



A multi-layered non-linear methodology to introduce alternative handheld drilling technology in tabular narrow reef mines

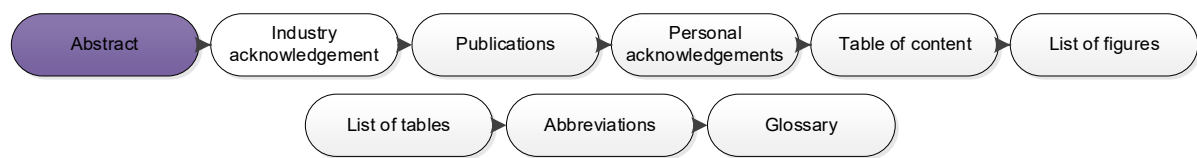
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ABSTRACT

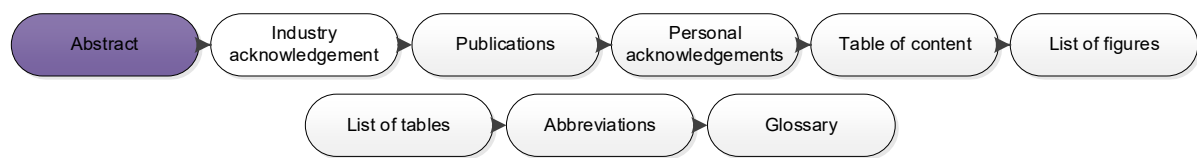
Title: A multi-layered non-linear methodology to introduce alternative handheld drilling technology in tabular narrow reef mines

Any mining operation that is unwilling or unable to adopt technological advancements will face profitability challenges throughout its lifespan. This statement is especially relevant to mature gold mines in South Africa that are air-reliant on compressed air rock drills. These operations were mainly sunk in the twentieth century, when compressed air drilling systems were the only effective method for drilling blastholes in narrow reefs. At that time, electricity was inexpensive and readily available, and the production blocks were close to the shafts. In the twenty-first century, the opposite is true, as compressed air drilling systems at certain mines are no longer techno-economically viable. Available literature indicates that alternative handheld drilling technologies exist but are rarely adopted due to insufficient implementation and change management methodologies.

This study employed the case study research methodology to develop a unique pragmatic approach to implementing alternative handheld drilling technologies in mature, deep-level, tabular narrow reef gold mines. The agile method enables mine management to anticipate the urgency for alternative drilling technology before the need becomes a necessity. Past failures were analysed to identify hidden risks and opportunities that had been previously overlooked or underestimated. These failure drivers were used as strategic guidance to formulate the study-specific method objectives. Kotter's change framework provided eight purposeful steps to introduce the alternative drilling system.

A non-linear, multi-layered methodology is proposed, in which each step hosts an array of strategies methodically crafted to be practical, actionable, and useful. To verify the urgency of the change, the method initiates the change process by providing means to distinguish between correlation and causation. Once verified, a simple change vision is crafted to highlight the benefits to all stakeholders. The vision aims to establish trust in the change idea while aligning interests, ultimately promoting stakeholder buy-in. Responsibility structures ensure that every actionable task has an accountable person assigned. Critical upgrades to the water and electrical networks may be required to support the alternative drilling system. However, methodologies for assessing the mine's standard network support capability were not found in the literature. To fill this gap, this study developed a novel infrastructure evaluation methodology to identify the network's limitations and required upgrades.

To implement the change, this study proposes a non-linear experimental approach that does not rely on a finite start and end state. In fact, the change idea is first tested on a small scale to

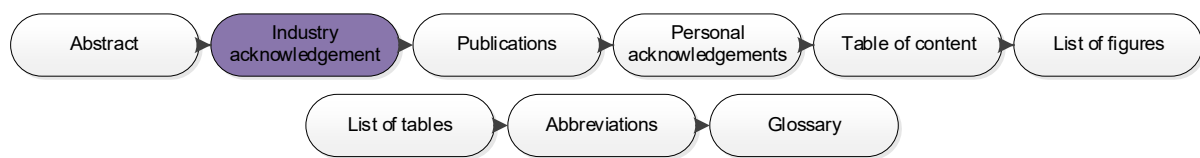


validate its change benefits before committing to large-scale roll-outs. This allows for real-world feedback and prevents impulsive decision-making, which can lead to costly mistakes. By balancing ambition with caution, the method provides a strategy to prioritise crews during the roll-out phase based on their actual drilling performance. A continuous improvement strategy was integrated into the method to enable stakeholders to analyse the change results and formulate and implement improvement opportunities. The improvement strategy is based on the 80/20 principle and prioritises actionable items by recognising that 20% of effort can yield 80% of the improvement.

A mature gold mine was used as a case study to validate the proposed methodology. Hydropower was selected as a feasible alternative drilling technology, and the method was iteratively applied to convert all the stoping crews from pneumatic to hydro drilling. The continuous improvement loop enabled the project team to implement low-risk, viable adjustments to the change process, resulting in a projected 17% improvement in production. This improvement translates into an additional revenue stream generated of R760 million per annum. Ultimately, all the compressed air stoping crews were converted to localised and micro hydropower, making it the first mature South African gold mine originally designed to operate with compressed air stopes to achieve this outcome. This result validates the method's effectiveness in addressing the study's need for an implementation and change management methodology to introduce alternative drilling technology in narrow reef gold mines. The study concludes with an overview of the key lessons learned to achieve this outcome.

The novel method proposed by this study is not simply based on theory; rather, it is supported by a firm foundation of real-world lessons learned and validated using a real-world case study to confirm its effectiveness.

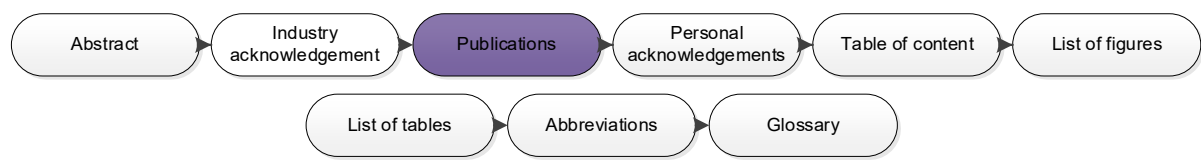
Keywords: Alternative handheld drilling technology, change management, hydropower, electro-hydraulic, continuous improvement



INDUSTRY ACKNOWLEDGEMENT: SAIIE AWARD FOR BEST INDUSTRIAL ENGINEERING WORK CONDUCTED IN INDUSTRY

The Southern African Institute for Industrial Engineering (SAIIE) recognised the unique method developed by this study as one of the top two contributions to the field of engineering in 2023*.

* The winners of the various SAIIE Awards categories. Retrieved August 18, 2023, from <https://www.saiie.co.za/awards/2023-saiie-awards>

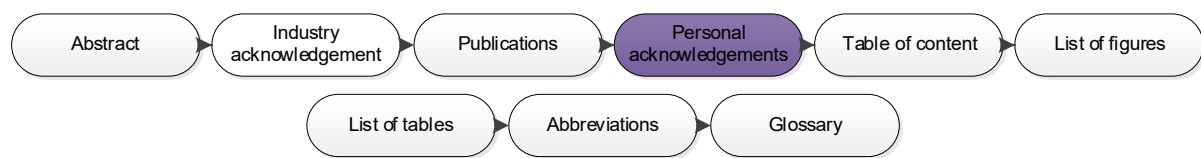


PUBLICATIONS

The following articles have emanated from this research work and were submitted for publication in 2026:

- B. van Rooyen, J. H. van Laar, J. C. Vosloo, “A techno-economic assessment of micro versus localised hydropower drilling systems for mature deep-level gold mines”, **Accepted for publication in the *Journal of Mining Technology*.**
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- B. van Rooyen, J. H. van Laar, J. C. Vosloo, “A deep dive into modern hydropower handheld drilling systems’ impact on production, cost, health and safety”, **Accepted for peer review at the *Journal of the Southern African Institute of Mining and Metallurgy*.**

Appendix D contains the acceptance letters from the respective Journals to confirm the statuses highlighted above.



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All information presented in this thesis regarding sources and published work has, to the best of my knowledge, been duly acknowledged and referenced. Please inform me of any oversights so that they can be rectified.

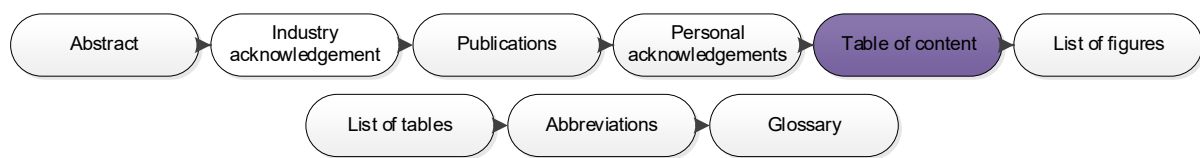
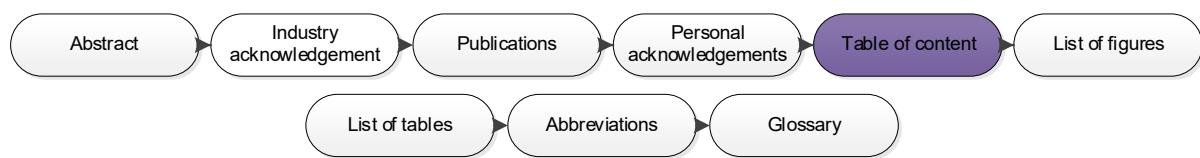
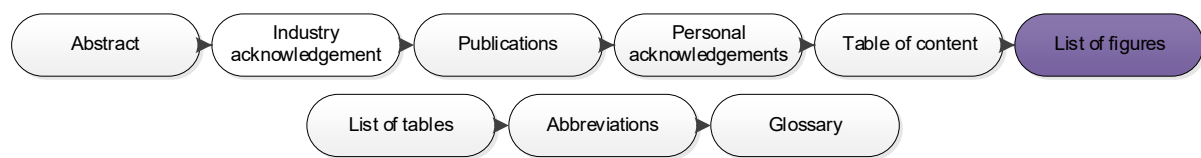


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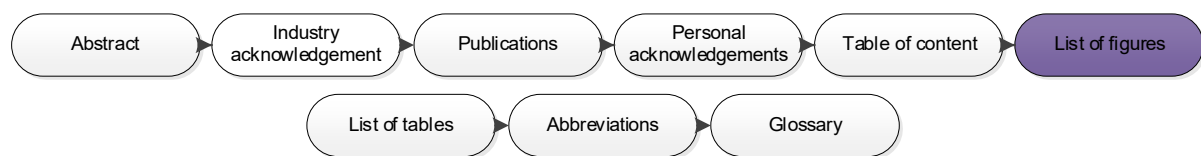


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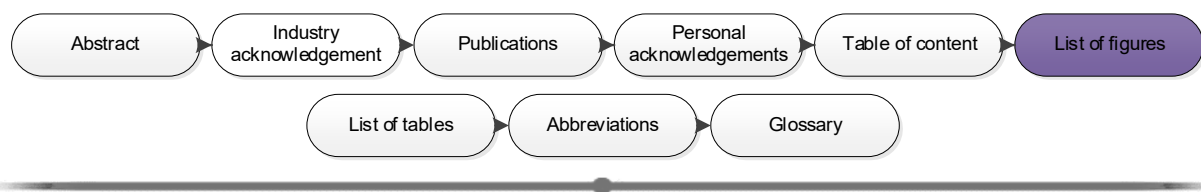


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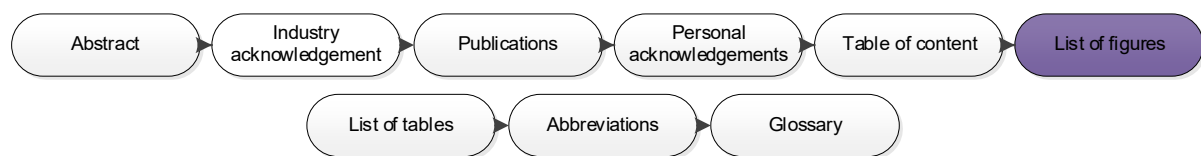


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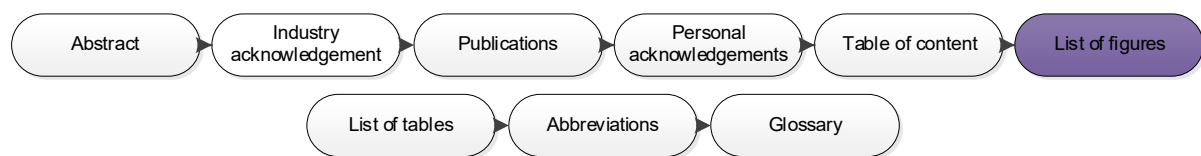
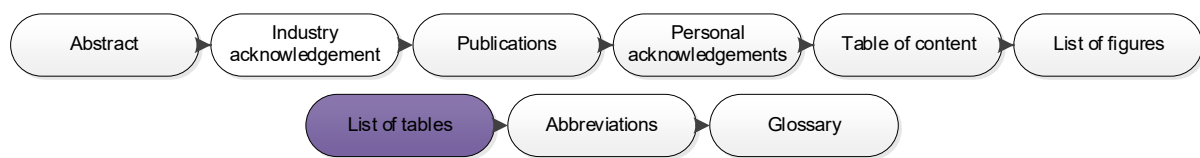


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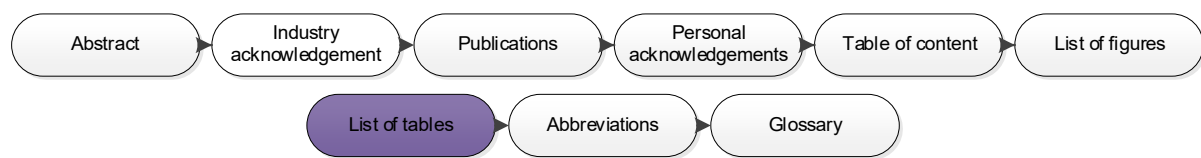


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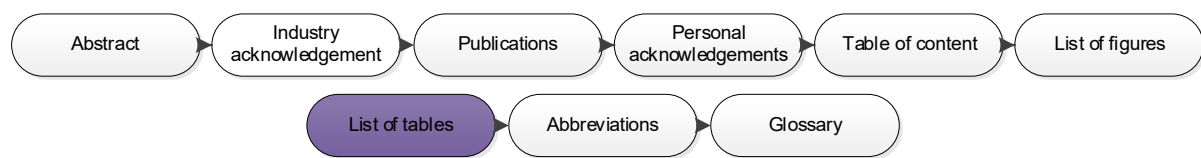


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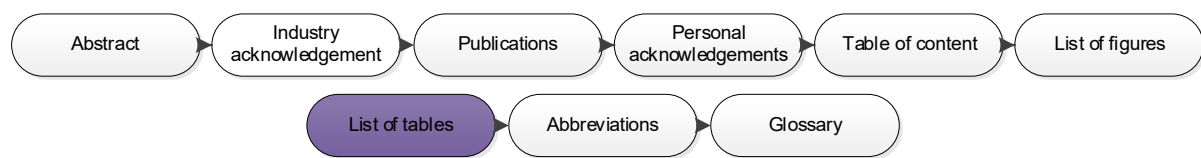
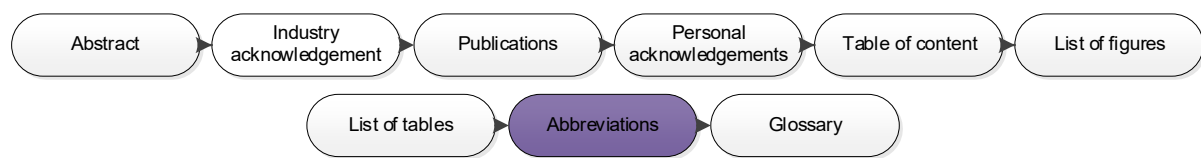
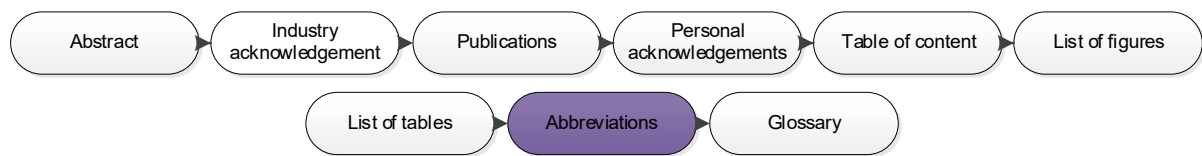


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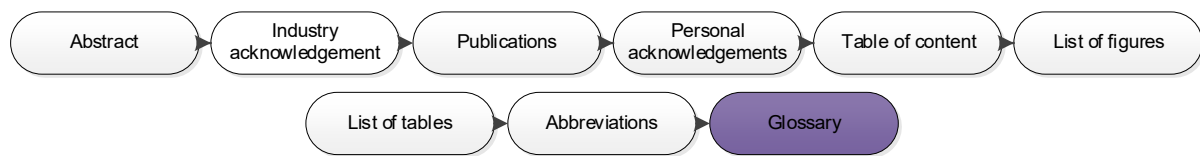


ABBREVIATIONS

Abbreviation	Description
ADT	alternative drilling technology
ADTT	alternative drilling technology transition
AME	absolute mean error
CA	compressed air
capex	capital expenditure
CIS	continuous improvement strategy
CR	consistency ratio
CRM	case study research methodology
CSM	case study mine
DXF	digital exchange format
GUI	graphical user interface
HRD	humanistic resistance driver
IEA	infrastructure evaluation assessment
KPA	key performance area
KPC	key process constraint
KPI	key performance indicator
LHS	localised hydropower system
MHS	micro-hydropower system
MPL	missing person locator
MTBF	mean time between failure
MTTR	mean time to repair
NIHL	noise-induced hearing loss
OEM	original equipment manufacturer
opex	operating expenditure
PDCA	plan-do-check-act
PLC	programmable logic controller
POC	point of contact
POS	point of supply
PRV	pressure-reducing valve
PTB	Process Toolbox
RACI	responsible, accountable, consulted and informed
RDO	rock drill operator
ROI	return on investment

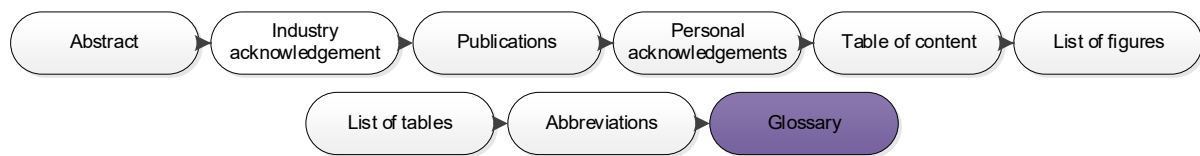


Abbreviation	Description
SFD	systemic failure driver
SHE	safety, health and (occupational) environment
TOPSIS	technique for order performance by similarity to the ideal solution
TWA	time-weighted average
VSD	variable speed drive
XC	cross-cut
SIV	Safety isolation valve
CV	Coefficient of variance



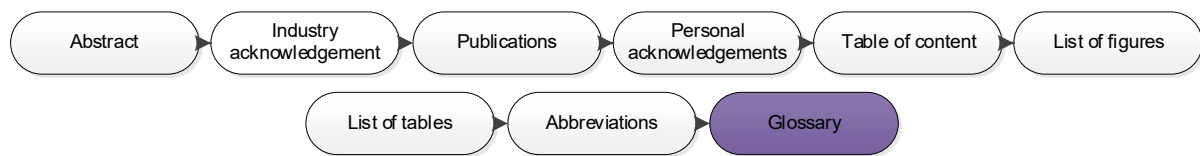
GLOSSARY

Term	Description
Auriferous	Containing gold.
Blasthole	The hole into which explosives are inserted to blast rock.
Cage	A metal structure which runs in the shaft used for the conveyance of men and material.
Centralised blasting	An arrangement for blasting all underground workings from a central point, usually situated on the surface.
Centre gully brattice	A curtain made from strips of material is installed in the centre gully to force ventilation into the advance strike gully.
Cross-cut	A horizontal underground drive developed perpendicular to the strike direction of the stratigraphy and reef.
Dip	The angle at which a planar geological feature (such as a reef horizon, bedding, or fault) is inclined relative to the horizontal plane, measured perpendicular to the strike.
Face advance	The rate at which a mining face advances (in the direction of mining), typically measured in metres per cycle, per day, or per shift.
Footwall	The underlying side of an ore body or stope.
Geological discontinuities	Faults: Geological fractures or zones of weakness in the rock where there has been displacement of the rock bodies on either side. In narrow reef mining, faults can offset the ore, create weak ground, disrupt reef continuity, affect stress, safety, etc. Dykes: Sheet-like igneous intrusions (often vertical or steeply inclined) that cut across existing rock strata (including reefs). Dykes are discordant (i.e. do not follow layering).
Grade	The average amount of gold (or other mineral) measured in grams per tonne of ore mined (or delivered to plant).
Ground	A continuous, naturally occurring concentration of mineral (in this case, gold) in the Earth's crust that is of sufficient size, geometry,

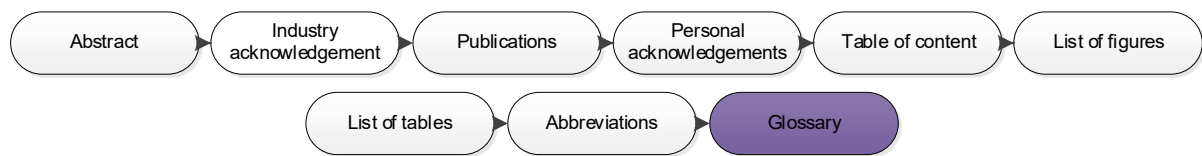


and grade that it can be mined economically under current conditions.

Hanging wall	The overlying side of an ore body or slope.
Haulage	A horizontal underground excavation which is used to transport mined ore.
Hoppers	Bins or funnel-shaped receptacles with a top opening for loading fragmented rock, and a bottom discharge (door or chute) for controlled release of rock into haulage systems or into ore passes.
Ledging	The initial stoping phase in a stope (often starting from a raise or gully) in which the first cuts of the reef are made to establish a stable footwall ledge, prepare for subsequent stoping, and install early support and infrastructure.
Life of mine	The projected remaining number of years during which the current mine plan anticipates mining and treating ore. It is based on declared reserves, planned production rates, economic (grade) cut-offs, planned development, etc.
Mud rushes	Mud rushes are sudden inflows of mud from drawpoints or other underground openings.
Ore	A mixture of valuable and worthless minerals from which the extraction of at least one of the minerals is technically and economically viable.
Orepass	A tunnel developed from a crosscut to the raise above at an inclination of 55° (or more) used for transferring the broken rock from the stope to the cross-cut.
Panel	A subdivision of a stope: a block or section (in strike or dip) which is being or scheduled to be mined at a given time. Panels allow orderly extraction of ore, face advance, ventilation, safety, and sequencing. In narrow reef stoping, panels are often relatively small (face length tens of metres), and several panels may be active in a stope.
Raise	Vertical or subvertical connections between levels are generally driven upward from a lower level through a process called raising.



	A raise in development becomes a centre gully in the stoping phase.
Reef	A tabular, often sedimentary or otherwise geologically distinct rock horizon which contains sufficient gold mineralisation to be considered ore. In SA gold mining, “reef” is used fairly specifically to refer to a gold-bearing horizon (e.g. conglomerate reefs on the Witwatersrand, or narrow auriferous reefs in the Free State, etc.).
Rock drill operator	A person who operates a handheld rock drill in underground workings (raises, drifts, stopes).
Shaft	A vertical or near-vertical excavation from surface down into the mine, used for hoisting ore and waste rock, moving personnel and equipment, ventilation, supplies, etc. In deep SA gold mines, shafts are fundamental for access to the narrow reefs several km below the surface.
Strike	The direction of the line formed by the intersection of a geological plane (such as bedding or reef horizon) with a horizontal plane. In mining, strike is used to describe the along-reef direction (i.e. along the length of the reef horizon).
Strike rate	In underground mining, strike rate typically refers to how often the panel is blasted.
Stope	The underground excavation from which the ore (the reef) is extracted (i.e. the void or mined-out area within the orebody). In narrow-reef SA operations, these are often narrow, steeply dipping or shallowly dipping, frequently supported, highly controlled working faces from which gold-bearing reef is removed.
Stoping	The process of extracting (i.e. removing) ore from the stope: drilling, blasting, cleaning, supporting, filling, etc. It is the productive mining phase, rather than development (access drives, shafts) or supporting infrastructure. In narrow-reef SA gold/mine settings, stoping is carried out using carefully controlled methods due to narrow widths and high depth.

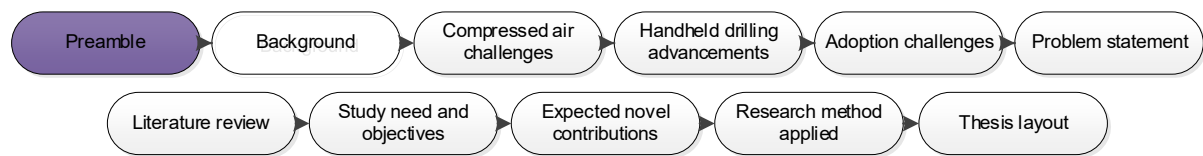


Scraper winch
driver

A person who operates a powered scraper winch (i.e. drum, cable, pulley system) to pull ore in underground workings (stopes).

Stope mother box

A main electrical distribution box that supplies power to all connected gully boxes.



1. INTRODUCTION AND LITERATURE REVIEW

1.1. Preamble

South Africa was the top gold-producing country from 1905 until 2007 [1]. Escalating operational costs and production constraints due to the ever-increasing mining depths dragged South Africa down to tenth place by 2021 [2], [3]. Recovery depths increased from near the surface to depths exceeding 4 km, and revenue margins decreased from 12 grams of gold per tonne of ore mined (g/t) in 1970 to 5 g/t [2], [4]. The introduction of new mining technology is widely regarded as a strategic necessity in efforts to reduce the operation's resource intensity and, consequently, improve revenue [5].

Regrettably, the South African gold mining industry is relentlessly risk-averse and conservative in its attempt to remain sustainable, and it has experienced very little change over the past 100 years [6]. Figure 1-1 shows the significant technologies that have been successfully applied to South Africa's narrow reef mines over the past 100 years [7], [8], [9]. In 2026, these same technologies are still predominantly used in South African gold mines.

Considering this information, it is not surprising that deep-level gold mining predominantly uses manpower with a low level of mechanisation. Numerous attempts made in recent years to introduce new technologies have been accompanied by disappointing failures [5]. One noteworthy failure is the introduction of alternative in-stope handheld drilling machines.

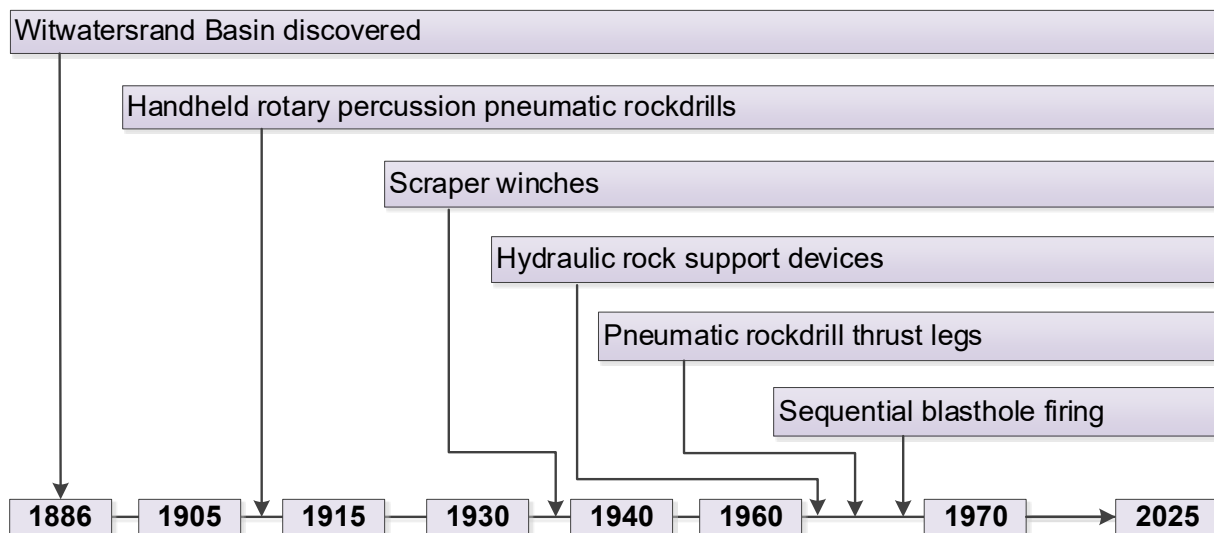
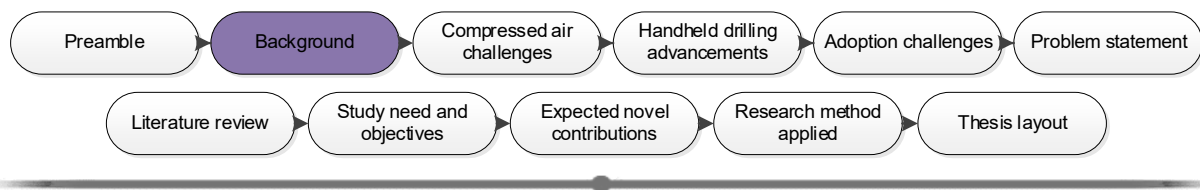


Figure 1-1: Technology applied with success to narrow reef stoping over the past 100 years



1.2. Background

A typical deep-level gold compressed air drilling system will be discussed to provide background on its operation and constraints.

South African tabular narrow reef gold mining

The South African goldfields are primarily located in the Witwatersrand Basin, illustrated in Figure 1-2, and are deposited mainly in narrow tabular seams [10]. These tabular goldfields extend over many kilometres along the strike and dip. The reef's dip angle varies between nearly horizontal and nearly vertical due to geological discontinuities, but generally dips between 10° and 30° [11]. The distance between the hanging wall and footwall, known as the stoping width, is determined by the width of the reef and averages approximately 1 m within the Witwatersrand Basin, which is characterised by narrow reefs [12].

Narrow stoping widths present a unique challenge for mechanised mining methods, as all previous attempts have demonstrated to be impractical in narrow reef stopes with stoping widths ranging from 1.0 m to 2.4 m [2], [13]. Machinery does not fit and lasts in the harsh, humid environmental conditions [9], [14], [15], [16].

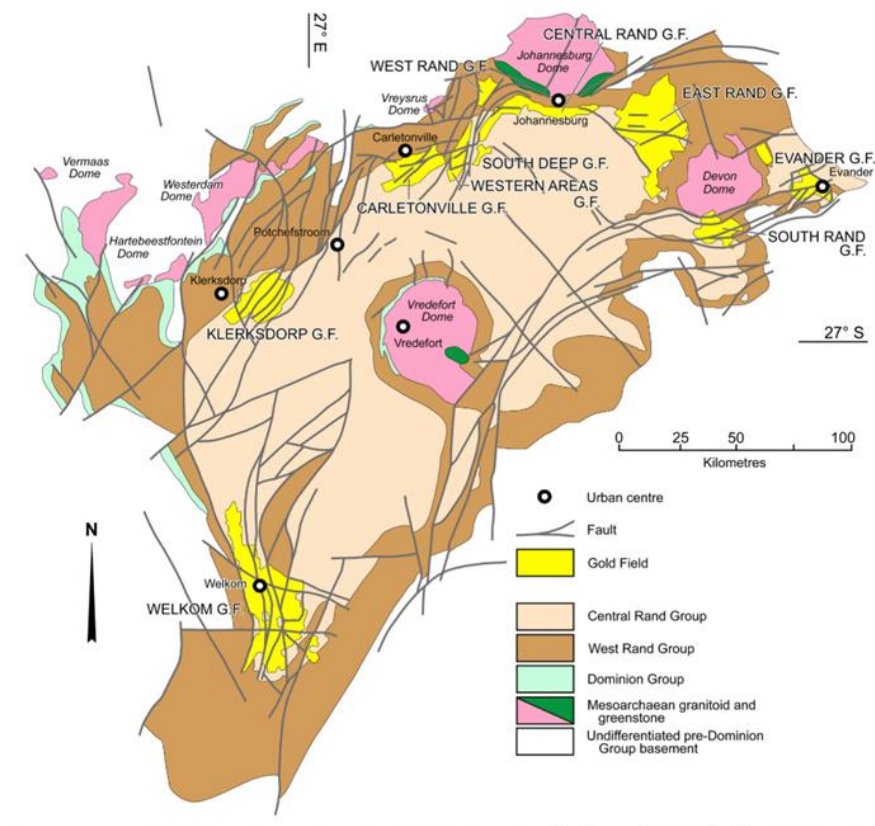
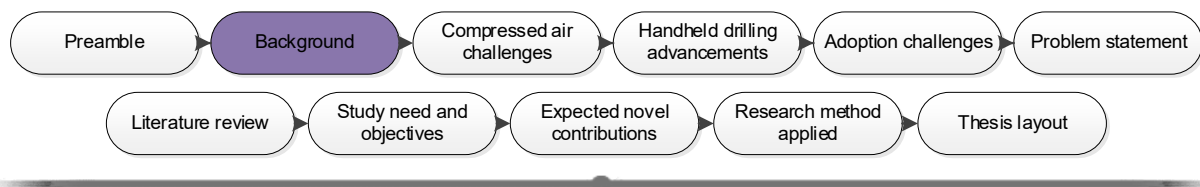


Figure 1-2: Witwatersrand Basin (Adopted from [17])



When stoping widths average around 1 m, the preferred mining method is conventional narrow reef mining [18], [19]. Blastholes are drilled into the rock mass using handheld rock drills, as depicted in Figure 1-3. High-energy explosives are placed inside the holes and used to break the ore from the host rock [20], [21]. Winches and scrapers are used to move the fragmented ore from the face into ore passes [19]. To prevent the mined-out void from collapsing, a combination of rock pillars, timber packs and elongates, backfill and steel roof bolts is used to support the hanging wall.

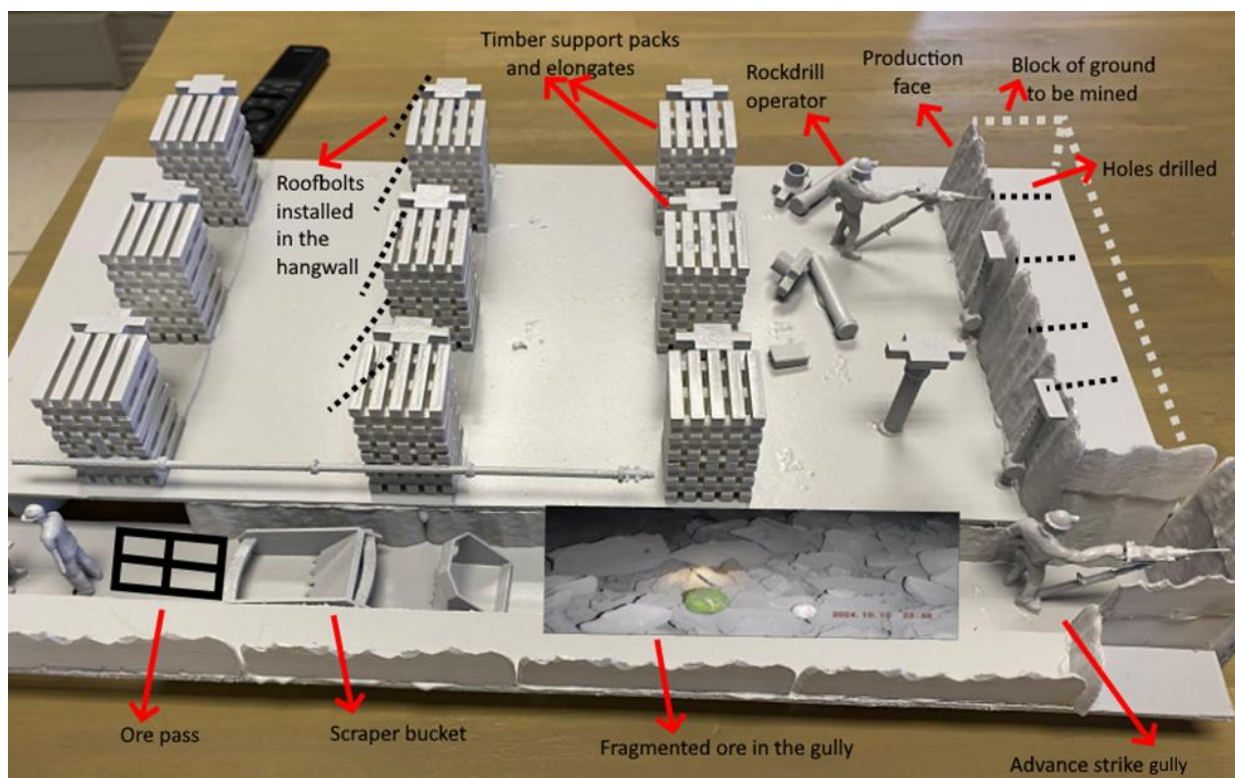


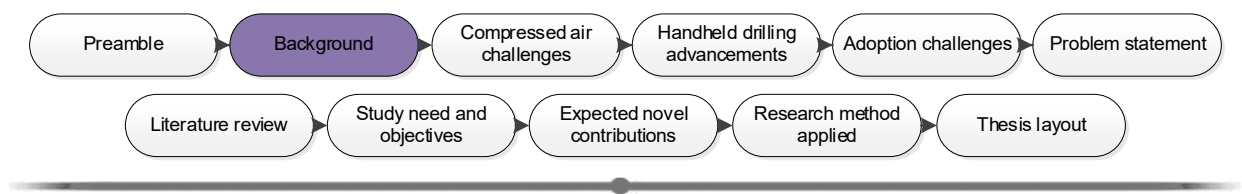
Figure 1-3: Narrow reef mining illustration²

As illustrated in Figure 1-4, these activities are executed in the following two sequential processes [21], [22]:

(1) Breaking:

- The day shift is responsible for drilling blastholes, installing the support, and charging blastholes with explosives. Safety is ensured when blasting the panel by evacuating the work team.
- A re-entry period (1 - 4 hours), governed by the mine's risk assessment and code of practice, is enforced to ensure that dust and gases are extracted before the night shift enters the stoping area [23], [24].

² B. van Rooyen, Personal photograph, "Stope model crafted by D. Grobler", Pretoria, 2024.



(2) Cleaning:

- The night shift is responsible for cleaning the panel. The cleaning cycle must be completed during this shift to enable the next drilling cycle to commence in the morning.

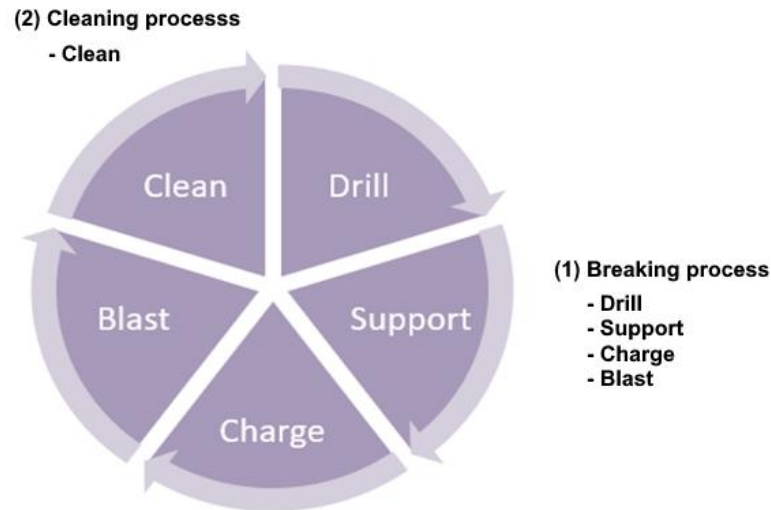


Figure 1-4: Cyclic mining cycle (Adapted from [22])

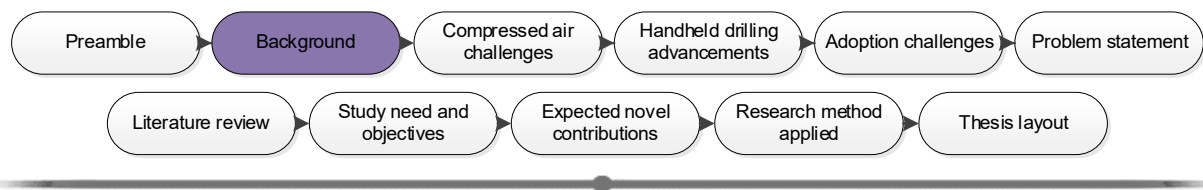
White *et al.* [25] claimed in 1975 that handheld drilling and blasting would be the primary mining method in South African narrow reef gold mines for the next decade. Today, in 2025, handheld drilling remains the preferred method as it provides the most economical and flexible means of accessing the orebody in narrow reef stopes [20], [21], [26]. Kienle *et al.* [9] and Marshall and Seawright [27] agreed on the following three factors that explain why handheld drilling has maintained its dominance in the narrow reef mining industry:

- **Simplicity:** The drill and thrust leg combination is simple to understand and maintain.
- **Ease of use:** Handheld drills are lightweight, compact and easy to manoeuvre compared to their in-stope drill rigs and jig counterparts.
- **Flexibility:** A handheld drill can be used to drill almost any hole in any direction within the confines of steep dipping, narrow stoping widths. Ultimately, this allows the operator to navigate along geological discontinuities.

Pneumatic handheld drilling

The rock drill motive energy sources utilised by 38 South African gold mines are illustrated in Figure 1-5. The figure shows that compressed air is predominantly used to power in-stope handheld drills. Replicas of the S215 pneumatic rock drills by Boart Longyear have predominantly been used in South African compressed air-driven mines since 1905 [28].

Illustrated in Figure 1-6, an air hose supplies the machine with compressed air. The internal percussive and rotary components are lubricated by an oiler filled with grease, which is



connected before the rock drill air inlet port. Compressed air not only percusses and rotates the drill steel but also provides thrust force using an air leg [29], [30]. Flushing water is supplied through a hose and is required to cool the machine and drill bit, flush crushed rock flakes from the hole, and suppress drilling-related dust [31].

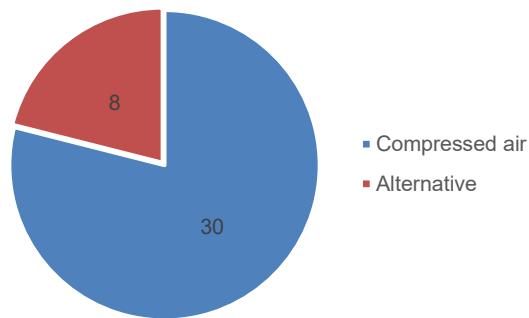


Figure 1-5: Number of compressed air gold mines vs gold mines using alternatives³

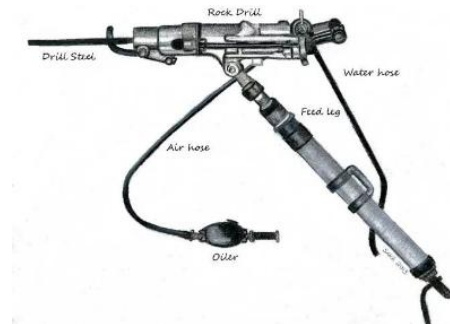
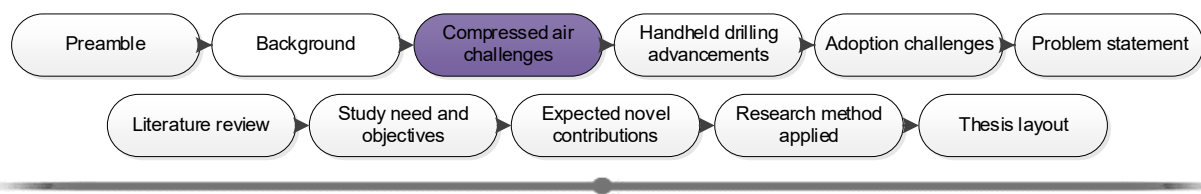


Figure 1-6: Conventional pneumatic rock drill⁴

This century-old tool was once an effective, reliable, and versatile tool in the hands of an experienced operator [32]. However, in the twenty-first century, the opposite is true, and South African gold mines are facing severe sustainability challenges when using compressed air as a motive energy source, as alluded to in the next section.

³ Department of Mineral Resources and Energy. (n.d.). Operating mines. Retrieved Jan 12, 2025, from <https://www.dmr.gov.za/mineral-policy-promotion/operating-mines>

⁴ Bisbee Mining & Minerals. (n.d.). Jackleg. Retrieved July 5, 2023, from <https://www.bisbeeminingandminerals.com/jackleg>



1.3. Challenges associated with pneumatic handheld drilling systems

The operations depicted in Figure 1-5 were mostly sunk in the mid-1900s [33]. Back then, from a techno-economic perspective, compressed air was the preferred motive energy source. Electricity used to power the compressors was also available at a low cost [34], [35]. In addition, pressure losses in compressed air distribution lines were minimal as the production blocks were close to the shafts. Nowadays, the cost and availability of electricity, along with inefficiencies (leaks and a lack of management and controls) in the compressed air distribution network, prevent this fundamental goal from being achieved.

Challenge #1: Electricity cost

Large industrial compressors are used to pressurise the air, and these units account for up to 20–40% of a mine's overall electrical bill [36], [37], [38]. In fact, the mining sector accounted for 13% of Eskom's electricity sales in 2023, highlighting the significant electrical dependency of the gold mining industry [39]. As shown in Figure 1-7: South Africa electricity cost vs inflation, South Africa's power producer, Eskom, charges some of the highest tariff hikes globally [39], [40], [41]. In addition to the 15.06% increase in 2022, the National Energy Regulator of South Africa announced a standard tariff increase of 9.61% for 2023. A further 12.74% was implemented for 2024 and 2025, respectively. While an additional 8.76% became the norm in April 2026. As a result, the energy cost of sustaining the compressed air supply required in underground production areas became a notable sustainability risk to the production of profitable gold ounces.

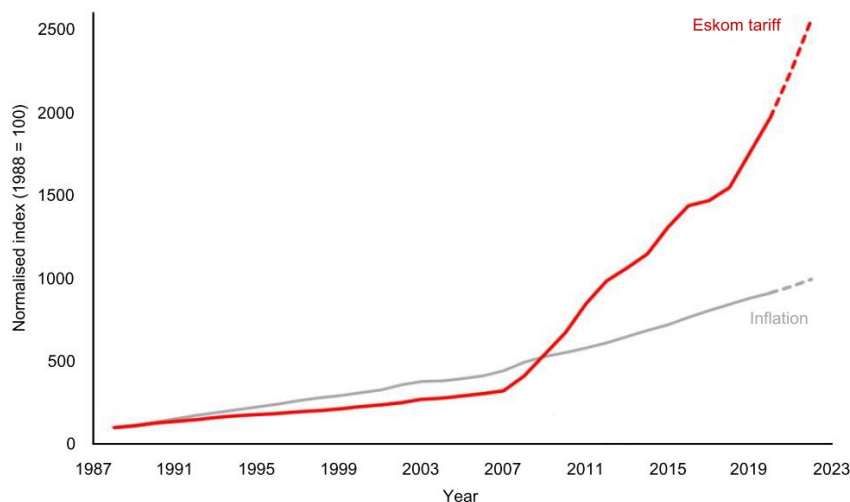
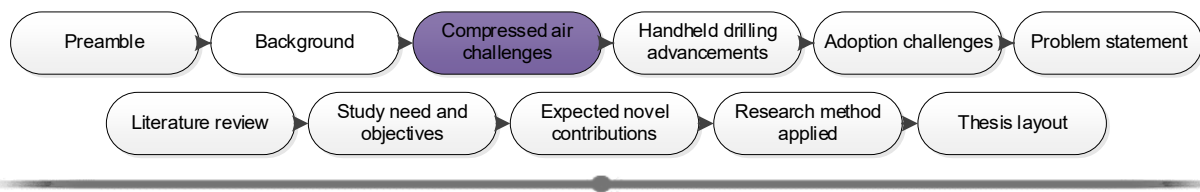


Figure 1-7: South Africa electricity cost vs inflation⁵

⁵ Green Economy (n.d.). "The price of water and electricity in South Africa". Retrieved Jan 12, 2023, from <https://greeneconomy.media/the-price-of-water-and-electricity-in-south-africa-a-tale-of-two-tragedies>



Challenge #2: Compressed air network inefficiencies

A large number of the underground mines in South Africa, particularly in the gold sector, must be classified as mature [42]. A recent study conducted by Fraser [28] revealed that the overall efficiency of a compressed air network applicable to a mature underground mine may be as low as 2%. Overall efficiency is defined as the ratio of the electrical input energy to the motive energy output available for drilling a hole. It is a function of the compressor's overall efficiency, reticulation pressure losses, leak losses and rock drill efficiency (Equation 1-1).

$$\begin{array}{|c|} \hline \text{Absorbed electrical} \\ \text{energy} \\ \hline 100\% \\ \hline \end{array} \times \begin{array}{|c|} \hline \text{Compressor overall} \\ \text{efficiency} \\ \hline 58\% \\ \hline \end{array} \times \begin{array}{|c|} \hline \text{Reticulation efficiency} \\ \hline 75\% \\ \hline \end{array} \times \begin{array}{|c|} \hline \text{Leaks} \\ \hline 18\% \\ \hline \end{array} \times \begin{array}{|c|} \hline \text{Drill efficiency} \\ \hline 24\% \\ \hline \end{array} = \begin{array}{|c|} \hline \text{Overall efficiency} \\ \hline 2\% \\ \hline \end{array} \quad \text{Equation 1-1}$$

Consequently, the average supply pressure at the face might be as low as 250 kPa. This alarming number corresponds to only 50% of the ideal design pressure requirement for drilling blastholes effectively [30]. To conceptualise the drivers behind the inefficiencies mentioned here, consider the following.

Equation 1-2 describes the energy losses associated with fluid motion in pipes. The formula describes energy lost between any two points within the network as a function of the following:

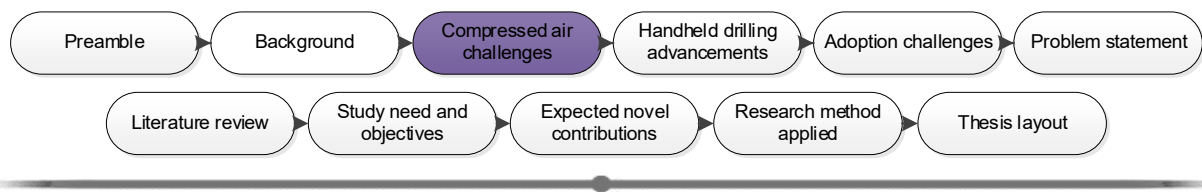
- Elevation changes,
- Flow resistance through system components such as valves and bends, and
- Viscosity-related flow resistance.

$$\Delta P_{12} = \gamma(z_2 - z_1) + h_{\text{minor losses}} + h_{\text{major losses}} \quad \text{Equation 1-2}$$

where:

- | | |
|---------------------------|--|
| ΔP_{12} | – Pressure energy loss between two points |
| $\gamma(z_2 - z_1)$ | – Pressure energy loss due to an elevation change |
| $h_{\text{minor losses}}$ | – Pressure energy loss due to pipe components (minor losses) |
| $h_{\text{major losses}}$ | – Pressure energy loss due to viscous effects (significant losses) |

Elevation changes are inevitable due to the mine's operational layouts. Therefore, component and viscous-related resistive flow pressure losses can be isolated as the most significant



contributors to efficiency loss. Component losses are generally considered minor losses, while viscous-related losses are described as substantial pressure losses. Figure 1-8 illustrates a dimensionless representation of pipe flow. It shows that the significant pressure loss between two points is a function of the pipe diameter, length, surface roughness, fluid density, and viscosity. In fact, it is evident from Equation 1-3 that major pressure losses are directly proportional to surface friction and the overall pipe length.

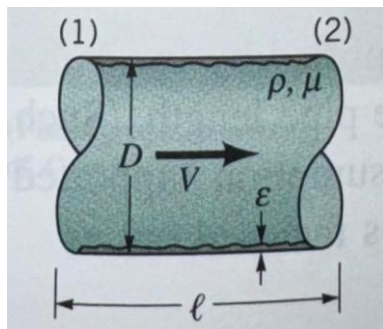


Figure 1-8: Dimensionless representation of pipe flow
(Adapted from [43])

$$h_{\text{major losses}} = f \times \frac{l}{D} \times \frac{V^2}{2g} \quad \text{Equation 1-3}$$

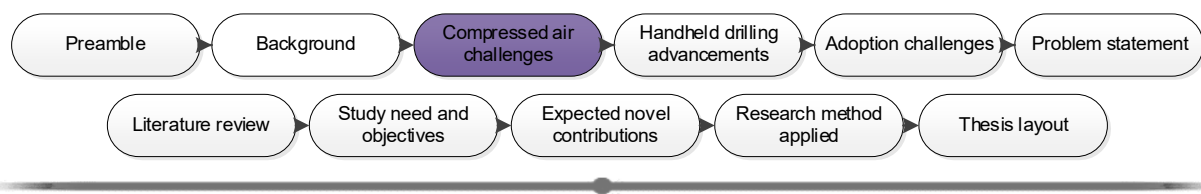
where:

$h_{\text{major losses}}$	– Pressure energy loss due to viscous effects
f	– Surface friction factor
l	– Pipe length
D	– Pipe diameter
V	– Average fluid velocity
g	– Gravitational acceleration

In South African gold mines, this presents the following unavoidable challenge. Most of South Africa's currently active deep-level gold mines were sunk in the 1980s. Ever since, production has progressed, and these mature operations now exceed depths of 3.8 km [2], [4]. Production blocks are several kilometres away from the compressors, which are generally located on the surface [44]. Several thousand pipe components and kilometres of pipe are used to reticulate compressed air to the workplaces, known as stopes. Consequently, the major pressure losses described by Equation 1-3 are unavoidable and detrimental to the system's overall efficiency.

Historically, this challenge was endured; however, it has now reached a point where production sustainability is severely threatened. The snowball effects of inadequate compressed air pressure are summarised as follows:

- Inadequate compressed air pressure leads to slow drilling [34], [35].
- Slow drilling automatically increases the drilling cycle time and operator fatigue levels, especially in the extreme heat conditions experienced in deep underground gold mines [45], [46], [47].
- Increased fatigue levels lead to high rates of absenteeism [2].



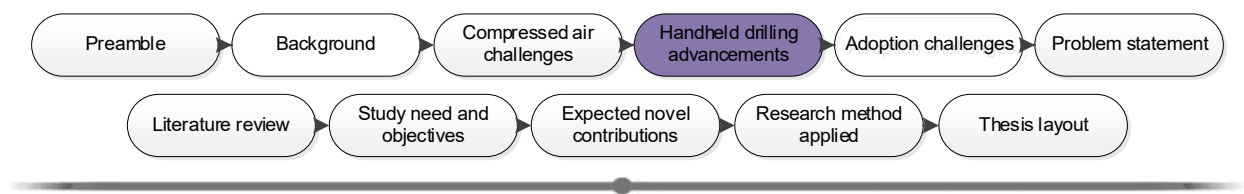
- Stretching the drilling cycle leads to delays in blasting and night shift clearance. Consequently, panels are not cleaned daily due to reduced cleaning shift cycle times, as the re-entry period remains non-negotiable.
- Additionally, increased time spent on the face increases the risk of falls of ground fatalities, injuries and operational illnesses [14].
- Support installations may be delayed because the panel does not have enough compressed air to drill and cut the support timber to size simultaneously. Hand saw cutting rates are insufficient to meet the required number of units for the support installation⁶.
- Travel times in and out of the mine as well as regulatory safety requirements further lead to additional face time lost.
- Ultimately, blasts are lost the following day due to the cyclic nature of the mining cycle, as described earlier by Figure 1-4.

Historical predictions

These fundamental challenges, however, are not new; they were predicted in the early 1970s by the late South African Chamber of Mines. Today, it is better known as the Mine Minerals Council of South Africa. In response, the Council initiated the development of the first handheld alternative drill – a robust, high-pressure, water-powered (hydropower) rock drill [48]. Since then, electric and electro-hydraulic drills have also been developed [28], [49]. Regrettably, as seen in Figure 1-5, these alternative technologies are poorly adopted by the industry, as the majority of South African mines are still using compressed air as a motive energy source.

Possible reasons for this are investigated next. At first, a review is presented to (i) understand the alternatives, (ii) determine if the benefits offered by each alternative offer solutions to the challenges of the compressed air systems highlighted in [Section 1.3](#), and, finally, (iii) identify the organisational changes that are required to implement these alternative systems.

⁶ Time studies were conducted of elongate cutting using both methods (hand and chainsaws) during the compressed-air baseline phase of the study. The diameter of the elongates was 200mm. Hand saw cutting times averaged around 00:08:25 [hh:mm:ss] per elongate compared to 00:01:05 [hh:mm:ss] using a compressed air-driven chainsaw. When factoring in the saw operator's fatigue experience in the extreme heat conditions, hand saws were found to be seldom used in cases of emergency only (i.e. failure of the chainsaw). The support density (amount of elongates to be installed) increased as mining migrated deeper in recent times



1.4. Advancements in handheld drilling technology

Historical overview

Historical advancements in handheld blasthole drilling technology are chronologically mapped out in Figure 1-9. As shown in the figure, the past four centuries have witnessed several advancements in blasthole drilling. These advancements are discussed in more detail here.

The hammer and chisel method (1613–1813)

Initially, in the sixteenth century, blastholes were drilled into the orebody using a hammer and a chisel. The hammer provided percussive force while the operator slowly rotated the chisel after each sequential hit [29].

Steam-driven rotary rock drills (1813–1844)

The hammer and chisel method later inspired inventors to develop the first rotary percussive steam-driven rock drill early in the eighteenth century [49]. Unfortunately, steam-driven drills were heavy and immobile. These ergonomic constraints forced inventors to seek alternatives. Compressed air-driven counterparts were developed in response [50].

The remainder of this section contains a detailed review of compressed air, hydropower, electric, and electro-hydraulic rock drilling technologies. To understand the distinct differences, each system review is conducted under four topics: layout configuration, performance and reliability, ancillary equipment and versatility, and system shortcomings.

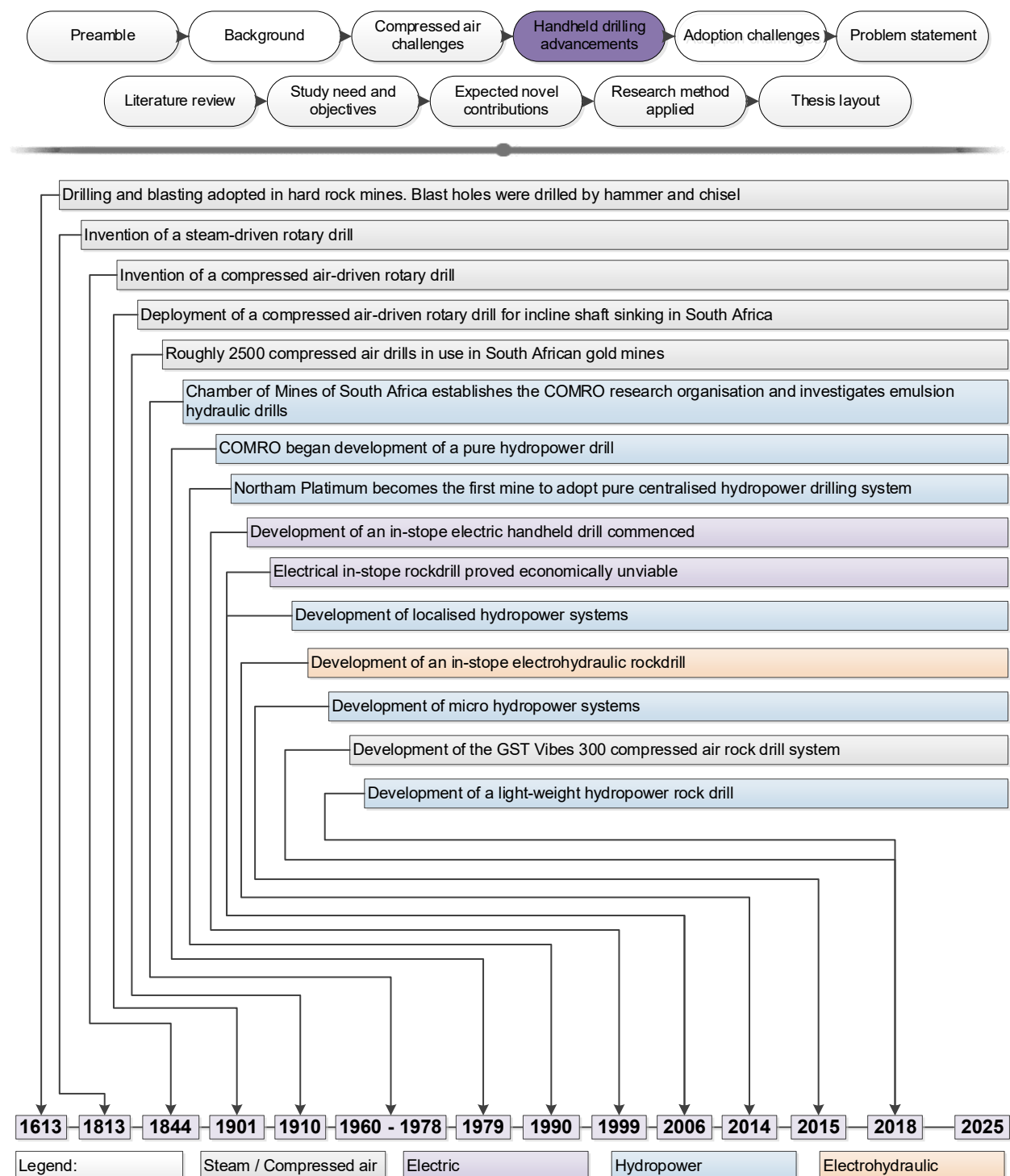
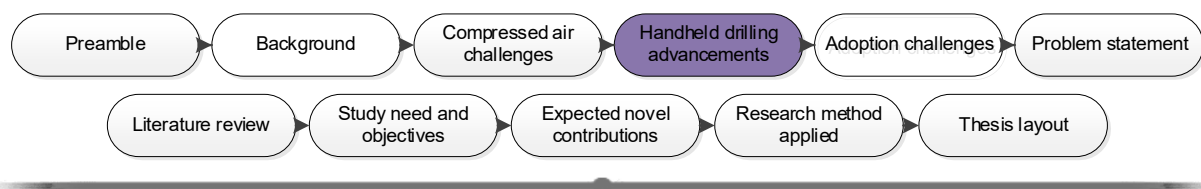


Figure 1-9: In-stope handheld drilling historical overview

Compressed air systems (1901–present)

Rotary percussive pneumatic rock drills were first deployed in a South African mine around 1901 [51]. Seventy years later, the drill's popularity increased to roughly 20 000 units deployed [52].

Layout configuration: Figure 1-10 provides a reticulation overview of a compressed air system. With compressed air configurations, large industrial compressors, ranging from 20 000 to 30 000 cubic feet per minute, are located on the surface to generate the energy medium. These compressors are typically driven by electric motors ranging from 2.5 MW to 4.5 MW [36]. Localised heating in intake airways and high electrical load requirements are some of the reasons why small compressors are not commonly used underground [32]. A vast pipe network



is used to reticulate the energy medium to the workplaces. In the workplace, as shown in Figure 1-11, rock drills are connected to the network by means of a manifold and flexible rubber hoses.

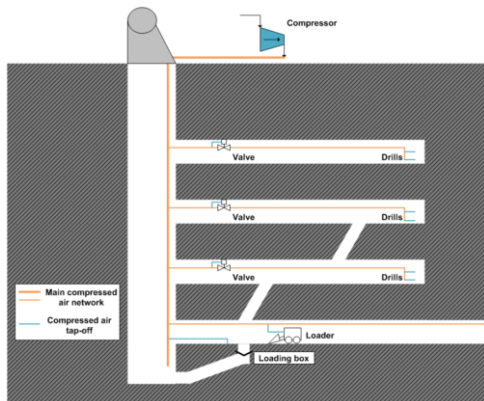


Figure 1-10: Compressed air reticulation layout (Adapted from [36])

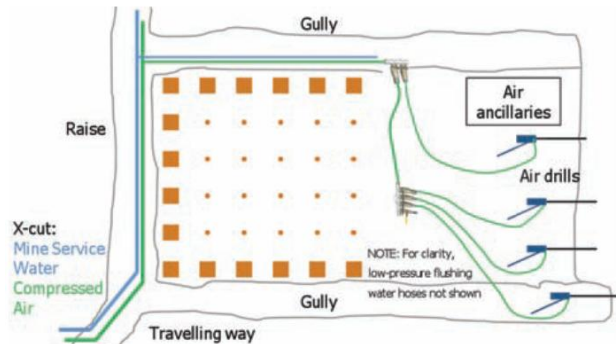


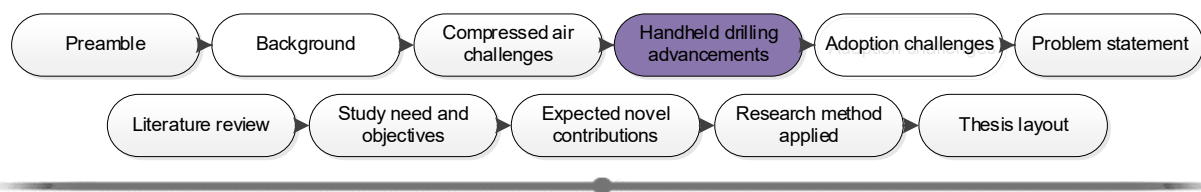
Figure 1-11: Compressed air-powered stoping configuration (Adapted from [53])

Performance and reliability: Pneumatic drilling systems are classified as intense energy consumers, absorbing up to 15 kWh per metre drilled [32]. Overall efficiency, described as the ratio of electrical input energy to motive energy output, can be as low as 2% [28]. As a general rule derived from penetrating performance, one rock drill is needed per 10 m of face length to drill the required blast and support holes [48], [54]. Rock drills typically consume between 0.2 l/s and 0.35 l/s of service water, depending on the rock drill's condition and supply pressure [49]. Over the past 100 years, design refinements have resulted in a robust and reliable rock drill. Reliability, quantified in mean time between failure (MTBF) and measured in metres drilled to failure, is as high as 800 m per failure [55]. The rock drill technology remained the same until 2018, when GST developed the Vibes 300 compressed air rock drill system⁷. What sets the Vibes 300 system apart is its innovative thrust leg and remote control design, which evidently removes the operator from the direct drilling area.

Ancillary equipment and versatility: Compressed air-driven ancillary equipment such as chainsaws, blasthole cleaners, charge-up units, prestressing devices, and grout and water pumps is used to fulfil all supplementary activities [53]. Crew moves, when production grounds become depleted, are facilitated with relative ease. Pipes are extended to the new workplace, while the equipment and manifolds are disconnected, transported to the new location, and then reconnected.

System shortcomings: Although the Vibes 300 system presents an innovative solution to revolutionise handheld drilling, the technology remains compressed air driven. Poor energy transfer within compressed air networks in mature, deep-level mines still leads to ineffective

⁷ GST Mining. Vibes 300. Retrieved Jan 21, 2026, from <https://gstsa.com/gst-products/gst-vibes-300/>



performance and high electrical energy costs. These shortcomings led to the development of the first dirt-tolerant gravity-based hydropower drilling system in the early 1960s, which became commercially available in 1990 [56]. There are three different configurations of hydropower systems: centralised, localised, and microsystems, as reviewed next.

Centralised hydropower systems (1990–present)

Gravity-based hydropower drilling systems utilise a vertical head to create the motive energy medium, known as high-pressure water, at 18 MPa [32], [48], [56].

Layout configuration: Gravity-based hydropower systems, as shown in Figure 1-12, use shafts and levels equipped with expensive high-pressure pipes to reticulate water throughout the mine [28], [32]. Pressure-reducing valves are generally installed at level stations to control the pressure within the 18 MPa limit. Various safety valves are incorporated to maintain safety standards in the event of sudden pipe bursts or routine pipe maintenance. Due to the significant performance increase, one rock drill per 15 m of face length will suffice, but it is cautioned against. Any attempt to reduce the workforce while implementing new technology will result in unwanted change resistance, while increasing the workload and fatigue of the operators [57], [58], [59].

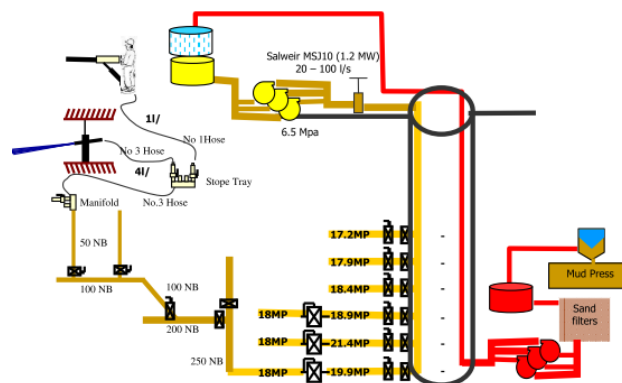
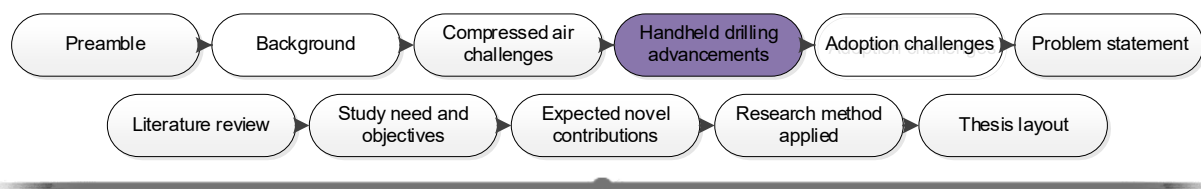


Figure 1-12: Centralised hydropower layout (Adapted from [53])

System performance: Contrary to compressed air efficiencies of around 2%, the overall system efficiency of centralised hydropower systems equates to 24% [28]. The vast efficiency improvement is attributed to the following factors. Unlike compressors, positive displacement pumps are more efficient, and system leaks are tolerated to a lesser extent. Additionally, finer component tolerances allow for efficient energy transfer [49]. Centralised drilling systems are classified as low-energy consumers, absorbing up to 0.613 kWh per metre drilled [32]. This equates to a factor of 9.3 lower than that of a compressed air system. Rock drills typically consume between 0.8 l/s and 1.0 l/s, depending on condition, ranging from new to worn-out [48]. As a result, instantaneous water consumption is expected to increase by roughly a factor of four



when compressed air rock drills are replaced with hydropower. Rock drill reliability was indicated as 500 m/failure, which is 300 m less than that of compressed air [28]. Water-hydraulic equipment operates at much finer component tolerances. For this reason, it is more sensitive to water quality and operator care [52].

Ancillary equipment and versatility: Hydropower is a mature alternative technology developed over the past 40 years [60]. Alternatives to all compressed air-driven ancillary equipment are available, which enable mining without compressed air, as illustrated in Figure 1-13 [49]. Crew moves are facilitated with ease, much like compressed air systems.

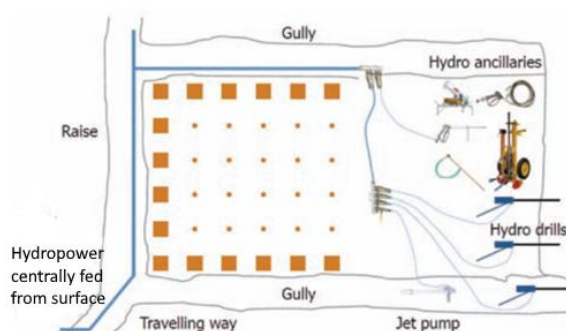


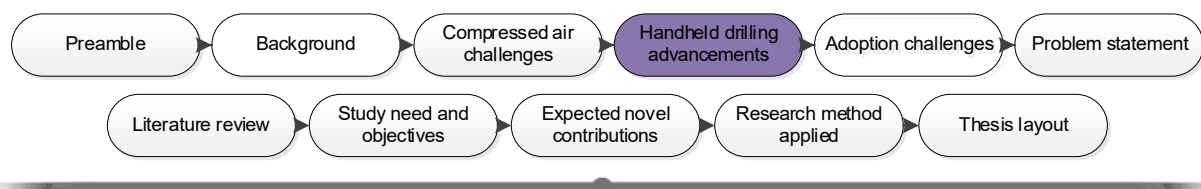
Figure 1-13: Hydro-powered stope configuration (Adapted from [53])

System shortcomings: Northam Platinum mine became the first South African mine to adopt a purely centralised hydropower system in the 1990s [61]. Soon after, three underground gold mines followed: Kloof 4 shaft, Beatrix 3 shaft and Tau Lekoa 10 shaft [62]. Unfortunately, on 13 October 1993, a shaft incident occurred at one of these mines when the mine commissioned a hydropower column⁸. Twenty-six tonnes of hydropower piping dislodged from its brackets and fell down the shaft. The incident destroyed all hoisting capability, resulting in 150 people being trapped underground, and contributed to the unpopularity of centralised hydropower systems. As a result, economies of scale prevented centralised hydropower from becoming a cost-effective alternative to existing pneumatic systems [28]. Furthermore, it proved challenging to maintain end-user water usage and leak control. The centralised system failed to maintain the minimum drill inlet water pressure requirement of 16 MPa.

Localised (2006–present) versus micro-hydropower systems (2015–present)

To address the aforementioned drawbacks of centralised systems, localised and micro-hydropower systems were developed.

⁸ Mining weekly. Mike Eksteen reflects on twenty-fifth anniversary of Kloof Gold accident . Retrieved May 16, 2026, from <https://www.miningweekly.com/article/mike-eksteen-reflects-on-twenty-fifth-anniversary-of-kloof-gold-accident-2018-10-19>.



Layout configuration: With localised systems, pressure generation units were innovatively moved underground into the cross-cut. Illustrated in Figure 1-14, localised systems (20–40 l/s) comprise a group of positive displacement pumps that are clustered together in the cross-cut to supply a full raise line [28]. The mine service water pressure is boosted from 4 bar to 180 bar. It is reticulated to the production areas using cost-effective small nominal bore piping. End user water control might be a challenge, as the same pump station supplies several panels.

Micro-hydropower systems (3.0–3.5 l/s) were developed to enable effective end user water control [28], [63]. Figure 1-15 shows the system configuration of micro-hydropower. A pressure generation unit is allocated per crew and placed in the stope, at least 20 m but no more than 90 m from the face.

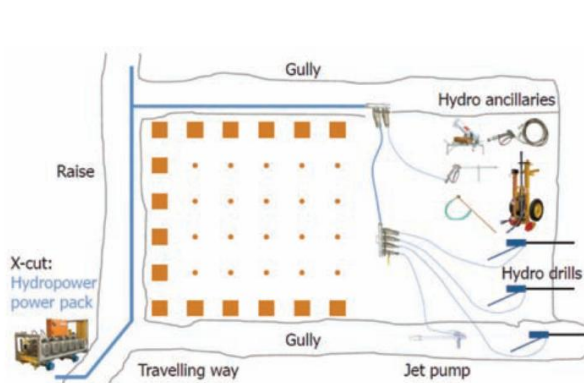


Figure 1-14: Localised hydro-powered stoping configuration (Adapted from [53])

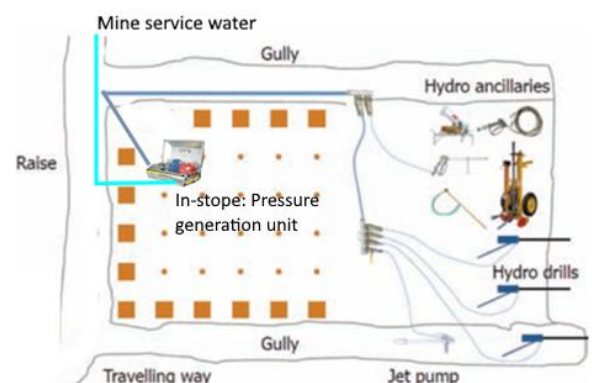
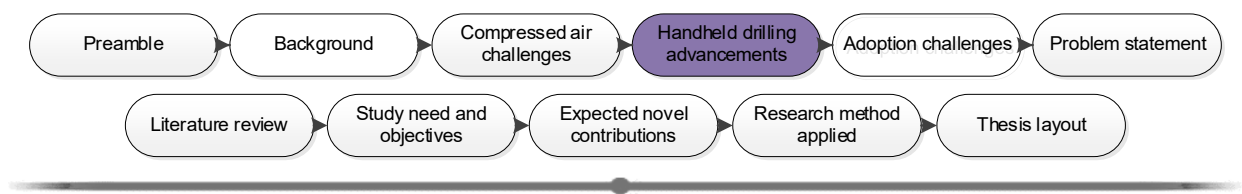


Figure 1-15: Micro-hydropower layout (Adapted from [53])

System performance: The overall efficiency of localised systems is estimated to be 23%, which equates to roughly a 20% improvement for a compressed air system used at a mature mine [28], while microsystems arguably have the best positional efficiency of around 24% due to optimal placement close to the face [28]. Leaks are managed automatically by either system since it is designed to trip when leaks are present [49], [63]. The Isidingo rock drill design challenge yielded a light-weight (18 kg) hydropower rock drill to encourage the development of non-compressed air rock drills [9]. Prototype development was initiated through a joint venture among the South African Council for Scientific and Industrial Research (CSIR), the Mandela Mining Precinct (MMP), and the Minerals Council of South Africa (MCSA).

Localised and micro-hydropower drilling systems also fall in the low-energy consumer class, absorbing up to 2.66 kWh per metre drilled [28], [49]. The reduced energy consumption might result in an 86% energy saving compared to compressed air drilling under similar operating conditions [48], [49], [62].



Pressure generation units are equipped with mechanical loader-unloader valves or variable speed drives (VSDs) to maintain system pressure without dumping water onto the footwall [9], [62]. This means the system will maintain pressure based on user demand, entering an idle state when no demand is detected.

System maintenance and versatility: With localised systems, system maintenance is done with relative ease since pumps are located in the cross-cut [28]. Clustered pumps also offer built-in redundancy, as the system design allows the exchange of pumps and motors during a drilling shift without disrupting production. Crew moves are facilitated with ease by extending the supply line to the new panel.

Unlike localised systems, microsystems are challenging to maintain in their locality on the reef horizon [41]. With microsystems, power packs typically weigh 1.3 tonnes and require rigging crews to mobilise them. Microsystems are expected to have a high-risk rating for lost blasts when system failures occur. Microsystems also require regular forward movements to remain within the locality limits of 90 m.

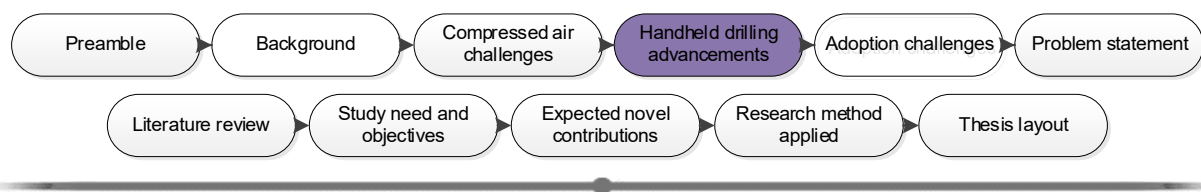
Critical spares, such as motors and pumps, need to be rigged into the workplaces via the centre gully. This might take several days since the centre gully supplies several panels with material and channels ore into the ore passes. Crew moves are expected to be time-consuming since the entire system must be decommissioned, transported, installed, and commissioned at the new workplace.

System shortcomings: Localised systems are limited to applications where up to five panels are clustered in the same raise line. Scattered mining applications with isolated blocks of ground are impractical when using a localised system. The improved positional efficiency comes at the cost of introducing additional electrical load and, ultimately, heat sources into the stope of 55 kW to 75 kW per pressure generation unit introduced [27], [49]. The additional electrical load might correlate to an increase of up to 0.6 °C per panel in ambient wet-bulb temperature [31].

With microsystems, power packs typically weigh 1.3 tonnes and require rigger crews to mobilise them. Microsystems carry a high risk of lost blasts due to the difficulties of maintaining equipment on the reef horizon. The improved positional efficiency comes at the cost of introducing additional heat sources into the stope, with 55 kW to 75 kW per power pack introduced. For five panels, this equates to between 275 kW and 375 kW.

Electric drilling systems (1999–2008)

Although hydropower is now considered a mature alternative with a proven track record, water consumption remains a concern for water-scarce operations or water-sensitive orebodies. As a



result, Anglo American, in collaboration with Hilti Power Tools, initiated development of an electric rock drill in 1999 [55].

Layout configuration: A typical stope layout for electric rock drills is depicted in Figure 1-16. The 2.2 kW Hilti TE MD20 electric handheld rock drill, as illustrated in Figure 1-17, is powered by an electrical supply box in the stope. The requirement is 240 V, 50–60 Hz [64]. A single gully supplies power to four rock drills and is reticulated to them via an armoured cable. Low-pressure water (at least 3 bar) is used in the pusher leg to provide thrust, cool the drill, and flush and cool the drill bit [30].

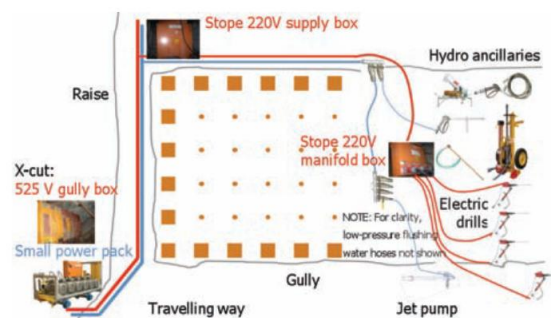


Figure 1-16: Electric drilling layout (Adapted from [53])



Figure 1-17: Electric rock drill (Adapted from [55])

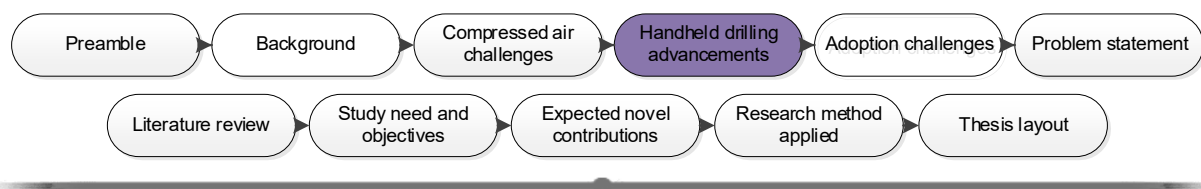
System maintenance and versatility: Electrical alternative technology only offered rock drills; therefore, either compressed air or hydropower ancillary equipment is required [53]. Rock drill maintenance was performed in underground workshops by specialised technicians.

Performance: The Hilti drilling system boasts the highest overall energy efficiency, estimated at 31%. Consequently, these systems have the lowest electrical energy consumption, only 0.24 kWh per metre drilled [28]. Unfortunately, compressed air drilling performance proved to be superior [55].

System drawbacks, including poor performance and high operational costs, prevented the drills from being widely adopted and have led to them no longer being commercially available [55], [65], [66].

Electro-hydraulic drilling (2014–present)

Electric rock drills failed to provide a solution to the hydropower system constraints highlighted earlier. In response, an electro-hydraulic in-stope drilling system was jointly developed by Anglo American Platinum and Epiroc [66]. The effort resulted in what is today known as the HRD100 system, as illustrated in Figure 1-18.



Layout configuration: Figure 1-19 provides an overview of the HRD100 system layout. The system comprises a power pack, rock drill, and water-powered thrust leg [67]. A gully box supplies 525 V to the power pack via an electrical cable. A pilot wire system is incorporated for earth supervision and emergency cut-off. The 10 kW power pack generates high-pressure (110 bar) hydraulic fluid to power the drill. Supply and return hoses deliver oil to and from the drill. A third hose supplies water. The water is used to cool the oil, the drill, and the drill bit; to flush the hole; and to provide thrust.

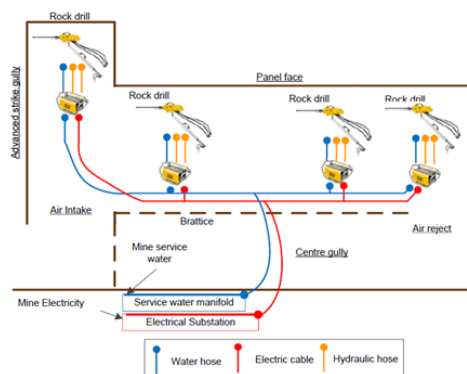


Figure 1-18: Electro-hydraulic drilling layout
(Adapted from [31])

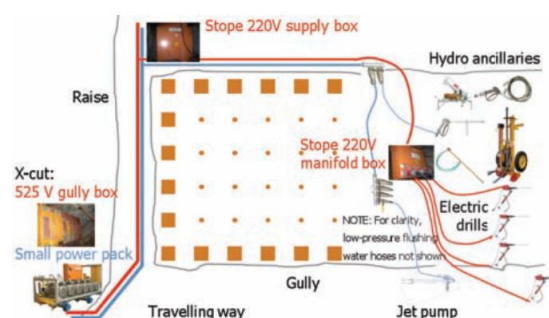
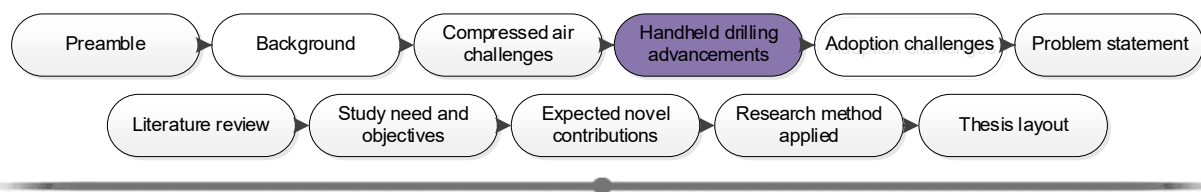


Figure 1-19: Electro-hydraulic drilling equipment configuration
(Adapted from [53])

System maintenance and versatility: Similar to electrical technology, electro-hydraulic equipment is serviced in underground workshops. The technology currently only offers a drilling solution, with no ancillary equipment available. This means that either compressed air or hydropower ancillary equipment is required to fulfil ancillary activities [53].

Performance: Overall system efficiency is estimated to be 24% [28]. Oil leaks are not tolerated, and the system automatically trips if detected. Oil-hydraulic drilling systems also fall within the low-energy consumer class, absorbing up to 0.55 kWh per metre drilled [66]. Penetration rates are similar to those of hydropower; one drill per 15 m of face length should suffice. In fact, electro-hydraulic technology offers performance identical to that of hydropower systems while requiring only a fraction of the water. Each drill requires a minimum of 0.2 l/s at a pressure of 3 bar, not more than 15 bar.

System drawbacks: The deployment of four electro-hydraulic HRD100 drilling systems introduces an additional 40 kW of electrical energy and heat. The equipment is heavier than its compressed-air counterparts. The power pack and drill-leg assembly weigh 45 kg and 28.5 kg, respectively. The rock drill controls are entirely different from their hydraulic and pneumatic counterparts.



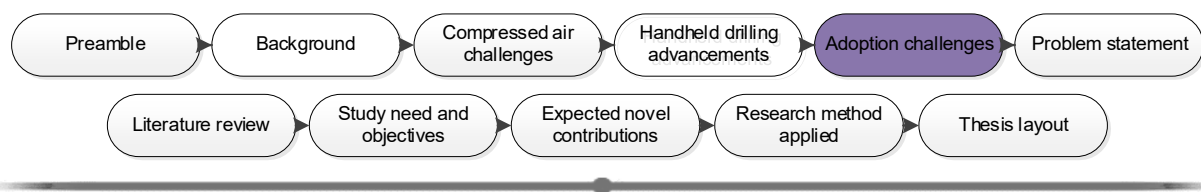
Overall alternative technology summary

[Section 1.3](#) highlighted two fundamental challenges threatening production sustainability when using compressed air to drill blastholes, namely:

- The cost and availability of electricity,
- Inadequate drilling performance due to network inefficiencies.

