchmark for tech-bench conditions.

This study does not include a simulation-based method for identifying the specific operating variables in a real-world mining environment, as these variables are precalculated. This can lead to overestimating the available BAC performance should the operational environment change.

4. "Operational energy minimisation for forced draft, direct contact bulk air cooling tower through a combination of forward and first-principle modelling, coupled with an optimisation platform" by W. Bornman, J. Dirker, D.C. Arndt, and J.P. Meyer [76]:

In reference to the primary guideline questions:

The research focused on optimising energy consumption and the performance prediction of BACs implemented in deep-level gold mines using a modelling method. The research investigated the possibility of accurately predicting the outlet conditions based on "pre-selected'' inlet conditions to establish the operational efficiency of the BACs. The root cause of the performance issues was outside the scope of this research, which focused on evaluating the effect of changing the "off-design" inlet conditions on the performance of a BAC.

The energy balance and heat transfer principles created forward and first-principle modelling methods. The data of an operational BAC within a gold mine was used to validate the model's predictions. The benefits of the modelling method proposed by this research include increased accuracy without reiterative calculations.

In reference to the secondary guideline questions:

The primary focus of this research was a mechanically ventilated, direct-contact BAC within the mine-cooling infrastructure. It focused on optimising the energy consumption of a BAC whilst considering the effect of altering multiple inlet operating variables. As a result, fouling was not investigated.

The altered modelling technique ensured predictions with increased accuracy. The research results were validated using operational data. The "pre-selection" and optimising of an operating variable led to increased performance and energy savings, even though the emergent operating variable responsible for the lack in BAC performance was not formally investigated.

Final analysis of the research:

The research aimed to use an improved modelling method to predict a BAC's performance. As a result, energy consumption and operational efficiency could be optimised. The model could, therefore, accurately predict the outlet conditions while considering the “pre-selected” conditions for multiple inlet variables. Although the specific operational variable, or a combination of variables, responsible for reduced BAC performance was not formally investigated, valuable insight into the effect of changing the inlet conditions of a BAC was provided by this research.

The research is justified because the effect of optimising the inlet variables could serve as a baseline to quantify the effect of the respective operating variables on the performance of the BAC before optimization. This would result in identifying the operating variables responsible for reducing BAC performance without bias towards any specific operating variable.

5. “Numerical study of heat transfer and fluid flow in large-scale spray cooling systems: Example of mine-bulk-air cooler” by A.F. Kuyuk, S.A. Ghoreishi-Madiseh, A.P. Sasmito, and N.B Keevil [77]:

In reference to the primary guideline questions:

The research focused on verifying the computational fluid dynamics (CFD) results based on the McPherson equations. Due to deeper deposits being mined, the simulations investigated a more integrated ventilation system. The study considered the combined effect of changing two operating variables at the inlet of an underground BAC to increase the operational efficiency. A previously verified CFD heat transfer (CFDHT) was used to assess the justification of a semi-empirical tool used for designing BACs. The research concluded that a CFDHT model correlated with the semi-empirical design tool, demonstrating that CFD simulations can be used to analyse BAC performance in a mining application effectively.

In reference to the secondary guideline questions:

The heat transfer of a direct-contact BAC was simulated in the McPherson-based CFD simulations to improve efficiency and achieve optimised performance. While two operating variables were considered, the effect of changing the quantities and temperatures of the working fluids was not directly investigated. Instead, focus the focus was on the CFD simulations, as the effect of fouling was not investigated.

The research results were not explicitly implemented or verified, as the study focused on the accuracy of the CFD models. This research validated the use of semi-empirical design tools, as it did not identify an emergent operating variable that could explain the lack of BAC performance.

Final analysis of the research:

The research aimed to compare and verify the results of CFD simulations for a direct-contact BAC using the McPherson analytical equations. To verify the accuracy of the CFD simulation results, only the effects of altering two operating variables on the performance of BAC were considered. Although the research did not include the effects of other operating variables or fouling, it did highlight the use of CFD simulations and validate their accuracy.

The implementation of CFD simulation software cannot provide a universal simulation-based method for identifying the operating variables responsible for a BAC's reduced performance. Instead, the simulation software can only be implemented in specific areas of operation, which excludes simulating an entire BAC during operation.

6. “Shape optimisation of air-cooled finned-tube heat exchangers” by H. Nemati, M.A. Moghimi, P. Sapin, and C.N. Markides [7]:

In reference to the primary guideline questions:

The research focuses on optimising the fin geometry of a finned-tubed BAC within the broader heat transfer and air-cooling discipline. The research focused on improving air-side heat transfer while reducing the pressure drop across the cooling-coils to increase BAC efficiency. The evaluation of the performance of different fin geometries was conducted through the implementation of a steady-state turbulent CFD simulation. Experimental data verified the results. Additionally, the research aimed to reduce manufacturing and material costs without compromising the performance of a cooling-coil.

The research concluded that circular fins maximised heat transfer at the entrance of the cooling-coil, while elliptical-shaped fins decreased the entropy generation and pressure drop across the cooling-coil. The result indicated an increase in the thermohydraulic efficiency of the cooling-coil.

In reference to the secondary guideline questions:

The research was applied to a general air-cooled system and not implicitly implemented on BACs used within the mining sector. As the research focused on air-side heat transfer, it did not directly investigate the effect of changing the quantities and temperature of the working fluids. As such, the impact of fouling was also excluded, as the research focused on optimising the fin-geometry for increased heat transfer efficiency and weight reduction.

The optimisation of the fin-geometry relied on the use of CFD simulations to predict the results. The results of the CFD simulation were validated through experimental data, as the research was not implemented in an operational environment. Due to the focus of the research, the investigation into the identification of causal operating variables affecting the BAC performance was not considered.

Final analysis of the research:

The research investigated the effect of an optimised finned geometry in a four-row finned tube BAC. The research objectives were achieved, as thermal efficiency increased while the infrastructure's weight was reduced. The research provided a different perspective on an additional operating variable of a BAC, as it considered the effect of changing the contact area between the working fluids. This provided valuable insight into how the operational performance of BAC could be improved.

Similar to the research done by Kuyuk [4], Nemati *et al.* [7] also used CDF simulations in their research. However, the simulation software was limited in geometry size. Therefore, the research did not provide an operationally focused method to identify the operating variables responsible for reduced BAC performance under current operating conditions.

7. “Integrated energy simulation of a deep-level mine cooling system through a combination of forward and first-principle models applied to system-side parameters” by W. Bornman, J. Dirker, D.C. Arndt, and J.P. Meyer [78]:

In reference to the primary guideline questions:

The research focused on the optimisation and prediction accuracy of an integrated mine cooling system through simulation software. Therefore, the simulation included continuous equations of various components such as pumps, fans, and cooling towers to mitigate the need for iterative calculations. The thermohydraulic analysis involved interconnecting the different elements within the simulation to improve the holistic energy consumption of the integrated system.

Data from the mine was used to validate the predictions made by the simulation. This research provided predictive insights into optimisation when system parameters were changed. Controlling the chilled water demand and air flow and rescheduling operations improved the energy efficiency of the entire system.

In reference to the secondary guideline questions:

The main contribution of this research was the development of an integrated cooling system simulation with an overview of the infrastructure involved. Secondary cooling infrastructure— BACs and CCs—was included despite the main focus being on the control system of the fridge plants. The research results indicated a cascading effect on the "downstream" infrastructure as changes were implemented on the "upstream" infrastructure.

Although the research did not investigate the emergent operating variables causing reduced BAC performance, it did provide for optimised energy consumption of an entire mine thermohydraulic system and an analysis-based method that does not rely on partial models or iterative computations.

Final analysis of the research:

By controlling various operating variables, this research developed a holistic and accurate simulation model that can be used to optimise the energy consumption of the thermohydraulic system used in a mine. Therefore, the model is a valuable tool for future optimisation strategies.

The consideration of this research is justified, as the isolated improvement of BACs can have a cascading effect on "downstream" cooling equipment within a mine. This serves as a notable consequence and is outside the scope of this study. Additionally, the simulation software used in this research can be implemented in this study, as it includes various working fluids while accurately simulating the infrastructure, contributing not only to energy consumption but to service delivery as well.

8. "Reconfiguring mine cooling auxiliaries for optimal operation" by K.J. Oberholzer [79]:

In reference to the primary guideline questions:

This research focused on optimising the cooling subsystem of the gold mine through reconfiguration. These systems were implemented shortly after the mine was commissioned, and operating efficiency was reduced due to age and lack of maintenance. Simulation software was used to develop a generic methodology to predict the effect of reconfigurations on the cooling system of the mine.

The research aimed to improve the cooling system's service delivery, reducing energy consumption and costs. The simulation results were validated by implementing respective reconfiguration suggestions on a mine's subsystems. Additionally, energy savings were realised as the setpoints on the chilled water were adjusted. This highlights that it is possible to achieve energy savings while maintaining effective cooling.

In reference to the secondary guideline questions:

The research focused on the surface cooling infrastructure and the respective operating variables, such as improving the performance of the secondary and tertiary cooling infrastructure. The study investigated whether a mine's cooling subsystems operated inadequately on the surface and investigated the downstream effect of changing a ''pre-selecting'' operational variable. Even though a surface BAC was included in the study, the cause of the operational inefficiency and the impact of fouling was not investigated.

The BAC data made available by this study cannot be used as an additional case study, as the research is intended to be implemented on underground BACs. The research also focused on the relevant surface BACs rather than underground BACs. However, the method followed by this research applies to this study, as it can serve as a reference guide for the method of this study.

Final analysis of the research:

The study aimed to improve the service delivery of a mine cooling system through reconfiguration. A universal methodology was developed through simulations to predict the effect of secondary and tertiary cooling infrastructure on the optimal operational performance. The reconfigurations were implemented, thereby validating the simulation models.

Additionally, baseline simulations for the required chilled-water temperatures were included to determine potential energy savings. This research is relevant because the general method developed can be applied to this study, as the process serves as an adequate reference or guide for establishing the method for this study.

9. "Optimal mine water management to improve ambient conditions" by S.M. Sithole [5]:

In reference to the primary guideline questions:

The research focused on improving the operational efficiency of CCs operating in a mining environment by installing regulation valves and reconfigurations. This methodology was based on simulations and data analysis of the pipework reticulations of CCs.

The suggested models, provided by the simulation software, were implemented, validating the results. This led to improved service delivery and operational efficiency. Additionally, as part of the reconfiguration of the scope of the research, pressure-regulating valves were successfully implemented, which resulted in energy savings and reduced water demands. The research goal was achieved, as the tertiary cooling system of the mine was optimised. The research methodology directly applies to this study as it was applied to cooling-coils. The method can be adapted and used to identify the effect of the water operating variable on the performance of finned-tube heat exchangers used within BACs.

In reference to the secondary guideline questions:

The research methodology identified CCs that operated inefficiently due to poor water management and inefficient pipeline configurations. Theses inefficiencies led to an increase in the water demand through the CCs to compensate for the lack of cooling. Removing the unnecessary equipment and fitting pressure valves led to more efficient water reticulation to and through the CCs.

Initial predictions, through the implementation of simulation software, indicated decreased outlet WB temperatures, subsequently confirmed by results. Even though the research focused on improving the efficiency of CCs operating with coils, it did not address the root cause of operating variables responsible for operational inefficiencies within a BAC.

Final analysis of the research:

The research aimed to improve the operation of CCs in a gold mine as the tertiary cooling systems. This was achieved through simulation software, which provided reconfiguration strategies that were validated and verified through data analysis and implementation results. The overall methodology of this study could be adapted or modified, demonstrating that a simplified solution through simulations is achievable.

Although the study increased the overall efficiency of CCs, a “pre-selected” variable was chosen and improved accordingly. As proposed by the research, the cooling car methodology can, therefore, be modified in terms of additional variables to identify the operating variables that most significantly hinder the cooling-coil performance of a BAC, which is in line with this study.

10. “Study on the thermal performance of new finned heat exchange tube bundles in cooling tower” by R. Zhao, S. Bu, X. Zhao, L. Zhang, W. Xu, Z. Yu, J. Fang, Y. Ji, Y. Hu, B. Bao [8]:

In reference to the primary guideline questions:

The research focused on the effects of introducing elliptical finned-tubes in closed wet-cooling towers to improve thermohydraulic efficiency. The improved heat and mass transfer were analysed using simulation software, with wind and spray velocities identified as the main operating variables of interest.

As an extension of the research conducted by Nemati [7], the research aimed to change the traditional circular geometry to elliptical tubes and address the issue of heat transfer inefficiencies and energy consumption in cooling towers as opposed to researching the maximised heat transfer in combination with reduced material of general heat exchangers. The result indicated an increased thermal performance, as geometric changes allowed for a more uniform velocity field and increased flow over the respective cylinders.

The success of this research was achieved by meeting practical engineering requirements whilst decreasing energy consumption.

In reference to the secondary guideline questions:

This study's primary contribution is the proposed elliptical finned-tube design. The results were predicted using CFD simulations. For this study, the results were gathered, verified against experimental data, and validated based on results from previous studies. The results of the research were verified and validated on a case-study basis.

While operational efficiency improved, the research did not investigate the operating variables that may cause inefficiencies within operational BACs. The scope of the research was limited, as the effect of "pre-selected" variables—such as air velocity and spray density—was investigated, thereby excluding other performance-limiting variables. The research methodology did not provide a simplistic method to analyse the operating variable responsible for reduced performance of indirect-contact BACs, as the effect of the contributing operating variables was not investigated.

Final analysis of the research:

This research aimed to improve the thermal efficiency of closed wet-cooling towers through the use of CFD simulations of an elliptical finned-tube design. The results indicated a stable heat transfer coefficient for the modified geometry, showing that an increase in air velocity, combined with lower inlet air temperatures, improved the operational efficiency. This justifies the research's consideration as changing the subject operating fluid's inlet conditions may improve the cooling-coils' efficiency within BACs.

Although CFD simulations were used, the research does not indicate which operating variable is responsible for the reduced BAC performance, as it focused on the effect of "pre-selected" variables. This study, therefore, lacks a simplified solution for highlighting the operating variables responsible for the reduced BAC performance.

11. “Fin and tube heat exchanger: Constructal thermal-economic optimisation” by M.S. Dehaj and H. Hajabdollahi [80]:

In reference to the primary guideline questions:

The research empirically modelled and optimised a constructal fin and tube heat exchange based on effectiveness and total annual costs. It introduced a constructal design approach to improve heat exchangers' performance and economic efficiency.

The outcomes of the constructal design were predicted through a multi-objective genetic algorithm (MOGA), and the results were compared to those of a conventional heat exchanger configuration with optimised design parameters.

The results indicated that the constructal design outperformed the traditional design. Additionally, a decrease in material and manufacturing costs was noted, which contributed to economic viability. The findings highlighted the connection between improving thermal efficiency and reducing operational costs. Furthermore, this research suggests that the constructal theory should be implemented more broadly across thermal system design applications rather than being limited to heat exchangers.

In reference to the secondary guideline questions:

The research contributed by applying constructal theory to optimise the design of FTHXs. Similar to the research conducted by H. Nemati and R. Zhou (studies 6 and 10), the elliptical structure of the FTHX provides an increased heat transfer efficiency by reducing surface area and air flow.

Although the research investigated the pressure drop across the airside of the FTHX it did not consider the effect of fouling or the implementation of simulation software. Multiple data sets, along with the actual OEM manufacturing costs, were used to verify the results of the MOGMA.

Furthermore, although the research succeeded in optimising the design of an FTHX, it did not investigate the operating variables that limit performance under real-world conditions. The research was considered because it highlighted the possible performance and economic benefits of changing the coil type used within BACs on gold mines.

Final analysis of the research:

Through constructal theory and MOGA, the research provided a conclusive method for optimising FTHXs. The primary goal of increasing the efficiency while lowering the costs of FTHXs was achieved through design and optimisation techniques.

However, the focus of the research was on the effect of adjusting “pre-selected” operating variables within a limited operational area instead of determining which operating variable—or combination of variables— is responsible reduced efficiency of an operational FTHX. Despite not using simulation software to predict the results of multiple coils in operation, the research provided additional potential for increasing the UA factor at lower costs and decreasing pressure differences.

12. “Calculation method for fin-and-tube heat exchangers operating with nonuniform air flow” by P. Blecich and K. Lenić [81]:

In reference to the primary guideline questions:

The research provided a method for calculating the thermohydraulic efficiency of FTHX operating under nonuniform air flow conditions. The method developed by the research is known as the Tube Element Method (TEM). The research indicated that fouling and poor design contributes to the effect of FTHX nonuniform flow.

The results of van Rooyen [6] support the research results of this study despite the goals of these studies being different. Traditional methods' limitations assume uniform flow across a heat exchanger. In contrast, this research aimed to overcome this limitation by creating a method capable of controlling nonuniform air flow profiles in two dimensions. By applying the mass and energy conservation laws, the TEM method divides the heat exchanger into tube elements to predict the efficiency, heat transfer rates, and working fluid outlet temperatures.

The measured data from the tests confirm the TEM method. The results showed that nonuniform air flow negatively affects the performance of a heat exchanger and is dependent on two variables: the UA factor rate and the number of heat transfer units. Consistent with all the previous research referenced in this literature review, the findings indicate that the effects of nonuniform air flow should be considered during the design process to mitigate the performance losses caused by this effect.

In reference to the secondary guideline questions:

The research contributes to optimising FTHX since the effect of nonuniform air flow was investigated. The TEM method was developed where industrial cooling processes and power plants within the construction discipline were the focus and not the mining discipline.

The research implemented simulation software that incorporated the TEM method to predict the performance of FTHXs with increased accuracy while accounting for two-dimensional air flows. The direct influence of fouling and different inlet conditions— such as temperature and quantities—were not considered, as the primary focus was on establishing the effect of the air flow patterns on the performance of a heat exchanger.

Additionally, the research indicated that for BACs that use FTHXs, consideration must be given to the air flow patterns at the inlet, as improvements in operational efficiency, increased reliability, and decreased operational costs can be achieved.

However, the research is limited, as the focus was on studying the effect of "pre-selected" operating variables and not on investigate the cause of the limited performance or the dynamic changes to conditions of a BAC operating within a mining environment.

Final analysis of the research:

More accurate results were achieved compared to the traditional method when the TEM method was applied due to the incorporation of two-dimensional air flow patterns. This is important to the broader discipline of cooling systems, as heat exchange results can lead to improved designs.

Even though the research focused on heat exchangers implemented in the industrial and commercial environment, the relevance of more accurate results can be directly applied to FTHX used within the mining industry. This research highlighted the effects of the air flow patterns and distribution within a system with balanced heat transfer rates.

While the TEM method used simulation software and could determine the effects of nonuniform flow over FTHX, a simpler method for determining the cause of reduced performance of a heat exchanger was not investigated. The research concluded that future studies could investigate dynamic real-world conditions, as experimental data validated the results. The research provided a method to improve the design of FTHX, providing valuable insight into the effect of air flow across an FTHX.

1.6.3 Aim of the review

The literature review aims to establish criteria based on the need for, an aim to, and objectives for a solution to the problem identified in Section 1.5. This ensures that the proposed solution of this study effectively addresses the reduction in BAC operating performance caused by the influential operating variables. As such, the criteria should include the following:

- **Identification of the operating variables**

A study by Du Plessis *et al*. [82] and Kleingeld *et al*. [83] highlighted the need for a detailed performance simulation of an overall mine cooling system to identify certain inefficiencies. Therefore, the solution must include a systematic approach for identifying and quantifying the operating variables responsible for reducing the BAC's operational performance.

- **Predictive capability of the simulation models**

Research done by Torri *et al*. [84] highlighted the crucial role of an accurately calibrated thermohydraulic model in the analysis of heat exchanger efficiency and emphasised the need for validating the simulation models. Therefore, the solution must utilise simulation software capable of accurately predicting the performance of a BAC at various operational conditions.

- **Gap analysis on the performance influence**

As part of the published work and research done by Kröger [85] on heat rejection systems, the importance of benchmarking techniques to quantify operational losses and the establishment of corrective measures was highlighted. The ability to then perform a direct comparison between the actual and achievable performance of BAC is essential.

- **Verification and validation**

Supported by the research conducted by Zhang *et al*. [86], operational validation through comparisons of the initial and re-audit performance results of a BAC provides empirical confirmation of the methodology. This highlights the critical criterion of ensuring the implemented corrective measures contribute to the improvement of BAC performance.

By achieving these criteria, the method used to solve the problem will address the operating variable/s responsible for reducing BAC performance and provides a repeatable framework for continuous performance improvement in deep-level mining applications.

1.6.4 Summary of previous research

Previous research indicated that the performance of a BAC has been extensively researched through various methods and application areas. As mentioned in Section 1.6.1, the chosen research was selected due to applicability, contribution, and insight into this study. Table 3 summarises the previous research relevant to this study in a state-of the-art matrix format.

Table 3: Previous Research Summary: State-of-the-art Matrix for Criteria Identification

Study no.	Source	Infrastructure		Quantity and/or Temperature		Fouling		Simulated	Verified	Implemented	Emergent causal operation variable
		BACs	Other	Air	Water	Air (External)	Water (Internal)				
1	van Rooyen, [6]	✓	×	×	×	✓	✓	×	✓	✓	×
2	Jordaan, [43]	✓	×	×	✓	×	×	✓	✓	✓	×
3	Hooman *et al*, [84]	✓	×	✓	✓	×	×	×	✓	✓	×
4	Borman *et al*, [85]	✓	×	✓	✓	×	×	✓	✓	✓	×
5	Kuyuk *et al*, [86]	✓	×	✓	✓	×	×	✓	×	×	×
6	Nemati *et al*, [8]	✓	×	✓	×	×	×	✓	✓	×	×
7	Meyer *et al*, [87]	✓	✓	✓	✓	×	×	✓	✓	✓	×
8	Oberholzer, [88]	×	✓	✓	✓	×	×	✓	✓	✓	×
9	Sithole, [5]	×	✓	×	✓	×	✓	✓	✓	✓	×
10	Zhoa *et al*, [9]	✓	×	✓	✓	×	×	✓	✓	✓	×
11	Dehaj *et al*, [89]	✓	×	✓	×	×	×	×	✓	×	×
12	Blecich *et al*, [90]	✓	×	✓	×	×	×	✓	✓	×	×

1.7 Need for the study

All twelve previous research papers had "pre-selected" specific operating variables through a rationale or a literature review to study the effects of increasing the operating performance of the BAC. However, the shortcoming in "pre-selecting" the operating variables of interest was that no consideration was given to establish whether or not the "pre-selected" operating variables were primarily responsible for reduced operational performance of a BAC when compared to the "non-selected" operating variables.

Furthermore, nine out of twelve research papers successfully incorporated simulation software to predict the results. This approach not only demonstrated how the simulation software was incorporated but also clarified the type, benefits, and shortfalls of the software to address the goals of the research. The use of simulation software to predict the results of this study was then justified, as simulation software could accurately and suitably predict the performance of a BAC operating at various conditions.

The previous research also highlighted the main operating variables that influence the performance of a BAC operating at "off-design" conditions within a mine. These operating variables are discussed in Section 1.4.3.

Additionally, the results of previous research did not clearly distinguish between the design, achievable, and actual duty of the BAC. For the purposes of this study, the design duty is considered as the operational capacity of the BAC in accordance with a standard OEM- and/or mine specifications under ideal conditions. For instance, should a BAC or cooling-coil be listed with a rated capacity of 500 kW, the design duty will be considered as the rated capacity of 500 kW.

The actual duty will be the operational performance of the BAC or cooling-coil as measured while the infrastructure operates in an underground environment. The achievable duty is considered as the operational performance of the infrastructure should all the limiting factors, in terms of the operating variables, be addressed. Alternatively, the achievable duty could be considered a measure of the available performance at "off-design" conditions and is provided by the simulations.

Following the literature review, only two of the twelve previous research papers focused on alternate cooling infrastructure, while the remaining ten focused on increasing the performance of a BAC. As a result, none of the previous research papers established the limiting operating variable/s or provided a method through simulation for analysing the operating variable/s responsible for reduced performance in BACs.

The main research findings obtained from Table 3 are as follows:

- The majority of the research was conducted on BACs or relevant aspects thereof that could be implemented within a mining environment.
- Even though the effect of internal and external fouling is a well-known phenomenon and has been extensively investigated, it is excluded from most previous research.
- None of the previous research considered whether the “pre-selected” operating variable/s are responsible for a reduction in BAC performance under “off-design” conditions.
- None of the researchers provided a method, through the implementation of simulation software, to establish the respective influence of the operating variables on the performance of a BAC.
- The majority of the research was conducted on FTHXs, while only one or two operating variables were investigated: however, only in a limited capacity.

Thus, none of the methods investigated are capable of identifying issues for immediate address, such as to increase the operational performance of an indirect-contact BAC.

Therefore, a need exists to **create a method, using simulation, for identifying specific operating variables reducing the performance of finned-tubed bulk air coolers** so that they can be addressed as part of corrective actions to improve performance when operating at ‘’off-design’’ conditions such as in a mining environment.

Henceforth, the study will focus only on BACs comprising FTHXs that are operational under “off-design” conditions in a mine.

1.8 Aim and objectives

The aim of the study is then to develop a simulation-based methodology to identify and quantify the impact of the operating variables on the performance of a BAC whereby the objectives set out to meet the need for the study must be able to provide the following:

1. The achievable duty for the finned-tubed BAC under current “off-design” operating conditions through simulations.
2. The identification, through the implementation of simulations, of the operating variables responsible for reducing BAC performance in terms of:

2.1. Air
    2.1.1. Inlet temperature (WB/DB)
    2.1.2. Quantity
2.2. Water
    2.2.1. Inlet temperature
    2.2.2. Quantity
2.3. Fouling
    2.3.1. Internal and external fouling in terms of the total UA factor

*(**Side note**: The geometry in terms of fin-shape and layout as an operational variable for the FTHXs are excluded from this study as it leads to a new design- and operational philosophy for a BAC, which ultimately falls outside the scope of this study)*

3. An improvement in the actual duty of a finned-tubed BAC.
4. A reduction in WB temperatures at the outlet of a BAC.

1.9 Research methodology

The methodology was designed to ensure the study's objectives could be achieved and reproduced. It can be defined as: "A methodological research approach used to generate an in-depth understanding of a contemporary issue or phenomenon in a bounded system" [87]. Therefore, for the study to be considered successful, the results must be valid and accurate [88].

This section includes the consideration of various research design methods established from previous research to determine the most applicable methodology for this study. The methodologies that were evaluated for this study include experimental analysis, relevant surveys, case study analysis, document analysis, and historical analysis.

Experimental analysis requires a large sample size to accurately determine the effects of changing control variables and is ideal for "how" and "why" questions. Surveys, when considered as a quantitative method, promote constructive feedback by allowing the participants to respond adequately. [89]. Document analysis, a qualitative approach, examines current documentation to investigate general research questions such as "who", "what", and "how" [89].

Past events and relevant theories are best approached through the historical analysis method, but it can be limited when applied to current data. Current events are best approached through a case study, as research questions such as “how” and “why” can be resolved in real-world conditions [89].

Given the scope of this study on present-day mining conditions, the various criteria of the different methodologies, limited control of the operating variables, and the objectives, as listed in Section 1.8, this study identified that an original case study research design methodology was most suitable for investigating the causes behind the reduced BAC performance under current operating conditions and developing a method to do so using simulation software.

The selected method is represented by Figure 12 and is further explained in Chapter 2.

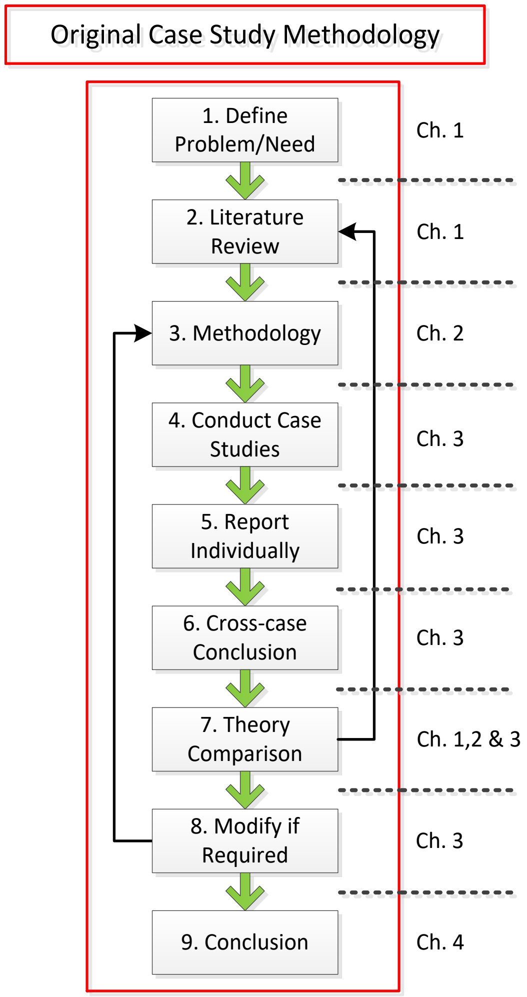


Figure 12: Initial Case Study Research Design Methodology (Adapted From [90])

1.10 Conclusion

Effective heat management is a critical process in deep-level mining to maintain miners' productivity, health, and safety. This is achieved through the implementation of effective cooling and ventilation systems. Finned-tubed or direct-contact BACs are key components of these systems, responsible for secondary cooling in mines deeper than 2 km. Despite variations in the types of BACs, their operating principles remain the same, as they allow heat transfer between working fluids to either dissipate or recover, depending on the requirements of the mining environment.

The operating performance of BACs deteriorates over time, resulting in downtime for maintenance and repair. Therefore, there is a need to develop a method to establish which operating variable/s causes the reduced performance for finned-tube BACs to ensure increased operational performance. While previous research explored “pre-selected’’ operational variable/s and their relevant effect, it did not consider whether the selected operating variable/s were directly responsible for decreased BAC performance.

The objectives of this study that set out to address this gap include a method, through the implementation of simulation software, to predict the following: the emergent operating variable/s responsible for decreased performance; the achievable duty, a decrease in outlet WB temperature, and an improvement in operational performance overall.

1.11 Chapter overview

Chapter 1: Introduction and Literature Review

In Chapter 1, the introduction, background, scoping literature review, the state-of-the-art, and the need for this study were presented. The chapter also included how the need for the study was established, along with a summary of the objectives which created the foundation for the study.

Chapter 2: Methodology

In Chapter 2, the study methodology was devised in line with the study objectives based on the knowledge and insights provided by the literature review. This chapter included verification, validation, and the relevant measuring techniques in addition to the process followed to adjust the original case study methodology to the reworked case study methodology.

Chapter 3: Implementation and results

In Chapter 3, four case studies were selected and investigated to ensure that all the objectives were met within the scope of this study as set out in Section 1.8. The results and the implementation stages were also discussed in this chapter and then compared to the study objectives to verify that the need for the study was addressed. Chapter 3 included the sub-steps no. 1 to 6, which concluded in the "Results" as indicated by Figure 25.

Chapter 4: Conclusion and recommendations

Chapter 4 presents an overview of the study as well as the successes and limitations of the study. Finally, a reflection of the study and recommendations were made to assist future studies.

CHAPTER 2 DEVELOPMENT OF METHODOLOGY

2.1 Preamble

The research methodology for this study is developed systematically to address the shortfalls of the previous research described in Section 1.7. Additionally, the methodology provides a structured approach for improving the performance of BACs operating under “off-design” conditions. The original case study research design methodology, as presented by Figure 12, provided a foundation for an experimental investigation; however, it was adjusted accordingly to align with the objectives and will henceforth be called the “reworked case study methodology.”

The reworked methodology incorporates a simulation-based approach with an analysis of the operating variables that influenced the performance of a BAC. Chapter 2, therefore, explores the adjustments to the original research design, the justification behind the adjustments, and the steps used to achieve the objectives of the study.

2.1.1 Change in the original research design

As presented in Figure 12, the original case study methodology follows a sequential process in which individual case studies are conducted, analysed, and compared to form a conclusion [91]. However, changes to the original methodology are required to better align with the objectives and aim of this study, as its general approach does not directly indicate applicability to the study. As such, the relevant changes include the following:

- **Inclusion of simulations**

The literature review highlights a shortfall in understanding the combined effect of the operating variables. Previous research “pre-selected” the operating variables and studied their effects in isolation rather than studying their relative effect when compared to the other operating variables. To address this, simulations are incorporated as a tool to analyse the performance of BACs and to ensure an emergent causal approach that is not limited to one specific operating variable.

- **Expansion of the methodology**

To enhance application, replicability, and alignment to the aim of this study, the “Methodology” step in Figure 12, is divided into six sub-criteria as follows:

1. Data gathering: Collecting performance data for the respective case studies.
2. First-principle cautions: Establishing a baseline performance.
3. Simulations: Identifying the limiting variables and predicting achievable performance.
4. Gap analysis: Comparing the actual, causal, and achievable duties.
5. Implementation: Applying corrective measures based on the results.
6. Verification and validation: Ensuring the performance improvements and validity of the methodology.

- **Combination of steps**

As presented in Figure 12, steps 4, 5, 6, 7 and 8 (Conduct Case Studies, Report Individually, Cross-Case Conclusion, Theory Comparison respectively, Modify if Required) are consolidated into a single category. Instead of treating each case study as a separate application of the method, results from the respective case studies are integrated within the method to allow for direct comparison and the validation of the corrective measures. This ensures that the methodology is solution-driven, as the focus is placed on influence identification and performance improvement rather than on reporting on the case studies individually.

2.1.2 Adaption of original research design

The adaption from the original methodology to the reworked methodology is summarised in Table 4 below, where an explanation for reworking the steps and supporting references are provided.

Table 4: Development of Methodology Matrix

Original step (Original case study methodology)	Reason for change	Justification based on Table 3	Reworked step		Support source
1. Define problem/need	Problem is identified from the background and is additionally summarised between the scoping review and the state-of—the-art matrix.	The shortfall of the previous research is established, which then includes the determination of the emergent causal operating variable influencing BAC performance along with the requirement of a reworked methodology.	1. Literature Review		[71], [72]
2. Literature review	A structural approach (matrix) is utilised to indicate the limitations of previous research.	The matrix is a summary of the literature review, allowing for a clear indication of the overall shortfall, as previous research is weighed against each other.	2. State of the Art		[92], [93]
3. Methodology	An expansion of six sub-steps defines the logical development from data collection to validation for this study.	The expansion provides a structural process to identify the limiting operating variables through simulations to ensure the application and the replicability of the method.	3. Methodology	3.1 Data Gather	[85], [94], [6]
				3.2 First-principle Calculations	[95], [96], [91]
				3.3 Simulations	[97], [5], [91]
				3.4 Gap Analysis	[95], [85], [91]
				3.5 Implement	[97], [91], [6]
				3.6 Verification & Validation	[91], [98]

4. Conduct Case Studies	Merge into a single step.	Steps 4 to 8 of the original methodology are then combined and integrated within individual steps of the reworked methodology to highlight the validity as it shifts towards a simulation-based methodology.	4. Results	[98],[6], [5]
5. Report Individually	Merge into a single step as findings are reported individually.			[93], [72]
6. Cross-Case Conclusion	Merge into a single step as findings are reported individually.			[97], [96]
7. Theory Comparison	Merge into a single step as the study validates the reworked methodology instead of comparing existing methods.			[91], [98]
8. Modify if Required	Merged into a single step and form part of the verification and validation.			[97], [6]
9. Conclusion	\	Confirms the success of the reworked methodology in terms of the identification of the limiting operating variables and if a structured framework for performance improvements is provided	5. Conclusion	[71], [91]

Figure 13 illustrates the process outlined in Table 4:

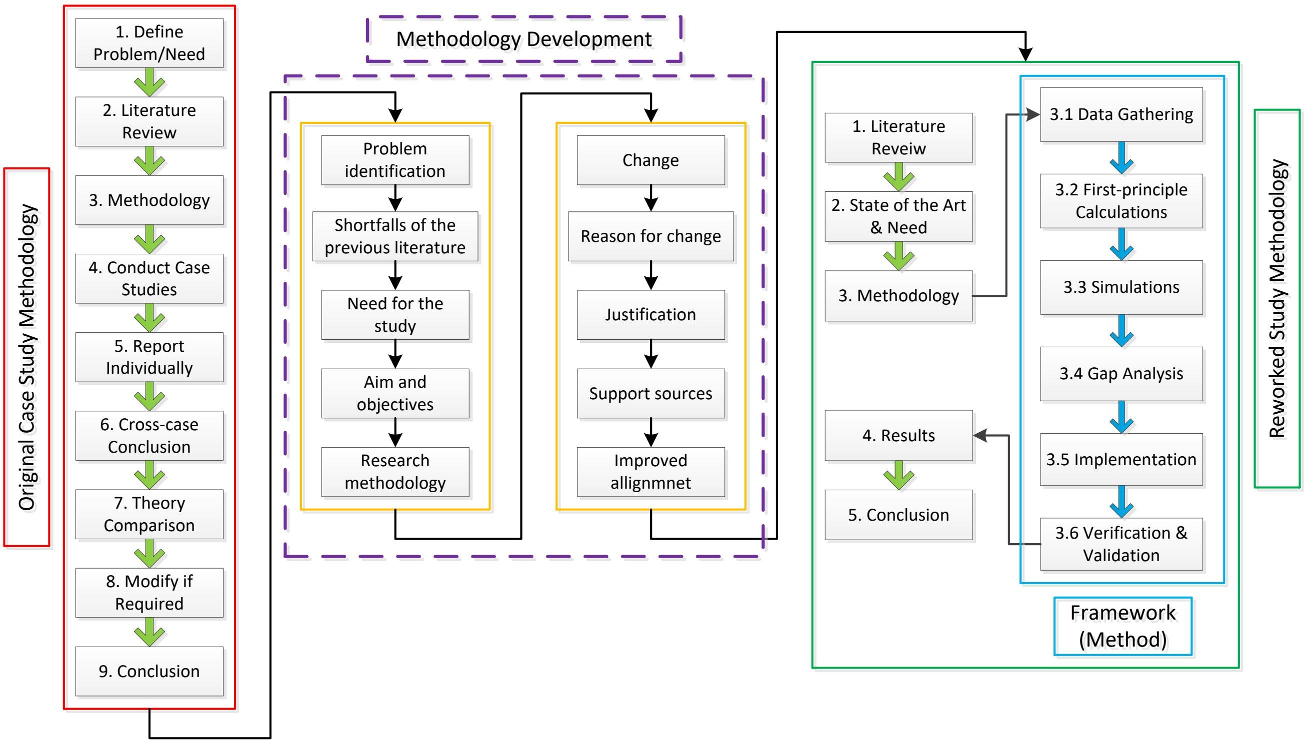


Figure 13: Overall Research Methodology Development

2.2 Sub-steps of the reworked case study methodology

In the reworked case study methodology, indicated by the green boundary in Figure 13, step 3, “Methodology”, has been expanded into six sub-steps. The six sub-steps, 3.1 to 3.6, indicated by the blue boundary in Figure 13, form a structured, systematic framework/method to analyse the performance of a BAC.

Each sub-step plays a specific role in achieving the aim and objectives of the study. The blue-boundary framework summarises the study’s method and contribution to the original case study methodology after the required modifications have been implemented to create the reworked case study methodology. The role of each sub-step within this framework is described as follows:

2.2.1 Sub-step 3.1: Data gathering/collection

The data gathering sub-step starts with establishing the location of the BAC and whether there is a query regarding its performance. The location of the BAC should be within a half-level of a gold mine, as the study aims to improve performance of BACs in the gold mining industry.

When a BAC is implemented in a mine, the overall efficiency should decrease over time due to the operational environment [24]. The cause of the decrease in BAC performance and the correct remedial actions should be of concern to the maintenance personnel of the mine [24].

After confirming the location, performance concern, and the type of BAC, the operational measurements are gathered. Measurements establish a baseline and serve as a reference for the verification and validation of the simulations after implementing the recommendations [5]. Figure 14 indicates, using purple numbering, where the measurements are taken for the various case studies applicable to this study.

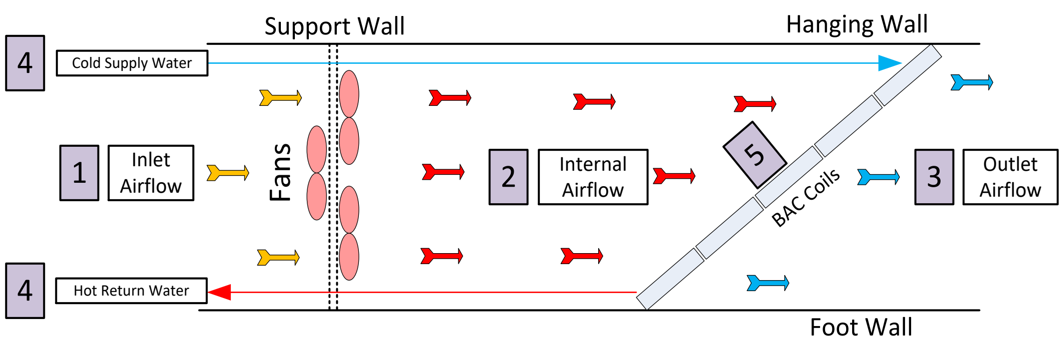


Figure 14: BAC Measuring Positions

From Figure 14, positions 1, 2, 3, and 4 are measured manually by following an internal mining standard, which is based on a standard provided by the Department of Mineral and Resources of South Africa [99].

The accuracy range of the instrumentation used for the measurements can be found in Appendix AA. If the mine has implemented instrumentation at the indicated locations, the Supervisory Control and Data Acquisition (SCADA) system could then be accessed for the required information [5].

Position 5 is a localised measurement and requires a manual measurement procedure with the same equipment used for positions 1 to 4. Each finned-tube coil is measured on both the up- and downstream side of the air flow. As such, the data gathering methods followed by Sithole [5], van Rooyen [6], and Blecich [96] had to be adapted to fit the scope of this study.

Nine measurement positions, indicated by the letter “A” in Figure 15, that are equally spaced across the through-flow area of the finned-tube coil are required for the air velocities, whereas one central measurement, indicated by the letter “B” in Figure 15, is required per coil for the air temperature. This procedure results in ten one-point measurements per side.

The one-point measurement strategy is implemented instead of transverse method proposed by du Toit [100] due to excessive air turbulence, equipment limitations, limited access, and the geometric layout of the coils. The air velocity measurements through the coils are taken close to the coil surface, while air temperature measurements were 300mm to 500mm away from the coil surface. Figure 15 is an illustration of the measuring procedure for position 5:

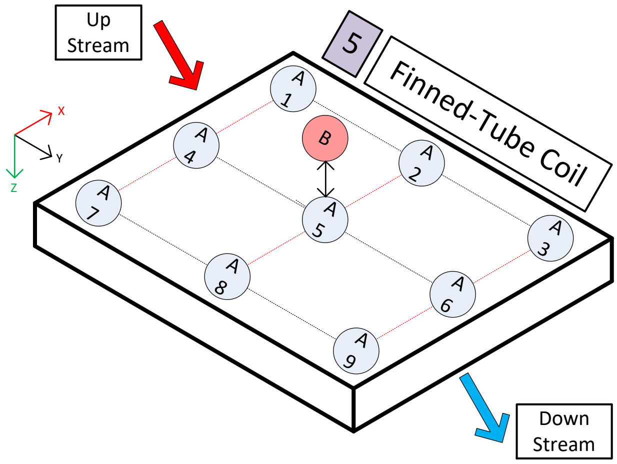


Figure 15: Finned-tube Coil Measuring Procedure

In accordance with the mass conservation law, the rationale behind the quantity of velocity measurements is to confirm the mass flow of the air on the up- and downstream side of the coil relative to the total amount of mass flow entering and exiting the BAC at position 1 and 3 [101]. Due to the size of the finned-tube coil, one centralised temperature measurement is required per side for reference purposes, as the distance between the various measuring points minimises any potential heat pickup.

As part of the “Data Gathering” criteria, it is also necessary to note the condition of the coils and obtain the OEM specification regarding the finned-tube coils and the design specification selected by the mine for the BAC [6]. These specifications are used as part of the validation process during the “Simulations” criteria of the proposed methodology [5], [6]. The “Data Gathering” sub-step is then visually represented by Figure 16, to source and ensure all the data is relevant to this study.

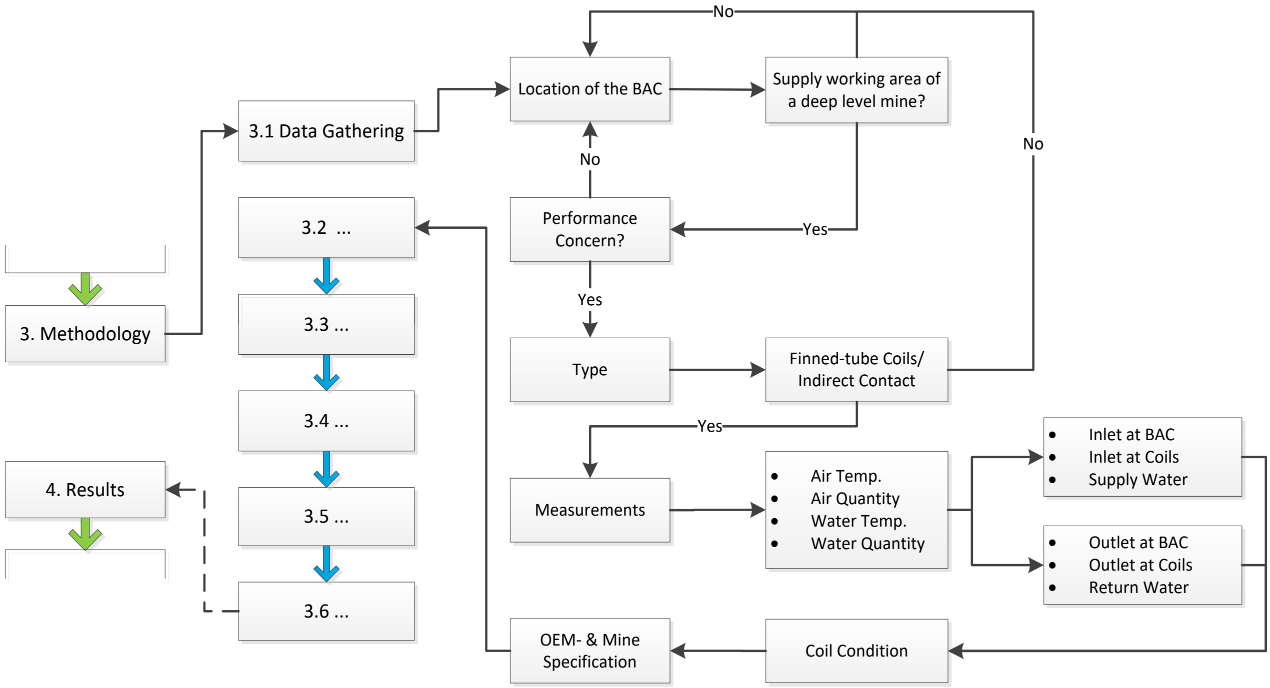


Figure 16: Sub-step 3.1 - Data Gathering

A detailed BAC measuring checklist can be found in Appendix AB.

2.2.2 Sub-step 3.2: First-principle Calculations

Following the “Data Gathering” sub-step, the measurements are processed through a calculation tool created in Microsoft (MS) Excel. The tool is based on a theoretical approach to analysing the operating performance of the BAC and the respective performances of the individual cooling-coils. As discussed in Section 1.4.3, cooling-coils play a critical role in the heat exchange process of an indirect-contact BAC, as they are primarily designed as air-to-water heat exchangers.

The analysis of critical parameters such as heat transfer duties of both air and water and the UA factor is essential in establishing the efficiency of the cooling-coils. The duty, which combines factors such as the surface area of the coil and the heat transfer coefficient, provides a measure of the cooling-coils' ability to transfer heat and is directly influenced by fouling.

To understand the performance of a cooling-coil and a BAC, the operating variables must be assessed to ensure the ventilation air temperature is sufficiently cooled before it is sent to the active/working areas in a mine. The empirical representation of the respective performances, also indicated by previous research, is as follows:

- **Ventilation air duty**

The air duty for direct- and indirect-contact BACs can be calculated from enthalpy. Sigma energies are traditionally used in the mining sector for calculating heat loads and duty calculations of BAC [5]. This section outlines the process of calculating the air duty by using the Delta-Enthalpy method shown in Equation (1) [5], [102]:

$$Q_a = \dot{m}_a(H_0 - H_i) \tag{1}$$

Here:

Q_a = Air Duty (kW)

$\dot{m}_a$ = Mass Flow Rate of Air (kg/s)

H_0 = Outlet Enthalpy (kJ/kg)

H_i = Inlet Enthalpy (kJ/kg)

From Equation (1), the mass flow rate of air can be calculated as follows:

$$\dot{m}_a = \rho_a(\dot{v}_a) \tag{2}$$

Here:

ρ_a = Density of Air (kg/m^3)

$\dot{v}_a$ = Volumetric Flow Rate of Air (m^3/s)

From Equation (2), the density of air can be calculated as follows:

$$\rho_a = \frac{1 + RH}{V} \tag{3}$$

RH = Relative Humidity of Air (%)

V = Specific Volume of the Moist Air (m^3/kg)

From Equation (3), the relative humidity can be calculated as follows:

$$RH = \frac{P\left(\frac{\left(\frac{R_{mol}P_{sat-WB}}{P-P_{sat-WB}}\right)\left(h_{fg}-T_{WB}\left(C_{pw}-C_{Pvap}\right)\right)-C_{pa}\left(T_{DB}-T_{WB}\right)}{h_{fg}+C_{Pvap}T_{DB}-C_{pw}T_{WB}}\right)}{(P_{sat})\left(R_{mol}+\frac{\left(\frac{R_{mol}P_{sat-WB}}{P-P_{sat-WB}}\right)\left(h_{fg}-T_{WB}\left(C_{pw}-C_{Pvap}\right)\right)-C_{pa}\left(T_{DB}-T_{WB}\right)}{h_{fg}+C_{Pvap}T_{DB}-C_{pw}T_{WB}}\right)} \tag{4}$$

Where:

$$W = \frac{\left(\frac{R_{mol}P_{sat-WB}}{P-P_{sat-WB}}\right)\left(h_{fg}-T_{WB}\left(C_{pw}-C_{Pvap}\right)\right)-C_{pa}\left(T_{DB}-T_{WB}\right)}{h_{fg}+C_{Pvap}T_{DB}-C_{pw}T_{WB}} \tag{5}$$

Which results in:

$$RH = \frac{P \times W}{(P_{sat})(R_{mol}+W))} \tag{6}$$

Variables:

P = Air Pressure (kPa)

P_{sat} = Saturated Air Pressure (kPa)

R_{mol} = Molecular Mass Ratio of Water Vapour to Air (0.62198)

P_{sat-WB} = Saturated Air Pressure at Wet Bulb Temperature (kPa)

h_{fg} = Heat of Evaporation at 0 ℃ ($250\ 1000\ J/kg \cdot K$)T_{WB} =Wet Bulb Temperature (K)

T_{DB} =Dry Bulb Temperature (K)

C_{pw} = Specific Heat of Water ($4.18\ kJ/kg \cdot K$) [5]

C_{Pvap} = Specific Heat of Water Vapor ($1.805\ kJ/kg \cdot K$) [5]

C_{pa} = Specific Heat of Air ($1.006\ kJ/kg \cdot K$) [5]

From Equation (4), the specific volume of the moist air can be calculated as follows:

$$V = \frac{R_{air}(T_{air-DB}+K_t)}{P \cdot P_{sat} \cdot RH} \tag{7}$$

Variables:

R_{air} = Ideal Gas Constant ($287.05\ J/kg \cdot K$)

T_{air-DB} = Dry Bulb Temperature of the Air (℃)

K_t = Absolute Temperature ($273.15\ K$)

From Equation (2), the volumetric flow rate of air can be calculated as follows:

$$\dot{v}_a = v_a(A) \tag{8}$$

Variables:

v_a = Velocity of Air (m/s)

A = Flow Area (m^2) calculated by $A = l \times b$ as the respective dimensions in (m) of a square coil.

From Equations (4), (5), and (6), the saturated air pressure can be calculated as follows:

$$P_{sat} = e^{(\frac{C_1}{T}+C_2+TC_3+T^2C_4+T^3C_5+C_6 logT)} \tag{9}$$

Variables:

T = Temperature (K) as ($T = T_{air-DB} + K_t$)

C_{xn} = Hyland- and Wexler Correlation Factors [103]:

$$C_1 = -5800.2206$$

$$C_2 = -5.516256$$

$$C_3 = -0.048640239$$

$$C_4 = -0.000041764768$$

$$C_5 = -0.000000014452093$$

$$C_6 = 6.54449673$$

Conclusively, after considering Equations (1) to (9), the respective inlet and outlet enthalpy of the air as it passes through the cooling-coils can be calculated as follows:

$$H_{xn} = C_{pa}T_{DB} + \left(\frac{R_{mol}P_{sat-DB}RH}{P-P_{sat-DB}RH}\right)(h_{fg} + C_{Pvap}T_{DB}) \quad (10)$$

- **Chilled water duty**

The water duty can also be calculated from enthalpy. This section outlines the process to calculate the water duty by using the Delta-Enthalpy method as follows [5], [102]:

$$Q_w = \dot{m_w}C_{pw}(T_0 - T_i) \quad (11)$$

Where:

$$(T_0 - T_i) = \frac{H_0 - H_i}{\dot{m_w}C_{pw}} \quad (12)$$

Variables:

Q_w = Water Duty (kW)

$\dot{m_w}$ = Mass Flow Rate of Water (kg/s)

C_{pw} = Specific Heat of Water $(4.18\ kJ/kg \cdot K)$

T_0 = Outlet Temperature (℃)

T_i = Inlet Temperature (℃)

H_0 = Outlet Enthalpy (kJ/kg)

H_i = Inlet Enthalpy (kJ/kg)

Collectively, the water duty should theoretically be equal to the air duty to comply with the Law of Energy Conservation [68]. Therefore, the water duty can be a baseline for the air duty, or vice versa.

- **UA factor**

The UA factor can be calculated using the water duty and the log mean temperature difference (LMTD). This section outlines the process of calculating the UA factor as follows [5], [104]:

$$UA_{factor} = \frac{(Q_w \times \left(\frac{lnln\left(\frac{\Delta T_1}{\Delta T_2}\right)}{\Delta T_1 - \Delta T_2} \right))}{100} = \frac{(Q_w \times LMTD)}{100} \tag{13}$$

Where:

$$\Delta T_1 = T_{air-WB}in - T_{water}out \tag{14}$$

and:

$$\Delta T_2 = T_{air-WB}out - T_{water}in \tag{15}$$

Variables:

UA_{factor} = UA Product Factor (%)

Q_w = Water Duty (kW)

$\Delta T_1 =$ Respective Temperatures of the Working Fluids (℃)

$\Delta T_2 =$ Respective Temperatures of the Working Fluids (℃)

$LMTD =$ Log Mean Temperature Difference (℃)

The heat transfer in parallel-flow and counter-flow heat exchanges is effectively calculated by the LMTD method [104]. The flow in the coiling coils, implemented by the gold mines, is in a crossflow configuration, which means the working fluids flow perpendicular to each other [24], [43], [48], [105]. This configuration leads to complicated flow conditions, resulting in a correction factor (F) that must be considered when calculating the UA factor of the cooling-coils.

The correction factor is employed to adjust the LMTD for the crossflow conditions. It can be derived from the one-shell pass and even-number correction factor chart to provide a more accurate representation of the cooling-coils' performance under crossflow conditions [5], [66], [102], [104]. The correction factor can be calculated as follows:

$$F_{1,2} = f(x) = \{\frac{\frac{\sqrt{1+R^2}}{(R-1)} log_{10}(\frac{1-P}{1-PR})}{log_{10}(\frac{\frac{2}{P}-1-R+\sqrt{1+R^2}}{\frac{2}{P}-1-R-\sqrt{1+R^2}})},\ R < 1\ \frac{\frac{P\sqrt{1+R^2}}{2.3(1-P)}}{log_{10}(\frac{\frac{2}{P}-1-R+\sqrt{1+R^2}}{\frac{2}{P}-1-R-\sqrt{1+R^2}})},\ R = 1 \tag{16}$$

Where:

$$P = \frac{T_{water}out - T_{water}in}{T_{air-WB}in - T_{water}in} \tag{17}$$

and

$$R = \frac{T_{air-WB}in - T_{air-WB}out}{T_{water}out - T_{water}in} \tag{18}$$

- **Fouling factor**

The fouling factor represents the level of foulant accumulation, which directly influences the UA factor and the overall efficiency of the cooling-coil. The fouling factor can be defined as the difference between the reciprocals of the overall heat transfer coefficients of the cooling-coil [5], [106]. Therefore, the fouling factor represents the internal and external fouling accumulation and can be calculated as follows:

$$F_f = \frac{1}{UA} - \frac{1}{UA_{Design}} \tag{19}$$

When a cooling-coil is implemented, the UA factor is determined by using measurements during operation, while the "UA_{Design}" factor represents the design UA factor under ideal or test-bench conditions.

Referring to Equations (1) to (19), the performance of the various coiling coils used to construct a BAC can be understood as managing sensible and latent heat related to the cooling and dehumidification of the ventilation air. From a secondary perspective on the operation of the cooling-coils within a BAC, sensible heat is the thermal energy required to change the temperature of a substance without undergoing a phase change and, when removed, results in a drop in air temperature [68]. This process is crucial for achieving cooler air temperatures in working/active areas.

Conversely, latent heat refers to the amount of thermal energy released or absorbed during a phase change at a constant temperature [68]. For example, liquid water evaporating into water vapour without causing a temperature change. As part of the operation of a BAC, the latent heat is removed as the air is dehumidified or the relative humidity (RH) is decreased.

This process leads to condensation, as cooler ventilation air has a lower capacity to retain water. As the latent heat is removed, humidity levels decrease, leading to a more controlled and comfortable working/active environment.

As the ventilation air passes through the BAC, both types of heat are extracted, and the combined effect is central to the overall cooling process and justifying the use of BACs. Sensible cooling reduces the air temperature, while latent cooling removes moisture, resulting in cooler and drier air ventilation. The overall efficiency of the BAC is a measure of its capacity to manage both forms of heat and, together, enhance the performance of a BAC [65], [104], [105].

From the theoretical assessment of the performance, the tool incorporated Equations (1) to (19), calculation logic, psychometric charts, and additional information such as fan sizes and coil areas. The tool is structured to rework the measurements through weighted averages of the known measured variables [107], to provide usable data for interpretation. An accuracy of ≥ 90% for the measurements was also confirmed by cross-referencing the heat transfer of the working fluids in terms of the temperature difference between the inlet and outlet conditions, which ensured compliance with the Law of Energy Conservation [101].

The "First-principle Calculations" sub-step is represented by Figure 17, illustrating how the measurements were reworked and interpreted into accurate and usable data. The data provided insight into the performance of the BAC and served as a baseline for the "Simulation" sub-step.

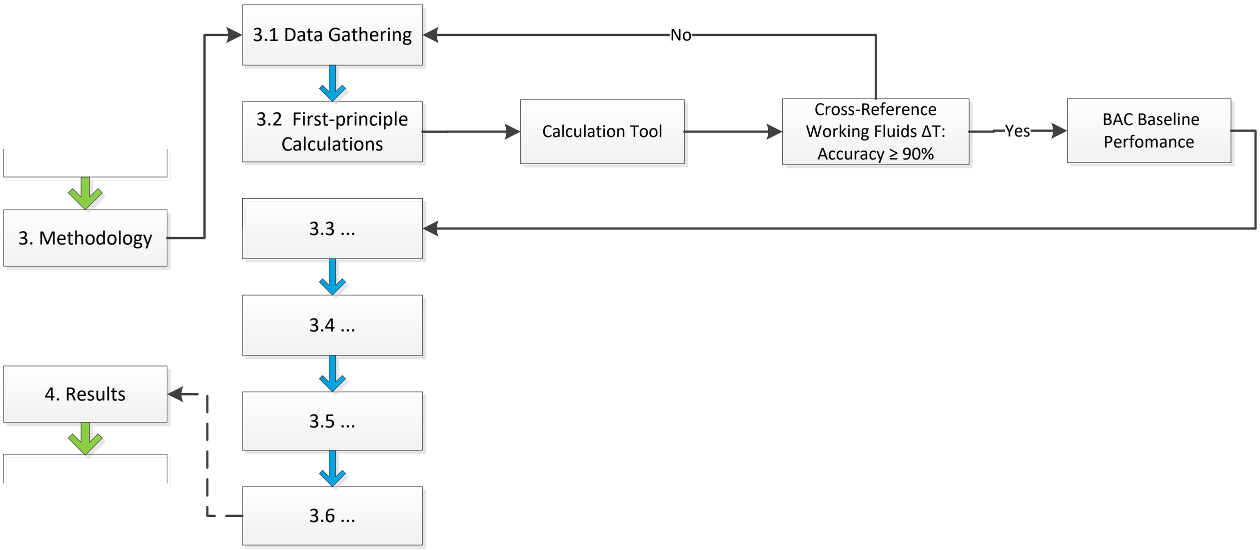


Figure 17: Sub-step 3.2 – First-principle Calculations

(***Side note***: *An image of a psychometric chart and the calculation tool, created in MS Excel, can be found in* Appendix AC *and* Appendix AE *respectively*.)

2.2.3 Sub-step 3.3: Simulation

From the research discussed in Section 1.6.2, it was found that the simulation phase commenced after establishing the current performance of the relevant infrastructure. As such, the individual and combined thermohydraulic analysis of the respective coils is complex. Therefore, simulation software can simplify the analysis by creating dynamic models and representations of the BAC system.

The simulation software can then be used to virtually increase the performance and identify potential inefficiencies of a particular BAC [108]. An advantage of simulation software is that it allows the user to conduct multiple quick analyses without actual physical testing. Due to the benefits of simulations, a wide variety of software is available [109].

The preferred choice for a specific simulation software depends on the analysis requirements and model capabilities [5]. This requires reviewing the available simulation software to establish which option is most applicable to the method. The simulation software must provide reliable results based on calibrated models and offer performance-increased solutions. Additionally, it must include the relevant components and input variables such as mass flow, temperatures, thermal heat transfer capabilities, and system inefficiencies. The following section discusses some of the available simulation software:

- **SolidWorks [110]**

The SolidWorks platform is extended through an HVAC add-on module whereby engineers can analyse the thermohydraulic analysis of air and gas movement. This module focuses on designing living and working environments such as human comfort factors and air flow optimisation. The internal flow simulator implements the Navier-Stokes equations for modelling various internal and external flow scenarios. The simulation strength of SolidWorks lies in its capability to effectively simulate specific components for precise studies and a flow characteristic within isolated/localised systems where precision is critical for individual parts.

Contrary to the component-specific simulation, SolidWorks is limited in simulating large-scale network systems. Other software is required to simulate larger systems with multiple components and dynamic interconnections.

- **PipeFlow [111]**

Engineers use the PipeFlow platform for its advanced capabilities in the simulation and design of complex pipe reticulations. It can accurately simulate fluid pressure drop and flow rates where multiple inlets, outlets, pumps, and pipe sizes are applicable. Different operational parameters can be used as input, resulting in applications to many industries. PipeFlow, therefore, allows the user to optimise the performance, efficiency, and safe fluid flow management for large pipe reticulation networks.

Due to its application to pipe reticulations, the simulation software only applies to the internal thermohydraulic properties of a fluid within a pipe. Therefore, other simulation software is required to simulate the two fluids' internal and external thermohydraulic interaction.

- **Flownex [112]**

The Flownex platform is a simulation software that can critically analyse and design fluid- and heat-transfer systems. It offers component sizing, determination of operating ranges, and verification, thereby ensuring the systems perform efficiently and optimally. The software also allows systems to be tuned through analogue or digital controllers and predicts transient behaviour. Engineers can, therefore, refine and predict the response of a thermohydraulic system. It also allows parametric studies and sensitivity analysis, as it explores different operating variables for improving operating efficiency.

Therefore, the Flownex simulation software is versatile and ideal for this study, as it meets the requirements of this study.

- **Process Toolbox (PTB) [5]**

The Process Toolbox simulation platform simulates systems in both steady-state and transient conditions. PTB surpasses other simulation software's capabilities in its ability to simulate system adjustments and real-time fluctuations, allowing engineers to predict the response of an entire system should changes such as load variations and equipment failures occur.

Additionally, PTB allows for the simulation of complex interactions between refrigeration, ventilation, cooling, and water reticulations within a single framework. This allows engineers to optimise a thermohydraulic system's operational efficiency and energy consumption. Additionally, the software allows engineers to take a holistic approach when analysing the overall impact of implementing changes to one or more subsystems. The ability of the PTB software to combine various components into a single model makes it the ideal software for identifying inefficiencies and testing possible solutions before actual implementation.

- **Simulation software summary**

The advantages and disadvantages of the respective software is evaluated in Table 5, and the preferred software is indicated in Section 3.4 based on relevance to the current study, the availability of the software, and the capacity for that software to provide the necessary results to achieve the objectives listed in Section 1.8.

Table 5: Pros and Cons of the Various Simulation Software

Simulation software	Advantage	Disadvantage
SolidWorks	1. Component-oriented for relatively small systems. 2. CFD Simulation. 3. Accurate. 4. Capable of thermo-hydraulic analysis.	1. Expensive when compared to other software. 2. Increased computation power required. 3. Not preferred by the mining sector. 4. Mainly used for design. 5. Every component must be individually constructed.
PipeFlow	1. Component-oriented. 2. Large system analysis. 3. Liquid and gas simulation in pipe networks.	1. Relevant components, BACs, not included in the software. 2. Does not include heat transfer capabilities.
Flownex	1. Applicable to various industries. 2. Component-oriented. 3. Capable of thermohydraulic analysis. 4. Used for optimisation.	1. Costly licences 2. Limited edition available to students.
Process Toolbox (PTB)	1. Applied to the mining environment. 2. Component-oriented. 3. User friendly. 4. Previous research was done while using PTB. 5. Capable of thermohydraulic analysis.	1. Not available to the open market. 2. Still in development by ETA Operations to include additional capabilities in terms of visualisation thus, no influence on the accuracy.

The implementation of simulation software allowed previous researchers to predict the effect on performance should "pre-selected" operating variables be adjusted [5], [42], [76], [77], [79]. Similar to the general process followed by previous research, the simulation process begins as the next step after the "First-principle Calculations" sub-step.

Considering the objectives of this study, the "Simulation" criteria of the reworked case study methodology should incorporate separate simulation models for the respective objectives. Therefore, this sub-step contains three different simulation models:

1. Actual model
2. Achievable model
3. Cause model

The "Simulation" is outlined in Figure 18.

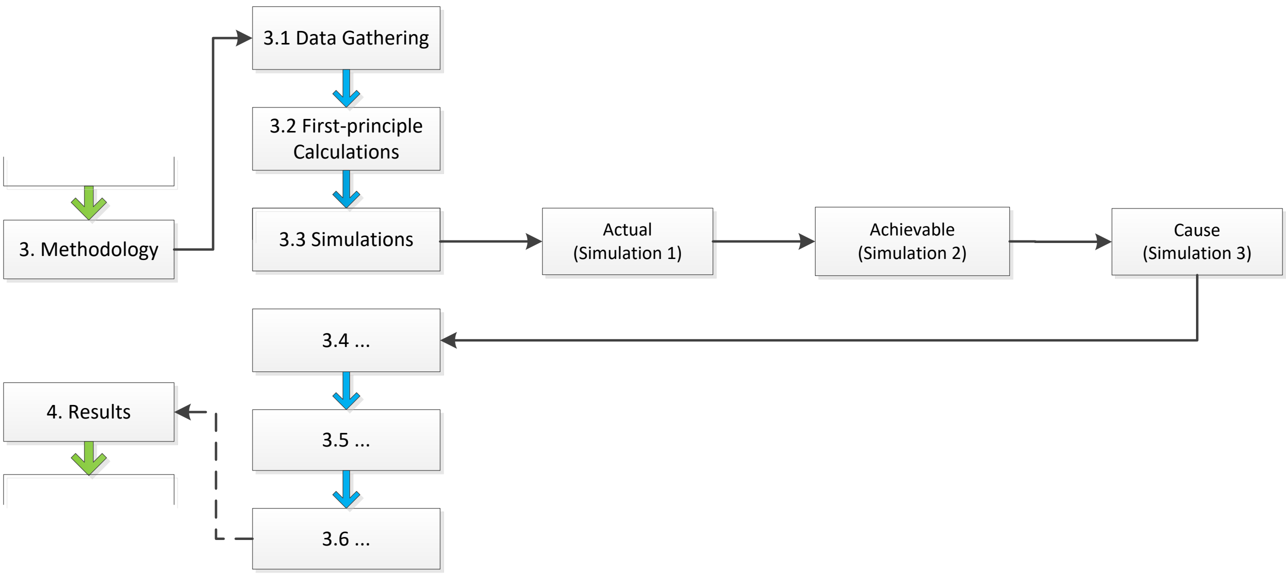


Figure 18: Sub-step 3.3 - Simulations

Form Figure 18, Simulation 1, the "Actual Model," represents the results from the "First-principle Calculations" step. The Actual Model is then calibrated to represent the actual BAC performance accurately [5]. The calibration process involves cross-referencing the data from the "First-principle Calculations" with the simulation outputs. Previous research, using simulations, achieved an error range of 0% to 15% between measurements and simulation outputs. Thus, the "Actual Model" outputs must produce results within the same error range before it is considered accurate.

Figure 19 outlines the expansion of Simulation 1's criteria to ensure that the first simulation is a "true" representation of the current BAC performance.

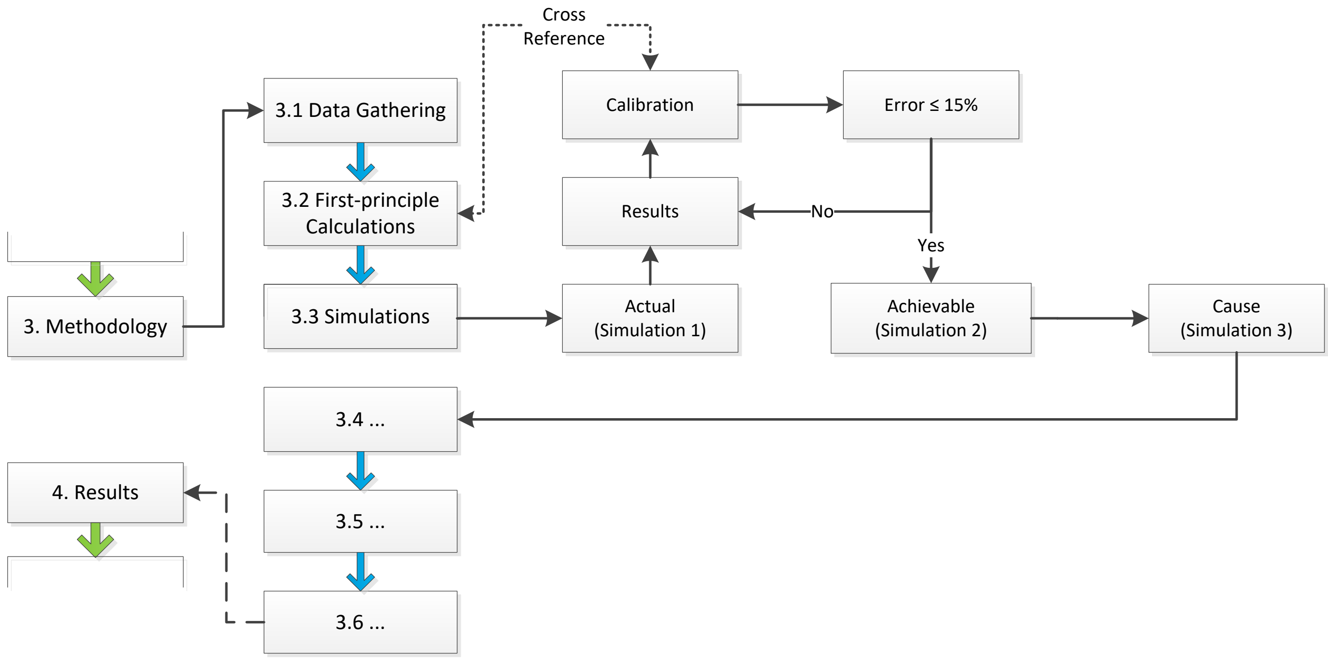


Figure 19: Simulation 1 - Actual Model

From Figure 19, Simulation 2, the "Achievable Model," is developed to represent the current BAC as a new BAC operating under the mine's relevant specifications. The results of this model would then be considered the desirable results, as they indicate the BAC's potential performance under optimal conditions.

When the results for Simulation 2 are determined, the Achievable Model is then calibrated to represent the achievable BAC performance, following the general approach of van Rooyen [6], Sithole [5], and Oberholzer [79]. The calibration process involves cross-referencing the simulation outputs to the operating specifications of the mine. When the mine specifications for the BAC are unknown, the OEM specifications that correlate closest to the current operating conditions are used.

As part of Simulation 2, the UA factor is artificially reduced from 100% to 80% of the total capacity to accommodate the irregularities of comparing design operating conditions to "off-design" operating conditions. The action of artificially lowering the UA factor to 80% is supported by the mine to ensure that performance targets on the BAC performance are practical and realistic.

Figure 20 outlines the expansion of the Achievable Model criteria.

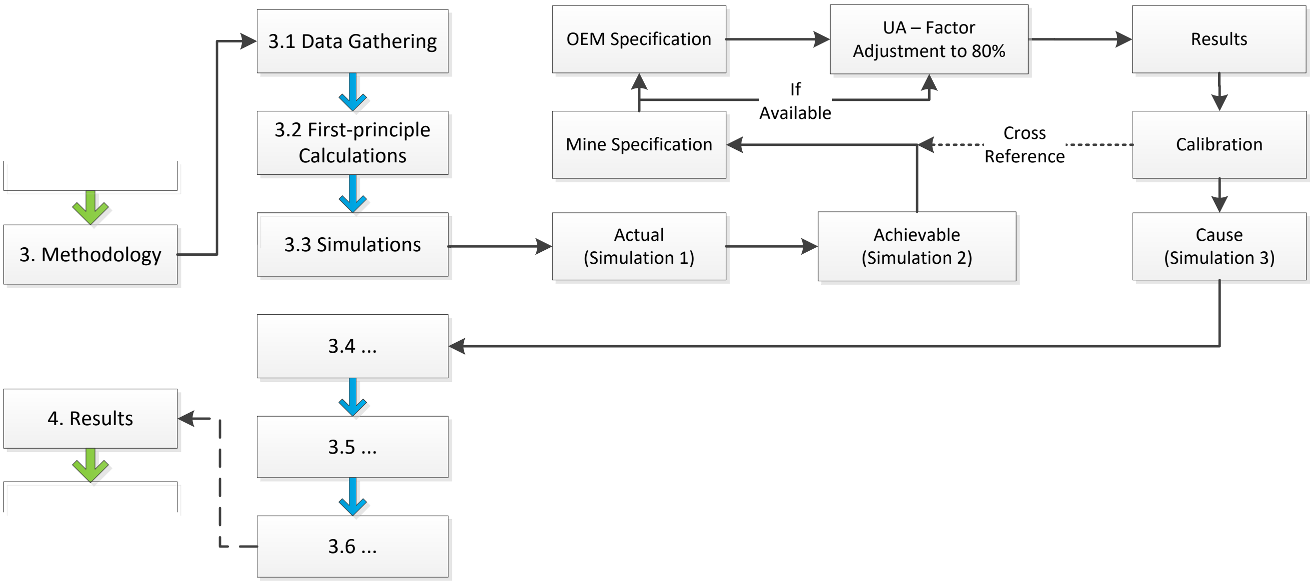


Figure 20: Simulation 2 - Achievable Model

From Figure 20, Simulation 3, the "Cause Model," is developed to identify the operating variable that causes the reduction in BAC performance. The "Cause Model" employs an iterative process in which each operating variable, as set out by Simulation 1, is adjusted to align with the results of Simulation 2 to establish potential performance gain or loss.