The alternative drilling technologies (ADTs) review showcased the following five improved benefits to address these two fundamental challenges, including:

- (1) **Energy efficiency:** Hydropower and electro-hydraulic drilling technologies boast improved efficiencies of up to 24% compared to the 2% of compressed air systems [48]. This might reduce the overall amount of electricity consumed during the drilling shift.
- (2) **Improved penetration rates:** The significant increase in efficiency results in more energy being supplied to the drill. This leads to an increased percussive power of 6 kW compared to 1.6 kW for a worn compressed air drill [60]. Thus, enabling operators to consistently complete blasthole drilling at reduced drilling cycle times, resulting in improved production [9].
- (3) **Absenteeism:** Improved penetration allows for the production face to be drilled faster [48], [66], [68]. Shortened drilling cycle times may decrease the mine's absenteeism rate, as operator fatigue is expected to reduce.
- (4) **Reduced exposure time to risk and occupational illness:** Since alternatives enable blastholes and roof bolt holes to be drilled more quickly, the exposure time to risk and occupational illnesses (i. e. noised induced hearing loss or white-knuckle disease) may be reduced notably [9], [51], [56]. Furthermore, available literature supports that hydropower rock drills emit lower noise levels [51], [56].
- (5) **Improved environmental conditions:** Grease is used to lubricate the internal parts of pneumatic rock drills. Inhalable grease particles are exhausted into the occupational environment, a phenomenon known as fogging. Alternatives use different lubrication. Hence, the absence of fogging improves visibility and reduces water contamination [60].



1.5. Major organisational changes required and adoption challenges

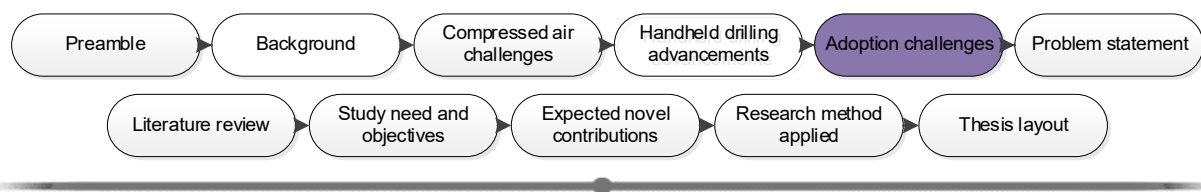
At this point, the existence of ADT has been established, offering improved benefits to address the challenges associated with compressed air. However, [Section 1.4](#) highlighted several significant organisational changes required when converting from a conventional compressed air drilling system, including:

- (1) **Rock drill ergonomics:** Control levers look and feel different. Control placement and sensitivity, as well as overall assembly manoeuvrability, are some of the ergonomic challenges operators need to adapt to [32], [64], [69].
- (2) **Support network infrastructure upgrades:** Instantaneous water consumption increases, requiring additional electrical supply infrastructure [48], [66], [70].
- (3) **Operational procedures and safety standards:** Since ADT uses different motive energy sources, updates to operational procedures and safety standards are required [32], [64], [69], [71]. As an example, the instantaneous increase in water consumption increases the risk for mud rushes if adequate water control standards and procedures are not in place [12], [72].
- (4) **Maintenance procedures and engineering support:** The complexity of maintenance procedures and engineering support increases when moving away from a central compressed air supply line [14], [48], [66], [70].
- (5) **Mining cycle impact:** Improved face advance rates induced by improved drilling rates affect the support and cleaning cycle [71].
- (6) **Heat load:** The improved positional efficiency offered by ATDs comes at the cost of introducing additional electrical load. This operational change might correlate to an increase of up to 0.6 °C per panel in ambient wet-bulb temperature [31].

General managers from eight notable South African gold mines in need of an alternative drilling system were asked to share their views on the forecasted challenges associated with these five major organisational changes. The following five significant adoption challenges were highlighted.

Challenge 1: Change resistance

Regardless of the benefits and value of alternative technology, numerous attempts in recent years to introduce alternatives have resulted in disappointing failures [5], [14], [73], [74], [75], [76]. Since South African gold mines are known for being notoriously conservative, change in the production environment does not come easily, and resistance to change is guaranteed [55].



Changes to rock drill ergonomics, operational procedures, and maintenance support will induce resistance to change, including:

“The workforce has used compressed air handheld drills for the past century. Several humanistic resistance drivers will prevent the introduction and adoption of an alternative drill.” – **General Manager Mine A**

“Of all areas to introduce change, narrow reef stopes are the most difficult. All previous efforts to introduce alternative drilling technology over the past 30 years resulted in disappointing failures.” – **General Manager Mine C**

“My on-shaft team is not geared up to handle transformation efforts as complex as converting a mine from conventional drilling to an alternative.” – **General Manager Mine D**

Challenge 2: The lack of independently verified cost and performance data of hydropower drilling systems

The lack of independently verified cost and performance data surfaced as a notable challenge to adoption. General managers highlighted the following important points:

“We cannot afford the severe production losses associated with the implementation and transformation phase when introducing alternative drilling technology.” – **General Manager Mine B**

“Alternative drilling technology is way more expensive to acquire and operate. We cannot afford it.” – **General Manager Mine F**

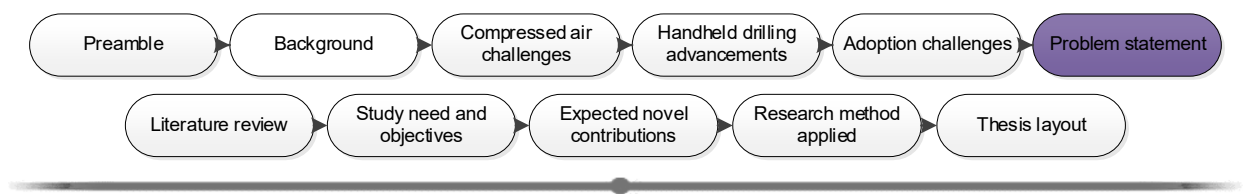
“First convince me with reliable & consistent performance and corresponding cost data, independent from what the OEM supplier claims, then I’ll consider it.” – **General Manager Mine I**

“Where do I start? Which system configuration is best, localised or micro in-stope applications? How do I prioritise workplaces during the implementation phase?” – **General Manager Mine E**

Challenge 3: Workplace prioritisation during the transformation phase

It was suggested that initiatives to implement ADTs fail to commence due to the lack of a strategy to prioritise workplaces during the implementation phase.

“How do I prioritise workplaces during roll-out?” – **General Manager Mine E**



Challenge 4: Inadequate water and electrical infrastructure to support the alternative

Critical design changes to water and electrical infrastructure may be required to support the ADT:

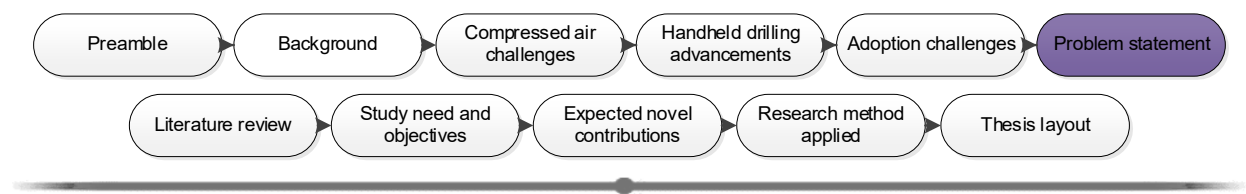
“It is believed that hydropower systems use three times more water compared to compressed air. Ore passes, cross-cuts, and return water dams will flood. Furthermore, our electrical network will become unstable when moving the pressure generation units underground.” – **General Manager Mine G**

Challenge 5: Hydropower drilling systems will have an adverse effect on the shaft call factor

Up to 50% of the gold content is present in fragments smaller than 2 millimetres. As a result, there is concern that the increased water used by hydropower drilling technologies will wash away the gold content, as noted by a general manager:

“The increased amounts of water introduced with hydropower will wash away the fine gold and reduce the operation’s shaft call factor.” – **General Manager Mine H**

Challenge 5, on the contrary, is a common myth in the mining industry, and was corrected in 1997 by the work published by De Jager [77], [78]. De Jager concluded at the time that shaft call factor discrepancies are mainly driven by accumulations in the gullies and sweepings left in the back areas, and not due to gold washed away by water. Two recent studies completed by Nelwamondo (2018) and Schwartz (2022) support De Jager’s conclusion [79], [80]. As a result, challenge 5 will not be focused on by this study.



1.6. Problem statement

It follows from [Section 1.3](#) that, from a techno-economic perspective, compressed air drilling systems were the preferred choice in the 1960s. Workplaces were located close to the shaft and drilling performance was adequate to support consistent blasthole drilling. However, as operations matured over the past 60 years, workplaces migrated several kilometres from the shaft. Compressed air network inefficiencies (i. e. leaks and mismanagement) became immense, and drilling performance deteriorated to a point where efficient blasthole drilling became a notable constraint. In turn, due to shorter face times from increased drilling time, mines fail to meet production targets, and sustainability is threatened by severe production losses.

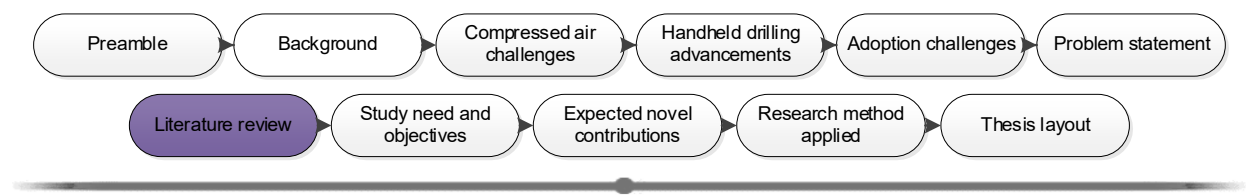
This challenge was foreseen in the early 1970s, which led to the development of numerous alternative drilling technologies (ADTs). However, the majority of South African mines are still using pneumatic rock drills as highlighted by Figure 1-5. The adoption challenges discussed in [Section 1.5](#) highlighted the following overall problem:

Problem identified:

The sustainability of some mature deep-level gold mines is challenged by:

- **The high electricity costs associated with running large industrial compressors to support blasthole drilling, and**
- **Compressed air network inefficiencies (i. e. leaks and mismanagement) are preventing the faces from being blasted as called for by the production schedule.**

[Section 1.5](#) provided an overview of the predicted major humanistic and systemic changes required when implementing an ADT. The perceived lack of a pragmatic approach to manage these changes emerged from the interactions with the General Managers highlighted in [Section 1.5](#). As a result, an in-depth understanding is developed from the literature on the humanistic and systemic drivers of resistance to change encountered when organisational change is introduced, as well as previous efforts to address it.



1.7. Lessons learned from past failures: Literature review

Preamble

Strategic resilience is not about avoiding failure but about leveraging it as a foundational element in formulating new implementation methodologies. Past failures hold valuable lessons.

A comprehensive literature review was conducted to analyse numerous publications and ascertain the methods used in previous attempts to introduce ADT into the South African narrow-reef mining industry. Keywords and combinations were used to search published work in peer-reviewed credible sources, including ScienceDirect, EBSCOHost, SpringerLink, Scopus, Web of Science, Google Scholar and Sabinet. The keywords included: “alternative in-stope drilling technology”, “hydropower drilling”, “electric drilling”, “electro-hydraulic drilling”, “new mine technology implementation”, “mine change management process”, “technology and knowledge transfer strategies”, “mine services simulations”, “narrow reef deep-level gold mining technology”, “humanistic change resistance” and “systemic change resistance”.

Since mature narrow-reef deep-level gold mines are largely unique to South Africa, information on in-stope handheld ADTs was found to be limited. A total of 126 studies were reviewed as part of the comprehensive literature review. All topic-related published literature available from 1930 to 2024 was considered. Figure 1-20 presents an overview of the literature review structure applied.

The literature review was structured to first identify universal humanistic change resistance drivers (Part A) that commonly exist across various industries (such as manufacturing, healthcare, and information technology). Consequently, Part B analyses the systemic resistance drivers. Part C presents an in-depth review of previous attempts to implement ADT, identifying existing methods to address the resistance drivers. A state-of-the-art overview is presented in Part D to highlight shortcomings identified in prior literature.

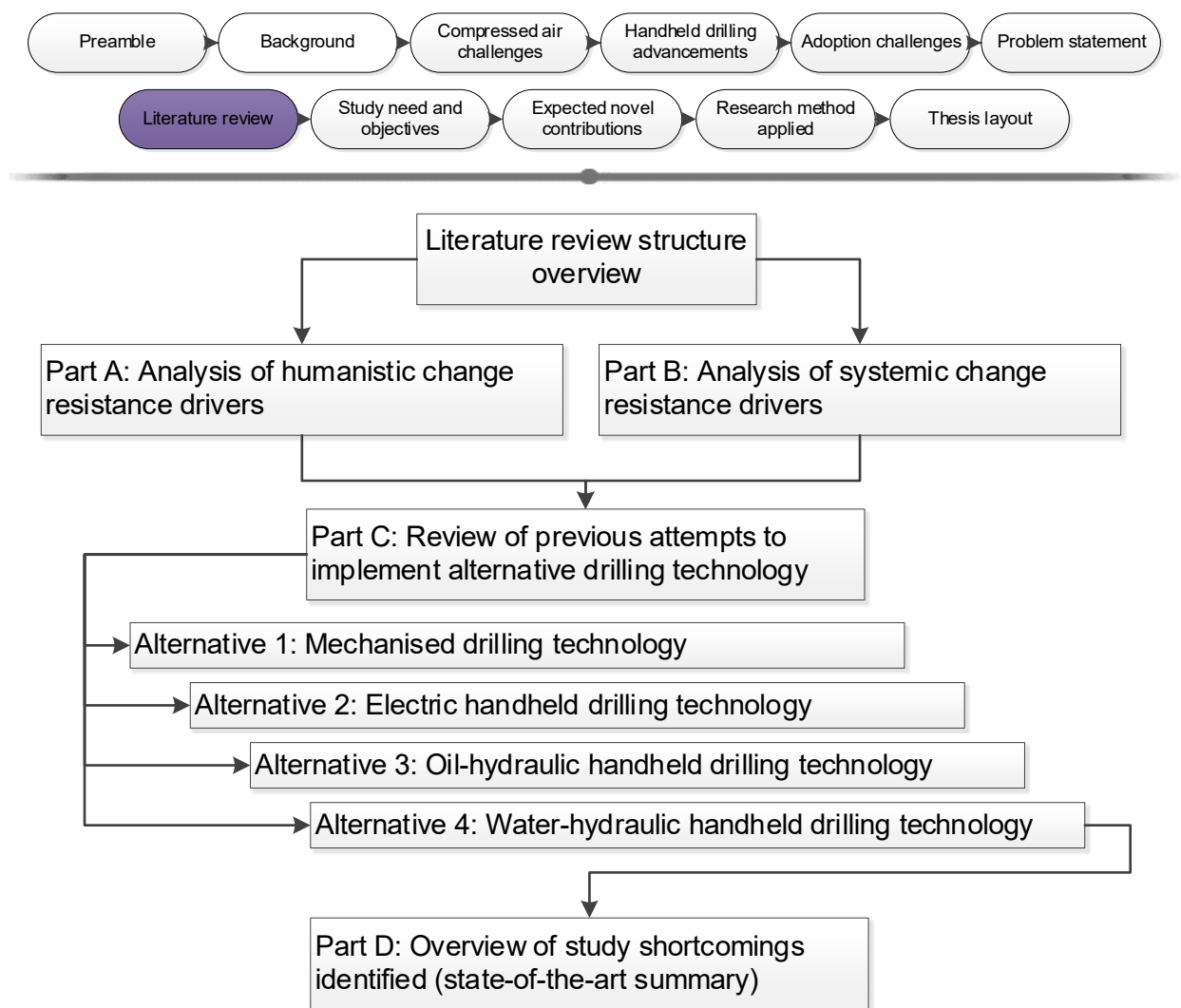


Figure 1-20: Literature review structure overview

Part A: Humanistic resistance drivers – Stakeholders’ reaction to organisational change

Part A uncovers the universal humanistic resistance drivers (HRDs) commonly encountered when major organisational changes are introduced. During the past two decades, several researchers have devoted considerable interest to understanding resistance to organisational change. Thirty of the studies reported extensively on humanistic resistance drivers. It was found that these drivers typically result from the cognitive and behavioural reactions of change recipients towards change. An overall findings summary is presented in Figure 1-21. It follows that the following four humanistic resistance drivers are generally encountered:

- HRD1: Perceptions,
- HRD2: Leadership,
- HRD3: Change willingness, and
- HRD4: Emotional wellness.

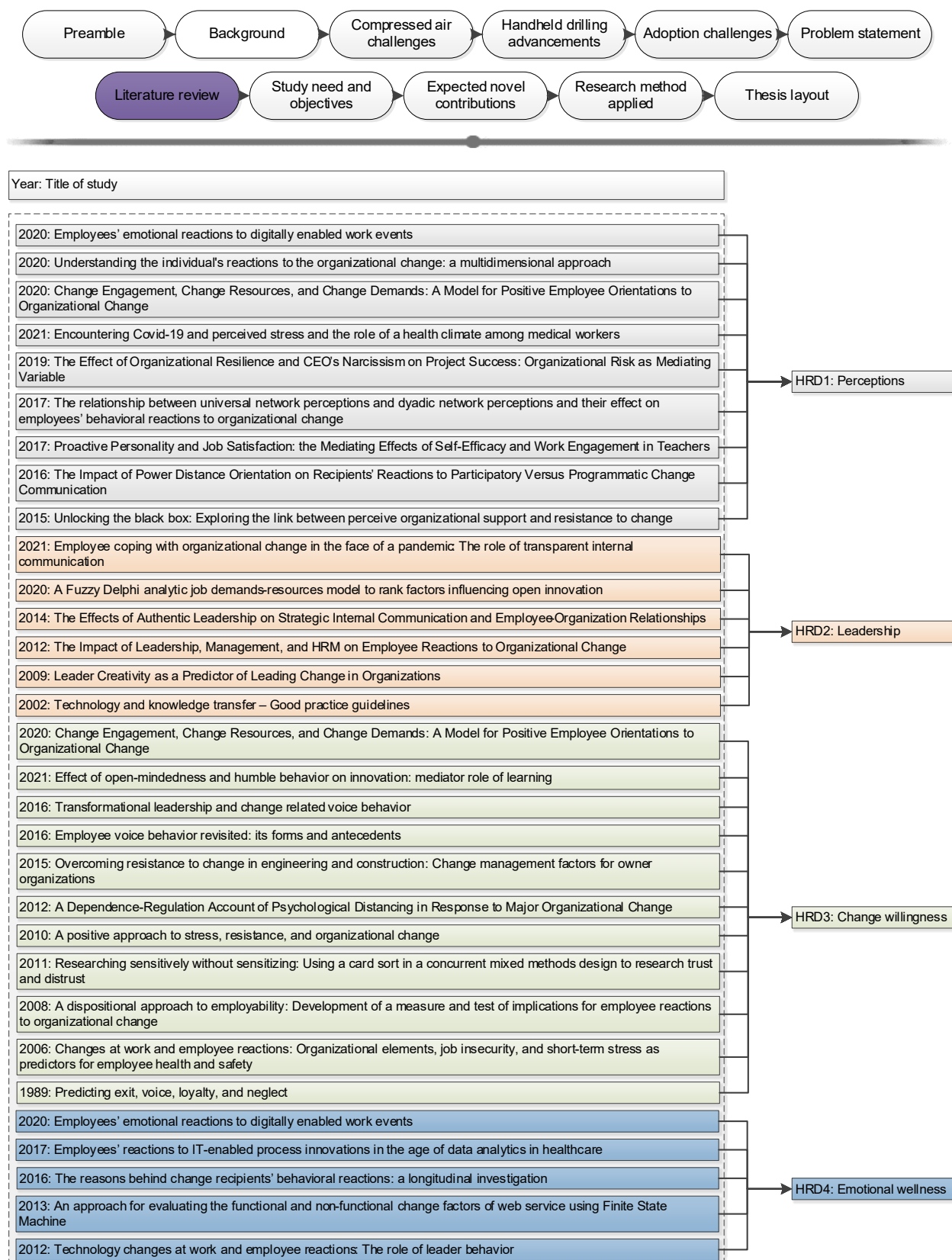
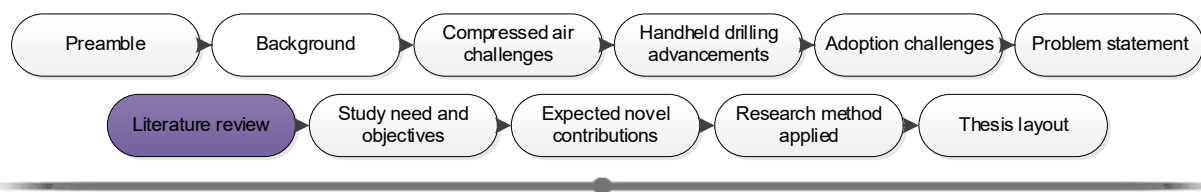


Figure 1-21: Humanistic resistance drivers⁹

HRD1: Passive leadership styles

Organisational support can either encourage or diminish employees' willingness to change [81], [82]. Credibility and trust are essential elements for leaders to promote [83]. It validates that employee interests are considered [84]. The often short tenure of leaders in some industries

⁹ Detailed reference list available in Appendix A.



frequently results in an unwillingness to support the transformation effort [85], [86]. This is simply because employees may not be in a position to enjoy the benefits [85]. Consequently, leaders fail to inspire employees and increase positive employee reactions [87], [88]. This leads to resistance to change [87].

HRD 2: False perceptions

Various researchers have observed a clear relationship between stakeholders' reactions to organisational change and their perceptions of the change [89], [90], [91]. Helpap [92] highlighted that stakeholders react more positively if their perceptions align with their expectations. On the contrary, negative reactions to the change are frequently observed when it is believed that the change will result in a greater workload, fatigue, and job uncertainty [93]. Albrecht *et al.* [94] and Hatjidis and Parker [95] agree that one of the greatest challenges for change managers is aligning perceptions and expectations.

HRD3: Unwillingness to change

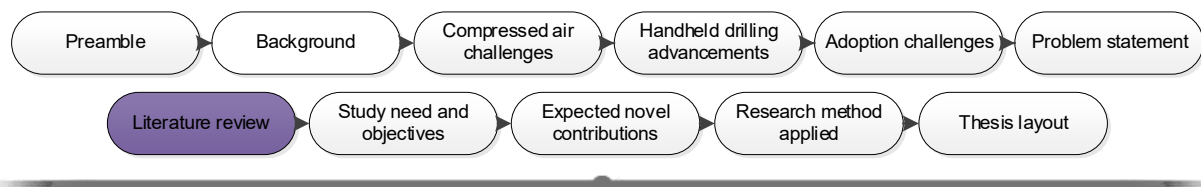
Stakeholders' understanding of the change vision is the key driver of willingness to change [96], [97], [98], [99]. Attitudes, beliefs, and feelings are influenced by the change vision, promoting either positive or negative reactions [100], [101]. Albrecht *et al.* [94] advocated that stakeholders are generally unwilling to change when the need for change and its benefits are unclear. In such cases, a negative attitude towards the change prevails. What typically follows are decreased work quality and increased absenteeism [102]. Unwillingness may increase further if stakeholders feel psychologically unsafe and uncertain about their resources to cope with the change [103]. Specifically, when a change affecting the whole organisation is applied rapidly [93], [104].

HRD4: Emotional wellness

Absolute fear is the most common emotional response when new technology is introduced [93], [105], [106], [107], [108]. Employees experience severe levels of anxiety and stress when they need to operate new, unfamiliar technology. This results in a severe resistance to change, especially if significant changes are implemented. Various researchers concluded that when fear of job security prevails, there is less job satisfaction and a reduced level of motivation [57], [58], [59]. Ultimately, employees may start to undermine their work tasks [109].

Part B: Systematic failure drivers – Inadequate change management processes

The remaining studies reported on previous failures to introduce new technology in South African mines [5], [14], [73], [74], [75], [76], [85], [110]. These failures were usually not driven by the technology itself but by inadequate change management [5]. Managing change entails



understanding, handling, and simplifying the process's complexity into a comprehensive change strategy [111]. The goal of this section of the literature review was to identify and understand the drivers of typical systemic failures in previous attempts.

Figure 1-22 illustrates the attempted technology and the associated systemic failure drivers (SFDs). Four phases exist during the transformation process, namely: change initialisation, implementation, review and integration [112], [113].

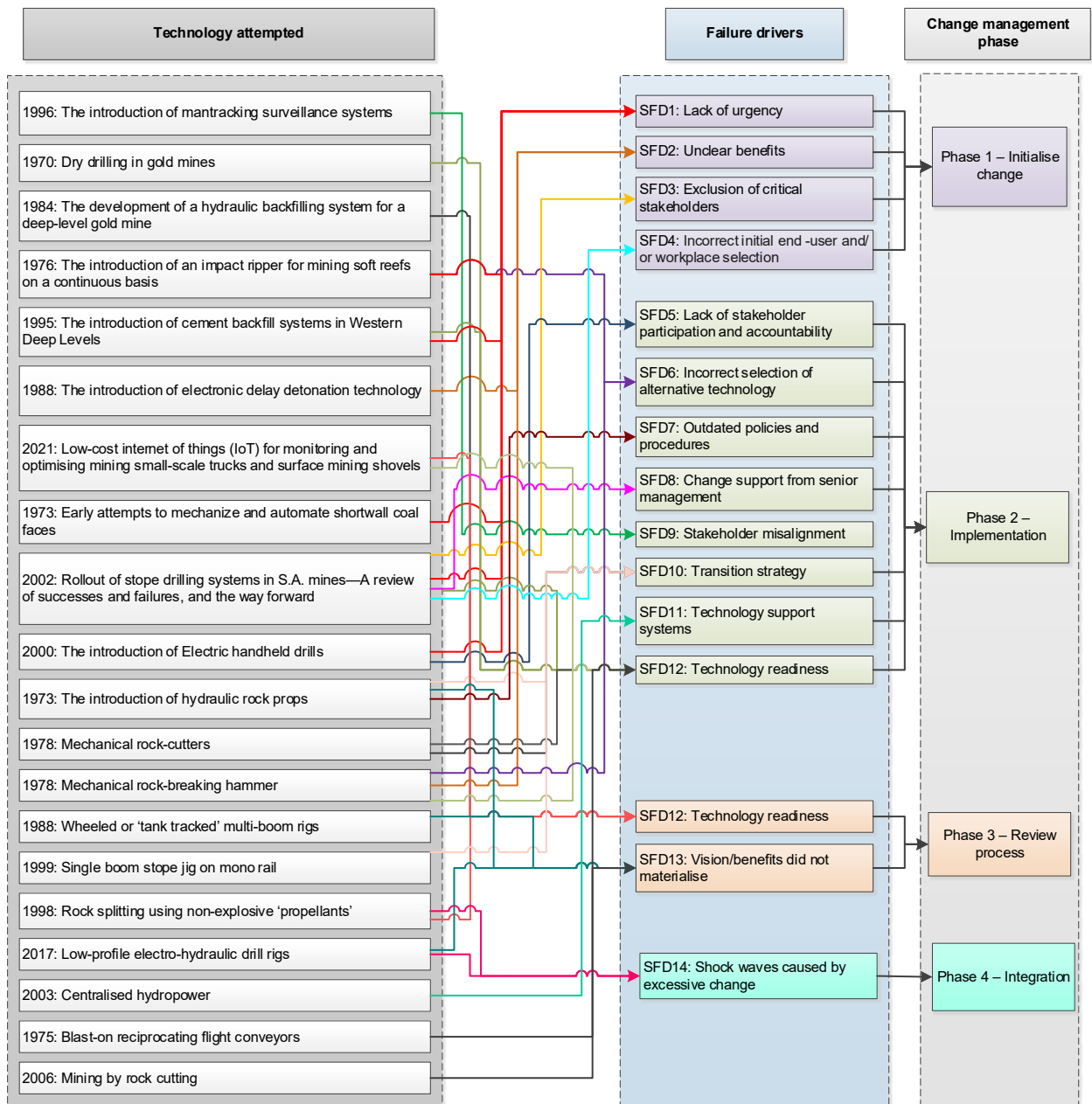
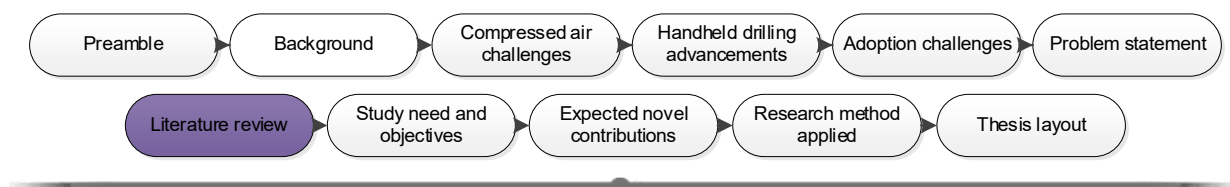


Figure 1-22: Systematic failure drivers identified¹⁰

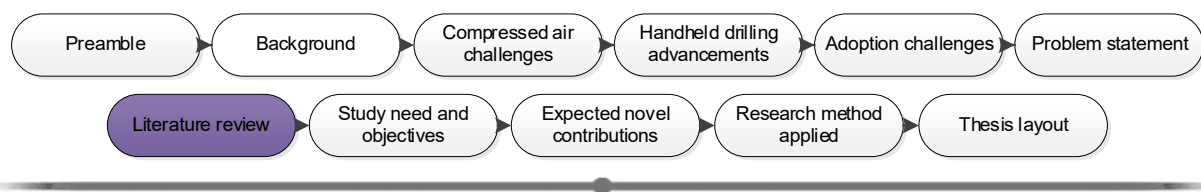
¹⁰ Detailed reference list available in Appendix A.



The following is essential to note from Figure 1-22. Fourteen failure drivers were identified, four of which were part of the initiation phase. The implementation phase included eight drivers, while the remaining three were identified in the review and integration phases. Each driver is discussed in Table 1-1.

Table 1-1: Systematic failure drivers

Failure driver	Critical finding
SFD1: Lack of urgency	- Stakeholders are reluctant to participate in transformation efforts if the urgency for change is unclear. - A sense of urgency to change needs to be clear.
SFD2: Unclear vision of benefits	- Since change benefits generally promote stakeholder buy-in, transformation efforts tend to fail when the change benefits are unclear. - Change vision must be easy for all stakeholders to comprehend.
SFD3: Exclusion of critical role players	- Failure to identify and include all stakeholders self-sufficiently leads to change rejection. - A conscientious stakeholder analysis is of paramount importance to identify all role players.
SFD4: Incorrect initial end user and/or workplace selection	- Mine management traditionally believes that if the technology works under the worst conditions with the least experienced crew, it will work anywhere. - Such a mindset sets the transformation effort up for failure from the very beginning. - Ideally, the initial crew must be young, energetic and open-minded.
SFD5: Lack of stakeholder participation and accountability	- Technology adoption involves stakeholder participation and accountability. - Roles and responsibilities must be clearly defined.
SFD6: Incorrect selection of alternative technology	- Technology must be compatible with the operations' geotechnical environment. - Drastic changes in ergonomics must be avoided.
SFD7: No updates to policies and procedures	- End user uncertainty regarding changes in performance bonuses, staff cuts, and other factors enhances resistance to change. - Policies and procedures need to be updated.



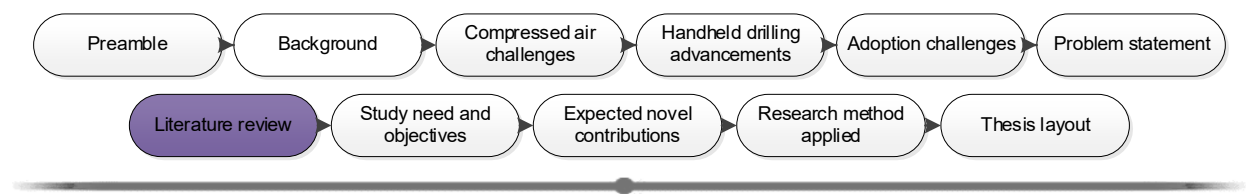
Failure driver	Critical finding
SFD8: Change support from senior management	- Mine management is not adequately trained to manage complex roll-outs of new technology. - Production targets are generally the primary focus for senior management. - A project champion is needed who is independent of production targets, skilled at handling human aspects, fluent in interpersonal communication, and part of line management with the authority to see the project through
SFD9: Stakeholder misalignment	- Misalignment between stakeholders' roles and responsibilities, caused by a lack of interpersonal communication, was identified as the most common derailment. - A strategy is needed to align stakeholders and maintain alignment.
SFD10: Transition strategy	- Inadequate transfer of knowledge, skills, policies and procedures during the training phase. - The change management method needs to include a transition strategy to provide structure and guidance to stakeholders.
SFD11: Technology support systems	- Transformation efforts most often fail when engineering support and services, such as water and electricity, are lacking.
SFD12: Technology readiness	- Technology must be fully functional, reliable and straightforward with little to no changes required. - Mature technologies are preferable.
SFD13: Vision/benefits did not materialise	- Change rejection typically follows when stakeholders fail to first prove the change on a small scale before attempting large-scale roll-outs.
SFD14: Shock waves caused by excessive change	- Dramatic changes adversely affect production and safety, consequently forcing management to halt further roll-outs. - A gradual approach is recommended to introduce the change.

Part C: Review of published work on attempts to introduce ADTs

To understand what had been done previously to overcome these industry-specific, humanistic, and systemic resistance drivers, published work on earlier attempts to introduce ADTs was reviewed. Literature on narrow reef mines was examined based on the following criteria:

- Did the study present an implementation and change management strategy focused on addressing these failure drivers?
- Did the study provide an independently verified techno-economic assessment to confirm the OEM supplier's claimed benefits?

Four ADTs were identified and reviewed from the literature, namely: mechanised, electric, oil-hydraulic and water-hydraulic technologies.



Alternative 1: Mechanised drilling technology

Overview: The review included 22 initiatives aimed at mechanising narrow reef stopes since 1975. These initiatives included stope drill rigs, drill guides, dozers, and rock cutters. The study conducted by Fourie *et al.* [76] in 2017 was the latest attempt to apply mechanised drilling technology to narrow reef stopes. The researchers tested ultra-low-profile (0.9–1.2 m) mechanised drill rigs and dozers in a narrow reef platinum stope. However, the study's outcome presented similar results to those of various other researchers who concluded that introducing mechanised drilling technology in narrow reef stopes was beneficial.

Key findings: The findings have shown that the ever-existing challenges associated with mechanised narrow reef mining equipment are yet to be solved, including:

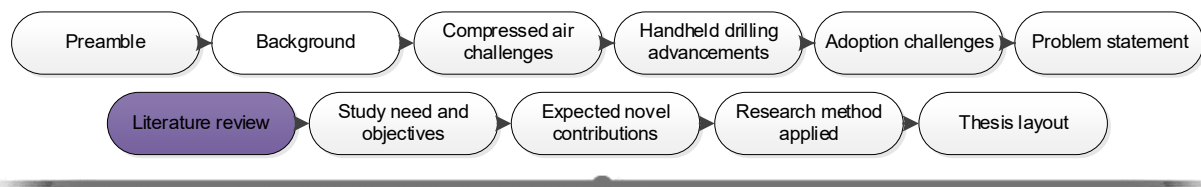
- Highly skilled operators and maintenance personnel are required [6], [68], [76], [114].
- Capital expenditure (capex) and operational expenditure (opex) are disproportionately high compared to conventional handheld drilling [12], [27], [66], [115].
- Unlike handheld drilling, mechanised equipment is incompatible with steep dipping stopes (those with an incline of more than 22°) [9], [18], [115], [116].
- Inability to mine along narrow reef geological discontinuities using the equipment [2], [14], [56], [74], [75].

Study shortcomings of mechanised drilling technology: Fourie *et al.* [74] presented an implementation and change management strategy. However, it focused explicitly on the introduction of mechanised drilling technology. The costs required operator skill, and incompatibility with South Africa's narrow reef gold mining environments eliminate mechanised equipment as a feasible alternative to handheld compressed air drilling.

Alternative 2: Electrical handheld drilling technology

Overview: Seven published sources reporting on electrical handheld drilling technology were reviewed [48], [51], [54], [55], [64], [65], [117]. Van Jaarsveld and Ebben [64] published the most recent paper on electrical drilling technology in 2008. The paper reviewed the development and implementation of Hilti electrical handheld rock drills in narrow reef gold mines. A detailed techno-economic assessment was presented by Petit [114] to benchmark the performance and cost benefits of using electrical rock drills in platinum mines. Overall, the seven studies concluded in the following key findings.

Key findings: Three key performance indicators (KPIs) were identified for the techno-economical assessments: (i) safety, health and occupational environment (SHE), (iii) performance, and (iii) opex.



- **SHE:** Noise, weight and visibility were evaluated. The results presented conclusive evidence that electric drills were less noisy, easier to manoeuvre, provided mist-free drilling and were lighter than their pneumatic counterparts [51], [54], [64], [65], [117].
- **Performance:** Production requirements were not met. Power-to-weight limitations and reliability challenges resulted in poor drilling performance, and an increase in drilling shift time was observed [48], [51], [54], [55], [64], [65], [117]. As a result, operators failed to adopt the technology.
- **Opex:** Total operating expenses were reported to be 5.5 times higher than for compressed air [64]. Due to poor performance and higher operational costs, management disregarded the technology from a techno-economic perspective as a feasible replacement for compressed air handheld drilling.

Study limitations of electrical drilling technology: The studies reviewed presented valuable KPIs that can be used when performing a techno-economic assessment. However, Hilti electrical handheld rock drills are no longer commercially available due to their limited performance and high operational costs.

Alternative 3: Oil-hydraulic handheld drilling technology

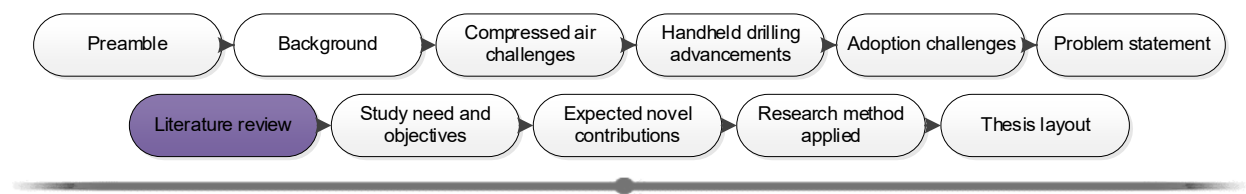
Four published sources were identified that reported on the application of oil-hydraulic drilling technology in deep-level gold mines.

Marshall et al. (1975) [27]

Overview: Marshall *et al.* [27] performed what appears to be the first comparative review of oil-hydraulic and compressed air rock drills in 1975. Their overall recommendation at the time was that oil-hydraulic rock drills should not be regarded as a substitute for compressed air rock drills.

Key findings: The identified disadvantages of electro-hydraulic systems include:

- **Power supply:** There is a greater need for a reliable power supply near the workplace, as pressure generation units must be close to the drills to achieve optimum efficiency.
- **Water quality:** Due to acceptable component clearances, the technology is vulnerable to dirt present in the service water.
- **End user skill set:** Control levels and component clearances differ, resulting in greater complexity for operation and maintenance.
- **Heat load:** The introduction of pressure generation units near the workplace releases additional heat into the working environment. Incidentally, additional cooling is needed to offset the heat generated.



- **Reliability:** Concerns regarding the inability of oil-hydraulic systems to tolerate dirt remain an unsolved technical challenge, preventing large-scale adoption.

Study limitations: The study did not present an implementation and change management strategy, nor did it conduct a techno-economic assessment of the technology.

Clement (1975) [70]

Overview: In response to the work published by Marshall *et al.* [27], Clement investigated the magnitude of the increased heat load when substituting compressed air rock drills with oil-hydraulic counterparts. The study concluded with the following key findings.

Key findings: Clement estimated that an additional heat load of up to 10 kW per rock drill introduced would be present if compressed air rock drills were substituted with comparable oil-hydraulic counterparts. A third study published by Whillier [118] supported this observation. A further 5 kW of cooling per rock drill, attributed to the flow and expansion of compressed air, would be lost. Consequently, the workplace would require an additional 15 kW of cooling for each oil-hydraulic rock drill introduced. This equates to an overall increase in cooling load of 180 kWh, given that the rock drills would operate for only four hours per day and that three rock drills were used to drill the 40 m face.

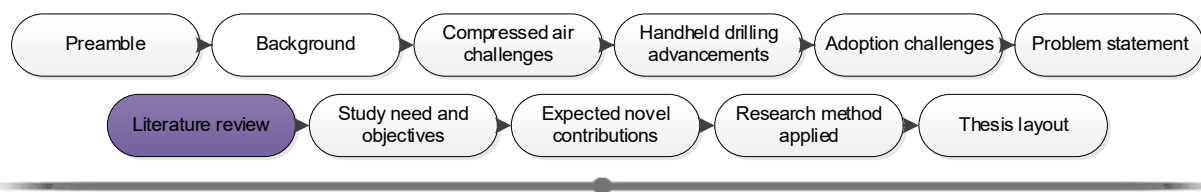
The results highlight the importance of accounting for the additional heat introduced, as workplaces with occupational temperatures close to the legal limit may be shut down if it is not removed.

Study limitations: The study focused on quantifying the additional cooling required to offset the heat generated by replacing compressed rock drills with oil-hydraulic counterparts. The study did not present an implementation and change management strategy, nor did it focus on a techno-economic assessment of the technology.

Fourie et al. (2017) [66]

Overview: Building on an understanding of the limitations of ultra-low-profile mechanised mining technology, Fourie *et al.* [66] tested an in-stope electro-hydraulic handheld drilling system in narrow reef platinum stopes. This paper, published in 2017, appeared to be the only published literature available on in-stope electro-hydraulic rock drills deployed in narrow tabular reefs; however, two other research papers reported on the use of the technology in development ends in the 1970s [27], [66].

Key outcomes: The study benchmarked the benefits of electro-hydraulic drilling technology against those of a compressed-air system using six KPIs. Table 1-2 showcases the results obtained, including:



- **SHE:** Electro-hydraulic drills were found to produce less mist and noise.
- **Performance:** The electro-hydraulic drilling speed in the Upper Group 2 Reef outperforms compressed air. As a result, only four rock drills, compared to six, are required to drill the face.
- **Instantaneous water consumption:** Electro-hydraulic drills offer the lowest water consumption.
- **Capex:** Electro-hydraulic equipment is 2.6 times more expensive than compressed air drilling equipment.
- **Opex:** Based on the business case presented in the study, it can be concluded that oil-hydraulic handheld drilling systems are comparable to their pneumatic counterparts. They are more efficient and yield improved drilling performance.
- **Reliability:** Concerns regarding an oil-hydraulic system's inability to tolerate dirt remain an unsolved technical challenge, preventing large-scale adoption. This specific limitation correlated with the findings presented by Marshall and Seawright [27] in 1975.

Table 1-2: Oil-hydraulic alternatives vs pneumatic benchmarking results [66]

KPI parameter	Unit	Compressed air	Electro-hydraulic
Penetration rate	m/min	0.45	1.1
Number of drills required per 30 m panel	-	6	4
Instantaneous water consumption	l/s	0.25	0.20
Capex cost per panel per day	R/drill/day	88	232
Opex cost per panel per day	R/drill/day	482	506

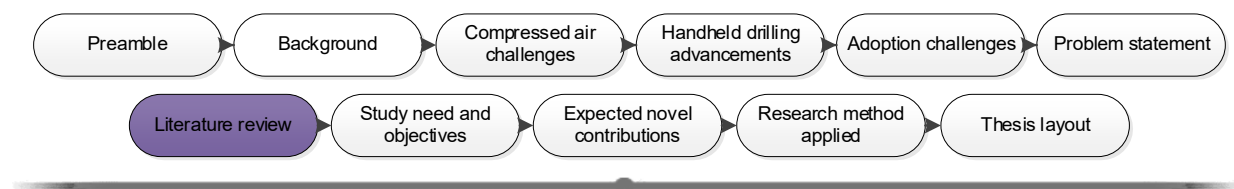
Study limitations: The data sets were not independently verified, as the authors were part of the technical team that developed the system. The study results cannot be applied to gold mines, as the study was conducted in a platinum stope. Additionally, the study did not include an implementation and change management strategy.

Alternative 4: Hydropower handheld drilling technology

The hydropower review comprised six recent studies obtained from the published literature, spanning the years 2006 to 2022.

Fraser (2006) [62]

Overview: Fraser [62], a design engineer for one of South Africa's most prominent hydropower original equipment manufacturers (OEMs), compiled a review of hydropower achievements, opportunities and challenges in 2006.



Key findings: At that time, Fraser attributed the most significant difference between South African and international hydropower technology to water quality. In South Africa, dirty mine water is used as hydraulic fluid, unlike closed-loop systems with high levels of filtration deployed elsewhere. Over the past 40 years, South African hydropower manufacturers have synchronised component tolerances and selected special materials to produce dirt-tolerant equipment. This limits the use of most off-the-shelf international hydropower equipment, confining the selection of equipment to South African OEMs.

Capex and opex were considered the Achilles heel of hydropower equipment at the time. The hydropower equipment was made of expensive stainless steel material, and the volumes produced were small. On the opex front, water hydraulics were hampered by the inability to reliably control water flow proportionally to user demand. Variable-displacement pumps did not exist, and proportional control valves were unreliable due to the erosive nature of high-pressure water on the valve seats.

Study limitations: The study only focused on hydropower achievements, opportunities, and challenges dating back to 2006.

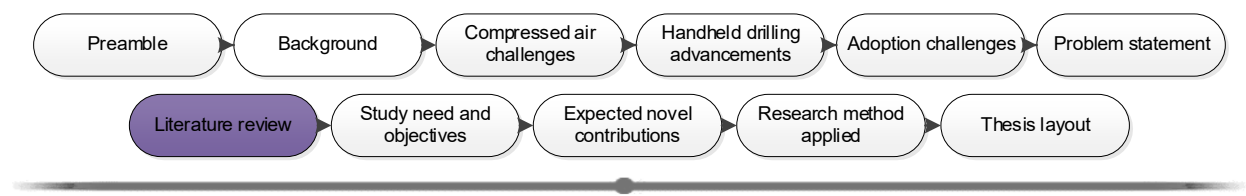
Kienle and Fraser. (2022) [49]

Overview: Kienle and Fraser [49], who are part of the directory team from one of South Africa's most prominent hydropower OEMs, conducted a study in 2022 to quantify the water and energy required for narrow reef mining using micro in-stope hydropower technology.

Key findings: The opex challenges highlighted in 2006 by Fraser [62] were addressed through digital hydraulics. Hydropower pumps are now equipped with unloader mechanisms controlled by programmable logic controllers (PLCs), which unload the pump when the drills are not operational. The results from this case study enable the mining industry to understand the hydraulic drilling performance of water in gold-bearing basal reef mines better. As shown in Table 1-3, the mining crew managed to drill a 30 m panel in only two hours, with an average collar-to-collar drilling time of 4.1 minutes per hole. The three-month average production achieved was measured at 477 m². Water consumption was reported to be 0.41 m³/tonne. The study reported that the energy consumed was 9.6 kW/drill.

Table 1-3: Hydropower drilling performance findings [49]

Performance parameter	Unit	Value
Water usage per tonne	m ³ /tonne	0.41
Energy used per drill	kW/drill	9.6
Drill time per 1.2 m deep hole	minutes	4.1
Drill operating time per drill per blast	hour	2.04
Production area mined (panel length: 30 m)	m ²	477



Study limitations: The sole focus of the study was to capture the performance metrics of micro-hydropower drilling systems. The results were not benchmarked against a compressed air system in the same production environment. The data presented was not verified independently, as the authors were part of the technical team that developed the system. Additionally, the study did not include an implementation and change management strategy.

Fraser (2010) [48]

Overview: In 2010, Fraser [48] set out to create a transparent and comprehensive methodology for calculating the water and energy required to drill a hole using handheld drilling in narrow reef orebodies. The energy mediums considered include compressed air, localised hydropower and electric drills.

Key outcomes: The study developed a conclusive and definitive method for quantifying drilling energy costs. The calculation comprehensively integrated all relevant energy-related factors, including drilling speed, number of drills per panel, blast design (hole density), pumping depth, dewatering pump efficiencies and refrigeration. It was concluded that, from a theoretical perspective, electric drills are the most energy efficient, followed by hydropower drills. However, the industry failed to buy into the theoretical results.

Study limitations: As highlighted in [Section 1.5](#), the industry has been slow to adopt the study findings, which are based solely on theoretical results published by the OEMs.

Fraser (2012) [63]

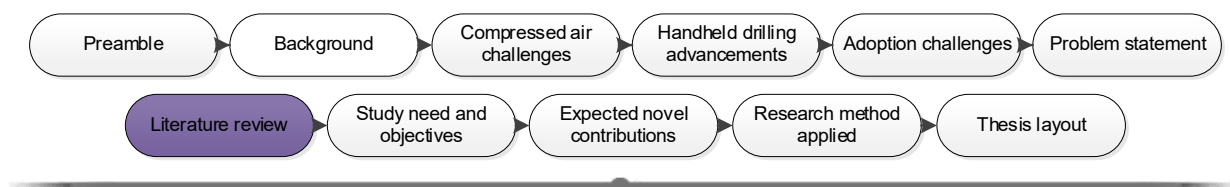
Overview: The focus of this study was to benchmark the operating costs of compressed air drilling against those of hydropower drilling.

Key outcomes: The total operating cost is 10% lower than for a pneumatic system. Examination of the cost breakdown reveals the following: The energy cost to power a hydropower drill is three times lower. Drill maintenance costs increased fivefold. Due to the increased drilling torque and thrust forces, the cost of bits and drill steel is expected to increase by 1.5 times.

Kienle et al. (2022) [9]

Overview: This paper provides detailed performance test results of a newly developed light-weight hydropower drill. The data was collected over six months in an underground platinum stope.

Key outcomes: The study reported improvements in safety, hole-to-hole drilling times, noise, vibration, water and energy usage, and operator acceptance. Although the drill weighs only 15.8 kg, it drills 2 to 3 times faster than its 23 kg pneumatic counterpart. The light-weight design



and improved performance resulted in immediate operator acceptance. Noise levels were reduced to 90.1 dB(A).

Study limitations: The study results cannot be applied to gold mines, as the study was conducted in a platinum stope. Additionally, the study did not include an implementation and change management strategy.

Petit and Fraser (2013) [53]

Overview: This paper aimed to provide a decision-making approach for selecting alternative drilling systems for stoping in narrow reef hard-rock mines. The study extensively considered 12 parameters to determine the best alternative energy medium for in-stope handheld drilling, including capex, opex, resulting financial returns, utility usage, production performance and life of mine. SHE concerns, along with legislative requirements, business risks and technological changes, were integrated qualitatively.

Key outcomes: The study provided factual evidence to support hydropower as the most suitable alternative drilling solution for narrow reef hard-rock mines in 2013.

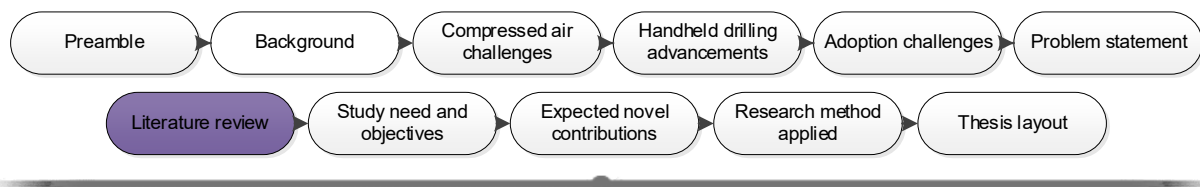
Study shortcomings of hydropower drilling technology:

- None of the studies presented independently verified performance versus cost data.
- None of the studies presented an implementation and change management methodology.

Part D: State-of-the-art overview

The most recent published literature on handheld in-stope ADTs was reviewed using the criteria listed in Table 1-4. The literature conclusively revealed the following, as summarised in Table 1-4:

- Hydropower and oil-hydraulic in-stope handheld rock drill systems are commercially available.
- **Literature shortcoming 1:** None of the studies reviewed on handheld drilling provided an implementation and change management strategy.
- **Literature shortcoming 2:** Mines invest in technologies based on their promised benefits and returns. However, none of the studies provided independently verified, unbiased performance, reliability and cost data.
- **Literature shortcoming 3:** The review highlighted the need for additional water and electricity to support ADTs. However, none of the studies provided a methodology to assess the mine's infrastructure capacity to support the alternative drilling system.
- **Literature shortcoming 4:** Continuous improvement strategies are crucial for achieving business success after implementing new technology. Yet, none of the studies provided a



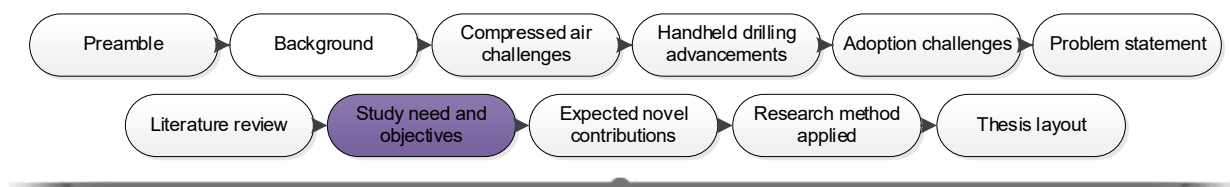
continuous improvement strategy as this outcome fell outside the scope of the handheld drilling studies reviewed. Additional research failed to yield any handheld drilling study addressing this shortcoming.

Overarching research gap identified:

There are currently no methodologies available to integrate ADTs with existing compressed air mines and to manage the change process.

Table 1-4: State-of-the-art overview

Source			Narrow reef gold mining industry	Provided a method to assess water and electrical	Implementation and change management strategy	Independently verified unbiased performance vs cost data
Year	References	Alternative type				
1975–2017	[2], [6], [9], [14], [18], [56], [68], [74], [75], [76], [114], [115], [116]	Mechanised: 13 studies reviewed	x	x	✓	x
1999–2008	[48], [51], [54], [55], [64], [65], [117]	Electrical: 7 studies reviewed	x	x	x	x
2017–1975	[27], [66]	Oil-hydraulic: 4 studies reviewed	x	x	x	x
2006–2022	[9], [28], [32], [48], [49], [53], [54], [56], [60], [62], [63], [69]	Water-hydraulic: 12 studies reviewed	x	x	x	x
Legend:			✓ The study provided information on this criterion x The study lacked information on this criterion.			

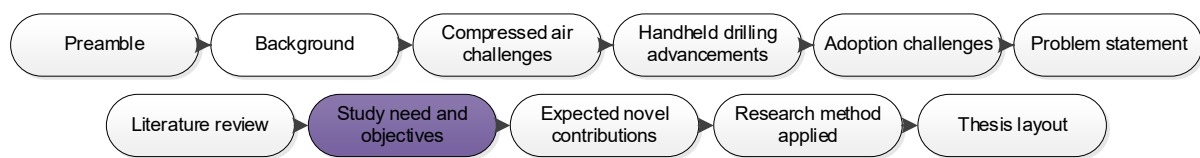


1.8. Need for this study and study objectives

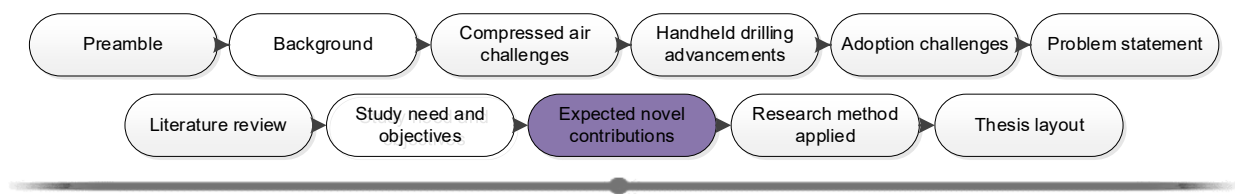
There is a need to simplify the complexities of introducing ADTs into narrow reef mines through an implementation and change management methodology. Here, complexities specifically refer to the humanistic and systemic failure drivers identified in Part A and Part B of the literature review, as outlined in [Section 1.7](#). To achieve this, the method must meet the key objectives as summarised in Table 1-5.

Table 1-5: Study objectives

Study objective number	Failure driver	Study objectives
1	HRD1: Passive leadership style	- Promote an active leadership style.
2	HRD2: False perceptions	- Rectify misperceptions using factual information.
3	HRD3: Change unwillingness	- Promote change willingness by ensuring the need for change is transparent to all stakeholders.
4	HRD4: Emotional illness	- Promote emotional wellness.
5	SFD1: Lack of urgency	- Establish and maintain a definite sense of urgency.
6	SFD2: Unclear vision of benefits	- Showcase the change benefits to all stakeholders.
7	SFD3: Exclusion of critical stakeholders	- Perform a conscientious stakeholder analysis to identify all role players
8	SFD4: Incorrect initial end user and/or workplace selection	- Provide clear strategic guidance for end user selection.
9	SFD5: Lack of stakeholder participation and accountability	- Define and track stakeholder roles and responsibilities.
10	SFD6: Incorrect selection of alternative technology	- Provide alternative technology selection guidance based on the operations' geotechnical environment.
11	SFD7: Outdated policies and procedures	- Highlight critical change updates to policies and procedures



Study objective number	Failure driver	Study objectives
12	SFD8: Change support from senior management	- Provide change support guidance to senior management.
13	SFD9: Stakeholder misalignment	- Provide a strategy to align stakeholders and maintain alignment.
14	SFD10: Transition strategy	- Ensure adequate transfer of knowledge, skills, policies and procedures during the training phase. - Provide a transition (implementation) strategy.
15	SFD11: Technology support systems	- Assess and integrate technology support systems.
16	SFD12: Technology readiness	- Provide a strategy to assess the technologies' fit-for-purpose to operate as a replacement. - Technology must be fully functional, reliable and straightforward with little to no changes required. Mature technologies are preferable.
17	SFD13: Vision/benefits did not materialise	- Provide a strategy to continuously monitor the change benefits as highlighted by the vision.
18	SFD14: Shock waves caused by excessive change	- Provide a strategy for applying a progressive and gradual approach to introducing change. - Provide a strategy for prioritising the expansion sequence. - Provide a strategy for integrating the change at the existing end users by maintaining focus on the existing end users.



1.9. Expected novel contributions

The following five novel contributions were formulated based on the problem statement, study needs and objectives.

Novel contribution #1

The development of an implementation and change management methodology to integrate alternative handheld drilling technologies into existing compressed air mines.

State-of-the-art and shortcomings of existing methods

The analysis of past failures showed that transformation efforts frequently fail when there is no implementation and change management strategy for guiding the change process. Due to the limited application of ADTs in mature, deep-level gold mines, published implementation and change management strategies for ADT selection appear to be non-existent.

What needs to be done?

An implementation strategy needs to be developed to guide mine houses through the process of integrating ADTs in existing compressed air mines. The primary objective of the method is to simplify the complexities (failure drivers, [Section 1.7](#), Part A and B) associated with implementing and adopting an ADT into a comprehensive implementation and change management strategy.

The forecasted outcome of this contribution

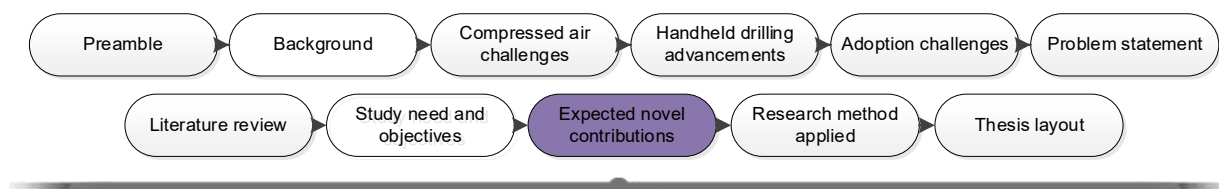
The first contribution aims to deliver a step-by-step, pragmatic implementation and change management strategy for alternative handheld drilling technologies in existing compressed air mines, addressing the implementation and change management challenges highlighted earlier. The new methodology will be practical and compatible with real-life case studies.

Novel contribution #2

The development of a multi-criteria decision-making methodology to select the most suitable ADT based on the mine's unique operational parameters.

State-of-the-art and shortcomings of existing methods

An analysis of past failures revealed that some change initiatives were set up to fail due to the incorrect selection of the implemented technology. Due to the limited application of ADTs in



mature, deep-level gold mines, published methodologies for selecting the best-fit-for-purpose ADT based on operation-specific requirements appear to be non-existent.

What needs to be done?

A selection methodology needs to be developed to guide mine houses through the process of selecting the best-fit-for-purpose ADT from commercially available options. The method should enable mine management teams to configure the selection criteria based on their operational needs. To confirm its functionality in addressing the study's needs, the method needs to be applied to a real-world case study.

The forecasted outcome of this contribution

The second contribution aims to deliver a step-by-step, pragmatic selection methodology. This methodology will enable mine management teams to minimise change resistance by selecting the most suitable technology based on their operational specifications.

Novel contribution #3

Development of a methodology to assess the mine's water and electrical networks' capability to support ADTs.

State-of-the-art and shortcomings of existing methods

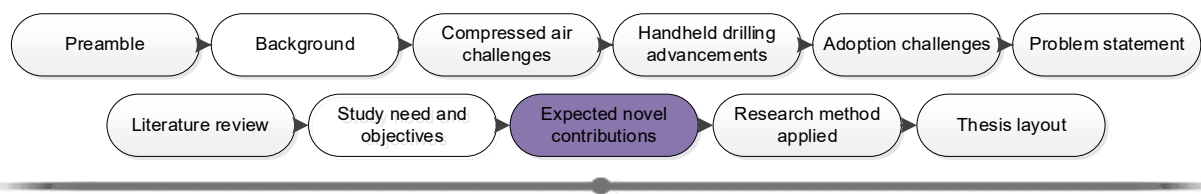
The failure drivers highlighted that technology implementation efforts frequently fail when engineering services, such as water and electricity, are insufficient to support the ADT. Published literature on methods to assess whether the mine's water and electrical networks are capable of supporting the ADT could not be found.

What needs to be done?

An infrastructure evaluation assessment methodology needs to be developed. The method should be versatile enough to serve as a framework for guiding the assessment processes of both water and electrical networks. A practical application should follow to confirm the validity of the new assessment method.

The forecasted outcome of this contribution

The third contribution aims to develop a multi-purpose method for mine management teams to assess the support capability of water and electrical networks and, if necessary, evaluate the feasibility of proposed design upgrades.



Novel contribution #4

Development of a benefit validation strategy for ADTs.

State-of-the-art and shortcomings of existing methods

All the studies reviewed were conducted by biased sources (such as OEM design engineers and/or OEM directors). Mine management teams tend to question the transparency and credibility of the data if biased sources are involved in evaluating the studies. Consequently, mining companies fail to select and implement ADTs. None of the studies reviewed presented a strategy to validate the actual benefits offered by the ADT.

What needs to be done?

A benefit assessment strategy needs to be developed to assess and validate the theoretical benefits claimed under the following key performance areas: performance, health and safety, mine suitability, human factors, and techno-economics.

The forecasted outcome of this contribution

This contribution aims to deliver a benefit validation strategy used to confirm the advantages of an ADT before committing to large-scale roll-outs. The results will provide unbiased cost and performance data for use by the industry when selecting an alternative drilling system.

Novel contribution #5

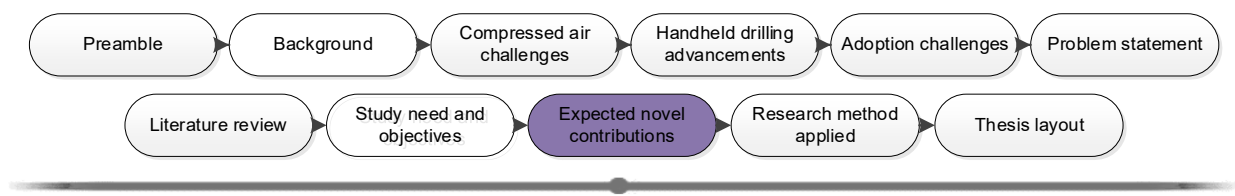
Development of a continuous improvement strategy to enable the benefits of ADTs after implementation.

State-of-the-art and shortcomings of existing methods

It follows from the literature review ([Section 1.7](#), Part B) that transformation efforts generally fail when the benefits are not realised after large-scale roll-outs. Continuous improvement strategies aim to identify operational constraints and implement ongoing efforts to maximise the benefits of the technology. None of the studies presented a continuous improvement strategy to enhance system effectiveness after implementing ADTs.

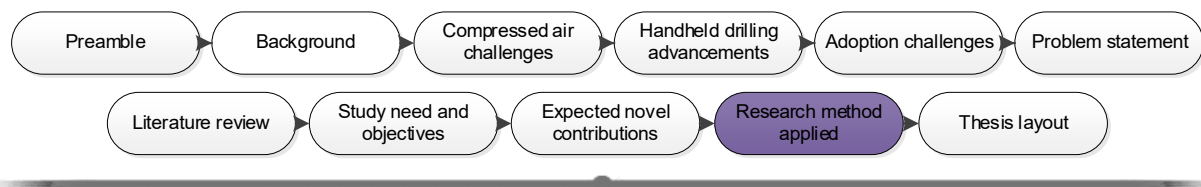
What needs to be done?

A continuous improvement strategy needs to be developed to identify operational constraints and to formulate and implement incremental changes specifically focused on improving the overall effectiveness of ADTs.



The forecasted outcome of this contribution

This contribution will yield a strategy that will assist mining companies in identifying operational constraints and implementing incremental changes to enable the ADT's intended benefits. A real-world application will follow the strategy validation.



1.10. Research methodology applied

Since this study focuses on developing an implementation and change management method, the research methodology employed follows the case study research methodology (CRM). This type of research methodology is frequently used in design research when the following three objectives are set [119]:

- Certain phenomena or data due to changes implemented need to be analysed,
- Hypotheses need to be generated, and
- Validation of the developed method is required.

A high-level overview of the CRM is shown in Figure 1-23. The chapters applicable to each step are outlined next.

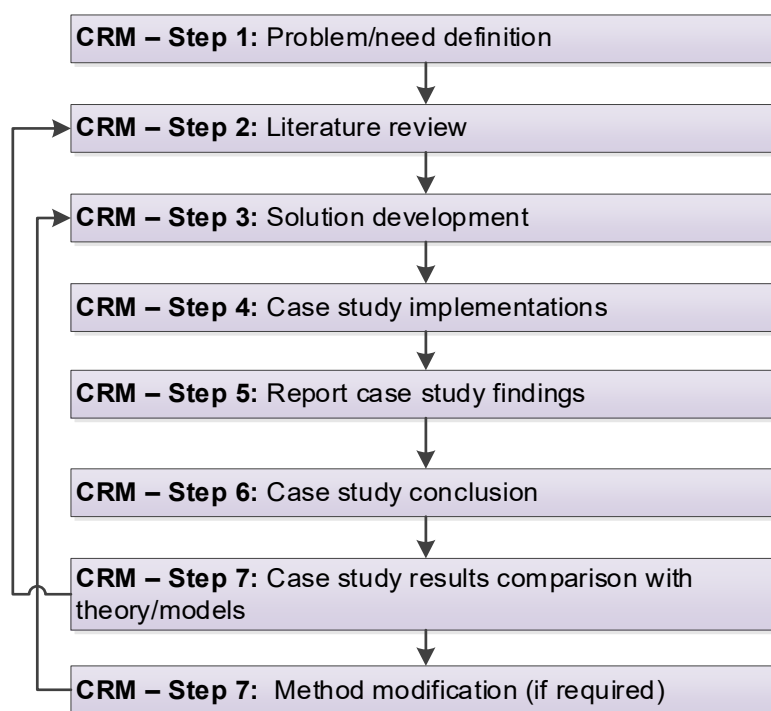
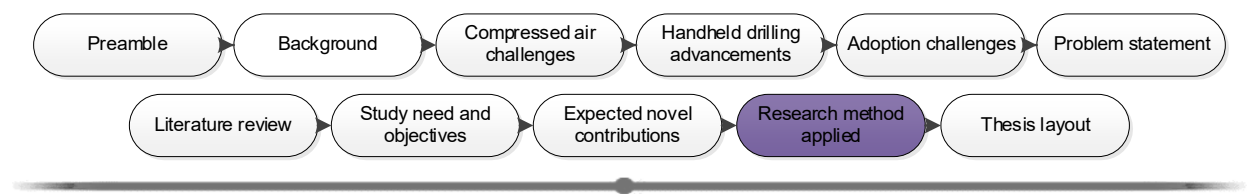


Figure 1-23: Case study research methodology overview (Adapted from [119])

Chapter 1: Introduction and literature study

Chapter 1 focused on providing sufficient background on compressed air handheld drilling systems to **define the problem (CRM – Step 1)** and highlight the urgency for mature gold mines to consider ADTs. The **literature review (CRM – Step 2)** revealed that implementation and change management strategies are currently unavailable. This has been proven to be the reason for the reluctant adoption of ADTs, despite compelling evidence of the improved benefits they offer. This highlighted the need for this study to develop an implementation and change



management methodology for introducing and integrating ADTs in mature gold mines. Eighteen failure drivers identified in the literature review were used to define the method's objectives.

Chapter 2: Method development

The **solution development (CRM – Step 3)** process applied is discussed in Chapter 2. The method's objectives served as guidance for developing the implementation and change management strategies.

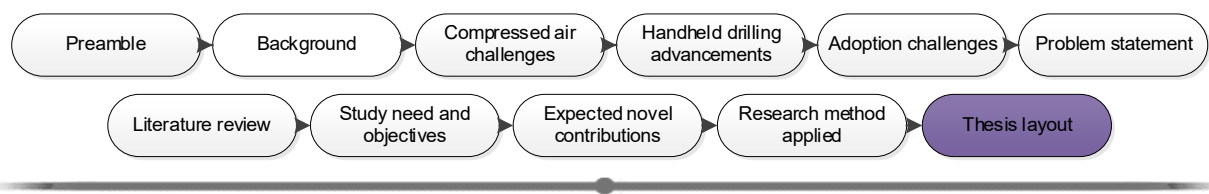
Chapter 3: Method validation through case study implementation

The implementation of a case study (CRM – Step 4) to validate the newly developed method was conducted at a mature gold mine located on the southern border of the Witwatersrand Basin. The change process was first tested on a small scale, where the alternative was evaluated with just one crew. **Results were recorded (CRM – Step 5)**, and **conclusions were formulated (CRM – Step 6)**. The **results obtained from the trial were compared to what was claimed in previous literature (CRM – Step 7)** and the findings were related. As a result, the benefits of the change were validated.

Since the method successfully introduced and integrated hydropower with the initial crew, no **method modifications (CRM – Step 8)** were required. A second layer of the method was applied to the next crew, and the change process was similarly expanded sequentially to the following crew. Ultimately, all stoping crews were converted successfully, as the crews adopted the hydropower technology. This outcome validated the proposed methodology for introducing ADT in narrow reef gold mines.

Chapter 4: Conclusion and recommendations

An overview of the study is provided in Chapter 4. The expected novel contributions are revisited, and recommendations for further work are made based on the limitations of this study.

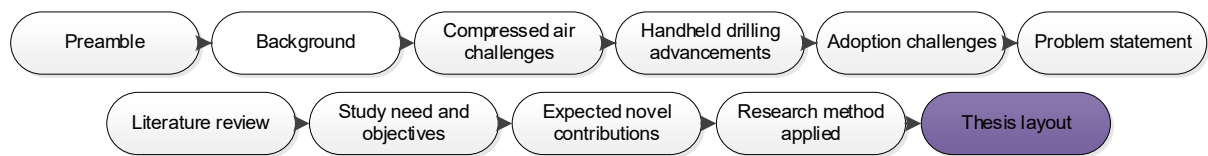


1.11. Reader orientation

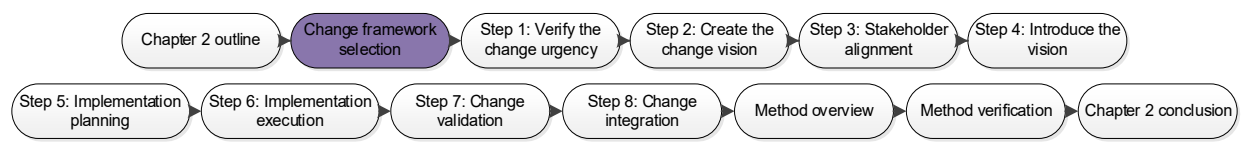
This section is aimed at orienting the reader towards what to expect in the chapter sections to follow. A lookup table is provided in Table 1-6 to guide the reader towards where to locate key outcomes and results.

Table 1-6: Reader orientation index table

Method outline	Section aim and information provided
Step 1: Verify the change urgency	The required strategies to verify the change urgency are developed in this section . Practical implementation follows here .
Step 2: Create the change vision	Mine management teams are referred to this step for an overview of the key actions required to formulate the vision. The vision crafted during the case study implementation can be found here .
Step 3: Establish stakeholder alignment	To enable stakeholder alignment, the mine management team is referred to the stakeholder alignment strategy developed and implemented .
Step 4: Introduce the vision	Step 4 is used to sell the vision as follows .
Step 5: Perform implementation planning.	The strategies and actions for implementing planning are presented in this section.
- Step 5.1: OEM supplier engagements	Key information to consider during the OEM supplier engagement stage is highlighted here human resources leader and the group legal representative.
- Step 5.2: Infrastructure evaluation assessments	A pragmatic strategy to perform water and electrical network infrastructure evaluation assessments is provided in this section . Practical application of the developed infrastructure evaluation assessment follows in Section 3 .
- Step 5.3: Updates to mine policies, procedures and standards	The shaft risk manager and training coordinator are referred to this section for all the details regarding the required updates to mine policies, procedures and standards.
- Step 5.4: Implementation plan	Critical details to consider during the development of an implementation are discussed in Section 2.4 .
- Step 5.5: Change management strategy	Mine management teams are referred to this step for an overview of the critical aspects to consider while establishing the change management plan.
- Step 5.6: Equipment transition strategy	An equipment transition strategy is provided here to enable seamless transition from the compressed air drilling system to the alternative system.
Step 6: Implement the change and sustain the change momentum.	Step 6 defines the strategies needed to implement the change as follow.
Step 7 to validate the benefits of the changes	Step 7 outlines the evaluation strategies developed to validate the theoretical benefits of the changes previously advocated in the change vision (Step 2).
- Step 7.1: Performance assessment	Production managers and engineering teams are referred to this section to review the strategies required to assess the performance (i.e. production and utilities) of the alternative drilling system.
- Step 7.2: Safety, health and environmental assessment	Occupational medical practitioners and occupational hygienists are directed to this section when assessing the impact of the alternative drilling system on safety, health, and the underground environment.



Method outline	Section aim and information provided
- Step 7.3: Mine suitability assessment	Production managers, engineers and training coordinators can find the required strategies to assess the alternative drilling systems' suitability to function as a replacement drilling system here .
- Step 7.4: Human factor assessment	The strategies for assessing human factors from an end-user perspective are provided in this section .
- Step 7.5: Techno-economic assessment	Financial managers are guided to this section to develop an understanding of how to assess whether the replacement technology is feasible from a techno-economic perspective.
- Step 7.6: Change benefit validation	This section provides mine management teams with a means to validate the benefits of the alternative drilling system.
Step 8: Change integration	This step is used to integrate the alternative drilling system once the benefits are successfully validated. Two key steps are required to foster this outcome:
- Step 8.1: Prioritise crews according to change urgency	The process required to prioritise the crew during the roll-out phase is covered here .
- Step 8.2: Define and implement a continuous improvement plan	This section provides an overview of possible improvement initiatives required to enable the full potential of the alternative drilling system.



2. METHOD DEVELOPMENT

2.1. Chapter outline

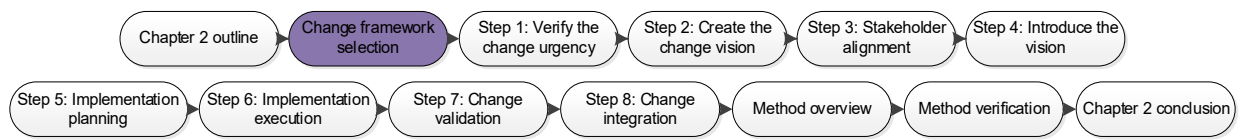
Chapter 1 highlighted the reliance of the narrow reef gold mining industry's on handheld rock drills to ensure a sustainable and growing mining environment in South Africa. It was established that these mines predominantly use compressed air to energise conventional pneumatic rock drills. From an electrical cost and system-efficiency perspective, this poses a serious sustainability risk in some mature operations. As such, the industry is forced to consider alternative in-stope handheld drills.

A critical review of previously published work on alternatives was conducted in Chapter 1. Unfortunately, official and published literature on the topic is limited. The need for an implementation and change-management methodology to introduce ADTs into existing compressed air mines has been identified. Past failures were explicitly analysed to identify the risks and opportunities that have previously been overlooked or underestimated. These failure drivers were used as strategic guidance to formulate the study-specific method objectives.

Chapter 2 aims to develop an implementation and change management methodology by using the lessons learned from past failures as study objectives. An overview of the overall development process is shown in Table 2-1. The table outlines the development section and the corresponding strategic aim.

Table 2-1: Method development outline

Development section outline	Section aim
2.2 Change framework selection	This section aims to select the most suitable change framework to foster the method development process.
2.3 Phase 1 – Development of strategies to initiate the change	Phase 1 focuses on developing the required strategies to initiate the change. The first four steps of the proposed method are used, with each step individually aimed at: - Step 1: Verify the change urgency. - Step 2: Create the change vision. - Step 3: Establish stakeholder alignment. - Step 4: Introduce the vision.
2.4 Phase 2 – Development of strategies to implement the change	The second development phase defines the strategies needed to implement the change. Two steps are defined to achieve this outcome, with each step serving as a guide to: - Step 5: Perform implementation planning. - Step 6: Implement the change and sustain the change momentum.
2.5 Phase 3 – Development of strategies to validate the change benefits	Phase 3 outlines the evaluation strategies developed using Step 7 to validate the benefits of the changes previously advocated in the change vision.



Development section outline	Section aim
2.6 Phase 4 – Development of strategies to integrate the change	The last phase of the development process focuses on integrating the change with the remaining crews. Strategies were developed to: - Step 8.1: Prioritise crews according to change urgency. - Step 8.2: Define and implement a continuous improvement plan.
2.7 Overall method overview	Section 2.7 provides an overview of the unique method that has been developed.
2.8 Method verification	This section aims to subject the developed method to a verification process. The aim of the verification process is to check and confirm whether the required strategies to address the study objectives were defined and integrated into the overall methodology.
2.9 Chapter conclusion	The method development section concludes with closing remarks and introduces the validation process to follow in Chapter 3 .

2.2. Change framework selection

To initiate the method development process, the selection of the change framework is based on an extensive literature review. It examines existing change frameworks frequently used in the industry to facilitate change processes. The process flow applied is illustrated in Figure 2-1. The framework selection consists of two distinct parts: Part A focuses on reviewing existing change frameworks, while Part B addresses the change framework selection process.

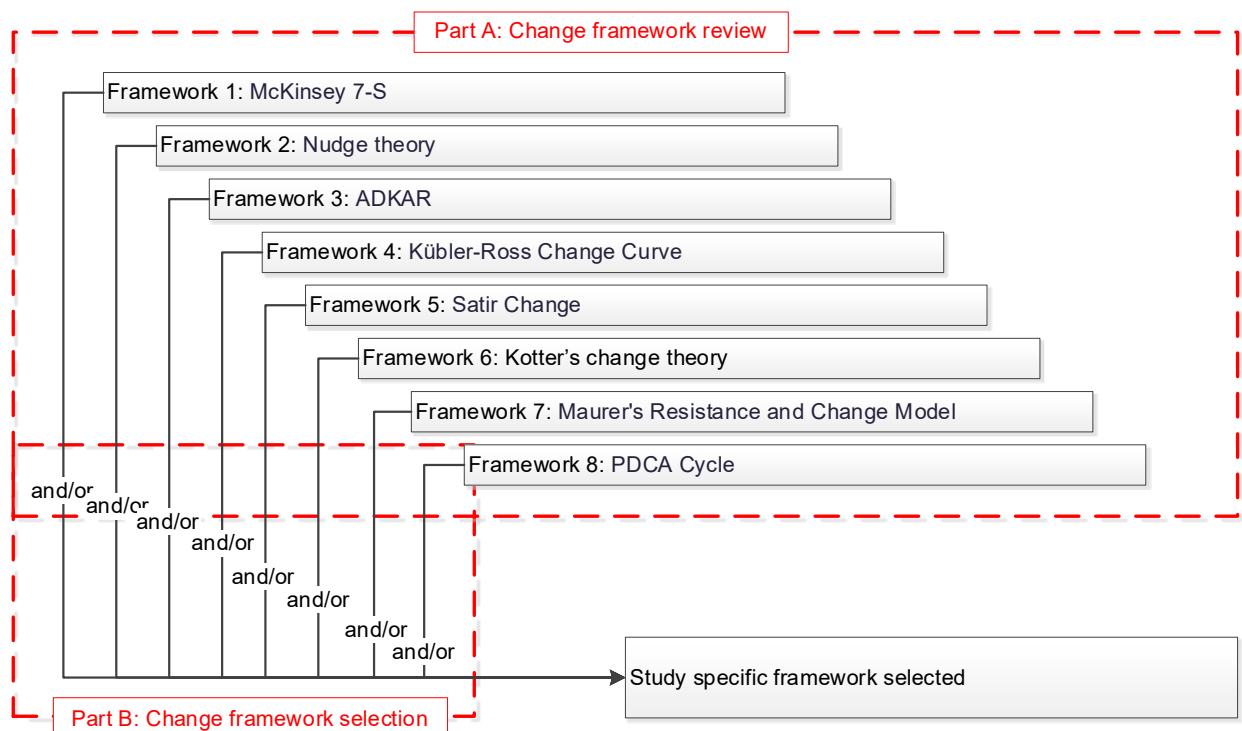
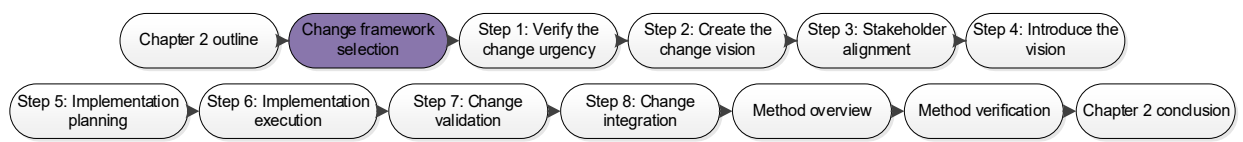


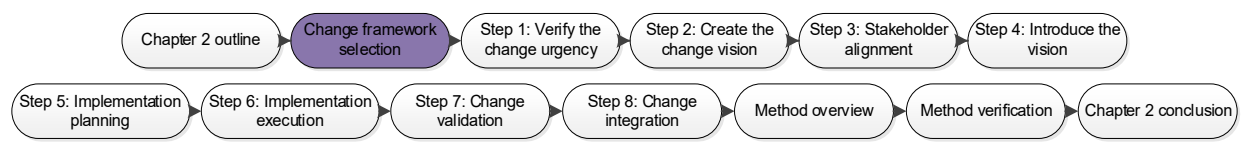
Figure 2-1: Change framework selection process flow



Part A: Change framework review: A literature survey of published work was conducted to identify the most effective change management frameworks as of 2025. Table 2-2 summarises the review findings, which identify eight distinct change management frameworks. By comparing the strategic outcomes of each, it becomes clear that each framework focuses on fostering different strategic outcomes. This means that the strategic outcomes of each need to be benchmarked against the study objectives outlined in [Section 1.8](#) to identify the most suitable framework for this study.

Table 2-2: Most effective change management frameworks in 2025

Strategic outcomes	1. McKinsey 7-S	2. Nudge Theory	3. ADKAR	4. Kübler-Ross Change Curve	5. Satir Change	6. Kotter's Change Theory	7. Maurer's Resistance and Change Model	8. PDCA Cycle
Mindset	✗	✗	✗	✓	✗	✗	✗	✗
Sense of urgency	✓	✗	✓	✗	✓	✓	✓	✓
Clear vision of benefits	✓	✓	✓	✗		✓	✓	✓
Stakeholder identification	✓	✓	✓	✗	✓	✓	✓	✓
Initial end user selection	✓	✓	✓	✗	✓	✓	✓	✓
Stakeholder participation and accountability	✓	✓	✓	✗	✓	✓	✗	✓
Technology appropriateness	✓	✓	✓	✗	✓	✓	✗	✓
Technology readiness	✓	✓	✓	✗	✓	✓	✗	✓
Change support from senior management	✓	✓	✓	✗	✓	✓	✗	✓
Stakeholder misalignment	✓	✓	✓	✗	✓	✓	✗	✓
Human factors	✓	✗	✓	✗	✓	✓	✗	✓
Ergonomics	✓	✓	✓	✗	✓	✓	✗	✓
Training	✓	✓	✓	✗	✓	✓	✗	✓
Incentive structure	✓	✓	✓	✗	✓	✓	✗	✓
Technology support systems	✓	✓	✓	✗	✓	✓	✗	✓
Policies and procedures	✓	✓	✓	✗	✓	✓	✗	✓
Vision/benefits did not materialise	✗	✗	✓	✗	✗	✗	✗	✓
Shock waves caused by excessive change	✗	✓	✗	✗	✗	✓	✗	✗
Change integration	✗	✗	✗	✗	✗	✓	✗	✗
Legend	✓	The study provided information on this criterion						
	✗	The study lacked information on this criterion						



Part B: Change framework selection: The strategic outcomes of each framework were benchmarked against the study objectives. The results are presented in Table 2-2. Green ticks confirm the individual framework's compatibility with the study's needs. The contrary is highlighted by the red crosses.

A close examination of the strategic outcomes reveals that none of the identified frameworks is fully compatible with the study-specific requirements. This limitation was resolved by combining the three frameworks shaded in purple, namely: Kotter's change theory, the plan-do-check-act (PDCA) cycle, and the Kübler-Ross change curve.

Kotter's sequential strategy entails the following eight steps to introduce change successfully [103]:

- Step 1: Verify the change urgency.
- Step 2: Create the change vision.
- Step 3: Establish stakeholder alignment.
- Step 4: Introduce the vision.
- Step 5: Perform implementation planning.
- Step 6: Implement the change and sustain the change momentum.
- Step 7: Validate the change benefits.
- Step 8: Integrate the change.

The PDCA cycle focuses explicitly on assessing and verifying the benefits of change. Kübler-Ross compiled work on understanding stakeholder emotions throughout the change process [120]. Her work led to the Kübler-Ross change curve, which is widely used to manage stakeholders' mindsets during the change management process. An overview of the change framework proposed by this study is illustrated in Figure 2-2.

Framework selection concluding remarks: The unique selection and combination of the Kotter, Kübler-Ross, and the PDCA frameworks provide sufficient means to foster the development processes of the strategies required to address the study objectives listed in [Section 1.8](#).

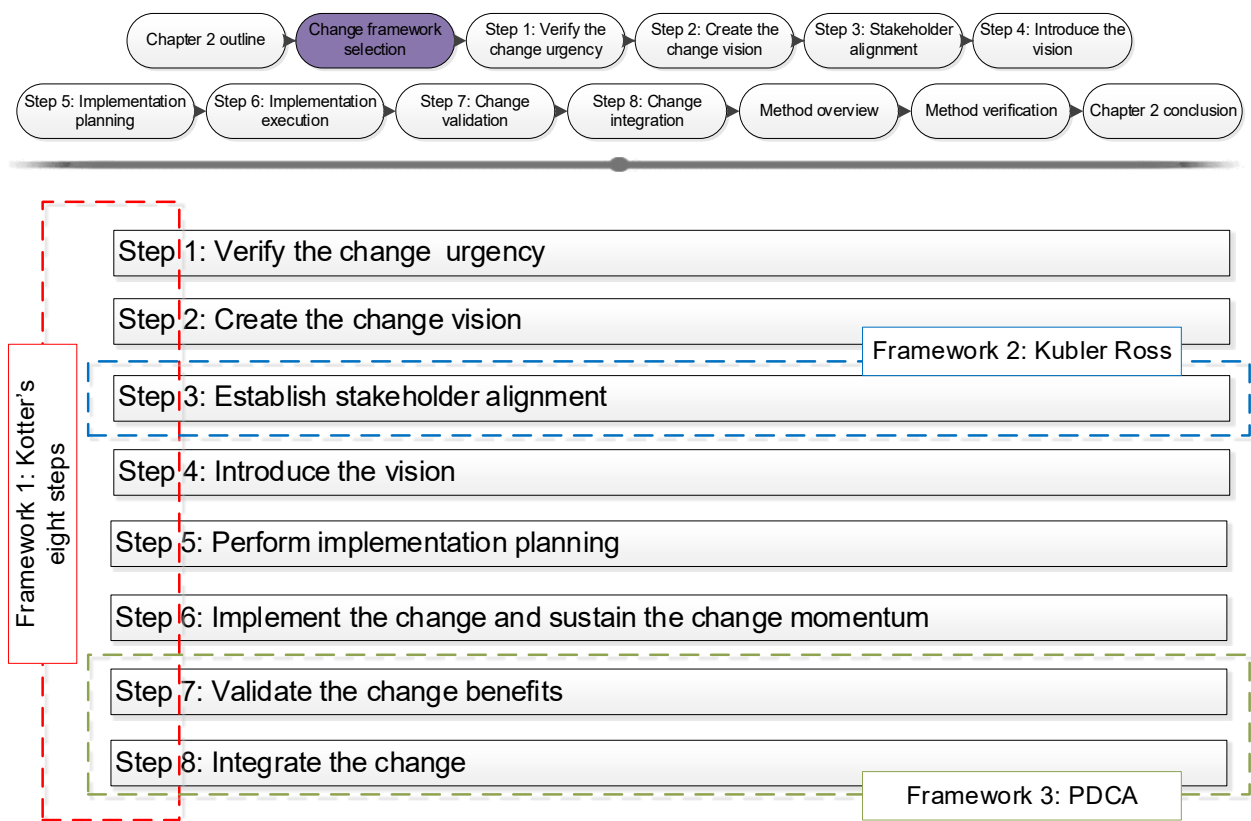
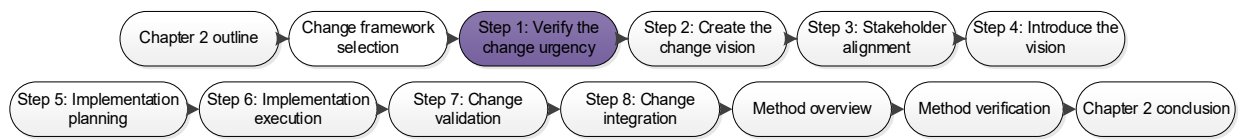


Figure 2-2: Overview of the selected study-specific framework



2.3. Phase 1: Develop strategies to initiate the change

The overarching objective of the first phase is to initiate the change process and influence stakeholder buy-in. This section aims to develop the strategies required to achieve this strategic outcome by using the process flow depicted in Figure 2-3.

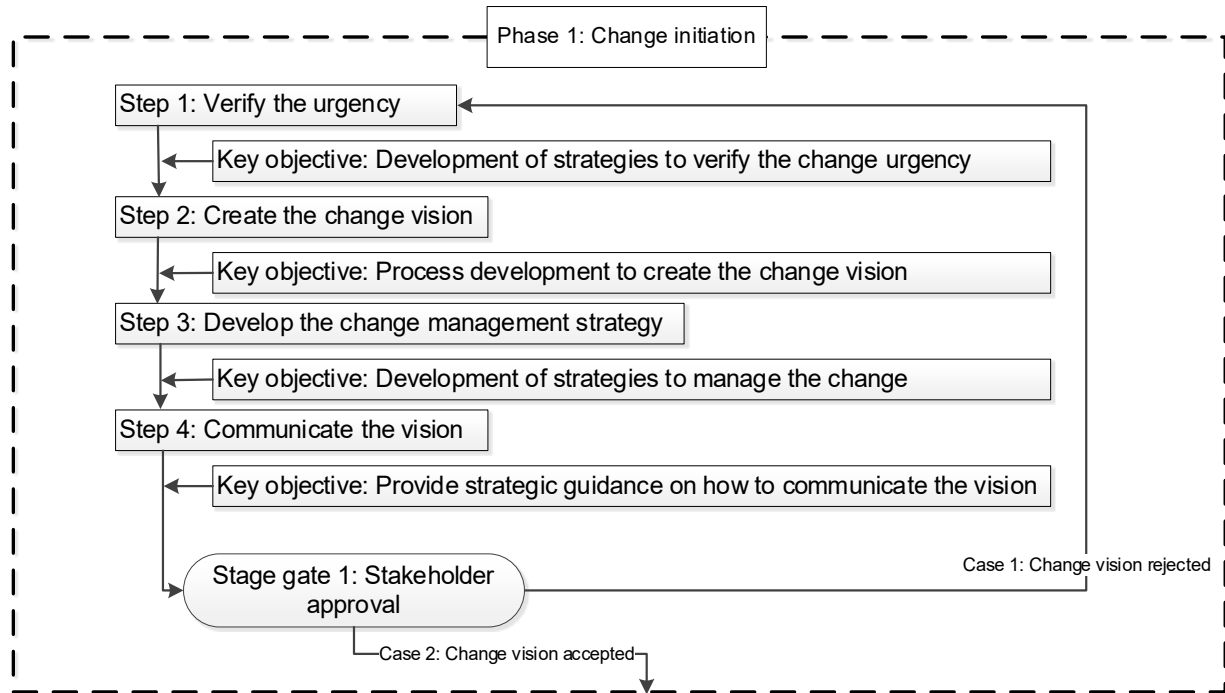


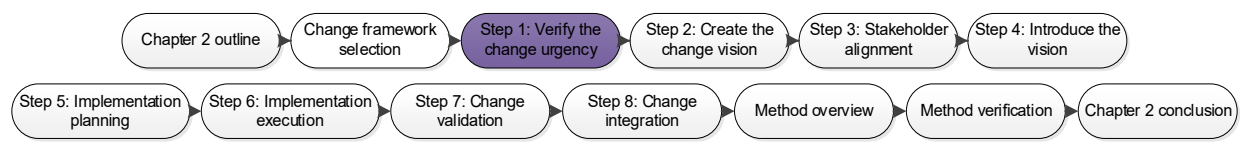
Figure 2-3: Method development process flow – Phase 1: Change initiation

Step 1: Verify the change urgency

It follows from the literature review presented in [Section 1.7](#) that the change process frequently failed in the past if the change urgency remained unverified. The need for change verification refers to a strategy for verifying that the correct production constraint is earmarked for change. As a result, the method objectives listed in Table 1-5 called for the development of a strategy to verify the change urgency. The main aim of the strategy is to prevent the mine management teams from misleadingly implementing ADTs in cases where the drilling cycle is, in fact, not the main bottleneck.

Overview – Step 1: Development of strategies to verify the change urgency

This overview describes the logic and rationale applied to develop the strategies required to verify the change urgency. Narrow-reef mining was described earlier in Section 1.2 as a cyclic process comprising two key outcomes: ore breaking and ore cleaning. Various activities are required to fulfil these outcomes, and multiple bottlenecks may exist that obstruct consistent production results [47], [114], [121], [122], [123], [124]. As proposed by Figure 2-4, mine



management teams will be required to execute two critical actions to verify the change urgency, namely: (i) gather data describing the actual time required by each mining activity, and (ii) benchmark the actual activity time duration against the theoretical estimates.

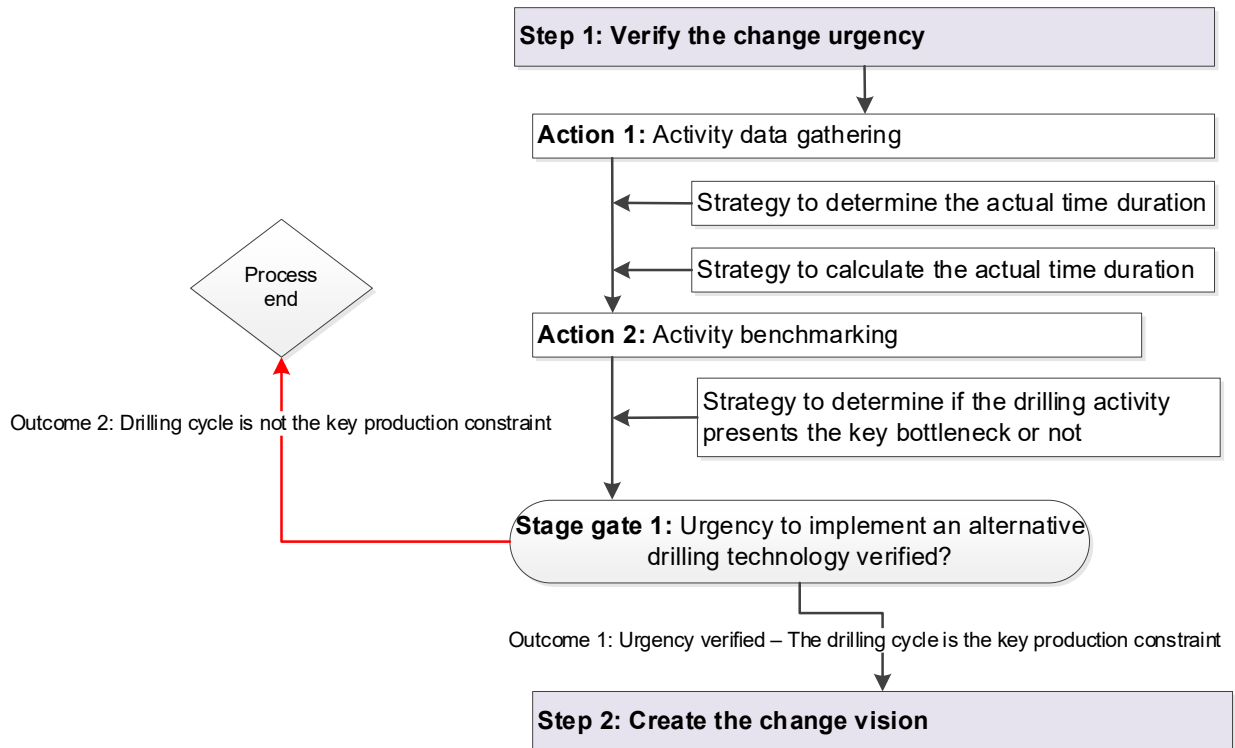


Figure 2-4: Step 1 overview

The benchmark results will show the individual difference between the actual and theoretical time required to execute the array of mining activities. This will be used to confirm whether the drilling cycle is the key bottleneck.

Action 1: – Gather data regarding the mining process activity duration

As a first action, it is necessary to identify all the mining activities to be included in the analysis. Stewart [121] studied labour time in South African gold mines and identified ten mining activities as listed in Table 2-3 to consider. To formulate a benchmark comparison between the actual time spent and the theoretical requirements to execute shift cycle activities, data is needed to quantify the actual and theoretical durations of each activity listed in Table 2-3.

A strategy was developed to quantify the actual duration of each activity. The data acquisition strategy for gathering data on the actual time spent to complete these activities is presented in [Appendix B](#). A strategy was also developed to quantify the theoretical time required to complete each activity. The formulas listed in Table 2-3 were derived in [Appendix B](#) to calculate the time requirements.

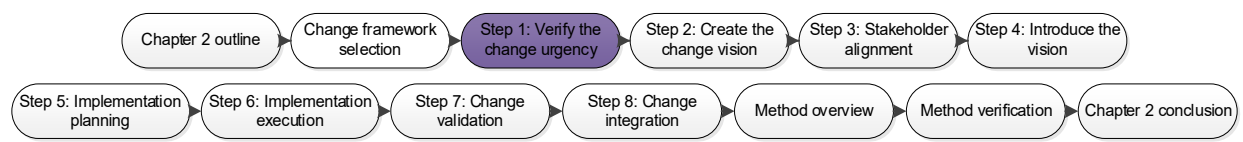


Table 2-3: Derived equations to calculate the theoretical time requirement to complete each activity

Mining activity	Source
1) Day shift travels down the mine and to the workplaces	Equation B-1
2) Day shift entry examination and face preparation	Equation B-2
3) Drilling and support	Drilling – Equation B-3 Support – Equation B-4
4) Charging up	Equation B-5
5) Day shift travel time out	Equation B-1
6) Blast and re-entry period	Legislative requirement [125]
7) Night shift travels in	Equation B-1
8) Night shift entry examination and watering down	Equation B-2
9) Cleaning	Equation B-6
10) Night shift travels out	Equation B-1

Action 2: Benchmark activities

To identify the key activity bottleneck, a strategy is needed to benchmark the actual and theoretical time requirements. This outcome is achieved by creating an activity benchmark curve, which led to the development of Figure 2-5. The curve visually represents the ten shift activities in order of events as expected within a 24-hour mining cycle. The inner ring represents the theoretical baseline time required to complete each activity. In comparison, the outer ring illustrates the actual time spent.

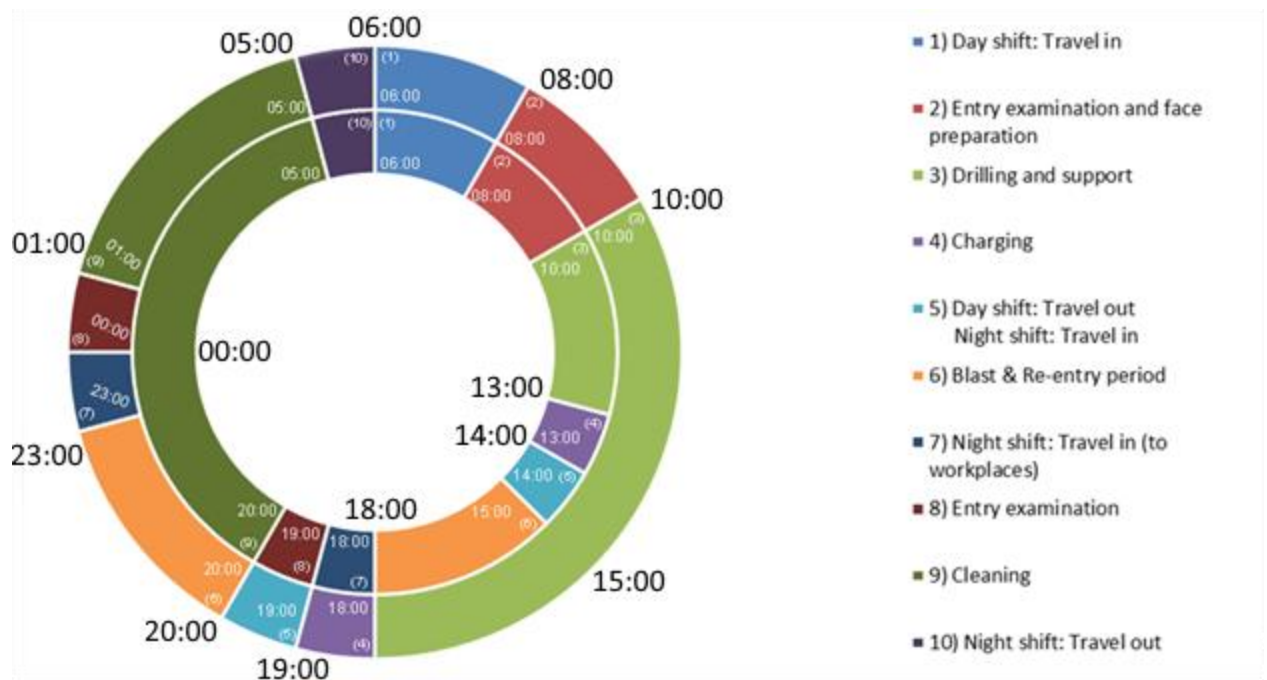
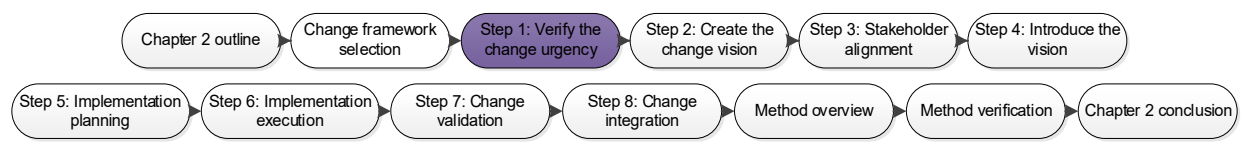


Figure 2-5: Actual vs theoretical shift cycle components

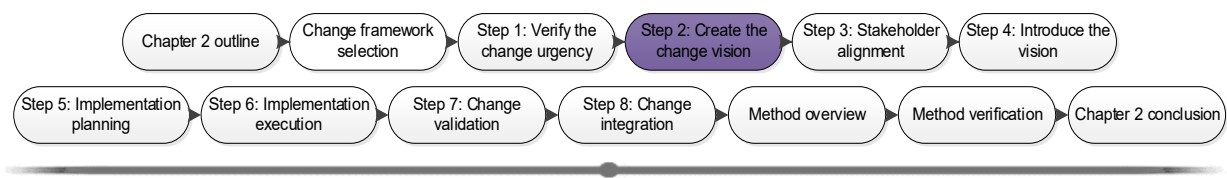


Guidance on how to use the benchmark curve to verify the change urgency: The circular representation clearly illustrates the time phasing effect on consecutive activities as individual activities begin to deviate from the theoretical baseline. For example, an increase in the drilling and support cycle will consequently delay the remaining activities, ultimately reducing the time available to clean the face. As illustrated by Figure 2-4, this result then feeds into a stage gate to verify the urgency of implementing an alternative drilling system. Once verified, the process flow guides the team to the next step of the change process.

At the same time, if the drilling cycle is not the key production constraint, the stage gate integrated into the process guides the team to conclude the process. This approach will prevent the mining operation from misleadingly implementing an alternative drilling system.

Step 1: Development summary

Change verification is essential to ensure that the appropriate mining process constraint is identified for change. Step 1 aimed to develop a process that mine management teams can use to verify the urgency of changes. Mine management teams can now use the proposed process flow provided in Figure 2-4 to identify the actual constraints of the mining process. The detailed development of Step 1 is presented in [Appendix B](#). An abbreviated summary of the strategy's development is presented here.



Step 2: Create the change vision

No idea, no matter how brilliant, can succeed in isolation. This statement is especially true when the new idea needs to be implemented in the stopes [55]. Van Jaarsveld and Ebben [64] and Macfarlane [5] agree that the ability to influence decisions, rally support for change, and persuade others often determines whether an idea remains theoretical or is successfully implemented.

Step 2 of the proposed change process involves developing a strategy to create the change vision. As shown in Table 1-5, the strategy is needed to create a change vision that resonates with the change benefits. Without a comprehensive change vision, failure is primarily driven by stakeholders' unwillingness to adopt the new technology due to a lack of opportunistic thinking [5], [96], [97], [98], [99], [126]. A vision that is too complex to comprehend is useless or, if it fails to inspire, is meaningless [125]. That said, the vision should articulate the solution with clarity and conviction to each stakeholder group.

Overview – Step 2: Develop strategies to create the change vision

The change vision presents the project team with an initial opportunity to positively influence the stakeholders' attitudes, beliefs and feelings towards the change [100], [101]. Previous research suggests that automatic buy-in from all stakeholders is certain when the answer to the instinctive question, "What is in it for me?", is crystal clear [94], [108], [127]. This inspired the development of the change vision creation strategy discussed here. The strategy is designed to build trust in the change idea while aligning interests so that others will willingly and enthusiastically support the change vision. The strategy, if executed successfully, will shift mindsets and inspire stakeholder participation.

A key aspect was that not all stakeholders in the South African mining environment are educated equally [128]. Educational levels vary from employees without a matriculation certificate to those with university degrees. As a result, the benefits of the change need to be comprehensible to all stakeholders. Figure 2-6 illustrates the proposed process flow to be used by mine management teams to create the vision. The method evolves around two actions, namely alternative technology selection and benefit showcasing.

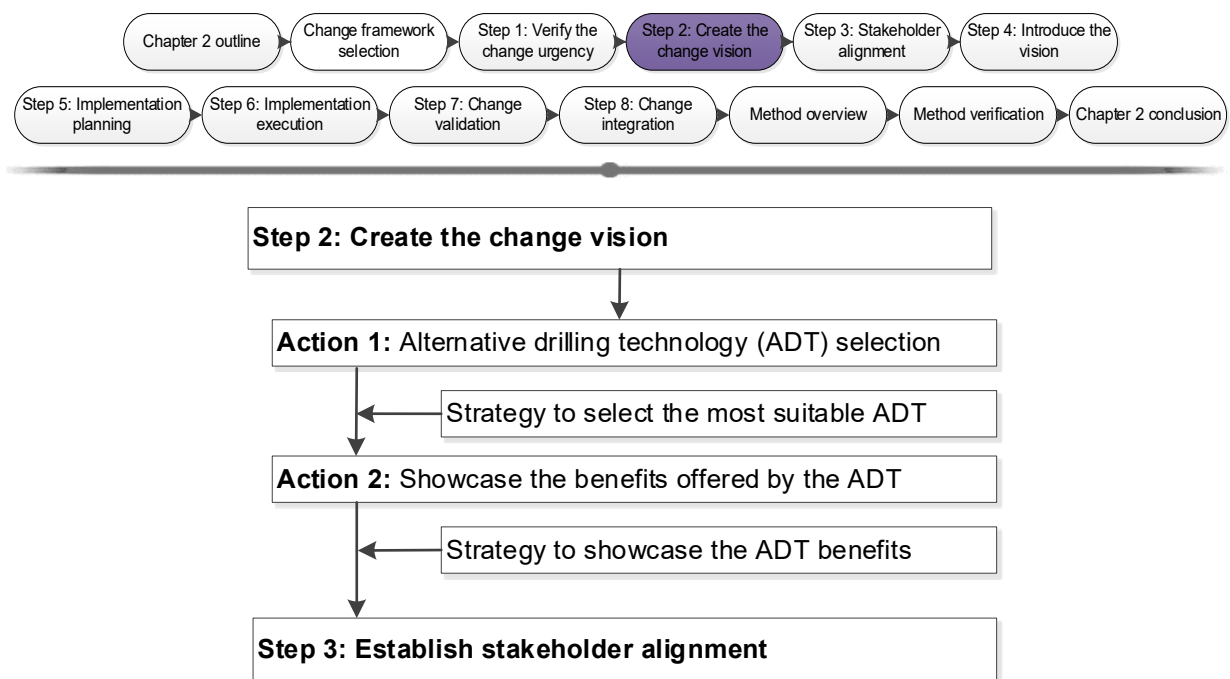


Figure 2-6: Vision creation process flow

Action 1: Develop a strategy to select an alternative technology

To summarise, [Section 1.4](#) presented a detailed review of the most recent advancements in handheld ADTs. The review covered the alternatives available at the time, and it was found that each offered different benefits. The key aim was to develop a strategy for identifying a fit-for-purpose alternative technology. Fit-for-purpose refers to an ADT that is compatible with specific key operational constraints. Failure to match product specifications and mining parameters frequently led to the incorrect selection of alternatives and subsequent adoption failure [9], [15].

To select the most suitable ADT, mine management teams are guided towards applying a multi-criteria decision-making process. Swanepoel *et al.* developed a novel method to identify the most appropriate ventilation projects [129]. This study applied a few modifications to the original framework to make it unique. Their proposed framework combined two well-known decision-making processes, namely the analytic hierarchy process and the technique for order performance by similarity to ideal solution (TOPSIS). The analytic hierarchy process is used to define the relative weights of each selection criterion. Based on these defined weights, TOPSIS is used to identify the most suitable solution among two or more very similar solutions. The selection methodology developed in this study comprises five steps, as illustrated in Figure 2-7 and discussed next.

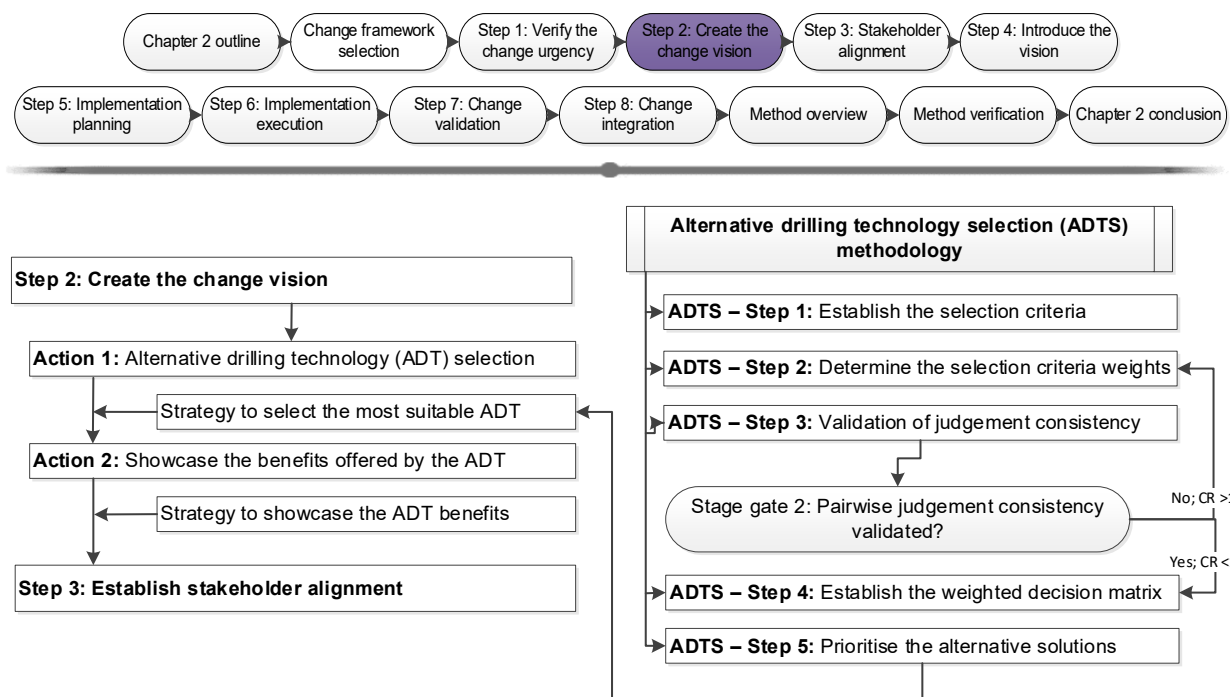


Figure 2-7: ADT selection methodology proposed by this study

ADT Selection Step 1: Establish the selection criteria

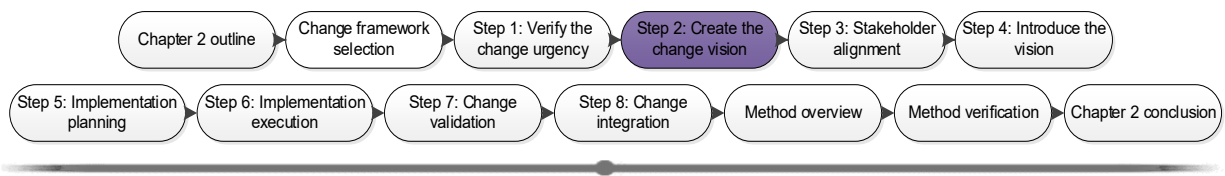
The selection criteria provide the mine management team with guidance when evaluating the various ADTs available. The selection criteria proposed in this study originate from insights gained from the published literature. Literature suggests that the following four key operational requirements need to be considered, where the alternatives are:

- An appropriate fit in terms of the operation's in-stope geotechnical parameters, such as stoping width and reef dip angle [5], [11], [14], [85], [130].
- Ergonomically compatible with the skill sets of the end users [60], [76], [85], [110].
- A fit-for-purpose replacement in terms of function, performance, reliability, and cost [5], [6], [12], [60], [66].
- A mature technology [53], [54], [60]. Maturity refers to an alternative that has a proven track record in terms of product readiness and OEM support.

As a result, the selection criteria established and proposed by this study include: (C1) technical compatibility, (C2) reliability, (C3) cost, (C4) ergonomic compatibility, and (C5) performance.

ADT Selection Step 2: Determine the selection criteria weights

The analytic hierarchy process is used to determine the weight of each selection criterion in Step 2. The five selection criteria should be weighed according to their relative importance in relation to each other based on judgement or preference. This outcome is achieved by constructing a pairwise comparison matrix (A), using Equation 2-1 [131]. In Equation 2-1, a_{12} , for example, represents the relative importance between criteria C_1 and C_2 . The predefined scale used for assigning the weights (matrix elements) is known as the Saaty fundamental scale [132]. In this matrix, the first nontrivial comparison is (C1, C2).



To initiate the comparison, mine management teams need to ask the question: “How much more important is criterion C_1 than criterion C_2 ?” Now, if C_1 is significantly more important than C_2 , then a value of, for example, 7 is assigned to a_{12} and the reciprocal value is assigned to a_{21} . The logic and rationale are applied to complete the rest of the matrix. Mine management teams can refer to the study published by Saaty for additional guidance on how to perform the pairwise comparison [131].

$$\begin{array}{c|ccccc}
 & C_1 & C_2 & C_3 & C_4 & C_5 \\
 \hline
 C_1 & 1 & a_{12} & a_{13} & a_{14} & a_{15} \\
 C_2 & a_{21} & 1 & a_{23} & a_{24} & a_{25} \\
 C_3 & a_{31} & a_{32} & 1 & a_{34} & a_{35} \\
 C_4 & a_{41} & a_{42} & a_{43} & 1 & a_{45} \\
 C_5 & a_{51} & a_{52} & a_{53} & a_{54} & 1 \\
 \hline
 \text{SUM} & \sum_{k=0}^5 a^{k1} & \sum_{k=0}^5 a^{k2} & \sum_{k=0}^5 a^{k3} & \sum_{k=0}^5 a^{k4} & \sum_{k=0}^5 a^{k5}
 \end{array}
 \quad \text{Equation 2-1}$$

where:

a_{ij} – Matrix element

C_{1-4} – Selection criteria

$\sum_{k=0}^5 a^{kj}$ – Sum of the individual criterion weights in column $j = 1, 2, \dots, 5$

After the comparison matrix is constructed, it is normalised to determine the criteria weight vector (W) [129]. This is done using Equation 2-2.

$$\begin{array}{c|ccccc|c}
 & C_1 & C_2 & C_3 & C_4 & C_5 & \text{Criteria weight} \\
 \hline
 C_1 & \frac{1}{\sum_{k=0}^5 a^{k1}} & \frac{a_{12}}{\sum_{k=0}^5 a^{k2}} & \frac{a_{13}}{\sum_{k=0}^5 a^{k3}} & \frac{a_{14}}{\sum_{k=0}^5 a^{k4}} & \frac{a_{15}}{\sum_{k=0}^5 a^{k5}} & \frac{\sum_{k=0}^5 a^{1k}}{n} \\
 C_2 & \frac{a_{21}}{\sum_{k=0}^5 a^{k1}} & \frac{1}{\sum_{k=0}^5 a^{k2}} & \frac{a_{23}}{\sum_{k=0}^5 a^{k3}} & \frac{a_{24}}{\sum_{k=0}^5 a^{k4}} & \frac{a_{25}}{\sum_{k=0}^5 a^{k5}} & \frac{\sum_{k=0}^5 a^{2k}}{n} \\
 C_3 & \frac{a_{31}}{\sum_{k=0}^5 a^{k1}} & \frac{a_{32}}{\sum_{k=0}^5 a^{k2}} & \frac{1}{\sum_{k=0}^5 a^{k3}} & \frac{a_{34}}{\sum_{k=0}^5 a^{k4}} & \frac{a_{35}}{\sum_{k=0}^5 a^{k5}} & \frac{\sum_{k=0}^5 a^{3k}}{n} \\
 C_4 & \frac{a_{41}}{\sum_{k=0}^5 a^{k1}} & \frac{a_{42}}{\sum_{k=0}^5 a^{k2}} & \frac{a_{43}}{\sum_{k=0}^5 a^{k3}} & \frac{1}{\sum_{k=0}^5 a^{k4}} & \frac{a_{45}}{\sum_{k=0}^5 a^{k5}} & \frac{\sum_{k=0}^5 a^{4k}}{n} \\
 C_5 & \frac{a_{51}}{\sum_{k=0}^5 a^{k1}} & \frac{a_{52}}{\sum_{k=0}^5 a^{k2}} & \frac{a_{53}}{\sum_{k=0}^5 a^{k3}} & \frac{a_{54}}{\sum_{k=0}^5 a^{k4}} & \frac{1}{\sum_{k=0}^5 a^{k5}} & \frac{\sum_{k=0}^5 a^{5k}}{n}
 \end{array}
 \quad \text{Equation 2-2}$$

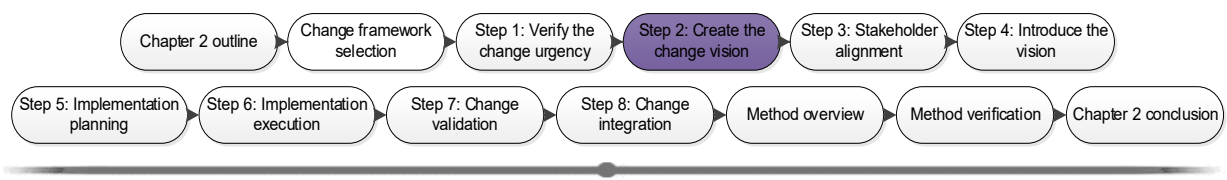
where:

a_{ij} – Matrix element [-]

C_{1-4} – Selection criteria [-]

ADT Selection Step 3: Validate the pairwise judgement

Some form of control is needed to validate the judgement consistency applied by the mine management team during the pairwise comparison. For this reason, a stage gate was



incorporated into the methodology, as illustrated in Figure 2-7. Judgement consistency is checked by calculating the consistency ratio (CR) [133]. A consistency ratio of less than 10% indicates that consistent judgement was applied [134]. On the other hand, consistency ratio values above 10% indicate high levels of error judgement, and the criteria weighting needs to be redone. As expressed by Equation 2-3, the consistency ratio is simply the ratio between the consistency index (CI) and the average random index (RI). Equation 2-4 is used to calculate the consistency index, which is a function of the maximum eigenvalue obtained from Equation 2-5. The individual consistency elements used to calculate the maximum eigenvalue are a function of the pairwise comparison (A) and the criteria weight vector (W), as given by Equation 2-7.

$$CR = \frac{CI}{RI} \quad \text{Equation 2-3}$$

where:

- CI – Consistency index [-]
- RI – Average random index = 1.15 when $n = 5$ [131]

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{Equation 2-4}$$

where:

- λ_{max} – Maximum eigenvalue [-]
- n – Number of criteria considered (i.e. $n = 5$ for this study)

$$\lambda_{max} = \frac{\sum_i^n \lambda_i}{n}, i = 1, 2, \dots, 5 \quad \text{Equation 2-5}$$

where:

- λ_i – Individual eigenvalues [-]
- n – Number of criteria considered (i.e. $n = 5$ for this study)

$$\lambda_i = \frac{cv_i}{w_i}, i = 1, 2, \dots, 5 \quad \text{Equation 2-6}$$

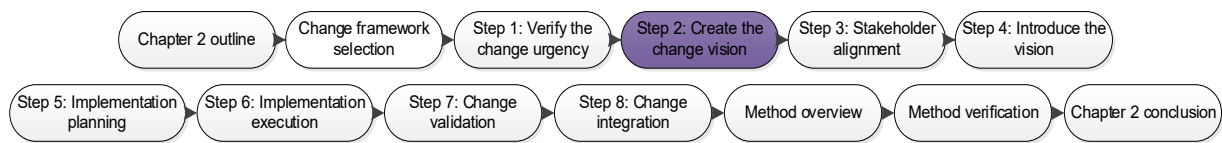
where:

- cv_i – Individual consistency elements [-]
- w_i – individual weight elements [-]

$$[CV] = [A] \cdot [W] \quad \text{Equation 2-7}$$

where:

- A – Pairwise comparison vector [-]
- W – Criteria weight vector [-]



ADT Selection Step 4: Establish the weighted decision matrix

At this point in the selection process, the mine management team has determined the weights of the selection criteria and validated the consistency of the judgment applied. It is now necessary to select the most suitable ADT based on the determined selection weights. To achieve this outcome, this study adopted the TOPSIS framework as a reference for establishing the study-specific decision matrix.

It was mentioned earlier that stakeholders in the mining industry are not equally educated. This fact necessitates a simplistic means of selecting the most suitable alternative. To address this shortcoming, the adoption of the TOPSIS framework provides a user-friendly and simplistic method for stakeholders who do not have a technical background [135]. The TOPSIS method prioritises preferences by relating the similarity between solutions to the most ideal solution based on the predefined selection criteria. Equation 2-8 is used to construct the decision matrix.

$$R = \begin{array}{c|ccccc} & C_1 & C_2 & C_3 & C_4 & C_5 \\ \hline ADT_1 & x_{11} & x_{11} & x_{13} & x_{14} & x_{15} \\ ADT_2 & x_{21} & x_{21} & x_{23} & x_{24} & x_{25} \\ ADT_3 & x_{31} & x_{31} & x_{33} & x_{34} & x_{35} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ADT_n & x_{n1} & x_{n2} & x_{n3} & x_{n4} & x_{n5} \\ \hline SUM & \sqrt{\sum_{j=1}^n x_{j1}^2} & \sqrt{\sum_{j=1}^n x_{j2}^2} & \sqrt{\sum_{j=1}^n x_{j3}^2} & \sqrt{\sum_{j=1}^n x_{j4}^2} & \sqrt{\sum_{j=1}^n x_{j5}^2} \end{array} \quad \text{Equation 2-8}$$

where:

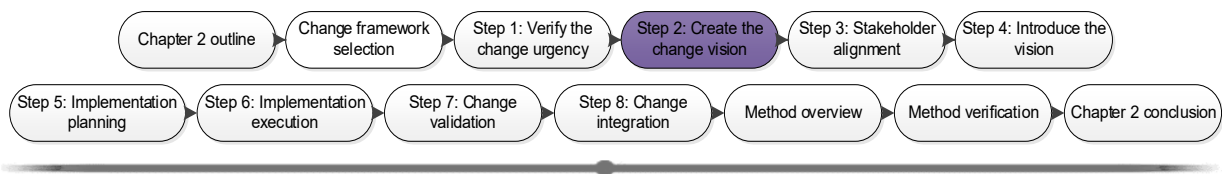
- x_{ij} – Actual criteria value of the ADT considered [-]
- C_{1-5} – Selection criteria [-]

As a subsequent action, the alternatives listed in the decision matrix need to be normalised using Equation 2-8 and Equation 2-9.

$$\bar{R} = \begin{array}{c|ccccc} & C_1 & C_2 & C_3 & C_4 & C_5 \\ \hline ADT_1 & \frac{x_{11}}{\sqrt{\sum_{j=1}^n x_{j1}^2}} & \frac{x_{11}}{\sqrt{\sum_{j=1}^n x_{j2}^2}} & \frac{x_{13}}{\sqrt{\sum_{j=1}^n x_{j3}^2}} & \frac{x_{14}}{\sqrt{\sum_{j=1}^n x_{j4}^2}} & \frac{x_{15}}{\sqrt{\sum_{j=1}^n x_{j5}^2}} \\ ADT_2 & \frac{x_{21}}{\sqrt{\sum_{j=1}^n x_{j1}^2}} & \frac{x_{21}}{\sqrt{\sum_{j=1}^n x_{j2}^2}} & \frac{x_{23}}{\sqrt{\sum_{j=1}^n x_{j3}^2}} & \frac{x_{24}}{\sqrt{\sum_{j=1}^n x_{j4}^2}} & \frac{x_{25}}{\sqrt{\sum_{j=1}^n x_{j5}^2}} \\ ADT_3 & \frac{x_{31}}{\sqrt{\sum_{j=1}^n x_{j1}^2}} & \frac{x_{31}}{\sqrt{\sum_{j=1}^n x_{j2}^2}} & \frac{x_{33}}{\sqrt{\sum_{j=1}^n x_{j3}^2}} & \frac{x_{34}}{\sqrt{\sum_{j=1}^n x_{j4}^2}} & \frac{x_{35}}{\sqrt{\sum_{j=1}^n x_{j5}^2}} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ ADT_n & \frac{x_{n1}}{\sqrt{\sum_{j=1}^n x_{j1}^2}} & \frac{x_{n2}}{\sqrt{\sum_{j=1}^n x_{j2}^2}} & \frac{x_{n3}}{\sqrt{\sum_{j=1}^n x_{j3}^2}} & \frac{x_{n4}}{\sqrt{\sum_{j=1}^n x_{j4}^2}} & \frac{x_{n5}}{\sqrt{\sum_{j=1}^n x_{j5}^2}} \end{array} \quad \text{Equation 2-9}$$

where:

- x_{ij} – Actual criteria value of the ADT considered [-]
- C_{1-5} – Selection criteria [-]



Thereafter, the mine management team needs to calculate the weighted normalised matrix using Equation 2-10.

$$\overline{WR} = \begin{matrix} & \begin{matrix} C_1 & C_2 & C_3 & C_4 & C_5 \end{matrix} \\ \begin{matrix} ADT_1 \\ ADT_2 \\ ADT_3 \\ \vdots \\ ADT_n \end{matrix} & \begin{bmatrix} \frac{x_{11}}{\sqrt{\sum_{j=1}^n x_{j1}^2} \times W_1} & \frac{x_{11}}{\sqrt{\sum_{j=1}^n x_{j2}^2} \times W_2} & \frac{x_{13}}{\sqrt{\sum_{j=1}^n x_{j3}^2} \times W_3} & \frac{x_{14}}{\sqrt{\sum_{j=1}^n x_{j4}^2} \times W_4} & \frac{x_{15}}{\sqrt{\sum_{j=1}^n x_{j5}^2} \times W_5} \\ \frac{x_{21}}{\sqrt{\sum_{j=1}^n x_{j1}^2} \times W_1} & \frac{x_{21}}{\sqrt{\sum_{j=1}^n x_{j2}^2} \times W_2} & \frac{x_{23}}{\sqrt{\sum_{j=1}^n x_{j3}^2} \times W_3} & \frac{x_{24}}{\sqrt{\sum_{j=1}^n x_{j4}^2} \times W_4} & \frac{x_{25}}{\sqrt{\sum_{j=1}^n x_{j5}^2} \times W_5} \\ \frac{x_{31}}{\sqrt{\sum_{j=1}^n x_{j1}^2} \times W_1} & \frac{x_{31}}{\sqrt{\sum_{j=1}^n x_{j2}^2} \times W_2} & \frac{x_{33}}{\sqrt{\sum_{j=1}^n x_{j3}^2} \times W_3} & \frac{x_{34}}{\sqrt{\sum_{j=1}^n x_{j4}^2} \times W_4} & \frac{x_{35}}{\sqrt{\sum_{j=1}^n x_{j5}^2} \times W_5} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{x_{n1}}{\sqrt{\sum_{j=1}^n x_{j1}^2} \times W_1} & \frac{x_{n2}}{\sqrt{\sum_{j=1}^n x_{j2}^2} \times W_2} & \frac{x_{n3}}{\sqrt{\sum_{j=1}^n x_{j3}^2} \times W_3} & \frac{x_{n4}}{\sqrt{\sum_{j=1}^n x_{j4}^2} \times W_4} & \frac{x_{n5}}{\sqrt{\sum_{j=1}^n x_{j5}^2} \times W_5} \end{bmatrix} \end{matrix} \quad \text{Equation 2-10}$$

where:

$\bar{R}_{ij}$ – Normalised decision matrix columns [-]

W_i – Criteria weight as determined by Equation 2-2 [-]

ADT Selection Step 5: Prioritise the alternative solutions

To determine the most suitable ADT, the TOPSIS method calculates the shortest geometric distance to the ideal solution. The selection criteria are used to determine the range of each column. Specific to this study, a high range (maximum value) is favoured for performance, geotechnical compatibility and ergonomic compatibility. On the contrary, a low range (minimum value) is favoured for cost and reliability (maintenance cost per metre drilled).

Equation 2-11 is used to identify the positive ideal solution, while the negative ideal solution is given by Equation 2-12.

$$V_j^+ = \{V_1^+, V_2^+, \dots, V_n^+\} = \{(max_i v_{ij} | i \in I'), (min_i v_{ij} | i \in I'')\} \quad \text{Equation 2-11}$$

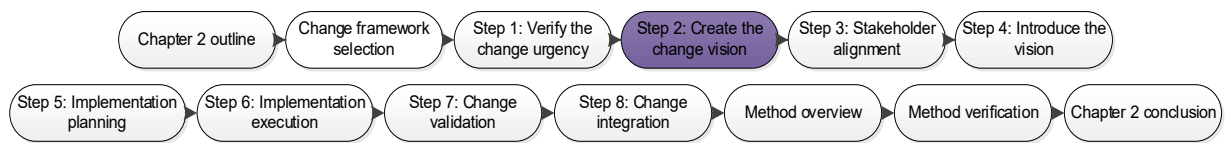
$$V_j^- = \{V_1^-, V_2^-, \dots, V_n^-\} = \{(min_i v_{ij} | i \in I'), (max_i v_{ij} | i \in I'')\} \quad \text{Equation 2-12}$$

where:

V_j^+ – Positive ideal solution [-]

V_j^- – Negative ideal solution [-]

In Equation 2-11, the highest value of that column must be added to the V^+ list for the maximum criteria while V^- is used for the minimum criteria value. For Equation 2-12, the inverse is true. The expected results are shown below:



	Geotechnical compatibility	Reliability	Cost	Ergonomic compatibility	Performance
ADT ₁	$\frac{x_{11}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1$	$\frac{x_{11}}{\sqrt{\sum_{j=1}^n X_{j2}^2}} \times W_2$	$\frac{x_{13}}{\sqrt{\sum_{j=1}^n X_{j3}^2}} \times W_3$	$\frac{x_{14}}{\sqrt{\sum_{j=1}^n X_{j4}^2}} \times W_4$	$\frac{x_{15}}{\sqrt{\sum_{j=1}^n X_{j5}^2}} \times W_5$
ADT ₂	$\frac{x_{21}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1$	$\frac{x_{21}}{\sqrt{\sum_{j=1}^n X_{j2}^2}} \times W_2$	$\frac{x_{23}}{\sqrt{\sum_{j=1}^n X_{j3}^2}} \times W_3$	$\frac{x_{24}}{\sqrt{\sum_{j=1}^n X_{j4}^2}} \times W_4$	$\frac{x_{25}}{\sqrt{\sum_{j=1}^n X_{j5}^2}} \times W_5$
ADT ₃	$\frac{x_{31}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1$	$\frac{x_{31}}{\sqrt{\sum_{j=1}^n X_{j2}^2}} \times W_2$	$\frac{x_{33}}{\sqrt{\sum_{j=1}^n X_{j3}^2}} \times W_3$	$\frac{x_{34}}{\sqrt{\sum_{j=1}^n X_{j4}^2}} \times W_4$	$\frac{x_{35}}{\sqrt{\sum_{j=1}^n X_{j5}^2}} \times W_5$
⋮	⋮	⋮	⋮	⋮	⋮
ADT _n	$\frac{x_{n1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1$	$\frac{x_{n2}}{\sqrt{\sum_{j=1}^n X_{j2}^2}} \times W_2$	$\frac{x_{n3}}{\sqrt{\sum_{j=1}^n X_{j3}^2}} \times W_3$	$\frac{x_{n4}}{\sqrt{\sum_{j=1}^n X_{j4}^2}} \times W_4$	$\frac{x_{n5}}{\sqrt{\sum_{j=1}^n X_{j5}^2}} \times W_5$
V_j^+	$\text{Max}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Min}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Min}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Max}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Max}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$
V_j^-	$\text{Min}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Max}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Max}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Min}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$	$\text{Min}(\frac{x_{j1}}{\sqrt{\sum_{j=1}^n X_{j1}^2}} \times W_1)$ $j = 1, 2, \dots, 5$

The distances to the ideal solution are obtained next. The Euclidean distance to the positive ideal solution and the negative ideal solution is calculated using Equation 2-13 and Equation 2-14, respectively.

$$S_i^+ = \sqrt{\sum_{j=1}^5 (V_{ij} - V_j^+)^2} \quad \text{Equation 2-13}$$

$$S_i^- = \sqrt{\sum_{j=1}^5 (V_{ij} - V_j^-)^2} \quad \text{Equation 2-14}$$

Where:

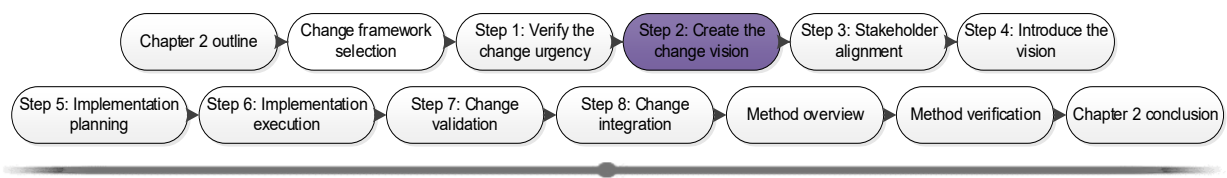
- S_i^+ – Euclidean distance from the ideal best [-]
- S_i^- – Euclidean distance from the ideal worst [-]

As a final action, the mine management team needs to prioritise each alternative to the ideal solution. This is done using Equation 2-15.

$$P_i = S_i^+ \frac{S_i^-}{S_i^+ + S_i^-} \text{ for } i = 1, 2, \dots, 5 \quad \text{Equation 2-15}$$

where:

- P_i Performance score (for $i = 1, 2, \dots, 5$) [-]



Action 2: Showcase the benefits

At this point, a strategy has been developed to guide the project team in selecting the best-fit-for-purpose ADT. A second strategy is now needed to identify and highlight the benefits of the chosen alternative. To achieve this outcome, a process of awareness creation through benchmarking was developed to measure the ADT's benefits against the established reference of compressed air.

Identify and adopt key benefit parameters: As mentioned earlier, the vision must be simple enough to be understood by all while providing sufficient information to highlight the business case to senior management. To achieve this outcome, an effective influencing technique, known as framing, is used [136]. Framing involves presenting the benefits of change in a way that speaks directly to the key areas of interest for stakeholder groups. It was learned from the literature review performed in [Section 1.7](#) that stakeholder interest areas in the gold mining industry comprise the following:

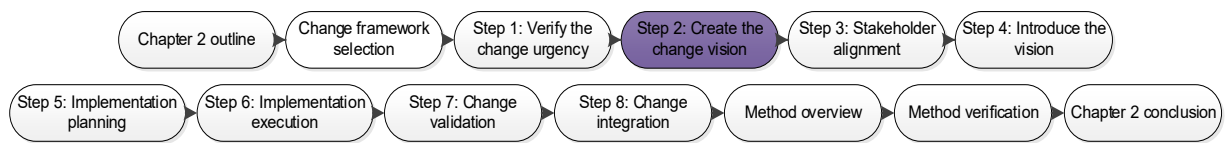
- 1) Performance (drill rate and face drilling cycle time) – [53], [66], [71].
- 2) SHE (noise, vibrations and heat load) – [9], [27], [66], [70].
- 3) Mine worthiness (equipment reliability) – [14], [48], [62], [66], [70].
- 4) Human factors (equipment mass load and ergonomics) – [32], [64], [69].
- 5) Techno-economics (energy cost and revenue generated) – [48], [49], [66].

Focus areas 1, 2, and 4 are specifically designed to demonstrate the benefits for end users, the rock drill operators (RDOs). In contrast, areas 3 and 5 are designed to present the business case to senior management.

Develop the vision: Table 2-4 shows the developed vision board for showcasing the benefits to all stakeholders.

Table 2-4: Proposed vision board

Focus area	Parameter	Pneumatic	Alternative	Expected benefit
1) Performance	Drill rate [Min/1.2 m hole]	A	B	A vs B
		Measurement	Literature	
	Face drilling cycle time [hours]	C	D	C vs D
		Measurement	Calculation	
	Production [% call achieve]	E	F	E vs F
		Measurement	Literature	
2) SHE	Water intensity ratio [tonne water/tonne ore]	G	H	G vs H
		Measurement	Literature	
	Energy intensity ratio [kWh/tonne]	I	J	I vs J
		Measurement	Literature	
		K	L	K vs L



Focus area	Parameter	Pneumatic	Alternative	Expected benefit
	Noise exposure (TWA) [dB(A)]	Literature		M vs N
	Vibrations exposure (TWA) [m²/s]	M	N	
		Literature		
	Occupational environmental temperature [°C]	O	P	O vs P
		Literature		
	3) Mine suitability	Reliability [m/failure]	Q	R
Literature				
Functionality		S	T	S vs T
		Literature/OEM supplier		
4) Human factors	Mass load [kg]	V	W	V vs W
		Literature		
	Ergonomics [–]	X	Y	X vs Y
		Literature/OEM supplier		
	Environmental contamination [–]	Z	AA	Z vs AA
		Observation	Literature	
5) Techno-economics	Opex [R/T]	BB	CC	BB vs CC
		Measurement	Literature/OEM supplier	
	Revenue [R]	DD	EE	DD vs EE
		Equation 2.1		

TWA: time-weighted average

Overview of strategies developed to evaluate each parameter:

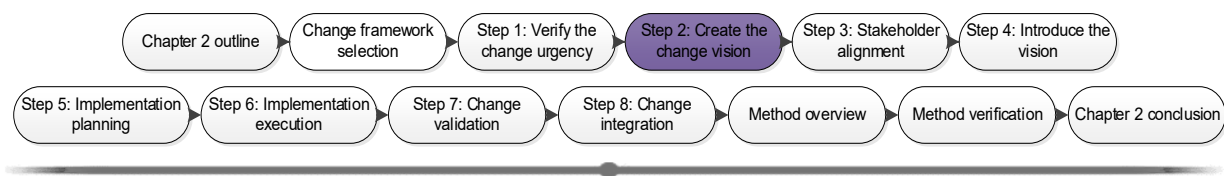
(1) Performance

Drill rate: The time spent drilling a hole is an effective and easy-to-comprehend metric frequently used in the industry to quantify a rock drill's performance [48], [49]. A benchmark comparison between the time required to drill a hole with a compressed air machine and the newly proposed machine will demonstrate the expected performance improvement to all stakeholders. The target audience is the RDOs, who would like to see how much faster they will be able to drill holes.

Drill rates are influenced by rock drill machine specifications and rock properties [137]. As a result, the alternative's drill rate might be unknown initially. To work around this limitation, proposed drill rates for various rock drills evaluated under the same conditions were obtained from published literature and are given in Table 2-5.

Table 2-5: Norite rock drill rates for various rock drills used in South African underground gold mines

Rock drill type	Drill rate [m/min]	Source
Compressed air*	0.30	[51]
Electric	0.13	
Hydropower	0.60	
Electro-hydraulic	0.60	



* Supply pressure @ 4 bar.

Face drilling cycle time: This parameter demonstrates the expected reduction in drilling cycle time. The benefit of a reduced drilling cycle time is twofold. Firstly, the probability of completing the blasthole drilling activity increases [9]. Secondly, the exposure time to risk and occupational illnesses [9], [51], [56]. The target audience is expanded to include RDOs and production managers, who will be interested in whether the alternative solution allows operators to complete the drilling activity within the same shift. Equation B-3 ([Appendix B](#)), is used to calculate the drill cycle times based on the drill rates provided in Table 2-5.

Production: The primary reason to consider an ADT is improved production. This parameter focuses on showcasing the ADT's production benefits. Production improvements are estimated based on historical data and improvements reported by previous studies.

Water intensity ratio: [Section 1.4](#) highlighted that ADTs have automated shut-off valves, which have the potential to save a significant amount of water. The water intensity ratio parameter is used to demonstrate this benefit and is estimated using historical data and published literature.

Energy intensity ratio: As discussed in [Section 1.3](#), the cost of operating large industrial compressors at a gold mine typically constitutes 20% to 40% of the mine's electricity bill. At the same time, alternative drilling systems might offer a significant improvement in energy costs [9], [117]. Consequently, the electrical energy intensity ratio presents an effective metric to showcase a drilling system's energy intensity benefits [9], [48]. Equation 2-16 is used to calculate the energy intensity ratio of each drilling system [48].

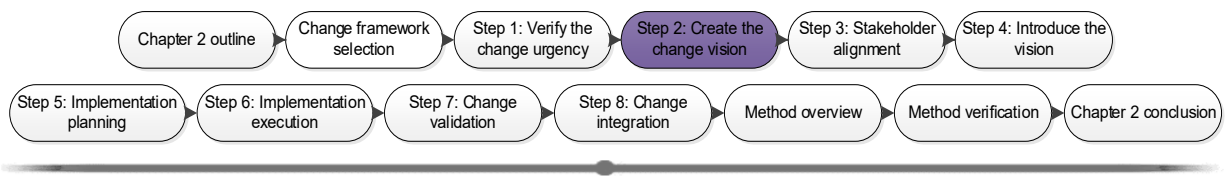
$$\text{Electrical energy intensity} = \frac{\epsilon}{\varepsilon} \quad \text{Equation 2-16}$$

where:

- ϵ – Electricity consumed by the pressure generation unit [kWh]
- ε – Corresponding production achieved [tonne]

(2) SHE

Noise and vibration: The expected benefits related to noise and vibration exposure levels need to be highlighted. Noise-induced hearing loss (NIHL) among South African gold stope team members was reported as an occupational illness in medical literature nearly three decades ago [138]. Stope teams exposed to noise levels above 82 dB(A) are considered to be at low risk for NIHL, while those exposed to levels above 90 dB(A) are at high risk [139]. All workers exposed to levels above 85 dB(A) are required to use hearing protection devices [51]. It is particularly important to consider the impact of noise exposure when introducing alternatives, since rock drills emit sound levels between 92 dB(A) and 105 dB(A).



Hand arm vibration syndrome is another occupational disease in South Africa that is documented in Schedule 3 of the Compensation for Occupational Injury and Disease Act, Act 130 of 1993 [140]. Initial cases of the syndrome in the South African mining industry were officially diagnosed in 2002 by Nyantumbu *et al.* [141]. Affected workers operated rock drills and experienced symptoms of hand and finger numbness followed by loss of grip strength and joint pain. Therefore, the impact of the alternative rock drill on vibration needs to be considered.

The target audience to influence here includes the stope team members, the shaft occupational hygienist and the medical practitioner. As a collective, they need to understand the impact that the alternative will have on these two health-related parameters. Noise and vibration exposure levels are calculated as follows:

Noise time-weighted average exposure calculation

Normalised to an eight-hour shift, a time-weighted average (TWA) noise level calculation estimates a worker's daily noise exposure [64]. It is measured electronically using a dosimeter issued by the shaft occupational hygienist to the RDOs. Alternatively, if electronic measurements are not possible, an employee's TWA noise exposure level can be estimated as a function of their noise dose percentage using Equation 2-17.

$$N(TWA) = 16.61 \times \log\left(\frac{D}{100}\right) + 90 \quad \text{Equation 2-17}$$

where:

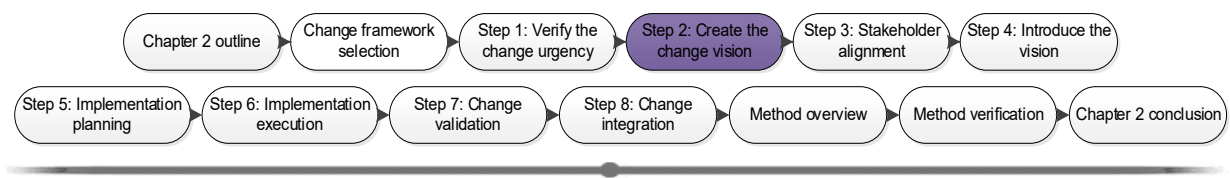
- D – Noise dose percentage [%] (Equation 2-18)
- $\log$ – Logarithm to base 10 [–]

Noise dose percentage (D) accounts for overall noise exposure to various levels over varying durations and is ascertained by Equation 2-18. It is a function of the time spent (C_n), in hours, at each noise level ($L_{1...2}$) and the corresponding reference duration. The reference duration calculation is expressed in Equation 2-19 and requires the measured rock drill sound pressure levels ($L_{1...2}$).

$$D = 100 \times \left(\frac{C_1}{T_n} + \frac{C_2}{T_2} + \dots + \frac{C_n}{T_n}\right) \quad \text{Equation 2-18}$$

where:

- C_n – Time spent at each noise level [hour]
- T_n – Reference duration [–] (Equation 2-19)



$$T_{1...n} = \frac{8}{2^{(\frac{L_{1...n}-90}{5})}} \quad \text{Equation 2-19}$$

where:

$L_{1...n}$ – Measured noise level [dB(A)]

Table 2-6 provides the sound pressure levels for various rock drills as obtained from literature.

Table 2-6: Sound pressure levels for various types of handheld rock drills

Rock drill type	Sound pressure levels as measured behind the drill [dB(A)]	Source
Pneumatic	104.4	[51]
Pneumatic exhaust with muffler	100.5	
Hydropower	98.9	
Electric	92.4	
Electro-hydraulic	100.0	[66]

Vibration TWA exposure calculation

A person's daily exposure to a certain vibration magnitude is expressed by Equation 2-20 and the proposed metric to quantify the vibration impact. The formula normalises vibration magnitude to actual exposure over an eight-hour base period. The vibration magnitude of the rock drill is normally provided by the OEM supplier. Alternatively, following in Table 2-7, Phillips *et al.* [51] made a comprehensive attempt to measure the vibration magnitudes of several rock drills used in South African underground mines. An RDO's exposure time represents the total time component during which the operator's hands made contact with the operational drill, which is estimated through the collar-to-collar drill rate multiplied by the number of holes drilled.

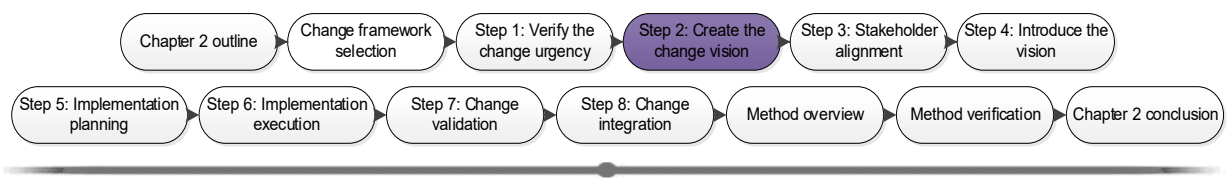
$$V(TWA) = a_m \times \sqrt{T/T_o} \quad \text{Equation 2-20}$$

where:

$V(TWA)$ – Daily vibration exposure [m/s²]
 T – Exposure time [hours]
 T_o – Reference duration of eight-hours [hours]

Table 2-7: Vibration levels for various handheld rock drills

Rock drill type	Weighted vibration acceleration [m/s ²]	Source
Pneumatic	21.9	[51]
Pneumatic with muffler	21.9	
Hydropower	31.0	
Electric	9.2	
Electro-hydraulic	11.0	[66]



Heat load: Compressed air drills offer up to 5 kW of cooling benefit per drill when operational [52]. This means that the ambient temperature around the RDOs will increase once the compressed air is removed from the workplace. Furthermore, the addition of electrical load to the pressure generation units of the alternative drilling systems might further increase the stope's heat load and ambient temperature [70].

Occupational environmental temperature: It is essential to highlight the temperature changes that may occur in the occupational environment.

(3) Mine suitability

Rock drill reliability: A metric commonly used in the mining industry to quantify a rock drill's reliability is mean time drilled between failures (MTBF) measured in m/failure [14], [48], [62], [66], [70]. This metric is crucial for the production team, as it informs them of the number of drills required to sustain production. Table 2-8 presents published reliability data for various rock drills used in underground gold mines.

Table 2-8: Reliability values for rock drills used in South Africa's underground gold mines

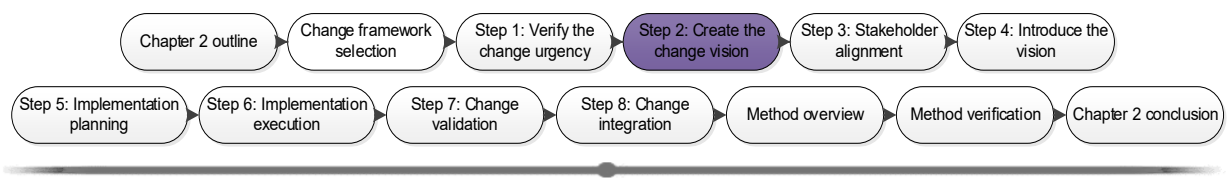
Rock drill type	MTBF [m/failure]	Source
Compressed air	800	[64]
Hydropower	500	[28]
Electric	128	[64]

Functionality: Functionality refers to all the key functions required to fulfil all the activities in the breaking cycle. Mine management teams are advised to assess whether the ADT offers the same functionality as its compressed air counterpart. Any key differences need to be noted and communicated under this parameter.

(4) Human factors

Equipment mass load and ergonomics: Previous researchers have found that operators are less resistant to change if significant changes to the equipment mass or ergonomics are avoided as much as practically possible [60], [76], [85], [110], [142]. The human factor focus presents an initial opportunity to sensitise the end user to possible changes in equipment mass or ergonomics. An OEM supplier consultation session may be necessary to quantify the changes in these parameters if they are not available in published literature.

Environmental contamination: Any changes to environmental contamination should be noted. For example, ADTs do not require oil or grease to lubricate the rock drill. This leads to the absence of oil contaminants in the ventilation air and service water.



(5) Techno-economics

A financial evaluation is needed to demonstrate the economic benefits of implementing and/or utilising new technology in mining projects [117]. It was uncovered in [Section 1.3](#) that the decision to implement ADTs is most frequently driven by one or both of the following operational constraints: the electrical costs associated with generating compressed air and the revenue lost due to insufficient compressed air supply pressure. As a result, the techno-economic parameters used to demonstrate the expected benefits were simplified to include opex cost reduction and additional revenue generated.

Opex: As noted in [Section 1.4](#), ADTs appear to be more energy efficient. This might offer a significant reduction in operational costs. The operational cost for the compressed air drilling system (R/tonne) can be obtained from the shaft financial manager. An opex estimate for the ADTs can be obtained from published literature or from the OEM supplier if no published data exists.

Revenue: Improved drilling performance and reduced operational costs may lead to increased revenue. The key consideration of ADTs is to eliminate losses related to compressed air. Revenue lost due to compressed air drilling constraints serves as an effective parameter to illustrate the potential revenue improvement. As expressed by Equation 2-21, revenue lost is simply the product of the lost production and the commodity price. Lost production due to drilling related reasons is generally accounted for by the mine's management team and can be obtained from them. Commodity prices used for business cases are available from the shaft financial manager.

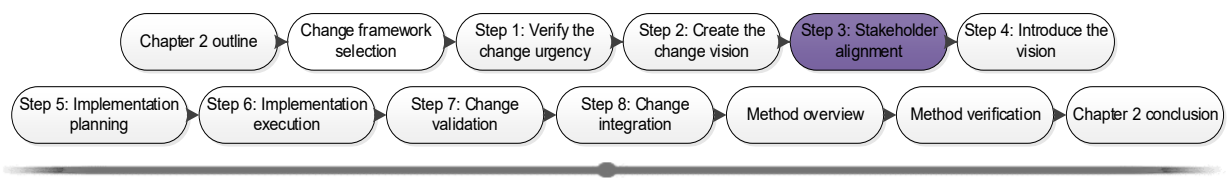
$$Revenue = (Lost_{production}) \times Commodity_{price} \quad \text{Equation 2-21}$$

where:

- $Lost_{production}$ – Gold lost due to inadequate drilling [kg]
- $Commodity_{price}$ – Commodity retail price [R/kg]

Step 2: Development summary

This section provided an overview of the strategies developed to guide the change vision creation process. The primary objective of Step 2 is to guide the project team through the process of creating a comprehensive change vision that clearly demonstrates the benefits and business case for the change to all stakeholders.



Step 3: Develop stakeholder alignment strategy

Previous research confirmed that poorly defined roles and corresponding responsibilities are the root causes of two failure drivers, namely lack of stakeholder participation and stakeholder misalignment [68], [88], [100], [125], [143]. These two failure drivers generally arise when stakeholders' perceptions of their roles and responsibilities do not align with organisational expectations. Consequently, role behaviour (the way a role owner executes actionable items) becomes unpredictable and unproductive. It was highlighted during the state-of-the-art review in [Section 1.7](#) that none of the studies reviewed presented a strategy to align stakeholders and encourage participation. To overcome this shortcoming, Step 3 focuses on developing such a strategy.

Responsibility charting is a strategy frequently used in industry to maintain stakeholder alignment and encourage participation [144], [145]. Responsibility charts specifically focus on aligning the stakeholders' role perceptions with organisational expectations. As illustrated in Figure 2-8, three distinct actions are required to develop a responsibility chart, which will be defined next.

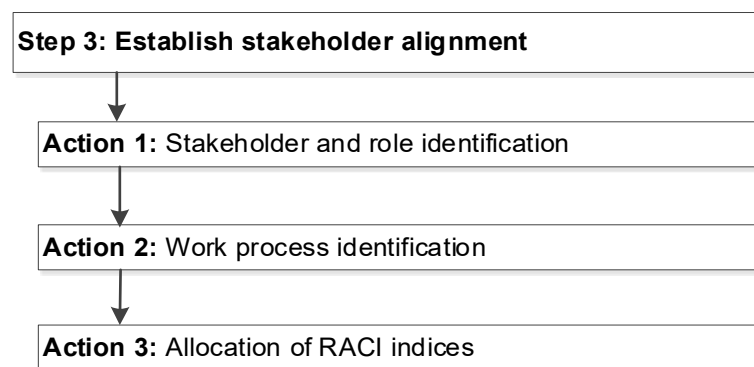


Figure 2-8: Step 3 – Development process flow

RACI: responsible, accountable, consulted, and informed.

Overview – Step 3: Development of a strategy to align stakeholders

Responsibility charts specifically applicable to the implementation of alternative drilling systems could not be found in the published literature. To overcome this shortcoming, Step 3 focuses in this section on developing such a responsibility chart. Table 2-9 shows the responsibility chart framework used.

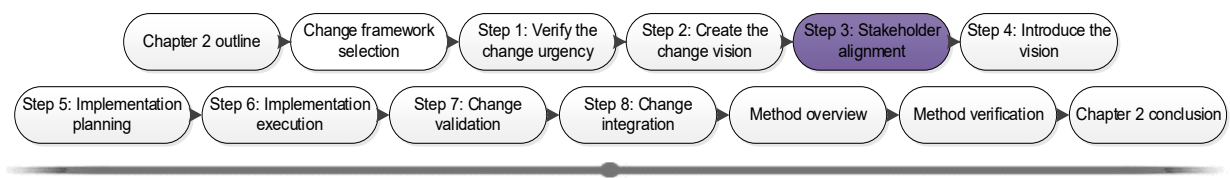


Table 2-9: Responsibility charting overview

C₁	C₂	...	C_n
	Stakeholder 1	...	Stakeholder <i>n</i>
Work process 1	R	...	A
.	.	.	.
.	.	.	.
.	.	.	.
Work process <i>n</i>	C	...	I

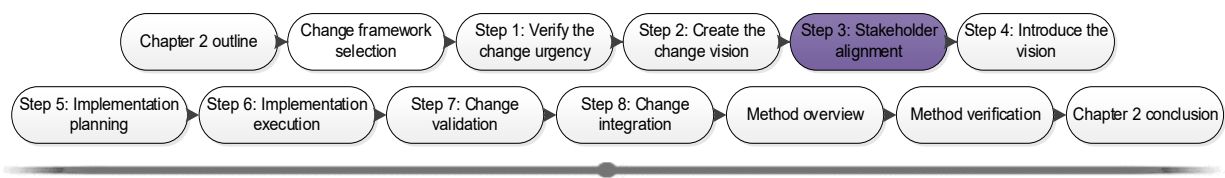
Action 1: Identify stakeholders and analyse roles

As the first step, all stakeholders (Stakeholder 1 to Stakeholder *n*) affected by the change must be identified [144]. These are the individuals who will form the multidisciplinary team responsible for implementing the change. They are added to the columns (C₂ to C_n) of Table 2-9.

Table 2-10 lists the key stakeholders and respective roles to consider in the analysis. The information provided here was gathered from previous attempts (published studies) to introduce new technology in narrow reef gold mines. The references to these specific studies are listed in [Appendix A](#), Table A-0-2.

Table 2-10: Key stakeholders and roles to consider

#	Stakeholder	Role
1:	The shaft general manager	General manager at the operation
2:	A shaft project engineer	Project engineer
3:	The shaft simulation engineer	Simulation engineer
4:	Shaft organised labour	Representatives from shaft organised labour
5:	The human resources leader	Coordinates all labour-related engagements
6:	Shaft risk manager	Legal coordinator of policies and procedures
7:	Shaft mine manage	Appointed as mine manager
8:	Shaft occupational hygienist	Appointed as occupational hygienist
9:	Shaft stope teams	End users
10:	Shaft engineering manager	Appointed as an engineering manager
11:	Shaft surveying department	Head of the survey department
12:	Product performance evaluator	Product performance evaluator
13:	Shaft's legal representative	Oversee all legal matters
14:	The shaft financial manager	Oversee all financial aspects
15:	An original equipment manufacturer supplier	Equipment manufacturer and supplier



Action 2: Identify the work process

Secondly, the work processes required to implement the technology need to be assigned to the matrix in the first column (C_1) of Table 2-9. These work processes represent the respective actions required under each of the eight steps of the method.

Action 3: Allocate RACI indices

Responsible, accountable, consulted, and informed (RACI) indices must now be assigned to each task under the respective stakeholders. Best practice success factors for assigning these indices were gathered from past literature and include the following five critical points:

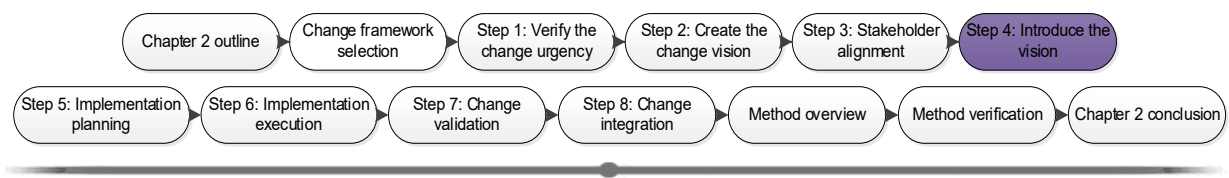
- **One accountable person per task:** There should only be one accountable (A) person per task [146].
- **At least one responsible person per task:** Assign at least one responsible (R) person with the required qualifications, appropriate skill, and experience needed to execute the task [145].
- **Balance workload:** Should be balanced by only assigning a manageable amount of work to each stakeholder [124].
- **Regularly review and update the RACI chart:** The chart should be reviewed and updated throughout the project life cycle [146].
- **Obtain stakeholder buy-in:** Review the initial draft with the identified stakeholders to promote buy-in and participation [14], [85]. If the stakeholders do not approve their assigned roles and responsibilities, then Step 3 needs to be revised. Stakeholder buy-in is obtained under Step 4: Introduce the vision.

To assign the RACI indices, the mine management team needs to determine the following:

- Who will be responsible for executing the task (R)?
- Who is the accountable person responsible for coordinating the task and providing answers to the project manager (A)?
- Who are the subject matter experts to be consulted during execution planning (C)?
- Who needs to be informed after a decision is made or an action is executed (I)?

Guidance on how to use the responsibility chart

The responsibility chart should be shared with the stakeholders initially when the vision is presented. Use the chart to share each stakeholder's roles and responsibilities with the team. Additionally, to track implementation and adoption progress, this study advocates for the use of a weekly progress alignment meeting.



The weekly interval was adopted from best practices compiled by Phillis and Gumede, who studied the success factors of 18 projects in South African platinum mines [123]. All stakeholders should be present, and each will provide feedback on the progress of their assigned tasks. This approach encourages participation, accountability, and ownership while promoting effective communication. More information on this topic will follow in Step 4

Step 3: Development summary

The literature review highlighted the shortcoming that none of the studies reviewed presented a stakeholder alignment strategy. To overcome this shortcoming, Step 3 aimed to develop a plan to maintain stakeholder alignment and encourage stakeholder participation by establishing a responsibility chart. Strategic guidance was provided on key stakeholders to consider and on how mine management teams should approach assigning the RACI indices.

Step 4: Introduce the vision and seek approval

Sharing the strategic vision is about persuading and shaping others' decisions. The outcome should be making stakeholders excited about being part of the future. The influencing technique proposed to sell the vision is known as framing [136]. How an idea is presented will influence how it is perceived and interpreted. People do not simply react to factual information; rather, they respond to how that information makes them feel.

As illustrated by the development process flow depicted in Figure 2-9, Step 4 provokes stakeholder buy-in by selling the vision to all stakeholders, which requires three actions, including: (i) selling the vision board (created in Step 2), (ii) introducing the equipment, and (iii) introducing the roles and responsibilities of all stakeholders affected by the change. A stage gate is incorporated to validate stakeholder buy-in for the proposed change idea. If the change idea is approved, the process flow will guide mine management teams to Step 5: Implementation planning. At the same time, if the change idea is rejected, it means the vision failed to sufficiently highlight the benefits. The proposed method will then redirect the team to reiterate. The strategies required to execute these three actions are defined next.

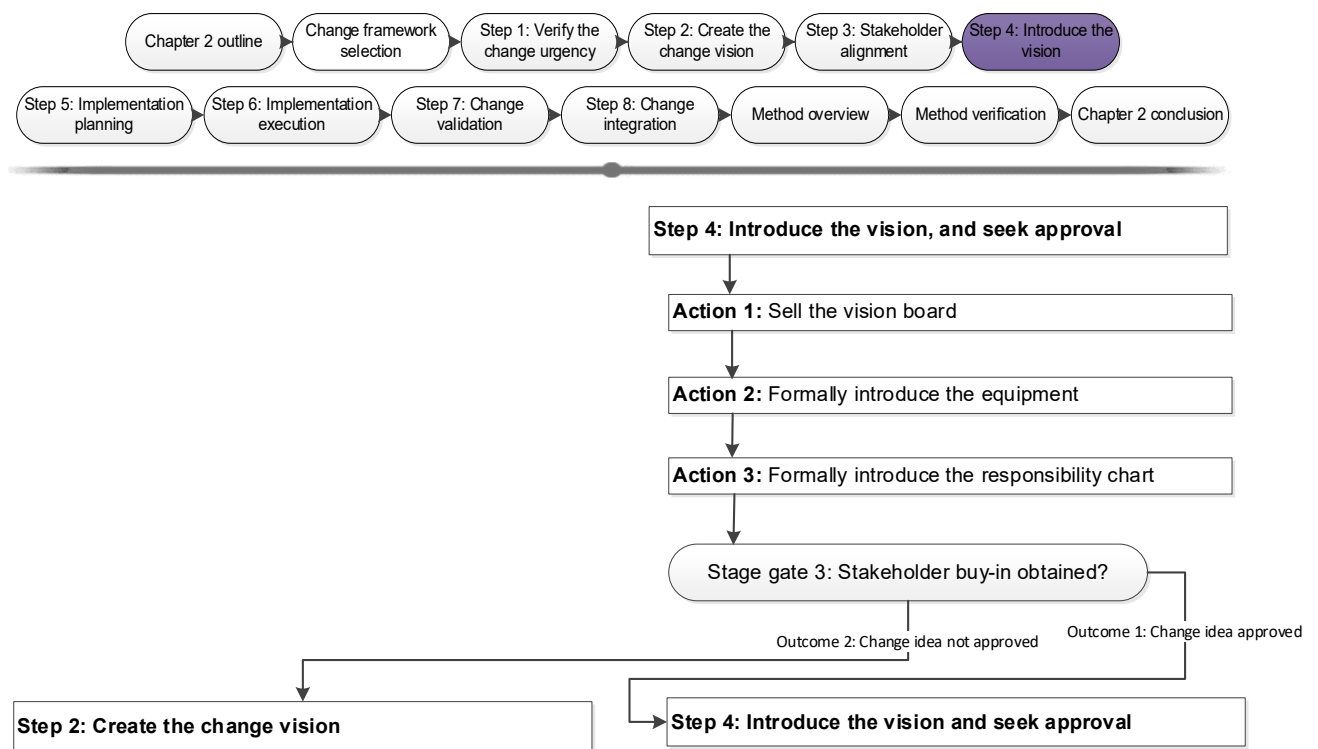


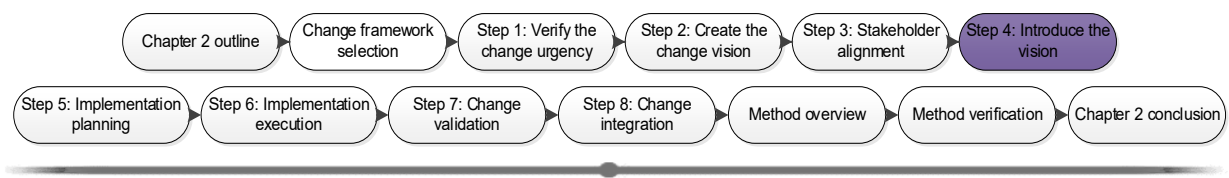
Figure 2-9: Step 4 – Development process flow

Action 1: Sell the vision board

Willis and Ashworth [85] and Wills and Buyens [14] recommended using interpersonal communication to sell the vision. A mass meeting with all the recommended stakeholders (listed in Table 2-10) present is required to share the vision. The shaft general manager is tasked with sharing the vision by presenting the vision board to the team. Relationships thrive on mutual benefits. The narrative should be tailored to resonate with each stakeholder group. For instance, RDOs who spend 12 hours underground will be moved to hear that the new drill enables them to exit the mine earlier. The additional equipment mass load should be framed as a quality requirement to support the high-performance output. Improved revenue figures at reduced operational costs will resonate well with senior management. The shaft general manager should be clear that the change initiative is aimed at helping them. When stakeholders grasp this, they will be much more receptive to the change idea.

Action 2: Formally introduce the equipment

Van der Meer *et al.* [126] advocated for the use of visual representations to assist in selling the vision. Visuals tend to stick longer in the human mind than simply being told that there is a problem and that change is needed [126]. A formal equipment introduction session should support the vision board that has been communicated. During this interactive session, stakeholders are encouraged to ask questions, and to see, feel, and experience the ADT's ergonomics, size, and other physical parameters.



Action 3: Formally introduce the change process

As final action, the responsibility chart needs to be shared with all the affected stakeholders. The goal here is to provide an overview of what the change process entails and who will be affected by it. This will promote interpersonal communication, stakeholder participation and buy-in.

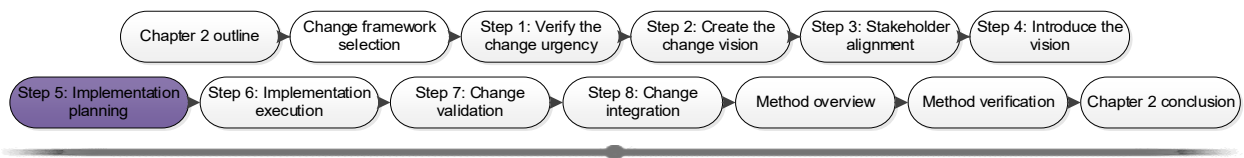
Stage gate 3 – Obtain stakeholder buy-in

At the end of the interactive session, stakeholders are asked to either approve or reject the proposed alternative.

- If the vision fails to convince the stakeholders, the project team needs to reiterate Steps 2, 3 and 4.
- If the vision is approved, the method guides the team to Step 5: Implementation planning.

Phase 1: Overview of strategies developed to initiate the change process

To summarise, the overarching objective of the first phase is to initiate the change process and influence stakeholder buy-in. Four steps and corresponding strategies are strategically defined to achieve this outcome, namely: Step 1: Verify the change urgency, Step 2: Create the change vision, Step 3: Establish stakeholder alignment, and Step 4: Introduce the change vision. These steps outline the necessary tactics to initiate the change process. The strategies defined under each step represent the blueprint for executing the tactics.



2.4. Phase 2: Develop and implement the change

The second phase of the change process, as highlighted in Figure 2-10, focuses on developing the necessary strategies to implement the change. It follows from the 50 studies reviewed in [Section 1.7](#) that failure to implement the change generally results from either one or a combination of the following failure drivers: (i) incorrect selection of alternative technology, (ii) lack of technology support systems, (iii) outdated policies and procedures, (iv) lack of an implementation strategy, (v) lack of stakeholder participation, and (vi) lack of a change management strategy.

The overarching objective is to develop strategies aimed at the following outcomes:

- (1) Provide system selection guidance.
- (2) Assess and recommend upgrades to support infrastructure.
- (3) Recommend updates to policies and procedures.
- (4) Develop an implementation plan.
- (5) Develop a change management strategy.
- (6) Reward stakeholder participation.

Steps 5 and 6 focus on developing these strategies using Figure 2-10 as guidance.

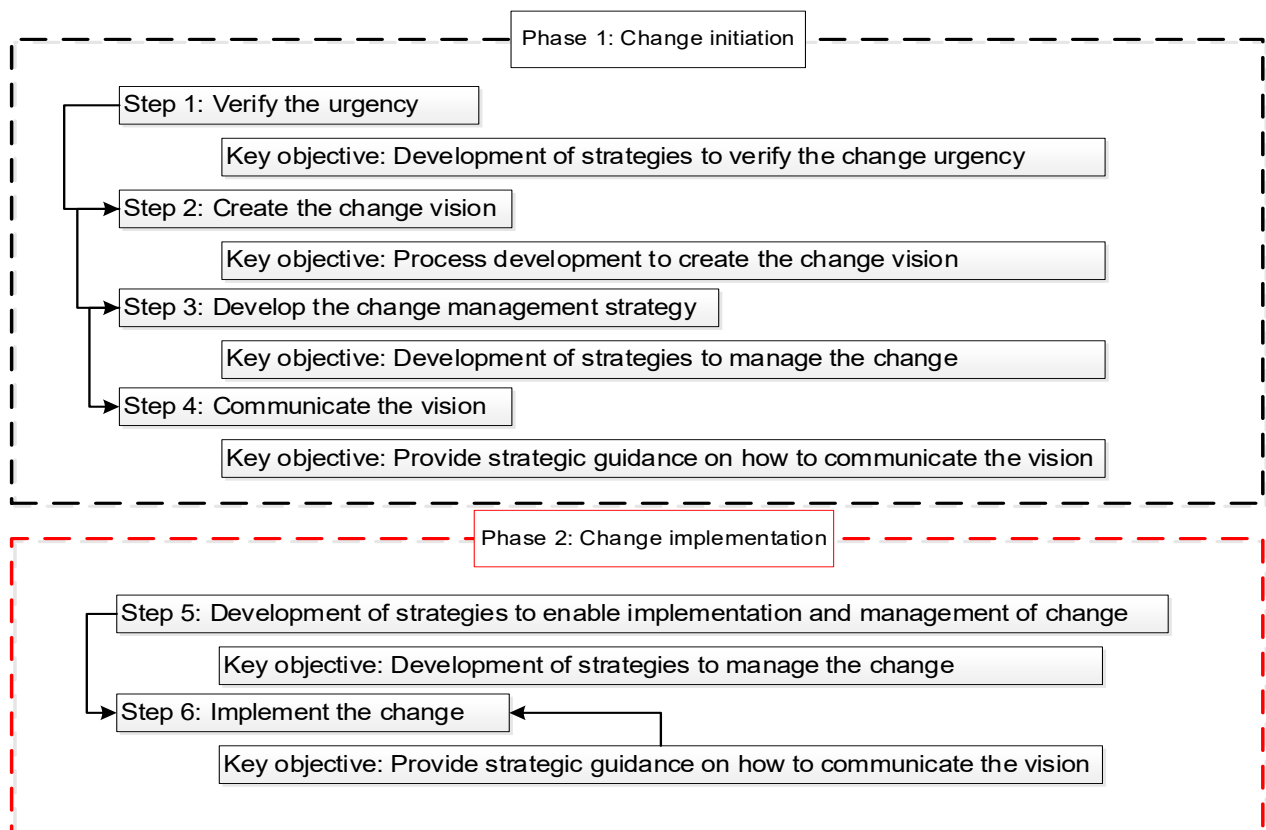


Figure 2-10: Method development process flow – Phase 2: Change initiation

Step 5: Plan the implementation

To enable change implementation, Figure 2-11 shows the strategies required to influence Outcomes 1 to 5 listed above. These strategies are developed through Steps 5.1 to 5.5 as demonstrated in the figure.