In keeping with the scope of the study, the aim and the objectives, the BAC operating variables that are considered are as follows:

1. Air
    1.1. Inlet temperature (WB/DB)
    1.2. Quantity
2. Water
    2.1. Inlet temperature
    2.2. Quantity
3. Foul
    3.1. Internal and external fouling in terms of the total UA factor

Therefore, the iterative process consists of five cycles, with each cycle's result serving as the next cycle's baseline. Ultimately, the combination of the five cycles equate to the result produced by Simulation 2.

For further clarification, depending on which specification is available, changing the current air temperature to the mine-/OEM-specified air temperature leaves only the current air mass flow quantity to be adjusted to the mine-/OEM specified air mass flow quantity. The results from changing the air operating variables serve as the baseline for changing the water operating variable after cross-referencing the specific actual and achievable results.

This is followed by changing the current water temperature to the mine-/OEM-specified water temperature, leaving only the current water mass flow to be adjusted to the mine-/OEM-specified water mass flow. The results from adjusting the water operating variables then serve as the baseline for adjusting the UA factor after cross-referencing the specific actual and achievable results. Finally, adjusting the current UA factor to 80% of the OEM-specified UA factor results in total performance, as set out by Simulation 2, which then concludes the cycle process.

The Simulation 3 step is expanded in Figure 21. Furthermore, Simulation 3 addresses the core question of this study by enabling a precise assessment of each variables' effect on the performance of a BAC.

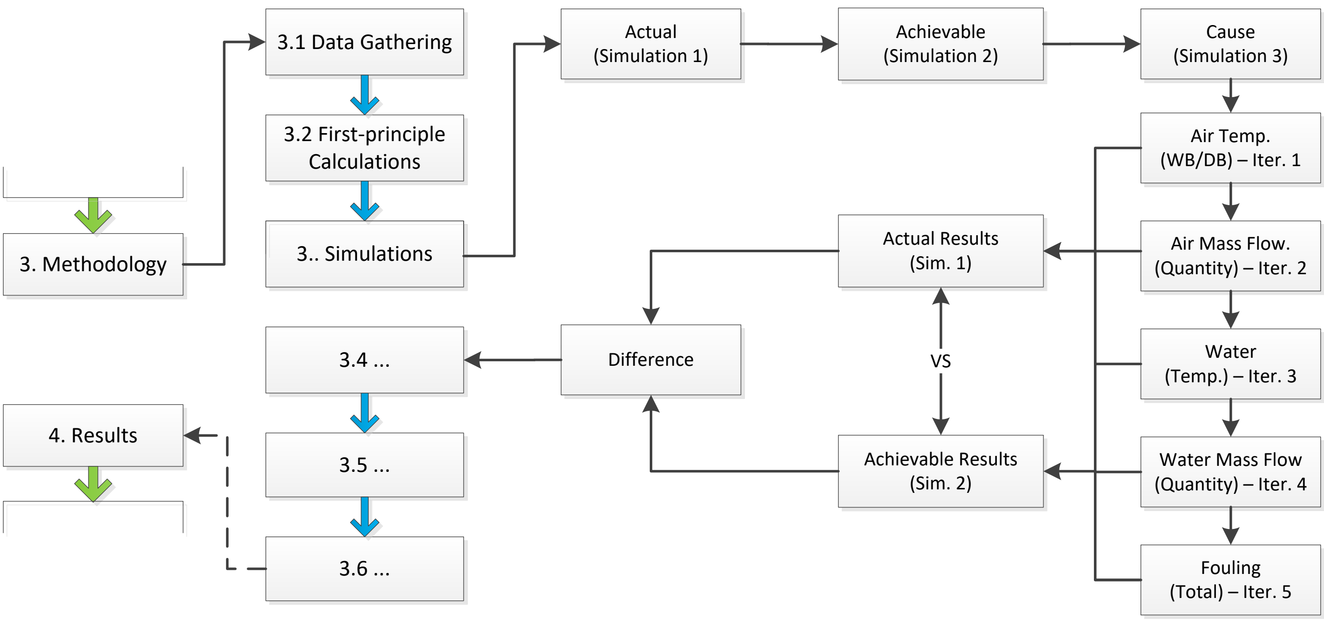


Figure 21: Simulation 3 - Cause Model

2.2.4 Sub-step 3.4: Gap analysis

After a consideration of the problem and the aim of the review, it became evident that the overall performance of finned-tubed BACs is negatively influenced when the conditions of the operating variable deviate from the mine/OEM specifications. Additionally, the literature review indicated that reduced performance is a result of the following factors:

- Poor distribution and/or insufficient quantities of both working fluids are supplied to BACs.
- Incorrect working fluid temperatures are supplied to BACs.
- Decrease in UA factor due to limited maintenance and impurities in the working fluids.

To address these issues, a gap analysis is conducted to assess the impact of individual operating variables on BAC performance. This analysis allows for the immediate identification of the operating variable that has the greatest influence on BAC performance. As such, the gap analysis sub-step is integrated into the reworked case study methodology in Figure 22.

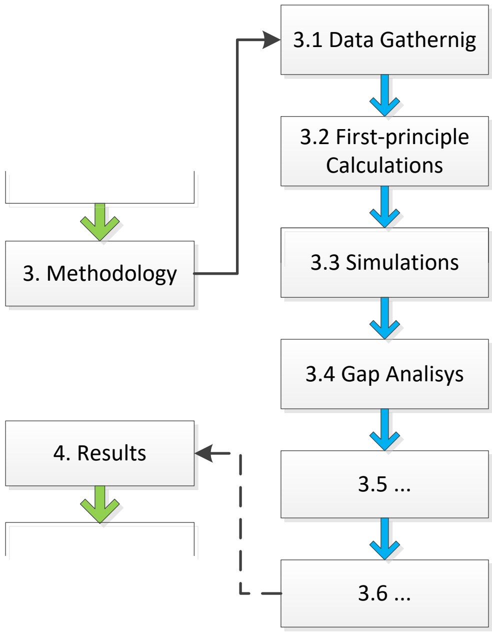


Figure 22: Sub-step 3.4 – Gap Analysis

2.2.5 Sub-step 3.5: Implementation

Based on the gap analysis, specific corrective measures are recommended and implemented to enhance the operational performance of BACs, thereby achieving the study's aim. These recommendations and corrective actions are based on previous research. Therefore, the implementation sub-step is added to the reworked case study methodology in Figure 23.

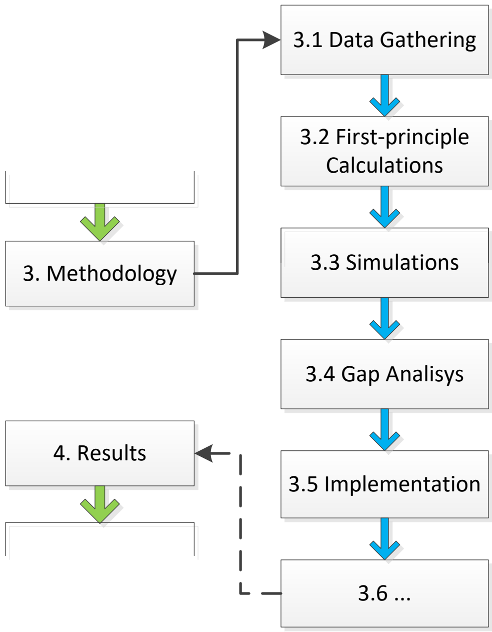


Figure 23: Sub-step 3.5 – Implementation

2.2.6 Sub-step 3.6: Verification and validation

After implementing the corrective measures, it is critical to distinguish between the validation and verification to effectively evaluate the improvement in BAC performance. Sub-step 3.6 therefore justifies whether this study achieves the goal successfully by resolving the aim and objectives of this study.

Similarly to previous research, the validation ensures that the corrective measures effectively addressed the performance issues caused by the operating variables of the BAC. Furthermore, the validation confirms that the changes to the operating variables of concern produce improved operational results.

However, verification focuses on comparing the influence of pre- and post-implementation to quantify and confirm performance improvement. By cross-referencing the initial and final effects of the operating variables after the corrective measures were implemented, the degree of operational performance gain is verified [5], [42], [76], [77], [79].

The verification and the validation sub-step is then added to the reworked case study methodology and is represented by Figure 24.

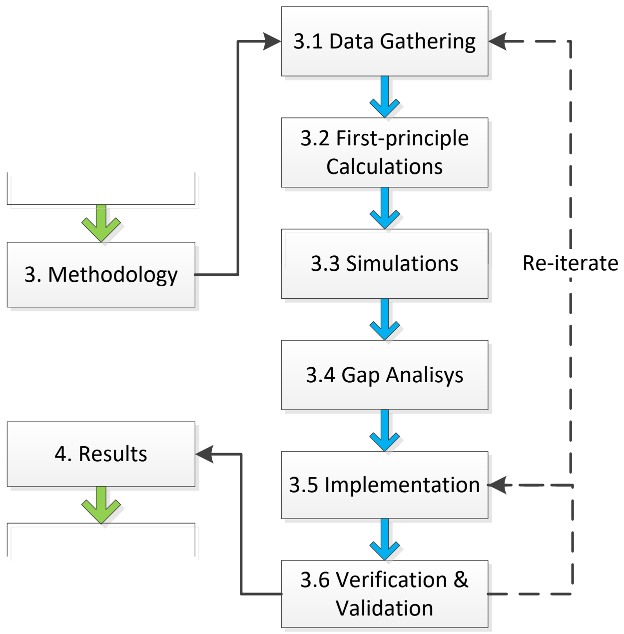


Figure 24: Sub-step 3.6 – Verification and Validation

2.3 Summary of the method

By developing a method based on the original case study methodology and incorporating the sub-steps outlined in Table 4, a reworked case study methodology has been created, where the framework/method of the study that is to be followed is indicated by the blue boundary within Figure 25.

As with Figure 12, the relevant sections of this study have been aligned with the respective criteria for ease of navigation and relevance throughout the dissertation, reflecting the transition from the original to the reworked case study methodology.

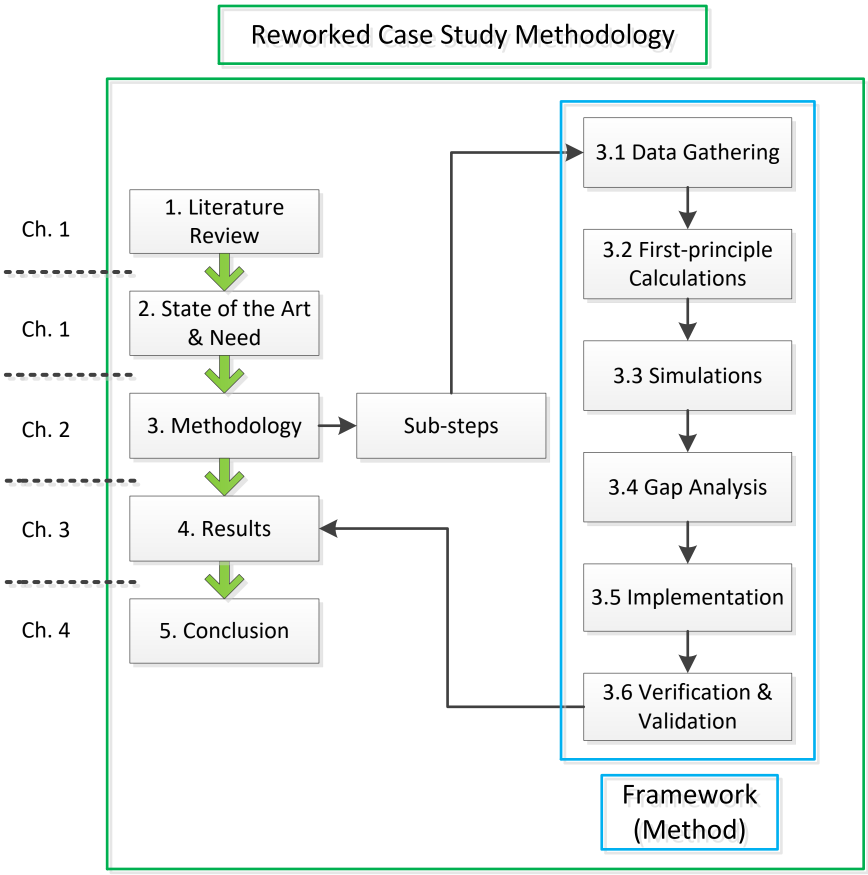


Figure 25: Reworked Case Study Methodology and Study Method

2.4 Verification of reworked case study methodology

To verify the reworked case study methodology, a cross-reference between the various steps and the state-of-the-art matrix was conducted. Therefore, sub-steps 3.1 to 3.6, as shown in Figure 25, are linked with the corresponding columns in Table 3.

As such, the "Data Gathering" sub-step corresponds to the "Infrastructure" column; the "First-principle Calculations" sub-step corresponds to the "Quantity and Temperature" and "Fouling" columns; the "Simulations" sub-step corresponds to the "Simulations" and "Emergent Causal Operation Variable" columns; the "Gap Analysis" sub-step corresponds to the "Emergent Causal Operation Variable" column; the "Implementation" sub-step corresponds to the "Implemented" column; and the "Verification and Validation" sub-step corresponds to the "Verified" column. This rework is shown in Figure 26.

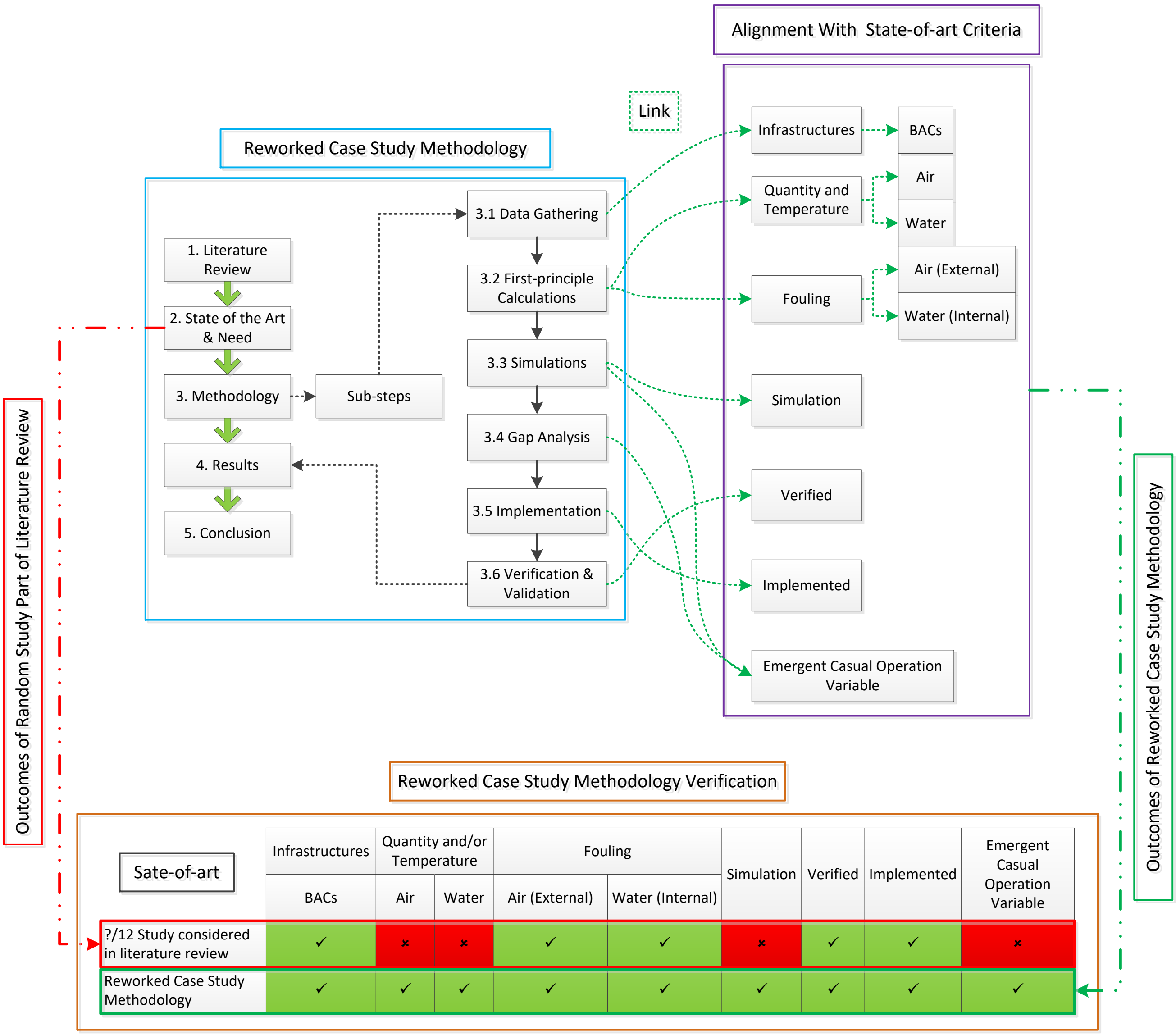


Figure 26: Cross-reference Reworked Methodology and the State-of-the-art

Figure 26 demonstrates how the reworked the methodology is theoretically verified. The cross-referencing of the sub-steps, indicated by the blue boundary, with the evaluation criteria of the state-of-the-art matrix, indicated by the purple boundary, ensures alignment with the study's aim and objectives. This systematic approach addresses the shortfalls of previous research, indicated by the orange boundary, as all previous "red-crossed" boxes became "green-ticked" boxes. [91].

2.5 Conclusion

By adjusting the original design methodology, a reworked methodology was developed to align with the scope of this study. The focus is on identifying and addressing the operating variables responsible for causing performance issues of finned-tubed BACs.

Sub-step 1, "Data Gathering", is systematically conducted across certain locations while complying with internal mining standards. This sub-step incorporates environmental constraints, equipment limitations, design geometries, mine-/OEM specifications, and coil conditions, thereby ensuring accurate data to establish a baseline, simulations, verification, and validation.

Sub-step 2, "First-principle Calculations", allows the measured data to be reworked using a calculation tool built in Microsoft Excel. The tool uses the equations outlined in Section 2.2.2 transform the measurements into interpretable data. The accuracy of the measurements, according to the Law of Energy Conservation, must be verified, as the results directly impact the subsequent sub-steps.

Sub-step 3, "Simulations", is conducted after establishing the current performance of the BACs through the second sub-step. Objectives 1 and 2 are partially addressed through the development of three separate simulation models, namely the "Actual", "Achievable", and "Cause" models. Each model addresses a specific aspect of the performance analysis and is calibrated accordingly to ensure accuracy.

Sub-step 4, "Gap analysis", synthesises the combined results of the simulations and assesses the individual effects of the BAC's operating variables. Additionally, the gap analysis enables the immediate identification of the operating variables with the greatest influence on BAC performance. The fourth sub-step directly addresses Objectives 1 and 2.

Sub-steps 5 and 6 "Implementation, Verification and validation", address the operating variables with the greatest influence on the performance of a BAC by implementing corrective measures to achieve the aim of this study. Following implementation, the improvement in BAC performance is verified and validated. Verification quantifies BAC performance gains by comparing pre- and post-implementation metrics, while validation ensured that the corrective measures effectively addressed the operating variables responsible for negatively influencing BAC performance. The combined consideration of the fifth and sixth sub-steps directly addresses Objectives 3 and 4.

CHAPTER 3 APPLICATION OF THE METHODOLOGY TO CASE STUDIES

3.1 Preamble

Chapter 3 applies the methodology developed in Chapter 2 to four different case studies. Each case study represents a separate and unique occurrence of a finned-tubed BAC within a gold mine. The analysis of each case study was structured by the defined sub-steps of the framework/method.

Chapter 3 is structured such that each sub-step serves as a heading, followed by the relevant criteria as the method is applied. For additional clarity and navigational-assistance, signposts are added to indicate the method's occurrence when applied to each case study, where the "orange-block" indicates the respective sub-step and the "green-text" the corresponding case study.

Each case study is presented sequentially under the "First-principles Calculations" criteria, allowing for a cross-case analysis and demonstrating how data gathering varied across different cases. This structure is then consistently applied throughout the chapter, aligning with the study's objectives in Section 1.8.

3.2 Sub-step 3.1: Data gathering

A multinational mining company provided the opportunity to investigate the capacity of the secondary and tertiary cooling equipment at a gold mine located in the North-Western region of South Africa. This gold mine will be referred to as Mine A in order to comply with the necessary confidentiality clauses.

Mine A consisted of various active and inactive shafts where various cooling methods and infrastructure were implemented. In keeping with the scope of this study, the active shafts' cooling infrastructure was considered as operational data fundamental for this research. Additionally, a simple conformance matrix, referencing the requirements of the data gathering sub-step in Section 2.2.1, was created to ensure the correct cooling infrastructure was selected for individual case studies for this research. The conformance matrix is shown in Table 6.

Table 6: Conformance Matrix for Case Studies

	Shaft No:	Levelof the BAC:	Supply working level?	Performance concern?	Type	Potential case Study	Case study number
Mine A	Shaft #1	23.5L	✓	✓	DC	×	\
		39L	✓	✓	FTHX	✓	1
		41L	✓	✓	FTHX	×	\
		43L	✓	✓	FTHX	×	\
		45L	✓	✓	FTHX	✓	2
	Shaft #2	23-60L	✓	✓	FTHX	✓	3
		23L	✓	✓	FTHX	×	\
		32L	✓	✓	FTHX	✓	4
		34L	✓	✓	FTHX	×	\

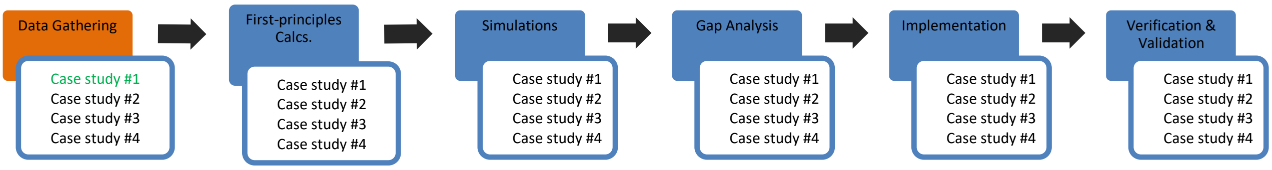
When conducting the research, Mine A had only two active shafts, Shaft #1 and Shaft #2, named in accordance with confidentiality clauses. As listed in Table 6, all the levels where BACs were in operation were evaluated for potential case studies.

For Shaft #1, the BACs on 39L and 45L were identified and then used as case study 1 and 2 respectively to align with the initial requirements set out by the "Data gathering" sub-step in Section 2.2.1. The BACs on 23.5L and 43L were excluded because they were direct-contact BACs and decommissioned BACs respectively. The BAC operating on 41L was not included as a potential case study, as the mine excluded this BAC from the possible investigation.

The BACs located on 23L and 34L at Shaft #2 were also excluded due to their decommissioning. Therefore, Shaft #2 only had BACs on 26-60L and 32L that were still in operation and were designated Case Study 3 and respectively because they met the selection criteria.

As such, Case Study 1, 2, 3, and 4, as highlighted in blue throughout Table 6, were discussed in the following sections:

3.2.1 Case study 1



The BAC on 39L was fitted with 3 x 37 kW fans that were all in operation at the time. It was constructed with 8 x 250 kW Manos FTHX coils aligned horizontally next to one another. The design specification equated to a 2 000 kW BAC, while the mine specification was set at 1 100 kW due to the underground operating conditions. This BAC was responsible for supplying the working areas on the half-level with cool air.

A performance investigation was launched by Mine A, Shaft #1, regarding the performance of the BAC, as the workers raised a concern about the working temperatures further into the level. The relevant measurements were taken and referenced in Appendix AD. Figure 27 indicates the general layout of Case Study 1.

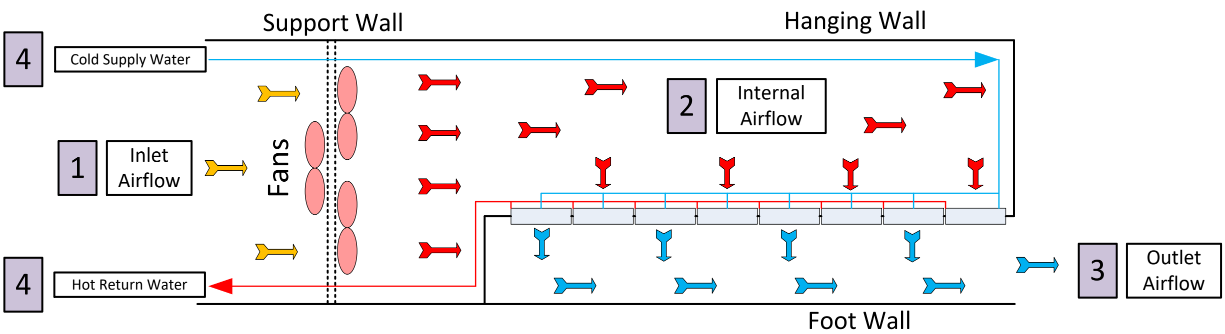
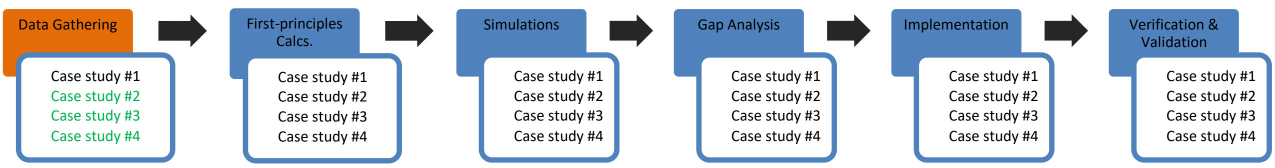


Figure 27: Case Study 1 Layout

3.2.2 Summary of Case studies 2, 3, and 4



Sub-step 3.1 was subsequently applied to Case Studies 2, 3, and 4 to ensure consistent application of the method across all case studies. The BAC characteristics are summarised in Table 7 to indicate the corresponding fan configurations, coil alignments, and operational constraints.

Table 7: Sub-step 3.1 Summary for Case Studies 2, 3, and 4

BAC Characteristic	Case study		
	2	**3**	**4**
Fan Configuration	4x 37 kW fans (3x in operation)	No fans, air flow driven by ventilation	4x 45 kW fans (all in operation), different fan layout
Coil Configuration	10x 250 kW Manos FTHX-Coils, diagonally aligned	3x 500 kW Manos FTHX-Coils, same alignment to Case study 2	5x 500 kW Manos FTHX-Coils, same alignment to Case study 2
Design Specification	2 500 kW (Reduced to 1 500 kW)	1 500 kW	2 500 kW (Reduced to 1 500 kW)
Performance Concern	Insufficient cooling deeper in the half-level	Questionable working temperatures within the half-level	Insufficient cooling deeper in the half-level
Image Reference	Figure 14	Figure 28	Figure 29
Data Gathering Summary	Appendix AI		

The general layout for Case Studies 3 and 4 was as follows:

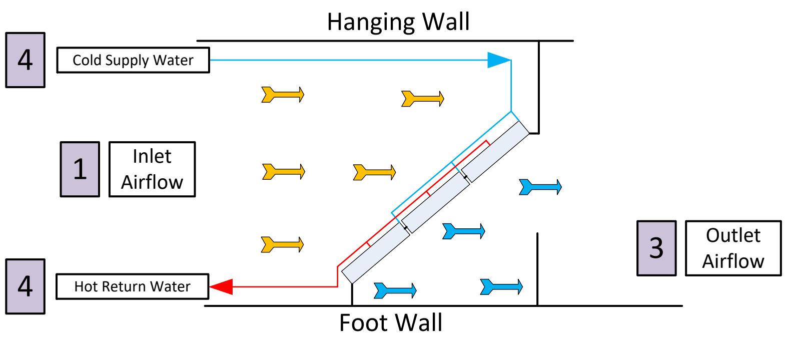


Figure 28: Case Study 3 Layout

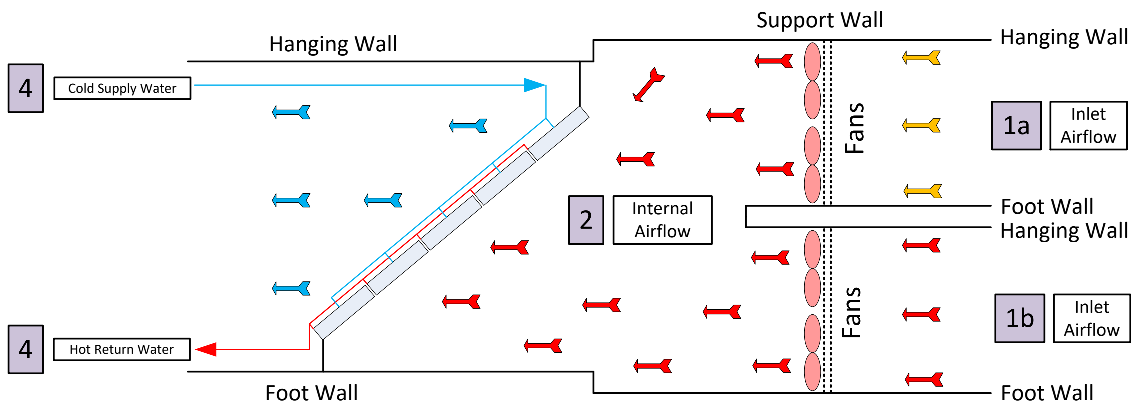


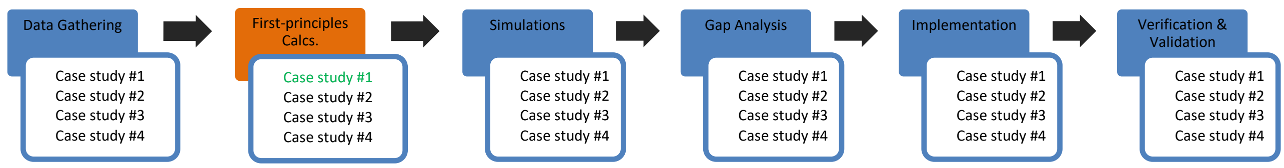
Figure 29: Case Study 4 Layout

Figure 27, Figure 28, and Figure 29 indicate individual BAC compliance with the sub-steps of Section 2.2.1.

3.3 Sub-step 3.2: First-principle calculations

The gathered measurements of the individual case studies were then reworked and analysed by incorporating a calculation tool, as mentioned in Section 2.2.2. The results of the individual case studies provided insight into the performance of the BACs. A short description of the results, along with the necessary compliance with the sub-criteria of Section 2.2.2, were discussed as follows:

3.3.1 Case study 1



The calculation tool indicated that the BAC had an operational capacity of 470 kW. This left the BAC with only 359 kW of sensible and latent cooling capacity after the initial energy input of the 3 x 37 kW fans was removed. Therefore, the BAC had an operational efficiency of 43%, provided the mine specification was set at 1 100 kW. The fans provided the BAC with 77.0 kg/s of air; only 56 kg/s went through the cooling coils. The difference resulted in an air leak of 27%. Based on the measured water and air temperatures, a 9% difference was calculated, as 511 kW of heat was gained by the water, and the air lost 470 kW of heat as the various working fluids passed through the BAC. In addition to the heat transfer, the performances of the individual coils were normalised through the amount of air flow through each coil and had a range of between 29 kW to 130 kW.

The respective water and air duties confirmed an accuracy of 91% for the overall measurements and ensured compliance with the sub-criteria outlined in Section 2.2.2. The results are summarised in Appendix AD and illustrated by Figure 30.

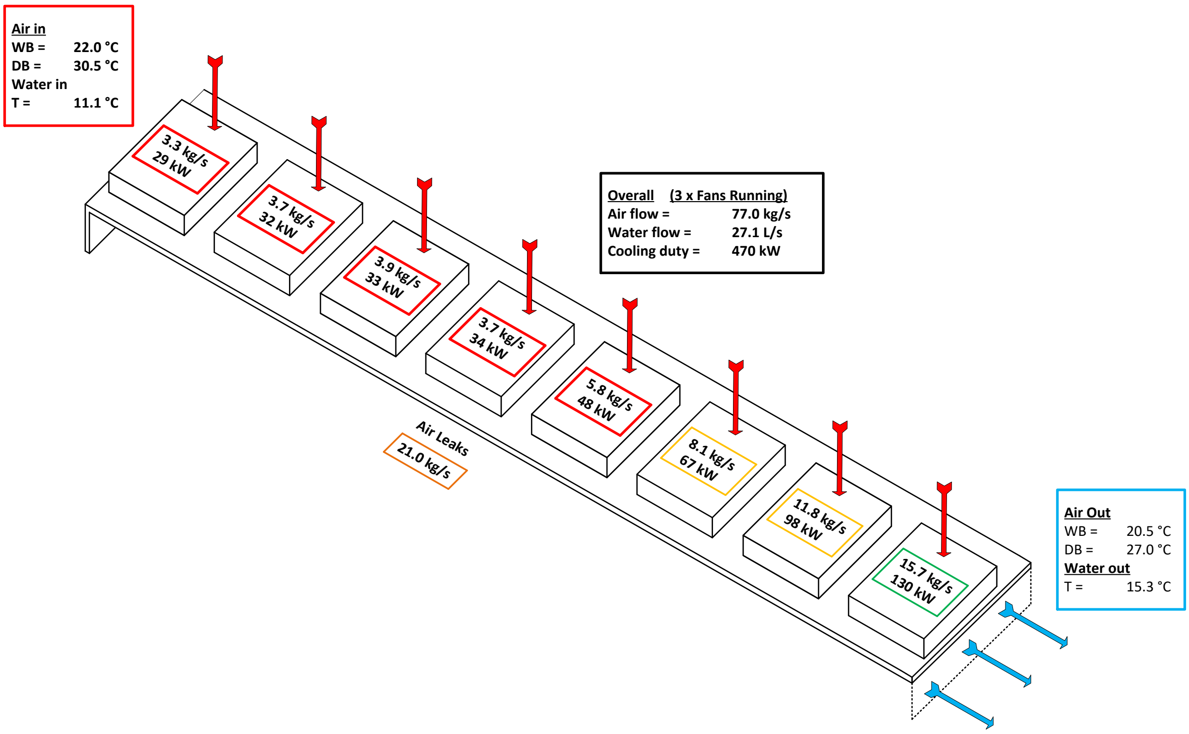
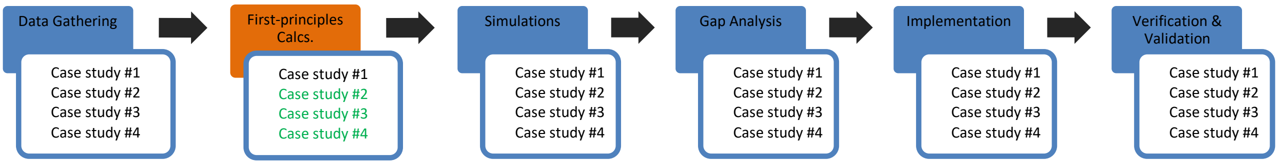


Figure 30: Case Study 1 - BAC Performance

3.3.2 Summary of Case studies 2, 3, and 4



Sub-step 3.2 was reapplied to Case Studies 2, 3, and 4 to ensure transparency and consistency. The performance results regarding the operational efficiencies, air flows, and heat transfer of the respective BACs were combined and summarised.

The summary highlights the difference in operational capacity, air leaks, coil performances, and the accuracy of the measurements to ensure compliance with the criteria of Sub-step 3.2 as described in Section 2.2.2. This summary is presented in Table 8.