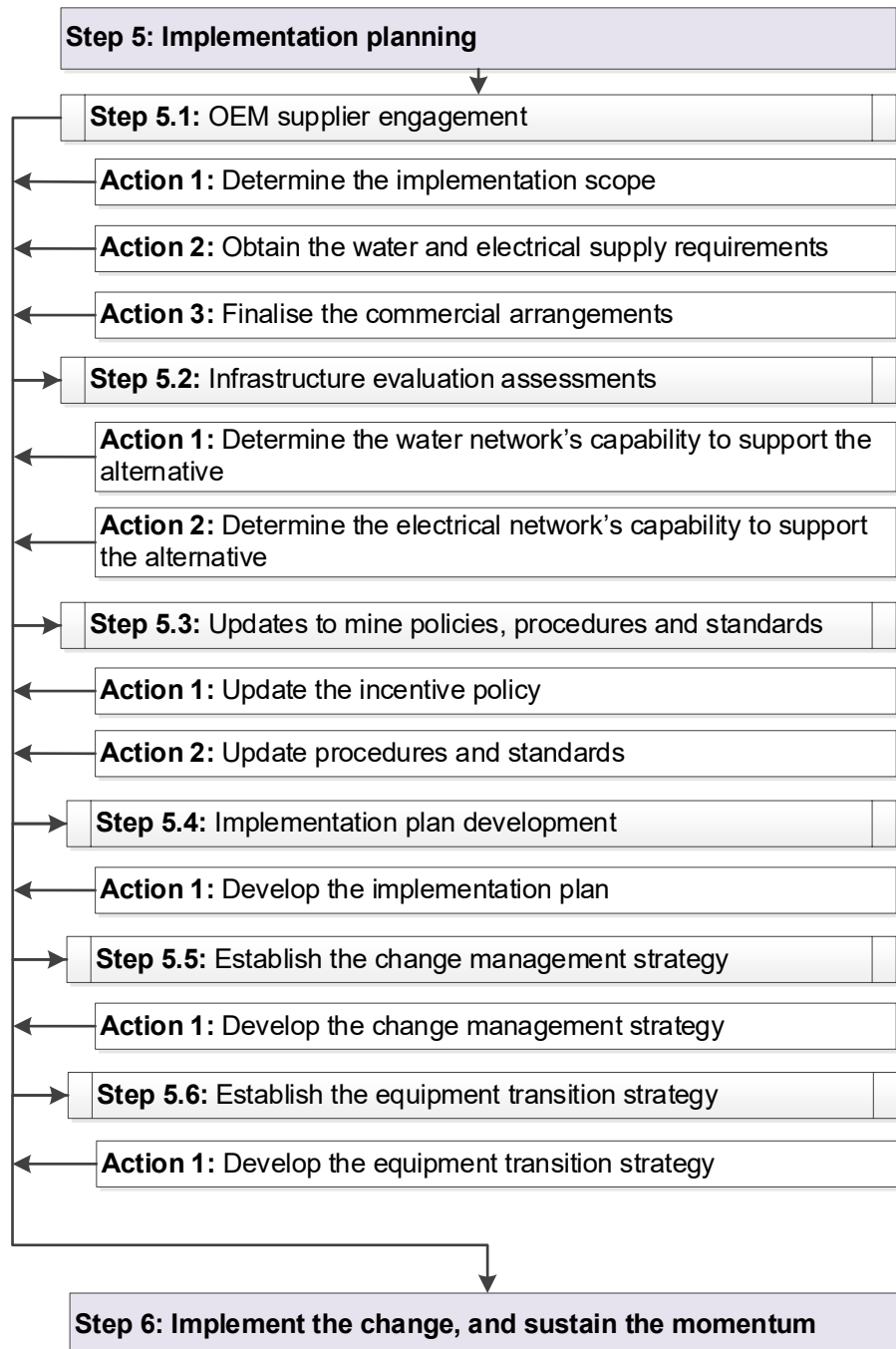
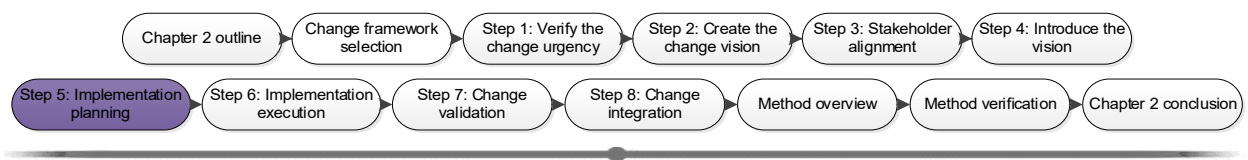


Figure 2-11: Step 5 – Development process flow

Step 5.1: Engage with OEM suppliers

As noted in the literature review of the available alternatives, two system configurations generally exist: in-stope microsystems, which supply only one panel per system, and localised systems,



which supply more than one panel from the same pressure generation unit. As a result, a strategy is needed to guide the selection of the optimal system configuration for the operation's implementation scope. The strategy development focuses on enabling three outcomes: Action 1: Determining the implementation scope, Action 2: Obtaining the water and electrical supply requirements, and Action 3: Finalising the commercial arrangement.

Action 1: Determine the implementation scope

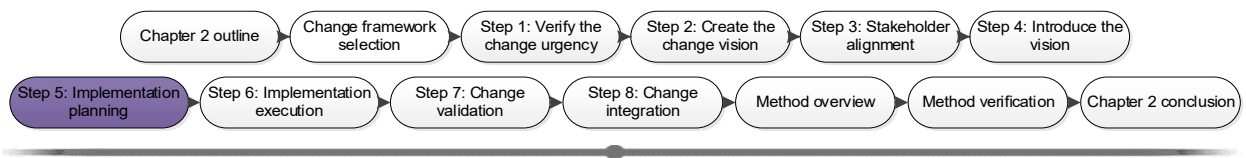
Step 2 provided guidance on selecting an alternative technology type based on a defined set of criteria. The need now exists to choose the system configuration type from the two available options, including in-stope or cross-cut based. An implementation scope needs to be established to enable the outcome.

This study adopted the CRM to develop a solution to the research problem (see [Section 1.10](#)). Figure 1-23 shows that the CRM is a non-linear research framework that provides a means to compare the actual case study results with what was claimed in the literature. This allows the method to be adjusted if the desired results do not materialise. Consequently, the proposed method recommends a sequential approach to introducing the alternative technology by first testing it on a small scale before rolling it out to the remaining crews. Once the trial yields the intended results to validate the claimed benefits, the technology will be deemed suitable for large-scale roll-out to the other panels. As a result, the initial implementation scope focuses solely on the trial site.

Vital information to disclose during the OEM supplier engagement session is listed in Table 2-11. It showcases the parameters, parameter descriptions, and data sources needed by the OEM supplier to recommend the most suitable system type and equipment configuration. These parameters should be as similar as possible between the initial trial and the baseline panel, subject to practical considerations.

Table 2-11: Mining, operational and drilling parameters

Parameter	Description	Data source(s)
Reef dip angle	- Mining parameters that describe the operation's geological constraints. - The OEM supplier will recommend the most suitable system configuration (localised/micro) based on these parameters.	Mine planning department
Reef type		
Ground conditions		
Stoping width		
Panel length		
Panel mapping		
Workplace location	- Operational parameters that will be used to derive the trial duration. - Workplace location will determine the size of the labour complement required. - Mining cycle overview will inform the OEM supplier regarding which equipment configurations to recommend.	Mine planning department and mine manager
Crew size (day shift)		
Production shifts		
Mining cycle overview		
Equipment used		



Parameter	Description	Data source(s)
Face burden spacing	- Blast and support design parameters. - Will be used by the OEM supplier to calculate maintenance cost.	Mine manager
Roof burden spacing		
Number of rows drilled		
Drill steel length (face)		
Drill steel length (gully)		
Drill steel length for roof support		
Drill steel length for siding		
Drill bit size		

Action 2: Obtain water and electrical supply requirements

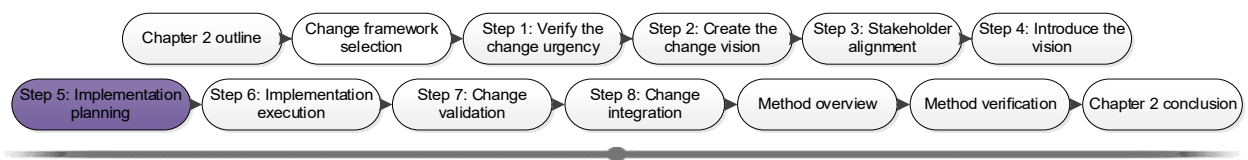
To reiterate [Section 1.5](#), there are concerns that alternative drilling systems may also introduce additional strain on the service water supply, dewatering network, and the electrical supply infrastructure. As a result, infrastructure evaluation assessments are required to identify limitations and recommend upgrades, as outlined in [Step 5.2: Infrastructure evaluation assessments](#). Table 2-12 provides an overview of the proposed request for information that will be used to perform the assessments.

Table 2-12: Request for information (RFI) on water and electricity supply requirements

Parameter	Description	Data source(s)
Water flow rate	- Water supply requirements. - Water flow rate and dynamic pressure requirements will determine what pipe sizes need to be used. - Water quality will inform whether the existing settler design is sufficient.	OEM supplier
Dynamic pressure		
Water quality		
Supply load	- Electrical supply requirements. - Supply load and power factor will determine the mini-sub capacity and supply cable size. - Switchgear ratings should be appropriate to maintain the desired supply voltage.	OEM supplier
Power factor		
Maximum/minimum supply voltage		

Action 3: Finalise the commercial arrangements

After the implementation scope is established, commercial arrangements are required to govern the agreed upon purchase and maintenance options, capex and opex, and equipment delivery lead times.



Purchase options: This action entails selecting the most suitable purchase option. Purchase options are generally OEM supplier dependent and may offer any of the following:¹¹ outright purchase, month-to-month rental, or rent-to-own options. The following purchase option selection guidance is recommended:

- Initially, while the alternative is being tested on a small scale with initial end users, a month-to-month rental agreement is recommended.
- After the alternative proves to be a suitable replacement, the remaining systems may be purchased outright if capital is available.
- If capital is not available, rent-to-own is advised.

Maintenance options: Typically, two maintenance options are available: service exchange and on-site repairs. The following maintenance option selection guidance is recommended:

- As the name implies, service exchange entails sending the faulty units from underground to the surface, where they are exchanged for a readily available serviced unit. Faulty units from various shafts are sent to a central OEM maintenance facility. This option generally results in lower repair costs, as multiple shafts help cover overhead expenses.
- However, an on-site underground repair facility is recommended if the mine is logistically constrained, as a one-week equipment turnaround time might lead to lost blasts due to equipment shortages.

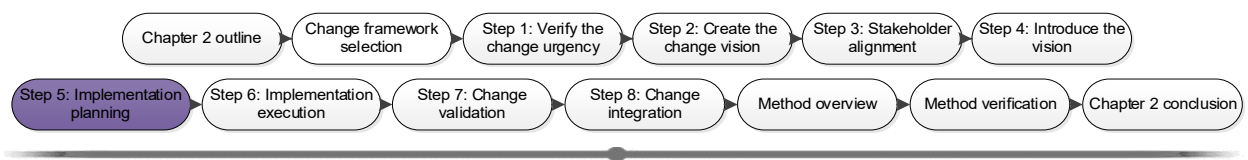
Contractual agreements: Based on the signed-off implementation scope, a formal quotation, including capex, opex, and lead times, must be obtained from the OEM supplier. The purpose is twofold: first, to seek capital approval from the executive management team, and second, to determine accurate roll-out timelines during the implementation plan development phase. Full details are available in [Step 5.4: Implementation planning](#). Once the capital request is approved, the group's legal department must draft a formal contract to protect the interests of both parties. Once the contract and the letter of award containing the order number are available, the OEM supplier may manufacture and deliver the equipment.

To protect the interests of both the mine and the OEM supplier, both parties need to formally sign off on the recommended system type, trial location and duration, capex and opex, purchase option agreement, equipment lead time, and maintenance agreement.

Step 5.2: Do an infrastructure evaluation assessment (IEA)

As highlighted earlier in [Section 1.5](#), the vast improvement in the efficiency of ADTs is attributed to enhanced positional efficiency. However, positioning the pressure generation units near the

¹¹ Gathered from unpublished personal communication with OEM suppliers.



working faces necessitates additional water and electricity [69], [70]. The mine's current water and electrical supply infrastructure may not be able to meet the increased demand for these resources. From an infrastructure support capability perspective, infrastructure evaluation assessments are necessary to verify the current (base case) system's support compliance with the design requirements of the new system (operational change) [147].

Published literature on existing methods specifically focused on assessing water and electrical systems when introducing ADTs to a narrow reef production environment is unavailable. Similar methods were considered to develop the approach proposed by this study. Lombard [147] developed a method to simulate electrical load changes to a mine's surface electrical distribution network when integrating a solar photovoltaic system with the existing network. Since Lombard's study focused only on the surface electrical network, Lombard's method was further expanded to meet the needs of this study.

Contrary to the electrical network, Maré [148] developed holistic frameworks and corresponding processes in 2016 to model mine refrigeration systems, air cooling systems, and water (supply and dewatering) reticulation networks. The method developed by Maré aimed to identify energy cost savings. This study highlighted the need to model the mine's flow and pressure requirements. As a result, Maré's method was adopted and adjusted to meet the needs of this study.

Overview – Step 5.2: Develop an infrastructure assessment method

This section provides an overview of the novel method developed to assess the mine's water and electrical infrastructure. Five steps are required to perform infrastructure evaluation assessments, including IEA Step 1: Simulation package selection, IEA Step 2: One-line diagram development, IEA Step 3: One-line diagram-to-digital twin translation, IEA Step 4: Base model set-up verification, and IEA Step 5: System evaluation.

IEA Step 1: Select a simulation package

The first step, as highlighted in Figure 2-12, provides strategic guidance for selecting an applicable simulation package. Two actions are required, namely establishing selection criteria and selecting the simulation package based on the selection criteria.

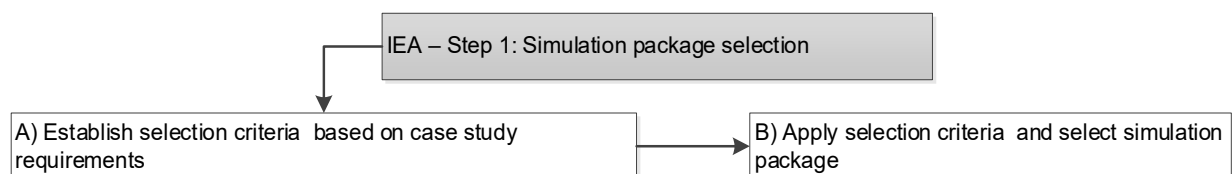
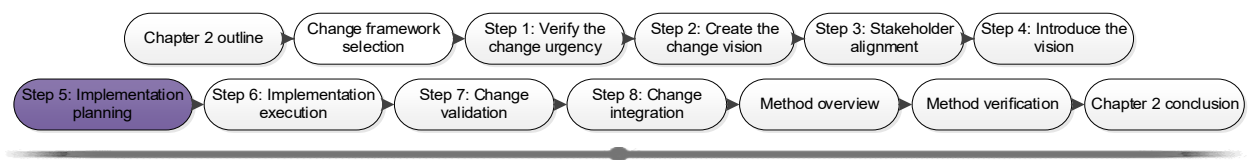


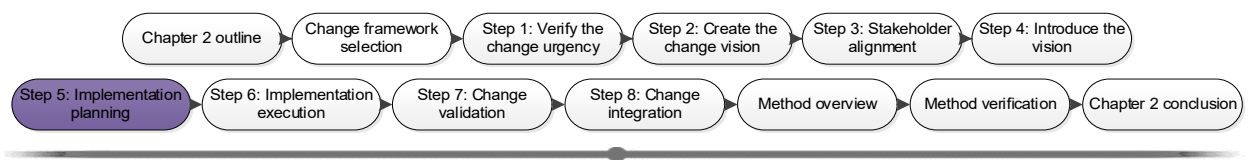
Figure 2-12: IEA Step 1 – Overview



(A) Establish selection criteria based on case study requirements

The following seven key selection criteria and questions were formulated to establish case study-specific simulation package selection requirements:

- 1) **Steady state and/or transient simulations – What system state needs to be simulated?**
 - If operational changes (mass flow, energy and momentum) occur throughout the simulation period, consider using packages capable of solving transient models [34], [148].
 - If not, steady state packages will suffice [31], [149].
- 2) **Open-source or licensed software – Is the operation willing to invest in licensed software?**
 - If yes, consider licensed packages as they generally offer end user support to assist the shaft simulation engineer [148].
 - If not, consider using a consulting firm with licensed software to perform the IEAs. Alternatively, an open-source package can be used, provided that any limitations are thoroughly understood.
- 3) **Assistance from existing resources – Do resources exist where the simulation package was used to model previous case studies?**
 - Select packages that come with established support resources. This will prevent the shaft engineer from “reinventing the wheel” while setting up models in the software.
- 4) **User interface – What user interface is used to depict the model?**
 - Drag-and-drop component interfaces tend to be more user-friendly and interactive [31], [34], [150].
- 5) **System size – What is the estimated size of the system to be simulated?**
 - This is an important factor to consider because many open-source packages limit the number of simulation nodes, which in turn restricts the size of the network that can be simulated.
- 6) **Simulation accuracy – What level of model accuracy is required compared to the base case?**
 - Simulation accuracy is a function of the specific solver used [147].
- 7) **Data import and export capability – Does the package have the ability to import and export component configuration characteristics?**
 - This becomes imperative when systems consisting of hundreds to thousands of components need to be modelled.



- Also, this function can be used to import digital survey plans to create a three-dimensional network [151], [152].

(B) Apply selection criteria and select a simulation package

After defining the selection criteria for the case study, the shaft simulation engineer must use these requirements to select the most appropriate simulation package. Software packages capable of simulating load flows of electrical networks include ETAP, DIgSILENT, MATLAB, PowerWorld, EasyPower, and MatPower [147], [153], [154]. Process Toolbox, Flownex, and VUMA3D are popular choices for simulating mine water networks [148], [149], [155].

IEA Step 2: Develop one-line diagram

A one-line diagram is used as a visual representation to define the system boundaries of the real-life system and to simplify system complexities into a single-line schematic. As exemplified in Figure 2-13, four actions were formulated to achieve this outcome: define system boundaries, perform a system audit, define operational changes, and develop the diagram.

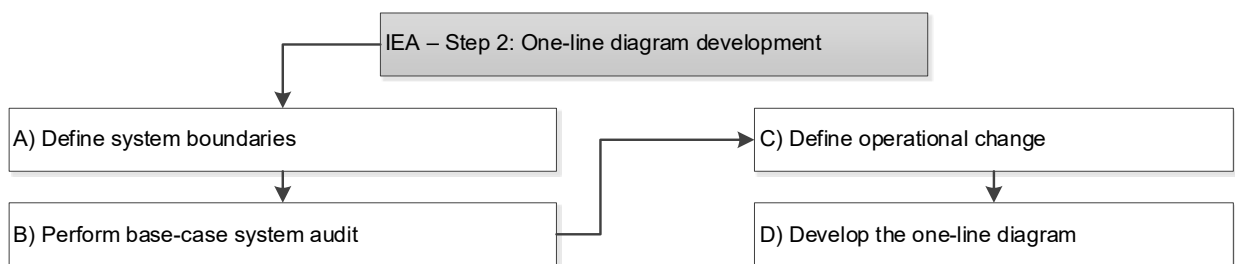


Figure 2-13: IEA Step 2 – Overview

(A) Define system boundaries

The first action focuses on defining the system boundary. This boundary should define the area of concern and enclose the base-case and operational-change focus areas. It is important to ensure that all base-case and operational-change system hardware components are accurately selected as boundaries, as this enhances simulation efficiency and effectiveness.

Electrical supply systems’ boundary-defining guidance: This study advises a bottom-up approach for defining the system boundary. As demonstrated in Figure 2-14, a bottom-up approach entails working from the load area backwards to the first point of supply (POS). If the simulation later in IEA Step 5 reveals voltage constraints at the point of contact (POC), expand the boundary selection to the next POS. This approach will enhance simulation efficiency and promote cost avoidance.

Water systems’ boundary-defining guidance: Contrary to the electrical supply system, a top-down approach is recommended when selecting the water network’s boundary, as illustrated in

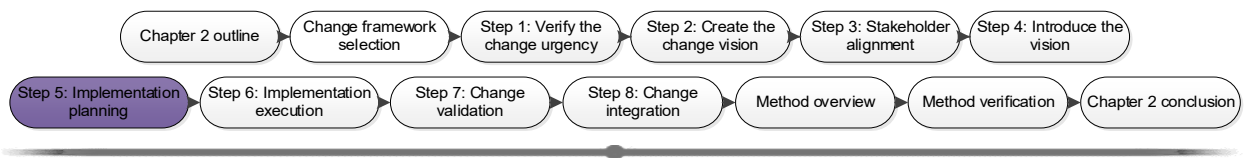


Figure 2-15. Water is usually supplied from surface storage dams to the underground mining levels. A series of dewatering pumps is used to return the water to the initial supply dam. As a result, the system boundary must encompass the entire network.

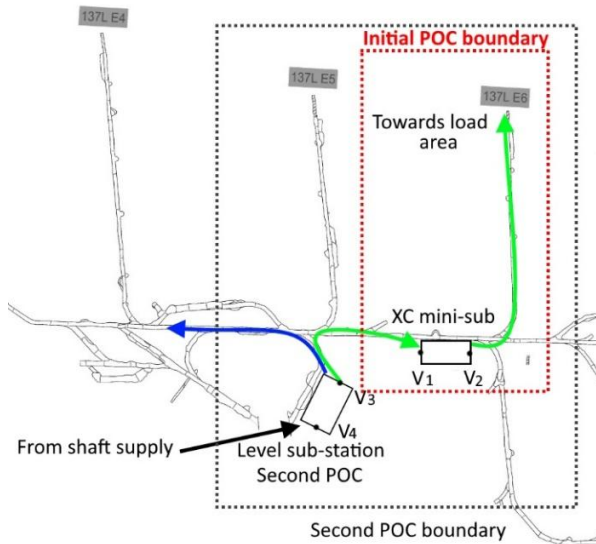


Figure 2-14: Electrical supply systems' boundary-defining guidance, where V_1 to V_4 denotes the voltage at the point of contact

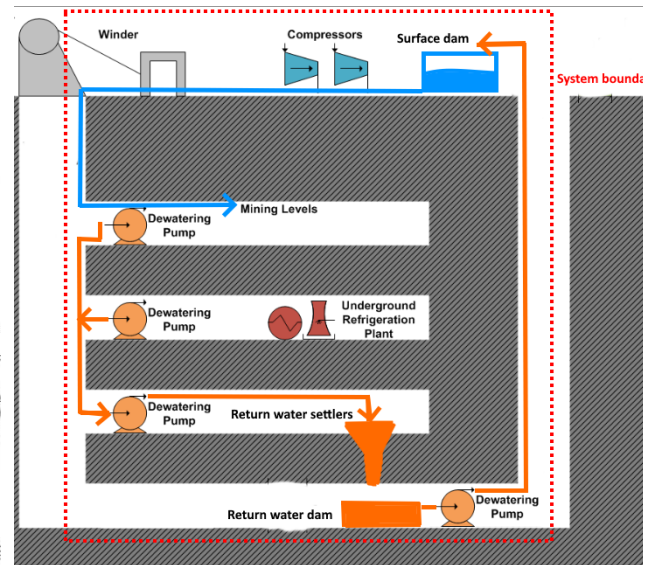


Figure 2-15: Water network system boundary selection guidance

(B) Perform a system audit

A formal system audit is needed to comprehend the system layout [31], [34], [147]. Digital system layouts are typically available from the shaft surveying department. The accuracy of the one-line diagram is paramount, as it is translated into a digital version in IEA Step 3 using simulation software. Therefore, the layout received from the shaft surveying department needs to be validated. To achieve this outcome, an underground audit is required.

All layout data is validated during the audit by comparing the layouts received with the actual infrastructure observed underground, and all system influencers are noted. Here, system influencers refer to all the characteristics of the system components that dictate system performance. Should system layouts not be available from the shaft surveying department, the layouts need to be developed using the audit data.

Table 2-13 lists the parameters of significance to check during the underground audit of electrical supply systems. Electrical cables are primarily sized by their cross-sectional area, representing the total surface area of the conductive core material [156].

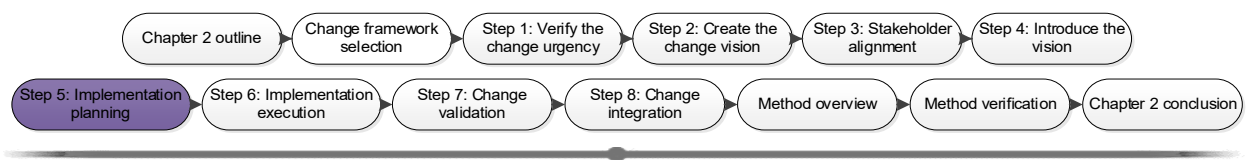


Table 2-13: Electrical supply infrastructure key audit information

Parameter	Unit	Source
In-stope electrical loads	kW	Measurements
In-stope load voltage	V	
Cable sizes	m ²	Visual inspection
Cable routing	–	
Contactors' rated current	A	
Mini-sub base-case load	kVA	
Mini-sub maximum load rating	kVA	Specification plates
Mini-sub no load voltage	V	
Mini-sub percentage impedance	%	
Reactance to resistance ratio	–	

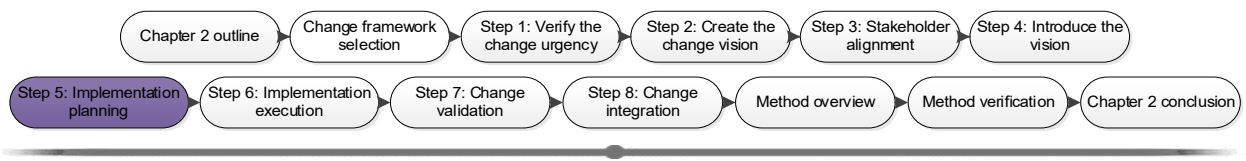
Water supply and dewatering systems: The parameters of significance to assess during the underground audit are listed in Table 2-14.

Table 2-14: Water network key audit information

Parameter	Unit	Source
Dam sizes	m ³	Design drawings
Dam levels	–	Logged data/manual measurements
Pipe sizes	mm	Visual inspection
Pipe routing	–	
Pipe material type	–	
Flow control valves rated flow rates	l/s	Specification plates
Flow control valves base-case flow rates	l/s	Logged data/manual measurements
Flow control valves base-case supply pressure	kPa	Logged data/manual measurements
Stope base-case flow rates	l/s	Logged data/manual measurements
Stope base-case flow rates	kPa	Logged data/manual measurements
Dewatering pump specifications	kW	Specification plates
Dewatering flow rates	l/s	PLC data/manual measurements

(C) Define the operational change

The objective of the IEAs is to assess the impact on the overall water and electrical network when introducing the alternative. The shaft simulation engineer needs to know which sections of the mine will be affected, when they will be affected, and to what extent. To achieve this outcome, the shaft simulation engineer must first understand the implications of the operational changes. The shaft simulation engineer will use the technical specifications acquired by means of Table 2-12 during [Step 5.1: OEM supplier engagement](#) to define the operational changes.



(D) Develop the one-line diagram

A one-line diagram is needed to provide a visual representation that defines the system boundaries and simplifies the system complexities into a single-line schematic of the base-case system and the operational change. The information gathered through the first three actions – (A) define system boundaries, (B) perform system audit, and (C) define operational change – is translated and consolidated into a one-line diagram. A drafting program such as Microsoft Visio™ may be used as a development tool to depict the one-line diagram graphically. The translation from the diagram to the digital twin follows in IEA Step 3.

IEA Step 3: Translate the one-line diagram to a digital twin to create the base-case model

IEA Step 3 covers the process of translating the one-line diagram into a digital version of the system using the simulation software packages selected in [IEA Step 1: Simulation package selection](#). The two actions required to achieve this outcome are summarised in Figure 2-16: construct a digital twin using the one-line diagram as a reference and configure components using system data collected.

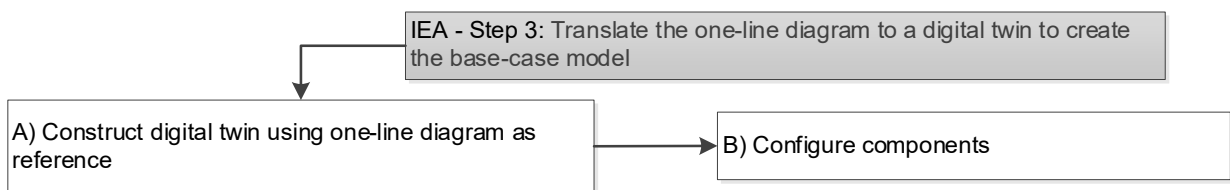


Figure 2-16: IEA Step 3 – Overview

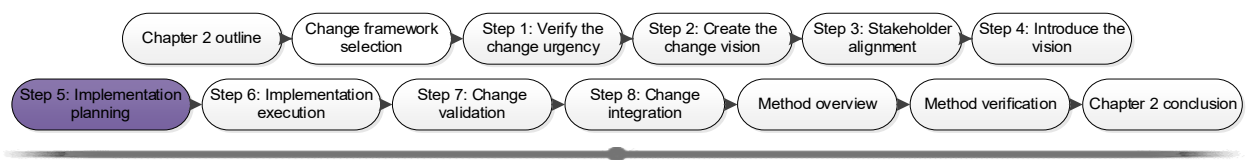
(A) Construct a digital twin using the one-line diagram as reference

The objective is to create a visual digital representation of the real-life system. The one-line diagram serves as a reference for constructing the digital model of the base model and the operational change. The term base model refers to a model representing the as-is system before the operational change is introduced. In contrast, operational change refers to the addition of the infrastructure needed to facilitate an alternative drilling system.

(B) Configure components

The digital model components need to be configured by adding the component characteristics. The objective is to transform the visual digital representation into a model that represents a digital twin of the real-life system. That is, a model that not only visually represents the real-life system but also mimics the real-life scenario in terms of component interactions. The data captured during the audits is used to facilitate the component configuration process as follows:

- Table 2-13 represents the data used to configure the transformers, cables, switchgear, and loads in the load flow simulation.



- Table 2-14 represents the data used to configure the water network's dams, pipes, control valves, pumps and heat exchangers.

IEA Step 4: Verify base model

At this stage, a review process is required to confirm whether the configured base model meets the system specifications as recorded during the audit. The review process developed by this study is illustrated in Figure 2-17.

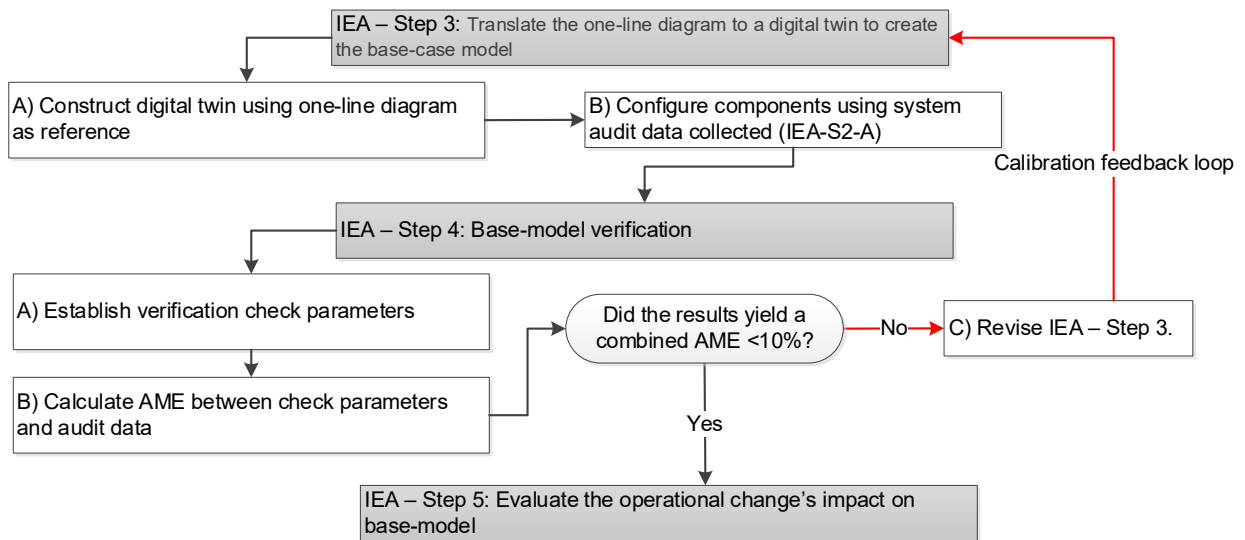


Figure 2-17: IEA Step 4 – Overview

(A) Establish verification check parameters

This action involves establishing verification check parameters. Verification check parameters refer to critical parameters used as data points to check and confirm the model's authenticity [31], [149].

Verification check parameters defined for the electrical network: The verification check parameters proposed by this study are listed in Table 2-15.

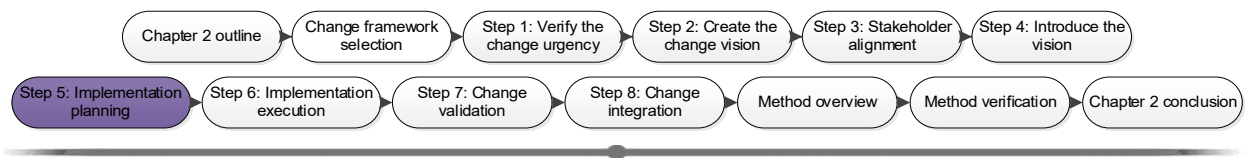


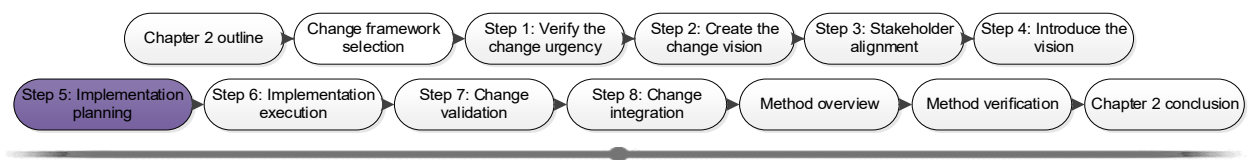
Table 2-15: Proposed verification check parameters for electrical load flow simulations

Parameter	Unit	Significance
1) Mini-sub base-case load	kVA	Simulated vs actual load: - If the simulated load exceeds the actual load, the load components were overmeasured during the audit phase and were consequently overconfigured. - If the simulated load is less than the actual load, the load components were undermeasured and underconfigured.
2) In-stope load voltages	V	Simulated vs actual voltages: - If simulated voltages are greater than actual voltages, the cable components were overconfigured or the loads were underconfigured. - If simulated voltages are less than actual voltages, the cable components were underconfigured or the loads were overconfigured.

Verification check parameters for water supply and dewatering systems: The four key verification check parameters, as shown in Table 2-16, are proposed. Parameters (1) and (2) are used to check the authenticity of the service water supply model, while parameters (3) and (4) are used to verify the dewatering model.

Table 2-16: Proposed verification check parameters for water network simulations

Parameter	Unit	Significance
1) Overall service water flow rate	l/s	A comparison between the simulated and actual water flow rates used by the mine indicates whether the end-user demands were configured correctly. - If the simulated flow is greater than the actual flow, the water demands were overestimated, and the water demand components were overconfigured. - If the simulated flow is less than the actual flow, it indicates that the water demands were underconfigured due to underestimated flow input data.
2) Cross-cut service water dynamic pressures	kPa	Similar to voltages, a comparison between the simulated and actual cross-cut service water dynamic pressures indicates whether pipe sizes and lengths were estimated correctly. - If the simulated cross-cut pressure is greater than the actual pressure, the pipe components were overconfigured or the water demands were underconfigured. - If the simulated voltages are less than actual voltages, the pipe components were underconfigured or the water demands were overconfigured.
3) Overall dewatering flow rate	l/s	A comparison between the simulated and actual water dewatering flow rates indicates whether the pumping infrastructure was configured correctly. - If simulated flow is greater than actual flow, the pumping infrastructure was overestimated, and the pump components were overconfigured. - If the simulated flow is less than the actual flow, the pumping infrastructure was underconfigured due to underestimated pumping input data.



Parameter	Unit	Significance
4) Dam levels	-	Simulated vs actual dam levels: - If dam levels simulated > actual: The dam sizes were overconfigured, or the pumping infrastructure was underconfigured. - If dam levels simulated < actual: The pipe components were underconfigured or the pumping infrastructure was overconfigured.

(B) Evaluate verification check parameters

The simulation is deemed accurate if the absolute mean error (AME) between the simulated and actual values of the proposed verification check parameters is 10% or less [31], [34], [149], [152]. The AME is ascertained by Equation 2-22. If the AME exceeds 10%, the verification check parameter guidance is used to revise [IEA Step 3: One-line diagram to digital twin translation](#).

$$AME = \frac{1}{k} \sum_{n=1}^{n=k} \left| \frac{M_n - S_n}{M_n} \right| \quad \text{Equation 2-22}$$

where:

- AME – Absolute mean error [%]
- k – Total number of data points [-]
- M_n – Measured data point value [-]
- S_n – Simulated data point value [-]

(C) Revise IEA Step 3: A calibration feedback loop is incorporated to cater for cases where the model presents an AME greater than 10%

The loop reverts the development process to revise IEA Step 3. During the revision process, the model's characteristics and assumptions are examined and updated. Further iterations of the process continue until the model presents an AME of less than 10%.

IEA Step 5: Evaluate the operational change's impact on the base model

As a final step, the operational change is applied to the calibrated base-case model and the impact is evaluated. The objective is to assess whether the base-case system can support the operational change. The three actions as illustrated in Figure 2-18 are required to achieve this outcome.

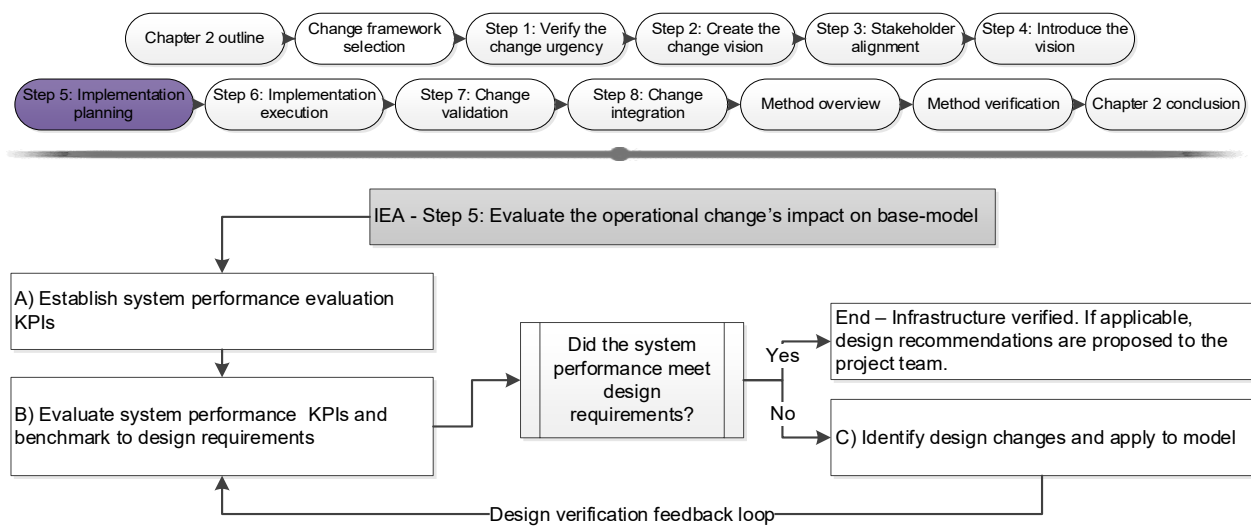


Figure 2-18: IEA Step 5 – Overview

(A) Establish the system design requirements

Performance indicators were defined to highlight key areas of concern when assessing the system's capability to support the operational requirements of alternative drilling systems.

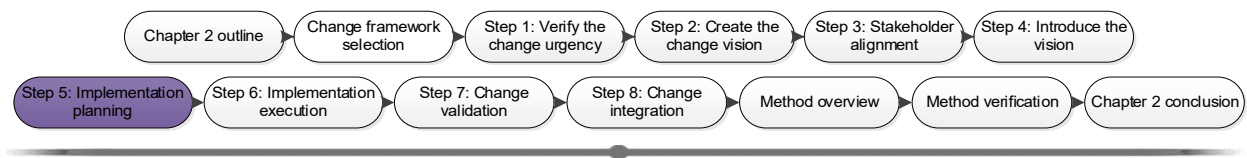
- (1) Mini-sub maximum load:** The mini-sub is considered to be the heart of the electrical network since its primary purpose is to convert distribution voltage (6.6 kV) to usable voltage (550 V) [157]. The supply capacity, rated in kilovolt-amperes (kVA), of common underground mini-substations typically varies from 3 kVA to 1 250 kVA. The mini-sub maximum load is, therefore, proposed as the primary performance indicator, as proper selection is imperative for safety and reliability.
- (2) Cable current limits:** Distribution cables represent the veins of the electrical network. Current and voltage requirements are the two primary considerations when evaluating whether the cables are sized correctly [158]:

- **Current requirement**

- To prolong cable lifespan by maintaining the cable temperature within acceptable limits (75–90°C), the continuous current through the cables must be less than the cable's maximum allowable current rating.
- The maximum allowable current rating for a single cable supplying an induction motor may not be less than 125% of the motor's full-load start-up current.
- For cables supplying more than one motor, the rated ampacity must be at least equal to the sum of the full-load current ratings, plus 25% of the highest rated motor in the cluster of motors.

- **Voltage requirement**

- The voltage drop across the cable from the POS to the load connection point must be within the equipment's allowable voltage limits. At the same time, overvoltages may damage the equipment. Undervoltages are defined as voltages below 85% of the nominal voltage [147], [159], as ascertained by Equation 2-23. Overvoltage limits are calculated using Equation 2-24.



$$V_{under} = 0.85 \times U_n \quad \text{Equation 2-23}$$

where:

U_n – Nominal voltage [V]

$$V_{over} = 1.1 \times U_n \quad \text{Equation 2-24}$$

where:

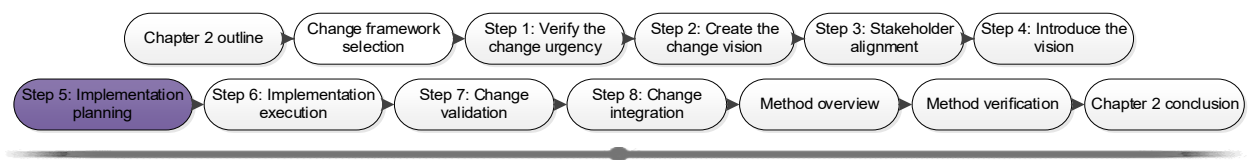
U_n – Nominal voltage [V]

(3) Switchgear trip rating: A circuit breaker is a vital safety device that trips and isolates the system in the event of a prolonged overload or short-circuit current [160]. Since overload is the primary concern here, the breaker guards against long-term current overloads that last more than 10 seconds. The trip action is accomplished by means of a bimetal strip, heated by the I^2R power losses. Manufacturers most often calibrate the thermal hardware in breakers to carry 100% of the continuous-rated current at 40 °C. The thermal element only defines overload at 125% of the continuous rated current, allowing for momentary overcurrent situations during the start-up of electric motors [161].

Proposed performance indicators for water supply networks:

The following three KPIs were defined to assess the electrical network's capability to support the operational changes:

- (1) Cross-cut dynamic supply pressure:** Water supply to the pressure generation units is essential for the system to operate without frequent low trips. Without enough water available, the dynamic water pressure will fall below the design requirements, and the system will trip.
- (2) Dewatering dam levels:** The key focus is to assess whether the existing dams have sufficient capacity to transfer water from underground to the surface without flooding the mine.
- (3) Dewatering column pressure:** A final KPI is incorporated to assess the dewatering column pressure.



(B) Benchmark system performance to operational requirements (Electrical network)

Finally, the electrical network operational change is activated in the model and the system's performance is evaluated. The KPIs are assessed as follows:

(1) Mini-sub load simulation result interpretation: If the simulated predicted load is greater than 80% of the maximum load, then:

- Overall system load exceeds 80% of the max available mini-sub capacity.
- Remedial action: Upgrade the mini-sub to the next available size [156].

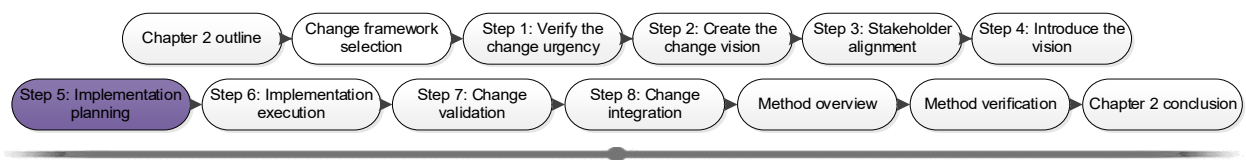
Key note: There is no set formula for determining the size of an underground mini-sub, as the mining process does not produce a constant load (i.e., not all loads connected operate simultaneously and continuously). As a starting point, the capacity may be estimated at between 50% and 80% of the connected horsepower [157]. However, take over winches and other additional loads might be installed as the stope matures¹². Therefore, to allow for flexibility, use the 50–80% rule as a reference and select the next available size.

(2) Cable current and voltage simulation result interpretation: Current and voltage requirements are the two primary considerations to review when evaluating whether the cables are sized correctly [158]:

- Current requirements to be reviewed
 - The continuous current through the cables must be less than the cable's maximum allowable current rating.
 - The maximum allowable current rating should exceed 125% of the motor's full-load start-up current.
 - For cables supplying more than one motor, the rated ampacity must be at least equal to the sum of the full-load current ratings plus 25% of the highest rated motor in the cluster of motors.

¹² Take over winches are not the norm in a well-developed stope. It is worth noting that the Candidate has experience at some mature gold mines where development is behind schedule, that take-over winches are frequently used when the face is pushed beyond the 90 m limit. Also, used when below step-over mining is done, and the ore needs to be pulled past the first short box into the second longer box. The Candidate further frequently observed taking over winches at gold mines where isolated blocks of ground (IBG) were targeted.

The additional loads referred to also include the introduction of tertiary ventilation fans (45 kW and smaller) on the reef horizon to force-ventilate the below step-over and IBG sections.



- **Voltage requirement** to be reviewed

- The voltage drop across the cable from the POS to the load connection point must be within the equipment's allowable voltage limits. Undervoltages are defined as voltages below 85% of the nominal voltage [147], [159].

If the simulated cable current loads breach the aforementioned current requirements, then:

- The cables are not capable of supplying the loads, which will result in the electrical equipment not starting up or in permanent damage to the cables due to excessive core temperature.
- Remedial action: Based on the current and voltage requirements, select the next available cable size and re-evaluate the system to determine whether the requirements are met. Repeat the process until the current and voltage requirements are met.

(3) Switchgear load simulation result interpretation: If the simulated breaker current loads exceed 125% of the continuous rated current, then:

- Switchgear is underdefined, which will result in frequent trip-outs.
- Remedial action: Upgrade the switchgear to the next available size, as per Table 2-17.

Table 2-17: Circuit breaker ratings for mining-service moulded-case circuit breakers (Adapted from [160])

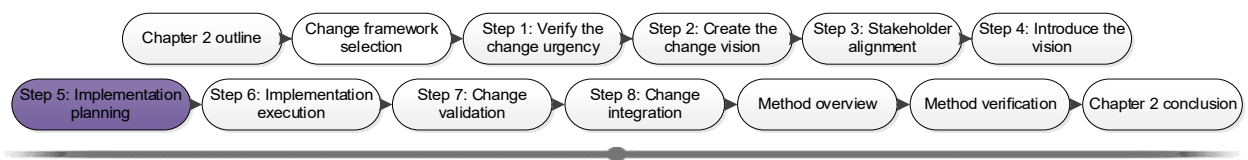
Circuit breaker frame size [A]	Maximum continuous-current ratings [A]	Lower continuous-current settings available [A]
100	100	70, 50, 30
225	225	175, 150, 125, 100
400	400	300, 225, 175, 150, 125, 100

(B) Benchmark system performance to operational requirements (Water network)

Finally, the water network operational change is activated in the model and the system's performance is evaluated. The KPIs are assessed as follows:

(1) Cross-cut dynamic supply pressure: Water supply to the pressure generation units is essential for the system to operate without frequent low trips. Without enough water available, the water dynamic pressure will fall below the design requirement, and the system will trip. If the simulated predicted cross-cut pressure is less than the design requirement, then:

- The system is not capable of supporting the alternative due to system constraints, such as small pipes and flow restrictions.
- Remedial action: Identify system constraints and implement the corresponding upgrades.



(2) Dewatering dam levels: The key focus is to assess whether the existing dams have sufficient capacity to transfer water from underground to the surface without flooding the mine. If the simulated predicted dam levels are greater than the design limit, then:

- The system is not capable of supporting the alternative due to system constraints, such as small pipes and flow restrictions.
- Remedial action: Identify system constraints and implement the corresponding upgrades.

(3) Dewatering column pressure: If the simulated predicted dewatering column pressure is greater than the design requirement, then:

- Pipes might burst.
- Remedial action: Identify system constraints and implement the corresponding upgrades.

Either of the following two cases will exist:

- **Case 1:** System performance based on model predictions meets the design requirements. In this case, the process concludes, and the system's capability to support the alternative is confirmed.
- **Case 2:** Model predictions reveal shortcomings, and infrastructure upgrades are required.

(C) Apply design changes and apply recommended changes to the model

Upgrades are formulated and applied to the model. A design verification feedback loop is incorporated to re-evaluate the system performance of the process (IEA Step 5-B). Reiterations of IEA Step 5 continue until the upgraded system meets the design requirements. The process concludes with a formal write-up to diligently compile system upgrade recommendations. This will be circulated to the project team during weekly stakeholder alignment sessions. The overall overview of the IEA method developed is provided using Figure 2-19.

IEA method development summary

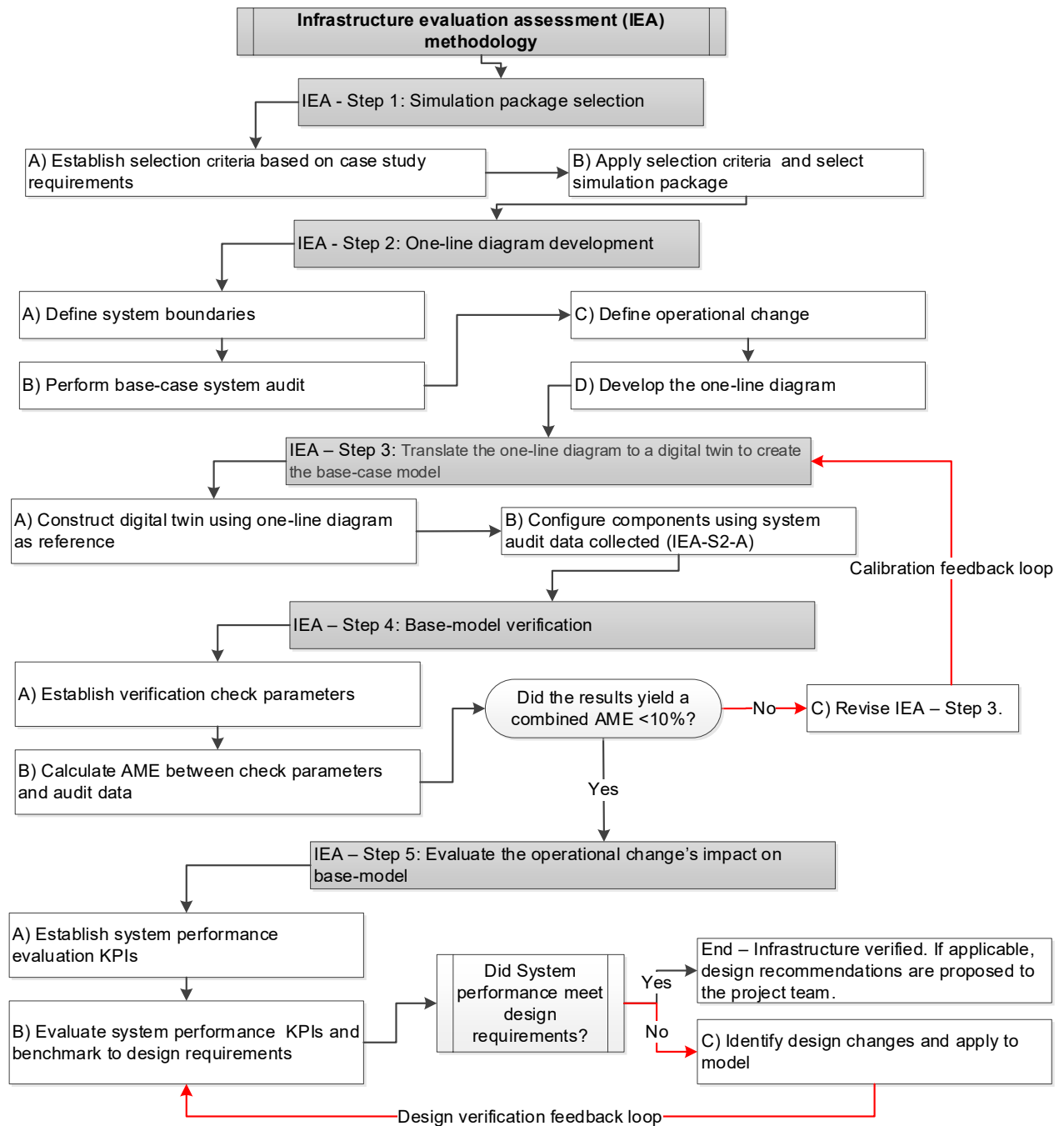
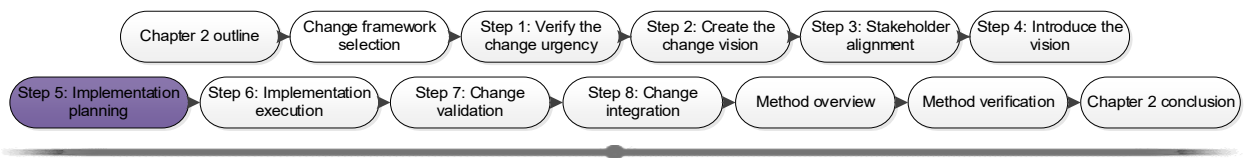


Figure 2-19: IEA method overview



Step 5.3: Update mine policies, procedures and standards

The importance of understanding the upstream and downstream impacts when improving the drilling cycle requires special focus [5], [14]. As such, personnel uncertainty regarding changes in policies, procedures, and standards was identified during the literature review as a significant contributor to change resistance (see Failure Driver 7 in Table 1-1). Crucial updates to this focus area, which were derived from best practices identified during the literature review ([Section 1.7](#)), are formulated in this section.

Action 1: Develop incentive policies

The significance of rewarding employees for participating in the transformation effort was emphasised by Willis and Ashworth [85] in [Section 1.7](#). The introduction of an alternative comes at the cost of reduced production during the implementation and training phase [46]. Consequently, a team must be established to redesign the adoption incentive structure to be compatible with the different phases of technology introduction. The end user, mining support, and engineering support are affected here, and key considerations are included.

(1) End user: End users refer to the crew who need to adopt the alternative. The following guidance was adopted from a previous study that implemented compressed air drill guides [14]:

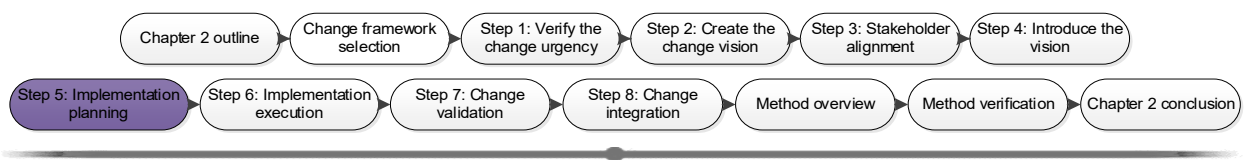
- For the first month, while familiarisation and training are underway, the crew's production target needs to be reduced to 75% of their normal target. This was derived from the fact that during the training phase, production typically reduces by 25% [8], [46].
- When training assessments are done during the second month, the target should be increased to 100% of normal. This will create a sense of urgency among the crew to take their training seriously and adapt more quickly.

(2) Mining support: This includes mining personnel responsible for supporting the end users:

- **Section managers:** The production target of section managers responsible for the end users must also be adjusted in accordance with changes made to the end users' call [14].
- **Equipping crews:** Be sure to revise the incentive structure for equipping crews. They are responsible for equipping the new workplaces with the alternative technology. Since the alternative technologies may require additional infrastructure to be installed, the incentive paid to equip a workplace must be revised.

(3) Engineering support: This includes the engineering personnel responsible for supporting the end users in terms of equipment, water, and electricity:

- Alternative technology usually requires more engineering support than conventional compressed air systems [62], [66], [76].



- If the engineering team is already fully occupied with the current workload, it is recommended to expand the team.
- No incentive changes are required if the engineering team has enough resources to absorb the additional workload.

Action 2: Develop procedures and standards

The introduction of new equipment naturally necessitates updates to the operational procedures. There are two key focus areas: Safe equipment operation and training.

Focus area 1: Safe equipment operation

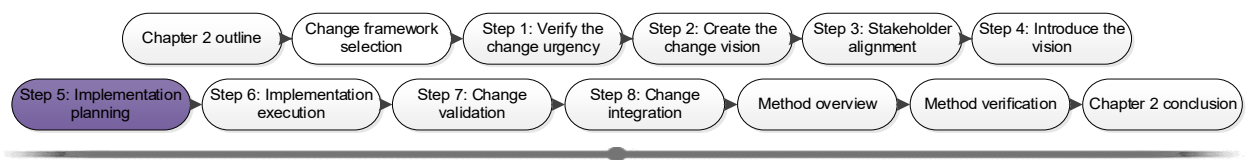
The shaft standards committee is advised to consult with the OEM supplier, who can serve as subject-matter experts. Updates to the following procedures, standards and codes of practice are required:

- (1) Equipment installation standard:** The best practice guidelines that define the safe installation standards for the alternative technology.
- (2) Baseline risk assessments:** The high-level assessment performed to identify the applicable risks and hazards of the system.
- (3) Task-based risk assessments:** A detailed assessment is performed to identify the risks and hazards associated with using the equipment to perform tasks such as drilling, support, cleaning and charging. Tasks to include follow from the baseline risk assessments (2).
- (4) Equipment safe operating procedures:** Best practice guidelines that ensure the safe operation of alternative equipment. Information gathered during the task-based risk assessment (3) is typically used to inform the safe operating procedures.
- (5) Planned task observations:** Assessments performed to prevent complacency regarding the prescribed safe operating procedures identified in (4).
- (6) Pre-use inspections:** Best practice guidelines for inspecting and identifying faulty equipment before use.
- (7) Code of practice:** Refers to the set of guidelines that ensures the health and safety of mining personnel.

Focus Area 2: Training

South African mining crews are generally scheduled for annual refresher training (Competency A and B) to prevent complacency and promote competence. The training modules need to be updated to include the following:

- (1) Learner guide:** The theoretical learning material used for annual refresher training needs to be revised in accordance with the updated procedures and standards.



(2) Training mock-up: Following theoretical training, practical training is necessary to reinforce the theoretical concepts. An additional equipment suite is needed at the training centre to replace the conventional system.

(3) Underground competency assessments: After completing surface training, crews undergo underground capability and competency assessments. The shaft training coordinator must also update the assessments used to reflect the specifics of the alternative.

Step 5.4: Develop implementation plan template

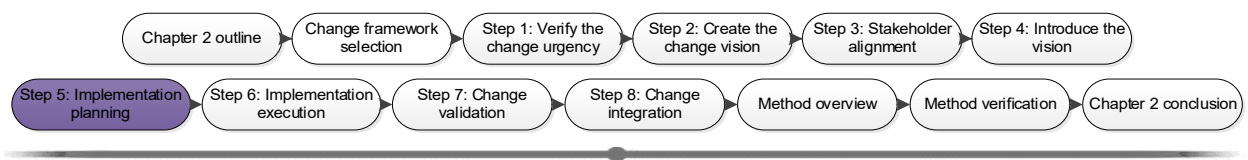
Past failures to introduce new technology, as identified in [Section 1.7](#), highlighted the lack of a formal implementation plan as a key driver of failure that hindered implementation. An implementation plan is used to consolidate the key strategies needed to execute the change effort, including implementation timelines and responsible persons [162]. In essence, it is a planning tool for enabling implementation by promoting stakeholder participation, accountability, and change management. The literature review performed in [Section 1.7](#) highlighted a clear research gap relating to implementation planning, as no plan could be obtained. This gap facilitates the introduction of an alternative drilling system in mature gold mines (see Table 1-4). To address this shortcoming, this step focuses on developing an implementation plan template to meet the study's needs.

Implementation plan template development process applied

Framework proposed: To initiate the development process, an implementation plan framework is necessary. The framework highlights the key elements needed to foster the implementation strategies. A literature study was conducted to review implementation frameworks that have been successfully applied to implement sustainable business processes in sectors other than mining. The review findings are summarised in Table 2-18, which shows several framework elements proposed by previous researchers. It is paramount to note that none of the frameworks is alike, as the outcomes driven by each framework differ. The review, therefore, suggests that the objective of the implementation method determines the framework's key elements.

Since the overall objective is to introduce ADTs in narrow reef gold mines, an implementation framework is needed to enable the strategies proposed by this study, including:

- **Analyse** the urgency by means of *Step 1: Verify the urgency* and *Step 2: Create the vision*.
- **Design** an organisational network to support the alternative through *Step 3: Change management*, *Step 4: Communicate the vision*, and *Step 5: Enable implementation*.
- **Implement** the alternative through *Step 6: Implement and sustain the change momentum*.
- **Monitor** the performance and **control** the rate at which the alternative is introduced by means of *Step 7: Continuous performance monitoring* and *Step 8: Sequential expansion of the change process*.



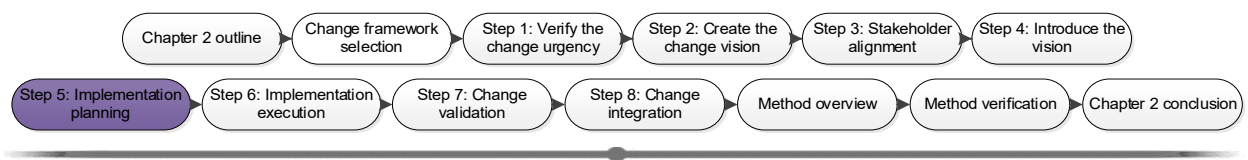
It follows logically to highlight the framework proposed by Gallotta *et al.* [163] in Table 2-18, which appear to be compatible with the four strategic outcomes of this study's method. Based on this rationale, the framework elements selected for this study's implementation plan are: analyse, design, implement, and monitor and control.

Table 2-18: Implementation plan framework elements proposed by past research

Source		Implementation plan framework elements	
Year	Reference		
2018	[164] Nawaz and Koç	1. Vision 2. Risk assessment and objectives 3. Risk reduction	4. Preparation and organisation 5. Implement, monitor, and analyse 6. Review and continual improvement
2017	[165] Sroufe	1. Drivers 2. Enablers	3. Evaluators 4. Change management
2017	[166] Jagoda and Samaranayake	1. System options 2. Selection methods 3. Readiness assessment	4. Partner selection and negotiation 5. Implementing 6. System impact assessment
2016	[167] Laurenti <i>et al.</i>	1. Plan 2. Do	3. Check 4. Act
2016	[163] Gallotta <i>et al.</i>	1. Analyse 2. Design	3. Implement 4. Monitor and control
2007	[168] Basoglu <i>et al.</i>	1. Technology 2. User	3. Organisation 4. Project management
2011	[169] Chofreh <i>et al.</i>	1. Initiating 2. Planning 3. Executing	4. Controlling 5. Closing
2003	[170] Al-Mashari <i>et al.</i>	1. Setting up 2. Deployment	3. Evaluation
2001	[5] Macfarlane	1. Vision 2. Change team 3. Work cycles 4. Task grouping	5. Structure 6. Systems 7. People 8. Culture

Development of the implementation plan template

To develop the implementation plan template, the tasks required to implement the ADT were grouped into subtasks, each with corresponding actionable items. To enforce accountability and participation, responsible persons and timelines were assigned to every actionable item. Table C-0-1 in Appendix C showcases the implementation plan template that was developed, where:



- *Step 1: Verify the urgency* and *Step 2: Create the vision* – analyse the urgency.
- *Step 3: Manage change*, *Step 4: Communicate the vision*, and *Step 5: Enable implementation* – design an organisational network to support the alternative through.
- *Step 6: Implement and sustain the change momentum* – implement the alternative.
- *Step 7: Monitor performance continuously* and *Step 8: Expand the change process sequentially* – monitor performance and control the rate at which the alternative is introduced.

Step 5.5: Establish a change management strategy

Overview – Step 5.5: Development of change management strategies

A significant obstacle to adaptability is resistance to change. Stakeholders generally fear change because it creates uncertainty and disrupts their comfort zone. Any change process requires stakeholders first to unlearn old, comfortable habits and then adopt new mindsets. Successful change management strategies create a culture in which evolution through experimentation is celebrated rather than feared. The strategy should encourage curiosity through innovation.

The literature review performed in [Section 1.7](#) was specifically focused on identifying the various forms of resistance to organisational change. It was well established from the 50 studies reviewed that humanistic and/or systemic drivers drive resistance to organisational change. Figure 2-20 summarises the humanistic and systemic resistance drivers identified in [Section 1.7](#). This highlights the need for a clearly defined change management strategy to influence the following six strategic objectives (as defined in Table 1-5):

- Promote change willingness,
- Manage misperceptions,
- Promote an inclusive leadership style,
- Manage emotional wellness,
- Ensure stakeholder alignment, and
- Align planned versus actual change implementation progress.

An overview of the relevant strategies developed to promote this outcome is presented next.

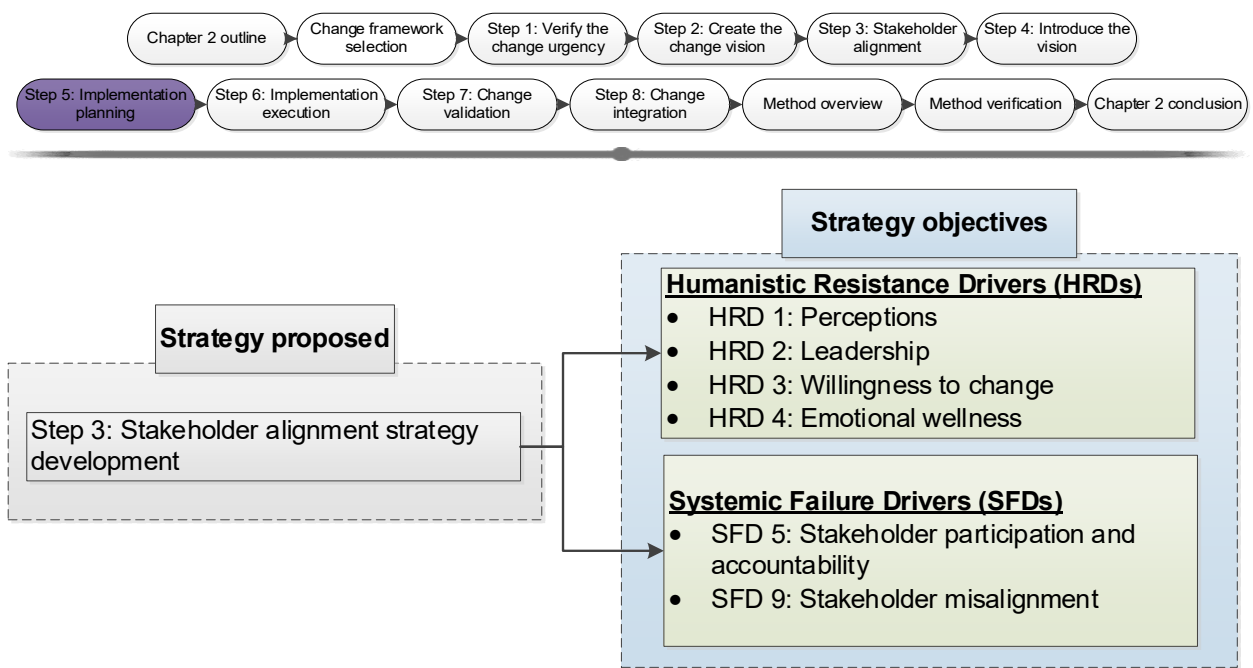


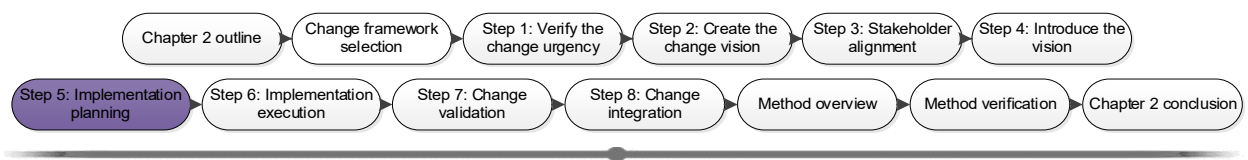
Figure 2-20: Defined objectives of the change management strategy

Action 1: Develop a strategy to promote change willingness

It follows from the literature review performed in [Section 1.7](#) that a stakeholder's willingness to change is influenced by their attitudes, beliefs, and feelings [96], [97], [98], [99], [100], [101]. Unwillingness to change may further increase if stakeholders feel psychologically unsafe and uncertain about their ability to cope with the change [103]. Specifically, when the change that affects the whole organisation is applied rapidly [93], [104].

With compressed air machines, end users are equipped with a tool that is familiar to them, simple to operate, reliable, and delivers consistent performance [55]. The willingness to change is expected to increase once end users start experiencing the improved benefits offered by the alternative technology. To influence this outcome, the following four key actions were established:

- (1) **Promote the vision:** Step 2 focused on developing the change vision. The vision collectively highlights the change benefits and aims to provoke stakeholder buy-in. Advocating the change vision presents the project team with an initial opportunity to positively influence the stakeholders' attitudes, beliefs, and feelings towards the change [100], [101]. [Step 4: Communicate the vision](#) aims to provide a strategy to promote it.
- (2) **Prove the change benefits on a small scale:** Stakeholders' attitudes, beliefs, and feelings are further influenced by first demonstrating the change benefits on a small scale. It follows from [Section 1.7](#) that employees experience severe levels of anxiety and stress when they need to operate unfamiliar technology [93], [105], [106], [107], [108]. This results in a severe and resistant response to change, especially when significant changes are implemented. Consequently, a gradual approach is necessary to introduce the technology, as crew-by-crew change implementation requires multiple iterations of the overall method to be developed (Steps 1–8).



Once the benefits materialise and the initial end users successfully adopt the technology, it may be rolled out to the remaining crews. As the initial iteration, the technology must first be trialled and tested on a small scale using a single panel. The trial provides practical exposure to enhance stakeholder confidence in the alternative technology. This highlights the need for a performance evaluation strategy developed in [Step 7: Validation of change benefits](#). This multi-layered approach ensures that end users are adequately resourced to cope with the change, thereby preventing a change shock wave.

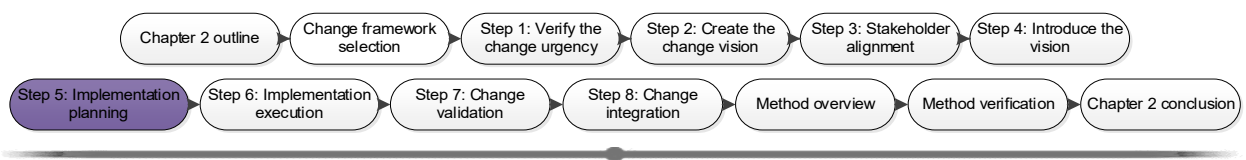
(3) Select the correct initial end user and workplace: Previous research suggests that the success of the initial trial strongly depends on the initial end users selected [14], [85]. Mine management traditionally believes that if alternative technology is successfully applied to the most extreme conditions, it will work anywhere [14]. ‘Most extreme conditions’ refer to the worst-performing crew mining in the most challenging workplace. In such cases, previous research suggests that the transformation efforts were set up to fail from the outset.

This study encourages the exact opposite mindset. The trial workplace must be well-ventilated, easily accessible, and have stable ground conditions. The initial end user is advised to be a young, average-performing crew with an approachable mindset [14]. Such a crew has little to lose but much to improve. Consequently, selecting the appropriate workplace and initial end user will promote a willingness to change.

(4) Celebrate short-term wins: Previous researchers agree that efforts to implement change often leave the stakeholders feeling uncomfortable [111], [113], [126]. This creates an automatic response to revert to the old, comfortable way of doing things. On the contrary, people tend to maintain their best performance when they know their current efforts are noticed and appreciated [171]. This emphasises the importance of celebrating short-term wins to promote a willingness to change further. The recommended short-term wins to be celebrated are highlighted in [Step 6: Establishment of short-term wins](#).

Action 2: Develop a strategy to identify and manage false perceptions

Research suggests a clear relationship between stakeholders’ reactions to organisational change and their perceptions of the change [89], [90], [91]. Adverse reactions to the change are frequently observed when it is believed that the change will result in a greater workload, increased fatigue, and/or job uncertainty [93]. Stakeholders will initially be unaware of the operational and performance parameters of the alternative technology, including its operational complexity, reliability, robustness, and drilling speed. As a result, misperceptions may originate from ignorance and can instigate resistance to change [85], [172]. A strategy was, therefore, developed to manage misperceptions by aligning stakeholders’ perceptions with the facts. The



approach requires two actions: identifying misperceptions and correcting misperceptions with facts.

(1) Identify false perceptions: The management of misperceptions must be an agenda item during weekly change management meetings. To identify possible misperceptions, the change manager should encourage all stakeholders to share any perceptions they may have. This will promote psychological safety.

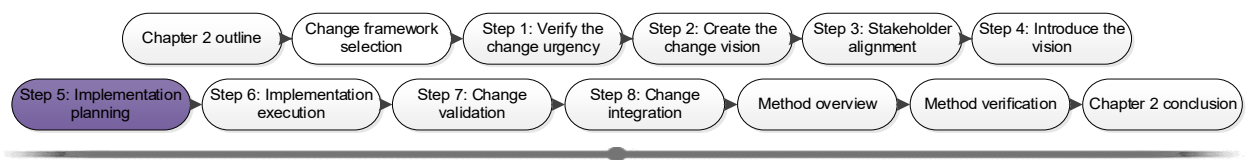
(2) Use facts to correct false perceptions: The change manager needs to formulate an in-depth understanding of the misperception. Factual information collected from trial data or other credible sources should be used to address knowledge gaps among stakeholders.

Action 3: Develop a strategy to promote an inclusive leadership style

The general short tenure of senior mine management team members often leads to passive involvement in supporting long-term technology transformation efforts [85], [143]. This is mainly because they may not be in a position to enjoy the future benefits. Passive involvement from the leadership team will result in stakeholders feeling isolated during the transformation effort and may lead to resistance. Credibility and trust are essential credentials to promote for effective leadership. It confirms that employee interests are taken into account [84]. This is achieved by fostering interpersonal communication and managerial involvement as follows.

(1) Promote interpersonal communication and managerial involvement: Change ownership should be cultivated through an inclusive leadership style [14]. Adding a voice for each stakeholder will promote ownership and accountability. This emphasises the importance of fostering interpersonal communication through a weekly change management meeting. Periodic underground visits by the multidisciplinary project team must be leveraged as an effective means to underscore that all stakeholders are working together in a collective effort. Adaptive communication is crucial, as some stakeholders respond best to detailed, data-backed explanations or logical arguments. In contrast, others are simply interested in concise, high-level summaries. Focus on sharing case study results and success stories to reinforce the credibility of the change initiative.

(2) Promote end user support: OEM supplier, engineering, and mining support play essential roles. Once the crew raises their needs or concerns, the multidisciplinary team must act swiftly to resolve them. The end user's trust is earned by addressing the concerns and suggestions raised during underground visits with management. The key is to keep the end user positive and motivated. The more the crew sees that the managerial team will accommodate their needs and address concerns, the more energy will be generated to drive the change. It is, however, critically important for the project lead to remain closely involved in the implementation and adoption actions. This will enable the shaft project manager to



filter out stakeholders' actual needs and concerns from poor excuses for not fulfilling their roles and responsibilities.

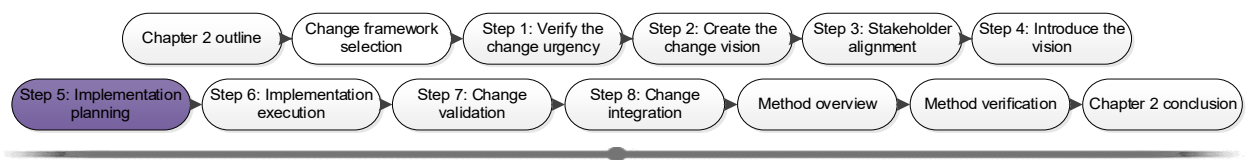
Action 4: Develop a strategy to manage emotional wellness

Emotional regulation is key. Difficulties experienced during the change process can trigger frustration, anxiety, and ultimately despair. Deliberate composure is necessary to prevent impulsive reactions that often lead to poor decisions. The remaining humanistic resistance driver refers to resistance stimulated by the deterioration of emotional wellness during the change implementation phase. In essence, reduced levels of change motivation might prevail when employees become negative towards the change [57], [58], [59]. The following factors were identified from the literature review in [Section 1.7](#) as the leading contributors to the deterioration of emotional wellness:

- Fear of job loss,
- The stress and anxiety experienced when expected to use the new, unknown equipment, and
- Excessive change sends shock waves through the organisation.

The developed strategy requires the following two actions to manage emotional wellness:

- (1) Introduce and integrate mentors:** An often underestimated aspect of influence is social proof. There is no substitute for learning from someone who has already been through the process [85], [121]. This stresses the importance of recruiting mentors to build alliances and share testimonials. Introducing a key influencer makes it easier to persuade an entire group. As highlighted in [Section 1.4](#), some ADTs have been available to gold or platinum mines in South Africa for the past decade. The implementation team is advised to recruit mentors from other operations that are already using the technology. The key role and responsibility of the mentors is not only to serve as initial ambassadors but also to promote the technology. Mentors will help alleviate fear of job loss, stress, and anxiety by highlighting the improved benefits.
- (2) Stick to the multi-layered sequential method to avoid excessive change:** To further manage stress and anxiety caused by excessive change, the overall key objective is to introduce ADT gradually. Shock waves are avoided by introducing the change in small, sequential layers using the proposed eight-step method. A detailed overview of the gradual approach is provided in [Step 8: Sequential expansion of the transformation effort to the remaining crews](#). The project team is advised against deviating from the proposed approach. Skipping steps in an effort to expedite implementation and adoption will only create illusory progress at the expense of promoting resistance to change [5]. A realistic roll-out plan is essential for managing stakeholder expectations. A detailed roll-out plan is developed under



[Step 5: Enable implementation and change management](#). A realistic roll-out plan prioritises workplaces – from worst performers to best performers. Step 8.1 deals with the development of a strategy to prioritise workplaces.

Action 5: Ensure that the strategy aligns planned vs actual change implementation progress

The literature review on implementation failure drivers highlighted several factors in this phase of the change process, including a lack of urgency, inadequate stakeholder participation, insufficient stakeholder accountability, ineffective transition strategies, and inadequate technology support systems. It follows from the study objectives defined in [Section 1.8](#) that a plan is needed to maintain the urgency of change, promote stakeholder participation, uphold stakeholder accountability, enforce transition strategies, and develop technology support systems.

To achieve this outcome, this study proposes the use of weekly change management meetings. The overarching objectives of these meetings are to align interests and foster a culture of shared purpose. Weekly progress comparisons to planned objectives will reinforce the urgency, inspire participation, impose accountability, enforce transition strategies, and assess the development of technology support systems. This highlights the importance of developing an implementation plan, as dealt with in [Step 5: Enable implementation and change management](#). Figure 2-21 illustrates an overview of the developed meeting agenda. It is at these meetings that the change management strategy is executed.

Step 5: Development summary

The overarching objective of Step 5 was to develop strategies aimed at fostering the following outcomes:

- Provide system selection guidance,
- Assess and recommend upgrades to support infrastructure,
- Recommend updates to policies and procedures,
- Develop an implementation plan, and
- Establish a change management strategy.

These strategies were developed and, if executed correctly, will guide mine management teams to the next step of the processes. Step 6, implement and sustain the change momentum, will be formulated next.

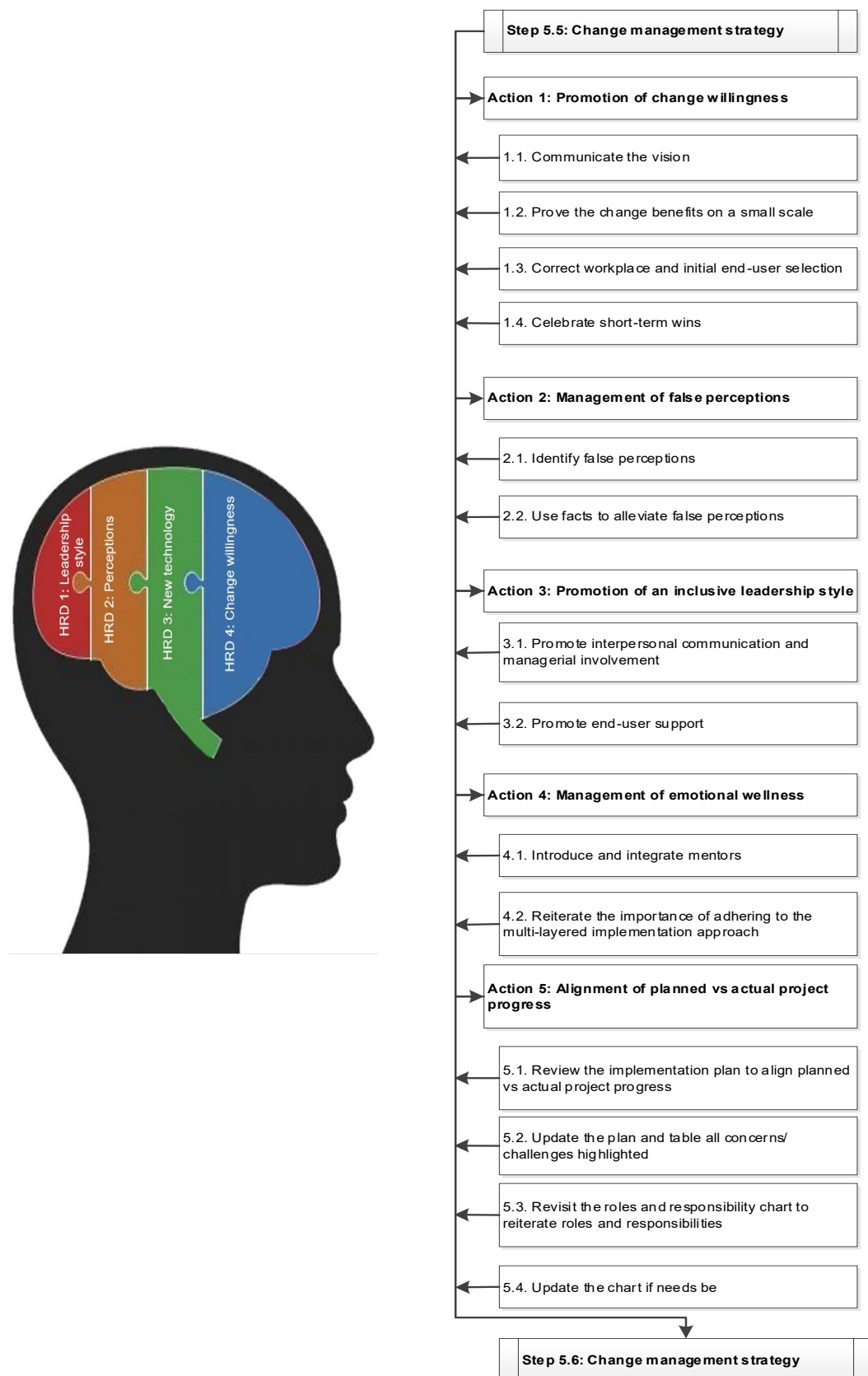
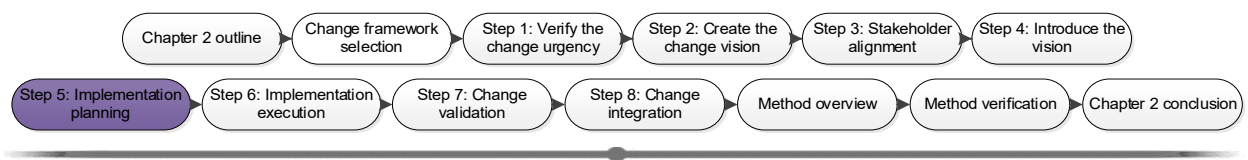


Figure 2-21: Study-developed change management strategy



Step 5.6 Develop an equipment transition strategy

It follows from the literature review that Wills and Buyens (2000) attempted to introduce stope drill guides into narrow reef gold mining stopes in the early 2000s [14]. Although the attempt failed, their work highlighted the importance of having an effective equipment transition strategy, since the greatest risk of revenue loss exists in this phase. To add perspective to this statement, the average revenue generated per blast when mining a 30 m panel at a stoping width of 1.5 m at a recovered grade of 4.25 g/t, equates to roughly R983 503¹³. Therefore, it will cost the operation R 983 503 per day if the crew fails to generate a blast during the equipment transition phase.

To mitigate this significant risk, the following sequential multi-layered approach to introducing alternatives was developed.

Overview – Step 5.6: Development of an equipment transition strategy

It is important to note that for the past 100 years, pneumatic drilling equipment has been and continues to be a part of narrow reef mines (Figure 1-1). The research and development invested in compressed air drilling equipment during this period yielded reliable, robust, and consistently performing equipment [7]. [Section 1.4](#) highlighted the key differences between compressed air drilling equipment and alternatives. To enable successful adoption, operators need to understand and accept the following key differences:

- **Ergonomics:** Control levers may look and feel different. Control placement and sensitivity, along with overall assembly manoeuvrability, are some of the ergonomic challenges operators will need to adapt to.
- **Operational procedures and safety standards:** Since ADTs use different motive energy sources, operators need to be trained on the new operational procedures and safety standards.
- **Mining cycle impact:** Improved face advance rates induced by improved drilling rates affect the support and cleaning cycle.
- **Maintenance procedures and engineering support:** Operators further need to adjust to the complexity of maintenance procedures and engineering support when moving away from a central compressed air supply line.

¹³ Calculated based on: Face length = 30 m, Stoping width = 1.5 m, Advance = 1.1 m, Rock density = 2.75 t/m³, Recovered grade = 4.25 g/t, Gold price = USD 91 000 per kilogram (February 2025).

An equipment transition strategy is needed to facilitate the transition from a compressed air drilling system to an alternative, with minimal to no production losses. The ADT transition (ADTT) methodology proposed by this study is implemented using six steps, as illustrated by the process flow depicted in Figure 2-22. Each step is defined next.

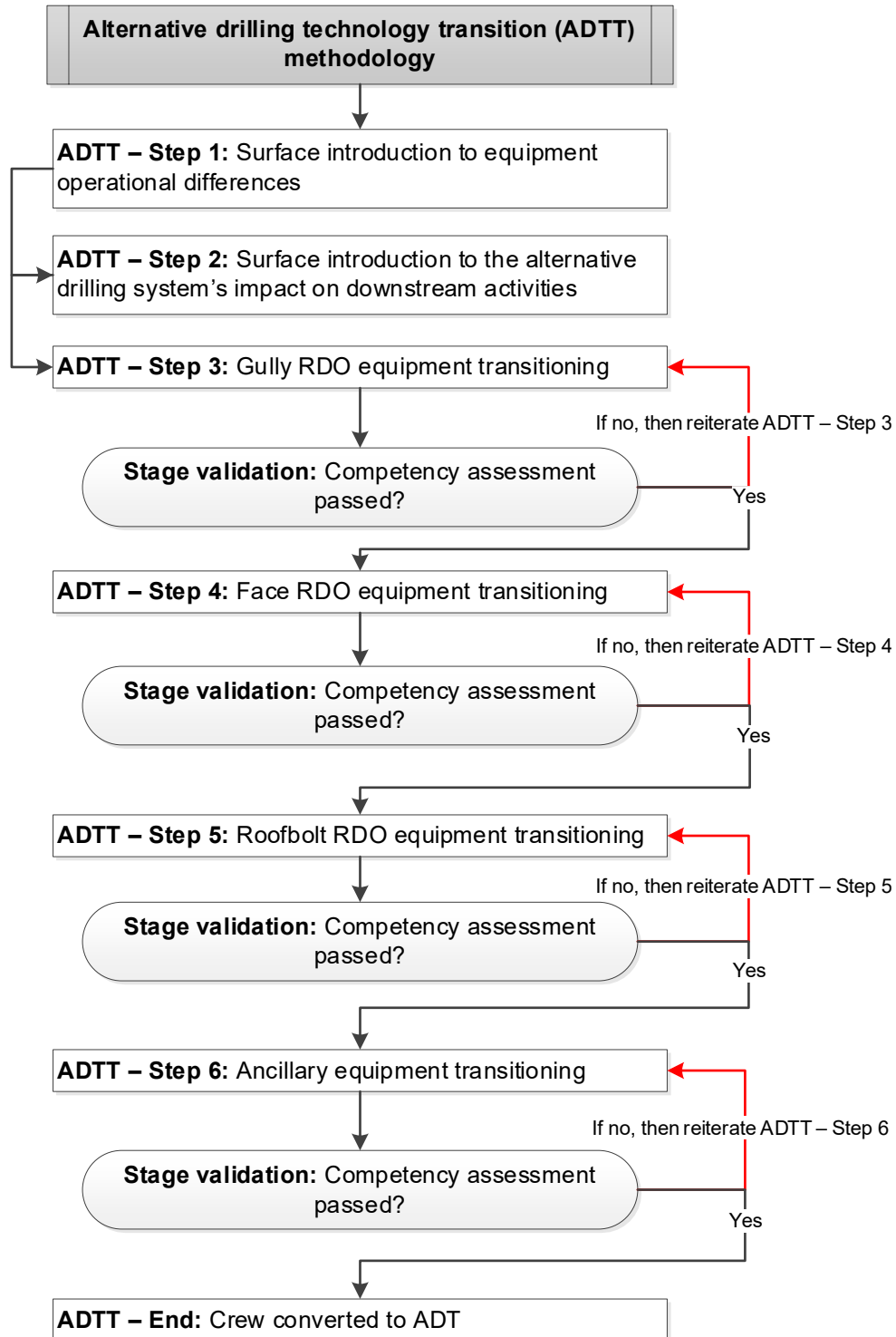
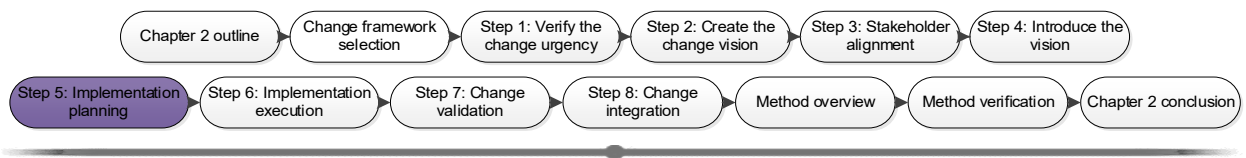


Figure 2-22: Equipment transition strategy process flow



Surface induction

As established during the literature review, it is best to remove individuals from their day-to-day production environment when introducing new and important concepts [14], [85], [106]. Therefore, the crew is formally requested to attend the surface induction session. Surface induction focuses on achieving two strategic outcomes: ADTT – Step 1: Introduction to fundamental equipment differences, and ADTT – Step 2: Introduction to equipment impact on the overall mining cycle.

ADTT Step 1: Introduce the fundamental differences of operational equipment

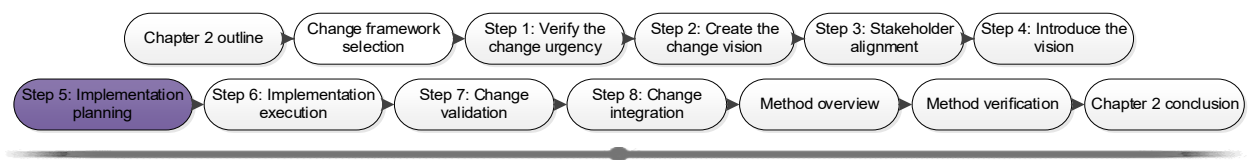
The strategy takes into consideration that the average age of RDOs in South Africa's narrow reef mines is around 45 years [14]. Thus, operators have been using the same type of equipment for the majority of their working careers, and transitioning to an alternative will require thorough familiarisation training. Consequently, the equipment transition process begins by formally introducing the fundamental differences in equipment operation and product support.

To gather and maintain the undivided attention of end users, the stope team is removed from the workplace, and equipment induction is conducted on surface. The following six key equipment operational focus areas were identified from the literature in Section 1.7 and must be shared with end users: overall equipment care, maintenance cycle, engineering support, equipping support, safety, and training.

The objective is to introduce the fundamental differences in equipment relating to the end users. To facilitate the session, the OEM supplier is requested to demonstrate the equipment on the surface. During this interactive session, the crew is encouraged to ask questions and to see, feel, and experience the ergonomics, size, and other physical parameters of alternative equipment. Members are shown how to connect the equipment, and a few sample holes are drilled. Interpersonal communication is used to promote participation, and crew members are encouraged to use the equipment under the strict supervision of the facilitators. The human brain tends to understand and remember better when visual representations are used to describe the following six important concepts:

(1) Overall equipment care

It is important to note from [Section 1.4](#) that pneumatic drilling equipment is robust and operates with greater component tolerances than oil- or water-hydraulic counterparts. Oil and water-hydraulic equipment are thus far less tolerant of abrasive particles from hose connections or supply water. Therefore, it is important to emphasise that the equipment's connection ports and hoses must be rinsed before use.



(2) Maintenance cycle

Jaarsveld and Ebben (2008) reported the expected MTBF of alternative drilling equipment to be 40% lower than its pneumatic counterparts [64]. The reduction in MTBF highlighted in the previous point highlights a twofold risk. Firstly, more drills are required per crew. Failure to maintain this number of drills will result in lost blasts due to rock drill shortages. Secondly, coordinating the logistics of this vast number of rock drills between the panels and the workshop will be a tremendous task. The shaft engineering manager needs to develop a procedure that ensures equipment is issued only on a one-to-one basis. This will ensure that faulty equipment is sent out to the maintenance facility.

(3) Engineering support

An OEM-driven maintenance plan is advised as the OEM is accountable for equipment performance. The maintenance rate should be production-driven. Equipment reliability is directly proportional to equipment availability. This enables the team to meet production calls. In this case, the OEM is incentivised to strive for continuous reliability improvements. Due to the aforementioned points, a mine-owned maintenance plan driven by mine personnel is strongly advised against.

(4) Equipping support

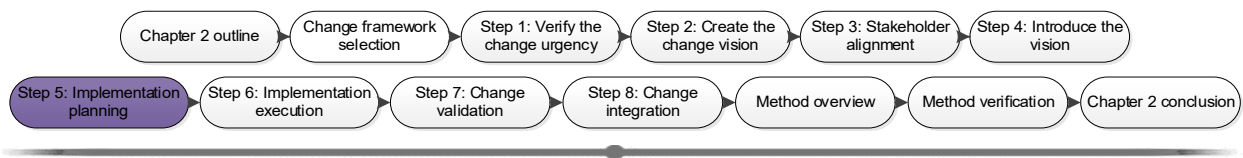
An OEM-driven maintenance plan is advised as the OEM is accountable for equipment performance. The maintenance rate should be production-driven. Equipment reliability is directly proportional to equipment availability. Hence, enabling the team to meet production calls. In this case, the OEM is incentivised to strive for continuous reliability improvements. Consequently, based on the aforementioned points, a mine-owned maintenance plan driven by mine personnel is strongly advised against.

(5) Safety

Safety aspects will differ significantly. Hydropower, for instance, operates at a working gauge pressure of 180 bar, while compressed air systems operate between 3 bar and 5 bar. As a result, end users need to be trained on the safe operating procedures developed in Step 5.3.

(6) Training support

Since the technology is new to the mine's trainers as well, they will not be competent to train the mining crews. Accordingly, the mine's trainers should participate in training with the mining crews during the equipment transition phase.



ADTT Step 2: Introduce the downstream impact of face advance improvement initiatives

The second strategic outcome of the surface induction session is to familiarise the end users with the downstream impacts of implementing an ADT. The primary driver of implementing ADT is to improve the operation's production rate. However, the downstream impact needs to be duly understood to avoid other bottlenecks from emerging. At this point, it is essential to note that [Section 1.2](#) described narrow reef mining as a cyclic process with five key activities. The second layer of the surface induction session focuses on sharing the impact of the ADT on the mining cycle, including drill rate, support, logistics, cleaning, and face length.

These five impact areas need to be explained not only to the stope team but also to line management. Macfarlane (2001), and Thompson and Holm (2004) agreed that the following five key focus areas are affected by face advance improvement initiatives [5], [71]:

(1) Drill rate

Improved drill rates generally lead to a desire to increase the length of the drill steel. Although this will result in a greater face advance per blast, the section mine overseers are tasked with ensuring that it is avoided at all costs. A greater face advance will generate a larger volume of ore to be cleaned, requiring more than one cleaning shift, ultimately resulting in a reduced production rate.

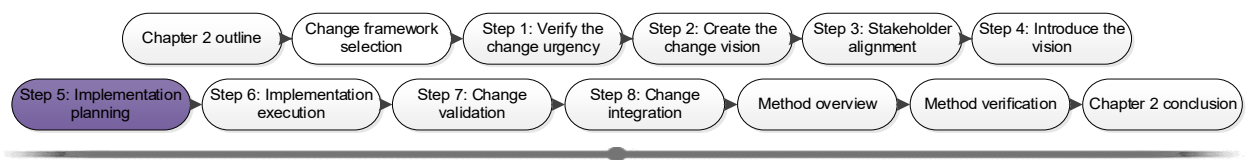
(2) Support

It was highlighted in [Section 1.2](#) that supports need to be installed to prevent the mined-out void from collapsing. As a result, improved production rates are only possible if the support cycle remains in sync with the drilling activity. The shaft mine manager and the shaft human resources leader are tasked with ensuring that each crew has sufficient stope team members and support materials.

(3) Logistics

Monthly face advances achieved after implementing the ADTs reviewed in [Section 1.7, Part C](#) are expected to improve by 2 m to 3 m [25], [64], [71]. Face advance tends to adversely affect production when the face advance (daily tonnes generated) exceeds the design capacity of the other mining activities. In such cases, the night shift fails to complete the cleaning cycle when face time is constrained. Additionally, the support installation activity may struggle to remain synchronised.

Improved production rates will require a greater volume of support materials and explosives. Section mine overseers need to adjust the call for materials and explosives accordingly. The shaft financial manager is expected to adjust the section mine overseers' budget to avoid



overspending penalties. They also need to adjust material and explosive orders to ensure demand meets supply throughout the production month.

(4) Cleaning

Cleaning cycles are expected to keep up with the improved production rate. Again, the shaft mine manager and the human resources leader are tasked with ensuring that each crew has enough winch drivers. It is also true that the tramming department needs to move a greater volume of ore per month. The shaft engineering manager is expected to implement preventive maintenance planning for locomotives and hoppers to avoid unplanned breakdowns.

(5) Face length

Improved strike rates further result in a greater area of production ground mined per month. This may lead to early depletion of available face length if footwall development and ledging activities are not in sync with the improved strike rate. It is the responsibility of the shaft general manager and the shaft mine manager to ensure a healthy Iceberg. An Iceberg remains healthy when enough main footwall development is done to ensure sufficient face length is opened to meet the business plan and mine profitable [173].

Equipment transition training

ADTT Step 3 to ADTT Step 6, as shown in Figure 2-22, describe the enabling strategies to transition from compressed air equipment to the ADT. The OEM supplier is encouraged to provide training facilitators. They are regarded as the subject matter experts who know how to transfer skills and bridge equipment differences [14]. These training facilitators will train both the crews and the mine trainers. As part of the change management process to promote change wellness, Step 5.4 refers to sourcing mentors from other operations who are already using the ADT. A crucial part of the transition strategy's success is integrating the mentors with the crew.

The significant risk of financial losses was highlighted earlier as a key driver of implementation failure. To overcome this significant risk, this study proposes the following sequential approach to introducing alternatives, as defined in the section below:

Figure 2-23 presents an overview of a marked-off face. The sections to be drilled are demarcated as follows: A–B represents the gully section, where A–C defines the bottom section of the panel, and C–D defines the top section. The top view showcases the roof bolt section. Ancillary equipment is used to install support timber along the full length of panel B–D. The RDOs transition sequentially (one by one) from the old drill to the new, while the remaining RDOs continue using their conventional equipment to sustain production.

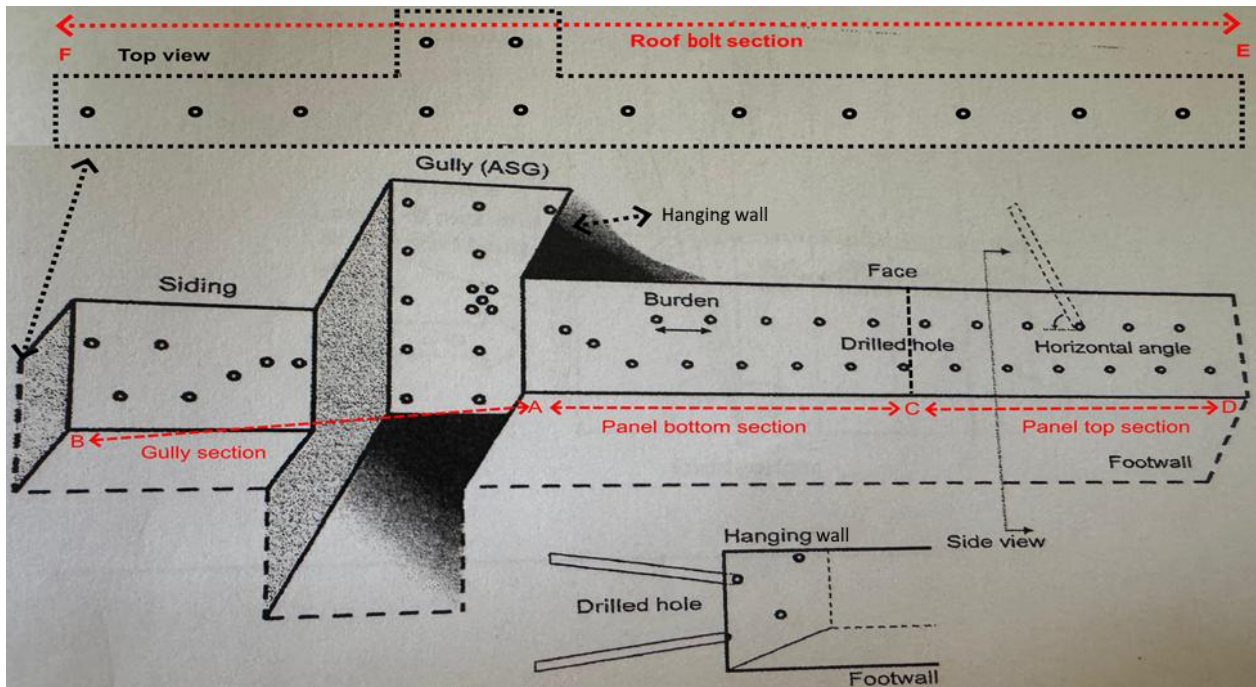


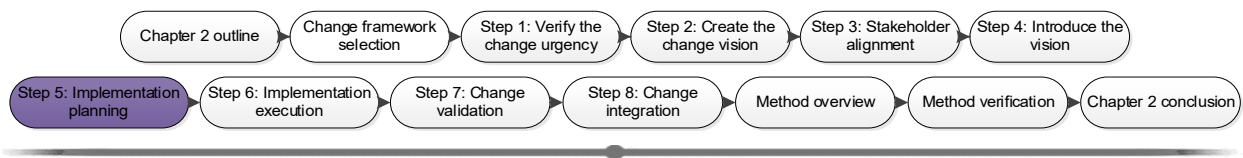
Figure 2-23: Illustration of the four drilling areas within a production panel¹⁴

ADTT Step 3: Transition gully RDO equipment

The first sequence of the strategy entails introducing the alternative drill to the RDO in the gully, drilling section A–B of the face. At the same time, the other RDOs continue to use conventional machines. This approach has the advantage of provoking interest. The RDOs drilling the face will continuously walk past the RDO in the gully and will be exposed to the new rock drill's performance.

The number of dedicated training sessions will depend on product ergonomics and RDO commitment [14]. The mentor fulfils an important catalytic role in helping the crew manage the stress and anxiety associated with the unknown equipment. A trainee is deemed capable once they can successfully demonstrate their ability to use the equipment for a full shift and apply basic fault-finding tactics with little to no facilitator intervention [64]. Wills and Buyens (2000) found that if ergonomics remain fairly consistent, a handheld RDO can be retrained to proficiency on a new machine within two days [14]. The RDO undergoes a competency validation assessment once deemed capable. The mine's trainer assessors perform this assessment, and the RDO will be asked to demonstrate all the skills required to operate the alternative equipment safely. Such a competency assessment usually takes one shift to complete. Once competent, the trainer will proceed to the next RDO (ADTT Step 4).

¹⁴ B van Rooyen, Personal illustration, "Illustration of the four drilling areas within a production panel", 2023.



ADTT Step 4: Transition face RDOs equipment

At this stage of the process, the gully RDO is deemed competent, and the RDO for the bottom section A–C of the panel is trained next. This allows the trainer to focus fully on the RDO at the bottom while being next to the gully RDO if assistance is required. The remaining RDOs will continue using the pneumatic equipment until the RDO for the bottom section is deemed competent.

The RDO for the top section C–D of the panel is trained next. Dedicated focus is applied to the next RDO in line while monitoring the RDO for the bottom section. By this time, the gully RDO is expected to operate the new machine independently. Two sequences are discussed here since the face lengths found in South African narrow reef gold mines average around 30 m, and one drill per 15 m of face length is required [49], [66], [114], [125]. Where faces are longer than 30 m, additional RDOs will be added, and the same logic will be applied to transform them sequentially.

ADTT Step 5: Transition roof bolt RDO equipment

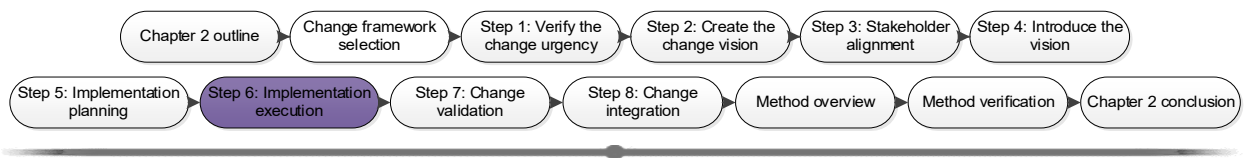
It is paramount to recall at this point that a compressed air-powered face's crew complement usually allows for one RDO per 10 m of face length. As a result, the fourth RDO is trained next after RDOs two and three (who are responsible for blasthole drilling) are competent. Roof bolt support holes are generally drilled using a dedicated RDO for roof bolts. The equipment used to drill roof bolts generally differs in some respects and requires dedicated attention. Training continues until the roof bolt RDO is deemed competent.

ADTT Step 6: Transition ancillary equipment

As a final step, the stope team members are trained to use the ancillary equipment. These typically include chainsaws, prestressing pistols, dewatering pumps, and blasthole cleaners. Naturally, this only applies if the ADT supports ancillary equipment. The stope team members will undergo a competency assessment to confirm they can operate the ancillary equipment safely. Two days are generally needed to complete the training & competency assessments.

ADTT End: Crew converted

At this point, the mine's trainer assessors have found that all RDOs and stope team members are capable of using the new equipment. This result confirms that the crew has been converted successfully. The OEM trainer is advised to remain at the workplace to provide additional support and refresher training if needed. As a general guideline, mine management teams need to plan a minimum of 16 shifts per crew to execute the transition strategy. The OEM trainer / facilitator's labour cost is typically around R 25 000 ~ R 30 000 per month. Equipment cost per panel depends on the alternative type selected and system configuration chosen; Localised hydro ~ R 740k, Micro hydro ~ R1.4m, Electro-hydraulic ~ R1.7m.



Step 6: Implement and sustain the change momentum

Step 6 focuses on developing the implementation execution strategy. It was found during the literature review ([Section 1.7, Part B](#)) that previous efforts to introduce ADTs failed during the implementation phase due to a lack of an implementation execution strategy and the failure to sustain the change momentum. As a result, the strategy should enable two strategic outcomes, namely implementation execution and sustaining the change momentum.

The overarching objective of this step is to develop strategies aimed at fostering the following two strategic outcomes:

- Change implementation, and
- Change momentum sustainability.

These strategies are developed in Step 6.1 and Step 6.2, as illustrated by the development process flow depicted in Figure 2-24.

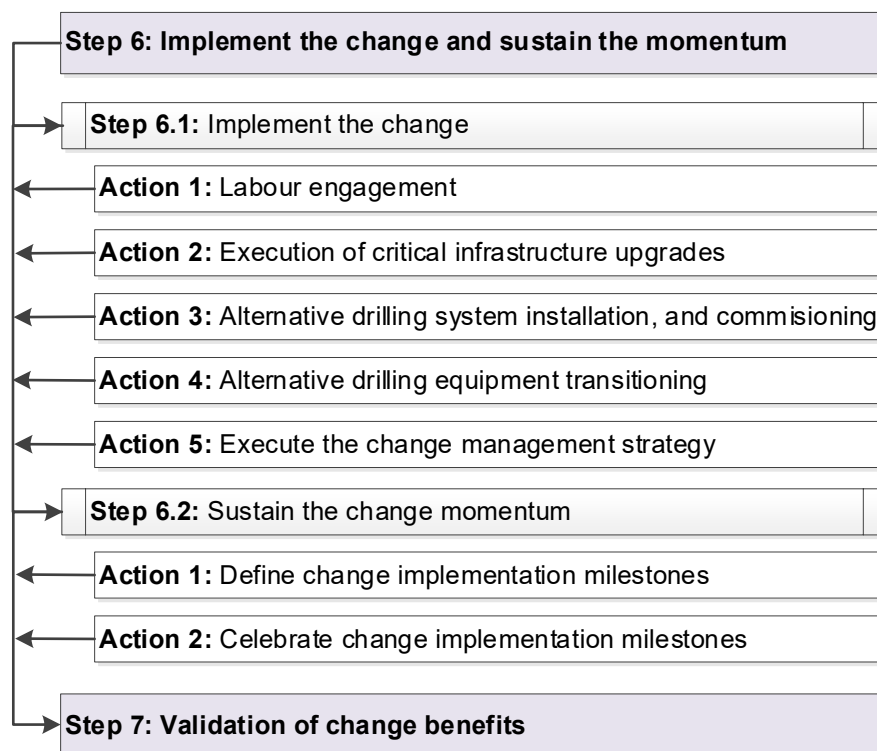
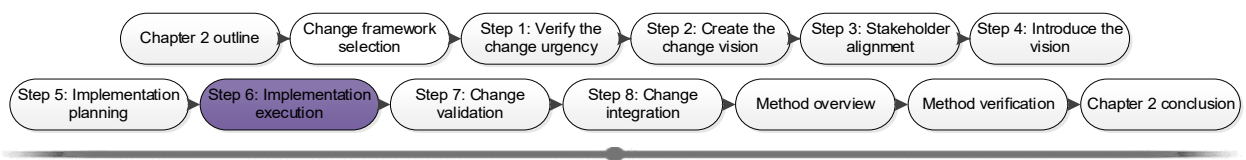


Figure 2-24: Step 6 development overview

Step 6.1: Develop implementation strategy

An implementation strategy is required to enable and coordinate the five actions needed to implement the change, as depicted in Figure 2-24. These five implementation actions follow from the implementation template developed in [Step 5.4: Implementation plan template development](#).



Action 1: Engage with labour

Reference was made to the recruitment of mentors and to the use of OEM subject-matter experts to transfer skills and knowledge to stakeholders. These individuals need to be hired. The human resources leader is tasked with executing labour engagements. The process varies among mining companies but usually includes security screening, completion of an authority-to-recruit form, medical screening, and shaft-specific induction. These site-specific actions are scheduled in the implementation plan under [Step 6.1.B](#).

Action 2: Upgrade infrastructure

Step 5.2 evaluated the water and electrical infrastructure to identify the design changes needed to support the alternative. This action coordinates the implementation of the proposed design upgrades. All the tasks required to execute the design changes are listed in the implementation plan under [Step 6.1.C](#).

Action 3: Install and commission the alternative drilling system

All tasks required to install the system are scheduled under [Step 6.1](#). The installation guidance is based on the equipment installation standard developed under [Step 5.3: Updates to mine policies, procedures, and standards](#). The mine's equipping crews will be unfamiliar with the installation procedures at first and will require familiarisation training facilitated by the OEM supplier.

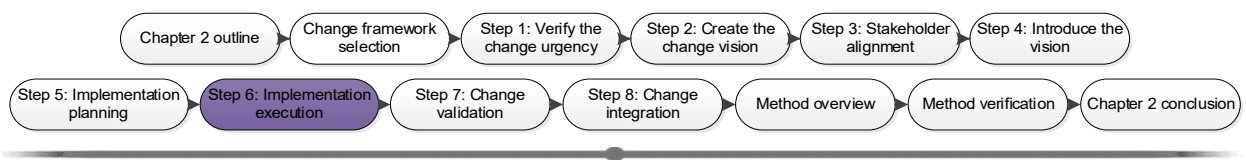
After completing the system installation process, the system should be commissioned. The process will require a start-up risk assessment involving all departments: mining, safety, ventilation, engineering, OEM supplier, and organised labour. The purpose of the risk assessment is for all departments to declare the system safe for commissioning. Thereafter, commissioning follows, and the OEM supplier checks the system to ensure it operates according to the design specification.

Action 4: Transition to the alternative drilling equipment

This action executes the equipment transition strategy developed in [Step 5.6: Equipment Transition Strategy](#).

Action 5: Manage the change

This action executes the change management strategy developed in [Step 5.5: Change management strategy](#).



Step 6.2: Execute the strategy to sustain the change momentum

Overview – Step 6.2: Development of a strategy to sustain the change momentum

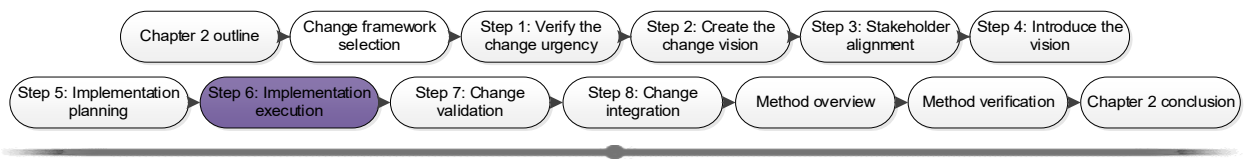
The implementation of a change process often leaves people feeling uncomfortable at first, triggering an automatic response to revert to the old, comfortable way of doing things [111], [113], [126]. To overcome this challenge, a strategy is needed to sustain the momentum for change. People tend to perform their best over the long run when they know their current efforts are noticed and appreciated [171].

To influence this outcome, this study adopted a strategy called “Celebration of small wins” from the world of sports. The initial success achieved by this method dates back to 1980 when the Pittsburgh Steelers celebrated their 88th win under coach Chuck Noll [174]. Coach Chuck did not win national football leagues by focusing solely on big games; instead, he achieved success by consistently emphasising winning smaller games. Another notable example is the success achieved by the well-known coach Pat Summitt. Summitt also intentionally focused on celebrating small wins and retired with 1 098 career wins [175], [176]. Similar to the intended outcome of this study, mine management teams will not fully convert a complete mine by focusing solely on the end goal of converting all crews.

Change initiatives are frequently launched with intensity but tend to lose momentum in the absence of immediate results [177]. Strategic execution requires consistency over intensity. Sustained, disciplined execution of the work processes described in this method is necessary to complete the change process. The objective here is not to look at the drill in isolation. For the team to achieve their monthly production call means that every cycle of the mining process comes together the way it should. It provides a sense of comfort, as the change introduced by the drill was successfully integrated. That is, the crew managed to complete the drill and support cycle timeously, nightshift managed to routinely clean the panel, and support services (i. e. water, electricity, logistics and materials) were in place to enable these cycles’ objectives. The following key milestones must be celebrated with each crew:

- Completion of the implementation phase,
- All RDOs trained and found competent, and
- Achieving production call.

Weekly safety meetings should be used to publicly acknowledge the achievements gained from the previous week’s progress. Jordaan *et al.* (2024) advocated for the use of a notice board to publicly recognise achievements [178].



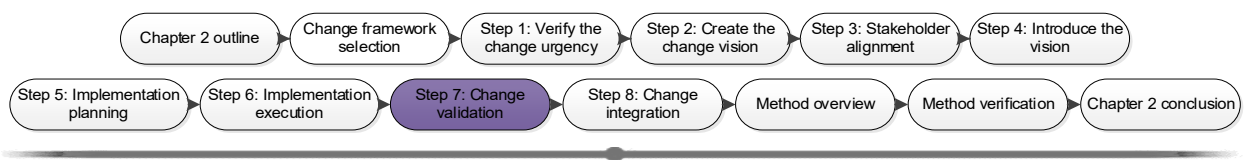
Step 6: Development summary

Strategies used to implement the change and sustain the momentum for change were formulated in this section. This led to the development of a unique equipment transition strategy aimed at minimising the risk of lost production during implementation and training. A second strategy was formulated to sustain the momentum generated by the transition methodology.

Phase 2: Summary of strategies developed to implement the change

The overarching objective of this phase was to develop strategies aimed at fostering the following outcomes:

- Provide system selection guidance: Step 5.1.
- Assess and recommend upgrades to support infrastructure: Step 5.2.
- Recommend updates to policies and procedures: Step 5.3.
- Develop an implementation plan: Step 5.4 and Step 6.1.
- Develop an equipment transition strategy: Step 5.6.
- Develop a change management strategy: Step 5.5.
- Reward stakeholder participation: Step 6.2.



2.5. Phase 3: Develop strategies to validate the change benefits

The following recollection from Figure 2-25 is needed at this point in the method development process. The first phase of the change process initiated the change. An array of strategies was developed under Step 1 to Step 4 to: (i) verify the change urgency, (ii) create the change vision, (iii) manage stakeholder resistance to change, and (iv) seek stakeholder approval. Once the vision is approved, the second phase of the change process provides strategies to foster implementation planning (Step 5) and execution (Step 6).

Phase 3 makes provision for the incorporation of a validation strategy into the change process. It follows from past failures ([Section 1.7](#), Part B) that change initiatives generally fail when the theoretical benefits of change do not materialise in practice after implementation. The verification strategy is thus needed to confirm that the theoretical change benefits highlighted by Step 2, Change vision, materialised after implementation. It is important to recall that the methodology advocates a sequential approach to introducing and embedding the alternative system. This means that Step 7 presents an early opportunity to collect data to inform the decision-making processes pertaining to the success and expansion. Additionally, it will highlight areas for continuous improvement and development.

The overarching objective of this phase is to develop strategies to:

- Assess the technology's overall readiness to function as a replacement system, and
- Validate the change benefits.

Step 7 focuses on developing these strategies.

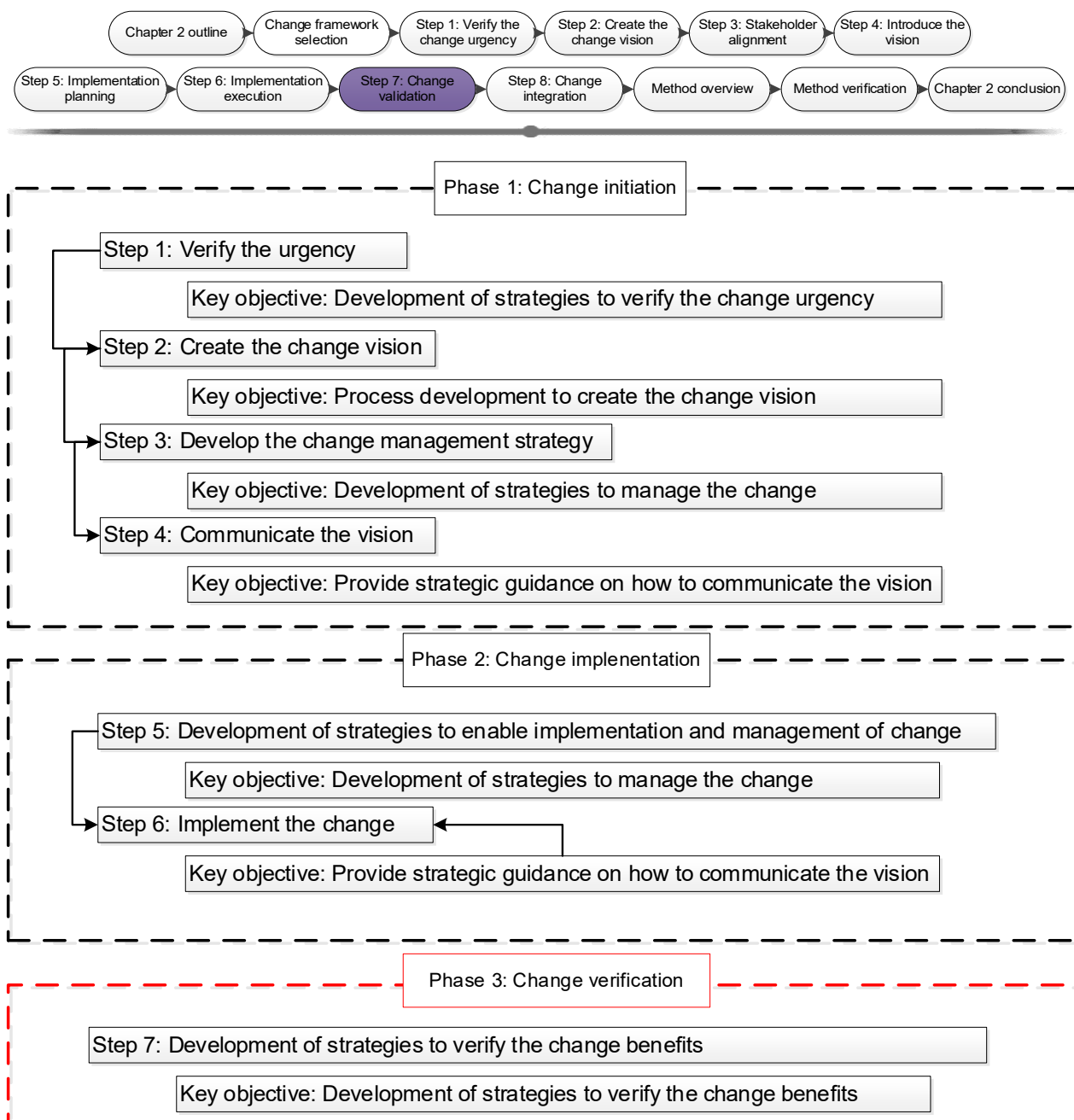
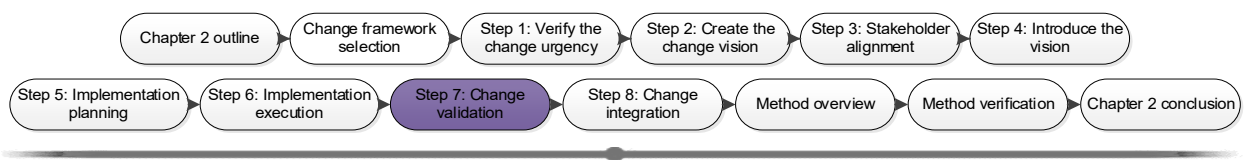


Figure 2-25: Method development process flow – Phase 3: Change verification

Overview – Step 7: Develop strategies to validate the change benefits

The vision created confidence and certainty for change once validated on a small scale to confirm initial assumptions. Once validated, the vision becomes unwavering, and the approach is applicable to the remaining crews.

Implementation challenges should be leveraged to refine the implementation strategy, sharpen the multidisciplinary team's skills, and fortify the vision for long-term change. The key is to maintain focus and clarity, especially when the benefits of change fail to materialise, which is an inevitable part of the process [5], [6], [14]. The case study research methodology calls for challenges to be analysed objectively, to comprehend the lessons learned, and to understand what process adjustments can be made. In cultivating a resilient mindset among stakeholders, challenges can be transformed into opportunities.



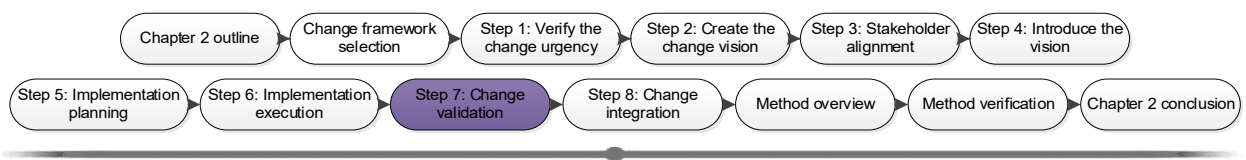
The key outcome of Step 7 is to develop an overall evaluation strategy to validate the improved benefits highlighted in the vision board developed and promoted in Steps 2 and 4, respectively. The key failure drivers and objectives that need to be addressed by the continuous performance strategies were identified from past failures ([Section 1.7](#), Part B) and are listed in Table 2-19.

Table 2-19: Key failure drivers and method objectives addressed by Step 7: Continuous performance assessments

Failure driver	Strategy objectives
HRD1: Passive leadership style	- Promote an active leadership style by enabling managerial involvement.
HRD2: False perceptions	- Rectify misperceptions by: - obtaining factual information, and - advocating for factual information.
HRD3: Change unwillingness	- Promote change willingness by: - strengthening psychological safety, and - eliminating any resistance factors identified.
HRD4: Emotional wellness	- Promote emotional wellness.
SFD4: Incorrect initial end user and/or workplace selection	- Provide clear strategic guidance to end user selection.
SFD6: Incorrect selection of alternative technology	- Provide an assessment strategy to validate that the selected technology is fit-for-purpose.
SFD8: Change support from senior management	- Provide change support guidance to senior management.
SFD9: Stakeholder misalignment	- Provide a strategy to align stakeholders and maintain alignment.
SFD10: Transition strategy	- Assess the adequate transfer of knowledge, skill, policies, and procedures during the training phase.
SFD12: Technology readiness	- Provide a strategy to assess the technologies' fit-for-purpose to operate as a replacement.
SFD13: Vision/benefits did not materialise	- Provide a strategy to continuously monitor change benefits as highlighted by means of the vision.
SFD14: Shock waves caused by excessive change	- Implement a progressive and gradual approach to introducing the change.

Development of an evaluation strategy to validate the benefits

This section describes the logic and reasoning applied while developing the evaluation strategies. Strategies were designed to assess the practical benefits of the alternatives achieved after their implementation. The purpose of the assessments is to gather the data required to validate the theoretical benefits promoted in Step 2, Table 2-4. The benefit focus areas proposed



in Table 2-4 follow from the literature review ([Section 1.7](#), Part C). As a result, assessment strategies are needed to confirm the benefits listed in Figure 2-26.

Statistical parameters proposed to evaluate data sufficiency and accuracy

The collected data should be analysed to ensure that statistically valid conclusions can be drawn. Since many of the parameters are likely to be variable, care should be taken to collect a representative data sample. The mean value of the defined KPI data population collected will ultimately be used to benchmark the overall impact of each KPI. To signal measurement inconsistency, the variability in the collected data needs to be benchmarked using the coefficient of variation (CV), which is the ratio of the standard deviation to the mean. A coefficient of variance value of less than 20% indicates that the observations are clustered closely around the population mean and are deemed consistent [179]. At the same time, coefficient of variance values greater than 30% indicate the need for additional data measurements.

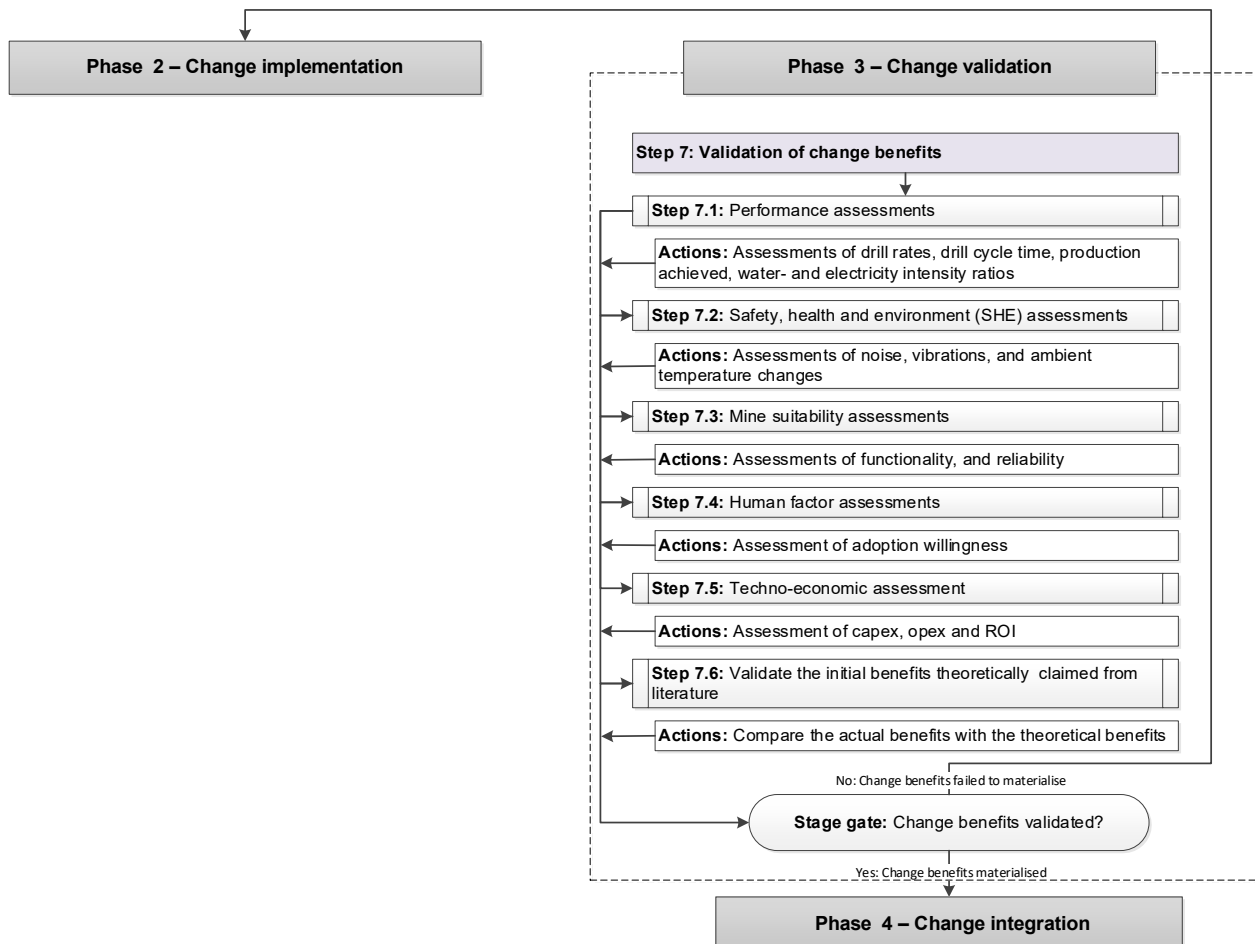


Figure 2-26: Step 7 – Assessment strategies needed

Step 7.1: Implement performance assessment strategy

This specific assessment strategy, as outlined in Figure 2-27, focuses on evaluating the ADT's impact on drilling performance, production, and utilities. It was found from the literature review that the following key criteria govern the performance of an ADT: collar-to-collar drill rate, face drilling cycle, production, water intensity ratio, and electricity intensity ratio.

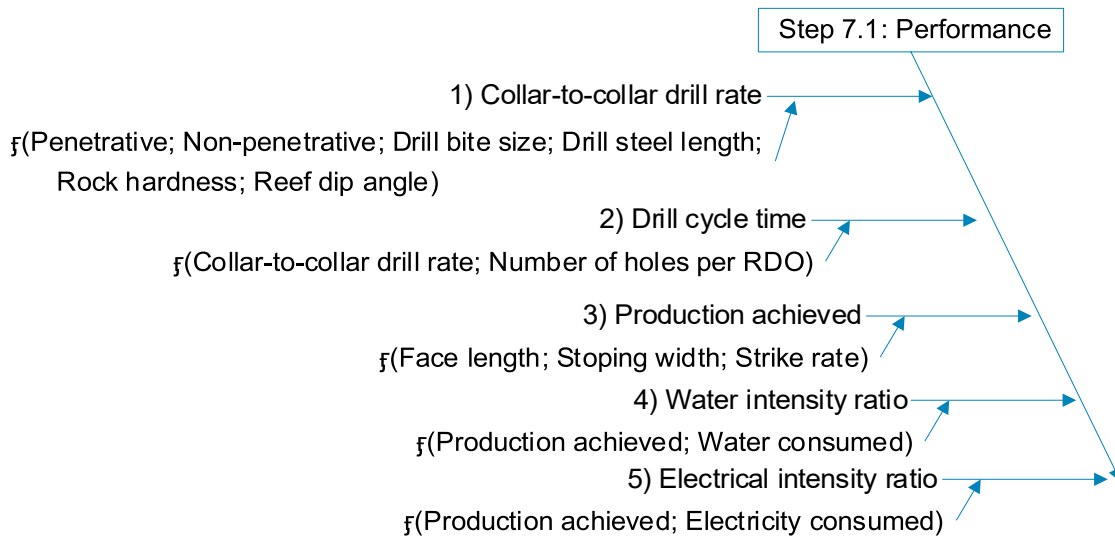
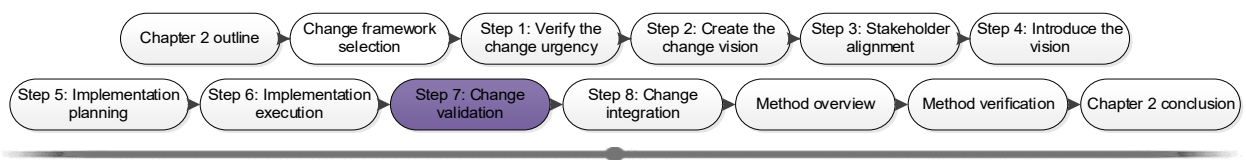


Figure 2-27: Performance assessment evaluation criteria

(1) Collar-to-collar drill rate

Previous studies have only considered the penetrative component when quantifying the rate of drilling a hole [48], [53], [54], [64], [66], [117]. This approach will skew the results as it does not account for the time to collar and move between holes. Time to collar a function of the rock drill's energy output and the time move between the holes is governed by the manoeuvrability and operator fatigue [27], [65]. Here, manoeuvrability mainly depends on the mass and balance of the rock drill and thrust leg assembly. Faster penetration rates result in an increased work rate, which in turn contributes to elevated levels of operator fatigue [180]. As a result, this study recommends using collar-to-collar times to quantify the ADT's impact on the overall drilling rate.

The sum of the penetrative and non-penetrative components of the drilling activity quantifies the time required to drill a hole. The penetrative component represents the duration required to penetrate the rock. It is a function of the supply pressure, drill bit size, drill steel length, and rock hardness [48], [53], [54], [64], [66], [117]. The non-penetrative component quantifies the time required to manoeuvre the rock-drill-thrust leg assembly to collar, eject, and move to the next hole. The reef dip angle, equipment assembly mass, and operator fatigue govern this component [9], [49], [65].



Collar-to-collar drill rates are measured using a stopwatch: Start the measurement once the drill steel makes contact with the intended hole position. Once the bit exits the hole, start measuring until it makes contact with the next intended hole. To quantify the ADT's impact on drilling rate, the trial data must be benchmarked against the baseline, as shown in Table 2-20.

Table 2-20: Collar-to-collar drill rate impact

Drilling technology	n [–]	CV [%]	$\bar{x}$ [hh:mm:ss]	Impact
Compressed air	TBD	< 20	E	(E–F)/E
Hydropower	TBD	< 20	F	

TBD – To be determined as the population size is dependent on the CV

(2) Face drilling cycle time

This criterion is used to confirm the ADT's impact on the face drilling cycle time. The impact is represented by the difference in the average time spent to complete the drilling cycle. It is governed by the collar-to-collar drill rate and the number of holes to be drilled by each RDO. The number of holes drilled per RDO is a function of the blast design, face length, and stoping width [181]. This highlights the importance of selecting a trial and baseline panel with the same face length and stoping width. Ultimately, the impact on face drilling time is represented by the difference in average drilling shift duration over the trial period, as shown in Table 2-21. In

Table 2-21: Impact on drill shift cycle time

Drilling technology	n [–]	CV [%]	$\bar{x}$ [hh:mm:ss]	Impact
Compressed air	TBD	< 20	N	(N–M)/N
Hydropower	TBD	< 20	M	

TBD – To be determined as the population size is dependent on the CV

(3) Production

To quantify the impact on production, a strategy is needed to compare the production achieved. Production, measured in tonnes, is determined by the product of the face length, stoping width, monthly face advance, and rock density. It is important to note that face length and stoping width may vary between panels. To normalise for varying face length and stoping width, this study proposes using the percentage call achieved as the benchmarking parameter. The mine's surveying department measures the monthly production achieved. To highlight the impact, a benchmark comparison of the percentage call achieved by each drilling technology is necessary, as shown in Table 2-22.

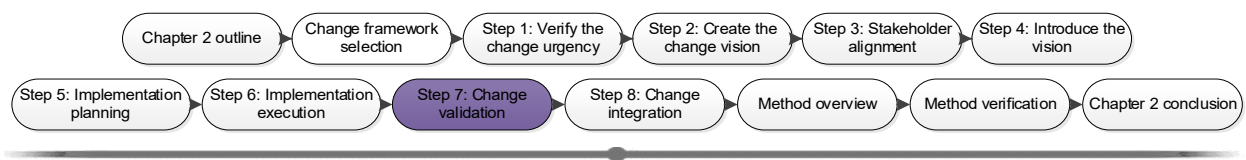


Table 2-22: Percentage call achieved production comparison

Parameter	Compressed air [%]	Hydro [%]	Impact [%]
Month 1	A	B	$(A-B)/A$
Month 2	C	D	$(C-D)/C$
Month 3	E	F	$(E-F)/E$
Average	G	H	$(G-H)/G$

(4) Water intensity ratio

The water intensity ratio refers to the volume of water required to produce a fixed volume of ore, measured in tonnes of water per tonne of ore. It is a normalised parameter to compare the difference in water usage between the conventional and alternative systems. It is determined by the ratio between water consumed and ore produced, as shown in Table 2-23. Water consumption is usually measured only up to the cross-cut level, if at all measured, due to the limited instruments installed underground [37]. Here, there is a need to measure the water consumed by each panel. This can be achieved by installing a mechanical flow totaliser in the water line that feeds the respective panels. The mine's survey department measures the monthly tonnage produced.

Table 2-23: Water consumption summary

Parameter	Unit	Compressed air	Hydro	Impact [%]
Water consumption – per production month#	[m ³]	A	B	$(A-B)/A$
Production per month	[tonne]	C	D	$(C-D)/C$
Water per tonne of rock – Total	[m ³ /tonne]	E	F	$(E-F)/E$

(5) Electrical intensity ratio

The electrical intensity ratio refers to the amount of electrical energy used to produce a fixed volume of ore, measured in kWh per tonne of ore. It also serves as a normalised parameter to compare the difference in energy usage between the conventional and alternative systems. To quantify the impact of electric power consumption, a benchmark comparison is needed between the energy consumed by the trial and the compressed air panel, as shown in Table 2-24.

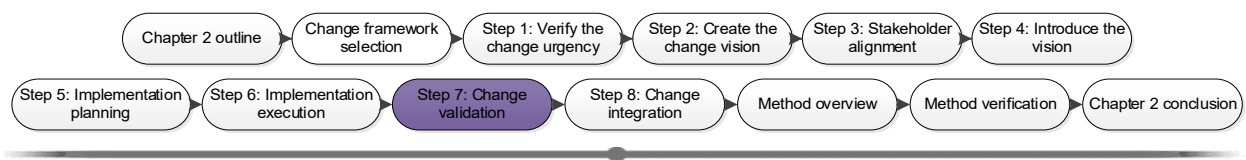


Table 2-24: Summary of energy intensities

Parameter	Unit	Compressed air	Hydro	Impact [%]
Drilling electricity consumption – per production month#	kWh	A	B	(A–B)/A
Dewatering electricity consumption – per production month#	kWh	C	D	(C–D)/C
Production per month	[tonne]	E	F	(E–F)/E
Electricity used per tonne of rock	[m ³ /tonne]	G	H	(G–H)/G

The energy consumed to drill the blastholes is driven by the number of holes prescribed by the blast design [48], [181]. Since the number of holes drilled is a function of the face length and stoping width, the energy consumed to drill the blastholes will vary. For this reason, the benchmark parameter needs to normalise the three parameters mentioned above. To achieve this, it is necessary to use the electrical intensity ratios as benchmark parameters. It follows from Equation 2-16 that the electrical energy intensity ratio relates the energy consumed to the corresponding production achieved in kWh/tonne. The electricity consumed consists of two components: the energy consumed to energise the rock drills and the energy consumed to dewater the service water used to drill the holes.

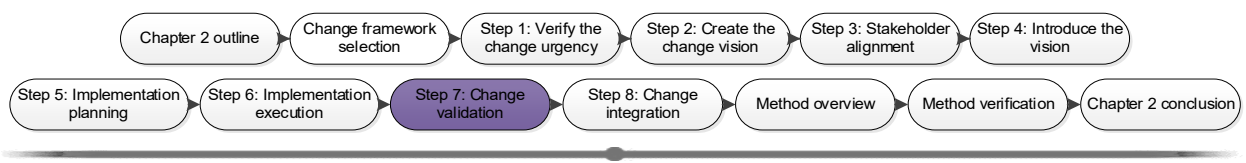
Energy consumed to energise the rock drills – Alternative technology

It follows from [Section 1.4](#) that ADTs are energised by means of either water-hydraulic or oil-hydraulic pumps, which are located underground as close as possible to the occupational environment. Mines generally have little to no installed instrumentation for measuring electric power consumption in the underground production areas [31], [36], [147], [149]. The lack of installed mine infrastructure will necessitate manual measurements to account for the absorbed electrical energy. Du Preez [149] recommended portable measuring equipment, such as DENT loggers, as being most suitable for measuring power, current, and voltage. The reader is referred to Appendix A of Du Preez [149] for a detailed explanation of how to use DENT loggers and the associated software to extract the data. Equation 2-25 presents the formula used to ascertain the total electricity consumed to energise the rock drills.

$$\text{Energy consumed to drill} = \omega_{pp} \times \Delta t \quad \text{Equation 2-25}$$

where:

- ω_{pp} – Electric power in [kW]
- Δt – Running hours during production month in [hours]



Energy consumed to energise the rock drills – Compressed air

Fraser [48] developed a comprehensive method to calculate the total electrical energy consumed to drill a blasthole using compressed air. This study adopted the same method. To summarise the method, it follows from Equation 2-26 that the energy consumed is governed by the flow rate, the electric power required per l/s air compressed, and the compressor running hours. The flow rate represents the amount of air consumed by the baseline panel and is quantified by installing a portable compressed air flowmeter.

$$\text{Energy consumed to drill} = \dot{a} \times \omega_{comp} \times \Delta t \quad \text{Equation 2-26}$$

where:

- $\dot{a}$ – Airflow rate per drill in [l/s]
- ω_{comp} – Electric power in [kW] to compress one litre of air per second [l/s]
- Δt – Compressor running hours during drilling shift [hours]

Fraser [48] further highlighted that the power consumed to compress air (kW per l/s) is a function of the absolute inlet pressure, compression ratio, number of compressor stages, and electrical and mechanical efficiencies. Equation 2-27 prescribes the formula used to calculate the absorbed power required to compress the air.

$$\omega_{comp} = N \times P_1 \times V_1 \times \left(\frac{k}{k-1} \right) \times \left(\frac{P_2}{P_1} \right)^{\left(\frac{k-1}{N \times k} - 1 \right)} \quad \text{Equation 2-27}$$

where:

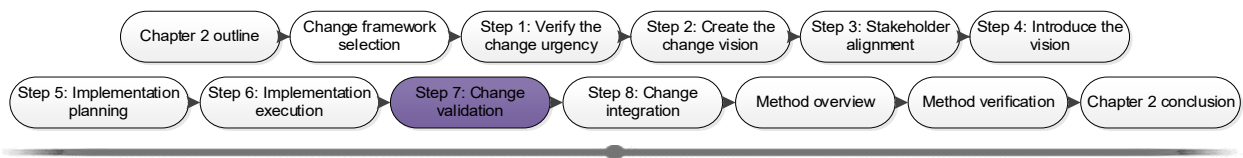
- N – Number of compressor stages [-]
- P_1 – Absolute inlet atmospheric pressure at utilisation altitude [kPa]
- P_2 – Absolute outlet atmospheric pressure at utilisation altitude [kPa]
- V_1 – Specific volume of inlet air [m³/kg]
- k – Specific heat ratio at constant pressure to constant volume [-]

Energy consumed by the system due to wastage

The energy consumed by the system due to wastage during non-drilling times is calculated using Equation 2-26. In this case, the mass flow rate ($\dot{a}$) represents the mass flow rate measured inside the panel.

Energy consumed to dewater

The energy absorbed to dewater the service water used for drilling is a function of the water flow rate, pumping head, and the overall efficiency of the system (motor, pump, and pipe network) [48]. It is ascertained by Equation 2-28.



$$\text{Energy consumed to dewater} = \frac{\rho \times g \times h \times \dot{c}}{\varphi} \quad \text{Equation 2-28}$$

where:

- ρ – Water density [kg/m³]
- g – Gravitational acceleration [m/s²]
- h – Dewatering pumping height [m]
- $\dot{c}$ – Dewatering flow rate per drill in [l/s]
- φ – Combined overall efficiency of the pump, motor and pump column [–]

Proposed data collection strategy

The input parameters to be collected are summarised in Table 2-25.

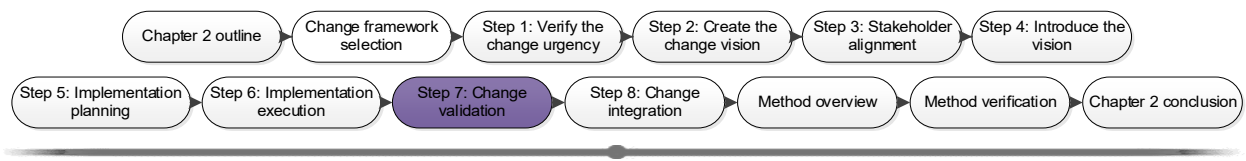
Alternative – drilling: The power logger must be installed in the power supply box that supplies the pressure generation units, following the prescribed method proposed by Du Preez [149]. It is essential that no other equipment is connected to the power supply box. The loggers can record data for several months, depending on the sampling frequency. It is recommended to extract and analyse the data monthly.

Dewatering: The volume of water to be dewatered is determined by the mechanical flowmeter, while the vertical pumping head can be obtained from the mine planning department. OEM data sheets can guide overall pump efficiency.

Compressed air – drilling and wastage: A portable compressed air flowmeter needs to be installed in the pipe supplying the baseline panel. It is important to ensure that the pipe being measured supplies air only to the baseline panel. These flowmeters can typically log the data. The flowmeter should log the compressed air usage for the entire production month.

Table 2-25: Input parameters required to calculate the electrical energy intensity ratio

Parameter	Unit	Data source
Pumping head	m	Mine planning department
Overall pump efficiency	%	EOM data sheets
Ratio of specific heats or polytrophic constant	–	EOM data sheets
No of compressor stages	–	EOM data sheets
Altitude	m	Mine planning department
Suction pressure (absolute)	kPa _{abs}	Measurement
Delivery pressure (gauge)	kPa _{Gauge}	Measurement
Deliver pressure (absolute)	kPa _{abs}	OEM data sheets
Compression ratio	–	OEM data sheets
Specific volume	m ³ /kg	0.967
Average mechanical efficiency	%	EOM data sheets
Motor efficiency	%	EOM data sheets



Parameter	Unit	Data source
Pipe friction adjustment – 15% (conservative)	%	Estimate
Wastage	kg/s	Measurement
Air consumption per drill	kg/s	Measurement

Step 7.2: Assess SHE

This specific assessment focused on understanding the impact of the alternative drilling system on SHE, as outlined in Figure 2-28. The assessment criteria used to quantify the impact after implementation included noise, vibration, and localised temperature changes during drilling.

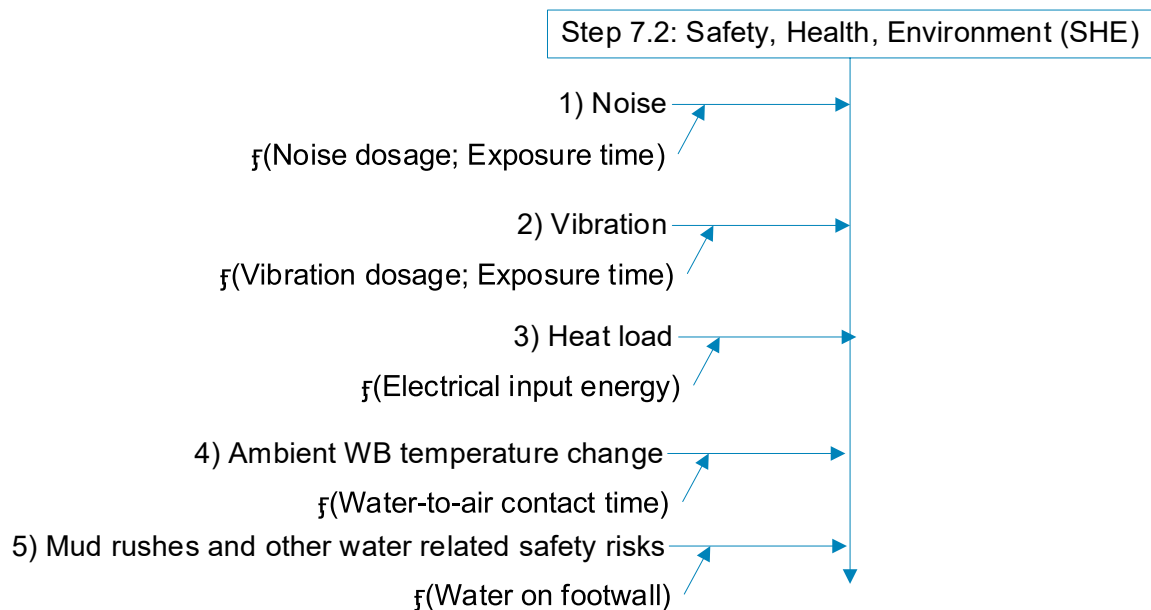


Figure 2-28: SHE assessment criteria

(1) Noise

A detailed description of the importance of noise measurements is followed in Step 2: Create the change vision. The TWA noise exposure is calculated using Equation 2-17. The data collection strategy for performing the noise comparison is presented in Table 2-26.

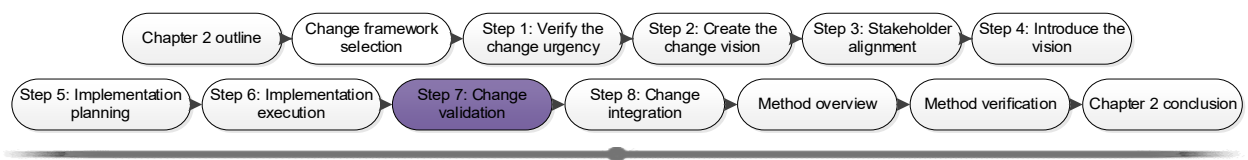


Table 2-26: Noise comparison

Rock drill	Sound pressure level [dB(A)]	Exposure time [hours]	Noise exposure	TWA noise exposure [dB(A)]	Impact
S215	As measured by the shaft occupational hygienist	Average drilling shift duration, as per Table 2-21	As per Equation 2-18	As per Equation 2-17 (A)	(A – B)/A
Hydropower	As measured by the shaft occupational hygienist	Average drilling shift duration, as per Table 2-21	As per Equation 2-18	As per Equation 2-17 (B)	

(2) Vibration

Similar to noise, Step 2: Create the change vision provides a detailed description of the importance of quantifying the impact of vibration exposure. The TWA vibration exposure is calculated using Equation 2-20. The data collection strategy for performing the vibration comparison is presented in Table 2-27.

Table 2-27: Vibration comparison

Rock drill	Magnitude [m/s ²]	Exposure time [hours]	TWA vibration exposure [m/s ²]	Impact
S215	As measured by the shaft occupational hygienist	Average drilling shift duration, as per Table 2-21	As per Equation 2-20 (A)	(A–B)/A
Hydropower	As measured by the shaft occupational hygienist	Average drilling shift duration, as per Table 2-21	As per Equation 2-20 (B)	

(3) Heat load

Several researchers cautioned against the additional heat introduced to the stoping environment when implementing ADTs [31], [49], [182]. The work performance of stope team members is sensitive to changes in ambient temperature and is strictly governed by legislation [47], [183]. Consequently, to understand and manage the impact, the introduced heat load needs to be evaluated.

Impact evaluation strategy: Figure 2-29 showcases a simplified energy balance of a water-hydraulic drilling system added to a panel. The energy absorbed by the motor at point (A) is used to drive the pump (B), resulting in a pressurised motive fluid medium. The motive fluid medium enters the pump at a specific temperature (C) and is discharged at an elevated pressure and

temperature due to the energy absorbed. The motive fluid medium is used to energise the drill-thrust assembly, cool the chuck bush and drill bit, and flush the hole. Water is discharged at the rock drill exhaust port and from hole (D), flowing down the panel to accumulate in the strike gully (E).

For oil-hydraulic alternatives, the scenario differs, and the following is true. Heat added to the oil while pressuring it will alter the oil's viscosity. To ensure that the oil's viscosity remains within acceptable limits, heat must be dissipated from the oil. To achieve this outcome, service water is circulated through an indirect contact heat exchanger located inside the power pack. Heat is added to the water, which is then used to cool the chuck and drill bit and flush the hole before being discharged to the footwall. Ultimately, the water accumulates in the strike gully.

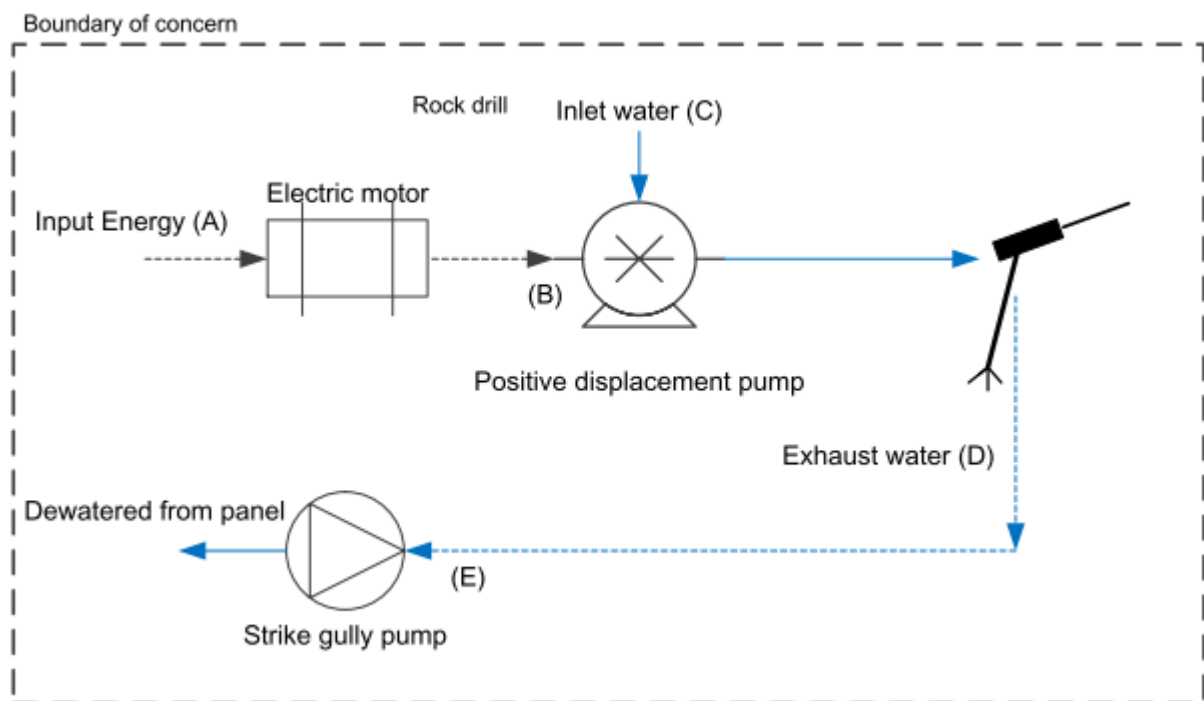
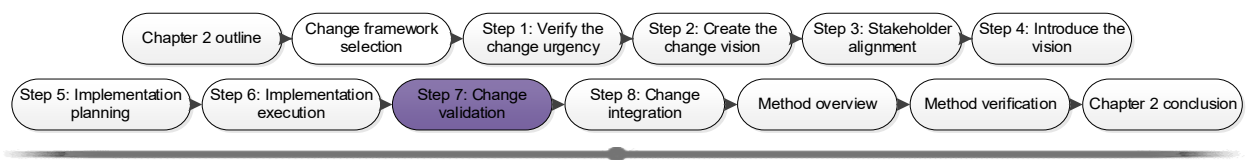


Figure 2-29: Energy balance in-stope (Adapted from [31])

To account for the heat added to the water, the significant points are Point C and Point E. From these two points, the net heat added to the water and lost to the air must be calculated. The net heat added to the water is given by Equation 2-29. It is a function of the total flow rate ($\dot{c}$) and the temperature difference between Points E and C ($T_E - T_C$). Finally, the heat added to the ambient air is obtained through the energy balance between the absorbed electrical energy (E_{absorbed}) and the heat added to the water (H_{water}), as expressed by Equation 2-30. The data collection strategy is outlined in Table 2-28.



$$H_{\text{water}} = C_p \times \dot{c} \times (T_E - T_C) \quad \text{Equation 2-29}$$

where:

- H_{water} – Heat added to the water [kW]
- C_p – Specific heat capacity of water [J/kg°C]
- $\dot{c}$ – Water flow rate [l/s]
- $T_E - T_C$ – Water temperature difference between Point E and C [°C]

$$H_{\text{air}} = E_{\text{absorbed}} - H_{\text{water}} \quad \text{Equation 2-30}$$

where:

- H_{air} – Heat added to ambient air [kW]
- E_{absorbed} – Absorbed electrical energy [kW]
- H_{water} – Heat added to the water [kW]

Table 2-28: Heat load comparison

Refer to Figure 2-29	Parameter	ADT	Compressed air	Data source
C	Manifold inlet water temperature [°C]	A	B	Manual measurement
E	Water temperature in strike gully [°C]	C	D	Manual measurement
–	Delta (C-E)	A–C	B–D	Calculation
–	Total flow rate through running drills [l/s]	2.2	1.2	Manual measurement
–	Maximum heat added/removed [kW]	38.7	15.0	Calculation using Equation 2-30

(4) Ambient wet-bulb temperature change

Krige and Barnard [47] studied various environmental factors affecting productivity in underground gold mines and concluded that the wet-bulb temperature was the key factor affecting productivity. The data presented evidently showed that a one-degree Celsius wet-bulb increase resulted in a 3% to 4% decrease in monthly productivity. That translates roughly to the equivalent tonnes generated by a full blast of an average production panel. Consequently, the corresponding localised temperature impact due to the added heat requires further consideration.

Impact evaluation strategy: The change in ambient wet-bulb air temperature before and during the drilling shift needs to be quantified, as shown in Table 2-29. Figure 2-30, which depicts the typical airflow through a narrow reef panel, is considered next. Primary and secondary ventilation fans move air through the mine, into the raise and along the strike gully. Ventilation curtains are

usually installed along the strike and dip. They are used to direct the air along the centre gully towards the face. It enters the face area at Point A and flows towards Point B, removing heat from the face. Its sources include geothermal heat from the rock, metabolic heat from the stope team members, and heat from the water.

The corresponding change in ambient wet-bulb temperature while drilling represents the impact of the additional heat introduced. It is obtained by subtracting the wet-bulb air temperature measurement at the inlet (Point A) from the measurement at the return (Point B).

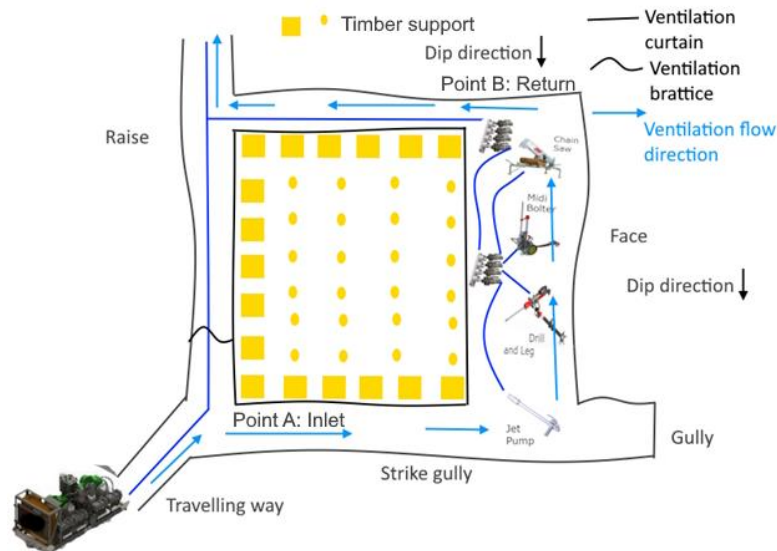


Figure 2-30: Ventilation airflow through a panel

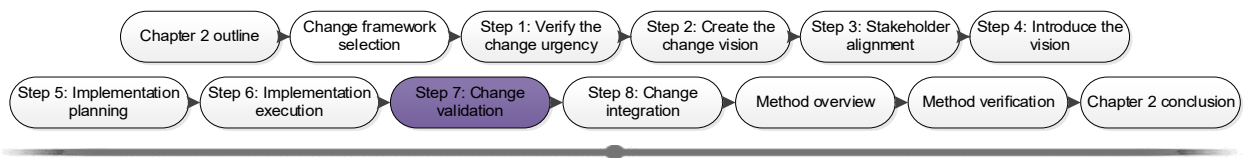
Table 2-29: Ambient wet-bulb temperature change

Parameter	Unit	Compressed air	Alternative	Impact
Ambient wet-bulb temperature change	[°C]	A	B	$(A-B)/A$

(5) Mud rushes and other water related safety risks

New safety risks generally accompany the introduction of new technology. It was stated earlier in the literature review section that hydropower drilling technologies use up to four times as much water as their compressed-air counterparts. This might increase the risk of mud rushes if the water is not managed adequately. Additionally, below-step-over workplaces might flood when pipes/hoses fail, and the necessary safety isolation valves (SIV) are not in place. Pipe or hose failures under pressure could injure the workforce if the required SIVs are ineffective.

Mud rushes: Buther *et al.* (2005) published a study highlighting several methods for combating mud rushes [72]. The most relevant method for this study is to establish an effective dewatering network within the stope. This study advocates the use of strike gully pumps to be used during



the drilling shift. Also, to be installed when the workplace is watered down by the night shift prior to commencing with the cleaning activity.

Mines that deploy waterjet face cleaning and scrapers in the strike gully pose an elevated risk of mud rushes during cleaning operations. To manage the risk, such mines should consider the research conducted at Northam Platinum, as published by Kendall and Gericke (2000) [12]. The study proposes a unique layout in which water sumps are integrated into the raise. In cases where the on-reef layouts cannot be altered, slotted door box front chutes can be considered, as advocated by Fraser (2014) [60].

Other water related safety risks: To prevent workplace flooding or employee injuries, safety valves are incorporated into the hydropower system design. Safety isolation valves safeguard against downstream failures in steel pipes [28]. Combined excessive flow and isolation valves safely isolate the water flow when a downstream hydraulic hose bursts [62].

Impact evaluation strategy: The effectiveness of these safety features is assessed by tracking the number of hydropower-related injuries, flooded workplaces and mud rush incidents. A record book is needed to record all the water related incidents, including:

- date and time of the incident,
- detailed description of what transpired, and
- location.

Step 7.3: Mine suitability assessment

The primary objective is to determine whether the alternative offers a suitable replacement for conventional drilling systems. Figure 2-31 shows that mine suitability is governed by two critical focus areas: functionality and reliability. Answers to the following essential questions need to be obtained:

- **Functionality:** Does the alternative provide the functionality to fulfil all the tasks required to complete the breaking cycle, including drilling, supporting, blasting, and clean?
- **Reliability:** Does the alternative offer the same or improved reliability levels than compressed air equipment?

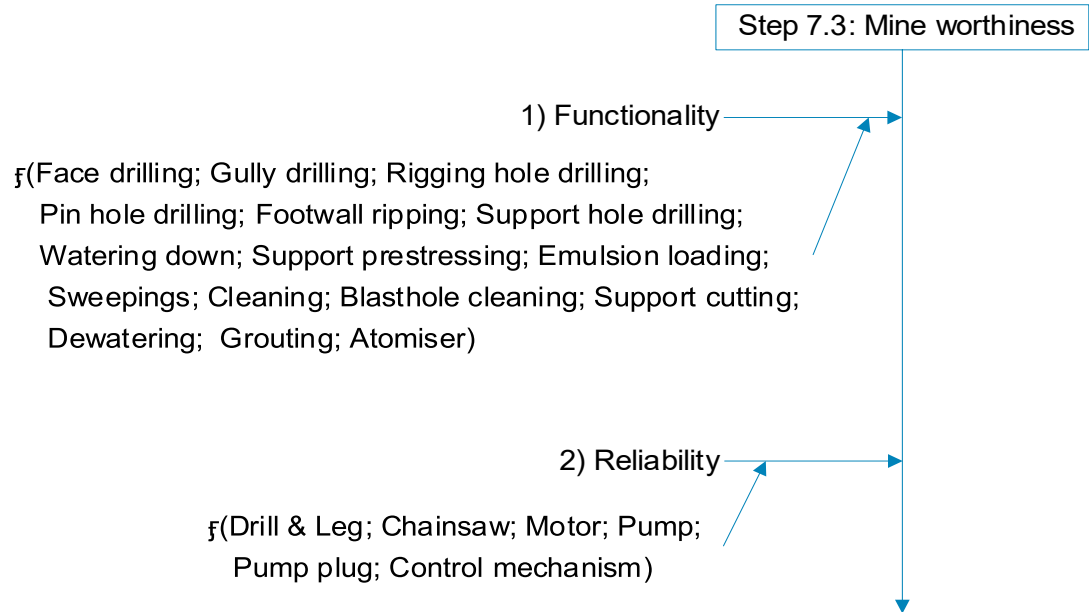
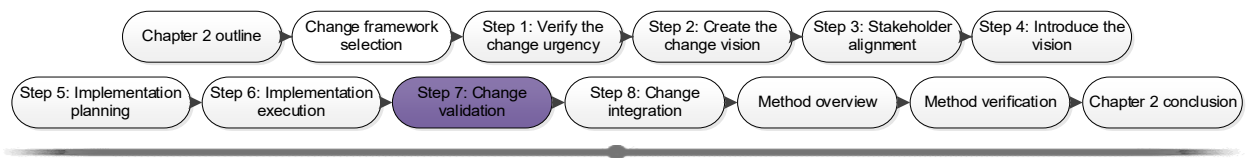


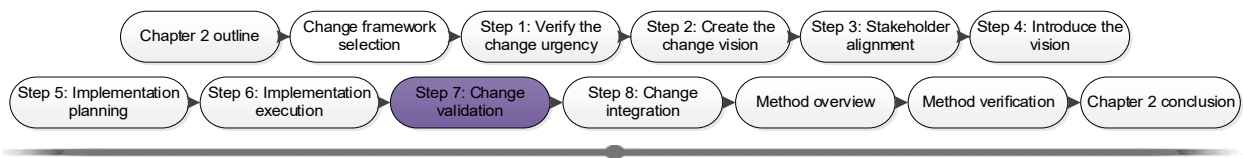
Figure 2-31: Mine worthiness assessment criteria

(1) Functionality

As substantiated by the literature presented in Chapter 1, Table 2-30 summarises the equipment functions required to support the basic tasks necessary to complete a narrow reef mining cycle [2], [62], [115], [184], [185]. To assess whether the alternative technology is a suitable replacement in terms of functionality, the product performance evaluator is required to determine the amenability of equipment functions, which are more fully outlined in Table 2-30.

Table 2-30: Equipment flexibility

Activity	Function required	Amenability
Drilling	Face drilling	Yes/No?
	Gully drilling	Yes/No?
	Rigging hole drilling	Yes/No?
	Pin hole drilling	Yes/No?
	Footwall ripping	Yes/No?
	Support hole drilling	Yes/No?
Support	Prestressing of: - Prestressing plates - Jackpods - Hydraulic props Matt packs	Yes/No?
	Chainsaw	Yes/No?
	Blasthole cleaning	Yes/No?



Activity	Function required	Amenability
Blasting	Emulsion loader	Yes/No?
Cleaning	Sweepings	Yes/No?
	Waterjet	Yes/No?
Other	Dewatering pump	Yes/No?
	Atomisers	Yes/No?
	Chain hoists	Yes/No?
	Watering down	Yes/No?

(2) Reliability

An equipment assembly is prone to failure if one or more of the individual components fail. A reliability study is required to assess the operational lifespan of all critical components. The results obtained are crucial information that will serve as guidance regarding the number of spare equipment required, all in an effort to minimise the likelihood of losing a blast due to component failures.

It follows from the detailed analysis of alternative drilling performed in [Section 1.4](#) that a system suite of alternative drilling equipment consists of six critical components. It is important to note that the functionality of the system depends on all elements being in working order. That is, the complete system will be without pressure if the pressure generation unit (C1) fails. A failure in the supply reticulation will prevent the operation of any other components (C3–C6). While any failure of components C3 and C4 will prevent them from performing their respective required functions as fully described in Table 2-30.

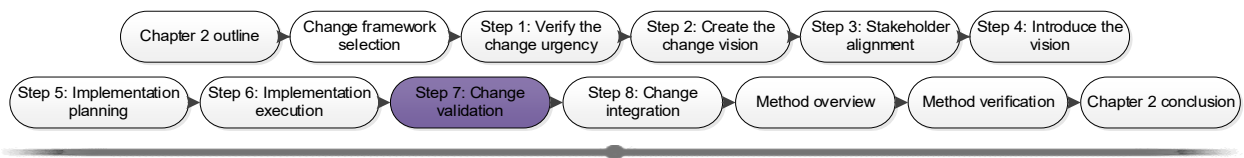
Proposed lifespan assessment strategy

C1: Pressure generation

The pressure generation unit typically consists of a motor, pump, and mechanism, such as a PLC or load/unloader valves, to control the supply based on user demand [49], [62]. The operational lifespan of these three components is measured in terms of cycles of operation, quantified as the number of operational hours until failure. The product performance evaluator is tasked with tracking operational shifts to failure using PLC data.

C2: Supply reticulation

As discussed in [Section 1.4](#), a supply reticulation network consists of various pipes that reticulate the energy medium (oil or water) from the pressure generation unit to components C3 to C6. It is essential to track reticulation failure rates, as a high failure rate can indicate incorrect pipe routing, end user abuse, or the use of substandard pipes. The operational lifespan of these pipes



depends on correct routing along the gullies (to prevent abrasive damage), operator abuse (damage caused by blasting or scraping), and pipe quality. Additionally, using PLC data, the product performance evaluator is responsible for tracking operational shifts that lead to failure.

C3: Rock drill and thrust leg assemblies

Informed by literature, linear metres drilled to failure appeared to be the preferred parameter for quantifying the operational lifespan of rock drills and thrust legs [48], [55], [66], [121], [186]. It is common practice at the operations to file a waybill for all equipment delivered to and removed from the mine. The product performance evaluator is advised to use a similar system in the stope to account for the number of shifts that the drills and legs were used before failure. The rock drill or thrust leg failure rate is calculated using Equation 2-31. The total meters drilled is obtained by multiplying the total number of holes drilled by the effective length of the drill steel. The waybill data is used to account for the number of rock drill failures.

$$\text{Drill or thrust leg failure rate} = \frac{\text{Total}_{\text{metres drilled}}}{N_{\text{failures}}} \quad \text{Equation 2-31}$$

where:

- $\text{Total}_{\text{metres drilled}}$ – Monthly total linear metres drilled [m]
- N_{failures} – Monthly total number of drills or thrust leg failures [–]

C4–C6: Emulsion loader pump drive, support installation devices, and cleaning equipment

Conventional compressed air-driven emulsion pumps used to charge blastholes can easily be converted by simply replacing the compressed air drive with an oil- or water-powered alternative to support the installation of ancillary devices, such as chainsaws and prestressing devices. Here, the product performance evaluator must track the number of shifts to failure using the same waybill system recommended above (Refer to C3: Rock drills and thrust leg assemblies).

Data collection strategy: Table 2-31 presents the proposed data collection strategy and data sources.

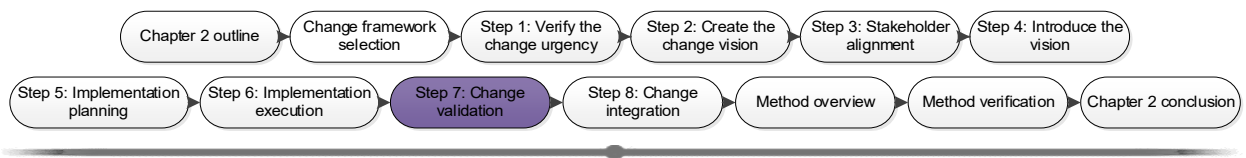


Table 2-31: Reliability data collection plan

Component	KPI	Unit	Source	Sample size
C1	Motor	[Hours]	PLC data	- The number of failures limits the sample size. - All failures are to be recorded.
	Pump	[Hours]	PLC data	
	Control mechanism	[Hours]	PLC data	
C2	Reticulation	[Shifts/failure]	Waybill data	
C3	Drill	[m/failure]	Waybill data	
	Thrust leg	[m/failure]	Waybill data	
C4	Emulsion loader drive	[Shifts/failure]	Maintenance reports	
C5	Chainsaw	[Shifts/failure]	Waybill data	
	Prestressing devise	[Shifts/failure]	Waybill data	
C6	Sweeping tool	[Shifts/failure]	Waybill data	
	Waterjet gun	[Shifts/failure]	Waybill data	

Step 7.4: Human factor assessment

Human factor assessment focused on formulating an understanding of the end users' experiences while using the alternative drilling system. Employees' reactions to organisational change, also known as adoption willingness, are well supported in the literature as being driven by fatigue and morale [68], [100], [143]. As seen in Figure 2-32, the assessment criteria adopted by this study included fatigue and morale as evaluation criteria.

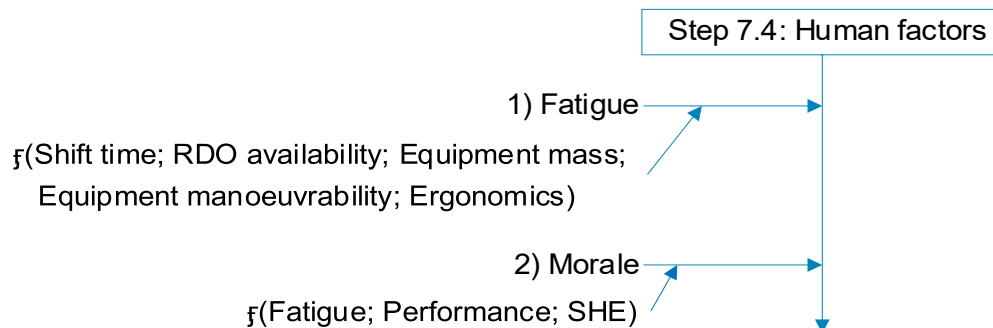
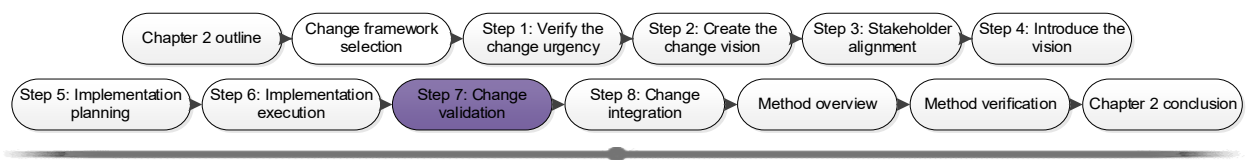


Figure 2-32: Human factors

(1) Fatigue

The first assessment criterion examines the impact of operator fatigue. It is well substantiated by the literature that RDO fatigue is a function of available shift time, workplace wet-bulb and dry-bulb temperatures, RDO availability, equipment mass load, equipment manoeuvrability, and ergonomics [31], [45], [47], [55], [121], [125], [143]. Since increased levels of fatigue frequently lead to high absenteeism rates, absenteeism and unpaid leave are recommended as useful parameters to quantify the impact of fatigue [2].