Table 8: Sub-Step 3.2 Summary for Case Studies 2, 3, and 4

Parameter	**Case study**		
	2	**3**	**4**
Operational Capacity	360 kW	196 kW	1 119 kW
Mine Cool-specification	1 500 kW	1 500 kW	2 500 kW
Operational Efficiency	24%	13%	45%
Air flow Through BAC	57.5 kg/s	29 kg/s	54 kg/s
Air Leakage	13.5 kg/s	None	None
Water Duty vs Air Duty (Difference)	5%	6%	3%
Coil Performance	6 kW – 136 kW	57 kW – 75 kW	103 kW – 354 kW
Measurement Accuracy	95%	95%	97%
Figure Reference	Figure 31	Figure 32	Figure 33
Calc. Tool Results	Appendix AE		
Calc. Description	Appendix AJ		

The respective performance of Case study 2, 3, and 4 were initially as follows:

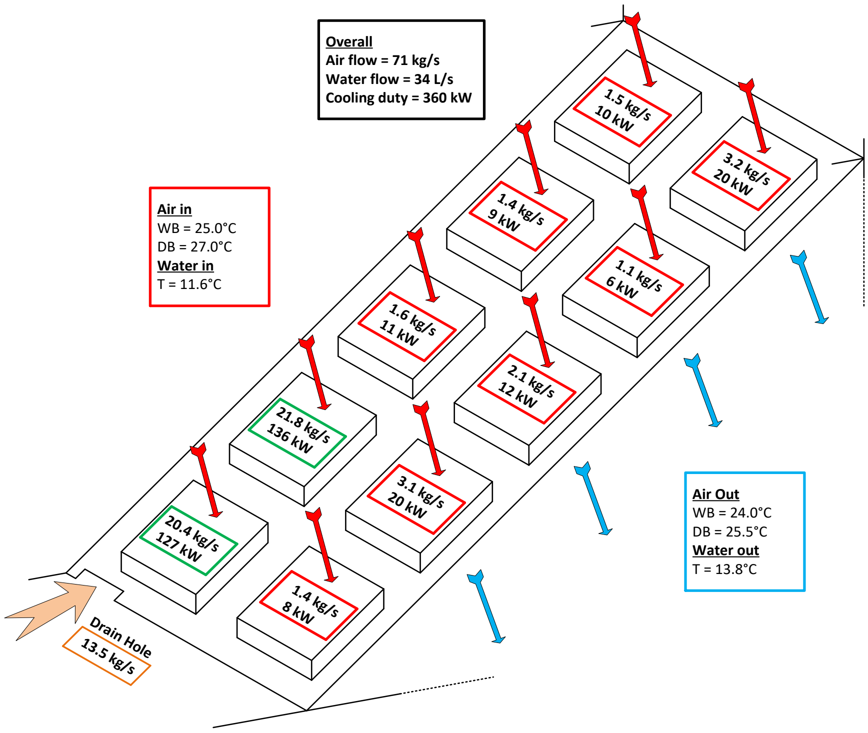


Figure 31: Case Study 2 - BAC Performance

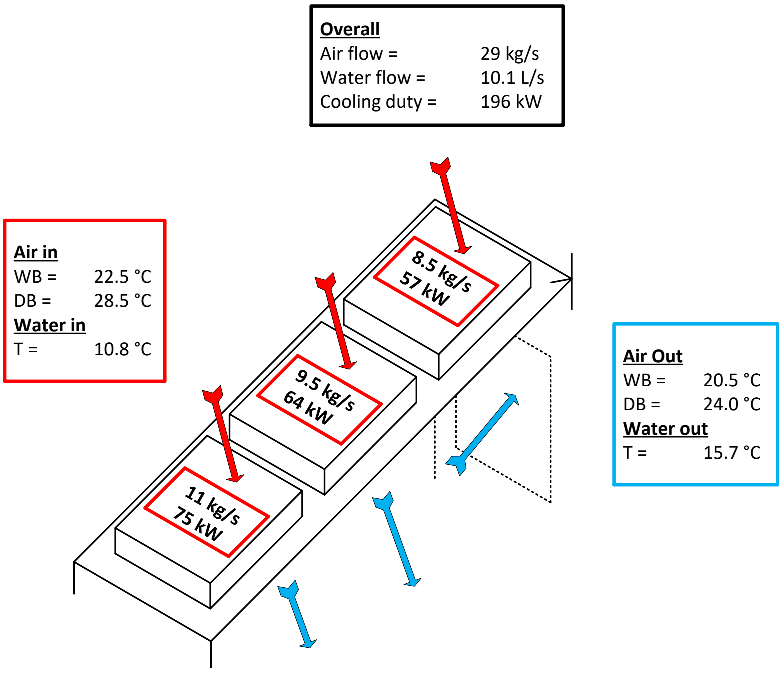


Figure 32: Case Study 3 - BAC Performance

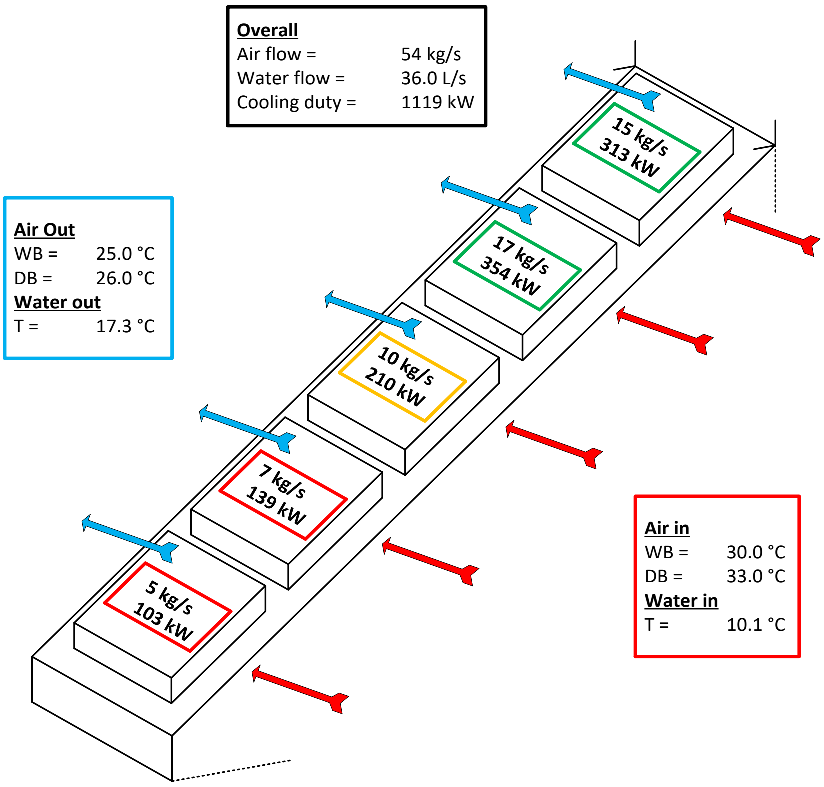


Figure 33: Case Study 4 - BAC Performance

3.4 Sub-step 3.3: Simulations

Based on the methodology described in Chapter 2, the simulation sub-step focused on creating a baseline performance, predicting the achievable performance of the BAC at "off-design" conditions, and identifying the operating variables most responsible for reducing BAC performance.

After considering the summary of the various available simulation software in Section 2.2.3, the selection of the appropriate software was based on a simple conformance matrix for the specific criteria, as required by this study. The matrix is summarised in Table 9, where "green-ticked" boxes are an indication of compliance, "orange-dashed" boxes are partial compliance, and "red-crossed" boxes are a no compliance.

Table 9: Conformance Matrix for Simulation Software Selection

Software	Relevance	Availability	Capability
SolidWorks	Limited to a small element and not a complete sub-system. -	Partial access through the study institution. -	Need to construct full sub-systems. -
PipeFlow	Limited to the thermos-hydraulic properties of pipe reticulations. -	No access through the study institution. ×	Does not include the required sub-systems. ×
Flownex	Conforms to the analysis requirements of the study. -	Partial access through the study institution. -	Includes all required sub-systems. ✓
PTB	Conforms to the analysis requirements of the study. ✓	Full access through the study institution. ✓	Includes all required sub-systems. ✓

The software of choice was "PTB", as it was the only simulation software that complied with all the requirements that were listed in Section 2.2.3, critical for ensuring reliable and accurate results.

The PTB-software provided a detailed analysis of the individual case studies. The respective analysis of the simulation results, where the relevant operating variables were incorporated, was structured systematically to align with the aim and objectives of this study listed in Section 1.8.

As such, the simulation criteria outlined in Section 2.2.3 was then implemented in the software. The general layout, construction, and method are indicated by Figure 34 where a description of the various components used during the summations is found in Appendix AO

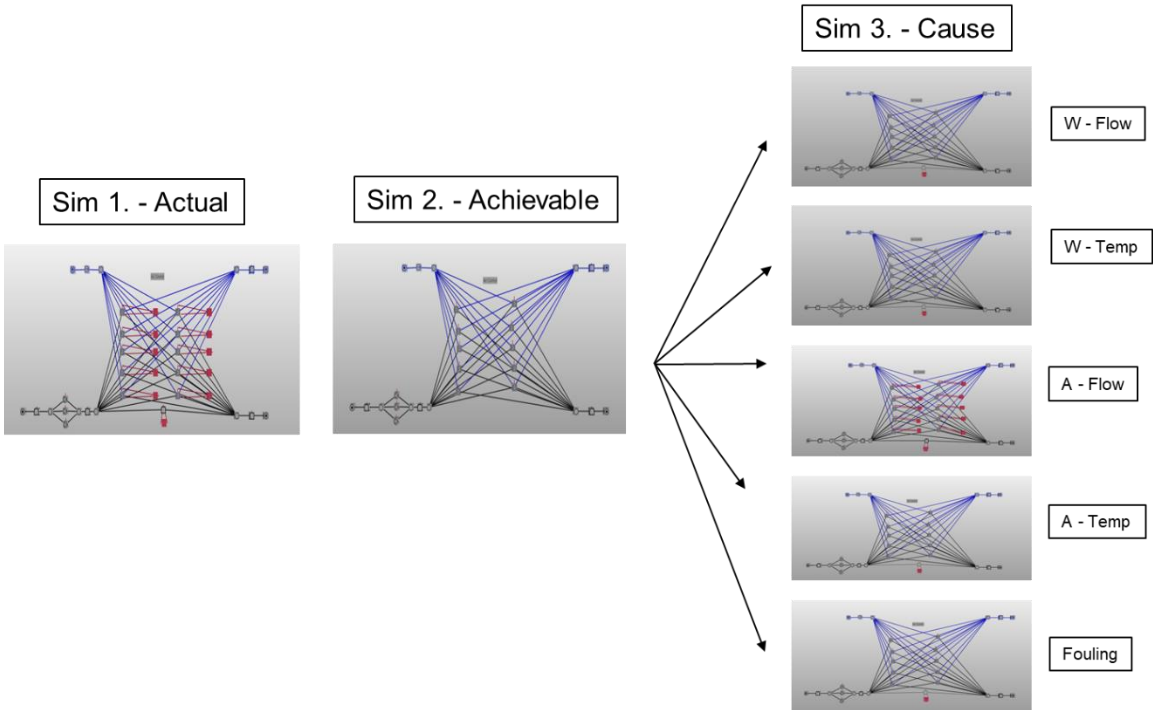


Figure 34: General Simulation Construction

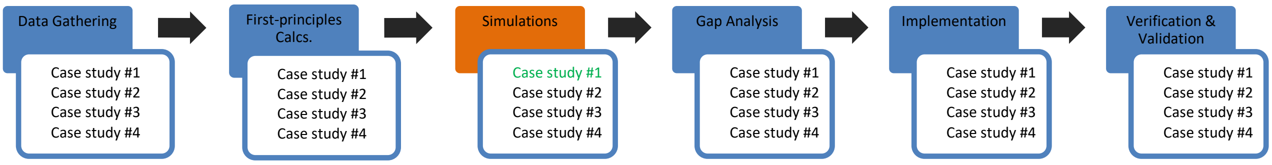
The simulation sub-step for the respective case studies is discussed below.

(***Side note***: *The use of the PTB-software served as the primary tool when identifying, quantifying and resolving the responsible operating variables that limited the performance of the respective BACs, in contrast to the preceding sub-steps, where the results of case studies 2, 3, and 4 have been summarised in a collective "Table" due to the repetitive method application. Sub-step no. 3.4., the "Simulations" were unique to each case study in terms of calibration, inlet conditions, and operating variable influence.*

The respective simulation models were individually developed and changed to indicate the distinct operating conditions of the BAC, as the next simulation was directly dependent on the results of the previous simulation. Therefore, summarising the respective simulation results of Case Studies 2, 3, and 4 into a collective table would compromise the integrity of the respective simulations, as each BAC required a specific analysis, which ensured the applicability of the method.

Therefore, maintaining separate simulation results indicates the versatility of the study's method.)

3.4.1 Case study 1:



Simulation 1, the "Actual" simulation, was constructed and calibrated to the "First-principle Calculations", whereby the error in the calibration was listed in Table 10.

Table 10: Case Study 1 Operating Variable Comparison - Initial Measured- vs Simulation

		BAC Inlet		BAC Outlet		
Operating Variable		**Measured / Calc. Tool**	**Sim. 1 - Actual**	**Measure/ Calc. tool**	**Sim. 1 - Actual**	**Avg. error**
Air	**WB temp.**	22.0 °C	22.0 °C	20.5 °C	20.3 °C	1%
	DB temp.	30.5 °C	30.5 °C	27.0 °C	27.0 °C	0%
	Mass flow	76.4 kg/s	76.9 kg/s	76.4 kg/s	76.9 kg/s	1%
Water	**Temp.**	11.1 °C	11.1 °C	15.6 °C	15.3 °C	2%
	Mass flow	27.1 L/s	27.1 L/s	27.1 L/s	27.1 L/s	0%
Fouling	**UA factor (Avg. Coil)**	/	0.43	/	0.43	/
Performance		/	/	469.1 kW	463.5 kW	1%

For Case study 1, when the error between the simulations and the measured results were considered after the required calibration, no error of the operating variables varied more than 15% as per the sub-criteria for the "Actual" simulation. As such, the Simulation 2 (Achievable)criterion was then pursued.

Simulation 2, the "Achievable" simulation, was constructed while considering the overall mine specification for Case Study 1. The specifications regarding the operating variables were partially available from Mine A, and, therefore, led to the inclusion of the respective OEM specifications.

Mine A provided a specification for the air temperatures where the OEM specifications were set when measured temperatures were rounded down to the closest whole number for the WB temperature and rounded up to a whole number for the DB temperature. The mine suggested this approach from a practical, achievable, and seasonal standpoint, as the RH of the supply air could influence the performance of a BAC, and the OEM specifications were not available at the temperature of interest.

Due to the layout, the mine specified that only two of the three available fans should operate to ensure infrastructure redundancy, despite the average OEM specification allowing for more air to pass through the coils. The specified temperature of the water supplied from the mine was less than the OEM specification, while the required water quantity was calculated from the average amount used on the OEM specification. The UA factor was at 0.8, as discussed in Section 2.2.3.

The inlet operating variables from the Simulation 1 (Actual) criteria were then adjusted accordingly to a combination of the mine and OEM specification, as highlighted in blue, and represented in Table 11.

Table 11: Case Study 1 Initial Sim. 1 "Actual" vs. Sim. 2 "Achievable"

		BAC Inlet			
Operating variable		**Sim. 1 - Actual**	**Mine A Specification**	**OEM Specification**	**Sim. 2 - Achievable**
Air	**WB temp.**	22.0 °C	22.0 °C	- °C	22.0 °C
	DB temp.	30.5 °C	31.0 °C	- °C	31.0 °C
	Mass flow	76.9 kg/s	67.5 kg/s	69.9 kg/s	67.5 kg/s
Water	**Temp.**	11.1 °C	- °C	14.6 °C	11.1 °C
	Mass flow	27.1 L/s	- L/s	52 L/s	52 L/s
Fouling	**UA Factor**	0.43	0.8	1.0	0.8
Performance		463.5 kW	1 100 kW	2 000 kW	889.3 kW

After the overall mining specification was finalised, Simulation 3 (Cause) was constructed according to Section 2.2.3. The results supplied by the simulation are summarised in Figure 35 and Figure 36.

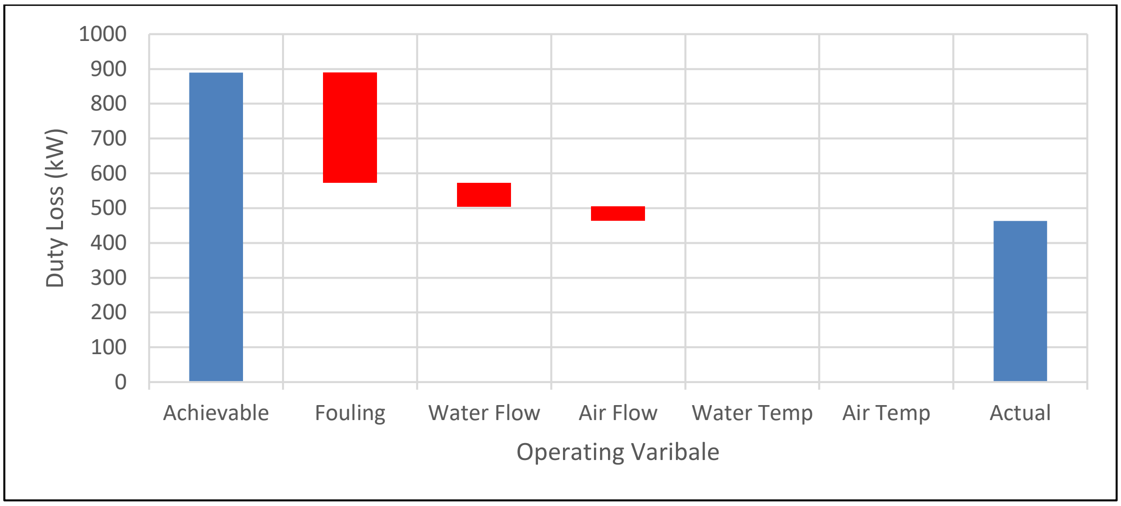


Figure 35: Case Study 1 – Waterfall Chart for Operating Variable Influence (kW)

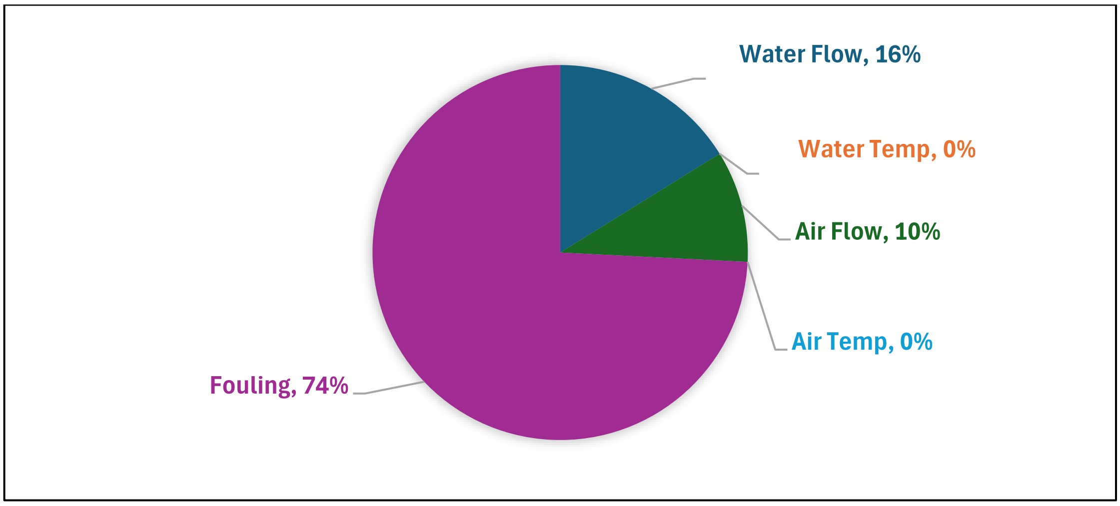
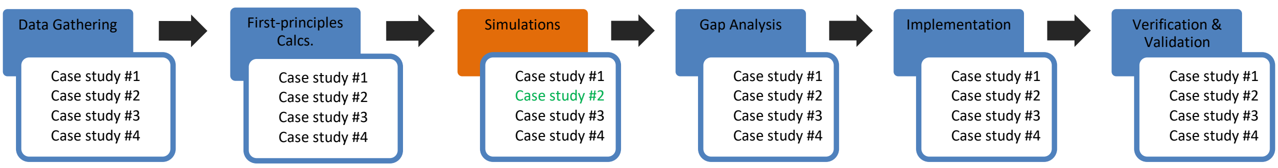


Figure 36: Case Study 1 – Breakdown of Operating Variable Influence (%)

3.4.2 Case study 2:



Simulation 1, (Actual) was constructed and calibrated to the "First-principle Calculations", The error in calibration is listed in Table 12.

Table 12: Case Study 2 Operating Variable Comparison - Initial Measured- vs Simulation

Operating Variable		BAC Inlet		BAC Outlet		
		Measured / Calc. tool	**Sim. 1 - Actual**	**Measure/ Calc. tool**	**Sim. 1 - Actual**	**Avg. error**
Air	**WB temp.**	25.0 °C	25.0 °C	24.0 °C	23.8 °C	1%
	DB temp.	27.0 °C	27.0 °C	25.5 °C	25.7 °C	1%
	Mass flow	71.1 kg/s	69.5 kg/s	71.1 kg/s	69.5 kg/s	2%
Water	**Temp.**	11.6 °C	11.6 °C	14.0 °C	14.3 °C	2%
	Mass flow	33.6 L/s	33.6 L/s	33.6 L/s	33.6 L/s	0%
Fouling	**UA factor (Avg. coil)**	/	0.19	/	0.19	/
Performance		/	/	359.0 kW	359.5 kW	1%

Similar to Case Study 1, the error between the simulations and the measured results for Case Study 2 was considered after the required calibration. No error of the operating variables varied more than 15%, aligning with the sub-criteria for the "Actual" simulation. As such, the Simulation 2 (Achievable) criteria were met.

Simulation 2 was constructed following a similar approach to Case Study 1. The specifications for the operating variables were only partially available from Mine A, which led to the inclusion of the respective OEM specifications.

The air temperature specifications were adjusted accordingly using the same approach described in Case Study 1. The air quantity specification was affected by the layout and specifications provided by the mine, as only three out of the four fans should supply air to the BAC for redundancy purposes. The specified temperature of the water supplied from the mine was less than the OEM specifications, while the quantity of water required was calculated from the average amount used on the OEM specification. The UA factor was also set at 0.8.

The inlet operating variables for Simulation 2 were adjusted and are represented in Table 13:

Table 13: Case Study 2 Initial Sim. 1 "Actual" vs. Sim. 2 "Achievable"

		BAC Inlet			
Operating Variable		**Sim. 1 - Actual**	**Mine A specification**	**OEM specification**	**Sim. 2. - Achievable**
Air	**WB temp.**	25.0 °C	25.0 °C	- °C	25.0 °C
	DB temp.	27.0 °C	27.0 °C	- °C	27.0 °C
	Mass flow	69.5 kg/s	128.4 kg/s	89.6 kg/s	128.4 kg/s
Water	**Temp.**	11.6 °C	- °C	14.6 °C	11.6 °C
	Mass flow	33.6 L/s	- L/s	65 L/s	65 L/s
Fouling	**UA factor**	0.19	0.8	1.0	0.8
Performance		359.5 kW	1 500 kW	2 500 kW	1 939.1 kW

Simulation 3 was constructed by following the method used and referenced in Case Study 1. The results are summarised in Figure 37 and Figure 38 as follows:

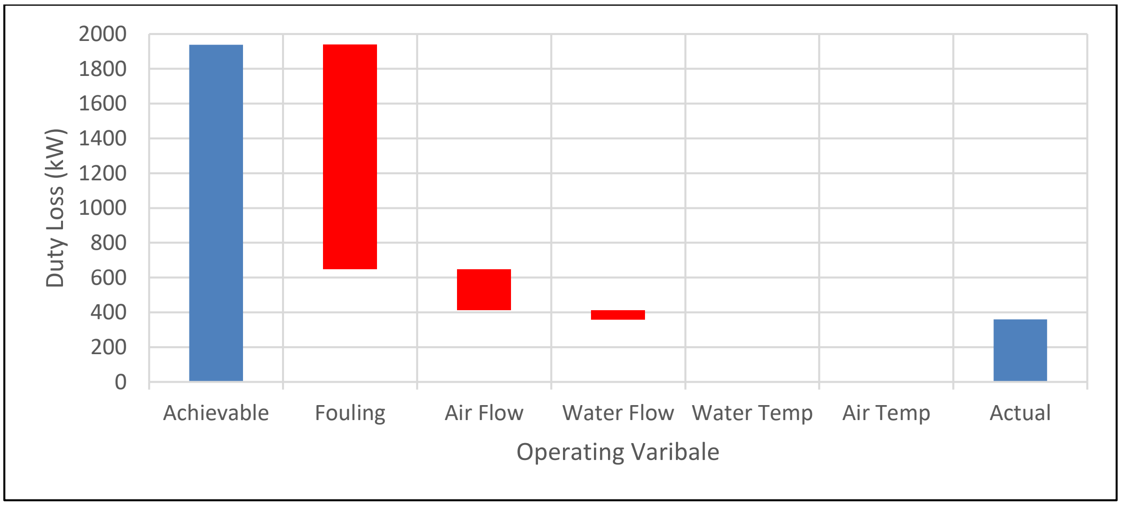


Figure 37: Case Study 2 – Waterfall Chart for Operating Variable Influence (kW)

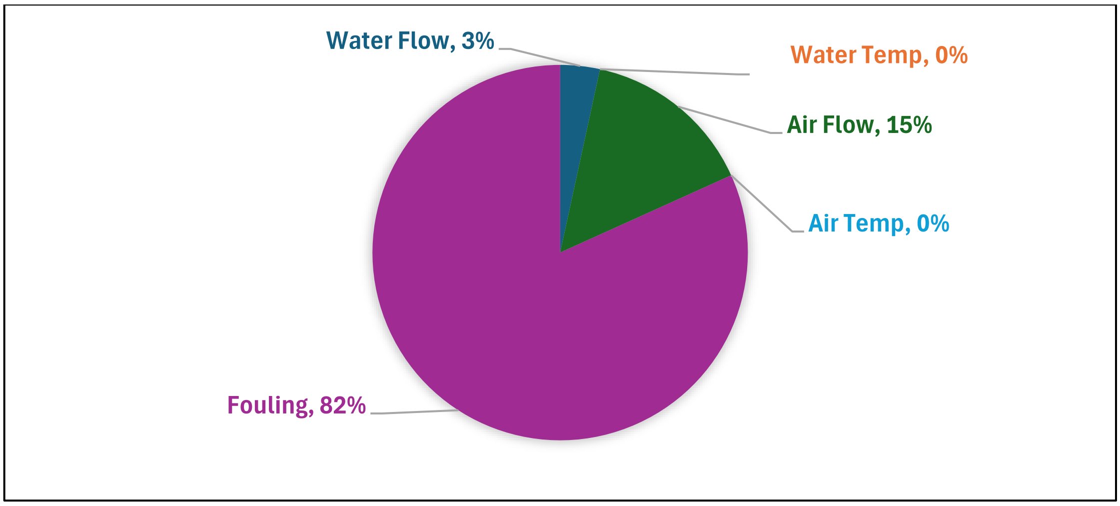
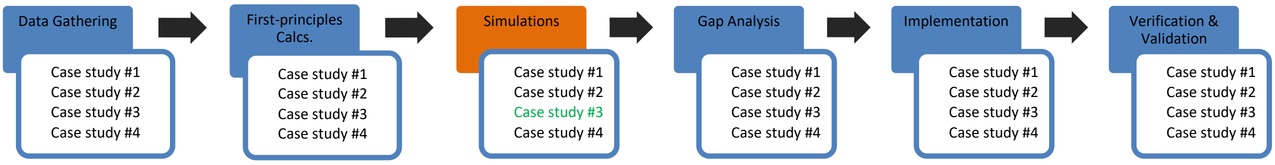


Figure 38: Case Study 2 – Breakdown of Operating Variable Influence (%)

3.4.3 Case study 3:



Simulation 1 was created and calibrated to the “First-principle Calculations”. The error in the calibration is listed in Table 14.

Table 14: Case Study 3 Operating Variable Comparison - Initial Measured- vs Simulation

		BAC Inlet		BAC Outlet		
Operating Variable		**Measured / Calc. tool**	**Sim. 1 - Actual**	**Measure/ Calc. tool**	**Sim. 1 - Actual**	**Avg. error**
Air	**WB temp.**	22.5 °C	22.5 °C	20.5 °C	20.5 °C	0%
	DB temp.	28.5 °C	28.5 °C	24.0 °C	24.9 °C	4%
	Mass flow	28.4 kg/s	28.5 kg/s	28.4 kg/s	28.5 kg/s	1%
Water	**Temp.**	10.8 °C	10.8 °C	15.7 °C	15.4 °C	2%
	Mass flow	10.1 L/s	10.1 L/s	10.1 L/s	10.1 L/s	0%

Fouling	**UA factor (Avg. coil)**	/	0.22	/	0.22	/
Performance		/	/	196.5 kW	193.9 kW	1%

For Case Study 3, the error between the simulations and the measured results was considered after the calibration, where no error of the operating variables varied more than 15% as required by the sub-criteria for the "Actual" simulation. As such, Simulation 2 was pursued.

Simulation 2 was constructed using a similar approach to Case Studies 1 and 2. The specifications for the operating variables were deduced from a combination of the mine and OEM specifications. The air temperature specifications were adjusted, and the mine provided the air quantity specification due to the operational philosophy of not implementing fans. The specified temperature of the water supplied from the mine was less than the OEM specification, while the quantity of water required was calculated from the average amount used on the OEM specification. The UA factor was also set at 0.8.

The inlet operating variables for Simulation 2 were adjusted and are represented in Table 15.

Table 15: Case Study 3 Initial Sim. 1 "Actual" vs. Sim. 2 "Achievable"

		BAC Inlet			
Operating variable		**Sim. 1 - Actual**	**Mine A specification**	**OEM specification**	**Sim. 2 - Achievable**
Air	**WB temp.**	22.5 °C	22.0 °C	- °C	22.0 °C
	DB temp.	28.5 °C	29.0 °C	- °C	29.0 °C
	Mass flow	28.5 kg/s	30.9 kg/s	40.4 kg/s	30.9 kg/s
Water	**Temp.**	10.8 °C	- °C	14.6 °C	10.8 °C
	Mass flow	10.1 L/s	- L/s	31.5 L/s	31.5 L/s
Fouling	**UA factor**	0.22	0.8	1.0	0.8
Performance		193.9 kW	1 500 kW	1 500 kW	545.7 kW

Similar to Case Studies 1 and 2, Simulation 3 provided the results that are summarised in Figure 39 and Figure 40.

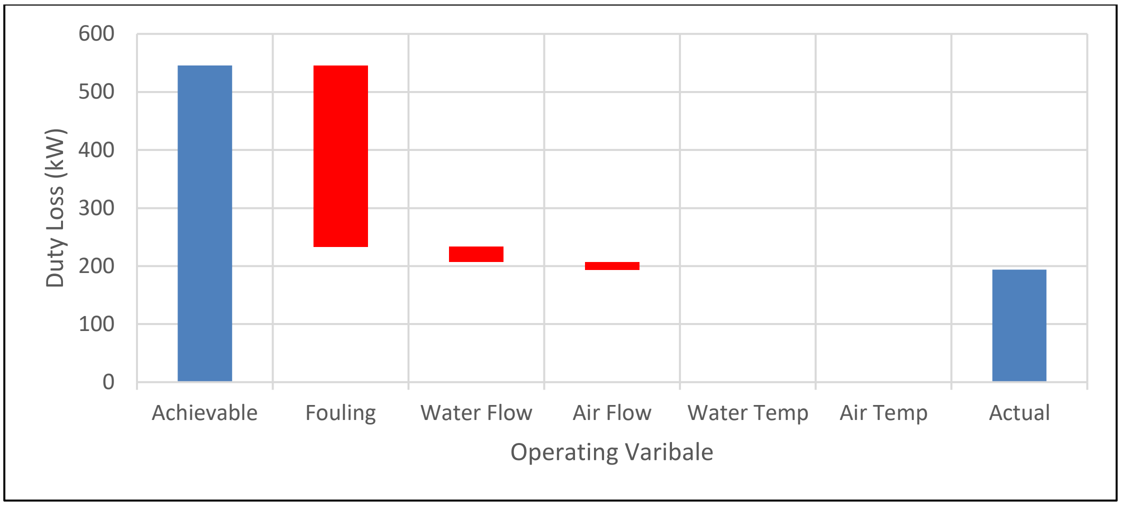


Figure 39: Case Study 3 – Waterfall chart for Operating Variable Influence (kW)

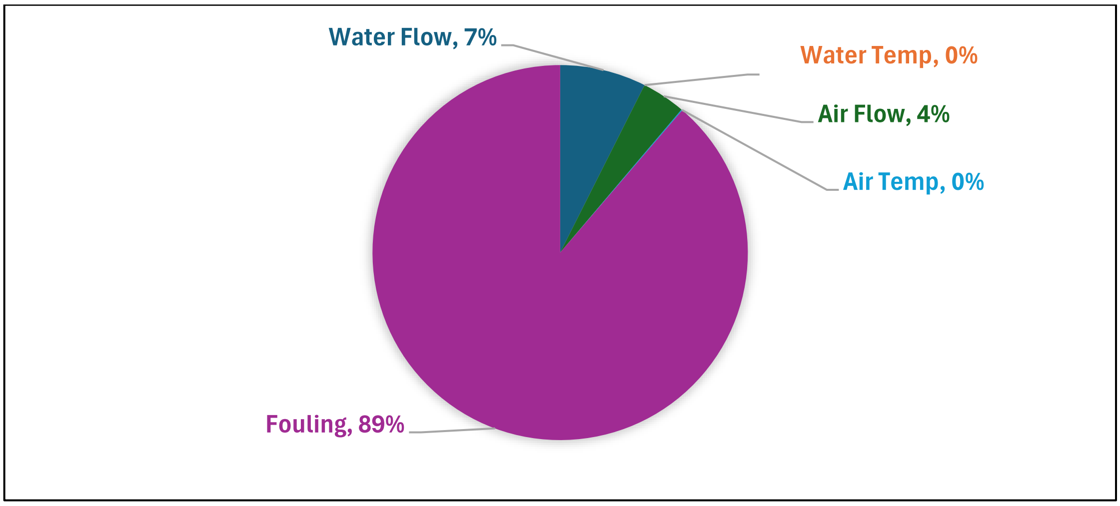
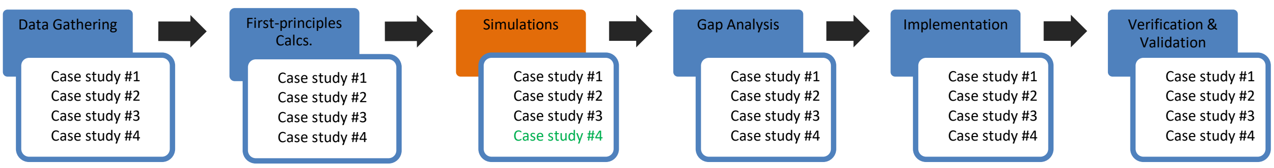


Figure 40: Case Study 3 – Breakdown of Operating Variable Influence (%)

3.4.4 Case study 4:



Simulation 1 was constructed and calibrated in the same manner as Case Studies 1, 2, and 3. The error in the calibration is listed in Table 16:

Table 16: Case Study 4 Operating Variable Comparison - Initial Measured- vs Simulation

Operating variable		BAC Inlet		BAC Outlet		
		Measured / Calc. tool	Sim. 1 - Actual	Measure/ Calc. tool	Sim. 1 - Actual	Avg. error
Air	**WB temp.**	30.0 °C	29.9 °C	25.0 °C	25.2 °C	1%
	DB temp.	33.0 °C	33.1 °C	26.0 °C	25.9 °C	1%
	Mass flow	52.7 kg/s	53.9 kg/s	52.7 kg/s	53.9 kg/s	2%
Water	**Temp.**	10.1 °C	10.1 °C	17.3 °C	17.3 °C	0%
	Mass flow	36.0 L/s	36.2 L/s	36.0 L/s	36.2 L/s	1%
Fouling	**UA factor (Avg. coil)**	/	0.37	/	0.37	/
Performance		/	/	1 118.8 kW	1 095.9 kW	2%

No error of the operating variables varied more than 15% as per the sub-criteria for the "Actual" simulation. Therefore, Simulation 2 did commence.

Simulation 2 was constructed by following the same approach as the previous case studies. The specifications for the operating variables were a combination of the mine and OEM specifications. The air temperature specifications were adjusted, and the air quantity specification was affected by the layout provided by the mine, as three out of the available four fans were required. The measured water temperature supplied by the mine was used as the mine specification due to the temperature being less than the OEM specifications, and the water quantity was calculated from the average amount used by the OEM specification.

The specified temperature of the water supplied from the mine was less than the OEM specification, while the quantity of water required was calculated from the average amount used on the OEM specification. The UA factor was also set at 0.8 to remain consistent with the method.

The inlet operating variables for Simulation 2 were adjusted and are represented in Table 17:

Table 17: Case Study 4 Initial Sim. 1 "Actual" vs. Sim. 2 "Achievable"

Operating Variable		BAC Inlet			
		Sim. 1 - Actual	**Mine A Specification**	**OEM Specification**	**Sim. 2 - Achievable**
Air	**WB Temp.**	29.9 °C	29.0 °C	- °C	30.0 °C
	DB Temp.	33.1 °C	33.0 °C	- °C	33.0 °C
	Mass Flow	53.9 kg/s	42.1 kg/s	70.5 kg/s	42.1 kg/s
Water	**Temp.**	10.1 °C	- °C	14.6 °C	10.1 °C
	Mass Flow	36.2 L/s	- L/s	52.5 L/s	52.5 L/s
Fouling	**UA Factor**	0.37	0.8	1.0	0.8
Performance		1 095.9 kW	2 500 kW	2 500 kW	1 488.2 kW

Simulation 3 provided the results that are summarised in Figure 41 and Figure 42.

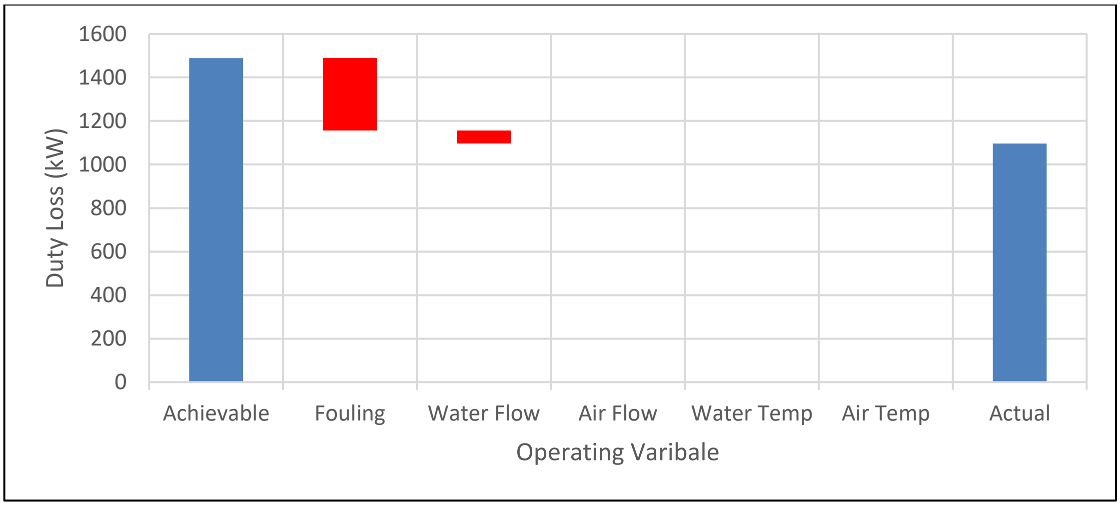


Figure 41: Case Study 4 – Waterfall Chart for Operating Variable Influence (kW)

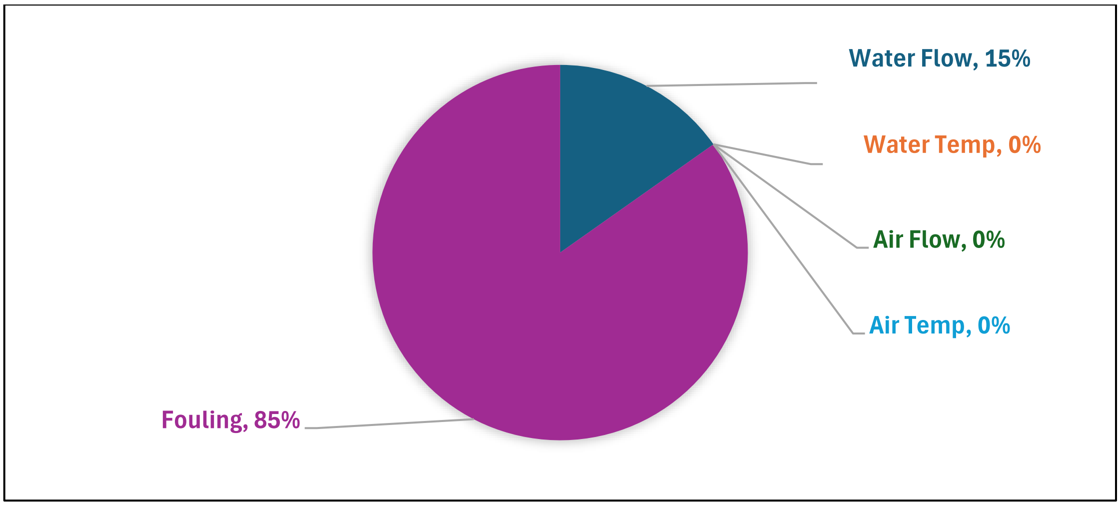
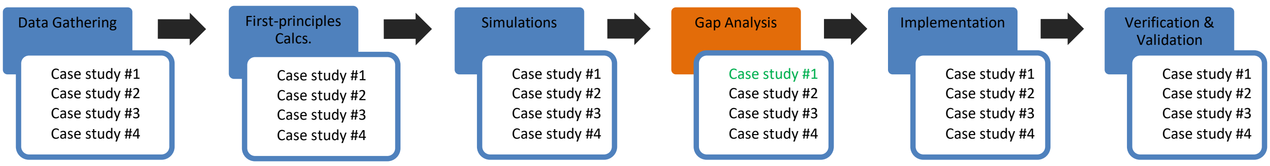


Figure 42: Case Study 4 Breakdown of Operating Variable Influence (%)

3.5 Sub-step 3.4: Gap analysis

The case study analysis allowed for the determination and identification of the influence of operating variables on BAC performance. The gap analysis was conducted based on the description in Section 2.2.4 and is discussed in terms of the impact of these operating variables in the next section.

3.5.1 Case Study 1:



After cross-referencing Figure 35 and Figure 36, it was established that fouling, water, and airflow were the operating variables with the most influence on Case Study 1. Fouling had a 74% influence and was the leading cause of reduced performance.

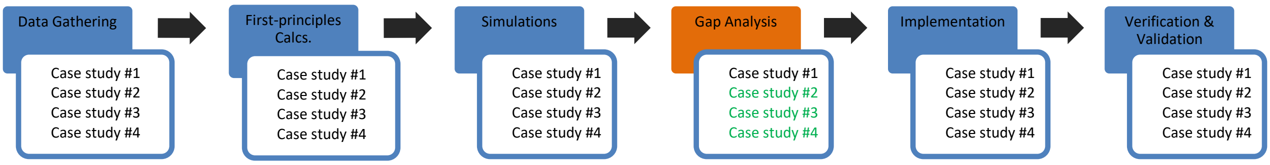
The water flow operating variable was responsible for 16% of the reduction in performance. This was due to the BAC only receiving 21.1 L/s instead of 52 L/s in accordance with the OEM specifications. Hence, the individual coils only received 2.64 L/s instead of 6.5 L/s each.

The air flow operating variable was responsible for 10% of the reduction in performance. This was caused by a 21.0 kg/s air leak throughout the layout of the BAC, as indicated by Figure 30. During the audit, the inlet area of the coils was identified as dirty, resulting in additional limited air flow through the coils. Reference images can be found in Appendix AG.

The measured water temperature supplied to the BAC was less than the OEM specification, resulting in a 0% contribution to the lacking BAC performance.

The mine specification regarding changing the air temperature by reducing the RH by 2% resulted in less than a 1% gain in the BAC performance. Therefore, the fractional change of implementing the mine specifications regarding the air temperature was then kept at 0% influence on the BAC performance for practical purposes.

3.5.2 Summary of Case Studies 2, 3, and 4



Following Case Study 1, the gap analysis for Case Studies 2, 3, and 4 was conducted using the same approach. The main findings are summarised in Table 18. Based on the respective results of the “Cause” simulations, the summary indicates the operating variables' relative influence on the BAC's performance. This allowed a comparison of the operating variables across the case studies and highlighted the prominent cause behind reduced performance.

Table 18: Sub-step 3.4 Summary for Case Studies 2, 3, and 4

Findings	Case Study		
	2	3	4
Fouling Influence	82%	89%	85%
Water Flow Influence	3%	7%	15%
Air Flow Influence	15%	4%	0%
Observations	External coil damage, air leakage at bottom of the BAC	No force fans implemented - limited air flow restricts cooling potential	Operating closest to achievable duty, only two variables limited performance
Figure Reference	Figure 37 & Figure 38	Figure 39 & Figure 40	Figure 41 & Figure 42
Detailed Analysis	Appendix AK		

In addition to Table 18, certain observations were also made, which included the following:

- Fouling was the primary cause behind reduced BAC performance across all the case studies, with the highest influence seen in Case Study 3 (89%).
- Water flow, within the limited supply, had varying influence on the respective case studies, with Case Study 4 indicating the greatest influence (15%) due to operating closest to the achievable duty.
- Air flow limitations, similar to water flow, had a varying influence. They had a greater impact on Case study 2 (15%) due to the 13.5 kg/s air leak at the bottom of the BAC, whereas in Case Study 3 (4%), it was due to the absence of forced ventilation.
- Water and air temperature both had a negligible influence across the respective case studies, where it was then confirmed that the operating variables had no practical impact on the limited BAC performance at that instance.

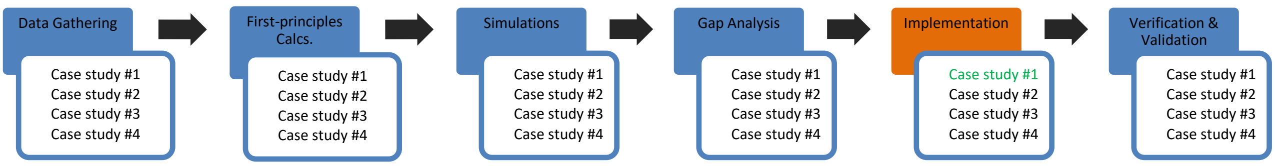
3.6 Sub-step 3.5: Implementation

The implementation criteria involved transitioning from establishing the cause behind reduced BAC performance—based on the operating variables—to action through corrective measures. Given the gap analysis, certain corrective measures were suggested, based on previous research, as practical and sustainable for Mine A when improving cooling performance.

Additionally, the implementation was intended to improve the operational performance of the BACs along with ensuring that the results of the improved performance aligned with the objectives listed in Section 1.8. Therefore, the methodology, as represented by Figure 25, was repeated so that the verification and validation criteria could be adhered to, and the respective case studies were re-audited after the suggested corrective measures were implemented.

As such, the relevant corrective measures were suggested, implemented by Mine A, and followed by the re-audited results as follows:

3.6.1 Case study 1:



- **Fouling Influence = 74%**
  - Corrective measure:

- Chemically rinse the coils externally to remove dust and debris and flush the coils internally to remove sedimentation deposits.
- Implemented:
  - Mine A only used high-pressure water to rinse and flush the coils.

- **Water flow = 16%**
  - Corrective measure:
    - Depending on the upstream infrastructure, increase the supply water flow to the BAC to 52 L/s.
  - Implemented:
    - Mine A increased the water flow within the operational justification of the upstream infrastructure.

- **Air flow = 10%**
  - Corrective measure:
    - Provided an air leak of 21.0 kg/s, a 1x 37 kW fan could be turned off to keep with the redundancy procedure of the mine, and all air leaks should be closed off as far as possible.
  - Implemented:
    - Mine A partially closed off the air leaks and ensured that only 2x, and not 3x, 37 kW were operating.

- **Water and Air temperature = 0%**
  - Corrective measure:
    - The water temperature could be ≤ 11.1 °C but not more, as the measured water temperature was already less than the OEM specification. Supplying the BAC with colder water than initially measured will only enhance the operational efficiency.
    - Lowering the RH of the supply air would allow the BAC to better utilise the relation between the sensible and latent heat, thereby increasing the operational efficiency.
  - Implemented:
    - Mine A supplied the BAC with colder water than what was initially measured.

➢ The inlet air temperature was a direct function of the overall ventilation of the mine and, therefore, increasingly challenging to comply with to meet the mine specifications.

- **Re-audit results:**

After reimplementing and following the “Data Gathering” and “First-principle Calculations” criteria, the relevant measurements were taken, reworked, and validated as stipulated in Section 2.2.1 and Section 2.2.2. The final data is visually represented by Figure 43.

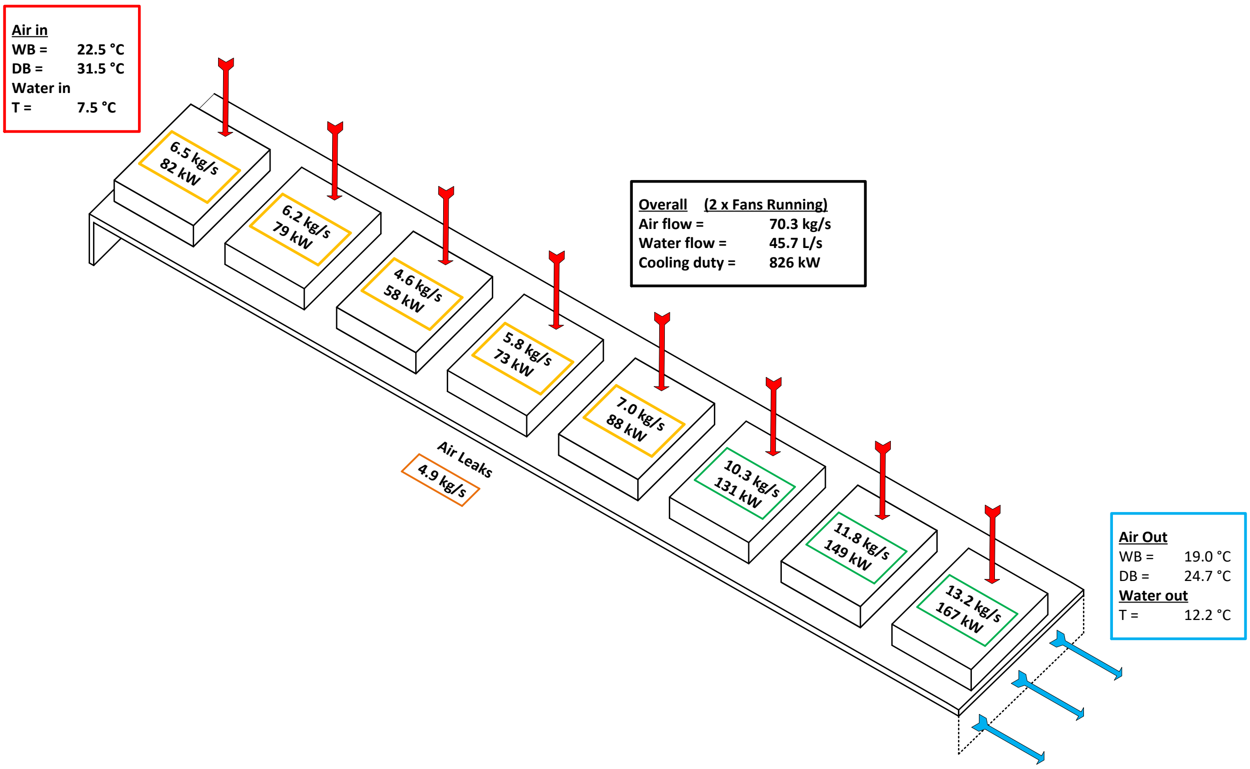


Figure 43: Case Study 1 - BAC Performance (Re-audit)

The “Simulations” criteria, outlined in Section 2.2.3, were then repeated and implemented in the PTB simulation software – similar to what was done and referenced in Figure 34.After repeating the cross-referencing of the “Actual” simulation with the “First-principle Calculations”, the average error for the simulation's accuracy came to 1%, which was less than the required 15%.

The comparison is summarised in Appendix AH. The "Achievable" simulation was then reconstructed while reconsidering the previously determined operational specifications, highlighted in blue throughout Table 11.

The inlet operating variables for the "Achievable" simulation were then adjusted accordingly and are represented in Table 19.

Table 19: Case Study 1 Re-audit Sim. 1 "Actual" vs. Re-audit Sim. 2 "Achievable"

Operating Variable		Sim. 1 - Actual	Mine A Specification	Sim. 2 - Achievable
Air	WB temp.	22.5 °C	22.0 °C	22.0 °C
	DB temp.	31.5 °C	32.0 °C	32.0 °C
	Mass flow	69.6 kg/s	67.5 kg/s	67.9 kg/s
Water	Temp.	7.4 °C	11.1 °C	7.4 °C
	Mass flow	45.7 L/s	52 L/s	52 L/s
Fouling	UA factor	0.48	0.8	0.8
Performance		825.7 kW	1 100 kW	1 156 kW

The results from the simulations based on Table 19 then serve as a baseline for the "Cause" simulation described in Section 2.2.3. The respective results from Simulation 3 are summarised in Figure 44 and Figure 45.

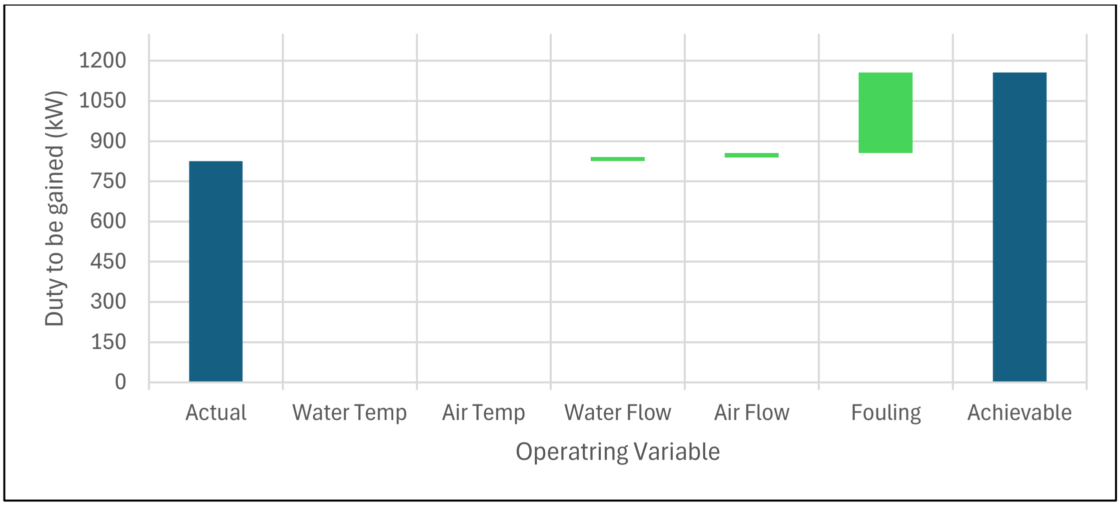


Figure 44: Case Study 1 – Waterfall Chart for Re-audit Operating Variable Influence (kW)

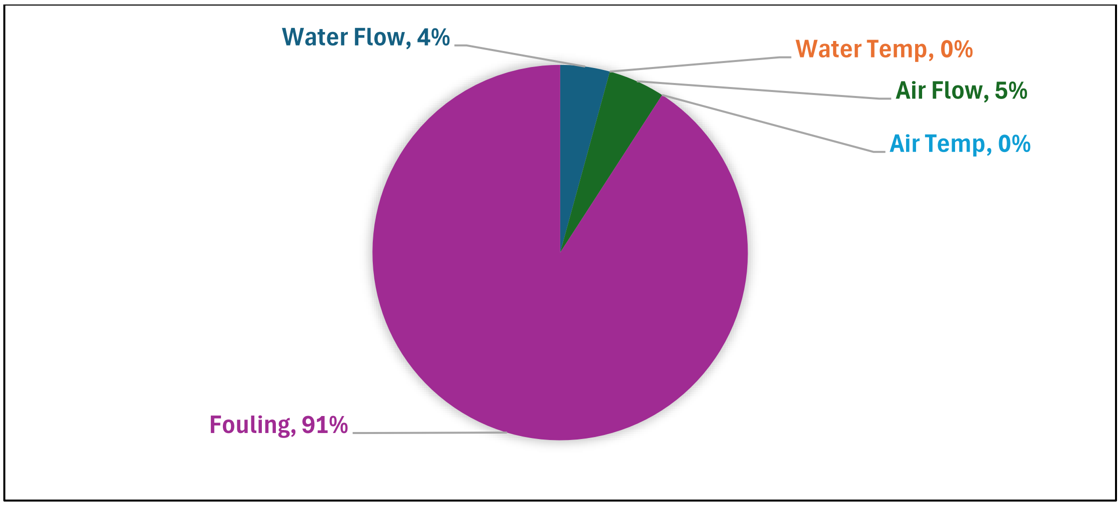


Figure 45: Case Study 1 – Breakdown of Re-audit Operating Variable Influence (%)

After repeating the method followed for the initial audit, a gap analysis was conducted again after cross-referencing Figure 44 and Figure 45. The results indicated that fouling, air and water flow remained the limiting operating variables across the BAC as the respective influences altered.

Fouling contributed 91% to the reduction in BAC performance, while it only contributed 74% during the initial audit. The increase in the fouling's contribution was caused by the diminished difference between the actual and achievable duties of the re-audit results and the remainder effect of the internal fouling that was insufficiently removed, as the coils were only rinsed and flushed with high-pressure water and not the suggested chemicals.

Additionally, the UA factor increased by 10% across the "Actual" simulations when compared, which indicated that the UA factor did increase when fouling was removed due to cleaning. However, due to fouling still being responsible for 91% of the reduction in performance, additional measures should be implemented, such as the initial suggestion of chemical cleaning.

After fouling, water flow was initially the operating variable with the next greatest influence on BAC performance. During the re-audit, however, water flow and air flow changed positions as the water flow increased by 40.7% and the total air flow decreased by 3%.

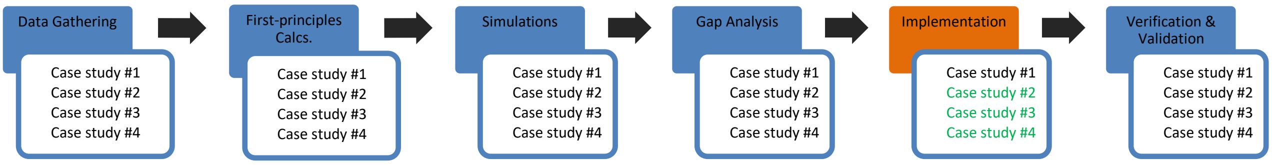
The air flow operating variable initially contributed 10%, whereas, after the re-audit, it only contributed 5%. This decrease was then accredited to the repaired air leaks. Despite less air flowing through the BAC in total, more air passed through the coils due to the leaks, which were reduced from 20.1 kg/s to 4.9 kg/s and thus increased the BAC performance. The air flow operating variable must, therefore, be further addressed by additionally mitigating the air leaks.

An increase from 27.1 L/s to 45.7 L/s in the water flow operating variable decreased the cause-effect in the reduced BAC performance. The low contribution to the cause of reduced BAC performance indicated that the internal fouling did not influence the amount of water flow through the BAC but rather the UA factor.

The water temperature supplied to the BAC was 3.7°C colder than the initial audit and the operational OEM specification. Therefore, 0% of this contributed to the BAC's reduced performance during the final audit.

The WB and DB temperatures changed marginally in accordance with the mine specifications, contributing 0% to the reduction in BAC performance when the "off-design" conditions and the mine specifications for the re-audit were considered.

3.6.2 Summary of Case Studies 2, 3, and 4



As indicated by the method, Sub-step 3.5, similar to Case Study 1, the suggested corrective measures were provided and implemented in the succeeding case studies based on the gap analysis results. As such, the prominent operating variables, fouling, air flow, and water flow, which caused the reduction in BAC performance, were addressed.

Given that the suggested corrective measures varied in scale and implication within the respective case studies, a comparison was permitted due to a similar approach consistently being implemented. Similar to the preceding sub-steps, Case Study 1 was described in detail, where the succeeding case studies were summarised. The summary provided an overview of the identified operating variables, the percentage of influence of the BAC performance, the suggested corrective measures, and how Mine A implemented them. The summary is presented in Table 20.

Table 20: Sub-step 3.5 Summary for Corrective Measures

Operating Variable	Initial Influence on BAC Performance	Corrective Measure	Implementation by Mine A
Fouling	Case 2: 82% Case 3: 89% Case 4: 85%	Chemically rinse and flush coils.	High-pressure water was used instead of chemical flushing.
Air flow	Case 2: 15% Case 3: 4% Case 4: 0%	Close air leaks and, where applicable, remove, replace, or refurbish damaged coils. Case 4: Reduce operating fans to 3x instead of 4x for redundancy.	Case 2: Two severely damaged coils were removed, and two more were replaced with refurbished coils. Partial air leak closure was completed. Case 3: No coils were removed. Case 4: Three fans were operated instead of four.
Water Flow	Case 2: 3% Case 3: 7% Case 4: 15%	Increase supply water flow to BAC to meet OEM specifications.	The mine increased water flow where possible within the limitations of the upstream infrastructure. Case 3: The water supply to one coil was closed to increase supply to the remaining two.
Water and Air Temperature	0% for all case studies	Ensure water temperature remains at or below OEM specification. Reduce RH of supply air where possible.	The mine successfully supplied colder water than initially measured. Case 4: Return airway supplying hot, humid air was closed, lowering the RH of supply air.
Corrective Measure Description	Appendix AL		

Given a similar approach to the suggested corrective measures for the respective case studies, Mine A's ability to implement them varied due to operational constraints, infrastructure limitations, and the availability of parts and crews, which led to a partial implementation of the respective case studies.

Similar to Case Study 1, the relevant measurements were then taken as part of a re-audit and then reworked and validated, as stipulated by Sub-step 3.1., and Sub-step 3.2 respectively. The final data is visually represented by Figure 46, Figure 47, and Figure 48.

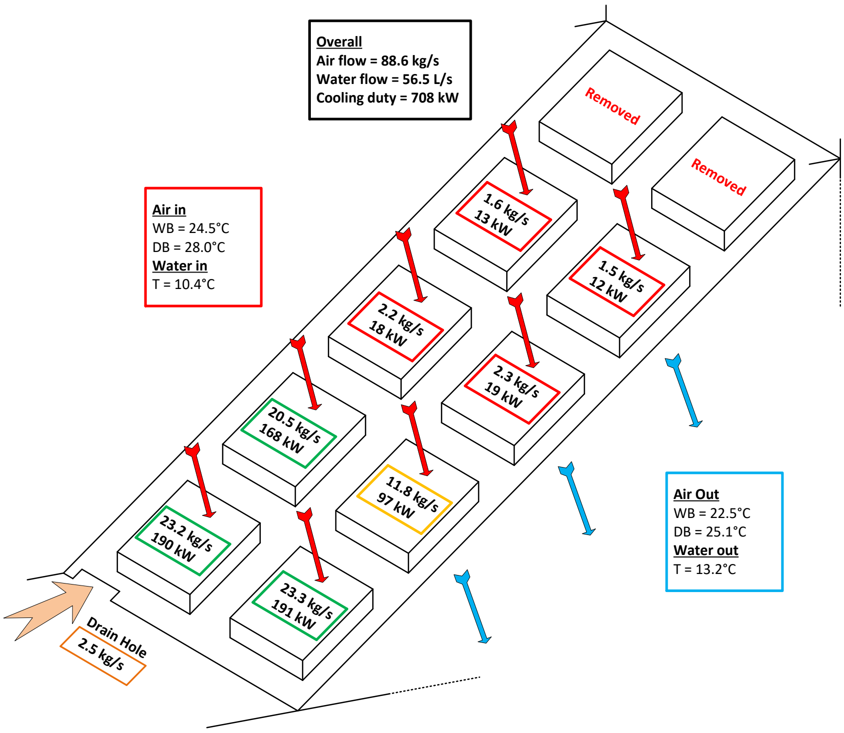


Figure 46: Case Study 2 - BAC Performance (Re-audit)

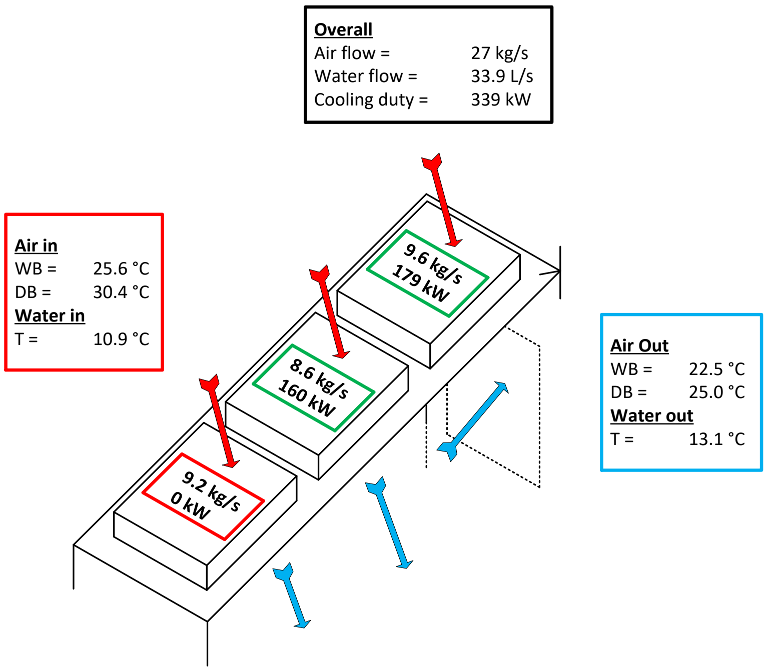


Figure 47: Case Study 3 - BAC Performance (Re-audit)

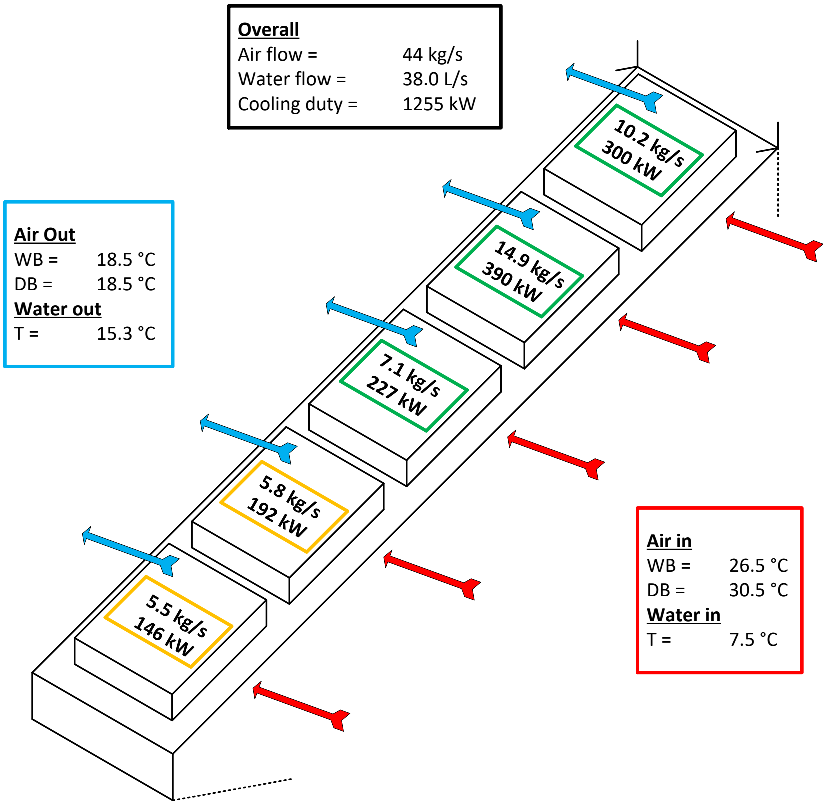


Figure 48: Case Study 4 - BAC Performance (Re-audit)

After repeating the method, similar to Case Study 1, the respective "Actual" simulations were again cross-referenced with the first-principle calculations to ensure accuracy. The results indicated that Case Studies 2, 3, and 4 had an average error of 1%, 4%, and 2% respectively, less than the error margin of 15%. The results of the respective "Actual" simulations, along with the error calculations, are listed in Appendix AH.

From the "Actual" model simulations, the "Achievable" model simulations followed according to Sub-step 3.3. Similar to Case Study 1, the results of these simulations then provided a baseline for the succeeding Sub-step 3.4, where the limiting effects of the operating variables were identified, quantified, and summarised. The respective simulation results are listed in Appendix AM. The summary of the gap analysis is shown below in Table 21.

Table 21: Sub-step 3.4 Summary for Case Studies 2, 3, and 4

Findings	**Case Study**		
	2	**3**	**4**
Fouling Influence (%)	82% → 77% ↓	89% → 82% ↓	85% → 39% ↓
Air Flow Influence (%)	15% → 23% ↑	4% → 13% ↑	0% → 25% ↑
Water Flow Influence (%)	3% → 0% ↓	7% → 0% ↓	15% → 36% ↑
Air Temperature	≈0% → ≈0%	≈0% → ≈0%	≈0% → ≈0%
Water Temperature	0%	0% → 1% ↑	0% → 0%
UA Factor Increase (Delta)	∆ 32% ↑	∆ 48.8% ↑	∆ 100% ↑
Figure Reference	Figure 55 & Figure 56	Figure 57 & Figure 58	Figure 59 & Figure 60
Detailed Analysis	Appendix AN		

In addition to Table 21, certain observations were also made, which included the following:

- The results from the re-audit indicated that fouling remained the prominent operating variable responsible for limiting the BAC's performance. In contrast to the improvements caused by the high-pressure cleaning, internal deposits were not fully removed. The influence reduced from 5% to 46%, and Case study 4 had the most significant decrease.

- The influence of the air flow varied across the case studies. As such, the air flow influences increased after the leaks were repaired. This observation was seen in Case Studies 2, 3, and 4, where specific damaged coils restricted air from passing through the BAC, and the effect became more prevalent as localised inefficiencies increased. Previous research indicated that incorrect air flow distribution across a heat exchanger could reduce the UA factor even when increased air flow is provided [8], [85].
- The water flow effect was different across the case studies. Case Studies 2 and 3 exceeded the specification, eliminating the effect, whereas in Case Study 4, the flow remained below the specification and resulted in an influence increase of 21%.
- The influence of the water temperature and air temperature operating variables had negligible effects on the performance of the BACs, as the measured values were below the required specifications.

3.7 Sub-step 3.6: Verification and validation

Following the implementation criteria, the verification and validation criteria was initiated. The respective case studies were re-audited after the suggested corrective measures were implemented as discussed in Section 3.6.

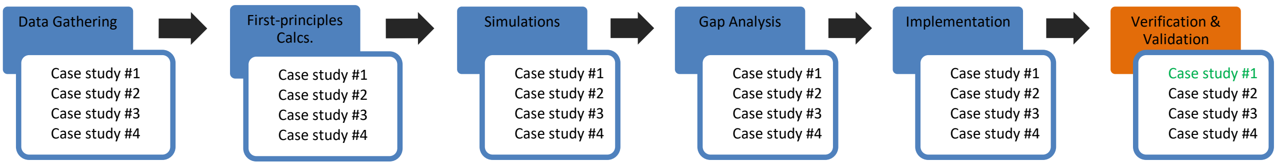
The validation ensured that the implemented corrective measures directly addressed the operating variables responsible for reduced BAC performance, while the verification analysed the performance gained and the remainder effect of the operating variables on the performance of the BAC. Therefore, the verification and validation criteria provided a comprehensive evaluation of the operational efficiency of the individual case studies, with a specific reference to the limiting operating variables, while additionally ensuring alignment with the aim and objectives indicated in Section 1.8.

The respective verification and validation explanations regarding the individual case studies are discussed below.

(***Side note****: Similar to Section 3.4, the verification and validation sub-step was critical in confirming the effectiveness of the corrective measures and ensuring that the objectives of the study were met. In contrast to the previous sub-steps, which allowed a results summary of the succeeding case studies due to the repetition of the method application, the verification and validation sub-step demanded a case-specific analysis, as the BACs operated at specific conditions due to the respective corrective measures.*

The validity of the study's method depended on a direct comparison of the initial and re-audit performance results of the respective case studies. This ensured that the corrective measures aligned with the results of the simulations. A summary of the results would have diminished the integrity of the analysis, as the performance verification and validation were being assessed. A summary of the results was, therefore, excluded to ensure that increased BAC performance was a result of the corrective measures and not the influence of external variables.)

3.7.1 Case Study 1:



The initial and re-audit results were cross-referenced, and a direct comparison is outlined and indicated by Figure 49.

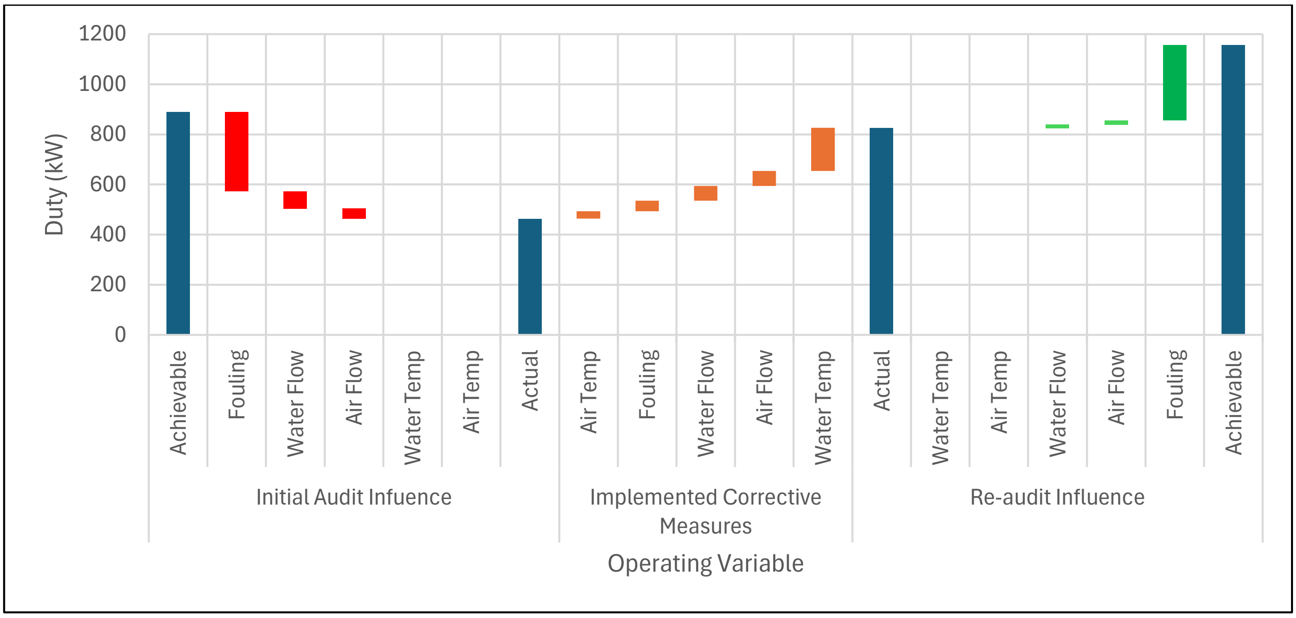


Figure 49: Case Study 1 – Waterfall Chart for Operating Variable Influence (kW)

The comparison indicated that the BAC had an initial operating capacity of 464 kW; however, after the implementation of the simulations and relevant specifications, an initial achievable performance of 889 kW is indicated. As a result of implementing the corrective measures, the re-audit simulations indicated an actual operational, calibrated, performance of 826 kW, where the achievable duty then changed to 1 156 kW after the required specifications were re-implemented.