(2) Morale

It is apparent from the literature that the morale of underground mining teams is primarily driven by job satisfaction [103], [125], [143], [187], [188]. Job satisfaction is governed by three key drivers: production bonus, reliable and efficient equipment performance, and a safe and healthy occupational environment. To secure a production bonus, the team needs to reach their production goal. Reliable and efficient equipment plays a crucial role while working in a safe and healthy environment.

Environmental contamination also plays a significant role. As highlighted in [Section 1.2](#), an oiler is filled with grease to lubricate the compressed air rock drill. A mixture of oil, air, and water forms a dense layer of fog inside the panel while drilling, reducing overall visibility and air quality [54], [56], [63]. A 2026 paper published in a toxicology journal reviewed the health side effects of continued exposure to oil-mist [189]. The airways and lungs are the primary target organs, which may result in reduce lung function, chronic cough, airway irritation, and pulmonary fibrosis. Due to the absence of grease in alternative drilling systems, the visibility and air quality in the panel while drilling are expected to improve.

Impact evaluation strategy:

A photo needs to be taken to capture the visibility in each panel. A side-by-side comparison of the photographs can be used to quantify the improvement, if any.

(3) Adoption willingness

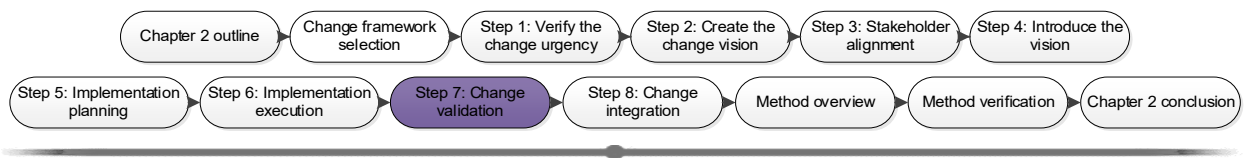
To assess the crew's willingness to adopt the technology, the shaft's human resources leader and union representatives will consult the crew. The three key questions to be considered are shown in Table 2-32. Actual production achieved, equipment performance, and health and safety parameters can be used to validate the crew's response.

Table 2-32: Human factor consultation questions

Human factors	KPI
Fatigue	Did the technology help reduce operator fatigue?
Morale	Did the technology help to improve the overall team morale?
Adoption willingness	Would you like to adopt the technology?

Step 7.5: Techno-economic assessment

A techno-economic assessment is required to systematically analyse the economic performance of the implemented technology [117], [190]. The purpose of the evaluation is to benchmark the performance and corresponding costs of the implemented technologies. As a result, the outcome provides strategic guidance for selecting the most economically viable option. It ultimately justifies capital expenditure based on the technology's performance [182].



The techno-economic input parameters, or KPIs, serve as key data inputs to inform the assessment results. As illustrated in Figure 2-33, the literature review in [Section 1.7](#) indicated that the KPIs to govern the assessment are capex, opex, and return on investment (ROI) [53], [64], [65], [66], [117].

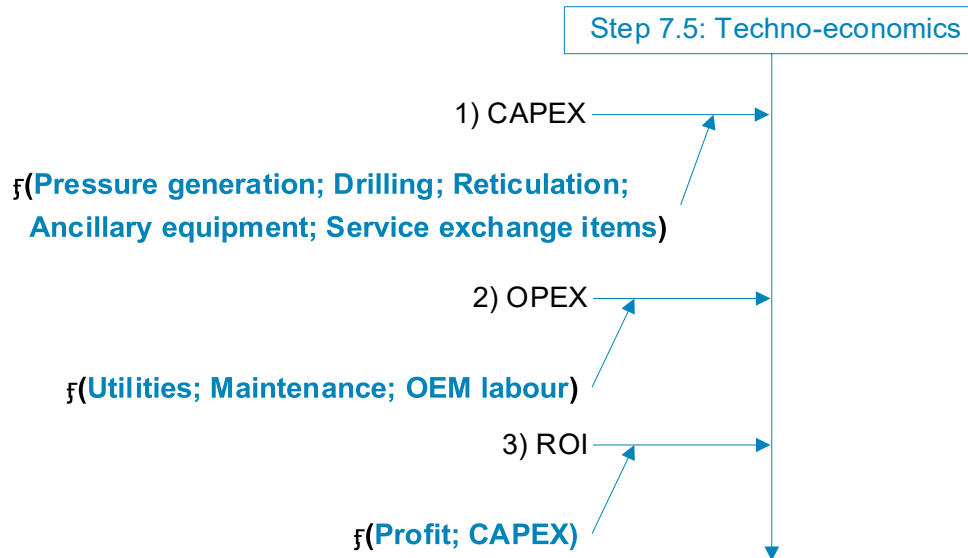


Figure 2-33: Step 7.5 – Techno-economics

KPI 1: Capex

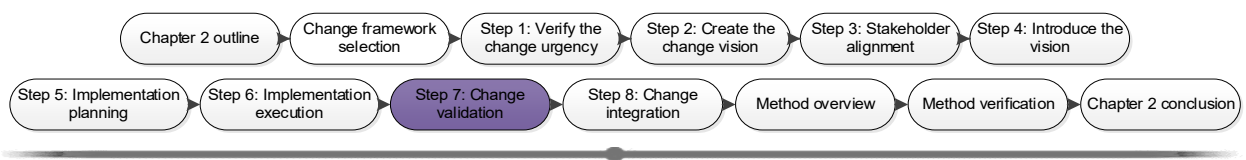
The first assessment criterion evaluates the capital cost of acquiring the infrastructure to equip the crews with the alternative drilling system. This includes pressure generation units, drills, thrust legs, reticulation, and ancillary equipment [53], [66]. It is essential to understand the capex requirements for capital application processes during the budgeting cycle.

KPI 2: Opex

Operational costs are governed by the utilities consumed, maintenance, and OEM labour [117], [190]. The cost of each component is considered, and data is collected from invoices submitted to the operation's financial manager.

KPI 3: ROI

As a third criterion, the fixed capital costs of each system configuration are evaluated in terms of ROI. It is an effective comparative metric for assessing the technology's sensitivity to capital costs and is calculated using Equation 2-32 [191]. The monthly profit generated by the workplace is obtained by multiplying the R/kg profit figure (as provided by the mine's income statement) by the gold content recovered from the workplace. The capex parameter denotes the once-off cost to acquire the panel's drilling equipment.



$$ROI = \left(\frac{\text{Monthly}_{\text{profit}}}{\text{Capex}} \right) \times 100 \quad \text{Equation 2-32}$$

where:

- ROI – Return on investment [R]
- $\text{Monthly}_{\text{profit}}$ – R/kg profit figure obtained from the mine's income statement multiplied by the gold content recovered from the workplace [R]
- Capex – Once-off capital cost per panel of the drilling system [R]

Data collection strategy: Table 2-33 presents the proposed data collection strategy and data sources.

Table 2-33: Techno-economic assessment data collection plan

KPI	Source	Sample size
Capex	OEM supplier invoices	Once-off
OPEX	OEM supplier invoices	Monthly
Monthly profit	Income statement	Monthly

Step 7.6: Validate the initial vision board

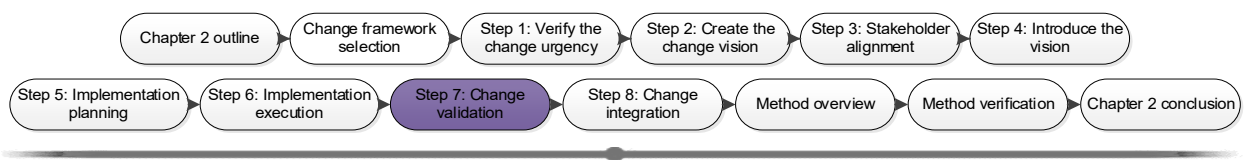
End users will revert to their old system if the alternative's proclaimed benefits fail to materialise during the continuous performance assessments. The seventh focus area of the case study research methodology (see Figure 1-23) calls for a strategy to compare actual results with theoretical predictions. Step 7.6 focuses on achieving this outcome by benchmarking the measured results against the theoretical claims made during the initial vision creation. The purpose of the assessment is to confirm whether the benefits materialised and to update the theoretical vision with actual case study results.

Phase 3: Overview of strategies developed to validate the change benefits

The overarching objective of this phase was to develop strategies to enable the two following strategic outcomes: (i) assess the technology's overall readiness to function as a replacement system: Step 7.1–7.5, and (ii) validate the change benefits: Step 7.6.

2.6. Phase 4: Development of strategies to integrate the change

A complete overview of the method and key objectives is shown in Figure 2-34. The first phase of the change process initiated the change. An array of strategies was developed to verify the change urgency (Step 1), create a change vision (Step 2), align stakeholders (Step 3), and share the vision to obtain approval to implement the change process (Step 4). Phase 2 focused on developing strategies to implement the change by performing implementation planning (Step 5), and implementing and sustaining the implementation momentum (Step 6). Phase 3 incorporated



a validation strategy to confirm that the theoretical change benefits (highlighted by Step 2, Change vision) have successfully materialised after implementation. The technology is classified as a suitable replacement once its benefits materialise.

As the final phase, Phase 4 focuses on developing the strategies required to integrate the change and expand it to the remaining crews. It follows from [Section 1.7](#) that failure to integrate the change generally results from organisational shock waves when excessive change is applied or when the change benefits fail to materialise during large-scale roll-outs. To remedy this, strategies are needed to sequentially expand the change to the remaining crews and to analyse the change results and formulate continuous improvement initiatives.

The overarching aim of this phase is to develop strategies to foster the following strategic outcomes:

- Provide a sequential approach to introduce the change, and
- Identify and implement continuous improvement initiatives.

Step 8 focuses on developing the relevant strategies needed to facilitate these three strategic outcomes.

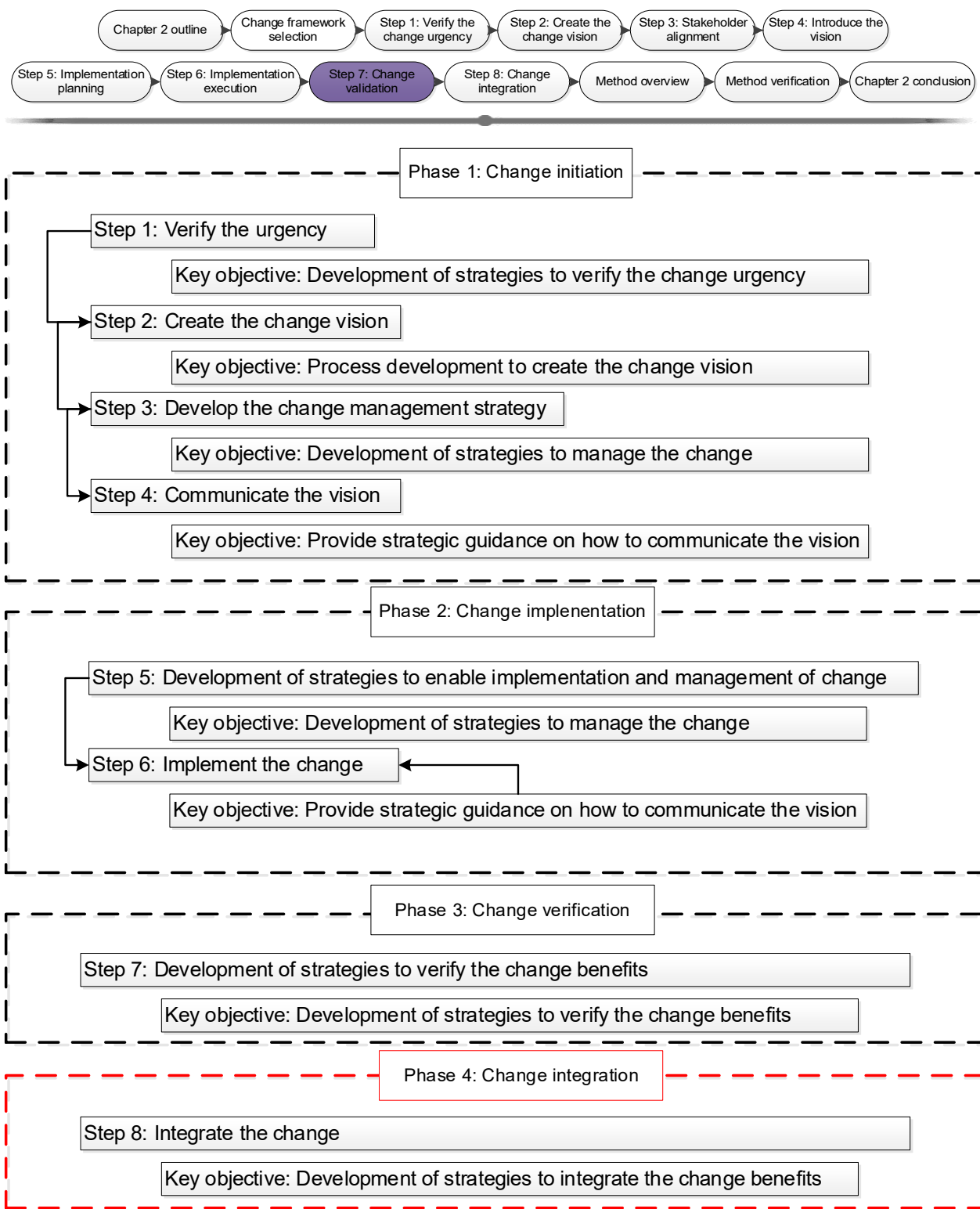
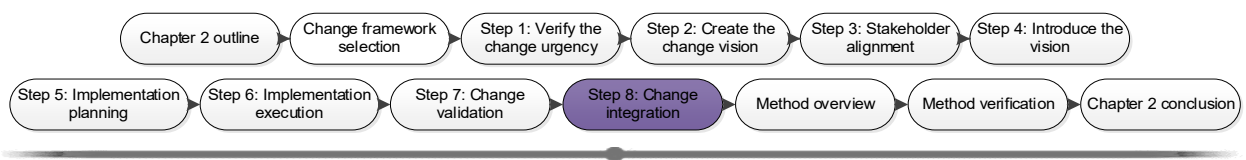


Figure 2-34: Method development process flow – Phase 4: Change integration



Step 8: Expand the change process sequentially

Once the change benefits have been successfully confirmed, the change process needs to be expanded to the remaining crews. It was established from the literature review that past initiatives to implement new technology generally failed during the change integration phase, when rapid changes caused shock waves to resonate throughout the organisation. Further to this, failure to identify opportunities for improvement frequently prevents transformation efforts from achieving their desired potential. Consequently, as seen in Figure 2-35, strategies are needed to sequentially expand the change process, crew by crew, and to evaluate performance on a continuous basis.

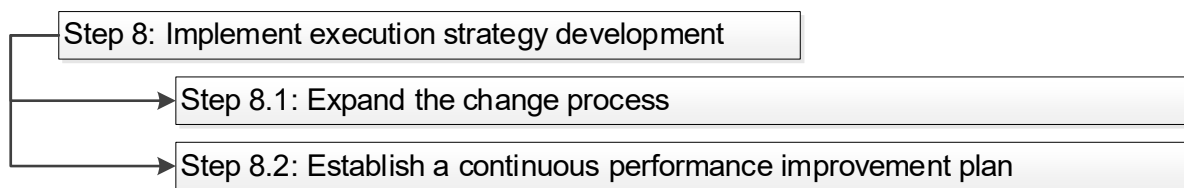


Figure 2-35: Step 8: Development overview

Step 8.1: Sequential multi-layered approach to expand the change process

A crucial element of successful execution is prioritisation. Failure often occurs when too many objectives are attempted simultaneously. Converting the most critical areas first will maximise the ROI and mitigate change resistance. The literature survey ([Section 1.7](#)) highlighted a clear gap, as none of the reviewed studies presented a strategy for prioritising crews during the roll-out phase. As a result, a strategy is needed to prioritise crews according to conversion urgency. The strategy needs to structure the expansion plan by prioritising crews according to compressed air performance in the workplaces. Figure 2-36 focuses on the development process flow applied to develop this prioritisation strategy.

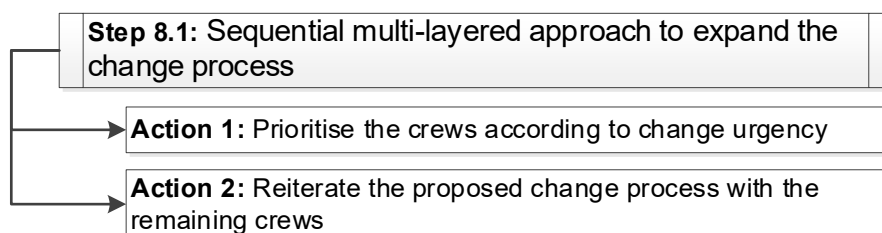
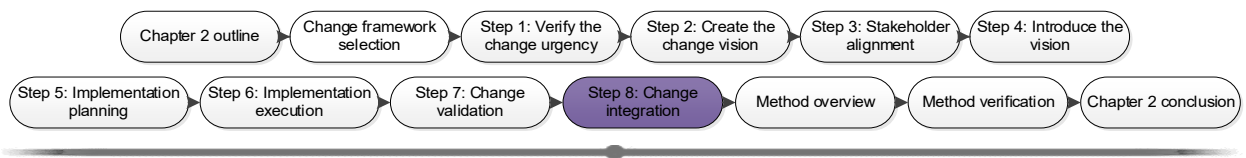


Figure 2-36: Step 8.1: Development overview



Action 1: Develop a strategy for prioritising crews during the change expansion process

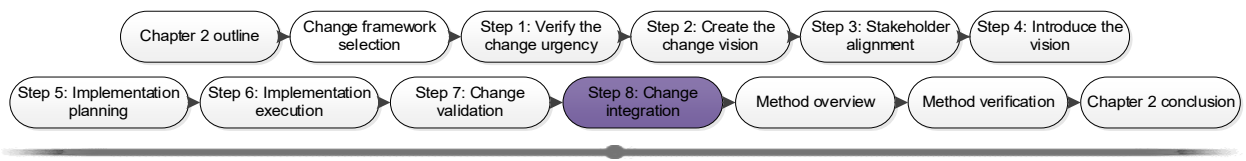
A strategy is needed to prioritise the crews from worst to best based on compressed air drilling performance. Lost blast data can be used to achieve this outcome. However, lost blast data may either not exist at the operation or may be logged incorrectly, as alluded to in Step 1. To overcome this shortcoming, a crew prioritisation strategy (CPS), independent of lost blast data, is proposed.

As discussed in [Section 1.3](#), drilling-related lost blasts due to inadequate compressed air are the typical outcome once the drilling shift duration exceeds the available shift time. A crew's need for an alternative drilling system is, therefore, a function of the available shift time and the actual time required to complete the drilling shift. The actual time to complete the drilling shift is a function of the rock drill's drill rate, which is governed by the supply of compressed air pressure. That is, the crews with lower compressed air pressures will experience a higher need for an alternative drilling system.

Table 2-34 showcases a simplified overview of the strategy proposed to prioritise the crews. Crews are listed from first to last. The travel time, entry examination time, and drilling activity durations are added to each crew entry. These times will differ between crews since they are generally scattered across multiple levels in mature gold mines. Ultimately, the shift time deficit is calculated by subtracting the available shift time from the duration of the drilling shift. Shift time deficits are ranked from largest (P_1) to smallest (P_n) to prioritise the crews from first to last on the roll-out schedule.

Table 2-34: Strategy to prioritise crews during the change expansion process

Crew	Total travel time [hh:mm]	Entry examination and face preparation [hh:mm]	Drilling activity duration [hh:mm]	Drilling shift duration [hh:mm]	Charge-up activity duration [hh:mm]	Available shift time [hh:mm]	Shift time deficit [hh:mm]
1	A	B	C	D = (Equation 2-33)	F	X	$P_1 = X - (A + B + C + D + F)$ (Equation 2-34)
⋮	...						
<i>n</i>	D	E	F	I = (Equation 2-35)	H	X	$P_n = X - (D + E + F + I + X)$



CPS Step 1: Estimate total travel time (A), entry examination and face preparation (B), and charge-up time studies

These time components can be estimated through either manual time studies or the use of technology, such as a missing person locator (MPL) system. With the MPL systems widely implemented in South African gold mines as a safety measure, a tag is added to every employee's cap lamp, which logs their whereabouts underground [178]. The data is uploaded to the mine's server once the employee clocks out from underground.

CPS Step 2: Do a collar-to-collar drill rate study

A general limitation of MPL systems is that the beacons used to register employee locations are only installed up to cross-cut level. As a result, the time spent to complete the various mining cycle activities (drilling, installing support, and charging the holes) remains unknown. To address this shortcoming, this study proposes using in-stope compressed air pressure to estimate the duration of drilling activity. Figure 2-37 presents an overview of the performance curves for the most common underground gold-mining stopes in South Africa. It is used to highlight the following point. Compressed air drilling performance is a function of supply pressure, applied thrust, and rock type. It is important to note that drilling performance is not linear; overthrusting results in reduced performance, and vice versa. Therefore, performance curves are site-specific and need to be derived accordingly.

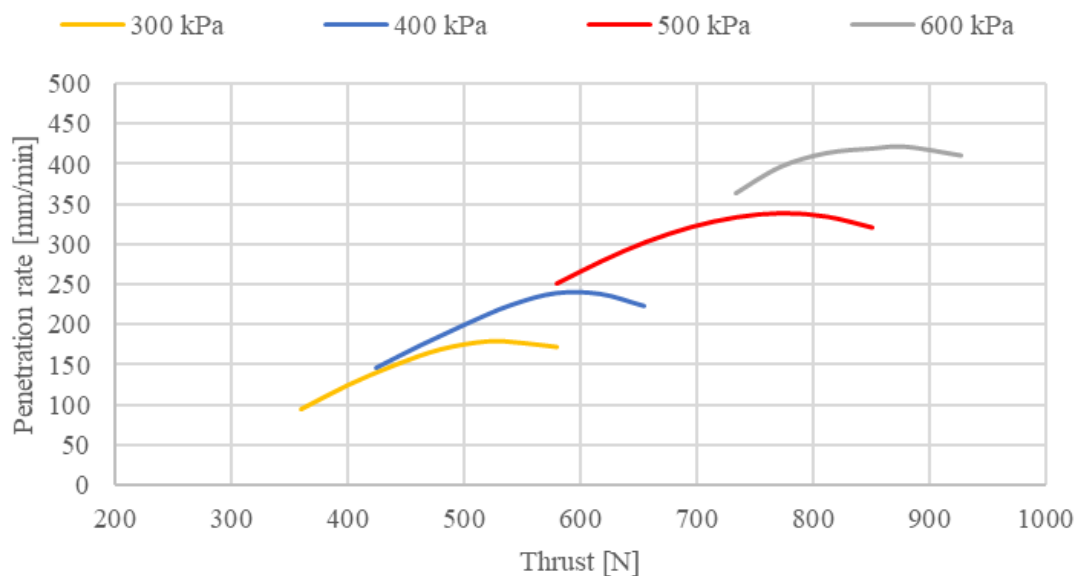
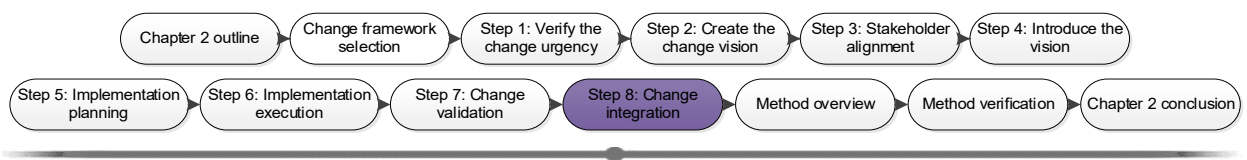


Figure 2-37: Drilling performance curve for an S215 pneumatic rock drill in norite rock (Adapted from [30])

To derive the site-specific performance curve, the case study mine's (CSM) average collar-to-collar compressed air drill rates ($\bar{x}$) at various compressed air pressures (A–J kPa), as presented in Table 2-35, need to be determined. The collar-to-collar data is gathered using the process



defined in [Step 7.1: Performance assessment strategy](#). Data integrity needs to be assured by collecting data at a specific compressed air pressure until the coefficient of variance is within the 20% threshold.

Table 2-35: Collar-to-collar drill rate study results at various compressed air pressures

In-stope pressure [kPa]	A	B	C	D	E	F	G	H	I	J
$\bar{x}$ [mm:ss]	AA	BB	CC	DD	EE	FF	GG	HH	II	JJ
n [–]	Function of the coefficient of variance that needs to be less than 20%									
Coefficient of variance [–]	Data integrity assurance parameter, where the coefficient of variance is less than 20%									

CPS Step 3: Establish the drill rate performance curve

The collar-to-collar drill rate data presented in Table 2-35 is translated into a graph using Microsoft Excel™, as illustrated in Figure 2-38. The curve, however, only accounts for drill rates within the A–J kPa pressure range, which is the available pressure range to gather data from. To overcome this shortcoming, the regression line describing the dataset is obtained using the Microsoft Excel™ trendline function.

$$Predicted_{drill_{rate}} = 8.2958 \times (x)^{-1.327} \quad \text{Equation 2-36}$$

where:

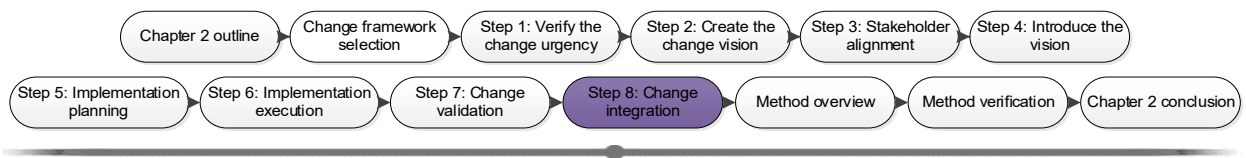
- $Predicted_{drill_{rate}}$ – Compressed air drill rate [minutes]
- x – In-stope compressed air pressure [kPa]

CPS Step 4: Validate the performance equation

The equation describing the line is validated by ensuring that R^2 exceeds the 0.70 threshold and equals 1.0, indicating a perfect fit. As a second validation measure, Equation 2-36 is used to predict the drill rates measured previously at the corresponding pressures. As shown in Table 2-36, the AME calculation is performed and should be less than 5% to confirm the performance equation's validity [147], [192].

Table 2-36: Performance curve equation validation results

In-stope pressure [kPa]	A	B	C	D	E	F	G	H	I	J
Measured [mm:ss]	AA	BB	CC	DD	EE	FF	GG	HH	II	JJ
Predicted [mm:ss]	AAA	BBB	CCC	DDD	EEE	FFF	GGG	HHH	III	JJJ
AME [%]	< 5									



CPS Step 5: Establish the holistic performance curve

Equation 2-36 is used to produce the holistic performance curve for pressures ranging between 240 kPa and 600 kPa, as illustrated by Figure 2-38. This curve describes the compressed air drill rates at the CSM and is specifically developed for the CSM's operational parameters, such as drill bit size, drill steel length, and rock properties. The red line represents the ADTs performance curve, ascertained by the average collar-to-collar drill rate, and follows from Step 7.1. It is a straight line since water- and oil-hydraulic alternatives operated at a constant fluid pressure [62], [66]. The key point to note is the inflection point at 507 kPa. In this example, all crews operating at compressed air pressures below 507 kPa will benefit from converting to hydropower and should proceed with the conversion. At the same time, compressed air will outperform hydropower for all the crews mining with compressed air pressures above 507 kPa and should not be converted.

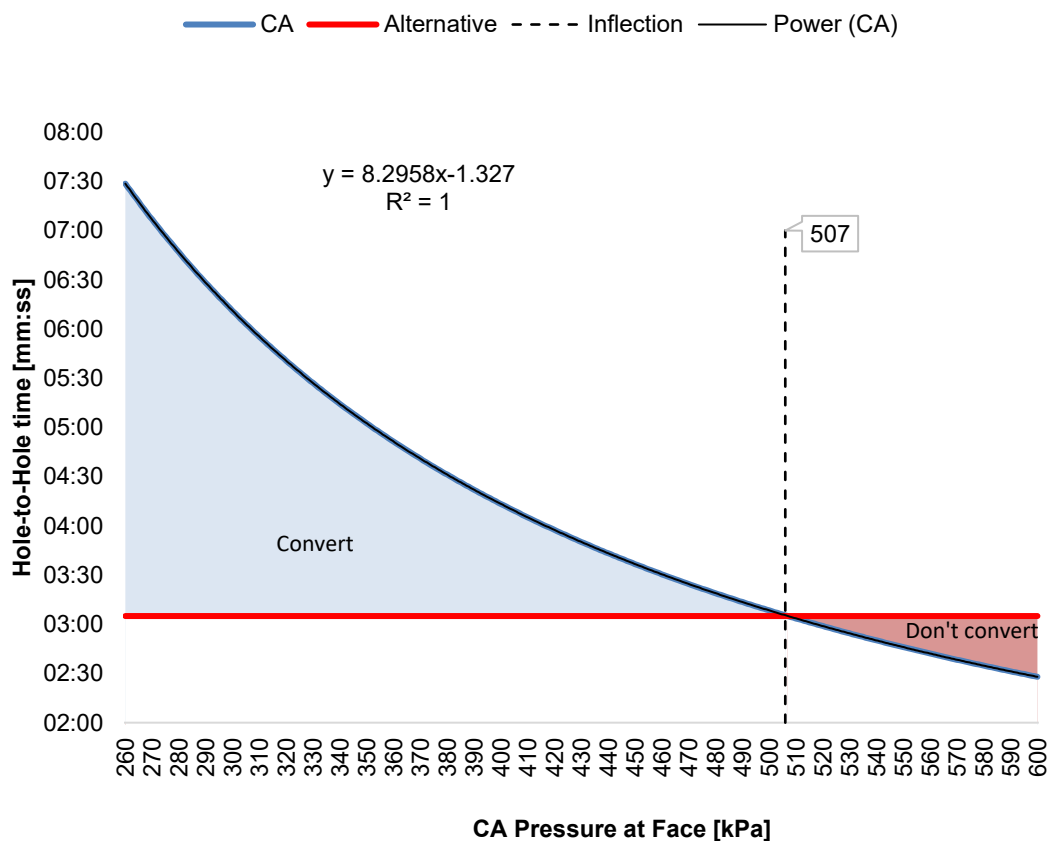
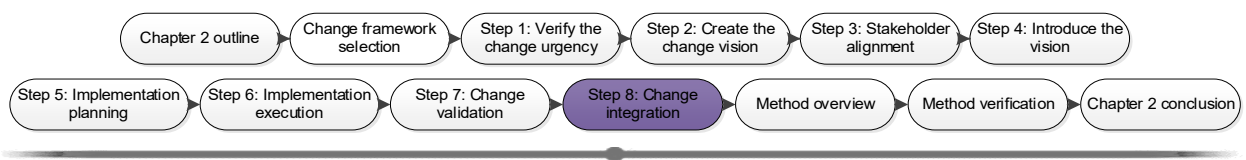


Figure 2-38: Site-specific performance curve

CPS pressure Step 6: Establish the roll-out plan

From the in-stope compressed air pressures, it must be determined how many crews should be converted. The data gathered for each of the mining sections is used to estimate the travel time,



entry examination, face preparation, and charge-up durations. The drilling activity duration is estimated using the in-stope pressures measured as well as Equation 3-1. Ultimately, the drilling activity duration is estimated using Equation 2-37. Thereafter, the crews are prioritised according to the shift time deficit to establish the roll-out plan as shown in Table 2-34. As expected, the crew with the longest travel time and lowest compressed air pressure is prioritised as the first crew to be converted, while the crew closest to the shaft with the highest pressure is the last to be converted.

$$Drilling_{activity\ duration} = CA_{drill\ rate} \times N_{holes} \quad \text{Equation 2-37}$$

where:

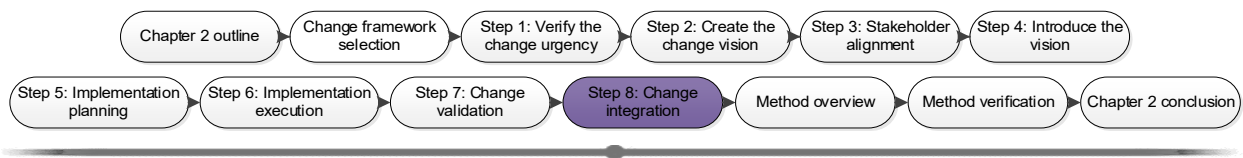
- $CA_{drill\ rate}$ – Compressed air drill rate as estimated from the performance curve [minutes]
- N_{holes} – Number of holes to be drilled [-]

Action 2: Sequentially expand the change process to the prioritised crews

The change process needs to be expanded to the remaining crews in accordance with the priority matrix that has been created. To achieve this end goal, a multi-layered sequential approach is used to implement the proposed method, whereby crews are converted to the alternative one by one. A detailed overview of the multi-layered approach is showcased in Figure 2-42. Once the change is integrated at the initial crew, a second layer is added to the overall change process and the change is adopted. The proposed change process is repeated until the ADT is adopted by all crews. To ensure that the change benefits materialise, a continuous improvement loop is introduced for each crew. The development of the continuous improvement strategy follows next.

Step 8.2: Develop a continuous performance improvement strategy

Challenges and setbacks during the change process are not a possibility but rather a certainty [5], [14]. Challenges, in any form, present critical obstacles that impede progress. These can be operational inefficiencies, a lack of resources, or internal resistance to change [6]. The difference between stakeholders who implement change successfully and those who fail lies in how they respond to challenges and setbacks. The lack of published continuous improvement strategies (CISs) to address challenges and setbacks during the implementation and integration of an ADT presents a critical shortcoming. As a result, a strategy needs to be developed to turn setbacks into strengths. An overview of the proposed strategy developed in this section is shown in Figure 2-41.



CIS Step 1: Implement the change and gather data

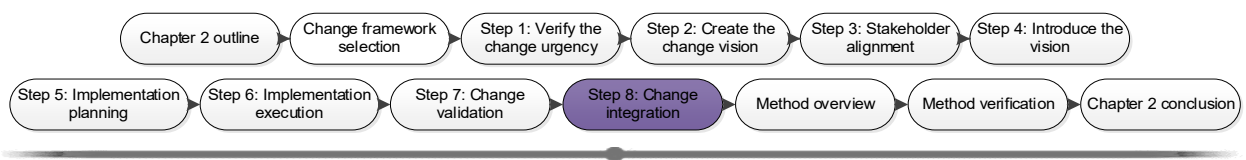
Step 1 of the proposed improvement strategy specifically focuses on gathering data after implementing the change. Any continuous improvement strategy relies on data to formulate change trends [193]. The faster an organisation can learn from change trends and integrate improvement initiatives into its approach, the greater its ability becomes to navigate change effectively [194]. That said, continuous improvement strategies generally initiate the improvement process through data gathering [195]. As a first step, a database needs to be established, and clear guidance is required on what data should be collected. Information describing the change results can be grouped into two value generating streams: business insight and process improvement.

Business insight data collection guidance: The study background ([Section 1.3](#)) highlighted that ADTs are mainly considered to counter production decay caused by the unavoidable inefficiencies associated with compressed air systems. As a result, the business insight will specifically refer to the production trends observed before and after implementation. The data required to formulate the production trends should be collected by an unbiased source, such as the mine's survey team. The percentage of calls achieved is proposed as the data point to normalise for variances in production dependencies, such as face length and stoping width.

Process improvement data collection guidance: Production data only provides insights into the production achieved. That said, data describing the drivers behind lost blasts needs to be collected to establish a database that guides process improvement. Data quality is crucial, as incorrectly logged reasons will lead mine management teams to commit to incorrect or less effective improvement initiatives. Consequently, the data collection strategy needs to include means to validate the reasons for logged lost blasts. Harmse *et al.* claimed that the South African mining industry is known for its lack of instrumentation in workplaces, thus making digital data gathering difficult [37]. Existing methods of collecting lost blast data mainly depend on claims made by shift managers and cannot be validated using data collected from alternative sources due to their unavailability.

To overcome this shortcoming, this study proposes combining the following data sources: (i) data logged by the shift managers, (ii) data logged by the OEM support team, and (iii) data logged by the alternative drilling systems. Data collection by the drilling system is achieved through a unique Internet of Things approach. While the use of data loggers to record operational data is not a new concept, integrating them with the ADT's PLCs is essential. This approach enables mining teams to collect daily datasets on the following operational parameters:

- **Operating hours:** This parameter indicates the total time the machine is switched on for the day and validates the overall time spent in the workplace. Once the crew arrives, the



machine is turned on for dust-allaying activities. It remains on for the remainder of the shift until the daily committed activities are completed.

- **Running hours:** As referenced in the literature provided earlier ([Section 1.4](#)), modern ADTs can supply energy based on end user demand. This means that the system will only pressurise itself if necessary and will enter an idle state when not in use. The running hour parameter provides timestamps that quantify the overall duration during which the system was pressurised. This parameter can be used to validate the activities completed for the day.
- **Energy consumption:** This parameter allows for the calculation of the corresponding water consumed. Furthermore, it provides insight into the overall energy intensity ratio.
- **Instantaneous water consumption:** Monitoring instantaneous water consumption provides valuable insights into which equipment was used for the day. This information can be used to validate the claims made by the shift managers. Additionally, the data enables mine management to calculate water intensity ratios. This provides valuable insight into the health of the equipment. Benchmarking the actual water consumption against the theoretical value will indicate the existence of water wastage [48].
- **Inlet water pressure:** This parameter quantifies the static and dynamic mine service water pressure at the pump's inlet. Inlet water pressure data can be used to validate lost blasts logged due to a shortage of mine service water.
- **Outlet water pressure:** Outlet water pressure provides insight into end user demand. Since ADTs use positive displacement pumps, the volume of motive energy medium supplied at a constant pressure is limited by the pumps' capacity. Once the end user demand exceeds the maximum volume, the pressure will drop below the required specification. That said, water outlet data provides valuable insights into end user demand. This data can be used to validate the existence of leaks in the system or additional equipment.
- **Supply voltage:** The supply voltage readings will provide insights to the failure of electrical components caused by over/under voltages.

Table 2-37 presents a summary of the operational parameters to be logged.

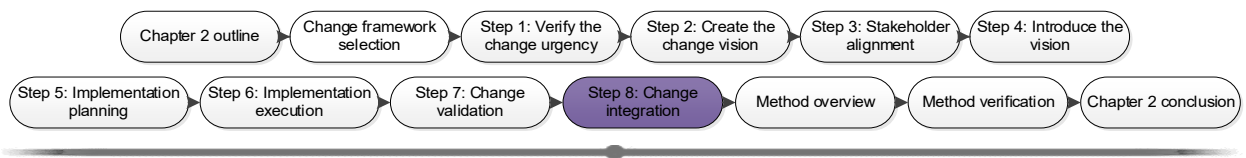


Table 2-37: Operational parameters to be logged

Operational parameter	Unit	Provides business insight to:
Operating hours	hours	Overall workplace shift duration
Running hours	hours	Activity duration
Energy consumption	kWh	- Amount of water consumed - Energy intensity ratio
Instantaneous water consumption	l/s	- Activity busy with at the time, such as drilling, sweepings, and support - Water intensity ratio
Inlet water pressure	kPa	Mine service water inlet pressure
Outlet water pressure	kPa	End user demand
Supply voltage	kV	- Over/under voltages - Power failures

CIS Step 2: Establish business insight

The data gathered in CIS Step 1 is used to develop the business insight curve. To establish business insight, a plot of the monthly production achieved versus the number of lost blasts per crew is proposed, as illustrated by Figure 2-39. The curve provides valuable business insights into production achieved, the number of lost blasts experienced by each crew, and is used to define the focus area for continuous improvement.

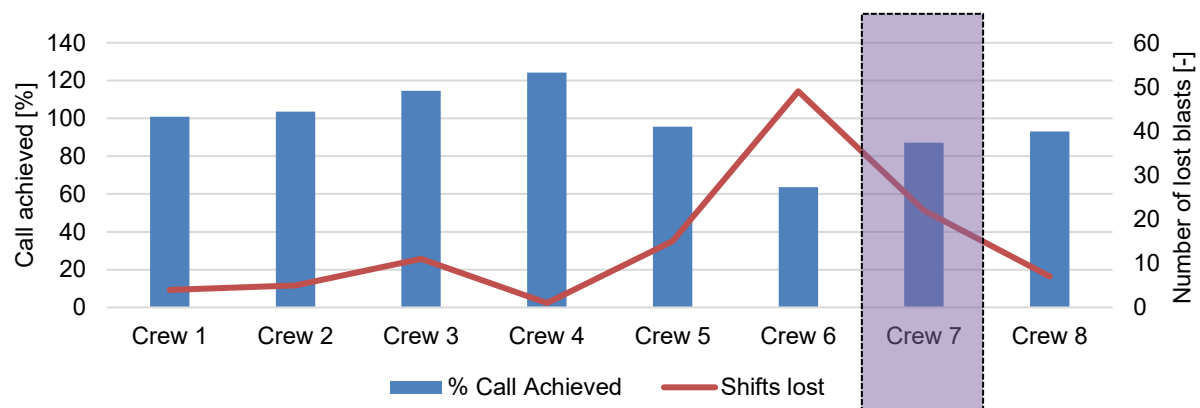


Figure 2-39: Business insight curve – Production achieved vs number of shifts lost

CIS – Step 3: Do a Pareto analysis

To illustrate the concept, from Figure 2-39, Crew 7 is identified as the crew in need of continuous improvement. Process optimisation of blasthole drilling involves three components: people, processes, and equipment. Consequently, a large number of contributing factors may account for the lost blast recorded.

Action 1: Develop the Pareto curve to identify the key process constraints

The need exists to filter through this large array of constraints to identify the vital few to focus on. A widely used principle to achieve this outcome is called the Pareto principle. The principle essentially states that around 80% of the overall impact of process constraints is caused by a small number of constraint types, termed the “vital few”, while the remaining 20% is driven by other constraint types, known as the “trivial many” [193]. Figure 2-40 illustrates the concept, where the number of lost blasts per constraint is shown on the primary y-axis. The overall Pareto impact, expressed as a percentage, is shown on the secondary y-axis. The x-axis shows the process constraints considered in the analysis. The black dotted line on the Pareto plot indicates that only three of the seven process constraints analysed account for 80% of the lost blasts. Therefore, these three are identified as the vital few and are analysed further to identify root causes and formulate improvement initiatives.

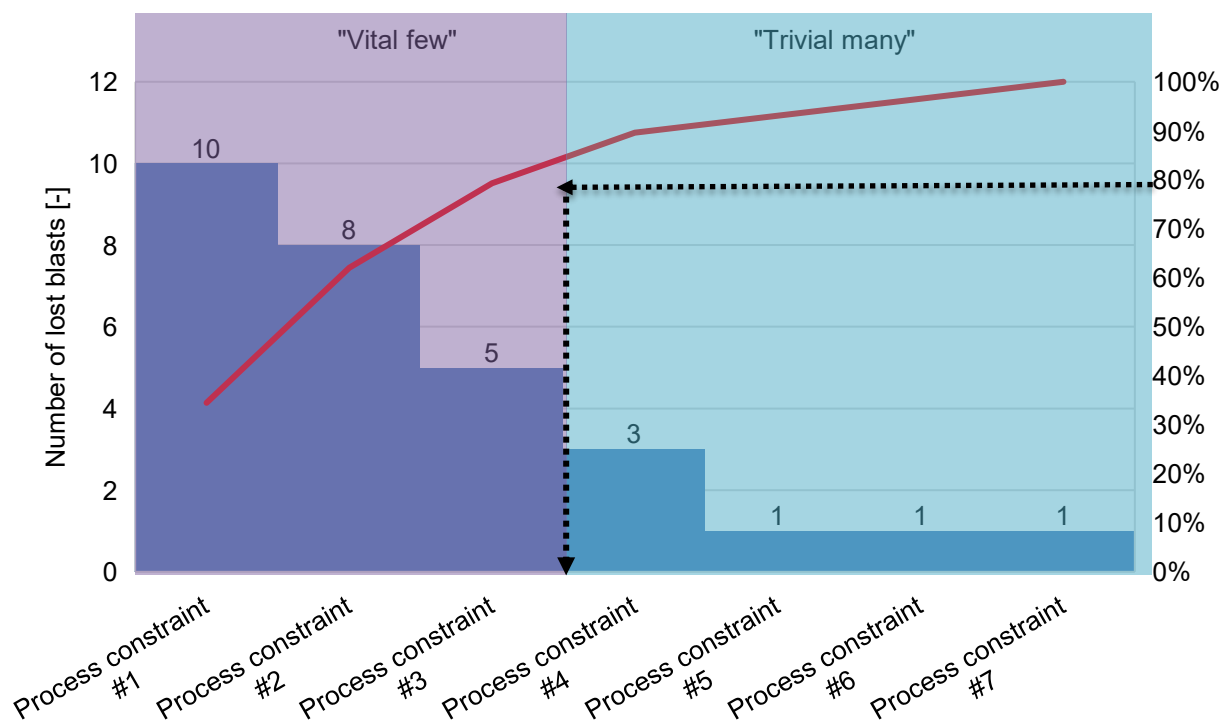
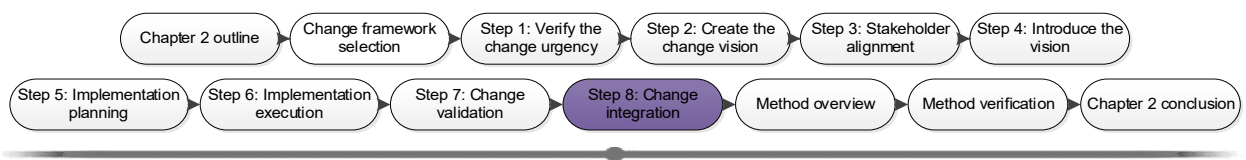


Figure 2-40: Practical application of a Pareto analysis

These key process constraints (KPCs) in the overall mining cycle are an area of research that has been extensively explored by previous researchers. The following researchers identified KPCs in the narrow reef gold mining cycle:

- KPC1: Cleaning [42], [196], [197].
- KPC2: Water [49], [148], [149], [198].
- KPC3: Electricity [36], [156].
- KPC4: Drilling equipment [14], [38], [61].



- KPC5: Labour [2], [121], [142].
- KPC6: Environmental temperatures [34], [47], [142], [152].
- KPC7: Safety stoppages [44], [199].

KPC1: Cleaning

Solomon and van Niekerk advocated in 1978 that improvements in drilling and blasting techniques would result in the cleaning cycle becoming the next process constraint in cyclic mining [200]. As a result, this KPC refers to lost blasts related to incomplete cleaning activity during the night shift.

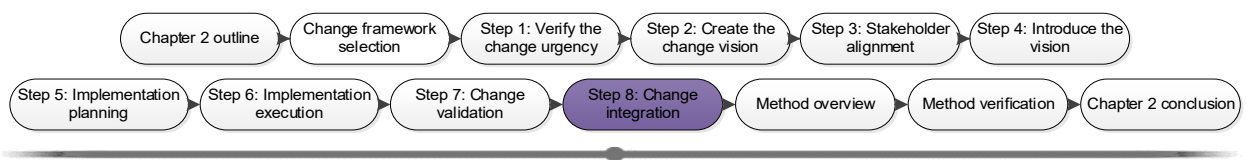
Root cause focus areas: The root cause focus area can either be related to equipment or time [42], [197]. Jacobs, who extensively studied failures in scraper winch systems, attributed equipment-related constraints to the failure of either winches and/or winch ropes [201]. Common root causes were found to be end-of-service-life failures or premature failures. On the contrary, the time-related focus area categories experienced lost blasts due to insufficient face time and/or ineffective cleaning processes. Insufficient face time refers to instances where crews simply do not have enough face time to clean the volume of ore generated through an effective cleaning process. Ineffective cleaning processes relate to instances where sufficient face time was available, but the crew failed to clean the face in the shift due to delays caused by process inefficiencies.

Recommendations to identify and address insufficient face time: Insufficient face time in deep-level gold mines was comprehensively studied by Rupprecht in 2003, who related the root cause to shaft schedule delays and/or ineffective personnel transportation means [196]. To identify remedial initiatives, mine management teams are advised to conduct logistic optimisation studies using digital simulation software. Methodological frameworks to perform such studies are provided by Fioroni *et al.* [202] and Greberg *et al.* [203].

Recommendations to identify and address inefficiencies in the cleaning process: Previous researchers recommended considering the following process inefficiencies in the cleaning cycle:

- Ineffective transportation processes [196], [204], [205],
- Insufficient ore movement capacity [12], [206],
- Defective scraper bucket runner and blades [197], [201], and
- Suboptimal fragmentation [16], [207], [208].

Inefficiencies in the transportation process can be identified and optimised through the guidance provided by Rupprecht [196], van Dyk [204], and Kendall and Gericke [12]. Ore movement capacity can be assessed and optimised by applying the method proposed by Rupprecht [197]. In contrast, Jacobs [201] recommended implementing a preventative maintenance strategy to address lost blasts due to defective scraper equipment. Suboptimal fragmentation refers to rocks



that are either too fine (particle size < 100 mm) or too large (particle size > 300 mm), and requires extra cleaning time [26], [207]. Mine management teams can refer to the methods presented by Tatiya and Al Ajmi [181], Chosi *et al.* [16], and Pearton [207] for fragmentation optimisation strategies. Best practices to consider when optimising a raise line for maximum ore hauling capacity are provided by Ragoonanthun [209].

KPC2: Water

Fraser [48] and Fourie *et al.* [66] highlighted the increased need for a reliable service water supply and dewatering network following the implementation of ADTs. This KPC focus area addresses lost blasts that may result from a shortage of service water or from flooding.

Root cause focus areas: The root cause focus area can be related to either supply or dewatering [149], [178]. Water supply-related lost blasts are caused by the network's insufficient supply capacity due to inadequate flow valve capacities, incorrect pipe sizes, and damaged infrastructure [149]. At the same time, dewatering-related lost blasts are generally caused by insufficient dewatering capacity due to insufficient storage capacity and insufficient pumping capacity [210].

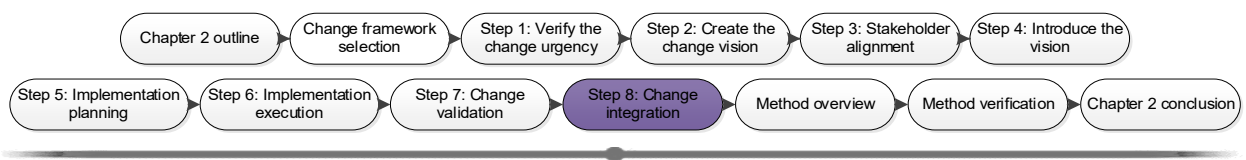
Recommendations to identify and address constraints in the mine's water network: Mine management teams are advised to reiterate the water network infrastructure evaluation methodology proposed by this study (refer to [Section 2.3, Step 5.2](#)) when the need arises to identify and address constraints in the mine's water network.

KPC3: Electricity

Fourie *et al.* [66] and Clement [70] advocated for the need for a reliable electrical supply network following the implementation of ADTs. This KPC focuses on lost blasts that may result from a shortage of electricity.

Root cause focus area: The root cause focus area is supply or damage related [149], [178]. The network's insufficient supply capacity causes electricity supply-related lost blasts due to either one or a combination of the following root causes: incorrect cable sizes, insufficient mini-sub supply capacity, and damaged infrastructure [154], [156].

Recommendations to identify and address constraints in the mine's electrical supply network: Similar to water, mine management teams are advised to reiterate the electrical network infrastructure evaluation methodology proposed by this study (refer to Chapter 2, Section 2.2.9, Step 5.2) when the need arises to identify and address constraints in the mine's electrical network.



KPC4: Drilling equipment

This KPC focus area addresses drilling equipment-related lost blasts. As highlighted in Section 1.4, a suite of drilling equipment comprises pressure generation units, rock drills, thrust legs, and ancillary devices. Failures experienced with any of these items may lead to lost blasts.

Root cause focus area: The root cause focus areas of these failures are mainly related to generated pressure and drilling and/or ancillary factors. Pressure generation unit failures to consider can either be mechanical (such as pumps or control valves) or electrical (such as motors or VSDs) [49], [62]. At the same time, drilling and ancillary-related failures specifically refer to rock drill-thrust leg assemblies, chainsaws, sweeping tools, and other ancillary equipment [14], [64]. Drilling equipment-related failure root causes can be classified as either end-of-service life or premature failures [12], [71].

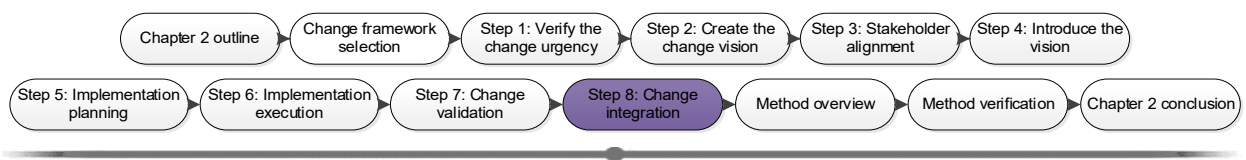
Recommendations to identify and address equipment reliability constraints: Jacobs, who studied the reliability of critical mining machinery, advocated using preventative maintenance strategies to enhance equipment reliability [201]. Jacobs advised mine management teams to first establish the MTBFs of the individual components. As a second step, equipment inventories are allocated accordingly to ensure that replacements are readily available.

KPC5: Labour

The underground workforce is generally considered the engine of the mine and is responsible for performing the physical activities required by the cyclic mining process [211]. When not at work, certain key activities, such as drilling and the operation of winches and locomotives, stand still, which frequently leads to lost blasts [2], [212]. Consequently, this KPC focuses on lost blasts caused by the unavailability of labour.

Root cause focus area: The two key root cause focus areas are related to absenteeism and complement. Absenteeism refers to health or desertion cases, where the required complement was allocated to the crew but some are not at work [211]. On the other hand, complement-related refers to instances where the crews are not resourced with sufficient people to perform the required tasks [121].

Recommendations to identify and address labour constraints: Labour health-related absenteeism and desertion are generally managed by the mine's human resources and health teams. Gouws [211] presented a detailed methodology to establish the real drivers behind labour absenteeism. Labour complement-related constraints can be resolved through robust labour planning [212]. Understanding the additional tasks required to operate the ADTs, as well as the actual daily actual number of employees on leave (sick and annual), will enable mining companies to plan labour accordingly.



KPC6: Environmental temperatures

Wet- and dry-bulb temperatures in the occupational environment are strictly governed by legislation. In South Africa, workers are required to withdraw from the workplace if the temperature exceeds 32.5 °C wet bulb or 37 °C dry bulb [152], [213]. The introduction of ADTs can add up to 0.6 °C per panel and lead to workplaces exceeding legal limits [27], [31], [49]. As a result, this KPC focuses on lost blasts due to undesirable workplace temperatures.

Root cause focus areas: The root cause focus area here can be related to either airflow or air temperature [214]. Flow-related lost blasts are generally caused by non-compliance with airflow requirements [31], [34]. In contrast, cooling-related lost blasts are driven by insufficient cooling provided to offset the actual heat load [214].

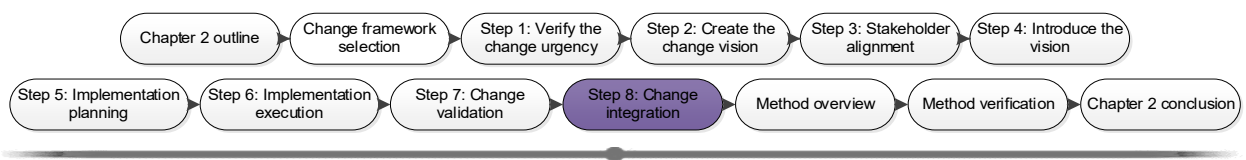
Recommendations to identify and address constraints in the mine's water network: Nell [214] provided a practical method for determining the heat load of deep-level gold mines. Mine management teams are advised to apply the method to estimate the amount of cooling to be provided. Insufficient flow scenarios can be addressed by ensuring that mine crews comply with critical ventilation controls in workplaces (such as centre line brattices and ventilation curtains on strike and dip). Mine ventilation networks can further be optimised using transient simulation models. Mine management teams are referred to the work completed by Fair, who presented a complete methodology to simulate integrated ventilation and cooling systems [34].

KPC7: Safety stoppages

Safety stoppages specifically refer to lost blasts caused by the incomplete or insufficient installation of support. From the cyclic mining process overview provided in [Section 1.2](#), recall that roof and sidewall support are installed to prevent the excavation from caving in [44], [199]. As a result, the mining process is halted once the support cycle falls behind. The implementation of ADTs is focused on improving face advance rates and, consequently, increases the rate at which support needs to be installed [71]. Failure to plan for and supply support material at the required rate will result in support-related lost blasts [215].

Root cause focus areas: The root cause focus area to be investigated is related to either incomplete or insufficient installation of support. Here, incomplete installation refers to cases where the crew failed to install the required support within the allowed shift time. Insufficient installation refers to instances where the support has been installed but not to the required standard.

Recommendations to identify and address support-related constraints: Best practices for material supply in deep-level gold mines were comprehensively established by Rupprecht in 2003, who linked the root cause to shaft schedule delays and/or ineffective transportation means [196]. To identify remedial initiatives, mine management teams are advised to perform logistic



optimisation studies using digital simulation software. Methodological frameworks to perform such studies are provided by Fioroni *et al.* [202] and Greberg *et al.* [203]. 4Sight™ is one of many industry partners that provide staff and material optimisation services using discrete event simulation software.

Action 2: Formulate and implement improvement initiatives

The first action guided mine management teams towards specific recommendations to identify and address the seven key process-related constraints, as identified from the literature. The second action requires mine management teams to formulate improvement initiatives based on the recommendations provided. Once formulated, the continuous improvement methodology guides mine management teams back to Step 1 to implement the improvement initiatives formulated. Once implemented, results will be available, and the continuous improvement strategy will be applied for a second iteration. It is important to note that continuous improvement is not just a one-time act but rather a cycle [216].

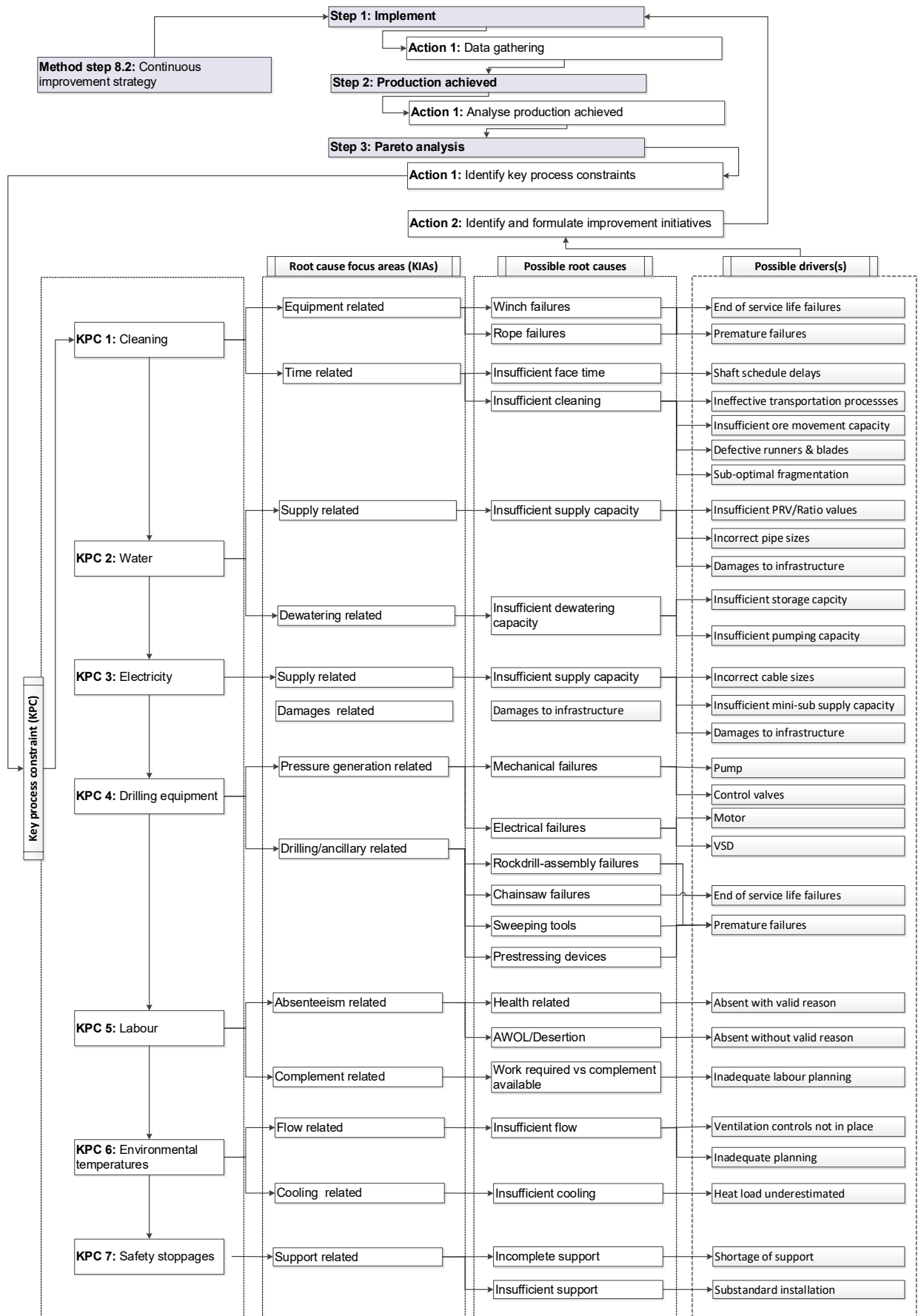
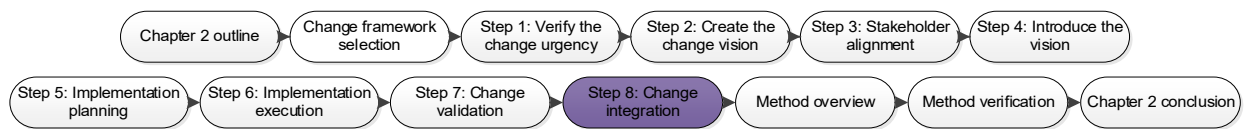
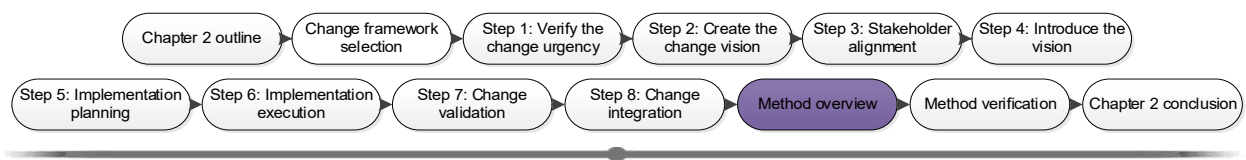


Figure 2-41: Study proposed continuous improvement plan



2.7. Overall method overview

An overview of the overall implementation and change management methodology developed in this chapter is illustrated in Figure 2-42. Eighteen key failure drivers were identified from the literature review on past failures to introduce new technology into narrow reef gold and platinum mines. The study objectives were formulated in Table 1-5 to resolve these failure drivers. The study objectives were used in this chapter as guidelines to develop corresponding strategies to address the failure drivers.

A multi-layered sequential approach to implementing the change is proposed by this study. The first layer is used to validate the benefits of the change on a small scale. Once the change benefits are confirmed to have materialised, additional layers are introduced and used to integrate the change with the remaining crews. The transformation process of each layer consists of the following four phases:

- Phase 1 – Change initialisation,
- Phase 2 – Change implementation,
- Phase 3 – Change benefit validation, and
- Phase 4 – Change integration.

Kotter's eight change steps were used as the change framework to facilitate the actions required to implement the change. Each step consists of various strategies, and an overview of each step and its corresponding processes is highlighted in Figure 2-42.

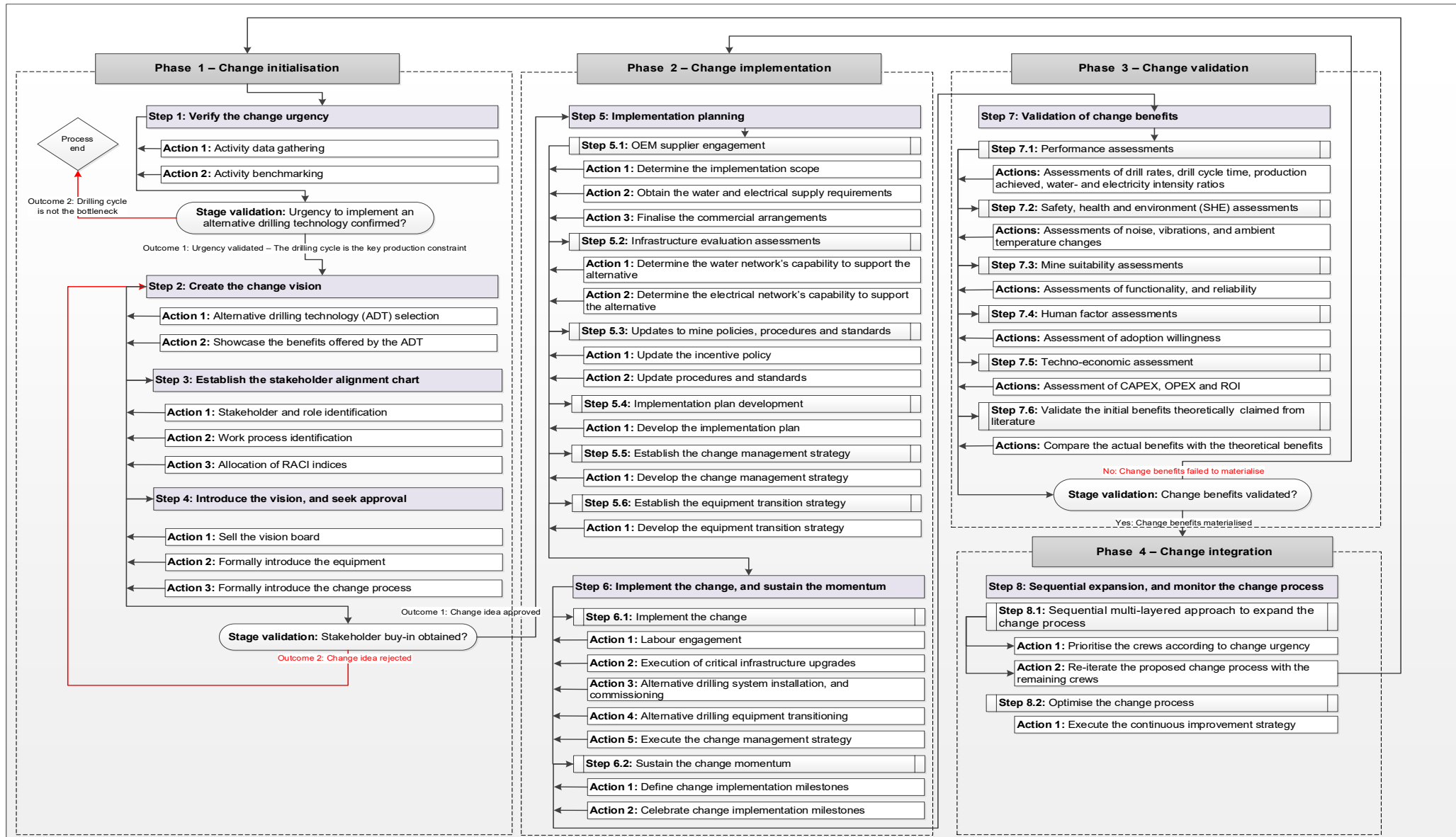
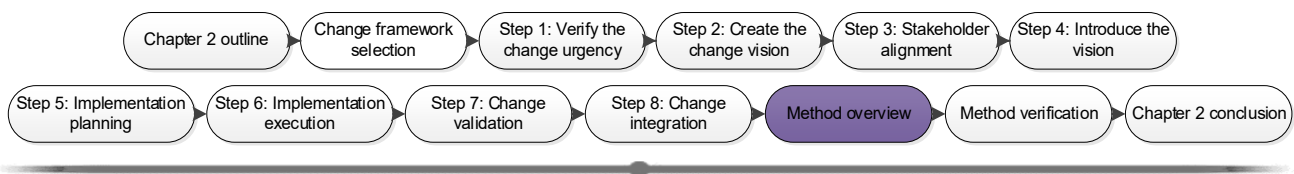


Figure 2-42: Complete overview of the study-proposed implementation and change management method for implementing alternative handheld drilling systems



Phase 1: Change initialisation

The change process is initiated during Phase 1 when the mine management team implements the first four of Kotter's steps (Steps 1 to 4).

- As a first step, the urgency of change is verified to confirm that the drilling cycle is indeed the main production bottleneck. As a result, the need for an ADT is confirmed.
- Step 2 focuses on selecting the most suitable ADT based on the site-specific operational parameters. A vision is created to provoke stakeholder buy-in by creatively promoting the benefits of the selected ADT.
- To promote stakeholder participation, alignment, and accountability, a responsibility chart (RACI matrix) is developed to clearly define the roles and responsibilities of the multi-disciplinary team accountable for the change process (Step 3).
- The vision is introduced to all stakeholders in Step 4 and used to seek implementation approval.

The detailed strategies for executing Steps 1 to 4 were defined in [Section 2.3](#).

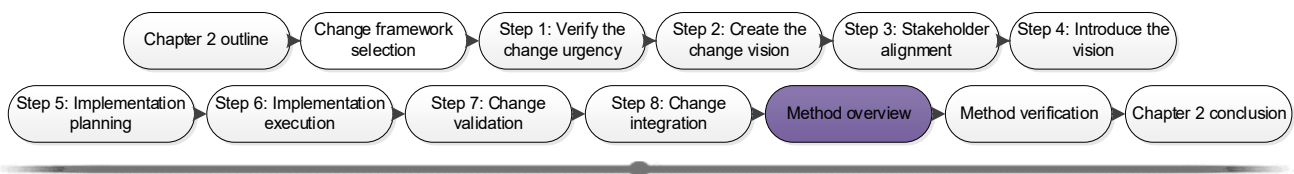
Stage validation: Stakeholder approval

Execution of the first four steps leads to the first gateway, known as stakeholder approval. This gateway was integrated into the method to ascertain stakeholder alignment and buy-in. There are two outcomes:

- **Outcome 1:** If the stakeholders reject the proposed alternative, it indicates that the vision failed to convey its benefits. Consequently, the methodology guides the mine management team to revise the vision and repeat Steps 2 to 4.
- **Outcome 2:** The change vision succeeded in convincing the stakeholders that the benefits of the proposed ADT outweigh their current situation and gained support for implementing the alternative solution. This is the desired outcome, as it ensures stakeholder participation and accountability during the implementation phase.

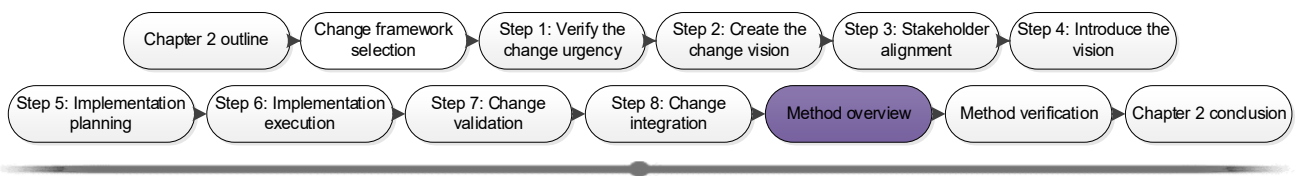
Phase 2: Change implementation

In this phase, the mine management team utilises Kotter's fifth and sixth steps to enable all the actions required to implement the alternative solution. Six critical actions are required to foster this outcome:



- **Step 5.1: OEM supplier engagement** – To select the best-fit-for-purpose system configuration based on the operation’s implementation scope.
- **Step 5.2: Infrastructure evaluation assessments** – Support services (water and electricity) may require critical upgrades to support the alternative. Due diligence in performing a support system capability assessment ensures that remedial actions for system restrictions are proactively planned and implemented.
- **Step 5.3: Updates to policies, procedures and standards** – The introduction of an alternative drilling system will require updates to mine policies, procedures, and standards. This step provides strategic guidance to identify all affected areas and the updates required.
- **Step 5.4: Implementation plan establishment** – Shock waves associated with change need to be managed adequately, as highlighted in [Section 2.3, Step 5.4](#). Consequently, a comprehensive transition strategy must be developed to ensure that shock wave amplitudes are kept to a minimum.
- **Step 5.5: Change management strategy** – Any change process requires stakeholders to first unlearn old, comfortable habits and then adopt new mindsets. The change management plan contains an array of strategies used to identify and manage any forms of humanistic and/or systemic change resistance.
- **Step 5.6: Transition strategy** – The greatest risk of financial loss lies within the equipment transition phase, where end users switch from the old drilling system to the new one. The equipment transition strategy proposes a unique sequential approach to introduce the new equipment while minimising production disturbances.

At this point in the transformation process, the Kübler-Ross curve predicts that stakeholder morale will be at its lowest. A practical approach is proposed to boost morale and sustain implementation momentum. The method incorporates Kotter’s sixth step to achieve this by creating and celebrating short-term wins. The strategies developed under Step 6 are used to enable two strategic outcomes: implementation execution and sustaining the change momentum. An experimental approach is proposed whereby the change is first validated on a small scale before committing to large-scale roll-outs.



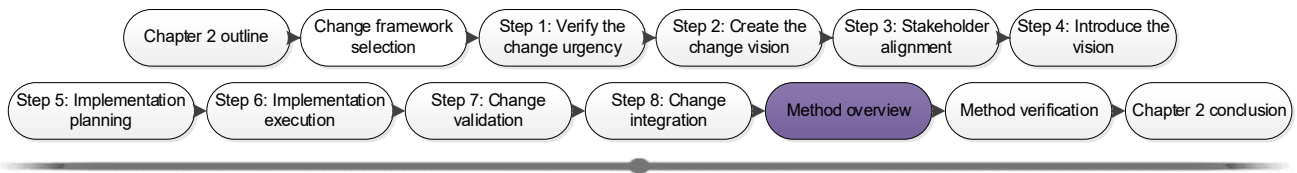
Phase 3: Change validation

The overarching objective of the change validation phase is to check, check, and recheck to ensure that the envisioned benefits presented to the stakeholders in Step 4 materialise. The validation step analyses and confirms whether the alternative fulfils the need to perform as a replacement for its pneumatic counterpart. Kotter's seventh step is used to influence this outcome in the small-scale experiment. Five key focus areas affected by the introduction of an ADT were identified in [Section 1.4](#), and the following assessment strategies must be executed to validate the change benefits:

- **Step 7.1: Performance** – This specific assessment is focused on understanding the impact that the ADTs has on drilling performance, production, and utilities.
- **Step 7.2: SHE** – An adverse impact on SHE during and after implementation should be avoided at all costs. The purpose of this assessment is to identify and evaluate any detrimental effects in terms of noise, vibration, heat, visibility, and exposure time.
- **Step 7.3: Mine suitability assessment** – [Section 1.7](#) revealed that technology fails when the equipment is unreliable or dysfunctional in the harsh underground stoping environment. This assessment focuses on evaluating the reliability and functionality of the alternative.
- **Step 7.4: Human factors** that may create resistance to change are a significant risk to adoption. This interactive practical assessment ensures the early identification of these factors.
- **Step 7.5: Techno-economics** – A techno-economic assessment is required to systematically analyse the economic performance of the implemented technology.
- **Step 7.6: Results benchmarking assessment** – Finally, this assessment checks to confirm whether the theoretical benefits envisioned during the change initiation phase materialised. This is done by benchmarking the actual results obtained through the aforementioned five assessments against the theoretical claims made by the change vision.

Stage validation: Resistance to adoption detection

The benchmarked results will guide the change implementation team to the second gateway to confirm whether the change benefits were successfully validated. Two cases exist:



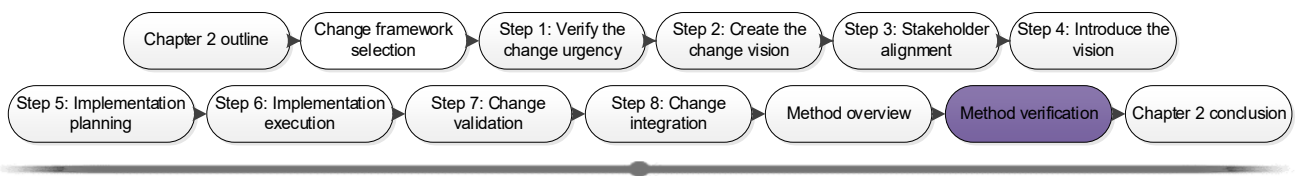
- **Outcome 1:** The change benefits failed to materialise, and resistance to adopting the alternative was detected. The method then guides the mine management team to revise the approach by reiterating Steps 2 to 7.
- **Outcome 2:** The actual change benefits correlate well with the theoretical estimates and were successfully validated. The change was successfully proven on a small scale, and the transformation effort can now be integrated sequentially with the remaining crew in Phase 4.

Phase 4 – Change integration

At this point in the transformation process, the ADT has been validated as a suitable replacement. Sequential change integration is needed to replicate transformation efforts for the remaining crews. Kotter's last step (Step 8) is implemented to achieve this by executing the following two processes:

- **S8.1: Sequentially expand the transformation effort to the remaining crews.** The purpose of this procedure is to apply the transformation effort to these crews. This is achieved by reapplying CMP1 through CMP4 until all the crews are converted. Change shock waves are minimised by implementing a sequential expansion effort, converting crews one by one.
- **S8.2: Optimise the change process** – Crews are most likely to revert to their old habits if continuous monitoring is not provided to reinforce the change benefits. The proposed continuous improvement strategy ensures that the benefits materialise during large-scale roll-outs. The improvement strategy is focused on analysing change benefits, identifying process constraints, and implementing improvement initiatives.

Transformation efforts frequently fail when the change process is treated as a linear process with a definite start and end date. The method proposed by this study encourages the exact opposite mindset, describing the change approach as a multi-layered, non-linear, sequential process that requires continuous monitoring.



2.8. Method verification

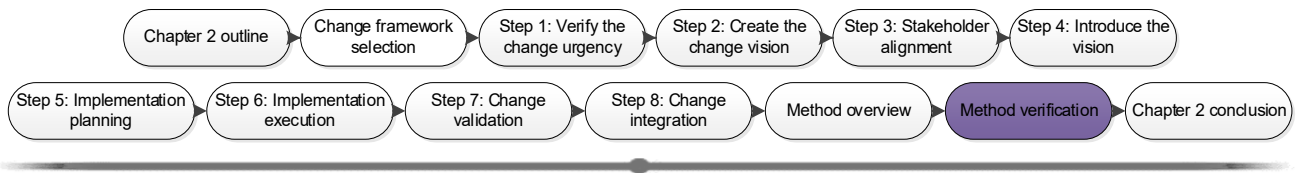
Verification in terms of inspections and reviews is required to ensure that the necessary building blocks were incorporated into the developed method to successfully address the study's needs when implemented [148].

Eighteen critical objectives were defined in [Section 1.8](#) and used to guide the development of the method to achieve this outcome. These objectives were derived from the failure causes associated with the failure of past initiatives to introduce new technology in South African gold mines, as listed in

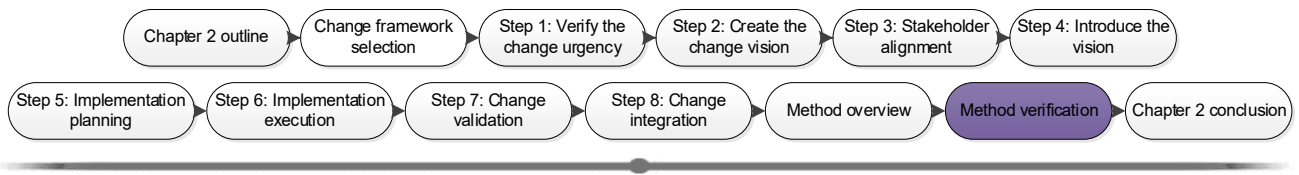
Table 2-38. The table summarises the outcome of the verification inspection to ensure that the method includes the required strategies to address each failure driver. Each objective set to address the corresponding failure driver was included in the method. The method reference column provides a reference to the respective portfolio of evidence.

Table 2-38: Method and objective overview

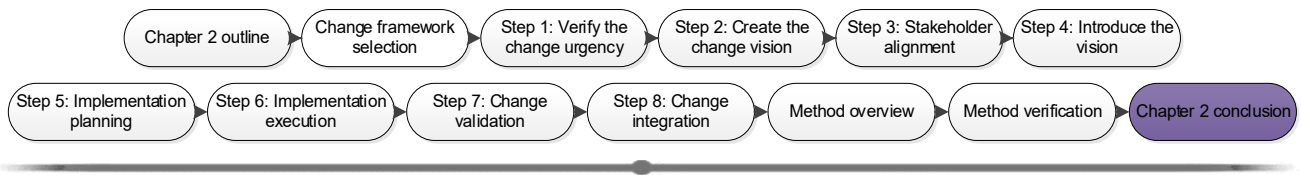
Failure driver	No.	Method objectives	Objective addressed?	Method reference
HRD1: Passive leadership style	1	- Promote an active leadership style.	✓	Step 3
HRD2: False perceptions	2	- Rectify misperceptions by means of factual information.	✓	Step 3
HRD3: Change unwillingness	3	- Promote change willingness by ensuring the need for change is clear to all stakeholders.	✓	Step 3
HRD4: Emotional wellness	4	- Promote emotional wellness.	✓	Step 3 Step 8
SFD1: Lack of urgency	5	- Establish a definite sense of urgency.	✓	Step 1 Step 3
SFD2: Unclear vision of benefits	6	- Highlight the change benefits to all stakeholders.	✓	Step 2
SFD3: Exclusion of critical role players	7	- Perform a conscientious stakeholder analysis to identify all role players.	✓	Step 3
SFD4: Incorrect initial end user and/or workplace selection	8	- Provide clear strategic guidance to end user selection.	✓	Step 3 Step 5.



Failure driver	No.	Method objectives	Objective addressed?	Method reference
SFD5: Lack of stakeholder participation and accountability	9	- Define and track stakeholder roles and responsibilities.	✓	Step 3 Step 4 Step 5
SFD6: Incorrect selection of alternative technology	10	- Provide alternative technology selection guidance based on the operations' geotechnical environment.	✓	Step 2 Step 5 Step 7
SFD7: No updates to policies and procedures	11	- Highlight critical change updates to policies and procedures	✓	Step 5
SFD8: Change support from senior management	12	- Provide change support guidance to senior management.	✓	Step 6 step 7
SFD9: Stakeholder misalignment	13	- Provide a strategy to align stakeholders and maintain alignment.	✓	Step 4
SFD10: Transition strategy	14	- Ensure adequate transfer of knowledge, skill, policies, and procedures during the training phase. - Provide a transition (implementation) strategy.	✓	Step 3 Step 5
SFD11: Technology support systems	15	- Assess and integrate technology support systems.	✓	Step 3 Step 5
SFD12: Technology readiness	16	- Provide a strategy to assess the technologies' fit-for-purpose to operate as replacement. - Technology must be fully functional, simple and reliable with little/no changes required. Mature technologies are preferable.	✓	Step 7
SFD13: Vision/benefits did not materialise	17	- Provide a strategy to continuously monitor change benefits as highlighted by means of the vision.	✓	Step 5 Step 7



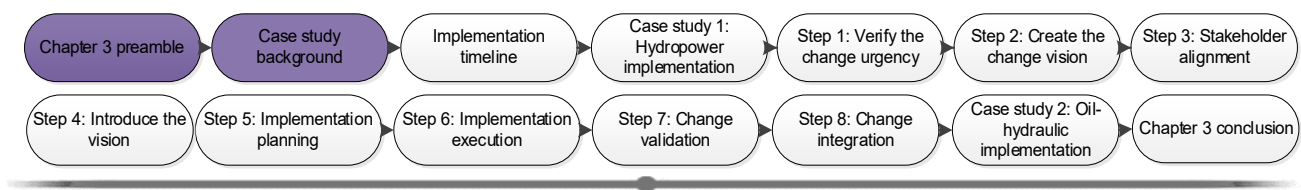
Failure driver	No.	Method objectives	Objective addressed?	Method reference
SFD14: Shock waves caused by excessive change	18	- Consist of a progressive and gradual approach to introduce the change.	✓	Step 3 Step 5 Step 8



2.9. Chapter conclusion

Chapter 2 focused on developing a new implementation and change management methodology. The development process was initiated by selecting the most suitable change framework. Strategies were formulated to address the 18 failure drivers identified, using Kotter's change theory, the PDCA cycle, and the Kübler-Ross change curve.

To confirm the usefulness of the developed method, it will be subjected to a real-world case study implementation in the next chapter.



3. METHOD VALIDATION THROUGH CASE STUDY IMPLEMENTATION

3.1. Preamble

An effective way to refine a strategy is through real-world application, as it allows for assumptions to be tested and the strategy to be adapted to actual conditions that theory alone could not fully predict. This chapter presents the implementation and refinement of the proposed method through a real-world case study.

Strategic execution is a key milestone in the change process, where the strategy either succeeds or fails. Successful execution requires discipline, adaptability, resource management, and a relentless commitment to progress. The purpose-driven chapter focuses on validating the method developed and verified in Chapter 2. The verification process confirmed that all strategies required to meet the study objectives were incorporated into the method. A validation process is needed to assess whether the method addresses the overall study needs and objectives, as identified in Chapter 1, [Section 1.8](#).

To achieve this outcome, the method was used to implement and integrate ADTs into a mature compressed air-driven gold mine.

3.2. Case study mine background

The CSM is located on the southern edge of the Witwatersrand Basin. It is classified as a mature operation, having commenced shaft sinking in 1986 and having been in production ever since. The operation utilises the conventional narrow reef mining method to extract the Beatrix Reef, which varies in thickness from 0.15 m to 3.0 m. Compressed air has always been used as the primary energy source. A complement of 1 800 labourers is present at the mine, and the operation hosts 27 stopping crews.

The operational layout is complex, with three shaft systems present, as illustrated in Figure 3-1. One shaft (1#) is located on the northern side of the mine and is surrounded by the production block. This specific shaft is only used as the ventilation downcast shaft and for slinging material. Three (3#) and four (4#) shafts are located 2.7 km to the south of 1#. Crew and material are conveyed using 3#, whereas 4# serves as the ventilation upcast shaft. Adding to the complexity is the fact that the compressor is located on the surface at 1# and produces compressed air at 570 kPa. Since 1# was never equipped, compressed air is reticulated on the surface for 2.7 km to underground via 3#. Subsequently, the pipe network spans roughly 14 km from the surface to the underground workings, and line inefficiencies are immense.