The initial “Achievable” simulation was verified with an accuracy of 93% compared to the re-audit actual operational, calibrated performance. Even when the different “off-design” operating conditions of audits at the BAC were considered, Objective1 was achieved.

When the initial and re-audit “Cause” models were considered, fouling emerged as the primary operating variable responsible for reducing the BAC's performance. Initially, fouling resulted in a 316 kW loss, whereas the re-audit results indicated a restriction of only 300 kW that could have been gained. The water flow operating variable caused the BAC to lose 69 kW, while only a 14 kW potential gain was present during the re-audit. The air flow was initially responsible for restricting 41 kW, later decreasing to 16 kW.

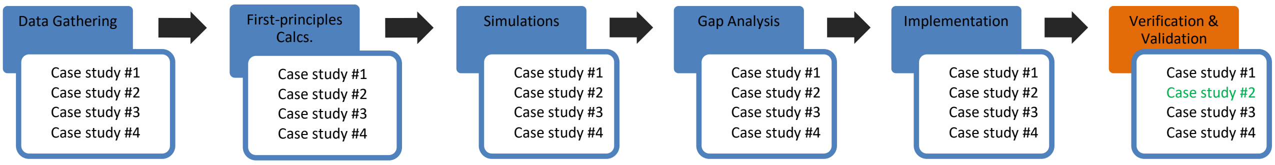
After the identification and quantification of the limiting effects caused by the operating variables, a general reduction in the respective influences was noticed. The identification and quantification of the respective operating variables aligned and achieved Objective 2.

As a result of the suggested corrective measures, based on the “Cause” model simulation results and the respective influence of individual operating variables outlined in Section 3.6, a steady increase in the operational capacity of the BAC was noticed when the audit results were compared. The corrective measures—based on the prominent operating variables—produced a performance increase of 42 kW for fouling and 59 kW for water and air flow.

The operating variables initially responsible for 0% influence on the BAC's performance contributed 30 kW and 172 kW for the air and water temperatures respectively. The respective performance increases caused by the corrective measures were validated along with the study's methodology.

Due to the different “off-design” operating conditions of the initial and re-audit influences, the BAC had a 44% increase in operational performance when the respective actual duties were compared and a decreased difference of 1.5 °C in the WB temperature. The results, therefore, achieved Objectives 3 and 4 respectively.

3.7.2 Case study 2:



Similar to Case Study 1, a direct comparison was created after cross-referencing the initial- and re-audit results and is represented by Figure 50.

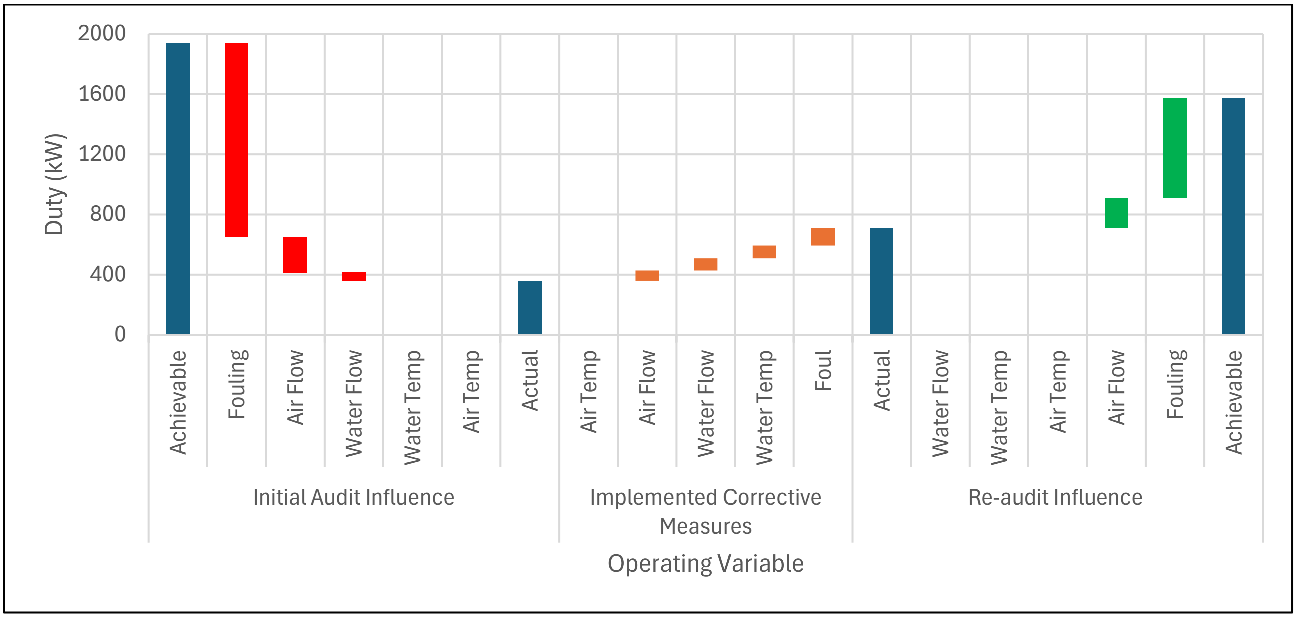


Figure 50: Case Study 2 – Waterfall Chart for Operating Variable Influence (kW)

After implementing and repeating the method used for Case Study 1, the comparison indicated that the BAC operated with an initial capacity of 360 kW. The "Achievable" simulation indicated a performance of 1 939 kW was possible with the applicable specifications. The "Cause" simulation indicated the operating variables responsible for reducing BAC performance. The corrective measures were then implemented according to Section 3.6.2. The action resulted in a calibrated "Actual" simulation where the re-audit results indicated an increased capacity of 709 kW.

During the implementation criteria, the operational methodology changed in terms of quantity coils that could have contributed to the achievable duty of the BAC. From the initial results, illustrated in Figure 31, two out of the ten coils were removed as per the corrective measures, and continued operating according to the re-audit results indicated by Figure 46.

Due to the study's aim, the simulations only accounted for identifying the current operating limitations and not optimising the BAC performance. A normalised efficiency was used for the verification, as the "Achievable" baseline was changed when the theoretical duty changed from 2 500 kW to 2 000 kW.

The "Cause" simulations from the initial and re-audit results identified fouling and air flow as the leading operating variables, while the water flow was only applicable during the initial influence. Initially, fouling was responsible for a 1 291 kW loss, whereas the re-audit results indicated a loss of only 663 kW due to the performance restrictions.

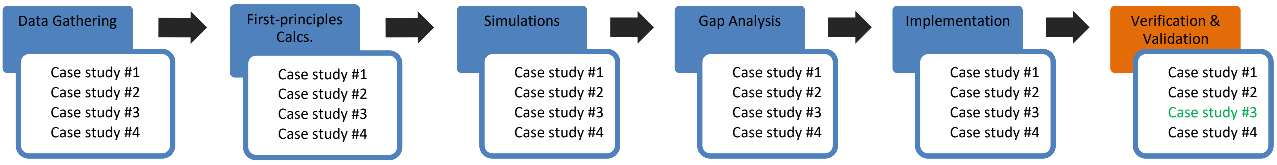
The effect of limited air flow was initially responsible for 234 kW loss and was reduced to, or seen as a potential gain of, 202 kW. The influence of the water flow operating variable was reduced with an absolute of 54 kW, as no limitation was determined during the re-audit. Therefore, the identification and quantification of the respective influence regarding the operating variable achieved Objective 2.

After the corrective measures were implemented according to Section 3.6.2, an increase in the actual operating performance of the BAC was noticed. A performance gain of 68 kW was attributed to addressing the air flow, 80 kW to the water flow, 86 kW to the water temperature, and 115 kW to fouling. The water and air temperature initially had 0% influence, which justified adjusting the operating variables accordingly, despite their compliance with the required specifications. This adjustment led to additional performance gains.

The method of identifying the operating variables responsible for limiting the performance of a BAC and the impact of the corrective measures based on the simulation results was validated due to these improvements.

The BAC had a 26% increase in normalised operational performance and a WB temperature difference of 1.5 °C. In addition to achieving Objectives 1, 3, and 4, the results were verified due to the increase in operational performance and the identification and quantification of the respective operating variable influence.

3.7.3 Case Study 3:



A direct comparison was created by cross-referencing the initial and re-audit results and is indicated by Figure 51.

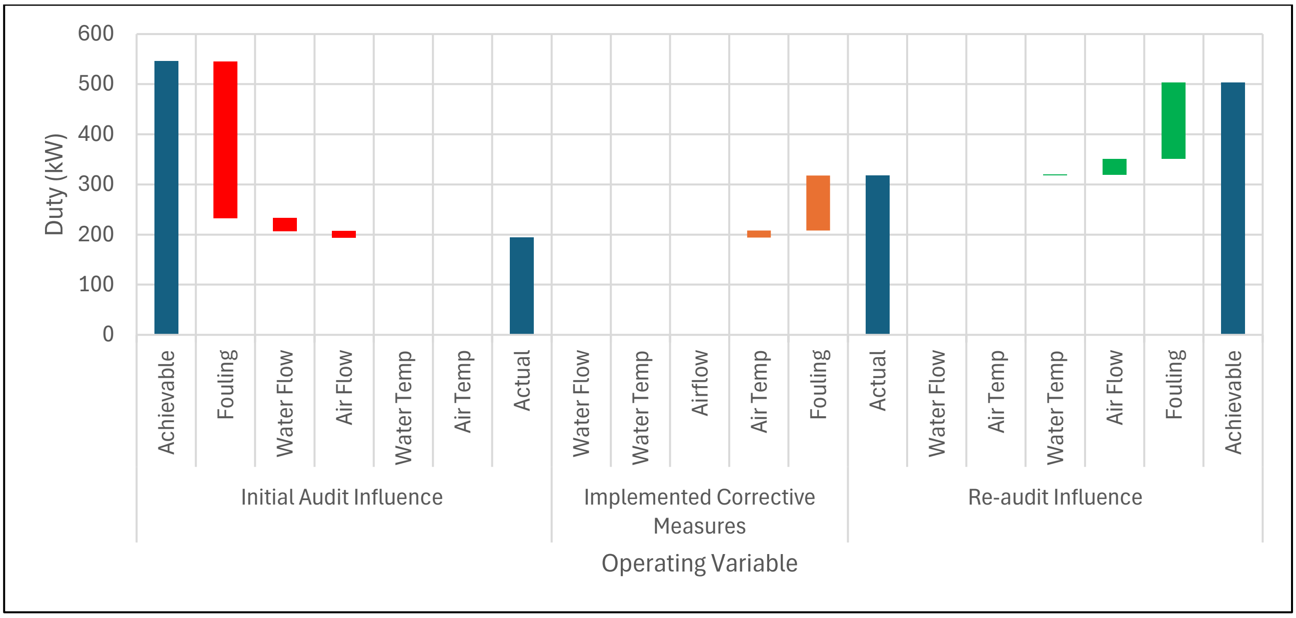


Figure 51: Case Study 3 – Waterfall Chart for Operating Variable Influence (kW)

The comparison indicated that the BAC had an initial operating capacity of 194 kW, while the achievable performance, determined through simulations and the relevant specifications, was calculated at 546 kW. After implementing the corrective measures discussed in Section 3.6.2, an actual operational performance of 318 kW was produced. After implementing the required specifications, the achievable performance was calculated as 503 kW.

Similar to Case Study 2, the operational methodology changed due to the implementation criteria caused by the water flow to one of the coils that was closed off, which could have potentially contributed to the performance. Figure 47 indicated a 0kW contribution, as 9.2 kg/s of air was passing through and resulted in the theoretical duty to change from 1 500 kW to 1 000 kW. Due to the aim of the study being improvement and not optimisation, a normalised efficiency was used for the verification, as the "Achievable" baseline was changed when one coil was allowing air to pass through but not water.

From the comparison, the respective "Cause" models indicated that fouling, water flow and air flow stood out as the primary operating variables that influence BAC performance. . Fouling initially resulted in a 313 kW loss and, after the re-audit, only had a 152 kW loss. Water flow had an absolute decrease of 26 kW, as no loss was caused during the re-audit results.

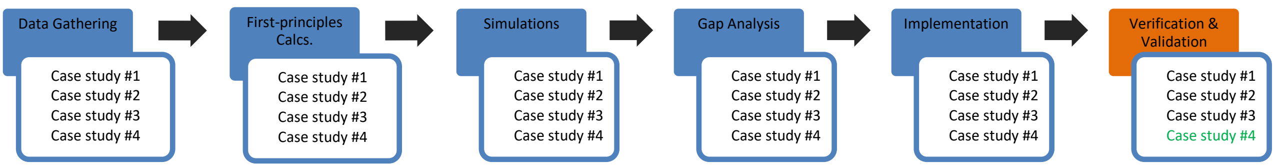
Air flow initially indicated a 13 kW loss compared to the 31 kW loss during the re-audit. The increase in the loss caused by the air flow was due to the lack of cooling from the coil, which allowed air to pass through without being cooled. After systematically identifying and quantifying the respective influences, Objective 2 was achieved.

After implementing the corrective measures, an increase in the BAC's actual performance was noticed. After addressing fouling, a performance gain of 110 kW was yielded. The air temperature contributed 14 kW to the performance, a result of the different “off-design” operating temperatures of the initial and re-audit results.

Therefore, the BAC performance increased primarily due to cleaning and the subsequent removal of fouling. Based on the results of the simulations, which aligned with the study's objectives, the impact of the corrective measures validated the methodology by improving the BAC's operational performance.

Given the normalised operational performance, the BAC had a 28% increase. The performance increase, along with the identification and quantification of the respective influences, verified the results and ensured that Objectives 1, and 4 were achieved.

3.7.4 Case Study 4:



The initial and re-audit results were combined for the purpose of a direct comparison and are indicated by Figure 52.

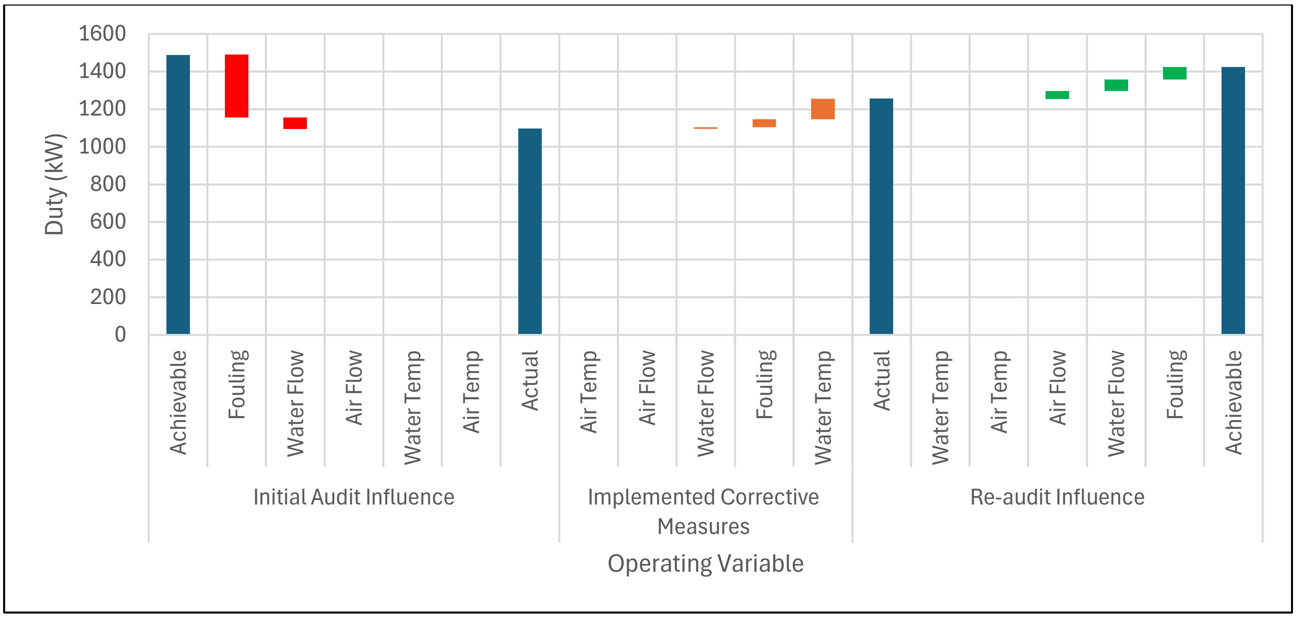


Figure 52: Case Study 4 – Waterfall Chart for Operating Variable Influence (kW)

The comparative evaluation showed that the BAC had an initial operating capacity of 1 096 kW compared to the achievable performance that was simulated as 1 488 kW. Similar to the previous case studies, the corrective measures were then implemented in accordance with Section 3.6.2 and increased the actual operating capacity to 1 255 kW. After the respective operating capacities were reintroduced, an achievable duty of 1423 kW should have been possible.

Similar to Case Study 1, the operating philosophy of the BAC remained the same between the audits, as the theoretical duty of 2 500 kW did not change. Given the different "off-design" operating conditions between audits, the "Achievable" simulation was verified with an accuracy of 85% when cross-referenced with the re-audit actual capacity, and therefore, Objective 1 was achieved.

The initial "Cause" simulation indicated that fouling caused a 333 kW loss, and the water flow caused a 60 kW loss. In comparison, the reduced air flow was responsible for a 42 kW loss, the limited water flow that did not equate to the specification was responsible for a 61 kW loss, and the remainder of the fouling was responsible for a 65 kW loss.

Even when only two operating variables were initially responsible for the limitation on the BAC performance compared to the re-audit operating variables, a steady decrease in the influence of the respective operating variables was noticed. The identification and quantification of the influence caused by the operating variables confirmed and achieved Objective 2.

From there, the corrective measures that were implemented ensured a 9 kW gain after the water flow increased, a 42 kW gain after the BAC was cleaned and a 109 kW gain by reducing the water temperature below the required specification. In a similar occurrence to the aforementioned case studies, previous negligible operating variables did contribute to the performance gain of the BAC when the mine corrected them in accordance with the suggested corrective measures for additional performance gains, confirming the necessity for a comprehensive performance assessment. The respective performance gains achieved by following the methodology were validated, as they aligned with the aim of the study.

The BAC had a 13% increase in performance and a 6.5 °C reduction in WB temperature after accounting for the various “off-design” operating conditions between audits. As a result, Objectives 1, 3, and 4 were achieved.

3.8 Cross-case discussion

The reworked methodology was solution-driven, focusing on identifying and mitigating the operating variables responsible for limiting the BAC performance. This approach allowed for a cross-case discussion of the results.

From the respective constructions, Case Study 1 was constructed horizontally, whereas the other case studies were constructed diagonally between the footwall and hanging wall. Case Studies 1 and 2 used 250 kW cooling-coils, while Case Studies 3 and 4 used 500 kW cooling-coils. Case Study 3 did not have a fan implemented to assist with air flow through the coils—all other case studies were fitted with force fans. Due to variations in operational conditions and specifications, the BACs could not be directly compared, as only initial and re-audit results were required to validate the methodology.

A consistent finding throughout the initial audit results was that fouling was the primary operating variable responsible for reduced BAC performance. The re-audit results reinforced this, showing that most performance gains were a result of the removal of fouling while high-pressure cleaning was used on most coils, internal fouling persisted, indicating that the mine should take additional steps to flush the coils with chemicals to ensure the internal fouling is removed sufficiently.

Beyond fouling, the quantities of working fluids supplied to the BACs was the next most significant influence on performance. This was primarily due to air leaks, which allowed air flow to bypass the coils, and a restricted supply of cooled water from the mine that further impacted efficiency. Initially, the impact of working fluid quantity, when compared to fluid temperature, was unexpected, as temperature theoretically has a more significant overall effect on BAC performance. However, during the re-audit, the mine successfully supplied the BACs with water at a temperature lower than required, and the resulting performance improvements became evident.

From the corrective measures, the primary operating variables influencing BAC performance were effectively addressed. As expected, the implementation of these measures resulted in increased performance between the initial and re-audit results.

Since all the BACs were initially underperforming, implementing the reworked case study methodology resulted in a performance increase in the respective BACs but indicated that the actual performances were still not equal to the achievable performance. A second iteration of the methodology could further enhance operating performance.

3.9 Study validation

In validation of the study, the verification and the validation of the respective case studies in Section 3.7 were directly cross-referenced with the objectives in Section 1.8 and summarised in Table 22.

Table 22: Study Validation

		Case studies				
No.	**Objective description**	**1**	**2**	**3**	**4**	**Validated by case study results**
1.	Determined the "Achievable" duty of a BAC at "off-design" conditions.	✓	✓	✓	✓	Yes, the simulations predicted the "Achievable" duties. ✓
2.	Identification of the operating variables limiting the BAC performance.	✓	✓	✓	✓	Yes, the simulations did indicate the limiting operating variables. ✓
2.1.	Analysing the influence of the air temperature and quantity.	✓	✓	✓	✓	Yes, the results did indicate the effect on the BAC performance. ✓
2.2.	Analysing the influence of the water	✓	✓	✓	✓	Yes, the results did indicate the effect on the BAC performance. ✓

	temperature and quantity.					
2.3.	Analysing the influence of fouling.	✓	✓	✓	✓	Yes, the results did indicate the primary effect on the BAC performance. ✓
3.	Increase the actual performance duty.	✓	✓	✓	✓	After the implementation of the corrective measures, improvements were measured. ✓
4.	Decrease the WB temperature.	✓	✓	-	✓	Performance gains were confirmed. ✓

The study was successfully validated by achieving the objectives through the implementation of the reworked case study methodology. In addition to determining the achievable performance—as an indication of what the BAC is capable of under the mining conditions—the methodology was validated as a reliable process for analysing and improving the performance of a BAC operating at "off-design" conditions, aligning with the aim of the study.

3.10 Conclusion

The reworked methodology was applied to four case studies and the individual results were documented and followed by the required simulations. The simulations then indicated the respective achievable duties—based on a calibrated baseline simulation—from where the cause for reduced performance based on operating variables, was identified and quantified. From the results, a gap analysis was conducted to establish the impact of these factors and determine corrective measures aimed at improving operational performance of BACs.

Following the implementation of the corrective measures, the BACs were re-audited, during which the methodology was reapplied. The respective initial and re-audit results were then directly compared to verify and validate the aim of the study, along with establishing whether the objectives were achieved.

CHAPTER 4 CONCLUSION AND FUTURE WORK

4.1 Conclusion

This study focused on creating a methodology, based on the general design methodology, through the implementation of simulation software that identified the operating variables responsible for a reduction in performance of finned-tubed BACs that operate in a deep-level gold mining environment. By implementing simulation software, the study identified key operating variables responsible for performance losses, allowing for their evaluation and subsequent mitigation.

BACs play a critical role in heat management within deep-level mines and secondary cooling systems, ensuring the miners' productivity, health, and safety. During the operation of a BAC in a harsh environment, performance of BACs declines due to environmental and operational factors, which, in turn, require a methodology that systematically identifies and mitigates the primary causes of the performance loss within the BAC.

Previous research primarily relied on “pre-selected” operating variables without the initial determination of the respective effect on the BAC performance, whereas this study developed and applied a methodology that highlighted the identification and quantification of the respective causal operating variables before implementing the suggested corrective measures in order to increase the current operational performance of a BAC.

By using a sequential methodology that consisted of six sub-criteria, the reworked methodology was designed to align with the aim of the study. The “Data gathering” sub-step was initially done conducted on four BACs that were incorporated at various locations within Mine A while keeping with the relevant mining standards and procedures. This ensured a baseline for the additional analysis after confirming the operational conditions, design and mine requirements, equipment limitations, and the location of the BACs.

As part of the “First-principle Calculations” sub-step, the collected data was then reworked after implementing a calculation tool that verified the accuracy of the measurements in terms of the Law of Energy Conservation before continuing to the “Simulations” sub-step.

After considering this study's objectives, it became apparent that three separate models should be incorporated into the “Simulations” sub-step. These three models, namely the “Actual", “Achievable", and “Cause” models, were established to simulate BAC performance under various operational conditions.

The “Simulations” sub-step determined the actual performance after the required calibration, which, in turn, served as a baseline for the achievable duty for the BAC while operating under “off-design” conditions and the identification and the quantification of the most influential operating variables that were responsible for any performance loss. The results of the “Simulations” sub-step then served as a basis for conducting a gap analysis, from which the suggested corrective measures to improve BAC performance were determined.

From the “Implementation” sub-step that followed the corrective measures, each case study was re-audited to validate the respective performances gained from correcting the limiting effect caused by certain operating variables.

A direct comparative analysis of the respective initial and re-audit performances then allowed for verification, as the initial and re-audit influences, along with the increase in operational performance, were cross-referenced to quantify the improvements and showcase the remainder effect of the operating variables. As such, the increase in operational capacity for Case Study 1 was 44%, 26% for Case Study 2, 28% for Case Study 3, and 13% for Case Study 4.

By identifying and addressing the effect of the operating variables responsible for reduced BAC performance, the study demonstrated an effective methodology for improving the operational efficiency of finned-tube BACs using simulations. Additionally, as indicated by the results, the reworked methodology confirmed a structured means to identify the operating variables responsible for causing a reduction in performance of a finned-tubed BAC, following which corrective measures could be implemented.

Following the final “Verification and Validation” sub-step of the reworked methodology, all the objectives were achieved across the various case studies, highlighting the methodology's relevance to the gold mining industry.

4.2 Recommendations

This study contributed to enhancing the cooling capacity of secondary cooling infrastructure within a gold mine by providing a reworked methodology for identifying and mitigating the performance limitations of a BAC. Future research can build on this study by expanding the methodology to include direct-contact BACs and not only indirect-contact BACs.

Therefore, the evaluation of hybrid systems, which include the combination of indirect- and direct-BACs, should not be excluded. Further studies could also focus on the continuous re-iteration of the reworked methodology to achieve optimisation and not only improvement results for a BAC, or refine the simulation models to account for:

- Various types of FTHX coils.
- Increased accuracy regarding the geometric positions of the coils relative to one another, in terms of positions within the BAC, as the current effect on performance was negligible.
- Water flow measurements to and from the individual coils, as the instrumentation used in this study was limited to measuring only the main supply and return water pipes.
- Time-dependent operating conditions are needed for an improved representation of the changes in the performance of a BAC during transient state analysis.
- Improved heat transfer model to account for the non-uniform distribution of fouling within the FTHX coils.

Further recommendations include using real-time monitoring equipment for increased accuracy on the initial and re-audit performances and predictive maintenance capabilities beyond establishing the optimal orientation of an FTHX coil when intended for use under “off-design” operating conditions within a gold mine.

Additional recommendations include the extension of the reworked case study methodology to other mining environments which can include platinum, coal, and diamond mines, where the operating conditions as well as the cooling requirements vary.

The methodology could, therefore, be adapted to applications, such as data centres with high thermal loads or underground transport tunnels. Alternatively, the reworked case study methodology could be applied to various mining environments and long-term case studies to validate the general application and sustained relevance of the method.

4.3 Reflection

Looking back on the study, specified improvements could have additionally contributed to the implementation of the methodology even when considering that the objectives have been achieved. An elaborated data gathering phase, through temporary real-time monitoring, may have increased the accuracy of the inputs for the simulations. Additionally, the validity of the methodology could have been improved had there been access to more case studies or other active mine shafts where indirect-contact BACs were being implemented at Mine A.

Various non-technical challenges also came about during this study. The coordination with the mine personnel in terms of gaining access to some restricted areas, the implementation of the corrective measures, and the procurement of refurbished/new coils were logistical challenges due to budget restraints, production schedules, and site restrictions.

Furthermore, ensuring the accuracy of the measurements proved to be challenging at times, as the areas surrounding the BACs restricted verbal communication between team members due to the noise, in addition to the damp, cold areas where the measurements needed to be written down. The challenges required overcoming and adaptability to ensure the study aligned with the objectives.

The reworked case study methodology has the potential to improve the operating performance of secondary cooling infrastructure of mines in South Africa, as well as reducing energy and operational costs, as the mine would have an increased thermal capacity to better ensure the conditions of the mining environment. Lastly, the hope is that the reworked methodology of this study could serve as a foundation for future research and development in improving the operational performance of underground BACs.

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APPENDIXES

i. Appendix AA

Description	Unit	Instrument	Accuracy within	Resolution	Range
Inlet and outlet water Temperature	℃.	Gemini Tinytag view 2 with Thermistor Probe	0,25%	0,02	-40,0~125,0
Inlet and Outlet Air Temperature	$℃_{wb}/℃_{db}$	Whirling Hygrometer	2%	0,5	-5,0~50,0
Inlet and outlet air pressure	kPa	Tenmar-404 Anemometer	+-2	0,1	0,35~110,0
Water Mass flow	kg/s	Portable water flow meter	5%	0,25	0,0~14,0
Air velocity into the cooling coils.	m/s	Tenmar-404 Anemometer	+-2%+0.2	0,1	0,4~20,0
Inlet fan/Ducting diameter	m	Bosch PLR-25 lase distance meter	2,0 %	0,001	0,05~25,0

Figure 53: Instrumentation Measuring Range [5]

ii. Appendix AB

Table 23: Measuring Checklist

Finned-Tube BAC Measurement Data:

Location	Measurement		Check
1. (Inlet Airflow)	Hualage Area		
	Air Velocity		
	Baromaetric Pressure		
	Temperature	WB	
		DB	
2. (Middle Sector)	Hualage Area		
	Air Velocity		
	Baromaetric Pressure		
	Temperature	WB	
		DB	
3. (Outlet Airflow)	Hualage Area		
	Air Velocity		
	Baromaetric Pressure		
	Temperature	WB	
		DB	
4. Water Flow	Cold Supply Water	Quant.	
		Temp.	
	Hot Return Water	Quant.	
		Temp.	

Location		Coil ID/number:					
		Position	Measurement	Check	Measurement		Check
5. Finned-Tube Coil	Up Stream	A1	Velocity		Temperature	WB	
		A2				DB	
		A3			Condition:		
		A4					
		A5					
		A6					
		A7					
		A8					
		A9					
	Down Stream	A1	Velocity		Temperature	WB	
		A2				DB	
		A3			Condition:		
		A4					
		A5					
		A6					
		A7					
		A8					
		A9					

iii. Appendix AC

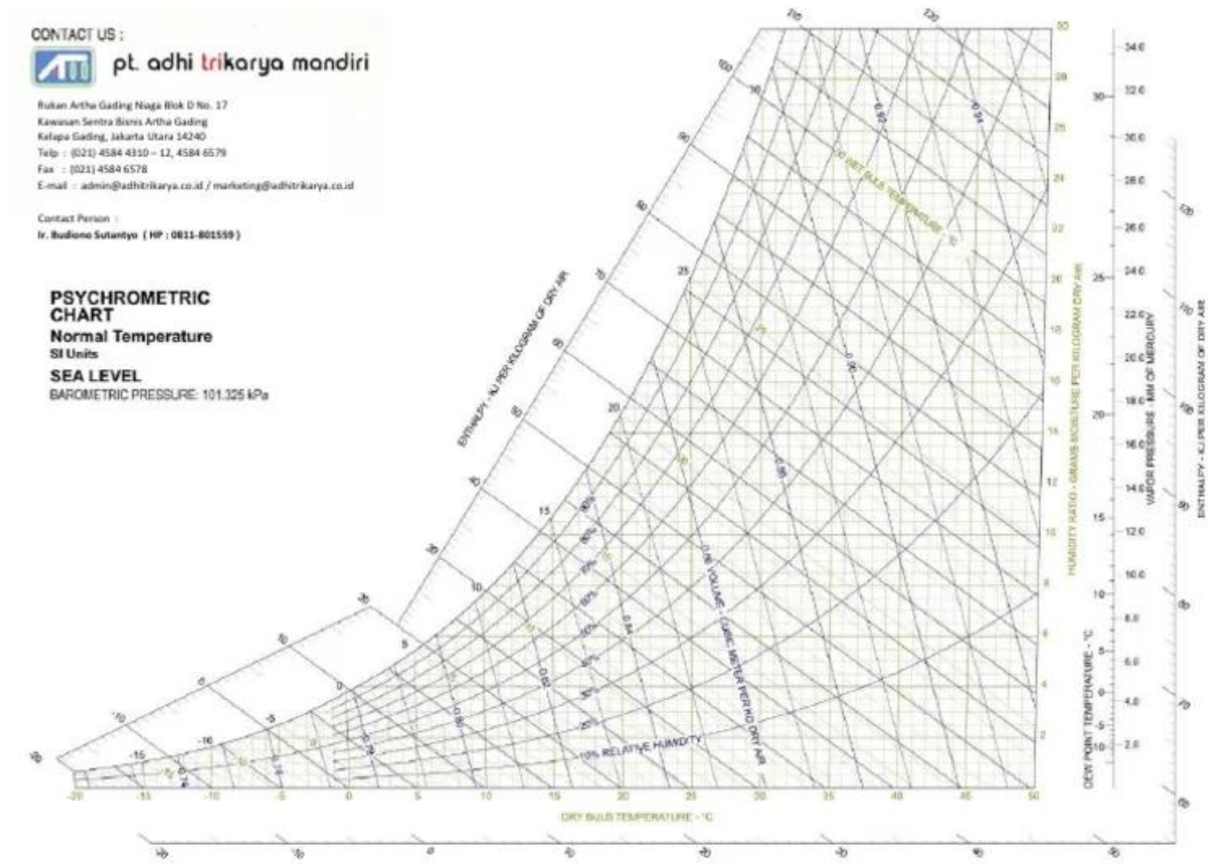


Figure 54: Psychometric Chart Example [113]

iv. Appendix AD

- **1. Case Study 1 - 39L Initial measurements**

Location	Measurement		Reading	Unit
1. (Inlet Airflow)	Haulage Area		17.5	m^2
	Air Velocity		3.7	m/s
	Barometric Pressure		118.6	kPa
	Air Temperature	WB	22.0	°C
		DB	30.5	°C
2. (Middle Sector)	Haulage Area		17.5	m^2
	Air Velocity		2.9	m/s
	Barometric Pressure		119.3	kPa
	Air Temperature	WB	22.3	°C
		DB	31.3	°C
3. (Outlet Airflow)	Haulage Area		2.2	m^2
	Air Velocity		22.8	m/s
	Barometric Pressure		118.6	kPa
	Air Temperature	WB	20.5	°C
		DB	27	°C
4. Water Flow	Cold Supply Water	Quant	27.1	l/s
		Temp.	11.1	°C
	Hot Supply Water	Quant	27.1	l/s
		Temp.	15.6	°C
5. Finned-Tube Coils	Coil ID/Number		1	
	Position	Inlet Air Velocity	Outlet Air Velocity	
	A1	1.4	1.4	m/s
	A2	1.4	1.4	m/s
	A3	1.4	1.3	m/s
	A4	1.3	1.4	m/s
	A5	1.4	1.4	m/s
	A6	1.4	1.3	m/s
	A7	1.4	1.4	m/s
	A8	1.4	1.4	m/s
	A9	1.4	1.3	m/s
	Average	1.4	1.3	m/s
	Inlet Air Temp.	WB	21.8	°C
		DB	30.4	°C
	Outlet Air Temp.	WB	20.6	°C
		DB	27.0	°C
	Coil Notes: All the coils were used and visibly fouled on the outside. The area of the coil is 1.8 m2. Coils were not fixed flush to the recesses wich cuased excessive air leaks on the sides of the coils.			