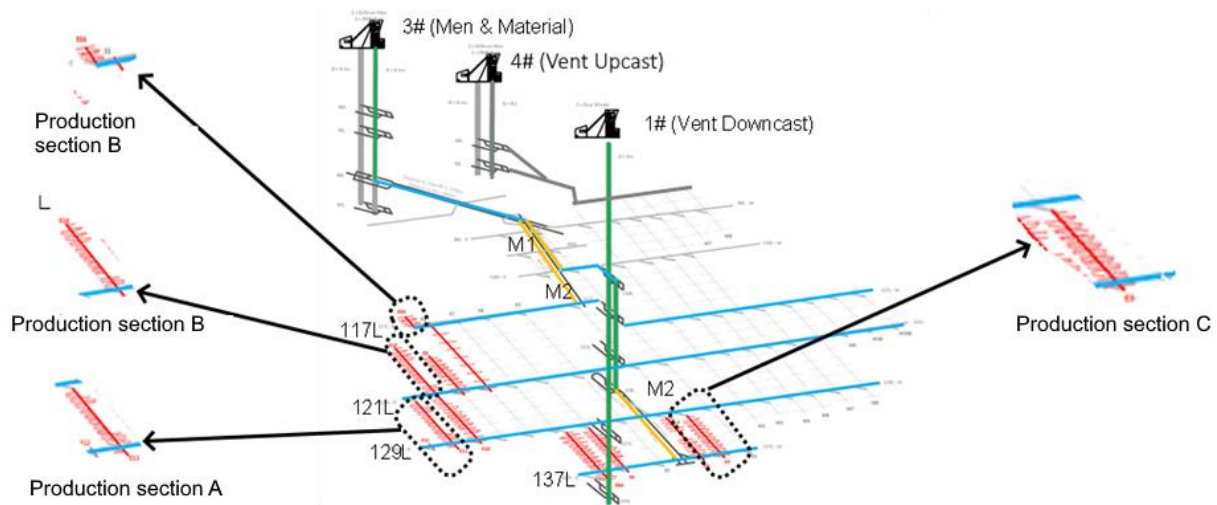
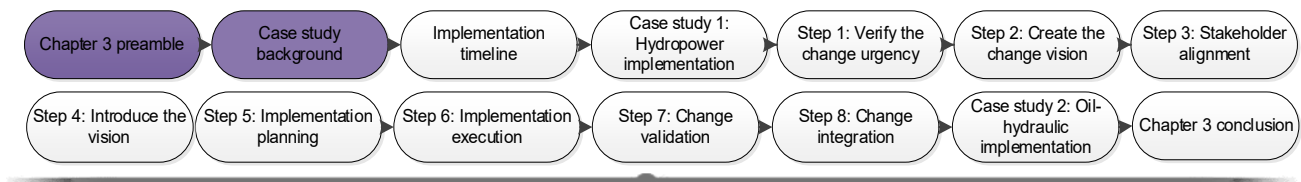


Figure 3-1: CSM layout

The supply pressure in the stopes was found to be as low as 220 kPa in some production sections, resulting in notable production losses, as illustrated in Figure 3-2. The graph shows the operations production achievement for the financial year 2020 (FY20), expressed as a percentage of the annual call achieved. A 18% shortfall is noted, and the operation indicated that it was mainly due to incomplete blastholes drilling caused by low compressed air pressure. It was also established that the average stoping width would increase from 1.3 m to 1.8 m over the following three years. This increase in stoping width required a new blast design, in which three lines of holes had to be drilled, compared to two. This highlighted the requirement for additional blastholes. As a result, the operation claimed to be in dire need of an alternative in-stope drilling energy source, which was fully compatible with this study.

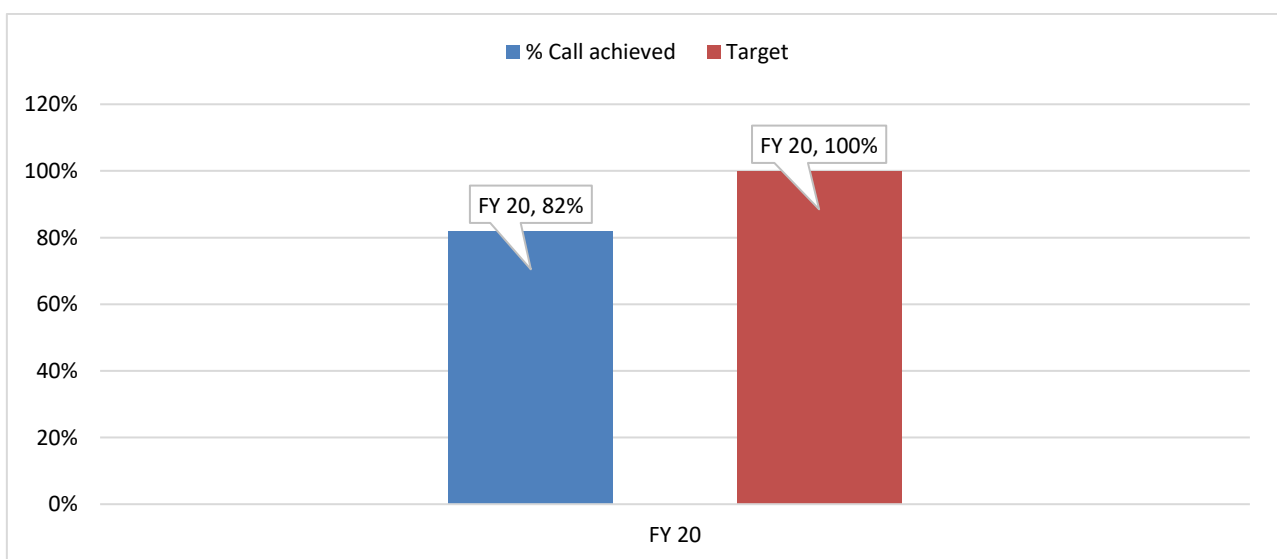
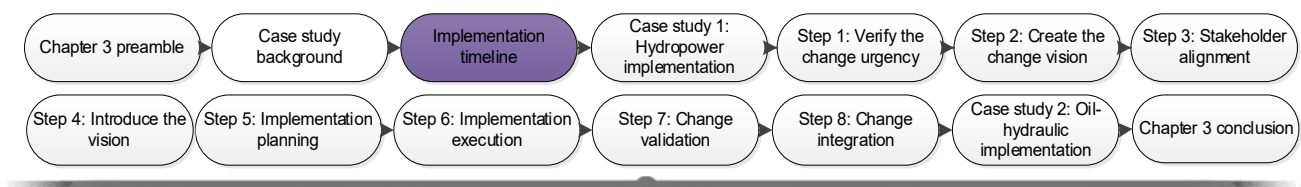


Figure 3-2: CSM – Production call achieved vs the production target



3.3. Implementation timeline

The method proposed by this study was validated using two case studies. The first case study reports the successful implementation of hydropower as an alternative energy source. On the contrary, the second case study presents an overview of the unsuccessful implementation of an oil-hydraulic alternative solution.

The implementation timeline is depicted in Figure 3-3. The selection methodology prioritised the oil-hydraulic system as the best fit-for-purpose alternative (see [Step 2](#)), and implementation commenced in August 2020.

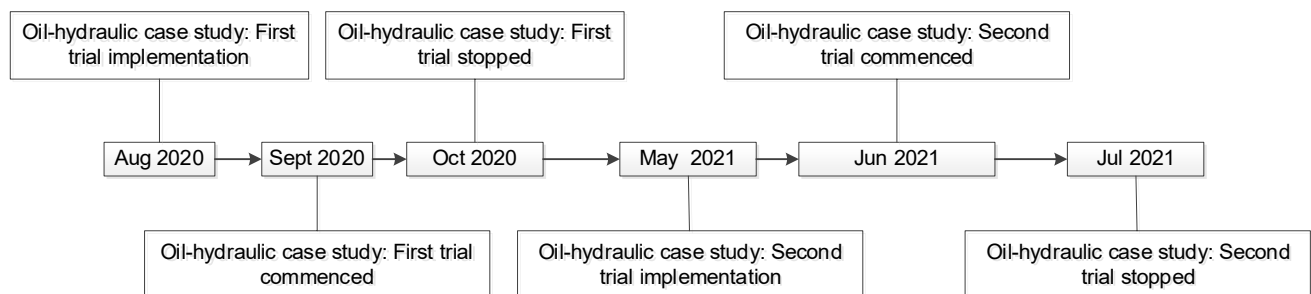


Figure 3-3: Oil-hydraulic alternative implementation timeline

The selection methodology prioritised hydropower as the second-best fit-for-purpose alternative, and hydropower was implemented according to the implementation timeline shown in Figure 3-4. Implementation commenced in April 2023, and the last crew was converted in January 2025. The benefits tracking period ended in July 2025. The successful introduction and adoption of hydropower is discussed next.

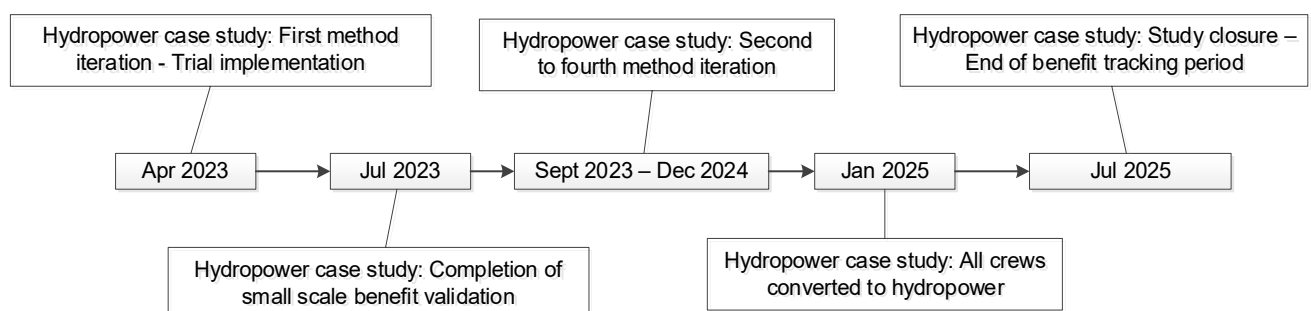
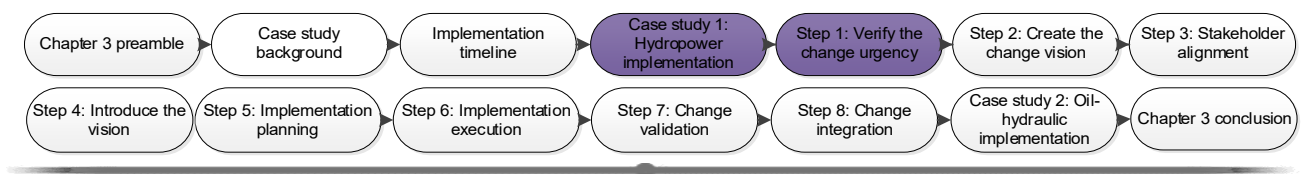


Figure 3-4: Water-hydraulic alternative implementation timeline



3.4. Case study 1: Implementation of hydropower drilling technologies

This section provides a detailed overview of the method used to implement hydropower as an ADT at the CSM.

Phase 1: Change initialisation

The overall objective of the first phase was to initiate the change process. The first four steps of the proposed method were used to influence this outcome, namely: Step 1: Verify the change urgency, Step 2: Create a change vision, Step 3: Develop a strategy to manage stakeholder resistance to change, and Step 4: Communicate the change vision.

Step 1: Verify the change urgency

As a first process, the sense of urgency to implement ADT was verified using Step 1. This was done by executing the following two actions as defined in Figure 2-4:

Action 1: Gather activity data

Mining process activity data were collected through underground time studies conducted over a two-week period, following the prescribed study methodology.

Action 2: Benchmark activity

Figure 3-5 shows the benchmark comparison results. The inner ring represents the theoretical baseline time required to complete each activity. The outer ring illustrates the actual time taken.

The following curtail observations were noted from the benchmarking results illustrated in Figure 3-5:

- (1) Travel time (1, 7, and 10), entry examination and face preparation (2 and 8), charging (4), blast and re-entry (6) were found to be on par with the theoretical benchmark.**

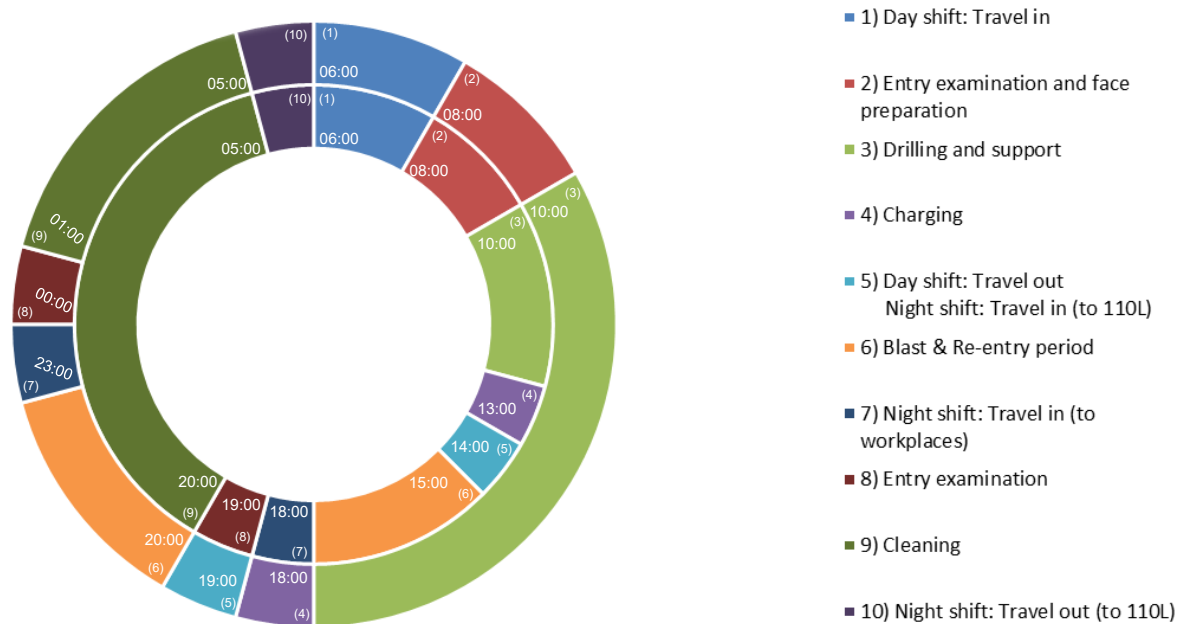
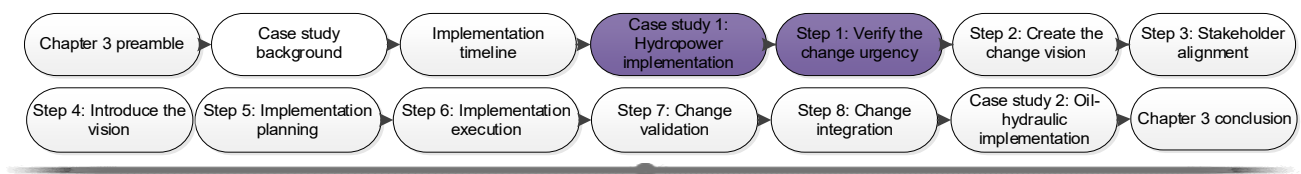
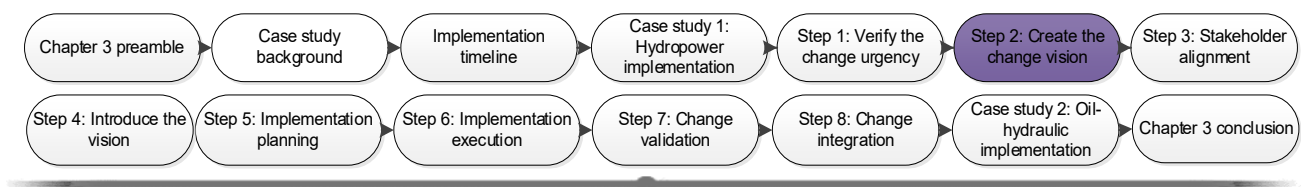


Figure 3-5: Theoretical vs actual shift cycle components

(2) Drilling and support (3): The actual drilling and support cycle was 5 hours longer due to the following contributing factors:

- The in-stope air pressure was measured at 270 kPa, resulting in an eight-hour duration to complete the drilling activity. The theoretical calculation at 400 kPa indicated a three-hour requirement, as per Equation B-3.
- It was observed that the RDOs stayed beyond the eight-hour shift requirement to complete the drilling cycle. Face drilling was therefore identified as the primary bottleneck.
- Only the face drilling time was used as a benchmark parameter since gully drilling occurred in parallel and concluded before the face drilling component.
- Low compressed air pressure resulted in slow cutting rates and reduced the elongate installation rate to only 3 units/hour, which is only 50% of what is needed to complete the supporting cycle (Equation B-4). Consequently, the support installation required two shifts to complete, which was classified as a downstream impact arising from the drilling constraint at Point 1.

(3) Cleaning: Ultimately, the actual mining cycle was extended by five hours, leaving only four hours to clean the panels. The theoretical calculation revealed that at least 5.2 hours were required to effectively remove the volume of ore daily (as per Equation B-6). This frequently resulted in lost blasts the following day, as the drilling shift had to clean the face before the drilling activity could commence. Since only four hours were available, the cleaning cycle was identified as an additional downstream impact of slow drilling.



(4) Shift cycle times: The actual morning shift cycle time was 14 hours compared to the nine-hour theoretical benchmark. This resulted in severe fatigue among the workforce. The RDOs admitted to having an internal rotating arrangement to manage fatigue, where one of the five operators was allowed to be absent once a week, which increased absenteeism¹⁵.

Summary – Step 1: Verify the change urgency

Step 1 aimed to verify the urgency of the change for an ADT. This outcome was successfully influenced by the proposed strategies in Step 1. The activity benchmarking strategy identified the drilling shift as the main bottleneck, due to a five-hour increase in shift time caused by low compressed air pressure. The downstream impact on the support and cleaning cycle was also noted. As a result, the urgency to implement an alternative drilling method was successfully validated, and the strategic objective of Step 1 was met.

Step 2: Create the change vision

Step 2 aimed to create a change vision that comprehensively showcased the change benefits and business case to all stakeholders. Intentional focus was placed on providing a clear answer to the stakeholders' instinctive question: "What is in it for me?" Two actions, Action 1: Select the alternative, and Action 2 – Showcase the benefits, were required to demonstrate the benefits.

Action 1: Select the alternative

The study proposed the ADT selection methodology formulated in [Section 2.3 – Step 3](#), which was used to identify and prioritise the available alternative technologies from best to least fit-for-purpose according to the CSM's operational requirements.

ADT Selection Step 1: Establish the selection criteria

The selection criteria established and proposed by this study include: (C1) technical compatibility, (C2) reliability, (C3) cost, (C4) ergonomic compatibility, and (C5) performance.

ADT Selection Step 2: Determine the selection criteria weights

The Saaty fundamental scale was used to conduct pairwise comparisons among the five selection criteria [132]. Table 3-1 shows the result of the pairwise comparison.

¹⁵ Oxford learners dictionary (n.d.). Absenteeism definition. Retrieved June 6, 2026, from <https://www.oxfordlearnersdictionaries.com/definition/english/absenteeism>

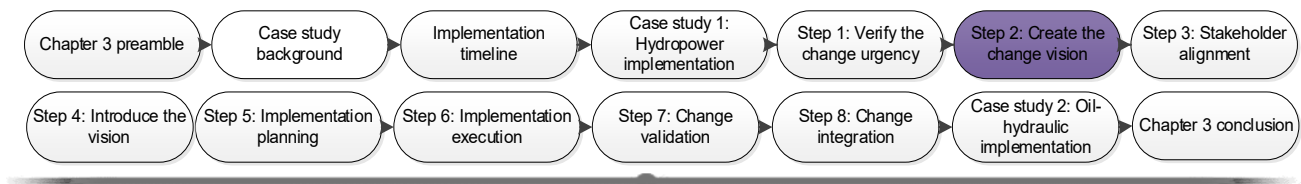


Table 3-1: Pairwise comparison of selection criteria

	C1: Technical compatibility	C2: Reliability	C3: Cost	C4: Ergonomic compatibility	C5: Performance
C1: Technical compatibility	1.00	6.00	7.00	9.00	5.00
C2: Reliability	0.17	1.00	1.00	2.00	0.33
C3: Cost	0.14	1.00	1.00	3.00	0.50
C4: Ergonomic compatibility	0.11	0.50	0.33	1.00	0.50
C5: Performance	0.20	3.00	2.00	2.00	1.00
Total	1.62	11.50	11.33	17.00	7.33

The pairwise comparison was normalised, and the weight of each criterion was established using Equation 2-2. Table 3-2 shows that technical compatibility carried the most weight, while ergonomic compatibility carried the least. These weights aligned with the expectations of mine management, as they argued that technical compatibility poses the greatest risk to selecting an inappropriate ADT.

Table 3-2: Normalised pairwise comparison with criteria weight

	C1: Technical compatibility	C2: Reliability	C3: Cost	C4: Ergonomic compatibility	C5: Performance	Weight
C1: Technical compatibility	0.62	0.52	0.62	0.53	0.68	59.4%
C2: Reliability	0.10	0.09	0.09	0.12	0.05	8.8%
C3: Cost	0.09	0.09	0.09	0.18	0.07	10.2%
C4: Ergonomic compatibility	0.07	0.04	0.03	0.06	0.07	5.4%
C5: Performance	0.12	0.26	0.18	0.12	0.14	16.3%

ADT Selection Step 3: Validate the pairwise judgement

The fourth step required the mine management team to validate the consistency of the judgement applied during the pairwise comparison. The consistency ratio was calculated using Equation 2-3. Table 3-3 shows that the calculated result is 4%. This result validated the judgement consistency applied by the mine management team since a consistency ratio of less than 10% is required.

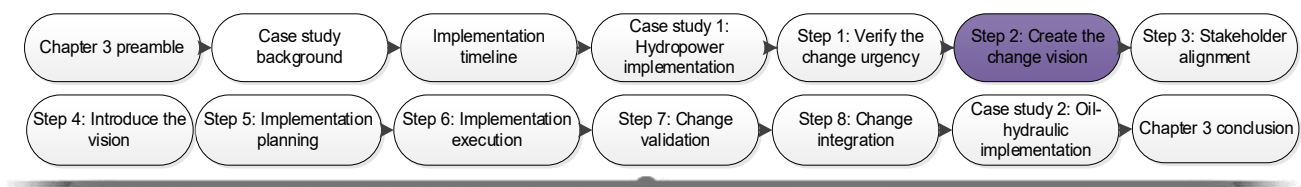


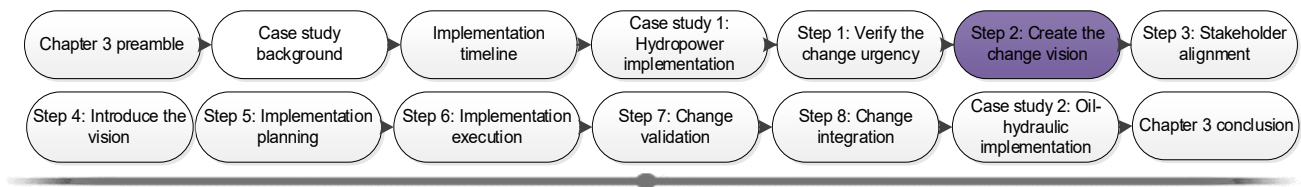
Table 3-3: Pairwise judgement validation

	C1: Technical compatibility	C2: Reliability	C3: Cost	C4: Ergonomic compatibility	C5: Performance	SUM	SUM/Weight
C1: Technical compatibility	0.59	0.53	0.71	0.48	0.81	3.13	5.28
C2: Reliability	0.10	0.09	0.10	0.11	0.05	0.45	5.11
C3: Cost	0.08	0.09	0.10	0.16	0.08	0.52	5.09
C4: Ergonomic compatibility	0.07	0.04	0.03	0.05	0.08	0.28	5.20
C5: Performance	0.12	0.26	0.20	0.11	0.16	0.86	5.26
						Lamba Max	5.19
						CI	0.05
						CR	4%

ADT Selection Step 4: Establish the weighted decision matrix

At this point, the selection criteria weights were known, and the decision matrix was established. As highlighted in Table 3-4, the only two ADTs that are still commercially available were identified during the literature review in [Section 1.7](#) as oil-hydraulic and water-hydraulic drilling systems. The only study that compared the performance, cost, and reliability results for these drilling systems was by Fourie *et al.* (2017) [66]. However, the CSM was a platinum mine. Although this study applies specifically to gold mines, the results of the platinum mine had to be adopted since it was the only unbiased data source available.

Technical compatibility was assessed using a 1–5 scale, where 5 represents fully compatible, and 1 represents that major changes will be required before the ADT can be implemented. It was found that an oil-hydraulic system consumes an equal amount of water as its compressed air counterpart. This meant that no upgrades were required to the water network infrastructure. The addition of oil-hydraulic drilling systems would require the installation of additional electrical supply infrastructure. Water-hydraulic equipment, on the other hand, would require both water and electrical infrastructure upgrades. As a result, the oil-hydraulic solution received a higher compatibility score of 3/5 than the



2/5 for the water-hydraulic solution. The remaining parameters were populated using the data adopted from Fourie *et al.* [66].

Table 3-4: Decision matrix established for the CSM

Selection criteria/ alternatives	Technical compatibility [–]	Reliability [R/m drilled]	Cost (opex + capex) [R per day]	Ergonomic compatibility [–]	Performance (time to drill a 1.2 m hole) [Minutes]
Oil-hydraulic	3.00	5.01	738.00	4.00	2.30
Water-hydraulic (micro)	2.00	4.52	702.00	5.00	2.59

The decision matrix was normalised using Equation 2-9, and the normalised decision matrix is shown in Table 3-5.

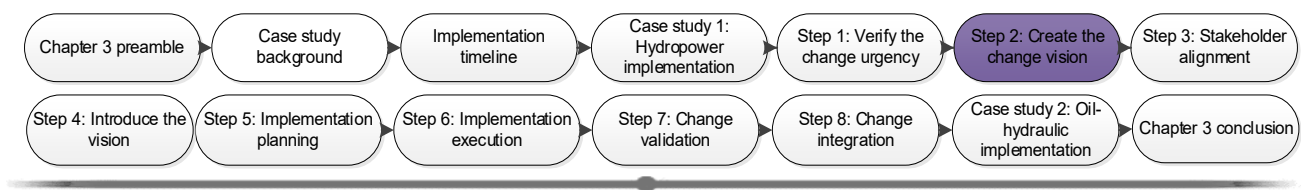
Table 3-5: Normalised decision matrix established

Selection criteria/alternatives	Technical compatibility	Reliability	Cost (opex + capex)	Ergonomic compatibility	Performance (time to drill a 1.2 m hole)
Oil-hydraulic	0.83	0.74	0.72	0.62	0.66
Water-hydraulic (micro)	0.55	0.67	0.69	0.78	0.75

The criteria weights as previously determined, as displayed in Table 3-2, were used to obtain the normalised weighted decision matrix using Equation 2-10. To recall, the weights were previously determined using Equation 2-2. The normalised-weighted results are shown in Table 3-6.

Table 3-6: Normalised and weighted decision matrix

Selection criteria/alternatives	Technical compatibility	Reliability	Cost (opex + capex)	Ergonomic compatibility	Performance (time to drill a 1.2 m hole)
Weight	59.4%	8.8%	10.2%	5.4%	16.3%
Oil-hydraulic	0.49	0.07	0.07	0.03	0.11
Water-hydraulic (micro)	0.33	0.06	0.07	0.04	0.12



ADT Selection Step 5: Prioritise the alternative solutions

The normalised and weighted decision matrix was used to determine the ideal best (V_{best}) and ideal worst values (V_{worst}), using Equation 2-11 and Equation 2-12. The corresponding results are shown in Table 3-7.

Table 3-7: Ideal best and ideal worst values

Selection criteria/alternatives	Technical compatibility	Reliability	Cost (opex + capex)	Ergonomic compatibility	Performance (time to drill a 1.2 m hole)
Oil-hydraulic	0.49	0.07	0.07	0.03	0.11
Water-hydraulic (micro)	0.33	0.06	0.07	0.04	0.12
Vbest	0.49	0.06	0.07	0.04	0.11
Vworst	0.33	0.07	0.07	0.03	0.12

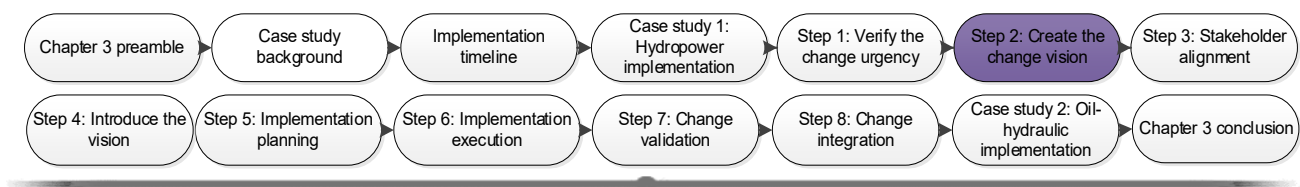
The ideal best and ideal works values were substituted into Equation 2-13 and Equation 2-14 to determine the Euclidean distances from the ideal best and ideal worst solutions, respectively. These distances were substituted into Equation 2-15 to prioritise the alternative solutions from best to worst. The results presented in Table 3-8 demonstrate that oil-hydraulic drilling systems provided the best alternative solution to the CSM.

Table 3-8: Prioritise an alternative solution

Alternatives	S_{best}	S_{worst}	$S_{best} + S_{worst}$	Pi	Alternatives ranked
Oil-hydraulic	0.01	0.17	0.18	0.94	1
Water-hydraulic	0.17	0.01	0.18	0.06	2

ADT selection result discussion

It follows from the normalised weighted results presented in Table 3-6 that the water-hydraulic alternative was outscored on four of the five selection criteria. As a result, the overall selection recommendation presented in Table 3-8 was in line with what the mine management team expected. An oil-hydraulic alternative was sourced and implemented, as highlighted by the implementation background presented in [Section 3.2](#). The trial results failed to validate the theoretical data adopted and used during the selection phase due to poor equipment reliability, as fully discussed in [Section 3.6](#). As a result, the second alternative listed in Table 3-8 was implemented successfully.



This result highlights an important limitation of the selection methodology developed and proposed by this study. The limitation is that the prediction results depend entirely on the data used, and the lack of reliable, unbiased performance and cost data has led to the incorrect prioritisation of available alternatives. The unbiased performance and cost data presented in this study are one of its key contributions to addressing this critical shortcoming.

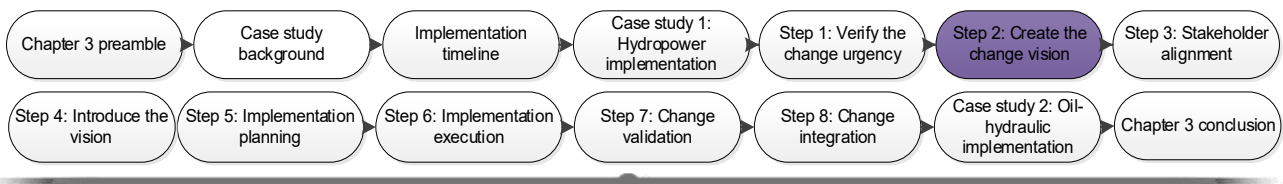
The rest of the implementation process focuses on the implementation of hydropower.

Action 2: Showcase the benefits

To promote stakeholder buy-in and confidence in the ADT's ability to serve as a replacement drilling technology, the benefits of hydropower drilling were showcased. This was accomplished by benchmarking its benefits offered against those provided by the compressed air system at the time. Table 3-9 gives an overview of the vision board created by following the proposed strategies.

Table 3-9: CSM-specific vision board developed

Focus area	Parameter	Pneumatic @ 270 kPa	Hydropower	Expected benefit
(1) Performance	Drill rate [min/1.2 m hole]	00:10:08	00:04:11	100% improvement
	Drilling cycle time [142 holes]	08:00:00 (using three RDOs)	04:57:00 (using two RDOs)	03:03:00 improvement
	Production [% call achieved]	82%	100%	18% improvement
	Water intensity ratio [tonne water/tonne ore]	1.5	0.41	73% reduction
	Energy intensity ratio [kWh/tonne]	120	5.16	96% reduction
(2) SHE	Noise exposure (TWA) [dB(A)]	103.8	95.4	8% reduction
	Vibrations exposure (TWA) [m ² /s]	21.9	24.4	11% increase
	Occupational environmental temperature [°C]	Provides localised cooling	Additional electrical load might increase the heat load	Expected to increase
(3) Mine suitability	Reliability [m/failure]	800	500	38% regression
	Functionality	Remains unchanged. Hydropower does offer ancillary equipment.		No change



Focus area	Parameter	Pneumatic @ 270 kPa	Hydropower	Expected benefit
(4) Human factors	Mass load [kg]	39	39	No weight increase
	Ergonomics	Handheld rock drill and thrust leg	Handheld rock drill and thrust leg	No operational changes
	Environmental contamination [–]	Present due to the presence of oil particles in the air	Hydropower does not use oil or grease	Expected to reduce
(5) Techno-economics	Opex [R/T]	136	80	41% reduction
	Revenue generated [%]	–18	+18	18% improvement

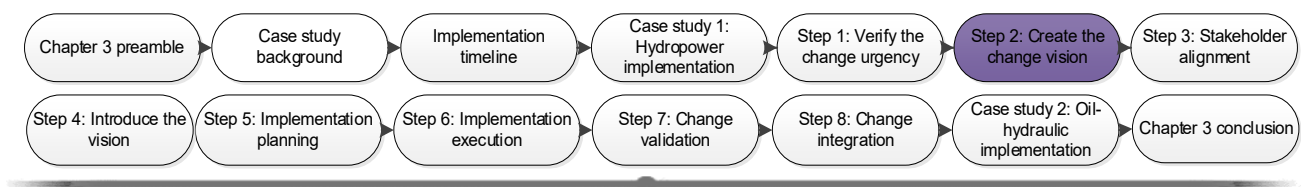
Vision board development of the process applied:

(1) Performance

Drill rate and face drilling cycle: The pneumatic drill rate was measured with a stopwatch using the prescribed method. The corresponding in-stope supply pressure was measured using a needle pressure gauge. The resulting face drilling cycle time was also recorded. The in-stope supply pressure was measured as 270 kPa, and the corresponding average time to drill a 1.2 m deep hole was found to be 10:08. As mentioned in [Section 3.2](#), Beatrix Reef is mined at the CSM. Unfortunately, no published literature was found on the actual hydropower drilling rates for this specific reef type. Alternatively, Fraser and Kienle [49] reported the hydropower drill rate in the Basal Reef to be 00:04:11 per 1.2 m hole. The vision board showcased a 100% improvement in drill rate, which could reduce the drilling cycle by three hours.

Production performance: Given the improved drilling performance, it was assumed that the new drill would enable the crews to complete the drilling activity within the allowable shift time of 9 hours. As a result, the production performance was forecasted to improve from 82% (see Figure 3-2) to 100%.

Water intensity ratio: Kienle and Fraser [9] reported the hydropower drill rate in Basal Reef to be 0.41 per tonne of ore mined. This result was adopted because no published data on water-intensity ratios for hydropower drilling systems in the Basal reef were available at the time. Historical data confirm the CSM historical water intensity ratio to be 1.5. As a result, the switch to hydropower may lead to a 73% reduction in water use.



Energy intensity ratio: Historical data recorded by the CSM showed that the energy intensity ratio averaged approximately 120 kWh/tonne. The data presented by Kienle and Fraser [9] advocated for an energy intensity ratio of 5.16 when mining Basal reef. This highlights the potential of achieving a 96% reduction in drilling energy costs if the initiative successfully converts the mine to hydropower.

(2) Mine suitability

Reliability: Rock drill reliability, characterised by linear metres drilled to failure, was used to benchmark equipment reliability. Transmittal notes between the shaft and the rock drill repair shop were used to quantify the reliability of the compressed-air rock drill at 800 m/failure. Published literature on hydropower rock drill reliability indicated 500 m/failure [28]. This highlights the concern that rock drill reliability might decrease by 38%.

(3) SHE

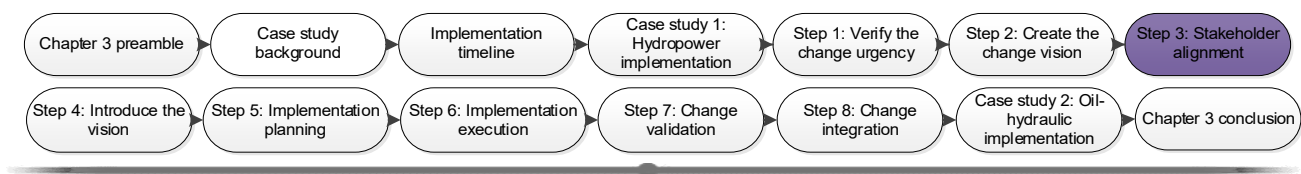
Noise: Historical data collected from the shaft occupational hygienist indicated a TWA exposure of 103.8 dB(A) due to the extra-long drilling shift. The vibration amplitude for hydropower drilling was adopted from Table 2-6, and the TWA exposure (based on an estimated drilling time of 04:57) was calculated to be 95.4 dB(A). This result highlighted a possible 8% reduction in noise exposure.

Vibration: Historical vibration measurements were not available at the CSM. To address this shortcoming, the study's proposed method was used to estimate the TWA vibration exposures based on the actual drilling time and theoretical vibration amplitudes obtained from literature (see Table 2-7). Equation 2-20 was used to estimate the vibration exposures at 21.9 m²/s and 24.4 m²/s, for compressed air and hydropower, respectively. This result showed an 11% increase in vibration exposure when using hydropower.

Occupational environmental temperature: Compressed air drills may provide up to 5 kW of cooling benefit per drill while in operation. As a result, the ambient temperature around the RDOs was expected to increase once the compressed air was removed from the workplace. Furthermore, the addition of electrical load to the pressure generation units of the alternative drilling systems might further increase the stope's heat load and ambient temperature.

(4) Human factors

Mass load: On-site mass measurements were conducted to quantify the combined mass of the compressed air rock drill, oiler, and thrust leg (750 mm) assembly. It was found to be 39 kg. No published literature could be found to quantify the mass of hydropower rock drill and thrust leg assemblies. The OEMs were consulted and highlighted the mass to be 39 kg for the same thrust leg length.



Ergonomics: Hydropower rock drill controls look, feel, and operate the same as their compressed air counterparts. The hydropower drill assembly also constituted a drill and a thrust leg.

Environmental contamination: As mentioned in [Section 1.4](#), hydropower rock drills do not use oil or grease as lubrication. As a result of the absence of oil and grease, this focus area was expected to improve.

(5) Techno-economics

Opex: The compressed air opex was obtained from the shaft financial manager and amounted to R136 per tonne produced. This included consumables, maintenance, and OEM labour. Previous studies showcasing the expected opex of hydropower rock drills used to mine Beatrix Reef could not be obtained. Consequently, the OEM supplier was consulted, who estimated opex to be R80 per tonne. The cost comparison highlighted a 42% cost reduction when using hydropower.

Revenue improvement: The CSM background section highlighted an existing 18% production shortfall. The targeted production improvement will be 18%, which aligns with the 2 m to 3 m expected face advance improvement advocated earlier [25], [64], [71].

Summary – Step 2: Create the change vision

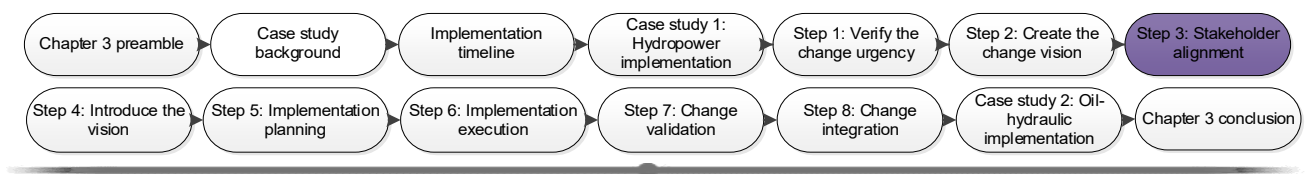
The strategies provided in Step 2 successfully guided the process of selecting the most appropriate replacement technology and creating a vision that showcases the theoretical benefits of the alternative. Step 4 later provokes stakeholder buy-in by selling the vision to all stakeholders.

Step 3: Development of the CSM-specific responsibility chart

Step 3 focused on developing the CSM-specific responsibility chart. The responsibility chart is needed later, in Step 4, to align stakeholders' role perceptions with organisational expectations. The strategic guidance provided in Step 3 was used to develop the CSM responsibility chart. The following three actions were executed to foster this outcome:

Action 1 – Stakeholder identification: As a first step, all stakeholders affected by the change were identified. These individuals became the multidisciplinary team responsible for implementing the change. A stakeholder analysis was performed based on the guidance provided in Table 2-9. The CSM-specific stakeholders identified were allocated to the top row of the alignment matrix, as shown in Table 3-10.

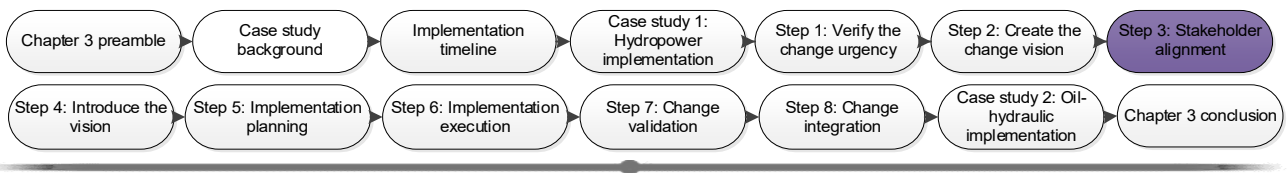
Action 2 – Work processes identified: As highlighted earlier in [Section 2.7](#), the proposed pragmatic methodology for introducing an alternative drilling system consists of eight steps and several corresponding work processes. These were transferred from the method overview presented in Figure 2-42 to the first column of the alignment matrix shown in Table 3-10.



Action 3 – Allocation of RACI indices: The RACI indices were assigned as shown in Table 3-10, using the strategic guidance provided in [Section 2.3, Step 3](#).

Table 3-10: Stakeholder alignment matrix

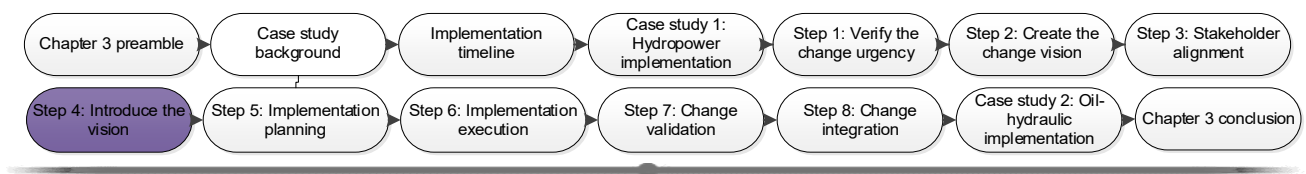
Actionable work process items	1. Shaft General Manager	2. Shaft Project Engineer	3. Shaft Simulation Engineer	4. Organised Labour Representative	5. Human Resources Leader	6. Shaft Risk Manager	7. Shaft Mine Manager	8. Shaft Engineering Manager	9. Shaft Financial Manager	10. Shaft Surveying Department	11. Shaft Legal Department	12. Original Equipment Manufacturer and Supplier	13. End Users	14. Product Performance Assessor	15. Shaft Occupational Hygiene Department
Step 1: Verify the change urgency	A	R	I	I	I	I	I	I	I	I	I	I	I	I	I
Step 2: Create the change vision	A	R	I	I	I	I	I	I	I	I	I	I	I	I	I
Step 3: Develop the CSM-specific responsibility matrix	A	R	I	I	I	I	I	I	I	I	I	I	I	I	I
Step 4: Communicate the vision	A R	I	I	I	I	I	I	I	I	I	I	C	I	I	I
Gateway 1: Stakeholder approval	A R	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Step 5: Develop and implement the change management strategy															
CMP2-S5.1: Supplier engagement	I	A	R	R	R	R	R	R	R	R	R	C	I	R	R
CMP2-S5.2: Infrastructure evaluation assessments	I	A	R	I	I	I	I	C		C		C			
CMP2-S5.3: Critical updates to policies and procedures	I	A	C	I	C	R	C	C	C			C			C
CMP2-S5.4: Implementation and transition planning	I	A R		I	C	C	C	C	C	C		C			
CMP2-S5.5: Implementation and transition execution	R	A	I	R	R	R	R	R	R	R	R	R	R	R	I
Task A – Labour engagements	I	A	I	I	R	I	I	I	I		I	I	I	I	I
Task B – Equipment layout audit	I	A	I	I	R	I	I	I	I		I	C	I	I	I
Task D – Equipment installations	I	A	C	I	I	I	R	C	I		I	C	I	I	I
Task E – Support infrastructure upgrades	I	A	C	I	I	I	R	R	I		I	I	I	I	I
Task H – Training	I	A	I	I	I	I	R	R	C		I	I	I	I	I
Step 6: Sustain the momentum by celebrating short-term wins	R	A	I	I	I	I	R	I	I	I	I	I	I	I	I
Step 7: Conduct continuous performance assessments															
CMP3-S7-A: SHE assessment	I	A	I	I	I	I	I	I	I		I	I	C	R	R
CMP3-S7-B: Human factor assessment	I	A	I	C	I	I	I	I	I		I	I	C	R	C
CMP3-S7-C: Mine worthiness assessment	I	A	I	I	I	I	R	I	I		I	I	C	R	C
CMP3-S7-D: Performance assessment and benchmarking	I	A	C	I	I	I	C	C	I		I	I	C	R	C



Actionable work process items	1. Shaft General Manager	2. Shaft Project Engineer	3. Shaft Simulation Engineer	4. Organised Labour Representative	5. Human Resources Leader	6. Shaft Risk Manager	7. Shaft Mine Manager	8. Shaft Engineering Manager	9. Shaft Financial Manager	10. Shaft Surveying Department	11. Shaft Legal Department	12. Original Equipment Manufacturer and Supplier	13. End Users	14. Product Performance Assessor	15. Shaft Occupational Hygiene Department
Gateway 2: Resistance to change detection	I	A	N A	C	C	C	C	C	C		C	C	C	C	C
CMP4-S8: Change integration															
CMP4-S8-A: Monitor the transformation effort at the initial crew continuously	I	A	N A	I	I	I	I	I	I		I	I	I	R	I
CMP4-S8-B: Sequentially expand transition effort to the remaining crews	C	A R	N A	I	I	I	C	I	C		I	C	I	I	I
Legend:										R - Responsible					
										A - Accountable					
										C - Consult					
										I - Informed					
										NA – Not applicable					

Summary – Step 3: Change management strategy

The CSM-specific stakeholder responsibility chart was developed, which served as an integral part of the change management process to maintain stakeholder alignment, promote participation, and ensure accountability during the change implementation phase.



Step 4: Introduce the vision and seek approval

The objective of Step 4 was to introduce the change vision in order to obtain stakeholder approval. Step 4 presented the project team with an initial opportunity to positively influence the stakeholders' attitudes, beliefs, and feelings towards the change. The three actions listed in the process flow (see Figure 2-9) were executed to influence this outcome.

Action 1 – Sell the vision board: Two separate mass meetings were scheduled with the day and night shift workforce as illustrated in Figure 3-6. The shaft general manager used interpersonal communication to sell the change vision as formulated in Table 3-9, and the benefits forecasted under each of the five key focus areas were duly articulated to the stakeholders.

Action 2 – Formal equipment introduction: Visual representations were used to help sell the vision. The OEM supplier was invited to the shaft to formally demonstrate the equipment to the workforce. This helped promote a willingness to change by managing the fear and anxiety caused by the introduction of something unknown. During the demonstration, stakeholders were encouraged to ask questions and see, feel, and experience the equipment's ergonomics, size, and other physical parameters. As illustrated in Figure 3-7, the equipment was also operated to showcase the performance benefits visually.

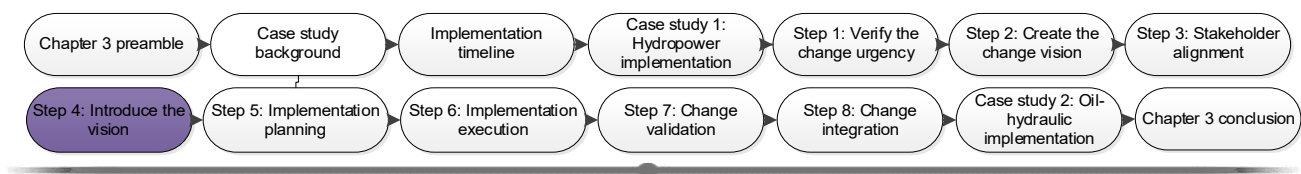


Figure 3-6: Mass meeting held to introduce the vision



Figure 3-7: Hydropower drill demo

Action 3 – Formal introduction of the change process: As part of selling the vision, the shaft general manager provided an overview of the change process. The responsibility chart was used to clearly outline the multi-layered sequential approach, and the roles and responsibilities were reviewed. Stakeholders were further assured that the benefits of the change would first be validated on a small scale using one crew. Emphasis was placed on avoiding excessive change at all costs, and changes would be introduced only once their benefits had been successfully validated.



Stage validation – Stakeholder approval

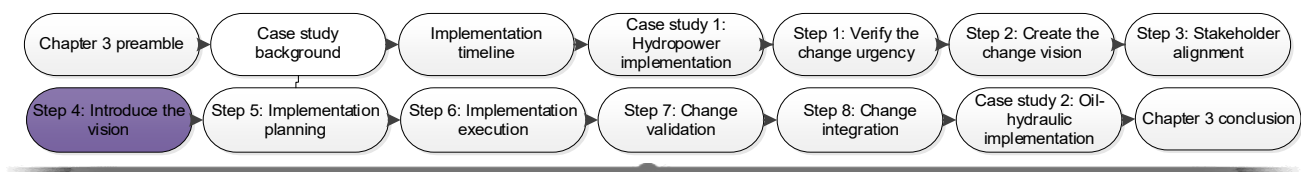
At the end of the interactive session, stakeholders were asked to reflect on the shared vision, and the following key points were acknowledged:

- (1) **Performance:** The potential to reduce the drilling cycle by three hours was highly appreciated by the RDOs. They acknowledged that such a reduction would help them manage fatigue and absenteeism. At the same time, the forecasted production improvement created notable excitement among line managers.
- (2) **SHE:** The shaft occupational hygienist was concerned about the introduction of additional heat, as the CSM does not mine with chilled water to offset this heat. It was highlighted that a strategy would be needed to manage the additional heat.
- (3) **Mine suitability:** Hydropower drilling technology operates with finer component tolerances, which may reduce the mean time between drill failures by 38%. Stakeholders highlighted that a 38% reduction in rock drill reliability might lead to lost blasts due to equipment unavailability if the equipment fleet is not managed correctly.
- (4) **Human factors:** The RDOs appreciated that the hydropower equipment had a similar mass load. Some operators also contributed to the conversation, expressing their delight to see that the ergonomics of the new equipment appear similar.
- (5) **Techno-economics:** The potential to improve revenue generation and reduce costs resonated well with the financial manager of the shaft. However, they highlighted the high risk of financial losses during the equipment transition phase, especially if the incorrect alternative technology is implemented.

At the end of this interpersonal session, stakeholders were asked to approve or reject the proposed change process. Due to the low emotional state caused by the slow compressed air drilling, all stakeholders approved the proposed ADT and the change process. This result validates that the vision created succeeded in its objective of promoting stakeholder buy-in.

Phase 1: Change initialisation summary

- The main objective of the method's first phase was to initiate the change process by enabling stakeholder buy-in through Steps 1 to 4. The strategic objectives of the corresponding strategies formulated to achieve this outcome are shown in Table 3-11.
- These strategies were implemented using Steps 1 to 4, and the stakeholders approved the change vision. This outcome validated the following:



- Step 1 successfully validated that the drilling cycle was indeed the main production constraint, confirming the urgency of implementing an ADT.
- Step 2 yielded a change vision that was understood by all stakeholders during Step 4.
- Step 3 involved crafting a RACI matrix to ensure stakeholder participation and maintain stakeholder alignment.
- Step 4 highlighted the urgency of the change and sold the vision to all stakeholders.

Table 3-11: Strategic objectives overview of Step 1–4

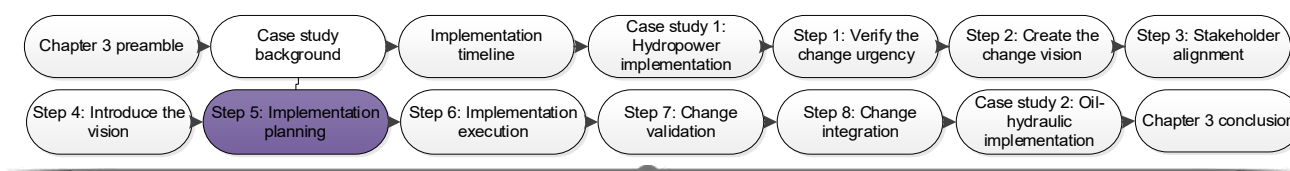
Method step	Strategy objective	Strategic objective met
Step 1: Verify the change urgency	Verify the change urgency	✓
Step 2: Create the change vision	Create the change vision	✓
Step 3: Integrate the change management strategy	Integrate the change management strategy	✓
Step 4: Introduce the vision and seek approval	To obtain stakeholder approval	✓
Legend:	✓ – objective met ✗ – objective not met	

Phase 2: Change implementation

The purpose of the second phase was to enable change implementation through the following five strategic outcomes:

- Provide system selection guidance,
- Assess and recommend upgrades to support infrastructure,
- Recommend updates to policies and procedures,
- Develop an implementation plan, and
- Reward stakeholder participation.

Step 5 and Step 6 were focused on planning and implementing the change.



Step 5: Plan the implementation

To enable the implementation of change, proper planning was needed. Figure 2-11 shows the strategies required to complete this process. The following five steps were used to enable this outcome:

- Step 5.1: Engage with OEM suppliers,
- Step 5.2: Assess and evaluate infrastructure,
- Step 5.3: Update policies, procedures, and standards,
- Step 5.4: Develop the implementation plan, and
- Step 5.5: Establish the change management strategy.

Step 5.1: Engage with OEM suppliers

The OEM supplier engagement session was focused on establishing the implementation scope (Action 1), obtaining the water and electrical supply requirements (Action 2), and actioning the commercial arrangements (Action 3).

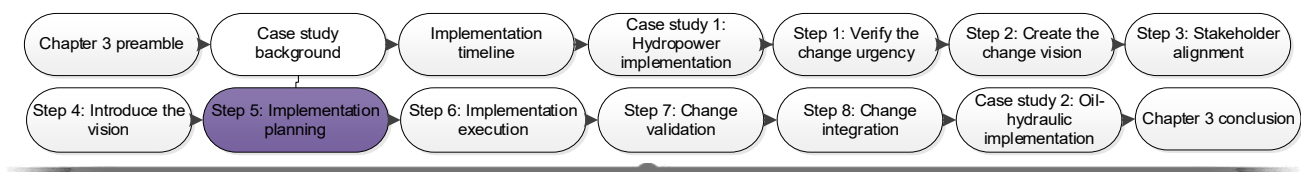
Action 1 – Determine the implementation scope

[Section 1.4](#) discussed the two commercially available hydropower system configurations, and the best-fit-for-purpose configuration had to be selected. The proposed method recommends a sequential approach to introducing the ADT by first proving it on a small scale before rolling it out to the remaining crews. Once the trial yields the intended results to validate the claimed benefits, the technology is deemed suitable for large-scale roll-out to the other panels. As a result, the initial implementation scope focused solely on the trial site using one crew. Based on this requirement, an in-stope micro-hydropower system was selected.

To ensure similar mining parameters as much as practically possible, the trial and baseline panels were selected as adjacent panels in the same raise line. A definite start and end date were agreed upon to manage stakeholder expectations. Operational parameters were kept similar, as shown in Table 3-12, by recommending the same drill lengths, drill bit sizes, and blast and support designs.

Table 3-12: Mining, operational and drilling parameters – Trial and compressed air baseline crews

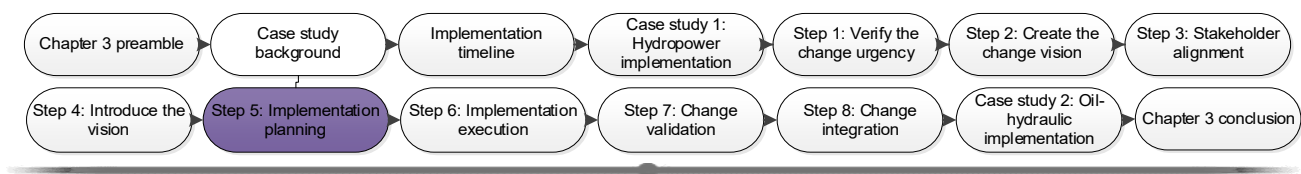
Description	Compressed air baseline crew	Hydropower trial crew
Trial date	01/06/2022–18/09/2022	01/06/2022–18/09/2022
Trial duration	Three months	Three months
Workplace name	137L E6 E5	137L E6 E4
Reef dip angle	10–20°	10–20°



Description	Compressed air baseline crew	Hydropower trial crew
Reef type	Beatrix Reef	Beatrix Reef
Ground conditions	Good	Good
Crew name	Opel Monza	Ford
Crew size (day shift)	11	11
Working days	69	69
Stoping width	1.09 m	1.09 m
Panel length	25.0 m	25.0 m
Face burden spacing	0.6–0.7 m	0.6–0.7 m
Roof burden spacing	1.5 m	1.5 m
Number of rows drilled	2	2
Drill steel length (face)	1.5 m (1.2 m hole)	1.5 m (1.2 m hole)
Drill steel length (gully)	1.8 m (1.5 m hole)	1.8 m (1.5 m hole)
Drill steel length for roof support	1.8 m (1.5 m hole depth)	1.8 m (1.5 m hole depth)
Drill steel length for siding	1.8 m (1.5 m hole depth)	1.8 m (1.5 m hole depth)
Drill bit	Five button – 34 mm	Five button – 34 mm
Equipment used	4 × Seco215 drills used on face and roof bolts and 1 × Seco215 drill used in gully Face thrust legs: 760 mm; Gully thrust legs: 850 mm – five-point stinger Compressed air diaphragm pump in the gully	2 × hydropower drills used on face, 1 in the gully and 1 drilling support Face thrust legs: 760 mm; Gully thrust legs: 1 000 mm – five-point stinger Hydropower jet pump in the gully
Mining cycle overview	Drilling: Handheld rock drills Support: Packs to support gully shoulder. Elongates and roof bolts to support the hang wall Cleaning: Face scraper integrated with strike and centre gully scraping	Drilling: Handheld rock drills Support: Packs to support gully shoulder. Elongates and roof bolts to support the hang wall Cleaning: Face scraper integrated with strike and centre gully scraping

Action 2: Obtain water and electrical supply requirements

As highlighted in [Section 1.4](#), the introduction of hydropower drilling systems may place additional strain on the service water supply and dewatering network, as well as on the electrical supply infrastructure. Table 3-13 provides an overview of the OEM supplier-recommended design requirements. These requirements will be used as input parameters to assess the capability of the



electrical and water networks to support the hydropower system in [Step 5.2: Infrastructure evaluation assessments](#).

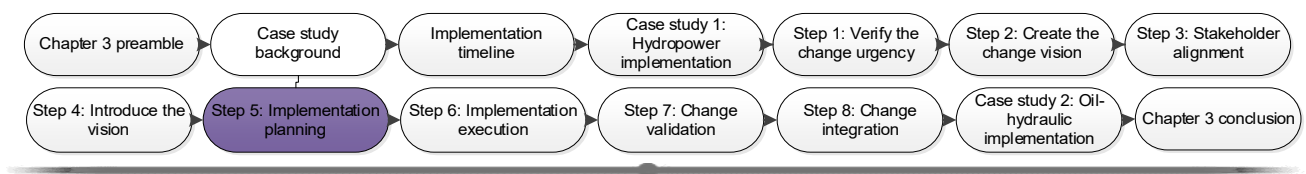
Table 3-13: OEM supplier-recommended design requirements – Water and electricity

Service type	Parameter	Unit	Design requirement
Water	Water flow rate	l/s	3.5
	Dynamic pressure	kPa	300
	Water quality	[-]	Mud-free water
Electricity	Supply load	kW	75
	Power factor	cos Φ	0.87
	Maximum supply voltage	V	580
	Minimum supply voltage	V	480
	Full-load start-up current	A	101
	Continuous current	A	60
	Nominal voltage	V	525

Action 3: Commercial arrangements

After establishing the implementation scope, the following commercial arrangements were dealt with:

- (1) **Purchase option:** While the hydropower system was tested on a small scale (with an initial end user), a month-to-month rental agreement was recommended. This was changed to an outright purchase agreement once the benefits were successfully validated (see [Step 7: Benefit validation](#)).
- (2) **Maintenance option:** Motivated by the small amount of equipment deployed, an off-site maintenance strategy was used during the trial phase. This was later changed to an on-site maintenance strategy, in which the equipment was serviced in an underground workshop.
- (3) **Contractual agreements:** The group legal department compiled a formal contract to protect the interests of all parties involved. Once the contract and letter of award containing the order number were made available, the OEM supplier was allowed to manufacture and deliver the equipment. To protect the interests of both the mine and the OEM supplier, both parties formally signed off on:
 - System type recommended,
 - Trial location and duration,
 - Capex and opex,



- Purchase option agreement,
- Equipment lead time, and
- Maintenance agreement.

Step 5.2: Assess and evaluate infrastructure – Electrical supply network

An infrastructure evaluation assessment was conducted to determine whether the initial electrical network was capable of supporting the alternative during the trial phase and during large-scale roll-outs. It followed from Table 3-13, which contains the system design requirements, that an electrical load of 75 kW was required. The existing infrastructure at the time supported electrical loads of up to 55 kW. As a result, an instinctive initial hypothesis emerged: the electrical network would not be adequate to meet the hydropower drilling system's load requirements, resulting in frequent lost blasts due to power failures.

To assess the required design upgrades, the proposed evaluation strategy was implemented by executing the five method steps as outlined in the process flow in Figure 2-19.

IEA Step 1: Select a simulation package

As a starting point, the simulation package was selected by executing the two required actions listed in Figure 3-8.

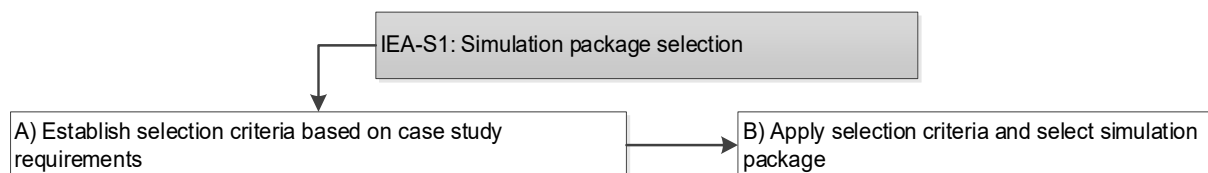
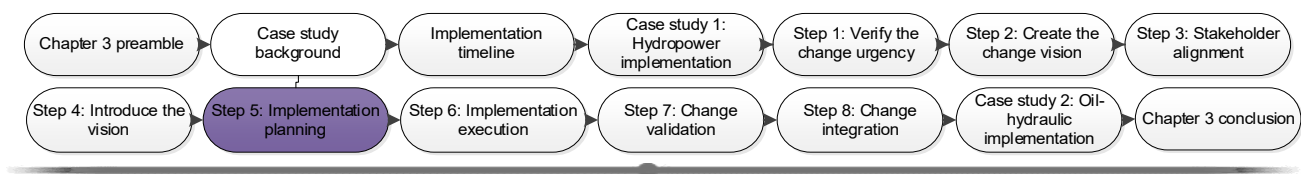


Figure 3-8: IEA Step 1 – Overview

The selection criteria were reviewed based on the requirements of the case study. The criteria were used to filter the available load flow simulation packages. PowerWorld Simulator was selected for the following three reasons:

- The software is capable of solving integrated dynamic component responses,
- Literature on previous applications to mine case studies is available, and
- The software was available to the author at the time of the study.

Additionally, PowerWorld Simulator is a power system simulation package developed to be user-friendly, featuring a graphical user interface (GUI) [147]. This enhances the simulation engineer's understanding of system characteristics and constraints, as well as conceptualising which design



changes will resolve them. The base package of the Simulator can solve power systems comprising up to 250 000 buses (nodes).¹⁶

IEA Step 2: Develop a one-line diagram

A simplified one-line definition of the stope electrical system was needed to understand the system's integrated behaviour. This diagram was further used to define the case study's system boundary and to simplify the three-phase system into a single-line schematic. To achieve this outcome, the four actions highlighted in Figure 3-9 were executed.

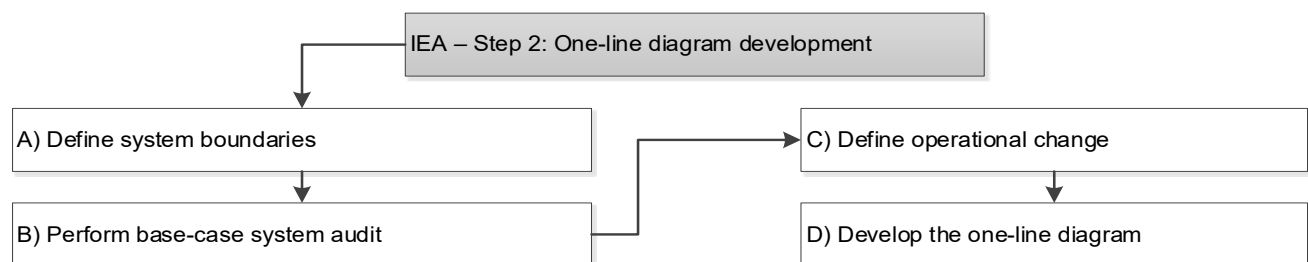


Figure 3-9: IEA Step 2 – Overview

(A) Defined system boundary

The recommended bottom-up approach was used to define the system boundary, which entailed working from the load area to the POC supply. Figure 3-10 illustrates the initial system boundary, which encloses all hardware found within. This boundary identifies the area of concern and encircles the base-case and operational-change focus area. The red circle presents the system boundary. Within the same figure, the respective audit data is presented and discussed in this section.

¹⁶ PowerWorld Corporation, "Online diagram overview", 2025. https://www.powerworld.com/WebHelp/Content/MainDocumentation_HTML/Online_Diagram_Overview.htm

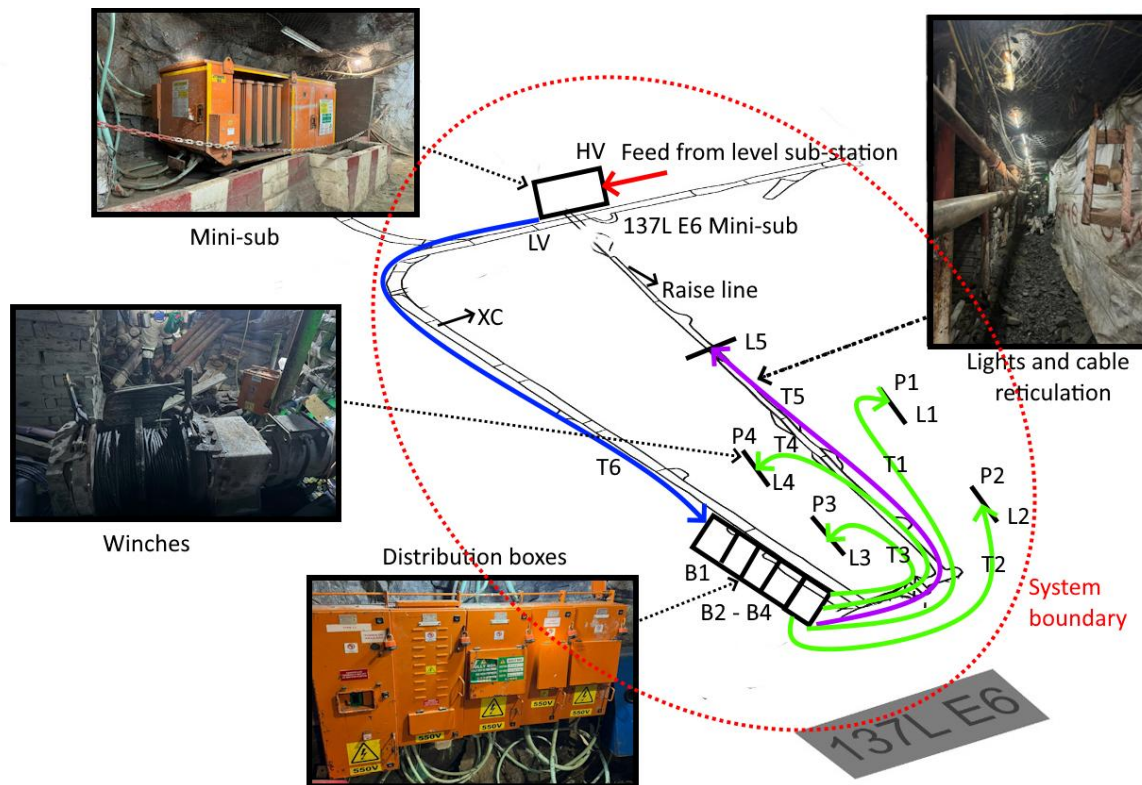
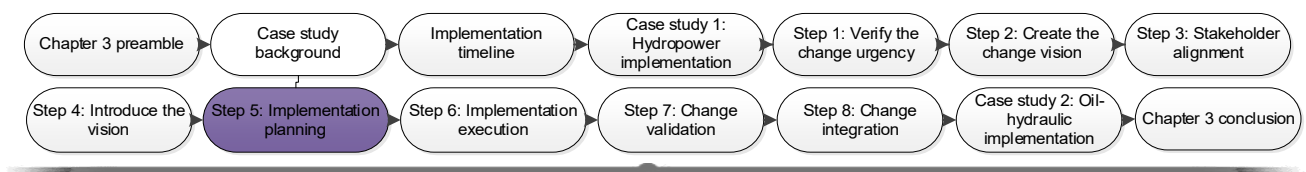
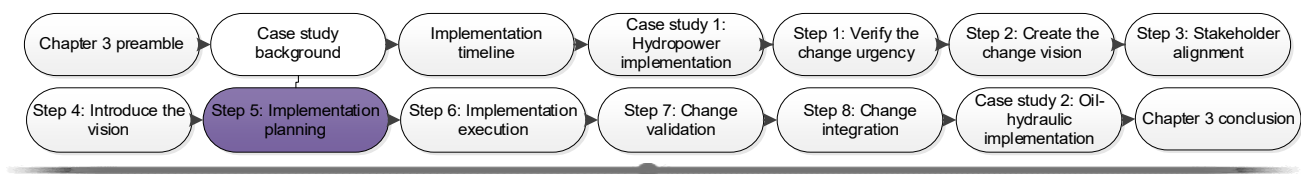


Figure 3-10: System audit sheet (1:200)

(B) Base-case system audit performed

An electrical reticulation layout, describing the trial stope's electrical infrastructure, could not be obtained from the shaft survey department. To overcome this limitation, a manual audit was performed. Figure 3-10 presents an overview of the following audit findings. The audit started in the stope. Four panels (P1–P4) were active and equipped with four face and four gully winches. P4 and P1 tipped into the same box, which was in line with the strike gullies. The same tipping arrangement existed for P3 and P1. As a result, no centre gully winches were installed. The hydropower pressure generation unit was assumed to operate only during the day shift since water jet cleaning was not considered at the time. For safety reasons, only strike gully winches were allowed to operate during the day shift. Consequently, the only loads present during the day shift were the four strike gully winches (L1–L4) and the hydropower pressure generation unit (L5).

The average loads of the winches (L1–L4) and lights (L5) were measured using portable power loggers as depicted in Figure 3-11. The data per load was logged using two-minute intervals over a one-week period. An example dataset logged for L1 is shown in Figure 3-12, where the curve represents the measured power profile of the winch, as logged over the defined period. After the logger was retrieved from underground, the data was analysed, and the average loads were



calculated using MS Excel. The results are captured in Table 3-14. The calibration certificate for each instrument was checked before use to verify its accuracy.



Figure 3-11: Portable power logger

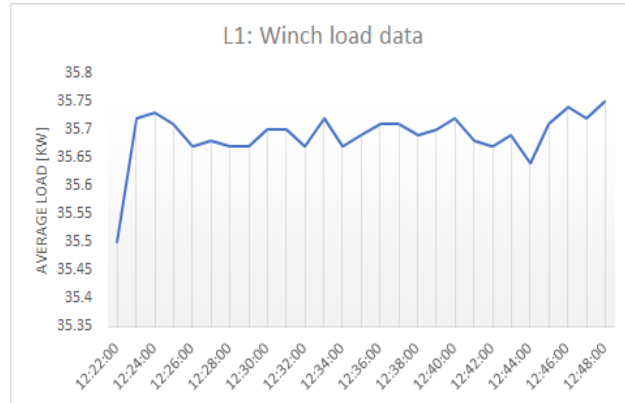


Figure 3-12: L1: Logged average winch load data

Table 3-14: Case study base-case load data

Load ID	Unit	Operational average load
L1 – L4	kW	35
L5		4

A summary of the transmission cable audit data is shown in Table 3-15. The installed transmission cable sizes (T1–T5) were noted. Cable routes were captured and later used to estimate the corresponding cable lengths using a 1:1000 mine plan and scale ruler. The distribution boxes, known as gully boxes, were located at the end of the cross-cut, near the travelling-way entrance. Each box had an identification sticker to highlight its application. One box (B1) fed the lighting circuit, and the remaining boxes (B2–B5) fed the winches. The switchgear load ratings were recorded.

Table 3-15: Transmission cable audit data

ID	Rated max. current [A]	Length [km]	Size [mm ²]	Resistance [ohm/km]	Impedance [ohm/km]	Switchgear rated max. current [A]
T1 & T4	77	0.08	16	2.39	1.38	80
T2 & T3	77	0.1	16	2.39	1.38	80
T5	77	0.4	16	2.39	1.38	50
T6	235	0.4	95	0.427	0.246	225

The information summarised in Table 3-16 was recorded from the mini-sub specification plates: maximum load rating, no-load high and low voltages, percentage impedance, and reactance-to-resistance ratio. Resistance (R) and reactance (X) per-unit values were obtained from the OEM datasheets, using %Z and the X/R ratio as lookup values.

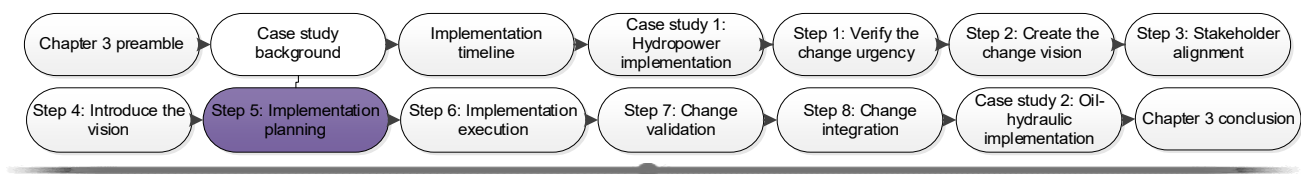


Table 3-16: Mini-sub characterisation data

ID	Max. load rating [MVA]	No load voltage [kV]	%Z	X/R	R [p.u]	X [p.u]
137L E6 Mini-sub	0.4	High: 6.6	4.47	3.85	0.008498	0.032719
		Low: 0.55				

(C) Defined operational change

As an initial operational change, one hydro vessel was added during the trial phase to panel number three (P3).

(D) One-line diagram developed

The intricate three-phase system from the system audit diagram was simplified into a one-line diagram. Figure 3-13 illustrates the resulting one-line diagram. The operational change is highlighted in red.

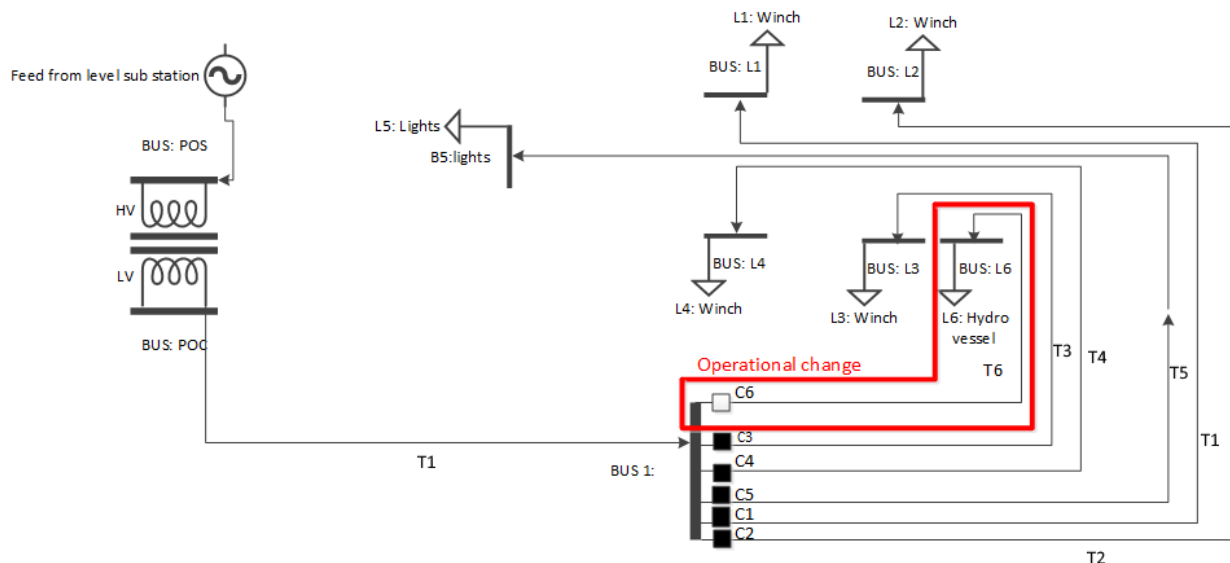


Figure 3-13: Case study one-line diagram

IEA Step 3: Translate the one-line diagram into a digital twin

As illustrated in Figure 3-14, IEA Step 3 translated the one-line diagram into a digital version of the base-case model using the selected simulation software package. Four component groups were used to achieve this outcome: a supply source, loads, transmission lines, and switchgear. The resulting digital version of the base-case model is shown in Figure 3-15.

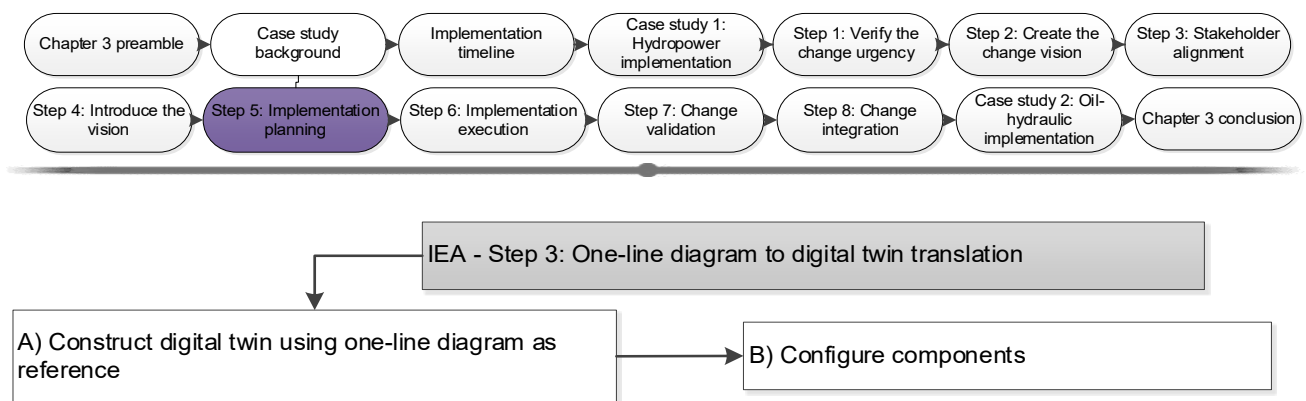


Figure 3-14: IEA Step 3 – Overview

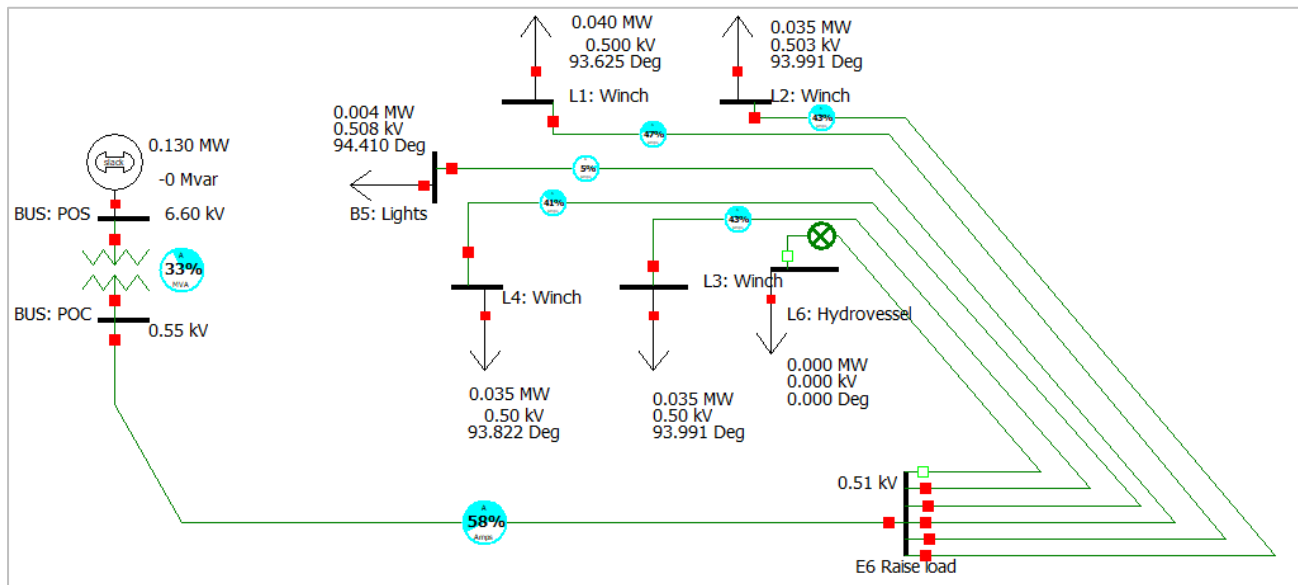


Figure 3-15: One-line diagram-to-digital twin translation

Supply source, mini-sub, POS and POC buses

A generator was added to simulate the power supply from the level substation. It was configured as a slack bus, as highlighted in Figure 3-16. The step-down transformer was used to represent the mini-sub. The data input tap was used to characterise the mini-sub using the data captured in Table 3-16. POCs and POSs were added and configured according to the nominal supply voltages captured during the audit (Table 3-16).

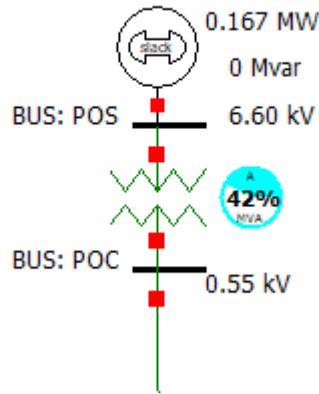
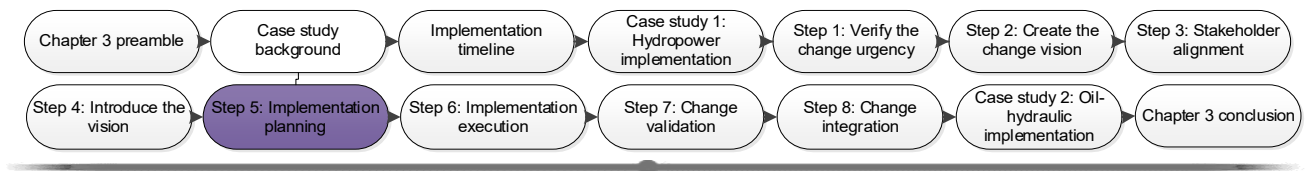


Figure 3-16: Supply feed, mini-sub, POS and POC bus characterisation

Loads

The load configuration tap is shown in Figure 3-17. Loads were added to represent the winches (L1–L4), lights (L5), and the operational change (L6). Each load was configured as per the audit data captured in Table 3-14 and the hydropower electrical load data as given in Table 3-13.

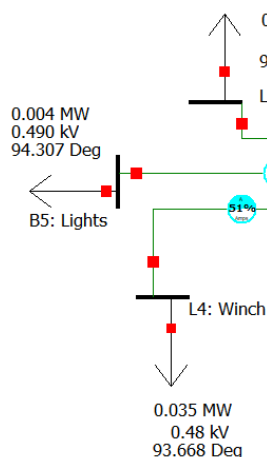
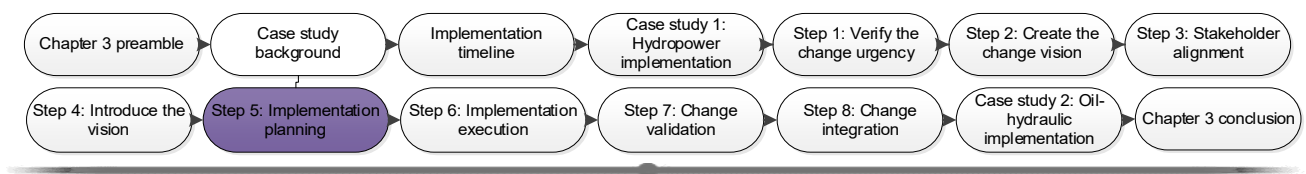


Figure 3-17: Loads and buses



Transmission lines

Finally, transmission lines were characterised using the audit data captured in Table 3-15. Actual impedance and current limits for all transmission lines (T1–T7) were calculated using the built-in *Line per Unit Impedance Calculator*, as showcased in Figure 3-18.

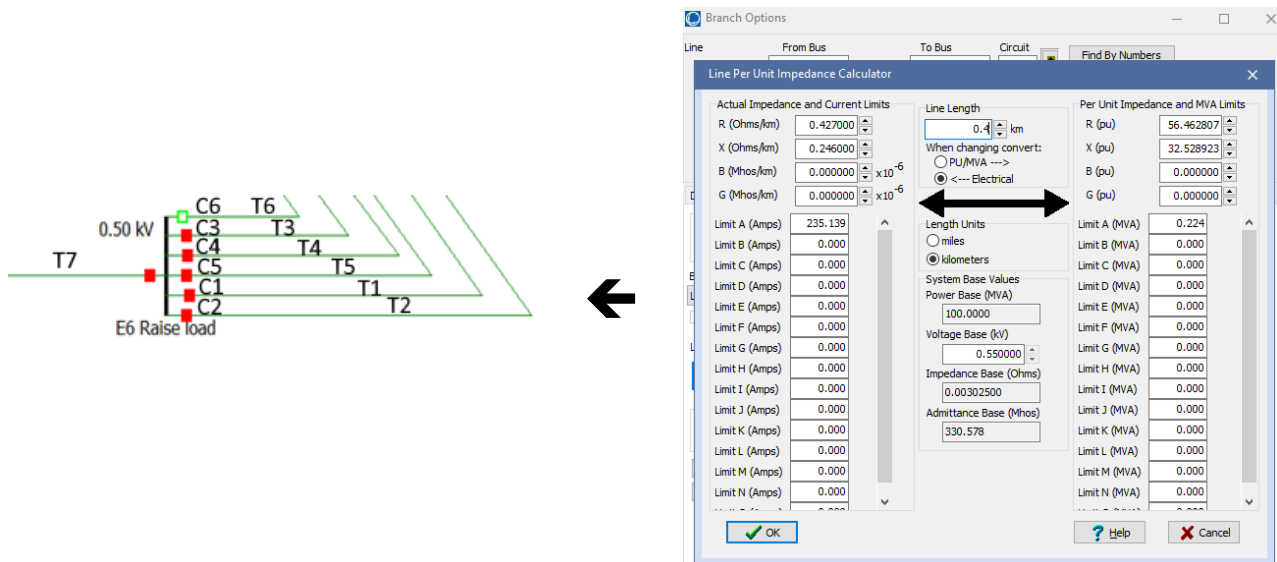


Figure 3-18: Transmission line characterisation

Switchgear

To ensure all base-case components were active, all switchgear contactors were configured as 'Closed'. The operational change contactor remained in the open position because the base-case model had to be verified first.

IEA Step 4: Base model verification

Figure 3-19 presents an overview of the process flow followed to verify the base model. The simulated voltage, load, and current data were compared with measurements from the underground audit (IEA Step 2) to ensure that the digital model was correctly characterised. The AMEs were calculated and used as a metric to verify the model's authenticity as a digital twin of the real-world case study. As stated earlier, an AME of less than 10% is acceptable.