Coil ID/Number		2	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	1.5	1.5	m/s
A2	1.6	1.5	m/s
A3	1.6	1.5	m/s
A4	1.6	1.5	m/s
A5	1.6	1.5	m/s
A6	1.5	1.5	m/s
A7	1.6	1.5	m/s
A8	1.6	1.5	m/s
A9	1.6	1.5	m/s
Average	1.6	1.5	m/s
Inlet Air Temp.	WB	22.4	°C
	DB	30.8	°C
Outlet Air Temp.	WB	20.2	°C
	DB	27.5	°C

Coil ID/Number		3	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	1.6	1.6	m/s
A2	1.6	1.6	m/s
A3	1.6	1.6	m/s
A4	1.6	1.6	m/s
A5	1.6	1.6	m/s
A6	1.6	1.6	m/s
A7	1.6	1.6	m/s
A8	1.6	1.6	m/s
A9	1.6	1.6	m/s
Average	1.6	1.6	m/s
Inlet Air Temp.	WB	21.8	°C
	DB	31.0	°C
Outlet Air Temp.	WB	20.8	°C
	DB	27.4	°C

Coil ID/Number		5	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	2.4	2.3	m/s
A2	2.4	2.3	m/s
A3	2.5	2.3	m/s
A4	2.4	2.4	m/s
A5	2.4	2.4	m/s
A6	2.4	2.3	m/s
A7	2.4	2.3	m/s
A8	2.4	2.3	m/s
A9	2.4	2.4	m/s
Average	2.4	2.3	m/s
Inlet Air Temp.	WB	21.8	°C
	DB	30.0	°C
Outlet Air Temp.	WB	20.7	°C
	DB	26.5	°C

Coil ID/Number		7	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	5.0	4.8	m/s
A2	5.0	4.7	m/s
A3	4.9	4.8	m/s
A4	4.9	4.8	m/s
A5	4.9	4.8	m/s
A6	5.0	4.8	m/s
A7	5.0	4.8	m/s
A8	4.9	4.8	m/s
A9	5.0	4.8	m/s
Average	5.0	4.8	m/s
Inlet Air Temp.	WB	22.3	°C
	DB	30.9	°C
Outlet Air Temp.	WB	20.2	°C
	DB	27.4	°C

Coil ID/Number		4	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	1.6	1.5	m/s
A2	1.5	1.5	m/s
A3	1.6	1.5	m/s
A4	1.6	1.5	m/s
A5	1.5	1.5	m/s
A6	1.6	1.5	m/s
A7	1.5	1.5	m/s
A8	1.6	1.5	m/s
A9	1.6	1.5	m/s
Average	1.6	1.5	m/s
Inlet Air Temp.	WB	21.9	°C
	DB	30.0	°C
Outlet Air Temp.	WB	20.5	°C
	DB	27.1	°C

Coil ID/Number		6	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	3.4	3.3	m/s
A2	3.4	3.3	m/s
A3	3.4	3.3	m/s
A4	3.4	3.3	m/s
A5	3.4	3.3	m/s
A6	3.4	3.3	m/s
A7	3.4	3.3	m/s
A8	3.4	3.3	m/s
A9	3.4	3.3	m/s
Average	3.4	3.3	m/s
Inlet Air Temp.	WB	21.8	°C
	DB	29.9	°C
Outlet Air Temp.	WB	20.8	°C
	DB	26.5	°C

Coil ID/Number		8	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	6.6	6.4	m/s
A2	6.6	6.4	m/s
A3	6.6	6.4	m/s
A4	6.6	6.4	m/s
A5	6.6	6.4	m/s
A6	6.7	6.3	m/s
A7	6.6	6.4	m/s
A8	6.6	6.3	m/s
A9	6.6	6.3	m/s
Average	6.6	6.4	m/s
Inlet Air Temp.	WB	22.2	°C
	DB	31.0	°C
Outlet Air Temp.	WB	20.2	°C
	DB	26.7	°C

- **2. Case Study 1 - 39L Re-audit measurements**

Location	Measurement		Reading	Unit
1. (Inlet Airflow)	Haulage Area		17.5	m^2
	Air Velocity		3.1	m/s
	Barometric Pressure		117.3	kPa
	Air Temperature	WB	22.5	°C
		DB	31.5	°C
2. (Middle Sector)	Haulage Area		17.5	m^2
	Air Velocity		2.9	m/s
	Barometric Pressure		117.7	kPa
	Air Temperature	WB	22.7	°C
		DB	31.9	°C
3. (Outlet Airflow)	Haulage Area		2.2	m^2
	Air Velocity		23.2	m/s
	Barometric Pressure		117.3	kPa
	Air Temperature	WB	19	°C
		DB	24.7	°C
4. Water Flow	Cold Supply Water	Quant.	45.7	l/s
		Temp.	7.5	°C
	Hot Supply Water	Quant.	45.7	l/s
		Temp.	12.2	°C
5. Finned-Tube Coils	Coil ID/Number		1	
	Position	Inlet Air Velocity	Outlet Air Velocity	
	A1	2.6	2.6	m/s
	A2	2.7	2.6	m/s
	A3	2.8	2.7	m/s
	A4	2.8	2.6	m/s
	A5	2.7	2.6	m/s
	A6	2.7	2.6	m/s
	A7	2.7	2.7	m/s
	A8	2.7	2.6	m/s
	A9	2.8	2.7	m/s
	Average	2.7	2.6	m/s
	Inlet Air Temp.	WB	22.5	°C
		DB	31.4	°C
	Outlet Air Temp.	WB	19.0	°C
		DB	24.9	°C
	Coil Notes:			

Coil ID/Number		2	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	2.6	2.6	m/s
A2	2.7	2.6	m/s
A3	2.7	2.6	m/s
A4	2.7	2.6	m/s
A5	2.7	2.6	m/s
A6	2.7	2.6	m/s
A7	2.7	2.6	m/s
A8	2.7	2.6	m/s
A9	2.7	2.6	m/s
Average	2.7	2.6	m/s
Inlet Air Temp.	WB	22.3	°C
	DB	31.3	°C
Outlet Air Temp.	WB	19.0	°C
	DB	24.9	°C

Coil ID/Number		3	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	2.0	1.9	m/s
A2	2.0	1.9	m/s
A3	2.0	1.9	m/s
A4	2.0	1.9	m/s
A5	2.0	1.9	m/s
A6	2.0	1.9	m/s
A7	2.0	1.9	m/s
A8	2.0	1.9	m/s
A9	2.0	1.9	m/s
Average	2.0	1.9	m/s
Inlet Air Temp.	WB	22.5	°C
	DB	31.5	°C
Outlet Air Temp.	WB	18.9	°C
	DB	24.8	°C

Coil ID/Number		4	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	2.4	2.3	m/s
A2	2.4	2.3	m/s
A3	2.4	2.3	m/s
A4	2.4	2.3	m/s
A5	2.4	2.3	m/s
A6	2.4	2.3	m/s
A7	2.4	2.3	m/s
A8	2.4	2.3	m/s
A9	2.4	2.3	m/s
Average	2.4	2.3	m/s
Inlet Air Temp.	WB	22.7	°C
	DB	31.6	°C
Outlet Air Temp.	WB	18.9	°C
	DB	24.8	°C

Coil ID/Number		5	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	3.0	2.9	m/s
A2	2.9	2.8	m/s
A3	3.0	2.8	m/s
A4	3.0	2.8	m/s
A5	3.0	2.8	m/s
A6	3.0	2.9	m/s
A7	3.0	2.8	m/s
A8	3.0	2.9	m/s
A9	3.0	2.8	m/s
Average	3.0	2.8	m/s
Inlet Air Temp.	WB	22.5	°C
	DB	31.6	°C
Outlet Air Temp.	WB	19.1	°C
	DB	24.8	°C

Coil ID/Number		6	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	3.5	3.3	m/s
A2	3.5	3.3	m/s
A3	3.5	3.3	m/s
A4	3.4	3.3	m/s
A5	3.4	3.3	m/s
A6	3.5	3.3	m/s
A7	3.5	3.3	m/s
A8	3.5	3.4	m/s
A9	3.4	3.3	m/s
Average	3.5	3.3	m/s
Inlet Air Temp.	WB	22.6	°C
	DB	31.6	°C
Outlet Air Temp.	WB	18.9	°C
	DB	24.8	°C

Coil ID/Number		7	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	4.3	4.2	m/s
A2	4.4	4.2	m/s
A3	4.4	4.2	m/s
A4	4.3	4.1	m/s
A5	4.4	4.2	m/s
A6	4.3	4.2	m/s
A7	4.3	4.2	m/s
A8	4.4	4.2	m/s
A9	4.4	4.2	m/s
Average	4.4	4.2	m/s
Inlet Air Temp.	WB	22.4	°C
	DB	31.3	°C
Outlet Air Temp.	WB	19.2	°C
	DB	24.7	°C

Coil ID/Number		8	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	5.6	5.4	m/s
A2	5.6	5.4	m/s
A3	5.6	5.4	m/s
A4	5.6	5.4	m/s
A5	5.6	5.4	m/s
A6	5.6	5.4	m/s
A7	5.6	5.4	m/s
A8	5.6	5.3	m/s
A9	5.6	5.3	m/s
Average	5.6	5.4	m/s
Inlet Air Temp.	WB	22.6	°C
	DB	31.6	°C
Outlet Air Temp.	WB	19.1	°C
	DB	24.7	°C

- **3. Case Study 2 - 45L Initial Measurements**

Location	Measurement		Reading	Unit
1. (Inlet Airflow)	Haulage Area		14.4	m^2
	Air Velocity		3.7	m/s
	Barometric Pressure		121.5	kPa
	Air Temperature	WB	25.0	°C
		DB	27.0	°C
2. (Middle Sector)	Haulage Area		16.4	m^2
	Air Velocity		3.2	m/s
	Barometric Pressure		122.3	kPa
	Air Temperature	WB	25.4	°C
		DB	27.9	°C
3. (Outlet Airflow)	Haulage Area		16.7	m^2
	Air Velocity		3.0	m/s
	Barometric Pressure		121.4	kPa
	Air Temperature	WB	24.0	°C
		DB	25.0	°C
4. Water Flow	Cold Supply Water	Quant	33.6	l/s
		Temp.	11.6	°C
	Hot Supply Water	Quant	33.6	l/s
		Temp.	14.0	°C
5. Finned-Tube Coils	Coil ID/Number		1	
	Position	Inlet Air Velocity	Outlet Air Velocity	
	A1	0.6	0.6	m/s
	A2	0.6	0.6	m/s
	A3	0.6	0.6	m/s
	A4	0.6	0.6	m/s
	A5	0.6	0.6	m/s
	A6	0.6	0.6	m/s
	A7	0.6	0.6	m/s
	A8	0.6	0.6	m/s
	A9	0.6	0.6	m/s
	Average	0.6	0.6	m/s
	Inlet Air Temp.	WB	25.5	°C
		DB	28.5	°C
	Outlet Air Temp.	WB	20.5	°C
		DB	23.5	°C
	Coil Notes: All the coils were used and visibly fouled on the outside. The area of the coil is 1.8 m2. Coils #1 to #4 were moderatly to severly damaged on the air inlet side. A major air leak was noticed at the bottom of the BAC.			

Coil ID/Number		2	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	1.3	1.2	m/s
A2	1.3	1.2	m/s
A3	1.3	1.2	m/s
A4	1.3	1.2	m/s
A5	1.3	1.2	m/s
A6	1.3	1.2	m/s
A7	1.3	1.2	m/s
A8	1.3	1.2	m/s
A9	1.3	1.2	m/s
Average	1.3	1.2	m/s
Inlet Air Temp.	WB	26.0	°C
	DB	29.0	°C
Outlet Air Temp.	WB	21.0	°C
	DB	21.5	°C

Coil ID/Number		3	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	0.6	0.6	m/s
A2	0.6	0.6	m/s
A3	0.6	0.6	m/s
A4	0.6	0.6	m/s
A5	0.6	0.6	m/s
A6	0.6	0.6	m/s
A7	0.6	0.6	m/s
A8	0.6	0.6	m/s
A9	0.6	0.5	m/s
Average	0.6	0.6	m/s
Inlet Air	WB	26.0	°C
Temp.	DB	29.0	°C
Outlet Air	WB	22.0	°C
Temp.	DB	23.0	°C

Coil ID/Number		4	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	0.5	0.4	m/s
A2	0.5	0.4	m/s
A3	0.4	0.4	m/s
A4	0.5	0.4	m/s
A5	0.5	0.4	m/s
A6	0.5	0.4	m/s
A7	0.5	0.4	m/s
A8	0.5	0.4	m/s
A9	0.5	0.4	m/s
Average	0.5	0.4	m/s
Inlet Air	WB	26.0	°C
Temp.	DB	29.0	°C
Outlet Air	WB	22.0	°C
Temp.	DB	22.5	°C

Coil ID/Number		5	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	0.7	0.6	m/s
A2	0.7	0.6	m/s
A3	0.7	0.6	m/s
A4	0.7	0.6	m/s
A5	0.7	0.6	m/s
A6	0.7	0.6	m/s
A7	0.7	0.6	m/s
A8	0.7	0.6	m/s
A9	0.7	0.6	m/s
Average	0.7	0.6	m/s
Inlet Air	WB	25.5	°C
Temp.	DB	29.5	°C
Outlet Air	WB	20.0	°C
Temp.	DB	20.5	°C

Coil ID/Number		6	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	0.9	0.8	m/s
A2	0.9	0.8	m/s
A3	0.9	0.8	m/s
A4	0.9	0.8	m/s
A5	0.9	0.8	m/s
A6	0.9	0.8	m/s
A7	0.9	0.8	m/s
A8	0.9	0.8	m/s
A9	0.9	0.8	m/s
Average	0.9	0.8	m/s
Inlet Air	WB	25.5	°C
Temp.	DB	30.0	°C
Outlet Air	WB	23.5	°C
Temp.	DB	24.0	°C

Coil ID/Number		7	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	8.9	8.6	m/s
A2	8.9	8.5	m/s
A3	9.0	8.6	m/s
A4	8.9	8.7	m/s
A5	9.0	8.5	m/s
A6	9.0	8.7	m/s
A7	8.9	8.5	m/s
A8	8.9	8.7	m/s
A9	9.0	8.7	m/s
Average	8.9	8.6	m/s
Inlet Air	WB	25.0	°C
Temp.	DB	30.5	°C
Outlet Air	WB	23.5	°C
Temp.	DB	24.0	°C

Coil ID/Number		8	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	1.3	1.3	m/s
A2	1.3	1.3	m/s
A3	1.3	1.3	m/s
A4	1.3	1.3	m/s
A5	1.3	1.3	m/s
A6	1.3	1.3	m/s
A7	1.3	1.3	m/s
A8	1.3	1.3	m/s
A9	1.3	1.3	m/s
Average	1.3	1.3	m/s
Inlet Air	WB	25.0	°C
Temp.	DB	30.0	°C
Outlet Air	WB	19.5	°C
Temp.	DB	20.0	°C

Coil ID/Number		9	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	8.4	8.0	m/s
A2	8.3	8.0	m/s
A3	8.4	8.1	m/s
A4	8.4	8.0	m/s
A5	8.4	8.0	m/s
A6	8.3	8.0	m/s
A7	8.4	8.0	m/s
A8	8.3	8.0	m/s
A9	8.4	8.1	m/s
Average	8.4	8.0	m/s
Inlet Air	WB	25.0	°C
Temp.	DB	30.5	°C
Outlet Air	WB	23.5	°C
Temp.	DB	25.0	°C

Coil ID/Number		10	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	0.6	0.6	m/s
A2	0.6	0.6	m/s
A3	0.6	0.6	m/s
A4	0.6	0.6	m/s
A5	0.6	0.6	m/s
A6	0.6	0.6	m/s
A7	0.6	0.6	m/s
A8	0.6	0.6	m/s
A9	0.6	0.6	m/s
Average	0.6	0.6	m/s
Inlet Air	WB	25.0	°C
Temp.	DB	30.0	°C
Outlet Air	WB	23.0	°C
Temp.	DB	24.0	°C

- **4. Case Study 3 - 23-60L Initial Measurements**

Location	Measurement		Reading	Unit
1. (Inlet Airflow)	Haulage Area		16.3	m^2
	Air Velocity		1.5	m/s
	Barometric Pressure		103.0	kPa
	Air Temperature	WB	22.5	°C
		DB	28.5	°C
2. (Middle Sector)	Haulage Area		\	m^2
	Air Velocity		\	m/s
	Barometric Pressure		\	kPa
	Air Temperature	WB	\	°C
		DB	\	°C
3. (Outlet Airflow)	Haulage Area		2.1	m^2
	Air Velocity		11.7	m/s
	Barometric Pressure		102.8	kPa
	Air Temperature	WB	20.5	°C
		DB	24.0	°C
4. Water Flow	Cold Supply Water	Quant	10.1	l/s
		Temp.	10.8	°C
	Hot Supply Water	Quant	10.1	l/s
		Temp.	15.7	°C
5. Finned-Tube Coils	Coil ID/Number		1	
	Position	Inlet Air Velocity	Outlet Air Velocity	
	A1	3.6	3.5	m/s
	A2	3.6	3.5	m/s
	A3	3.6	3.4	m/s
	A4	3.6	3.4	m/s
	A5	3.6	3.4	m/s
	A6	3.6	3.5	m/s
	A7	3.6	3.5	m/s
	A8	3.6	3.5	m/s
	A9	3.6	3.4	m/s
	Average	3.6	3.5	m/s
	Inlet Air Temp.	WB	22.5	°C
		DB	28.5	°C
	Outlet Air Temp.	WB	19.9	°C
		DB	24.5	°C
	Coil Notes: All the coils were used and visibly fouled on the outside. The area of the coil is 2.04m2. No fans are implemented			

Coil ID/Number		2	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	4.0	3.9	m/s
A2	4.1	3.9	m/s
A3	4.0	3.8	m/s
A4	4.0	3.9	m/s
A5	4.0	3.9	m/s
A6	4.0	3.8	m/s
A7	4.0	3.9	m/s
A8	4.0	3.8	m/s
A9	4.0	3.8	m/s
Average	4.0	3.9	m/s
Inlet Air Temp.	WB	22.5	°C
	DB	28.5	°C
Outlet Air Temp.	WB	19.8	°C
	DB	24.9	°C

Coil ID/Number		3	
Position	**Inlet Air Velocity**	**Outlet Air Velocity**	
A1	4.7	4.5	m/s
A2	4.6	4.5	m/s
A3	4.6	4.5	m/s
A4	4.7	4.5	m/s
A5	4.7	4.5	m/s
A6	4.7	4.5	m/s
A7	4.6	4.5	m/s
A8	4.7	4.5	m/s
A9	4.7	4.4	m/s
Average	4.6	4.5	m/s
Inlet Air Temp.	WB	22.5	°C
	DB	28.5	°C
Outlet Air Temp.	WB	19.6	°C
	DB	24.3	°C

- **5. Case Study 4 - 45L Initial Measurements**

Location	Measurement		Reading	Unit
1a. (Inlet Airflow)	Haulage Area		7.4	m²
	Air Velocity		3.0	m/s
	Barometric Pressure		109.6	kPa
	Air Temperature	WB	27.0	°C
		DB	27.5	°C
1b. (Inlet Airflow)	Haulage Area		8.7	m²
	Air Velocity		2.6	m/s
	Barometric Pressure		109.6	kPa
	Air Temperature	WB	31.5	°C
		DB	32.5	°C
2. (Middle Sector)	Haulage Area		3.5	m²
	Air Velocity		12.7	m/s
	Barometric Pressure		110.4	kPa
	Air Temperature	WB	30.0	°C
		DB	33.0	°C
3. (Outlet Airflow)	Haulage Area		13.4	m²
	Air Velocity		3.1	m/s
	Barometric Pressure		109.6	kPa
	Air Temperature	WB	25.0	°C
		DB	26.0	°C
4. Water Flow	Cold Supply Water	Quant	36.0	l/s
		Temp.	10.1	°C
	Hot Supply Water	Quant	36.0	l/s
		Temp.	17.3	°C
5. Finned-Tube Coils	Coil ID/Number		1	
	Position	Inlet Air Velocity	Outlet Air Velocity	
	A1	6.2	6.0	m/s
	A2	6.2	5.9	m/s
	A3	6.2	5.9	m/s
	A4	6.2	6.0	m/s
	A5	6.1	5.9	m/s
	A6	6.2	5.9	m/s
	A7	6.2	5.9	m/s
	A8	6.2	6.0	m/s
	A9	6.2	6.0	m/s
	Average	6.2	5.9	m/s
	Inlet Air Temp.	WB	29.4	°C
		DB	32.3	°C
	Outlet Air Temp.	WB	24.9	°C
		DB	25.5	°C
	Coil Notes: All the coils were used and visibly fouled on the outside. The area of the coil is 2.06 m2. All availibe fans were operating as one set received air directly from the RAW.			

Coil ID/Number		2	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	7.0	6.8	m/s
A2	7.0	6.8	m/s
A3	6.9	6.7	m/s
A4	7.0	6.8	m/s
A5	7.0	6.7	m/s
A6	6.9	6.7	m/s
A7	7.1	6.7	m/s
A8	7.0	6.7	m/s
A9	7.0	6.7	m/s
Average	7.0	6.7	m/s
Inlet Air Temp.	WB	29.6	°C
	DB	32.5	°C
Outlet Air Temp.	WB	24.1	°C
	DB	25.3	°C

Coil ID/Number		3	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	4.2	4.0	m/s
A2	4.2	4.0	m/s
A3	4.2	4.0	m/s
A4	4.3	4.1	m/s
A5	4.2	4.0	m/s
A6	4.2	4.1	m/s
A7	4.2	4.1	m/s
A8	4.2	4.0	m/s
A9	4.2	4.0	m/s
Average	4.2	4.1	m/s
Inlet Air Temp.	WB	29.4	°C
	DB	32.1	°C
Outlet Air Temp.	WB	24.1	°C
	DB	25.8	°C

Coil ID/Number		4	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	2.7	2.6	m/s
A2	2.7	2.6	m/s
A3	2.7	2.6	m/s
A4	2.8	2.7	m/s
A5	2.7	2.6	m/s
A6	2.7	2.6	m/s
A7	2.8	2.6	m/s
A8	2.7	2.6	m/s
A9	2.7	2.6	m/s
Average	2.7	2.6	m/s
Inlet Air Temp.	WB	29.9	°C
	DB	32.5	°C
Outlet Air Temp.	WB	24.6	°C
	DB	25.2	°C

Coil ID/Number		5	
Position	Inlet Air Velocity	Outlet Air Velocity	
A1	2.1	2.0	m/s
A2	2.1	2.0	m/s
A3	2.1	2.0	m/s
A4	2.1	2.0	m/s
A5	2.1	2.0	m/s
A6	2.1	2.0	m/s
A7	2.1	2.0	m/s
A8	2.1	2.0	m/s
A9	2.1	2.0	m/s
Average	2.1	2.0	m/s
Inlet Air Temp.	WB	28.9	°C
	DB	32.5	°C
Outlet Air Temp.	WB	24.8	°C
	DB	25.8	°C

v. Appendix AE

1. Case Study 1 – 39L Initial Calculations

Description	Unit	Value
Bulk air cooler design duty	kW	2000
Air inlet conditions (A)		
Fan size (1)+(2)+(3)+(...)	kW	111.0
Air temperature WB	°C	22.0
Air temperature DB	°C	30.5
Barometric pressure	kPa	118.6
Air velocity	m/s	3.7
Cross sectional area	m^2	17.5
Air outlet conditions (B)		
Air temperature WB	°C	20.5
Air temperature DB	°C	27.0
Barometric pressure	kPa	118.6
Air velocity	m/s	22.8
Cross sectional area	m^2	2.2
Air results		
Average air density	kg/m3	1.3
Average air flow	m3/s	56.8
Air mass flow	kg/s	76.4
Cooling duty air	kW	358.1
Cooling duty BAC	kW	469.1
Air circuit efficiency	%	17.9
Water inlet conditions (C)		
Water temperature in	°C	11.1
Measure/estimated water flow rate	l/s	27.1
Water outlet conditions (D)		
Water temperature out	°C	15.6
Measure/estimated water flow rate	l/s	27.1
Water results		
Measure/estimated water flow rate	l/s	27.1
Cooling duty	kW	511.2
Water circuit efficiency	%	25.6
Calculated water flow rate	l/s	18.9
Checks		
Air duty vs water duty	kW	42.1
Air duty vs water duty	%	9.0

Coil No.	Air velocity	Massflow	Air in		Air out		Cooling duty (adjsuted)
			Wet Bulb (°C)	Dry Bulb (°C)	Wet Bulb (°C)	Dry Bulb (°C)	
	(m/s)	(kg/s)	(°C)	(°C)	(°C)	(°C)	(kW)
1	1.4	3.4	21.8	30.4	20.6	27.0	28.4
2	1.5	3.6	22.4	30.8	20.2	27.5	30.5
3	1.6	3.9	21.8	31.0	20.8	27.4	32.5
4	1.5	3.6	21.9	30.0	20.5	27.1	30.5
5	2.4	5.8	21.8	30.0	20.7	26.5	48.7
6	3.3	8.0	21.8	29.9	20.8	26.5	67.0
7	4.9	11.9	22.3	30.9	20.2	27.4	99.5
8	6.5	15.7	22.2	31.0	20.2	26.7	132.0
9	Leak	20.46					
	Coil Total	56.0				Total cooling (kW)	469.1
	Calc T. Total	76.4					

2. Case Study 1 – 39L Re-audit Calculations

Description	Unit	Value
Bulk air cooler design duty	kW	2000
Air inlet conditions (A)		
Fan size (1)+(2)+(3)+(...)	kW	74.0
Air temperature WB	°C	22.5
Air temperature DB	°C	31.5
Barometric pressure	kPa	117.3
Air velocity	m/s	3.1
Cross sectional area	m^2	17.5
Air outlet conditions (B)		
Air temperature WB	°C	19.0
Air temperature DB	°C	24.7
Barometric pressure	kPa	117.3
Air velocity	m/s	23.2
Cross sectional area	m^2	2.2
Air results		
Average air density	kg/m3	1.3
Average air flow	m3/s	52.645
Air mass flow	kg/s	70.27
Cooling duty air	kW	760.8
Cooling duty BAC	kW	834.8
Air circuit efficiency	%	38.0
Water inlet conditions (C)		
Water temperature in	°C	7.5
Measure/estimated water flow rate	l/s	45.7
Water outlet conditions (D)		
Water temperature out	°C	12.2
Measure/estimated water flow rate	l/s	45.7
Water results		
Measure/estimated water flow rate	l/s	45.7
Cooling duty	kW	902.1
Water circuit efficiency	%	45.1
Calculated water flow rate	l/s	38.5
Checks		
Air duty vs water duty	kW	67.3
Air duty vs water duty	%	8.1

Coil No.	Air velocity	Mass flow	Air in		Air out		Cooling duty (adjsuted)
			Wet Bulb (°C)	Dry Bulb (°C)	Wet Bulb (°C)	Dry Bulb (°C)	
	(m/s)	(kg/s)	(°C)	(°C)	(°C)	(°C)	(kW)
1	2.7	6.5	22.5	31.4	19.0	24.9	82.0
2	2.6	6.2	22.3	31.3	19.0	24.9	78.9
3	1.9	4.6	22.5	31.5	18.9	24.8	57.7
4	2.4	5.8	22.7	31.6	18.9	24.8	72.9
5	2.9	7.0	22.5	31.6	19.1	24.8	88.0
6	4.3	10.3	22.6	31.6	18.9	24.8	130.5
7	4.9	11.8	22.4	31.3	19.2	24.7	148.7
8	5.5	13.2	22.6	31.6	19.6	24.7	167.0
9	Leak	4.92					
	Coil Total	65.4				Total cooling (kW)	825.7
	Calc T. Total	70.3					

- **3. Case Study 2 – 45L Initial Calculations**

Description	Unit	Value
Bulk air cooler design duty	kW	1500
Air inlet conditions (A)		
Fan size (1)+(2)+(3)+(...)	kW	111.0
Air temperature WB	°C	25.0
Air temperature DB	°C	27.0
Barometric pressure	kPa	121.5
Air velocity	m/s	3.7
Cross sectional area	m^2	14.4
Air outlet conditions (B)		
Air temperature WB	°C	24.0
Air temperature DB	°C	25.5
Barometric pressure	kPa	121.4
Air velocity	m/s	3.0
Cross sectional area	m^2	16.7
Air results		
Average air density	kg/m3	1.4
Average air flow	m3/s	51.55
Air mass flow	kg/s	71.09
Cooling duty air	kW	248.0
Cooling duty BAC	kW	359.0
Air circuit efficiency	%	16.5
Water inlet conditions (C)		
Water temperature in	°C	11.6
Measure/estimated water flow rate	l/s	33.6
Water outlet conditions (D)		
Water temperature out	°C	14.0
Measure/estimated water flow rate	l/s	33.6
Water results		
Measure/estimated water flow rate	l/s	33.6
Cooling duty	kW	340.1
Water circuit efficiency	%	22.7
Calculated water flow rate	l/s	24.5
Checks		
Air duty vs water duty	kW	18.9
Air duty vs water duty	%	5.3

Coil No.	Air velocity	Mass flow	Air in		Air out		Cooling duty (adjsuted)
			Wet Bulb (°C)	Dry Bulb (°C)	Wet Bulb (°C)	Dry Bulb (°C)	
	(m/s)	(kg/s)	(°C)	(°C)	(°C)	(°C)	(kW)
1	0.6	1.5	25.5	28.5	20.5	23.5	9.3
2	1.3	3.2	26.0	29.0	21.0	21.5	20.1
3	0.6	1.5	26.0	29.0	22.0	23.0	9.3
4	0.4	1.0	26.0	29.0	22.0	22.5	6.2
5	0.6	1.5	25.5	29.5	20.0	20.5	9.3
6	0.8	2.0	25.5	30.0	23.5	24.0	12.4
7	8.8	21.8	25.0	30.5	23.5	24.0	136.2
8	1.3	3.2	25.0	30.0	19.5	20.0	20.1
9	8.2	20.4	25.0	30.5	23.5	25.0	126.9
10	0.6	1.5	25.0	30.0	23.0	24.0	9.3
11	Leak	13.50					
	Coil Total	57.6				Total cooling (kW)	359.0
	Calc T. Total	71.1					

- **4. Case Study 3 – 23-60L Initial Calculations**

Description	Unit	Value
Bulk air cooler design duty	kW	1500
Air inlet conditions (A)		
Fan size (1)+(2)+(3)+(...)	kW	0.0
Air temperature WB	°C	22.5
Air temperature DB	°C	28.5
Barometric pressure	kPa	103.0
Air velocity	m/s	1.5
Cross sectional area	m^2	16.3
Air outlet conditions (B)		
Air temperature WB	°C	20.5
Air temperature DB	°C	24.0
Barometric pressure	kPa	102.8
Air velocity	m/s	11.7
Cross sectional area	m^2	2.1
Air results		
Average air density	kg/m3	1.17
Average air flow	m3/s	24.20
Air mass flow	kg/s	28.35
Cooling duty air	kW	196.47
Cooling duty BAC	kW	196.47
Air circuit efficiency	%	13.10
Water inlet conditions (C)		
Water temperature in	°C	10.8
Measure/estimated water flow rate	l/s	10.1
Water outlet conditions (D)		
Water temperature out	°C	15.7
Measure/estimated water flow rate	l/s	10.1
Water results		
Measure/estimated water flow rate	l/s	10.1
Cooling duty	kW	207.4
Water circuit efficiency	%	13.8
Calculated water flow rate	l/s	9.5
Checks		
Air duty vs water duty	kW	10.9
Air duty vs water duty	%	5.5

Coil No.	Air velocity	Mass flow	Air in		Air out		Cooling duty (adjsuted)
			Wet Bulb (°C)	Dry Bulb (°C)	Wet Bulb (°C)	Dry Bulb (°C)	
	(m/s)	(kg/s)	(°C)	(°C)	(°C)	(°C)	(kW)
1	3.5	8.5	22.5	28.5	19.9	24.5	57.4
2	3.9	9.5	22.5	28.5	19.8	24.9	64.1
3	4.6	11.1	22.5	28.5	19.6	24.3	74.9
4	Leak						
	Coil Total	29.1				Total cooling (kW)	196.5
	Calc T. Total	28.3					

- **5. Case Study 4 – 32L Initial Calculations**

Description	Unit	Value
Bulk air cooler design duty	kW	2500
Air inlet conditions (A)		
Fan size (1)+(2)+(3)+(...)	kW	0.0
Air temperature WB	°C	30.0
Air temperature DB	°C	33.0
Barometric pressure	kPa	110.4
Air velocity	m/s	12.7
Cross sectional area	m^2	3.5
Air outlet conditions (B)		
Air temperature WB	°C	25.0
Air temperature DB	°C	26.0
Barometric pressure	kPa	109.6
Air velocity	m/s	3.1
Cross sectional area	m^2	13.4
Air results		
Average air density	kg/m3	1.23
Average air flow	m3/s	43.00
Air mass flow	kg/s	52.69
Cooling duty air	kW	1118.76
Cooling duty BAC	kW	1118.76
Air circuit efficiency	%	44.75
Water inlet conditions (C)		
Water temperature in	°C	10.1
Measure/estimated water flow rate	l/s	36.0
Water outlet conditions (D)		
Water temperature out	°C	17.3
Measure/estimated water flow rate	l/s	36.0
Water results		
Measure/estimated water flow rate	l/s	36.0
Cooling duty	kW	1088.6
Water circuit efficiency	%	43.5
Calculated water flow rate	l/s	37.0
Checks		
Air duty vs water duty	kW	30.1
Air duty vs water duty	%	2.7

Coil No.	Air velocity	Mass flow	Air in		Air out		Cooling duty (adjsuted)
			Wet Bulb (°C)	Dry Bulb (°C)	Wet Bulb (°C)	Dry Bulb (°C)	
	(m/s)	(kg/s)	(°C)	(°C)	(°C)	(°C)	(kW)
1	6.1	15.4	29.4	32.3	24.9	25.5	313.0
2	6.9	17.4	29.6	32.5	24.1	25.3	354.1
3	4.1	10.3	29.4	31.2	24.1	25.8	210.4
4	2.7	6.8	29.9	32.5	24.6	25.2	138.6
5	2.0	5.0	28.9	32.5	24.8	25.8	102.6
6	Leak	1.0					
	Coil Total	55.0				Total cooling (kW)	1118.8
	Calc T. Total	52.7					

The respective duties of the coils were calculated and adjusted after a normalised factor of the respective air flows were multiplied with the overall duty of the BAC. Due to the limiting capabilities of the instrumentation, this rational was justified, as the average temperature difference along with the accuracy of the individual temperature measurements could not be verified at the localised measurement positions, as indicated by Figure 16.

vi. Appendix AF

- **1. OEM – specification 250 kW**

Date : **19 April 2023**

Type of Coil : **300kW PS 1 Type Coil for ETA**

Temperature of Water In	14.57 °C
Wet Bulb Temperature of Air In	23.97 °C
Dry Bulb Temperature of Air In	31.2 °C
Barometric Pressure	103.4 kPa

MANOS ENGINEERING (PTY.)LTD.

L (l/s)	ΔP_w (kPa)	G' / ΔP_a	3 / 102	4 / 167	5 / 247	6 / 339	7 / 443	8 / 559	9 / 687	10 / 826	m³/s / Pa
3.0	55	q	64.84	75.06	82.5	88.1	92.39	95.77	98.47	100.67	kW
		two	19.73	20.55	21.14	21.58	21.93	22.19	22.41	22.58	°C
		tao	18.41	19.21	19.83	20.32	20.72	21.04	21.3	21.53	°C
4.0	96	q	70.19	83.31	93.55	101.67	108.23	113.6	118.07	121.81	kW
		two	18.76	19.54	20.16	20.64	21.03	21.35	21.62	21.84	°C
		tao	17.89	18.63	19.23	19.71	20.12	20.45	20.74	20.98	°C
5.0	148	q	73.52	88.69	101.03	111.19	119.67	126.81	132.91	138.15	kW
		two	18.08	18.81	19.4	19.88	20.29	20.63	20.92	21.17	°C
		tao	17.56	18.25	18.81	19.28	19.67	20.01	20.3	20.55	°C
6.0	210	q	75.78	92.44	106.36	118.13	128.2	136.85	144.37	150.96	kW
		two	17.59	18.25	18.8	19.27	19.67	20.02	20.32	20.58	°C
		tao	17.34	17.97	18.5	18.95	19.34	19.67	19.96	20.21	°C
7.0	283	q	77.41	95.18	110.34	123.41	134.74	144.67	153.42	161.19	kW
		two	17.21	17.82	18.33	18.78	19.17	19.51	19.8	20.07	°C
		tao	17.18	17.77	18.28	18.71	19.08	19.4	19.69	19.94	°C
8.0	367	q	78.63	97.26	113.41	127.49	139.91	150.91	160.73	169.51	kW
		two	16.92	17.47	17.96	18.38	18.75	19.08	19.37	19.63	°C
		tao	17.05	17.62	18.1	18.51	18.87	19.18	19.46	19.71	°C
9.0	460	q	79.58	98.91	115.83	130.79	144.1	155.99	166.7	176.39	kW
		two	16.68	17.19	17.64	18.04	18.39	18.71	18.99	19.25	°C
		tao	16.96	17.5	17.96	18.35	18.7	19.01	19.28	19.52	°C
10.0	564	q	80.35	100.23	117.83	133.48	147.53	160.2	171.71	182.16	kW
		two	16.49	16.96	17.38	17.76	18.09	18.4	18.67	18.92	°C
		tao	16.88	17.4	17.84	18.22	18.56	18.86	19.12	19.36	°C

L = Water flow in l/s
ΔPw = Water pressure drop in kPa
G' = Air flow in m3/s
ΔPa = Air pressure drop in Pa
q = Duty of coil in kW
two = Temperature of water leaving coil
tao = Temperature of air leaving coil

- **2. OEM – Specification 500 kW**

Date : **19 April 2023**

Type of Coil : **500kW ZEUS Type Coil for ETA**

MANOS ENGINEERING (PTY.)LTD.

Temperature of Water In	*14.57*	*°C*
Wet Bulb Temperature of Air In	*23.97*	*°C*
Dry Bulb Temperature of Air In	*31.2*	*°C*
Barometric Pressure	*103.4*	*kPa*

L (l/s)	ΔP_w (kPa)	G'▸ / ΔP_a▸	8 / 251	9 / 308	10 / 370	11 / 437	12 / 508	13 / 584	14 / 665	15 / 750	m³/s / Pa
7.0	100	q	145.33	154.29	162.22	169.33	175.7	181.45	186.65	191.38	kW
		two	19.53	19.83	20.1	20.35	20.56	20.76	20.94	21.1	°C
		tao	19.38	19.66	19.91	20.13	20.34	20.52	20.68	20.83	°C
8.0	130	q	151.48	161.49	170.46	178.57	185.93	192.61	198.73	204.33	kW
		two	19.09	19.39	19.66	19.9	20.12	20.32	20.5	20.67	°C
		tao	19.17	19.44	19.69	19.91	20.11	20.29	20.45	20.61	°C
9.0	163	q	156.47	167.38	177.26	186.26	194.47	202.02	208.94	215.32	kW
		two	18.72	19.01	19.27	19.51	19.73	19.93	20.11	20.28	°C
		tao	18.99	19.26	19.5	19.72	19.91	20.09	20.26	20.41	°C
10.0	199	q	160.6	172.28	182.95	192.71	201.71	209.99	217.64	224.75	kW
		two	18.41	18.68	18.94	19.17	19.39	19.59	19.77	19.94	°C
		tao	18.84	19.11	19.34	19.56	19.75	19.93	20.09	20.24	°C
11.0	240	q	164.07	176.43	187.75	198.23	207.87	216.83	225.15	232.91	kW
		two	18.13	18.4	18.65	18.87	19.08	19.28	19.46	19.63	°C
		tao	18.72	18.98	19.21	19.42	19.61	19.79	19.95	20.1	°C
12.0	283	q	167.01	179.96	191.9	202.96	213.22	222.78	231.7	240.04	kW
		two	17.89	18.15	18.39	18.61	18.81	19	19.18	19.35	°C
		tao	18.62	18.87	19.09	19.3	19.49	19.66	19.82	19.97	°C
13.0	331	q	169.54	183.01	195.49	207.09	217.89	227.98	237.45	246.33	kW
		two	17.68	17.93	18.16	18.37	18.57	18.76	18.93	19.1	°C
		tao	18.53	18.77	18.99	19.2	19.38	19.55	19.71	19.86	°C
14.0	381	q	171.75	185.66	198.62	210.7	221.98	232.56	242.5	251.86	kW
		two	17.5	17.74	17.96	18.16	18.36	18.54	18.71	18.87	°C
		tao	18.45	18.69	18.9	19.1	19.29	19.46	19.61	19.76	°C

L = Water flow in l/s
ΔPw = Water pressure drop in kPa
G'▸ = Air flow in m3/s
ΔPa▸ = Air pressure drop in Pa
q = Duty of coil in kW
two = Temperature of water leaving coil
tao = Temperature of air leaving coil

vii. Appendix AG

- **1. Case Study 1 – Initial images**

- **2. Case Study 2 – Initial images**

- **3. Case Study 3 – Initial images**

- **4. Case Study 4 – Initial images**

viii. Appendix AH

- **Case Study 1 – Simulation 1 (Re-audit calibration)**

Table 24: Case Study 1 Operating Variable Comparison – Re-measured- vs Simulation

Operating variable		BAC Inlet		BAC Outlet		
		Measured / Calc. tool	Sim. 1 - Actual	Measure/ Calc. tool	Sim. 1 - Actual	Avg. error
Air	WB temp.	22.5 °C	22.5 °C	19.0 °C	18.8 °C	1%
	DB temp.	31.5 °C	31.5 °C	24.7 °C	24.4 °C	1%
	Mass flow	70.3 kg/s	69.6 kg/s	70.3 kg/s	69.6 kg/s	1%
Water	Temp.	7.5 °C	7.4 °C	12.2 °C	11.8 °C	3%
	Mass flow	45.7 L/s	45.7 L/s	45.7 L/s	45.7 L/s	0%
Fouling	UA factor (Avg. coil)	/	0.48	/	0.48	/
Performance		/	/	834.8 kW	825.7 kW	1

- **Case Study 2 – Simulation 1 (Re-audit calibration)**

Table 25: Case Study 2 Operating Variable Comparison – Re-measured- vs Simulation

Operating Variable		BAC Inlet		BAC Outlet		
		Measured / Calc. tool	Sim. 1 - Actual	Measure/ Calc. tool	Sim. 1 - Actual	Avg. error
Air	WB temp.	24.5 °C	24.5 °C	22.5 °C	22.3 °C	1%
	DB temp.	28.0 °C	28.0 °C	25.1 °C	24.9 °C	1%
	Mass flow	88.6 kg/s	88.5 kg/s	88.6 kg/s	88.5 kg/s	0%

Water	Temp.	10.4 °C	10.4 °C	13.2 °C	13.5 °C	2%
	Mass flow	56.5 L/s	56.5 L/s	56.5 L/s	56.5 L/s	0%
Fouling	UA factor (Avg. coil)	/	0.28	/	0.28	/
Performance		/	/	709.1 kW	708.6 kW	0

- **Case Study 3 – Simulation 1 (Re-audit calibration)**

Table 26: Case Study 3 Operating Variable Comparison – Re-measured- vs Simulation

		BAC Inlet		BAC Outlet		
Operating variable		Measured / Calc. tool	Sim. 1 - Actual	Measure/ Calc. tool	Sim. 1 - Actual	Avg. error
Air	WB temp.	25.6 °C	25.6 °C	22.5 °C	22.6 °C	0%
	DB temp.	30.4 °C	30.4 °C	25.0 °C	25.4 °C	2%
	Mass flow	28.0 kg/s	27.2 kg/s	28.0 kg/s	27.2 kg/s	3%
Water	Temp.	10.9 °C	10.9 °C	13.1 °C	11.1 °C	15%
	Mass flow	33.9 L/s	33.9 L/s	33.9 L/s	33.9 L/s	0%
Fouling	UA factor (Avg. coil)	/	0.43	/	0.43	/
Performance		/	/	338.8 kW	318.0 kW	6 %

- **Case Study 4 – Simulation 1 (Re-audit calibration)**

Table 27: Case study 4 Operating Variable Comparison – Re-measured- vs Simulation

	BAC Inlet	BAC Outlet	

Operating variable		Measured / Calc. tool	Sim. 1 - Actual	Measure/ Calc. tool	Sim. 1 - Actual	Avg. error
Air	WB temp.	26.5 °C	26.9 °C	18.5 °C	18.6 °C	1%
	DB temp.	30.5 °C	30.4 °C	18.5 °C	18.7 °C	1%
	Mass flow	44.1 kg/s	42.5 kg/s	44.1 kg/s	42.5 kg/s	4%
Water	Temp.	7.5 °C	7.5 °C	15.3 °C	15.3 °C	0%
	Mass flow	38.0 L/s	37.9 L/s	38.0 L/s	37.9 L/s	0%
Fouling	UA factor (Avg. coil)	/	0.74	/	0.74	/
Performance		/	/	1368.8 kW	1255.3 kW	8%

ix. Appendix AI

- **Sub-step 3.1: Data gathering summary**
  - **Case Study 2**

The BAC on 45L was fitted with 4 x 37 kW fans, but only three were in operation at the time. The BAC was constructed using similar coils to Case Study 1. Instead of eight coils, Case Study 2 had 10 x 250 kW Manos FTHX-Coils that were aligned diagonally between the footwall and the hanging wall. This resulted in the design specification being set at 2 500 kW where the mine specification required a reduction to 1 500 kW due to the underground operating conditions.

Similar to Case Study 1, the purpose of Case Study 2 was to supply the half-level with cooled air. A performance concern was raised, as the air did not provide sufficient cooling to the workers deeper within the half-level. The relevant measurements regarding Case Study 2 were then taken and are referenced in Appendix AD. The general layout for Case Study 2 is confirmed in Figure 14.

- **Case Study 3**

The operating philosophy of the BAC on 23-60L was different to the conventional method, as no fans were implemented to push air through the cooling coils. Instead, the general ventilation philosophy of the half-level was used to force air through the BAC. The BAC was constructed with similar coils to Case Studies 1 and 2, except with an increase in capacity. The 3 x 500 kW Manos FTHX coils were aligned in a similar manner to Case Study 2.

The design specification for the BAC was 1 500 kW, as Shaft 2 implemented no reduction in performance specification. A performance concern was raised by Shaft 2, as workers questioned the working temperatures within the half-level. The relevant measurements regarding Case Study 3 were then taken and are referenced in Appendix AD.

- **Case Study 4**

The BAC on 32L was fitted with 4 x 45 kW fans, and all of them were operating at the time. The layout of Case Study 4 differed from Case Studies 1 and 2, as the fans were separated into two pairs to supply air from different intake areas instead of working together from one intake area. The construction of Case Study 4 was similar to Case Study 3 but used 5 x 500 kW Manos FTHX coils instead of only three. The configuration resulted in a design specification of 2 500 kW for the BAC. Additionally, Shaft 2 implemented no performance reduction, and a performance concern was raised similar to that of the previous case studies. The relevant measurements regarding Case Study 4 were then taken and are referenced in Appendix AD.

x. Appendix AJ

- **Sub-step 3.2: First-principle calculations summary**

  - **Case study 2**

An operational capacity of 360 kW was calculated for the BAC of Case Study 2. After the initial energy input of the force fans, only 248 kW was available for cooling the air deeper within the working level. The BAC had an operational efficiency of 24%, given the mine specification of 1 500 kW. The fans provided the BAC with a total of 71 kg/s of air where only 57.5 kg/s of air passed through the cooling-coils. This resulted in an air leak of 19%.

Given the difference between the water and air temperatures, 5% was calculated as the water duty equated to 340 kW and the air duty equated to 360 kW respectively. Additionally, the lowest performing coil had a duty of 6 kW where the coil with the highest performance had a duty of 136 kW.

The respective water and air duties confirmed an accuracy of 95% for the overall measurements and ensured compliance with the sub-criteria that were set out by Section 2.2.2. The results, as provided by the calculation tool for Case Study 2, are summarised in Appendix AE.

- **Case Study 3**

The results from the calculation tool indicated that the BAC had an operational capacity of 196 kW. Due to the operational philosophy of no fans, a total of 196 kW was available for cooling of the ventilation air. The BAC had a mine specification of 1 500 kW, indicating an operational efficiency of 13%. From the measurements, it was calculated that a total of 29 kg/s of air passed through the BAC, which equated to the same total air passing through the individual coils. This indicated that the BAC had no inherent air leaks.

From the measurements, a total difference of 6% in heat transfer between the working fluids was calculated. The coils had an average performance of around 65 kW.

The respective water and air duties confirmed an accuracy of 95% for the overall measurements and ensured compliance with the sub-criteria that were set out in Section 2.2.2. The results are summarised in Appendix AE.

- **Case Study 4**

The calculation tool determined that the BAC had an operational capacity of 1 119 kW. The approach used for the calculation tool regarding Case Study 4 was similar to Case Study 3, where the incorporation of the fans was excluded. This was done due to the relative distance between the BAC and the respective fans, as the temperature measurements at 2, as indicated by Figure 29, incorporated the increase in air temperature caused by the kinetic energy transfer of the fans. Given the mine specification of 2 500 kW, the BAC had an operational efficiency of 44.8%. The calculation tool indicated no air leaks, as the total amount of air passing through the BAC equated to the total amount of air passing through the individual coils.

An accuracy of 97% for the overall measurements confirmed that the BAC's water and air duty differed by 3%. The results complied with the sub-criteria set out in Section 2.2.2. The calculation tool for Case Study 4 is summarised in Appendix AE.

xi. Appendix AK

- **Sub-step 3.4: Gap analysis summary (Initial)**
  - **Case Study 2**

After the consideration of Figure 37 and Figure 38, it was also found that fouling, water, and air flow were the operating variables with the most influence on BAC operation. Fouling was the leading cause of reduced performance and had an 82% influence on the BAC.

The air flow operating variable was responsible for 15% of reduced performance. This was caused by a 13.5 kg/s air leak at the bottom of the BAC, as indicated by Figure 31. During the audit, the inlet area of the four topmost coils bordering the hanging was significantly externally damaged, resulting in additional limiting air flow through the BAC. Images of the relevant coils can be seen in Appendix AG.

The water flow had a 3% influence, as the OEM specification required 65 L/s, while the BAC received only 34 L/s at the time.

Similar to Case Study 1, the measured water temperature supplied to the BAC was less than the OEM specification, and the RH of the inlet air did not change; both had a 0% influence on the BAC operations.

- **Case Study 3**

The gap analysis, based on Figure 39 and Figure 40, indicated that fouling was the primary cause of reduced BAC performance and had an 89% influence. To a far lesser but still influential effect were the respective water and air flow operating variables.

Water flow had a 7% influence, as the OEM supplications required that the water quantity be increased from 10.1 L/s to 31.5 L/s. The 68% increase in water quantity had a lesser effect than expected and was limited due to the amount of air flow through the BAC.

The air flow only had a 4% influence on the performance of the BAC, as the coils were externally dirty. Even though the coils could handle an average of 30% increase in air flow, the operating philosophy of not implementing force fans was seen as a major drawback in increasing cooling from the BAC. Images regarding Case Study 3 can be seen in Appendix AG.

Similar to Case Studies 1 and 2, the measured water temperature was less than the OEM specification. Both the water temperature and a 6% difference to the RH of the inlet air had 0% influence on the BAC operations.

- **Case Study 4**

The gap analysis based on Figure 41 and Figure 42 revealed that fouling and the water flow were the only two operating variables reducing the performance of the BAC. Fouling had an 85% influence, and was considered as the leading cause, whereas the water flow only had a 15% influence.

Case Study 4 was operating, comparatively, closest to the achievable duty, as only two operating variables were limiting the operation. As with the preceding case studies, the coils were externally fouled, and the water quantity for BAC was required by the OEM specifications to increase by 31% in total. Images regarding Case Study 3 can be seen in Appendix AG.

xii. Appendix AL

- **Sub-step 3.5: Corrective measures**

- **Case Study 2**

- **Fouling influence = 82%**

    - Corrective measure:
        - Chemically rinse and flush coils.
    - Implemented:
        - Mine A only used high-pressure water to rinse and flush the coils.

- **Air flow = 15%**

    - Corrective measure:
        - Due to the extent of the external damage, 4x coils with the lowest performance must be removed, replaced or refurbished, and all air leaks should be closed off as far as practically possible.
        - Given the mine-speciation, current operation and the capacity of the coils, the BAC could operate more efficiently with 8x instead of 10x coils. Hence, 2x coils could be removed.

- Implemented:
    - Mine A partially closed off the air leaks, removed 2x of the severely damaged coils bordering the hanging wall and replaced the 2x worst-performing coils on the footwall with refurbished coils.

- **Water flow = 3%**

    - Corrective measure:
        - Increase the supply water flow to the BAC to 65 L/s.
    - Implemented:
        - Mine A increased the water flow within the operational justification of the upstream infrastructure.

- **Water- and Air temperature = 0%**

    - Corrective measure:
        - The water temperature could be ≤ 11.6 °C but not more, seeing that the measured water temperature was already less than the OEM specifications.
        - Lowering the RH of the supply air would allow the BAC to better utilise the relation between the sensible and latent heat, thereby increasing the operational efficiency.
    - Implemented:
        - Mine A supplied the BAC with water colder than initially measured.
        - The inlet air temperature was considered as measured during the audit.

- **Case Study 3**

- **Fouling influence = 89%**

    - Corrective measure:
        - Chemically rinse and flush coils.
    - Implemented:
        - Mine A used high-pressure water to rinse and flush the coils.

- **Water flow = 7%**

  - Corrective measure:
    - Increase the supply water flow to the BAC to 31.5 L/s.
  - Implemented:
    - Mine A increased the water flow within the operational justification of the upstream infrastructure.
    - Additionally, Mine A closed the water supply to the 1x coil on the footwall, thereby increasing the water supply to the remaining 2x coils.

- **Air flow = 4%**

  - Corrective measure:
    - The operational philosophy of the limited air flow restricted the performance of the 500 kW coils. Therefore, given the OEM specifications, current operation and the capacity of the coils, the BAC could operate more efficiently if only 2x coils were used.
  - Implemented:
    - Mine A did not remove any coils.

- **Water and Air temperature = 0%**

  - Corrective measure:
    - The water temperature could be ≤ 10.8 °C but not more, seeing that the measured water temperature was already less than the OEM specifications.
    - Lowering the RH of the supply air would allow the BAC to better utilise the relation between the sensible and latent heat, thereby increasing the operational efficiency.
  - Implemented:
    - Mine A supplied the BAC with water that was 0.1 °C warmer that what was initially measured.
    - The inlet air temperature was considered as measured during the audit.

- **Case Study 4**

- **Fouling influence = 85%**

  - Corrective measure:
    - Chemically rinse and flush coils.
  - Implemented:
    - Mine A only used high-pressure water to rinse and flush the coils.

- **Water flow = 15%**

  - Corrective measure:
    - Increase the supply water flow to the BAC to 52.5 L/s.
  - Implemented:
    - Mine A increased the water flow marginally due to the limited operational capacity of the upstream infrastructure.

- **Air flow = 0%**

  - Corrective measure:
    - In order to keep with the redundancy procedure of the mine, 1x 45 kW could be turned off and all air leaks should be closed off as far as practically possible.
  - Implemented:
    - Mine A did ensure that 3x and not 4x 45 kW were operating.

- **Water and Air temperature = 0%**

  - Corrective measure:
    - The water temperature could be ≤ 10.1 °C but not more, seeing that the measured water temperature was already less than the OEM specifications.
    - Lowering the RH of the supply air would allow the BAC to better utilise the relation between the sensible and latent heat, thereby increasing the operational efficiency.
  - Implemented:

- Mine A supplied the BAC with water colder than what was initially measured.
- The RH of inlet air temperature was reduced, as the mine closed the return airway that was initially open and supplied the BAC with hot, humid air.

xiii. Appendix AM

- **Sub-step 3.3: Simulations summary**
  - **Case Study 2**

The inlet operating variables for the "Achievable" simulation were adjusted accordingly and are represented in Table 28.

Table 28: Case Study 2 Re-audit Sim. 1 "Actual" vs. Re-audit Sim. 2 "Achievable"

Operating variable		Sim. 1 - Actual	Mine A specification	Sim. 2 - Achievable
Air	WB temp.	24.5 °C	24.0 °C	24.0 °C
	DB temp.	28.0 °C	28.0 °C	28.0 °C
	Mass flow	88.5 kg/s	126.9 kg/s	126.9 kg/s
Water	Temp.	10.4 °C	11.6 °C	10.4 °C
	Mass flow	56.5 L/s	52 L/s	56.5 L/s
Fouling	UA factor	0.28	0.8	0.8
Performance		708.6 kW	1 500 kW	1 573.6 kW

A baseline for the "Cause" simulation was created from the results in Table 28. The respective result from Simulation 3 is summarised in Figure 55 and Figure 56.

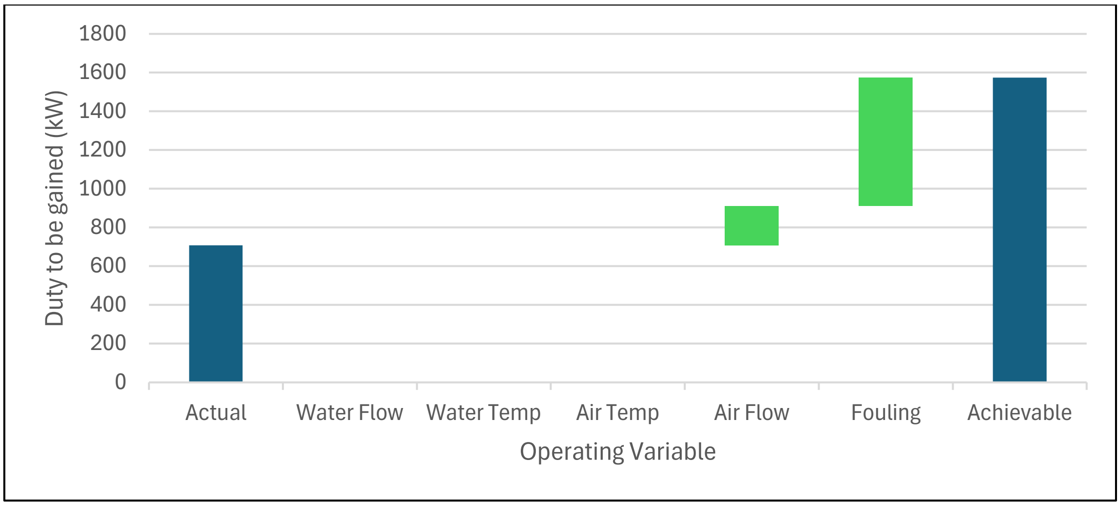


Figure 55: Case Study 2 - Waterfall Chart for Re-audit Operating Variable Influence (kW)

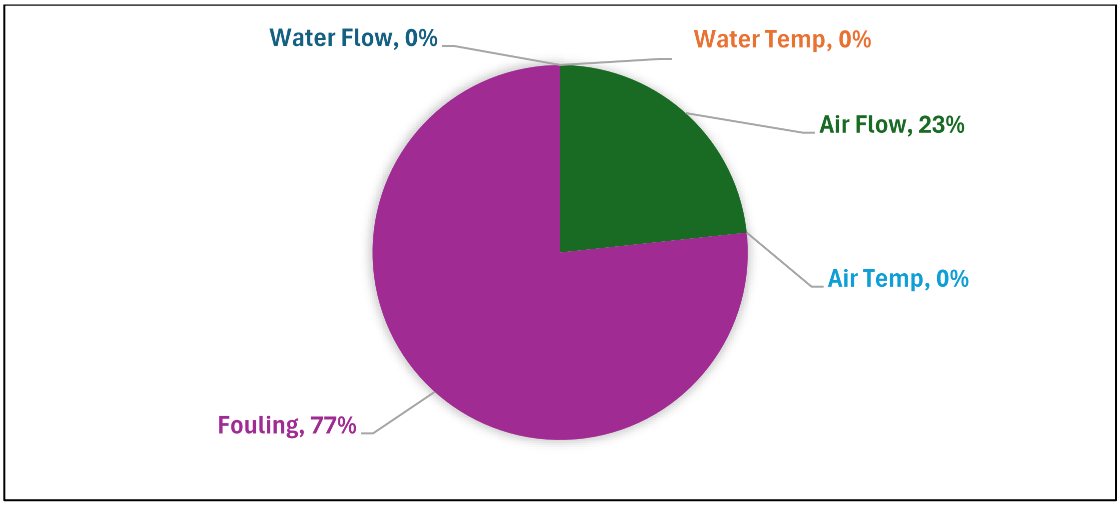


Figure 56: Breakdown of Case Study 2 - Re-audit Operating Variable Influence (%)

- **Case Study 3**

The inlet operating variables for the "Achievable" simulation were adjusted accordingly and are represented in Table 29.

Table 29: Case Study 3 Re-audit Sim. 1 "Actual" vs. Re-audit Sim. 2 "Achievable"

Operating Variable		**Sim. 1 - Actual**	**Mine A specification**	**Sim. 2 - Achievable**
Air	**WB temp.**	25.6 °C	25.0 °C	25.0 °C
	DB temp.	30.4 °C	30.0 °C	30.0 °C

	Mass Flow	27.2 kg/s	30.9 kg/s	30.9 kg/s
Water	**Temp.**	10.9 °C	10.8 °C	10.8 °C
	Mass flow	33.9 L/s	31.5 L/s	33.9 L/s
Fouling	**UA factor**	0.43	0.8	0.8
Performance		318.0 kW	1 500 kW	503.3 kW

From the results based on the inputs of Table 29 a baseline was created. the operating variable results are illustrated in Figure 57 and Figure 58.

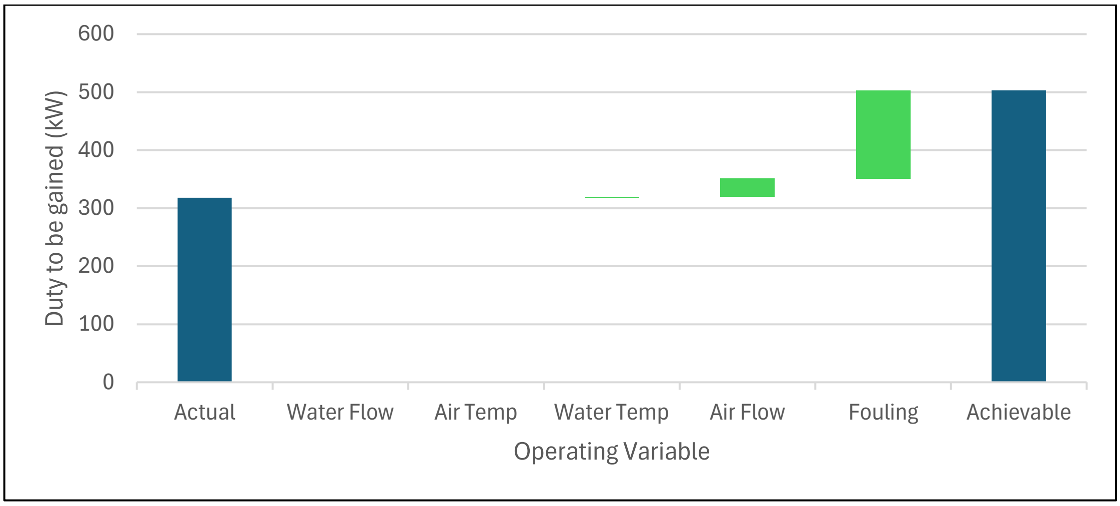


Figure 57: Case Study 3 – Waterfall Chart for Re-audit Operating Variable Influence (kW)

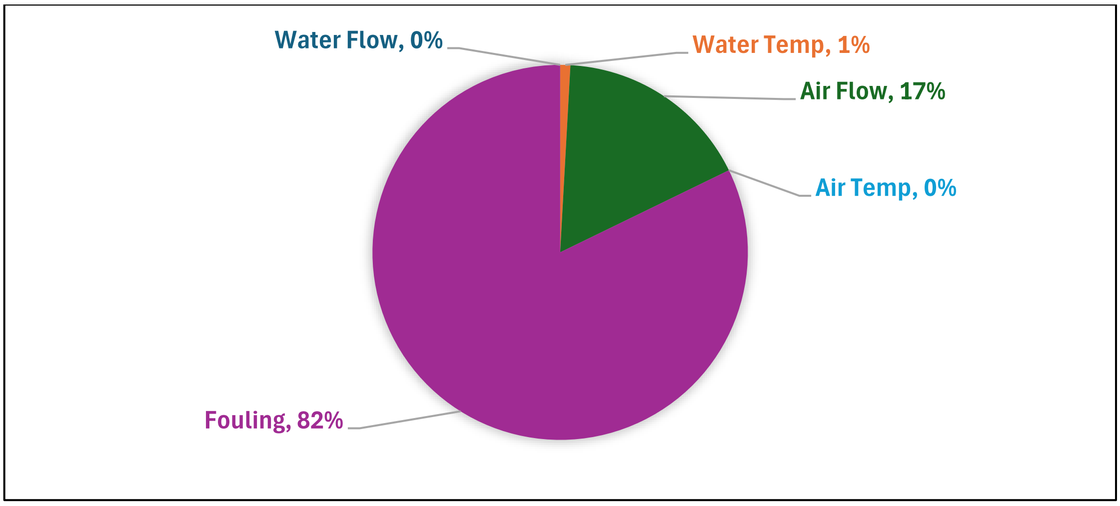


Figure 58: Case Study 3 – Breakdown of Re-audit Operating Variable Influence (%)

- **Case Study 4**

The inlet operating variables were changed for the construction of the "Achievable" simulation and are represented in Table 30 below:

Table 30: Case Study 4 Re-audit Sim. 1 "Actual" vs. Re-audit Sim. 2 "Achievable"

Operating variable		Sim. 1 - Actual	Mine A specification	Sim. 2 - Achievable
Air	WB temp.	26.9 °C	26.0 °C	26.0 °C
	DB temp.	30.4 °C	30.0 °C	30.0 °C
	Mass flow	42.5 kg/s	43.5 kg/s	43.5 kg/s
Water	Temp.	7.5 °C	10.1 °C	7.5 °C
	Mass flow	37.9 L/s	52.5 L/s	52.5 L/s
Fouling	UA factor	0.74	0.8	0.8
Performance		1 255.3 kW	2 500 kW	1 423.0 kW

From the results based on the inputs of Table 30, a baseline was created. The influence of the individual operating variables is illustrated in Figure 59 and Figure 60.

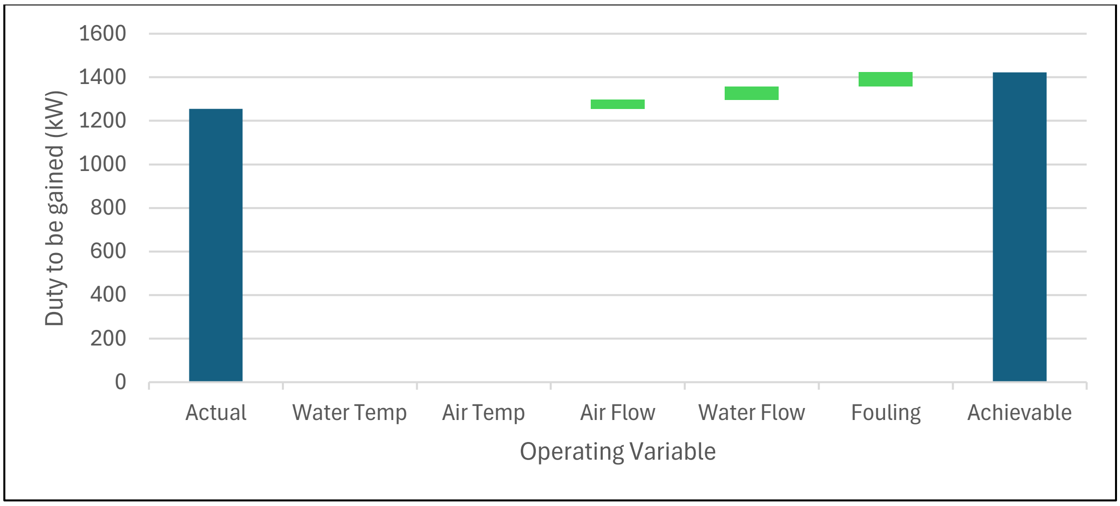


Figure 59: Case Study 4 – Waterfall Cart for Re-audit Operating Variable Influence (kW)

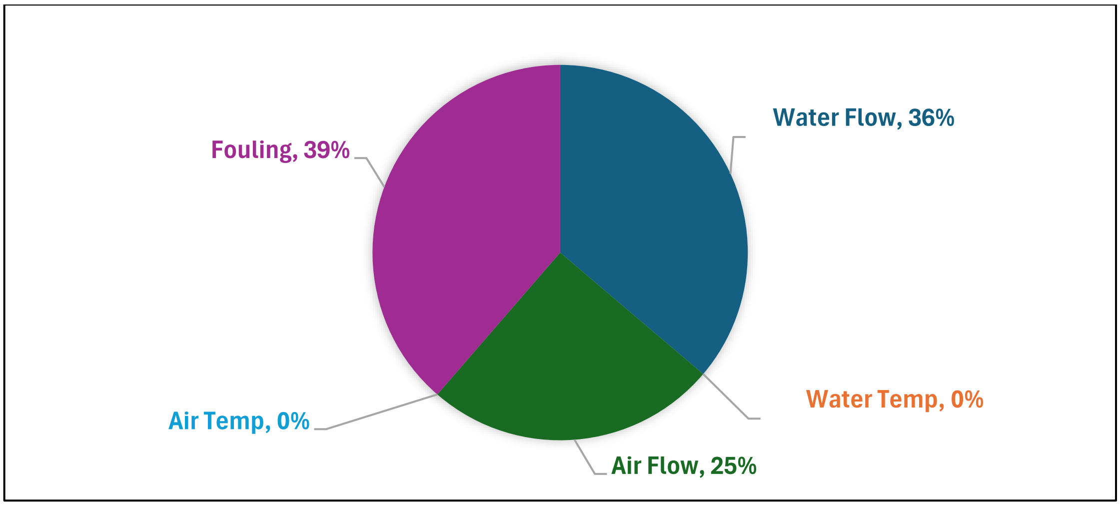


Figure 60: Case Study 4 – Breakdown of Re-audit Operating Variable Influence (%)

xiv. Appendix AN

- **Sub-step 3.4: Gap analysis summary (Re-audit)**
  - **Case Study 2**

The gap analysis commenced after cross-referencing Figure 55 and Figure 56. The results indicated that only two rather than three operating variables were responsible for reducing the performance of the BAC.

As such, after implementing the suggestions based on the insight of the initial simulations, fouling contributed 77% and air flow 23%. The decrease in the influence of fouling was attributed to the combination of cleaning the coils and replacing two of the low-performing coils. However, fouling remained the primary influencing factor, attributed to internal fouling not being sufficiently removed in the coils that were not replaced, as the coils were externally visibly clean and debris-free during the time of the audit. Due to the implementation of cleaning, the UA factor additionally increased by 32% after comparing the relevant, calibrated, "Actual" simulations and improved UA factor. After the effect of fouling was partially addressed, the initial suggestion of chemical cleaning should be implemented.

The total air flow through the BAC increased by 19 kg/s, while the negative influence of the operating variable increased by 8%. This occurrence is contradictory, as the effect, reduced BAC performance, should decrease as the quantity of air through the BAC increases. This increase in the effect of the air flow was a direct result and indication of the limited and restricted air flow through the damaged top four coils that were indicated by Figure 46.

Even with the major air leaks partially repaired and total air flow through the BAC increased, it remained imperative that the damaged coils also be replaced.

The effect of the water flow operating variable contributed 0% to the reduction in BAC performance, as the water flow increased by 22.9 L/s between audits and was simultaneously 4.5 L/s more than the respective mine specifications. The water flow operating variable, therefore, did not contribute to the reduction in performance of the BAC, as it exceeds the specification.

To a similar extent, the temperature of the supply water decreased by 1.2 °C between audits, less than the OEM specifications during the audit. Therefore, the temperature of the supply water did not contribute to the reduced performance of the BAC.

The marginal change in the RH did not contribute to reducing the performance of the BAC, as the comparative effect of the other operating variables far exceeded the marginal change in the DB and WB temperature of the inlet air towards the BAC.

- **Case Study 3**

Similar to Case Studies 1 and 2, the gap analysis occurred after cross-referencing Figure 57 and Figure 58. The results indicated that three operating variables remained the primary cause of reduced BAC performance.

The corrective suggestions were implemented by the mine and decreased fouling by 7% between the audits. This decrease was caused by the cleaning that was implemented and resulted in the UA factor increasing by 49%. The overall performance of the BAC improved due to the increase in the UA factor. Due to the fouling that was mostly responsible for 82% of the lacking performance, the initial suggestions should be reimplemented by the mine, as the rinsing and flushing of the coils with high-pressure water only partially addressed the issue.

The effect of the air flow operating variable increased by 13% and was a result of the bottom coil not contributing to the cooling capacity of the BAC. Therefore, the effect of the air flow became more prevalent. As indicated by Figure 47, the bottom coil didn't have a cooling duty, as no water was passing through the coil. This could have been seen as an "air leak" of 9.2 kg/s and did reduce the performance of the BAC. Whilst reconsidering the BAC's operational philosophy and the coils' OEM specifications, it was suggested that the bottom coil be removed entirely to minimise the effect of the air flow operational variable.

The water temperature effect increased by 1% between the audits due to the increase in temperature of the supply water. It was previously suggested that the temperature should not exceed 10.8 °C, which occurred during the re-audit. Even though the water temperature was less than the OEM specifications during the audits, the effect of a minimal temperature increase in the supply of water did become increasingly prevalent. Therefore, the initial suggestion of a water supply of ≤ 10.8 °C was still applicable.

The water flow effect subsided completely as a result of the increase in the water flow to the BAC. The water that was supplied to the BAC exceeded the mine specifications and, therefore, did not contribute to the limited performance of the BAC.

The WB and DB temperature changed marginally in accordance with the mine specifications and caused a 0% contribution to the reduction in BAC performance when the overall change between audits in the operating environment occurred.

- **Case Study 4**

A gap analysis was conducted by cross-referencing Figure 59 and Figure 60, whereafter it was revealed that three operating variables, rather than the initial two operating variables, were responsible for reducing the performance of the BAC.

Fouling initially contributed 85% and was reduced to 39% by cleaning the BAC. The decrease in fouling indicated that the cleaning process of using high-pressure water was more successful for Case Study 4 when compared to Case Study 1, 2, and 3. This could also have been attributed to the fact that the coils were relatively new, as the internal fouling was successfully removed, and the average UA factor increased from 0.37 to 0.74. Fouling, after all, was the primary operating variable reducing BAC performance, and as such, it was suggested that increased maintenance intervals were required to prevent the internal fouling from solidifying in the future.

The effect of the water flow operating variable increased from 15% to 36%. Similar to the contradictory occurrence of Case Study 2, where the increase in the working fluid should have decreased the limiting effect, the opposite in terms of increasing the working fluid also increased the limiting effect. Due to the water flow not being in line with the mine specification of 52.5 L/s, the limiting effect increased due to the BAC operating relatively close to the achievable duty. The initial suggestion of increasing the water flow to mine specifications was still relevant.

The air flow factor increased by 25% as a result of less air flowing through the BAC when compared to the initial audit and mine specifications. The reduction in air supply occurred due to the incorporation of the redundancy procedure of the mine, where three instead of four fans were operating.

The water temperature operating variable of the re-audit preceded the measurement of the initial audit and the mine specified temperature. Therefore, the water temperature operating variable did not contribute to the reduced performance of the BAC.

Similar to Case Study 1, 2, and 3, the WB and DB temperature changed marginally in accordance with the mine specifications and caused a 0% contribution to reduced BAC performance.

Due to the actual duty of Case Study 4 being comparatively close to the achievable duty, a small alteration of the inlet operating variables resulted in a significant contribution or rebate to the influencing effect on the performance of the BAC.

xv. Appendix AO

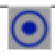
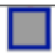
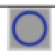
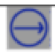
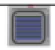
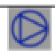
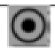
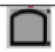
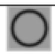
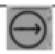
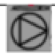
Component	Name
	Water pressure boundary
	Water pipe
	Water node
	Water mass flow
	Water to air heat exchanger
	Water pump
	Air pressure boundary
	Air tunnel
	Air node
	Air mass flow
	Air fan

Figure 61: PTB Simulation Components [5]