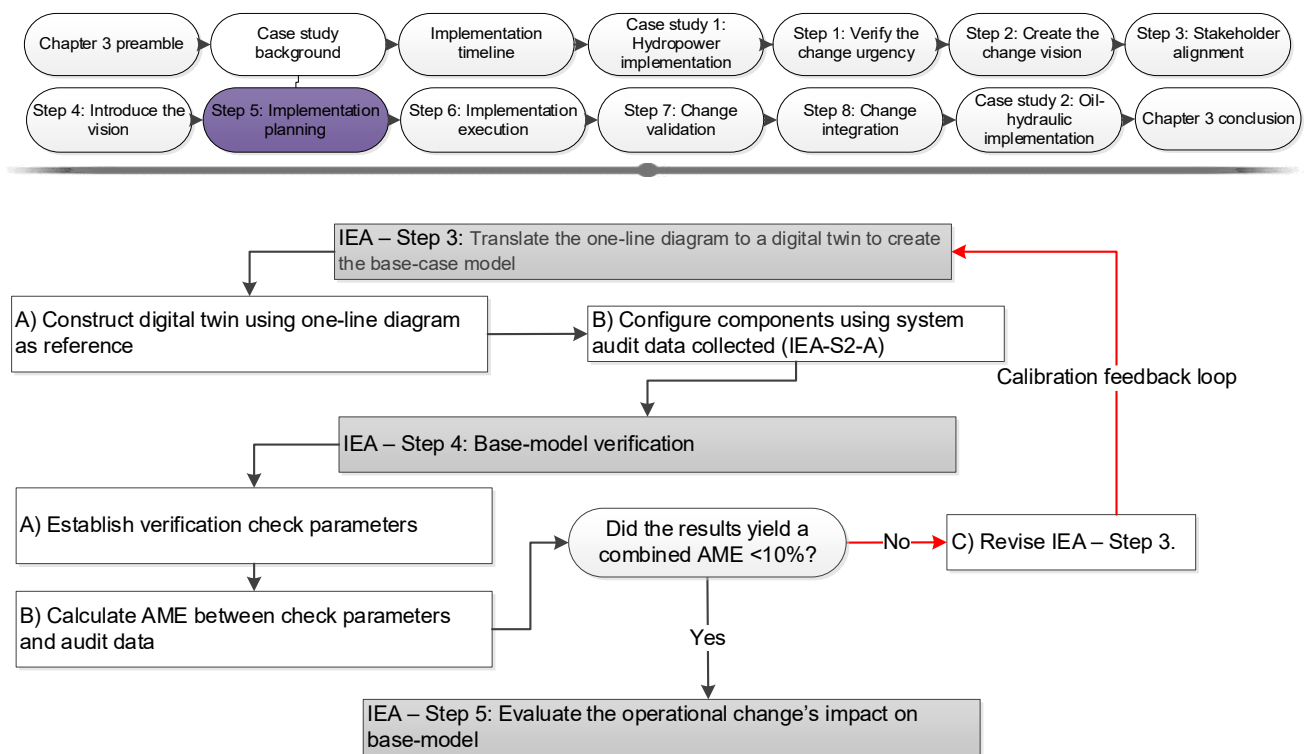


Figure 3-19: IEA Step 4 – Overview

Mini-sub base-load verification

Table 3-17 shows that the load AME equated to 1.75%, indicating that the loads were configured correctly.

Table 3-17: Load calibration data

ID	Measured [MW]	Simulated [MVA]	Individual AME [%]	Overall AME [%]
Mini-sub	0.132	0.130	1.52	1.75
L1	0.035	0.035	0.00	
L2	0.034	0.035	2.94	
L3	0.033	0.035	6.06	
L4	0.035	0.035	0.00	
L5	0.004	0.004	0.00	

Load voltage verification

As a second check to verify transmission-line characteristics, the measured and simulated bus voltages were compared. An AME of 4.04% was reportable as per Table 3-18, and it was confirmed that the transmission lines were configured correctly.

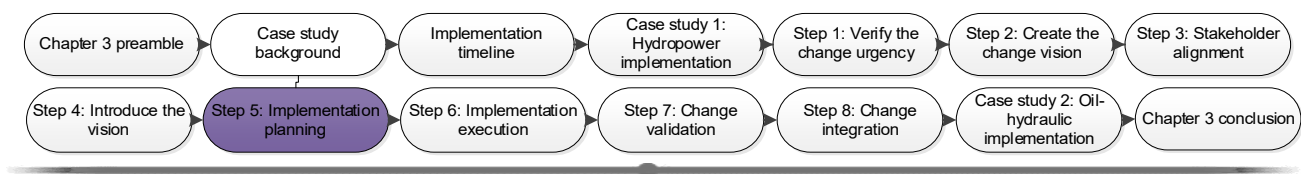


Table 3-18: POS and POC bus voltage calibration data

ID	Measured [kV]	Simulated [kV]	Individual AME [%]	Overall AME [%]
POS Bus	6.6	6.6	0.00	4.04
POC Bus	0.55	0.55	0.00	
L1	0.53	0.50	5.66	
L2	0.53	0.50	5.66	
L3	0.53	0.50	5.66	
L4	0.53	0.50	5.66	
L5	0.53	0.50	5.66	

IEA Step 5: Evaluate the operational change's impact on base model

IEA Step 5 focused on evaluating the impact of the operational change on the base model. The execution of the required three actions, as illustrated by Figure 3-20.

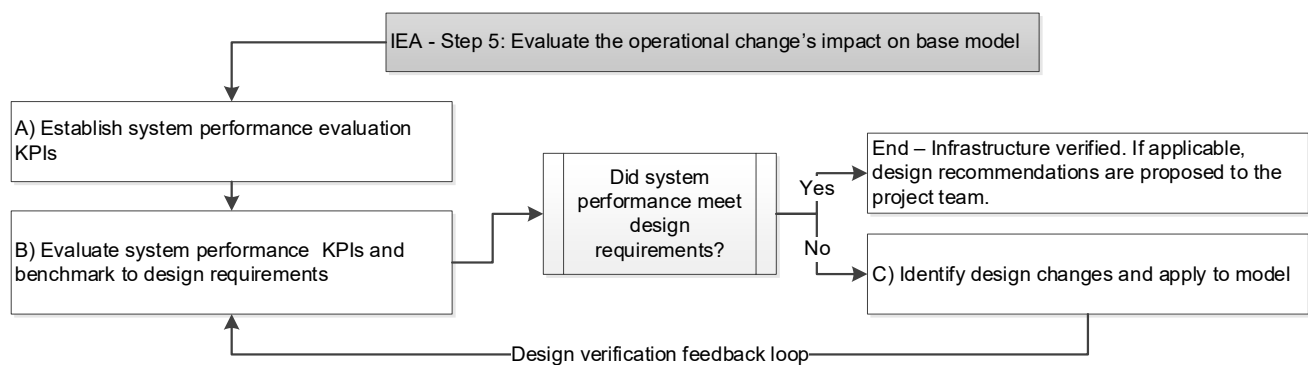


Figure 3-20: IEA S5 – Overview

(A) Establish verification check parameters

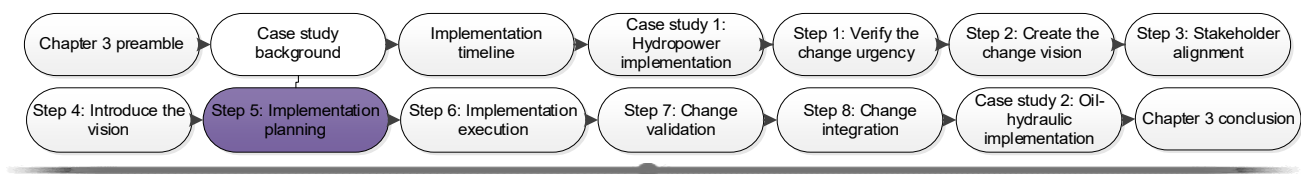
(1) Mini-sub maximum allowable load: The maximum allowable transformer load was specified to be 80% of the full-load rating to accommodate future network expansion, as listed in Table 3-19.

Table 3-19: Transformer load design requirement

ID	Rated maximum load [MVA]	Maximum allowable load [MVA]
Transformer	0.4	0.32

(2) Cable load requirements: Current and voltage were the two main considerations used to determine the required cable sizes.

Cables T1 to T4 each supplied a 37 kW winch. The maximum allowable current rating for a single cable supplying a single induction motor may not be less than 125% of the motor's full-load start-



up current. The full-load start-up current for these 37 kW winch motors was obtained from the specification plate, which listed 50.7 kW. As a result, the maximum required cable load was 64 A.

Table 3-20 shows the comparison between the simulated cable loads and the requirements. To recall, cable T7 is the main supply cable from the mini-sub to the stope gully boxes. Cables supplying more than one motor must have a rated ampacity equal to the sum of the full-load current ratings plus 25% of the highest-rated motor in the cluster. The sum of the full-load start-up currents, plus 25% of the highest rated motor, equated to 330 A.

Table 3-20: Cable load defined KPIs

ID	Full-load start-up current [A]	Required line current [A]
T1–T4	50.7	64.0
T6	101.0	127.0
T7	304.0	330.0

As shown in Table 3-21, the undervoltage limits at the point of mini-sub supply and the points of load supply were calculated at 85% of the nominal voltage, using Equation 2-23.

Table 3-21: POS and POC bus minimum voltage defined KPIs

ID	Nominal voltage [kV]	Minimum [kV]
POS bus	6.60	5.61
POC buses	0.525	0.46

(3) Switchgear required trip ratings: The switchgear trip ratings shown in Table 3-22 were defined at 125% of the continuous-current ratings.

Table 3-22: Switchgear trip ratings KPIs

ID	Continuous current [A]	Switchgear trip rating [A]
T1–T4	43.5	55.0
T6	60.0	75.0
T7	234.0	250.0

(B) Benchmark system performance against operational requirements – Initial iteration

To evaluate the initial impact of the operational change, the operational change contactor was closed, and the load flow was assessed. To account for the worst-case scenario in which all the motors started up simultaneously, the main contactor (C7) was opened and closed. Figure 3-21 shows the graphical output of the initial evaluation iteration. The red circles indicate the locations of the initial system constraints identified.

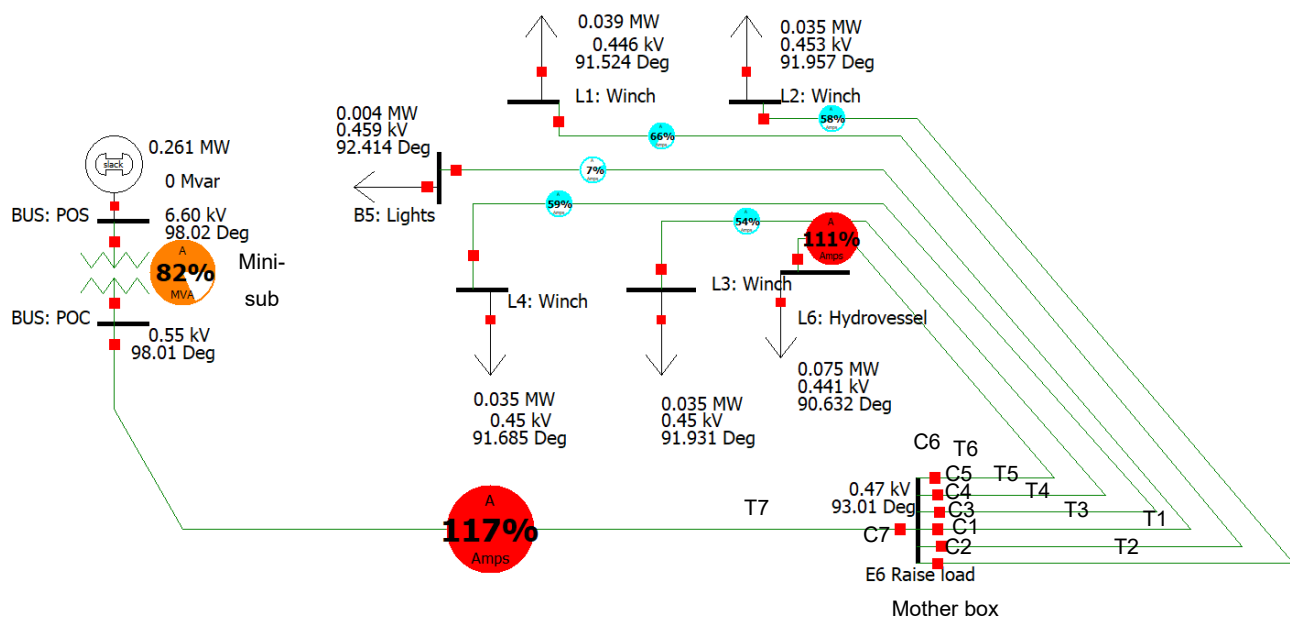
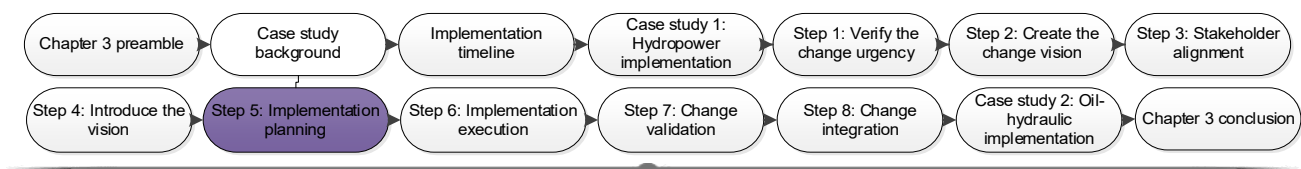


Figure 3-21: Initial iteration of the electrical infrastructure evaluation assessment

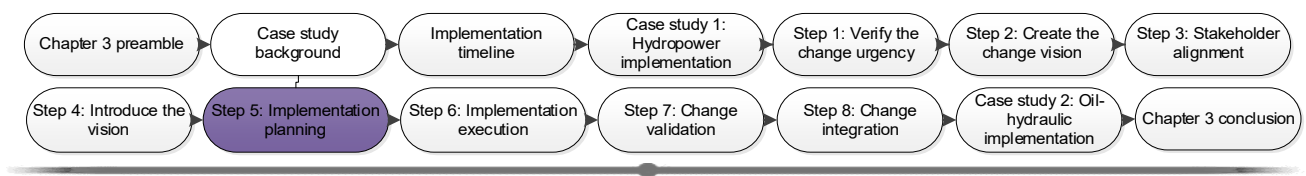
The initial simulated loads were benchmarked against the design requirements, as shown in Figure 3-21. From the figure, the following electrical network constraints are evident and are listed in Table 3-23.

Table 3-23: Transformer and transmission line load KPIs

ID	Maximum [kVA]	Maximum line current of initial cable [A]	Required line current [A]	Simulated load	Required contactor size	Initial contactor current [A]
Transformer	0.32	—	—	0.26 [kVA]		—
T7	—	235	330	230 [A]	250	225
T1	—	77	64	46.2 [A]	55	80
T2		77	64	37 [A]	55	80
T3		77	64	43.9 [A]	55	80
T4		77	64	41.6 [A]	55	80
T6	—	77	127	97 [A]	75	80
Legend:					Constraint identified	

Mini-sub -

The mini-sub load was already 82% of the allowable load (0.26 kVA versus 0.32 kVA). This result indicates that the initial installed capacity will be insufficient to support the alternative drilling systems if the trial is successful and three additional pressure generation units are added. Additionally, the



initial installed capacity will not accommodate the addition of extra winches and fans as the stope matures.

Main supply cable (T7) -

As shown in Table 3-23, the maximum allowable current was less than the design requirement (235 A versus 330 A). The initial contactor trip rating was lower than the design requirement (225 A versus 250 A). As a result of the mini-sub supply limitation and the cable current limit (T7), Table 3-24 shows the supply voltages at loads L1 to L4 were below the minimum allowable undervoltage limit (0.46 kV).

Table 3-24: First iteration – POS and POC bus voltage predictions

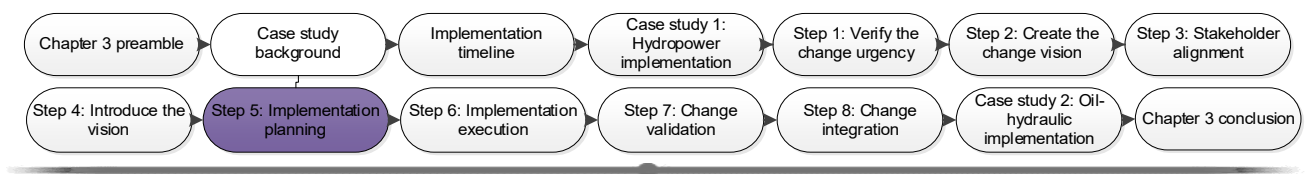
ID	Minimum [kV]	Simulated [kV]
POS bus	5.61	6.60
POC bus (mini-sub)	0.46	0.55
POC bus (mother box)	0.46	0.47
L1	0.46	0.45
L2	0.46	0.45
L3	0.46	0.45
L4	0.46	0.45
L6	0.46	0.44
Legend:		Constraint identified

Hydropower pressure generation unit supply cable (T6) -

The maximum allowable current was less than the design requirement (77 A versus 97 A). As a result of the mini-sub supply limitation and the cable current limit (T7), the supply voltages at the pressure generation unit (L6) were below the minimum allowable undervoltage limit (0.46 kV).

(C) Design changes applied

The stage validation step confirmed that the electrical supply infrastructure in its initial form would not be sufficient to support the extra load introduced by ADT. As a result, design changes were applied to the simulation model to rectify the previously identified constraints. The design changes applied include:



- Mini-sub: The initial 0.4 MVA mini-sub was upgraded to the next available size of 0.63 MVA.
- Main supply cable (T7): Based on the required load, the initial 95 mm² cable was upgraded to 150 mm². To meet the load requirements, the initial contactor was upgraded from 225 A to 300 A.
- Hydropower pressure generation unit supply cable (T6): The initial 16 mm² cable supplying the pressure generation unit was upgraded to the next available size of 35 mm².

B) Benchmark system performance against operational requirements – Second iteration

The design changes were applied to the model, and the model was re-evaluated, as illustrated in Figure 3-22. A comparison between the user interfaces of the first and second iterations shows that all the network constraints previously highlighted in Figure 3-21 were resolved through the design upgrades applied. The simulated load results obtained from the second iteration are shown in Table 3-25 and Table 3-26.

Transmission lines: The second iteration simulation predictions are shown in Table 3-26. It follows from the results that the implemented cable upgrades resolved the current constraints highlighted by the first iteration. Consequently, as shown in Table 3-27, the voltage requirements were satisfied after the transmission lines were upgraded

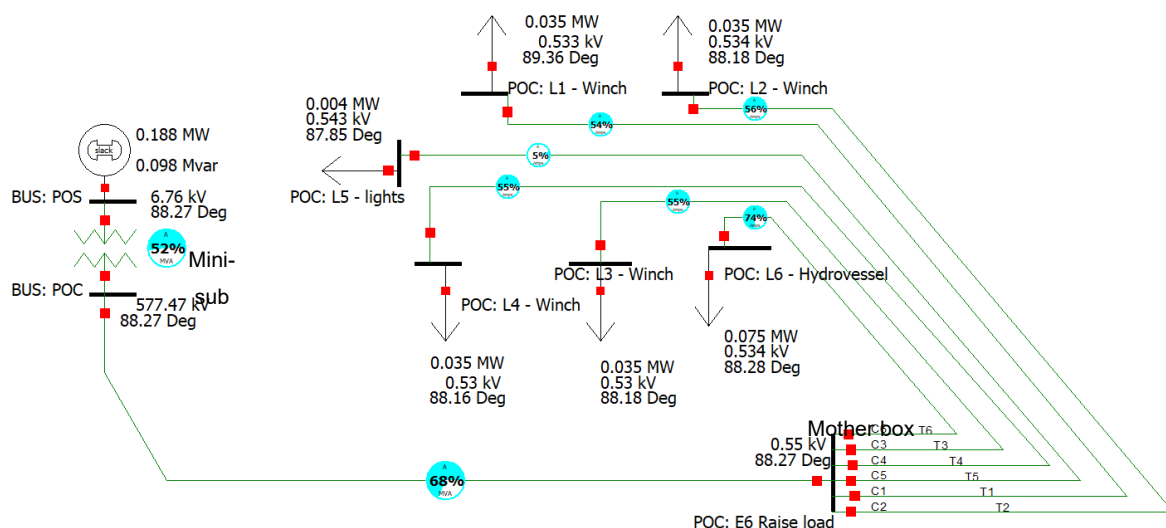


Figure 3-22: Second iteration of the electrical infrastructure evaluation assessment

Mini-sub: A critical comparison of the mini-sub simulated loads before and after the design upgrades shows that the upgrade successfully resolved the supply constraints initially identified. The results listed in Table 3-25 show that the system operated at only 52% of the new maximum full-load rating. This provided sufficient redundancy to support additional equipment as the stope matures.

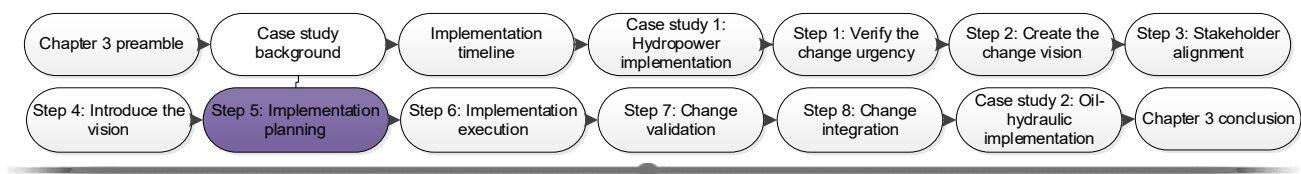


Table 3-25: Transformer load data before and after the upgrade was applied

Method iteration	ID	Maximum [kVA]	Simulated load [kVA]	Load/full-load ratio [%]
1	Mini-sub	0.32	0.26	82
2	Mini-sub	0.5	0.26	52
Legend:			Constraint identified	
			Constraint resolved	

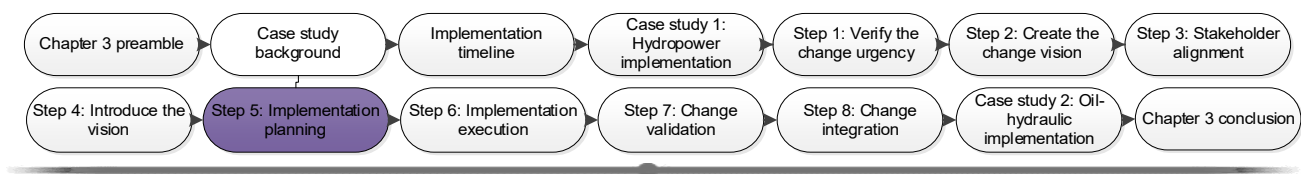
Transmission lines: The second iteration simulation predictions are shown in Table 3-26. It follows from the results that the implemented cable upgrades resolved the current constraints highlighted by the first iteration. Consequently, as shown in Table 3-27, the voltage requirements were satisfied after the transmission lines were upgraded.

Table 3-26: Simulation-predicted cable loads after upgrades were applied

ID	Required cable current [A]	Initial iteration – maximum line current [A]	Second iteration – maximum line current [A]	Second iteration – simulated continuous load [A]	Second iteration – contactor trip ratings [A]
T7	330	235	336	272	300
T6	127	77	136	60	80
Legend:				Constraint identified	
				Constraint resolved	

Table 3-27: Second iteration – POS and POC bus voltage predictions

ID	Minimum [kV]	Initial iteration – simulated voltage [kV]	Second iteration – simulated voltage [kV]
POS bus	5.61	6.60	6.60
POC bus (mini-sub)	0.46	0.55	0.57
POC bus (mother box)	0.46	0.47	0.55
L1	0.46	0.45	0.53
L2	0.46	0.45	0.53
L3	0.46	0.45	0.53
L4	0.46	0.45	0.53
L6	0.46	0.44	0.53
Legend:			Constraint identified
			Constraint resolved



Electrical infrastructure evaluation assessment summary

The overall objective of the electrical infrastructure evaluation was to determine whether the existing electrical infrastructure would have been sufficient to support the additional electrical load required to power the hydropower pressure generation unit. The original hypothesis was that electrical infrastructure upgrades would be needed to support the additional load introduced by the alternative drilling system.

The proposed infrastructure evaluation assessment methodology was used to create a digital model of the base-case stope electrical network. The hydropower pressure generation unit was added as an operational change, and the corresponding impact was evaluated. Model predictions from the first iteration showed that the base-case electrical network could not support the operational change, and the initial hypothesis was confirmed. The model was used to identify the system constraints, and design changes were implemented to address them. A second iteration of the evaluation strategy was applied, and the model was re-evaluated.

The predicted results obtained from the second iteration demonstrated that the design changes rectified the system constraints initially identified. The cable and switchgear sizes recommended for implementation are shown in Table 3-28. The mini-sub also needs to be upgraded to a 0.63 kVA unit. These overall results highlight the critical importance of performing infrastructure evaluation assessments before implementing an alternative drilling system.

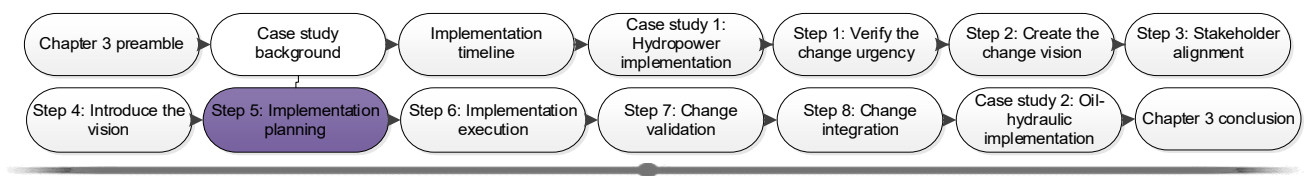
Table 3-28: Recommended cable upgrades

ID	Required cable current [A]	Maximum line current [A]	Recommended cable size [mm ²]	Simulated continuous load [A]	Recommended contactor trip ratings [A]
T7	330	336	150	272	300
T6	127	136	35	60	80

The proposed electrical infrastructure evaluation assessment methodology was successfully validated through the implemented case study, and the modelling method's objectives were met:

- ✓ Identify electrical network infrastructure limitations.
- ✓ Make design changes to remedy the limitations.
- ✓ Verify that the proposed design changes resolved the network constraints.

The design changes recommended by this model were validated through their implementation in Step 6.



Step 5.2: Assess and evaluate infrastructure – Water network

This section of the method validation process focused on validating the evaluation strategy for the water network infrastructure. In the case of water-hydraulic alternatives, the instantaneous water consumption per rock drill is three times that of its compressed air counterpart. As a result, there is an instinctive hypothesis that includes:

- The supply network may not be adequate to meet the flow and pressure requirements, resulting in frequent lost blasts, and/or
- The dewatering network may be insufficient to handle the instantaneous increase in water, resulting in an increased flood risk.

Following the five proposed steps, the water network infrastructure evaluation assessment method was implemented to assess the network's capacity to support the hydropower drilling systems.

IEA Step 1: Select the simulation package

As a starting point, the simulation package was selected by executing the two required actions listed in Figure 3-23.

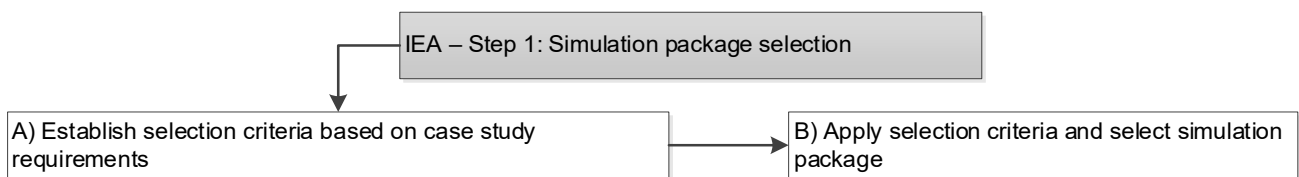
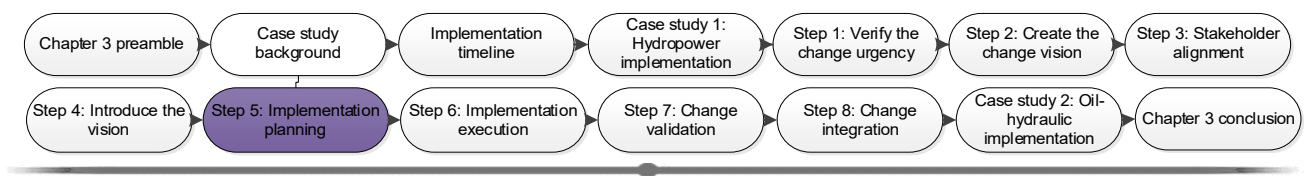


Figure 3-23: IEA Step 1 – Overview

The selection criteria were reviewed and used to filter the available simulation packages against the case study requirements. In a mine supply and dewatering network, where pipes, pumps, valves, and other components are integrated, system components will have both immediate and delayed responses to related network components [217]. This complexity necessitates the use of an integrated dynamic-transient process simulation package to assess the network's capabilities. From the list of available transient packages recommended in [Section 2.3](#), Process Toolbox (PTB) was selected for the following three reasons:

- The software can solve integrated dynamic component responses,
- Literature on previous applications to mine case studies is available, and
- The software was available to the author at the time of the study.

PTB is a simulation software package based on computational fluid dynamics code, which is designed to solve complex thermo-hydraulic networks [34]. The software offers drag-and-drop components on a three-dimensional GUI to develop large networks at scale, using digital mine plans as a reference.



Similar to the PowerWorld simulator used to model the electrical network, the PTB GUI enhances the simulation engineer's understanding of system characteristics and constraints, and helps conceptualise which design changes will resolve those constraints.

IEA Step 2: Develop a one-line diagram

To comprehend the system's integrated behaviour, a simplified one-line definition of the water supply and dewatering network was created using the process flow depicted in Figure 3-24. Four actions were executed to achieve this outcome.

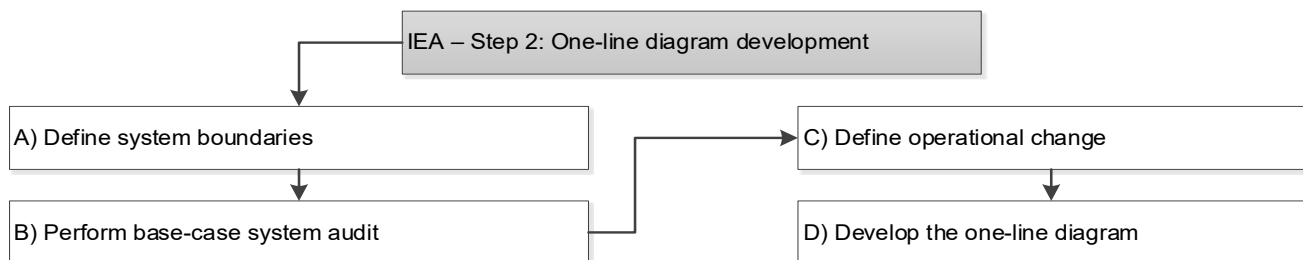


Figure 3-24: IEA Step 2 – Overview

(A) Define system boundary

The recommended top-down approach was used to define the system boundary, as water was supplied from a surface dam to the mining levels and returned to the same dam surface through the dewatering network. Figure 3-25 illustrates the initial system boundary, which encloses all hardware found within. This boundary identified the area of concern and circled the base-case and operational-change focus area.

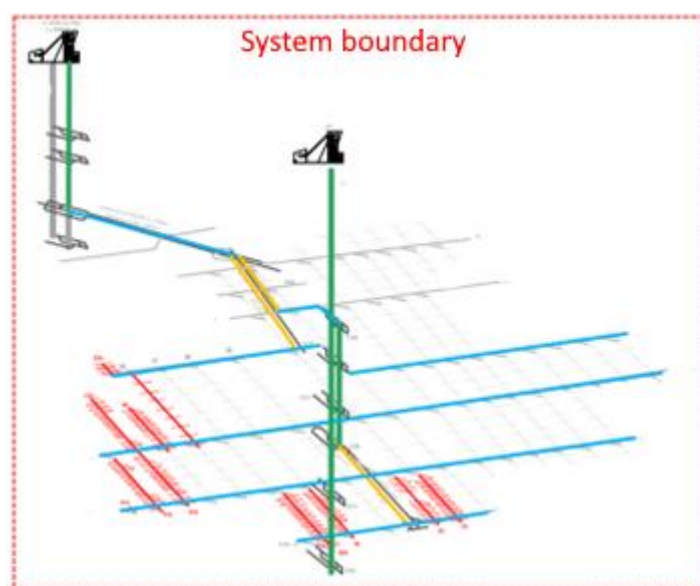
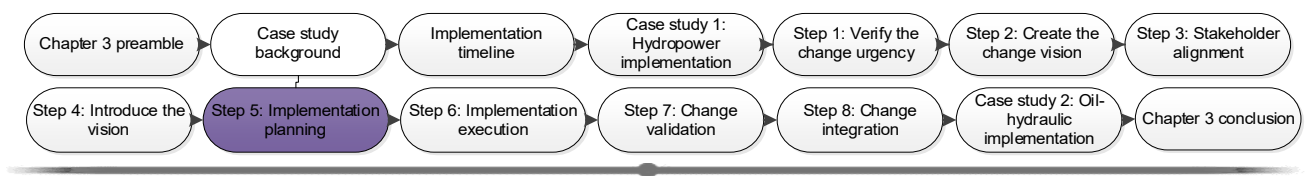


Figure 3-25: Water network system boundary



(B) Perform base-case system audit

Network infrastructure -

Manual audits were performed to gain a comprehensive understanding of the supply and dewatering infrastructure involved. Phase 1 focused on understanding the composition of hardware components in the water supply network, and Phase 2 focused on analysing the dewatering network.

To achieve these two objectives, the audit began on surface, and the network was traced throughout all the mining levels. The audit sheet provided in Table 2-14, which outlines the key audit information to capture, was used to gather all the relevant specifications needed to configure the digital components during the model development stage (IEA Step 3).

Data gathering -

Mine plan: To identify the areas of concern, the 1:2000 mine locality plan was obtained from the mine planning department. The mine plan provided information on the locations of active mining crews and on key infrastructure, such as dams and pump stations.

Supply network: The operation had no installed water network instrumentation. As a result, historical flow and pressure data were not available. To overcome this limitation, manual measurements were performed at strategic points, as shown in Table 3-29. Specialised ultrasonic measuring equipment was used to collect water flow data, while electronic pressure loggers were used to capture the corresponding water pressure data.

An abbreviated version of the dataset collected for the total instantaneous water flow rate to all the mining levels is illustrated in Figure 3-26. The flow measurements provided insights into the following important parameters, and the significance thereof is summarised in Table 3-29:

- Maximum instantaneous flows,
- Daily volumes of water consumed, and
- Time-of-use periods.

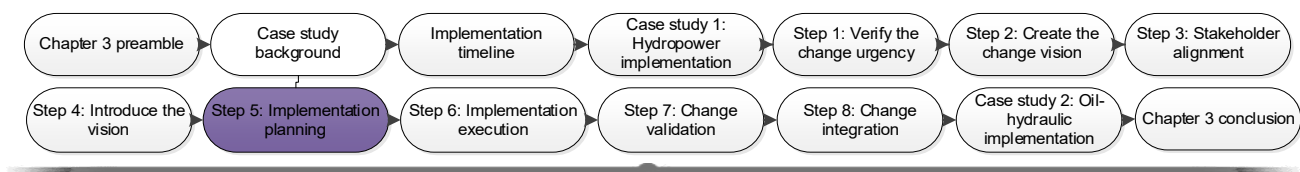


Table 3-29: Service water supply network strategic measuring points

Location	Parameters measured	Significance
(1) Surface dam	Mass flow	- Data was used to quantify the total instantaneous water flow rate of the base-case system - Data was required to calibrate the base-case model
(2) Control valves	Pressure	- Data was used to quantify the control valve outlet pressures - Data was used in IEA Step 5 to assess the control valves' capability to support the network with the required flow rate and pressure
(3) Half levels	Mass flow Pressure	- Data was used to quantify the base-case water consumption per cross-cut - Data was required to calibrate the base-case model
(4) Cross-cuts	Mass flow Pressure	- Data was used to quantify the base-case water consumption per cross-cut - Data was required to calibrate the base-case model
(5) Panel	Mass flow Pressure	- Data was used to quantify the base-case water consumption per crew - Data was required to calibrate the base-case model

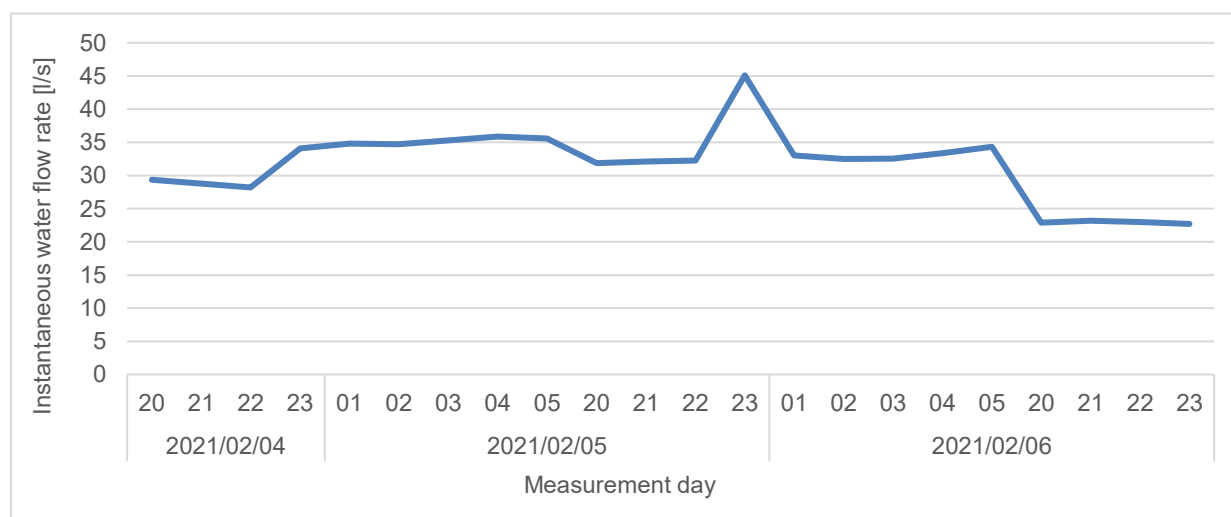
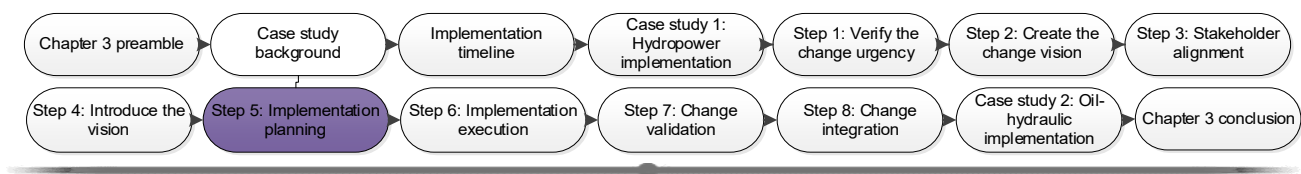


Figure 3-26: Surface dam flow profile

Dewatering network: Similar to the supply network, it had no instrumentation. As a result, manual flow and pressure measurements were taken at each dam's inlet and discharge column. The measurements provided information on the pumping schedule, time to fill, dam levels, and the number of pumps operational.



(C) Define operational change

All stopping crews who used the compressed air drilling system needed to be converted to hydropower drilling systems. The in-stope water flow measurements suggested that only 75% of the drills operated simultaneously. As a result, the average consumption per hydropower stopping crew was estimated to be 75% of the total value. The flow and pressure requirements were obtained from the OEM supplier and are summarised in Table 3-30. It is paramount at this step to not only account for the drills but also for any other water consumers added to the stopes, like waterjets, and/or backfill. The CSM, however, indicated that they will continue to use the existing face scraper cleaning and timber support strategies until the end of the life of the mine.

Table 3-30: Base-case vs operational change flow and pressure requirements

Type	Activity	Number of drills	Minimum pressure [kPa]	Average water consumption per drill [l/s]	Average water consumption per crew [l/s]
Compressed air (base case)	Development	3	250	0.22	0.66
	Stoping	5			1.10
Hydro (operational change)	Development	3	300	0.76	2.28
	Stoping	3			2.85

(D) Develop one-line diagram

The audit data were used to develop a simplified one-line diagram of the supply and dewatering networks, as depicted in Figure 3-27 and Figure 3-28, respectively. The simplified view of the supply water network showed that the in-stope water pressure and flow were governed by two key factors: pipe sizes and the flow-capacity ratings of the pressure-reducing valves (PRVs). Following Figure 3-28, the return water network's dewatering capacity was governed by three factors: the respective dam sizes, pump sets, and pipe sizes.

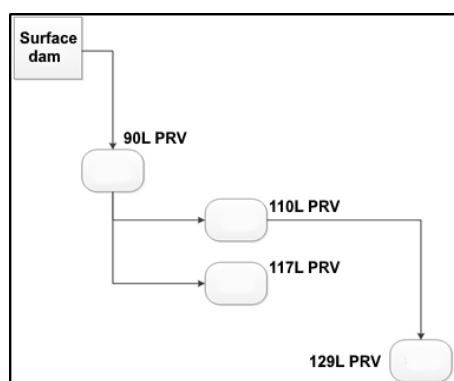


Figure 3-27: One-line diagram of the supply water network

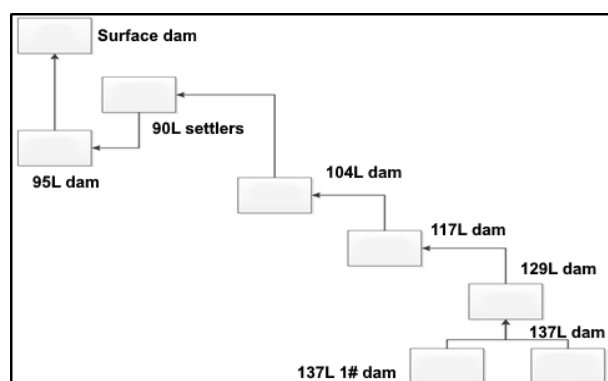
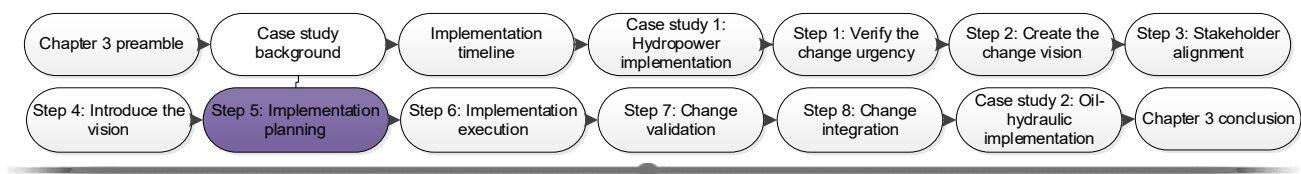


Figure 3-28: One-line diagram of the dewatering network



IEA Step 3: Translate one-line diagram into a digital twin

IEA Step 3 covers translating the one-line diagrams into digital versions of the base-case water supply and return water models using the selected simulation software package. Five component groups were used to achieve this outcome: dams, pipes, PRVs, pumps, and water demands.

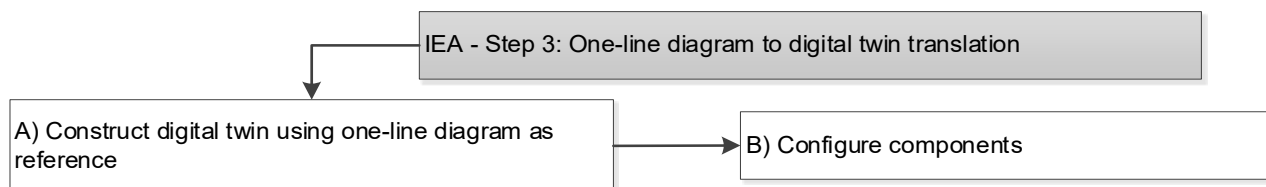


Figure 3-29: IEA Step 3 – Overview

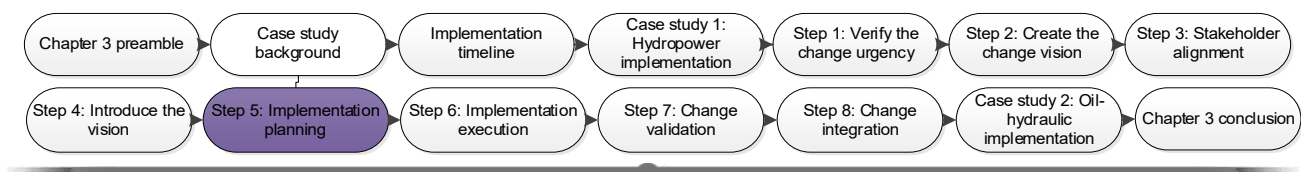
(A) Construct the simulation model using the one-line diagrams as reference

The simulation model was developed using the components in the standard PTB component library.

DXF layouts: DXF files from the mine's CADmine™ system were imported into the simulation environment to develop the supply network to scale. The DXF layouts provided the required X, Y, and Z coordinates for accurate component placement. Accurate component placement is imperative, as differences in component elevation significantly affect the model's accuracy.

Dams: Dam components were added to represent the water storage unit found on surface. The dam size was specified, and the initial dam level before the drilling shift commenced was configured.

Stope water demands: A component unique to PTB, called a stope water demand, was added to mimic the water used by the crews. This component controls the flow by assigning a specific flow based on the monthly mining schedule and activity (such as drilling, sweeping or waterjetting). These water demands were configured based on the input parameters illustrated in Figure 3-30.



Name	Unit	Initial
Width	m	1.600
Length	m	25.000
Number of Advance Holes		125.000
Advance Hole Length	m	0.800
Number of Roof Tendon Holes		0.000
Roof Tendon Hole Length	m	0.000
Number of Side Tendon Holes		0.000
Side Tendon Hole Length	m	0.000
Advance Per Blast	m	0.800
Drill Penetration Rate	m/min	0.800
Drill Water Flow Rate	l/s	0.850
Rock Density	t/m³	2.754
Water Jet		No
Monthly Tons	t	0.000

Figure 3-30: Mining water demand input window

Pipes: The surface dam was connected to each mining section using a series of pipe components. Pipe sizes and material types were specified based on the audit data and used to assign the pipe roughness coefficients automatically.

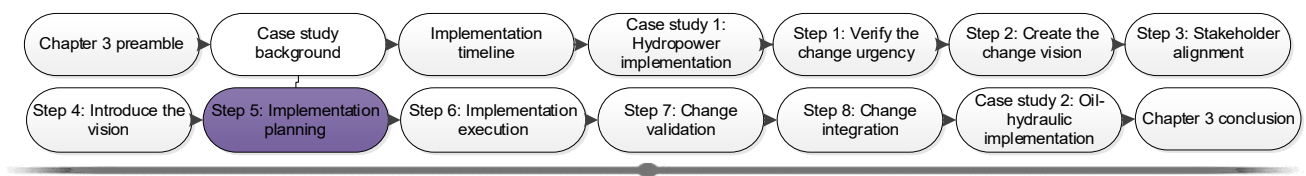
Valves: The variable valve fraction property, which represents valves, was incorporated into the standard pipe component. The mine utilised PRVs to alleviate the pressure head at strategic points. Additionally, isolation valves were commonly found at half-level breakaway, cross-cut breakaway, and in the raises.

Nodes: To adopt the network coordinates incorporated into the DXF files, nodes were added along the network route. The adopted coordinates were automatically assigned to the connected components.

Pumps: Pump sets are represented by the pump components used to generate the pressure difference in the network to induce the required flow. Pump performance curves were used to configure the pumps. The following input parameters were used to configure the pump sets: pressure coefficients, speed, mass flow rate, and motor efficiency.

Water pressure boundary: The network boundary was defined by a water pressure boundary at the start of the network and at the end of each mining process. This component was used to assign water pressure at the boundaries.

Network integration: To understand the intricate network behaviour, the service water supply and dewatering networks were integrated into a single model. This approach enabled the shaft simulation



engineer to predict the impact of increased service water demand on the dewatering network. An overview of the integrated model is shown in Figure 3-31. In Figure 3-31, the blue lines depict the service water supply network and the red lines the dewatering network.

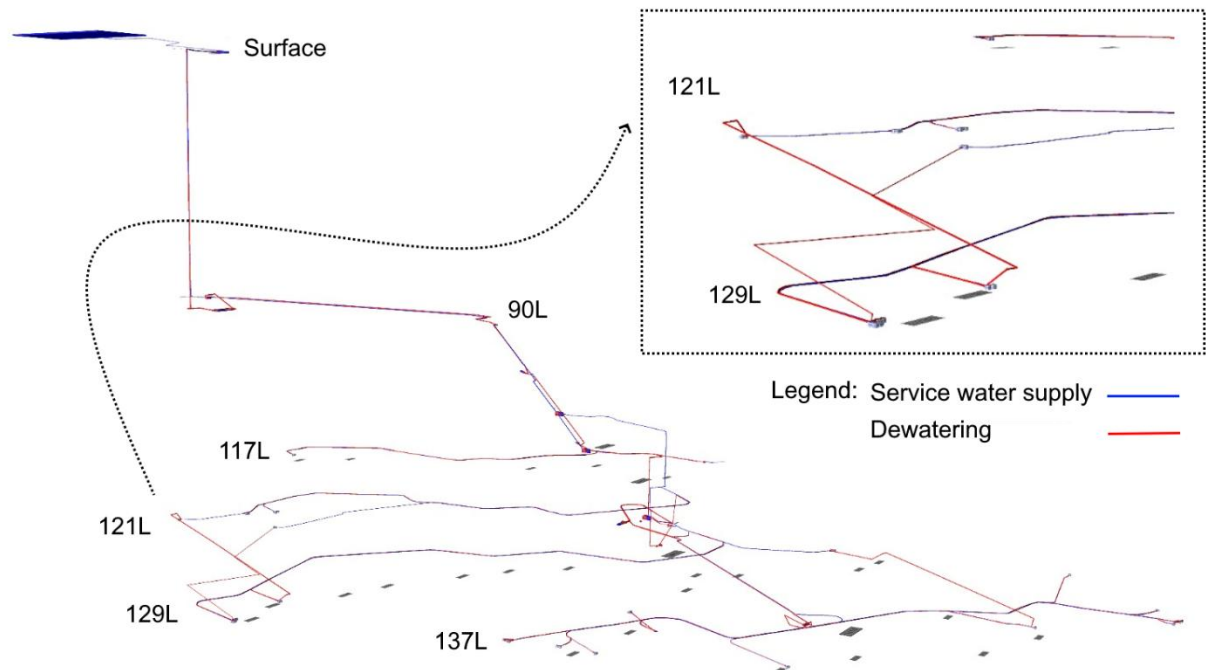


Figure 3-31: Integrated service water supply, and dewatering network

IEA Step 4: Verify base model

The process flow depicted in Figure 3-32 was used to verify the base model. The simulated flow and pressure data were compared with the measurements obtained during the underground audit (IEA Step 2) to ensure that the digital model was correctly characterised. The AMEs were calculated and used as a metric to verify the model's authenticity as a digital twin of the real-life case study. As stated earlier, an AME of less than 10% is acceptable.

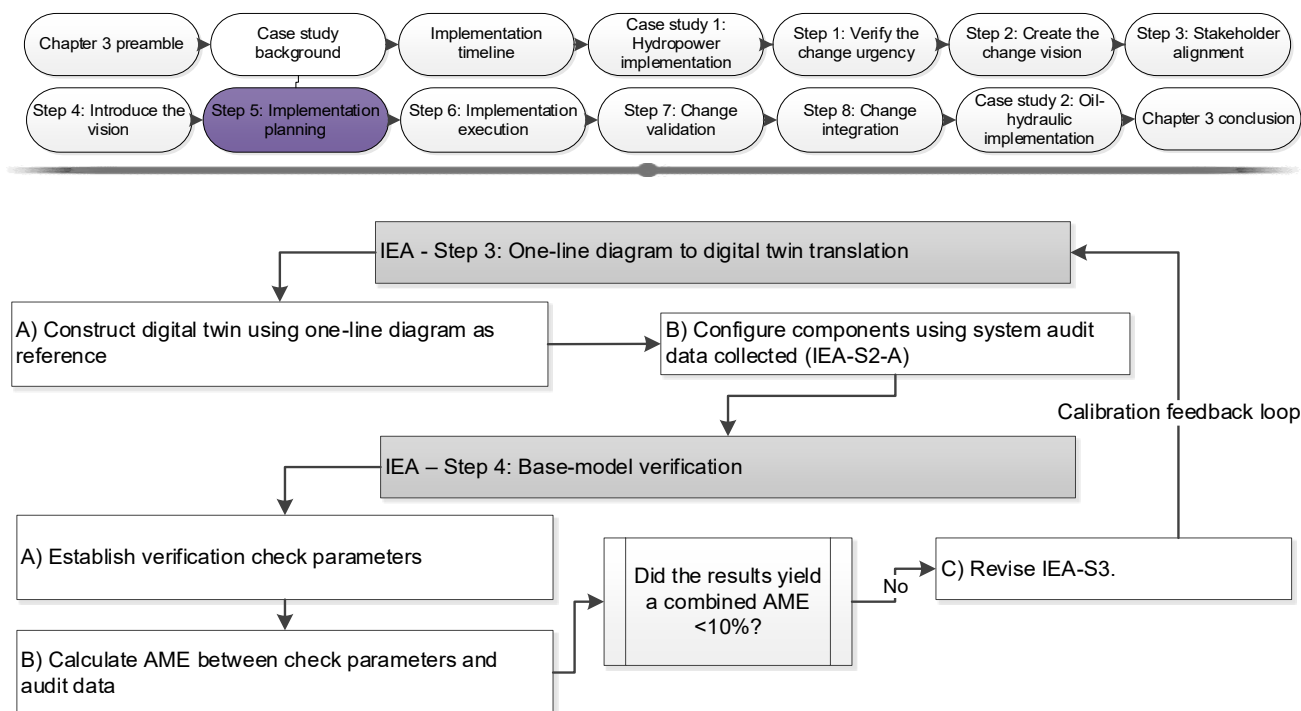


Figure 3-32: IEA Step 4 – Overview

(A) Establish verification check parameters

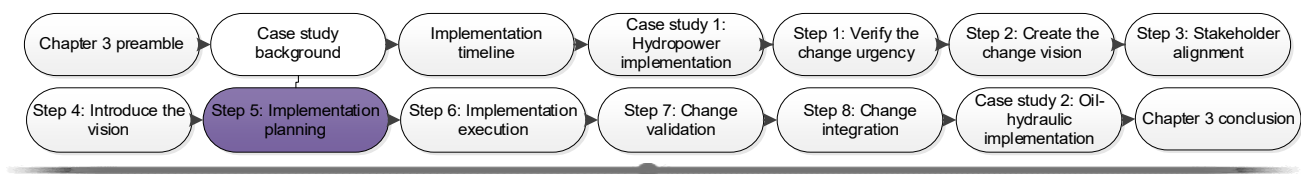
The guidance provided in Table 2-16 was used to establish the following verification check parameters, which were used in Action B to confirm the model's authenticity in terms of:

- Overall service water flow rate,
- Cross-cut service water dynamic pressures,
- Overall dewatering flow rate, and
- Dam levels.

(B) Calculate AME between the check parameters and the audit data

First iteration: The model was solved, and the verification check parameters established above were used to assess its accuracy. As an initial iteration, the AMEs calculated for the verification check parameters all exceeded the 10% threshold, as shown in Table 3-31. These results indicated the following:

- The overall flow rate from surface to the underground workings exceeded the actual measured value. This indicated that water demand was overestimated.
- An excessive pressure drop was observed at 137L. This indicated that the water pipe sizes were configured incorrectly.
- The dewatering network's overall simulated flow rate to surface was far less than measured. As a result, the underground dams flooded. This indicated that the pump sets were configured incorrectly. The pump sets were revisited, and it was noted that running schedules were configured incorrectly.



Second iteration: The shortcomings identified from the first verification iteration were revisited and rectified.

- The water demand outlet pressures were defined incorrectly.
- A follow-up underground visit revealed that the pipes on 137L were sized incorrectly during the initial audit due to a measurement error (the compressed air pipe was measured instead of the water pipe).
- The pump sets were revisited underground, and it was noted that running schedules were configured incorrectly.

The model was re-evaluated following the configuration rectifications made, and the AMEs were less than 10%, as indicated in Table 3-31. Consequently, the model was deemed an accurate representation of the base-case water network.

Table 3-31: Water network AMEs

Verification check parameter	AME – initial iteration [%]	AME – second iteration [%]
1) Overall service water flow rate	12	5
2) Cross-cut service water dynamic pressures	13	4
3) Overall dewatering flow rate	30	5
4) Dam levels	30	4

IEA Step 5: Evaluate the operational change's impact on the base model

IEA Step 5 focused on evaluating the impact of the operational change on the base model. The process followed required three actions as illustrated in Figure 3-33.

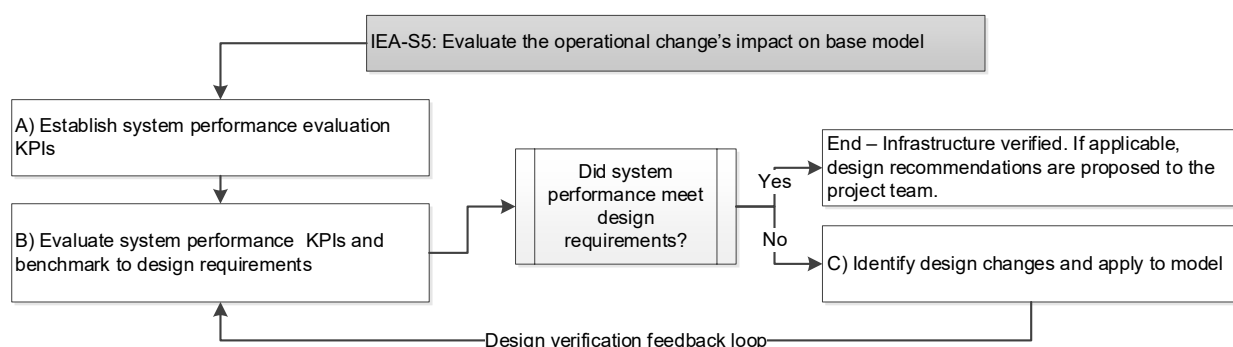
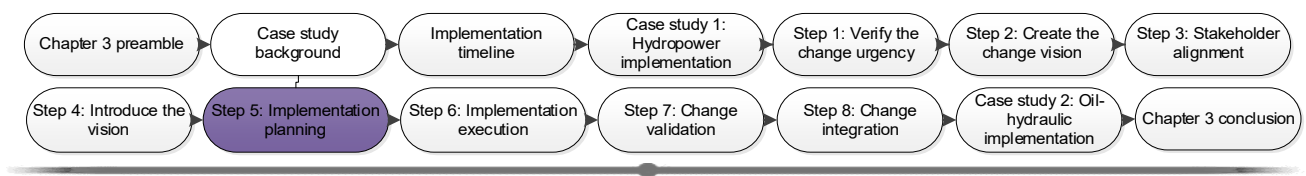


Figure 3-33: IEA Step 5 – Overview

(A) Establish evaluation KPIs

The evaluation KPIs proposed in [section 2.5](#) were adopted.



(B) Benchmark system performance against operational requirements – Initial iteration

Service water supply network: An overview of all the cross-cut pressures is showcased in Figure 3-34. The following constraints were identified from the model:

- The flow capacities of the pressure-regulating valves restricted the overall system from producing the required flow at the correct pressure.
- The main supply line on 129L reduced from 6" to 4" and continued as 4" for 400 m.
- The main supply line on 121L reduced from 6" to 4" and continued as 4" for 80 m.

It is clear from the figure that three mining sections were below the design pressure requirement of 300 kPa. As a result, Figure 3-34 shows that the constraints identified prevented the network from supplying the required flow rate at the OEM pressure specification. As a protective measure, the pumps will trip when the inlet pressure falls below 300 kPa, resulting in unwanted production losses.

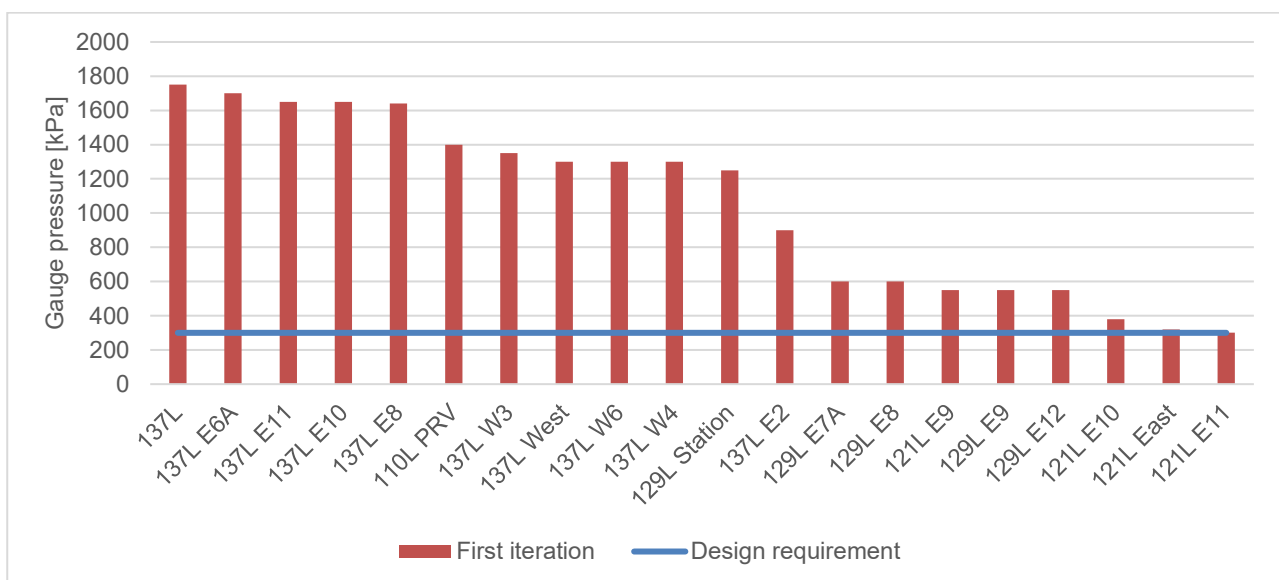


Figure 3-34: Supply water network performance vs design requirements – Initial iteration

Return water network: The return water network simulation predictions confirmed that the base-case return network infrastructure would be insufficient to support the additional return water load, as illustrated in Figure 3-35. The following constraints were identified from the model:

- The 129L pump set could not keep the dam levels within the desired levels.
- The 137L 1# pump set was not capable of keeping the dam levels within the desired levels.

These constraints result in the two main dewatering dams overflowing within the first 80 minutes of the drilling shift, and will result in flooding the levels if not addressed.

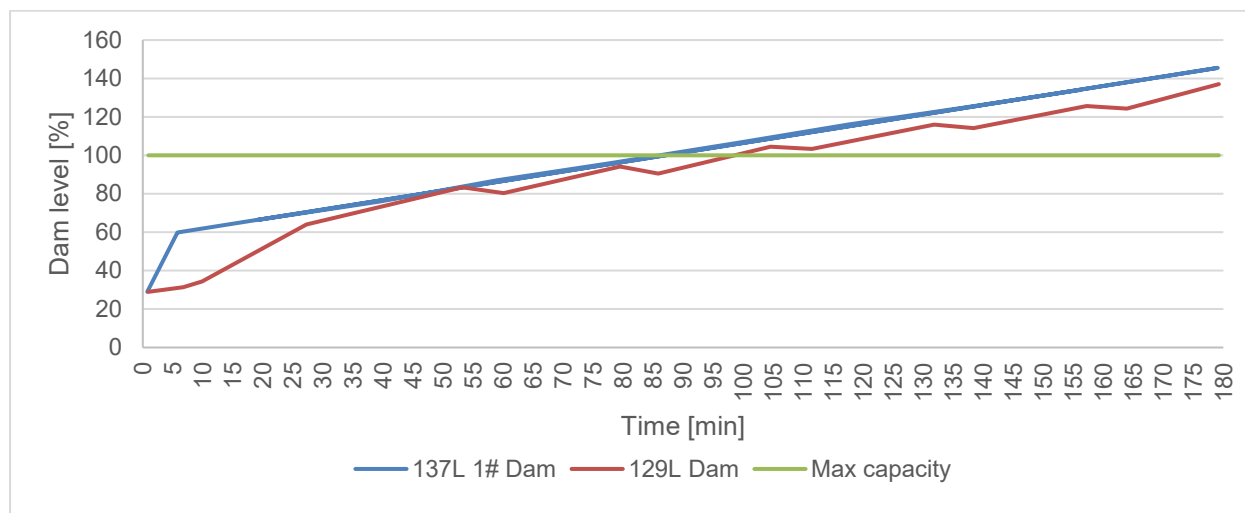
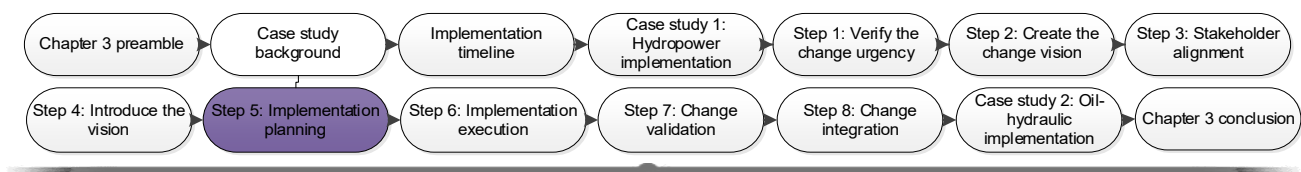


Figure 3-35: Return water network performance vs design requirements – Initial iteration

(C) Apply design changes

Based on the identified system constraints, the following design changes were applied to the simulation model:

- The ratio valve stations were upgraded from 150 NB to 200 NB.
- The 4" pipe sections were upgraded to 6" in the main haulage of 121L and 129L.
- One additional C5 pump set was installed at 129L dam.
- One additional C5 pump set was installed at 137L 1# dam.

(B) Benchmark system performance against operational requirements – Second iteration

The initial design changes in the iteration were implemented in the modelling environment, and the systems were re-evaluated.

Supply network: The second iteration, following the implementation of the design changes, produced the desired results. Figure 3-36 highlights that the cross-cut pressure profile exceeds the design requirement of 300 kPa. This result shows that the network will be able to supply the required service water flow at the specified pressure following the implementation of the proposed network upgrades.

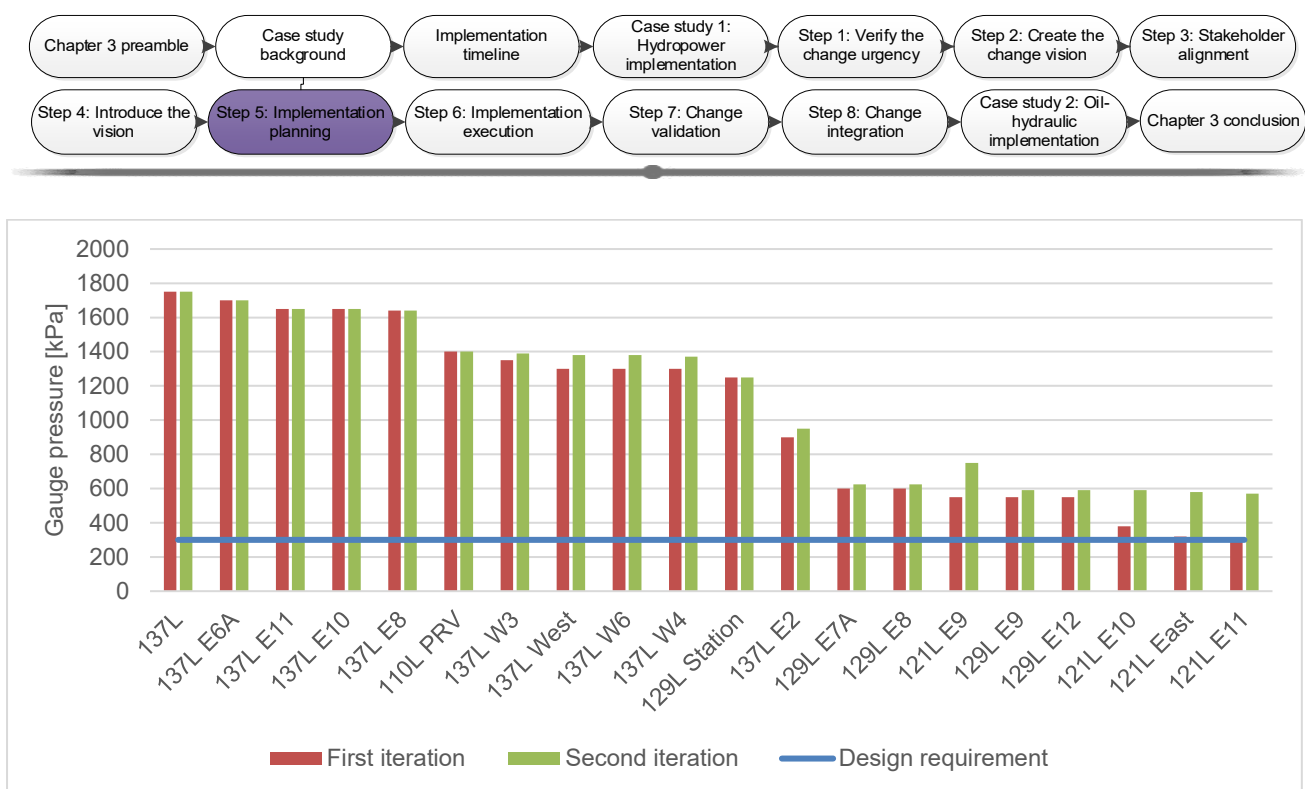


Figure 3-36: Supply water network performance vs design requirements – Second iteration

Return water network: The design changes kept all the dam levels below 100%. As a result, the proposed design changes were verified and recommended for implementation.

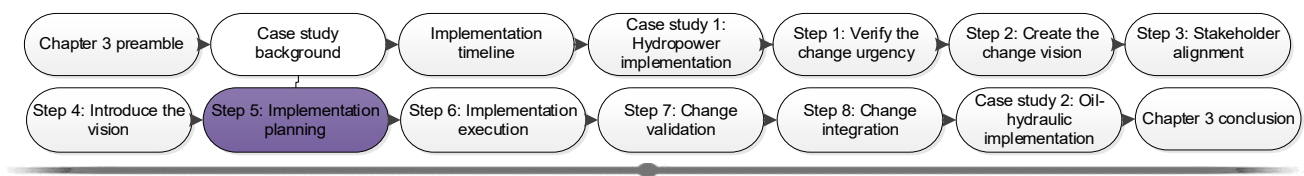
Water network evaluation assessment summary

The overall objective of the water network infrastructure evaluation was to assess whether the existing infrastructure at that time would be sufficient to support the additional water load required to accommodate the hydropower drilling systems. The original hypothesis was that infrastructure upgrades would be needed to support the additional load.

The proposed infrastructure evaluation methodology was used to create a digital model of the base-case water network. The hydropower systems were introduced as an operational change. Model predictions from the first iteration indicate that the base-case water network was unable of supporting the operational change, confirming the initial hypothesis. This result highlights the critical importance of conducting infrastructure evaluation assessments on the overall water network.

The models were used to identify the system constraints, and design changes were applied to remedy them. A second iteration of the evaluation strategy was applied, and the model was re-evaluated. Predicted results from the second iteration confirmed that the design changes resolved the system constraints initially identified. The following design changes to the base-case network were recommended:

- The PRV units must be upgraded from 150 NB to 200 NB.
- The 4" pipe sections must be replaced with 6" pipes in the main haulage of 121L and 129L.
- An additional C5 pump set must be installed at the 129L dam.



- An additional C5 pump set must be installed at the 137L 1# dams.

The proposed water infrastructure evaluation methodology was successfully verified through a case study application, and the following objectives of the modelling method were met:

- ✓ Identify water network infrastructure limitations.
- ✓ Design changes to remedy the limitations.
- ✓ Verify that the proposed design changes resolved the network constraints.

The design changes recommended by the model were validated later in Step 6 through implementation.

Step 5.3: Updates to policies, procedures and standards

Special focus was placed on advocating for the upstream and downstream impact when improving the drilling cycle. As such, personnel uncertainty regarding policy and procedural changes was addressed under Step 5.3.

(1) Incentive policies

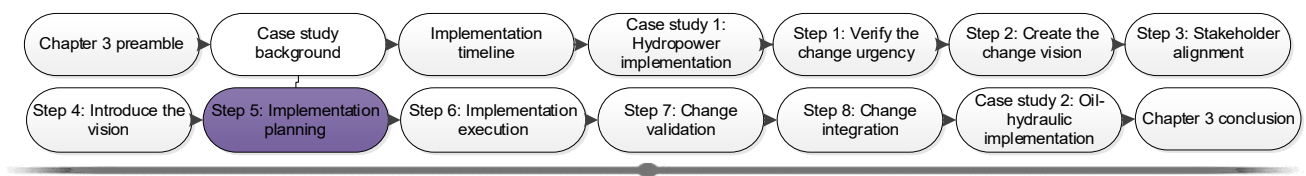
The team responsible for ensuring that the adoption incentive structure was revised to be compatible with the different phases of the change process. The end user, mining support, engineering support, and project champion were affected.

(a) End user: During the first month, while familiarisation and training were underway, the crew's production target was reduced to 75% of their normal target. For the second month, when training assessments were completed, the target was increased to 100% of normal. Assigning a production call during the transformation phase aimed to create a sense of urgency among the crew to take their training seriously and expedite adoption.

(b) Mining support: Mining personnel responsible for supporting the end users were the next focus.

- **Section managers:** The production target for Production Supervisors (Mine overseers and Shift bosses) responsible for the end users was adjusted in accordance with the changes made to the end users' call.
- **Equipping crews:** Since the hydropower drilling systems required additional infrastructure to be installed, the incentive paid to equip a workplace was revised to account for the extra time spent.

(c) Engineering support: Engineering personnel are responsible for assisting end users with equipment, water, and electricity as applicable. Hydropower drilling systems require more



engineering support than conventional systems. Since the engineering team was already fully occupied with the current workload, additional stope electricians were onboarded.

(2) Procedures and standards

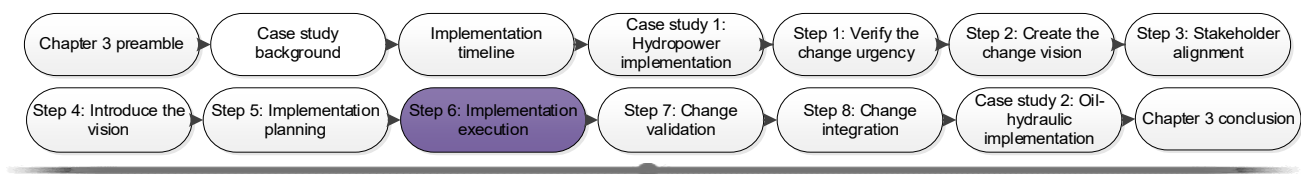
(a) The introduction of hydropower equipment necessitated updates to the operational procedures and standards. Due to confidentiality requirements, the actual procedures and standards derived are not disclosed. Instead, an overview of the process applied to perform these critical updates is provided. The two key focus areas addressed are safe equipment operation and refresher training.

(b) **Safe equipment operation:** The shaft standards committee consulted with the OEM subject matter experts. The following procedures and standards were updated:

- **Equipment installation standard:** Best practice guidelines were compiled to promote the installation of hydropower systems to standard.
- **Baseline risk assessments:** OEM high-level assessments were used as a reference to develop mine-specific high-level hydropower risk assessments.
- **Task-based risk assessments:** The high-level risk assessment identified all the equipment used to perform the mining cycle tasks. Task-based risk assessments were developed to identify all the risks associated with the equipment used to execute each task. Special awareness of the risk of mud rushes was created to highlight this new elevated risk not only to the stoping crews but also to the tramming crews, responsible for pulling the boxes.
- **Equipment safe operating procedures:** Safe operating procedures were developed to mitigate the risks involved.
- **Planned task observations:** Assessments were developed to test the crew members' understanding and compliance with the safe operating procedures.
- **Pre-use inspections:** Best practice guidelines were developed to inspect and identify faulty equipment before use.
- **Codes of practice:** The relevant codes of practice (COPs) were updated, including the compilation of a new COP for the prevention of mud rushes, as the introduction of hydropower elevated the mine's risk to mud rushes.

(c) **Refresher training:** The CSM's labour force was scheduled for annual refresher training.

- **Learning guide:** The theoretical learning material used for annual refresher training was revised in accordance with the updated procedures and standards.



- **Underground competency assessments:** After completion of surface training, crews underwent underground competency assessments. The shaft training coordinator updated these assessments to reflect the particulars of the hydropower drilling systems.

Step 6: Implement and sustain the change momentum

Step 6.1: Implement the change

The proposed implementation strategy was used to coordinate the five actions needed to implement the change, as depicted in Figure 2-24.

Action 1 – Labour engagement: Mentors and OEM subject-matter experts needed to transfer skills and knowledge were hired. The human resources leader was tasked with executing the labour engagements. The process required three months to complete.

Action 2 – Infrastructure upgrades: Step 5.2 evaluated water and electrical infrastructure assessments and recommended that critical design changes are needed to support the alternative. This action coordinated the implementation of the proposed design upgrades. The following electrical upgrades were implemented:

- **Mini-sub:** The minimum mini-substation supply capacity installed per four operational crews was 630 kVA. Figure 3-37 shows the upgraded mini-substation installed at the trial workplace.
- **Main supply cable from the mini-substation to the stope mother box:** Based on the required loads, 150 mm² cables were installed to feed the stope mother boxes, using 300 A circuit breakers.
- **Hydropower pressure generation unit supply cables:** 35 mm² cables were installed to supply the pressure generation units.

The infrastructure upgrades shown in Figure 3-39 were applied to the water infrastructure network:

- **Ratio valves:** The ratio valve stations were upgraded from 150 NB to 200 NB. Figure 3-38 illustrates one of the upgraded ratio valve stations.
- **Pipe sizes:** The 4" pipe sections (1.6 km in total) were replaced with 6" pipes in the main haulage of 121L and 129L.
- **Dewatering pumps:** An additional C5 pump was installed at both the 129L and 137L1# dams.

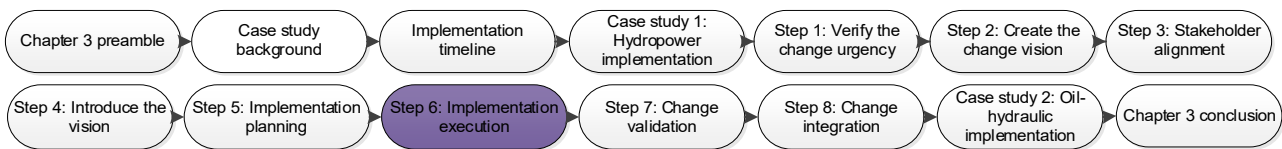


Figure 3-37: Newly installed 630 kVA mini-substation¹⁷



Figure 3-38: Newly installed 200 NB ratio valve station¹⁸

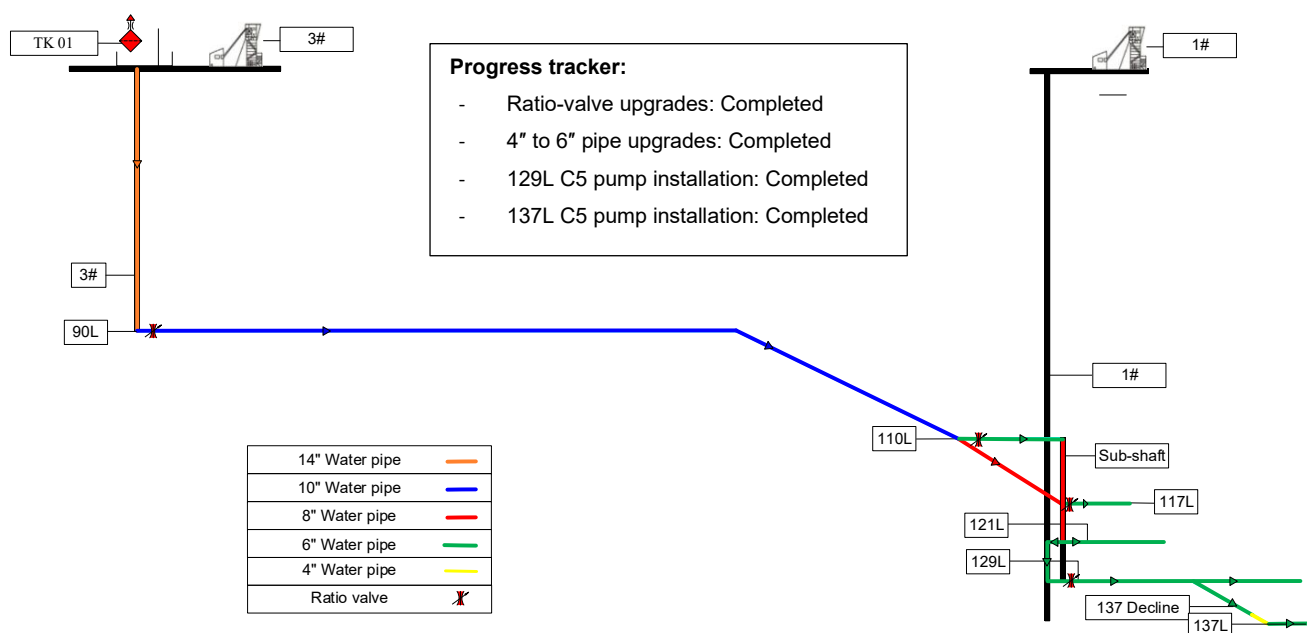


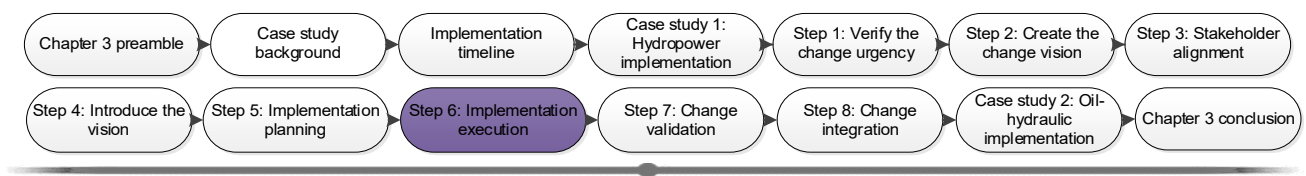
Figure 3-39: Service water supply network overview after implementation of infrastructure upgrades

Action 3: Alternative drilling system installation and commissioning

All tasks required to install and commission the alternative system, as scheduled in Step 6.1.D, were executed. The installation standard developed in [Step 5.3: Updates to mine policies, procedures, and standards](#) was used to ensure the equipment was installed to standard. The mine's equipping crews

¹⁷ B van Rooyen, Personal photograph, "Newly installed 630 kVA mini-substation", 2023.

¹⁸ B van Rooyen, Personal photograph, "Newly installed 200NB ratio valve station", 2024.



were initially unfamiliar with the installation procedures and received familiarisation training facilitated by the OEM supplier.

After completing the system installation process, the system was commissioned. The process required a start-up risk assessment involving all departments, including mining, safety, ventilation, engineering, OEM supplier, and organised labour. The purpose of the risk assessment was to ensure that all departments declared the system safe for use by the mining crew.

Action 4: Alternative drilling equipment transitioning

This action was used to execute the equipment transitioning strategy developed in [Step 5.6: Equipment transition strategy](#).

Surface induction

Surface induction focused on achieving two strategic outcomes, including: ADTT Step 1: Introduction to fundamental equipment differences and ADTT Step 2: Introduction to equipment's impact on the overall mining cycle.

ADTT Step 1: Introduction to equipment operational fundamental differences

The equipment transition process was initiated by formally introducing the fundamental differences in equipment operation and product support. Surface mock-ups were constructed to serve as training facilities, as illustrated in Figure 3-40 and Figure 3-41. To gather and maintain the end users' undivided attention, the stope teams were removed from the workplace, and equipment induction was conducted on the surface. The six key operational differences in equipment focus areas were shared with the end users, including: overall equipment care, maintenance cycle, engineering support, equipping support, safety, and training.

The objective was to introduce the fundamental differences in equipment for end users. To facilitate the session, the equipment demonstrated in the surface mock-up was used. During this interactive session, the crews were instructed how to connect the equipment. They drilled a few sample holes to introduce the ergonomics. Interpersonal communication was used to promote participation. This approach exploits the fact that the human brain tends to understand and remember better when visual representations are used to describe important concepts.

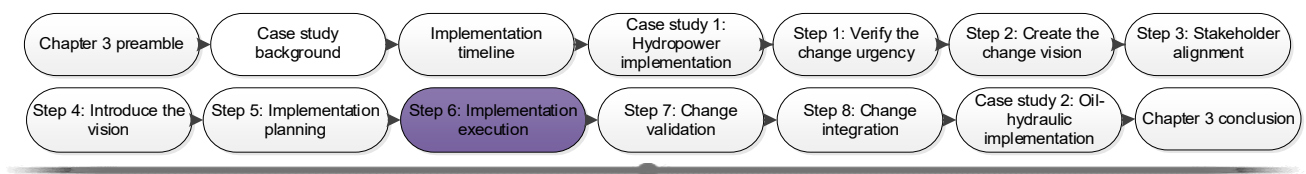


Figure 3-40: Surface waiting area mock-up constructed as a training facility¹⁹

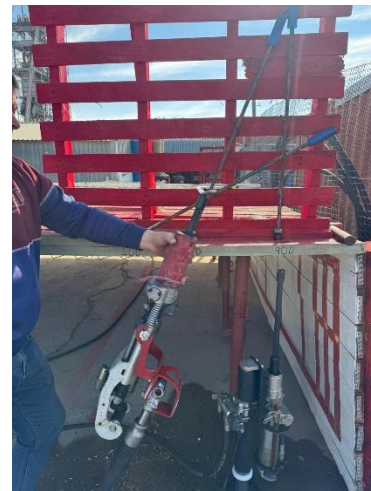


Figure 3-41: Surface stope mock-up constructed as a training facility²⁰

ADTT Step 2: Introduction to the downstream impact of face advance improvement initiatives

The second strategic outcome of the surface induction session was to familiarise the end users with the downstream impacts of implementing an ADT. Consequently, the second layer of the surface induction session focused on sharing the ADT's impact on the mining cycle, including drill rate, support, logistics, cleaning, and face length. These five impact focus areas were duly explained not only to the stope team but also to line management.

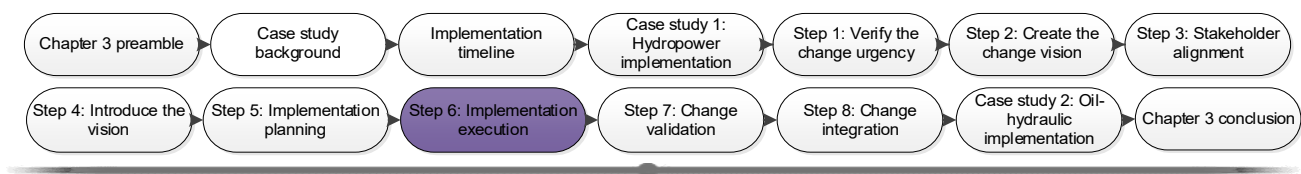
Equipment transition training

ADTT Step 3 to ADTT Step 6, as shown in Figure 2-22, contain the enabling strategies to transition from compressed air equipment to the alternative. The OEM provided trainer facilitators. They were the subject matter experts who trained both the crews and mine trainers. A key component of the transition strategy's success is the integration of the mentors with the crew. Mentors were sourced and integrated with the crews.

The significant risk of financial losses was highlighted earlier as one of the key implementation failure drivers. To overcome this significant risk, this study used the proposed sequential approach (see Figure 2-22) to integrate the equipment as follows:

¹⁹ B van Rooyen, Personal photograph, "Surface waiting place mock-up constructed as training facility", 2022.

²⁰ B van Rooyen, Personal photograph, "Surface stope mock-up constructed as training facility", 2022.



ADTT Step 3: Gully RDO equipment transitioning

The first sequence of the strategy involved introducing the alternative drill to the RDO in the gully. At the same time, the other RDOs continued to use conventional machines. This approach generated remarkable interest as the RDOs drilling the face were exposed to the new rock drill's performance. The number of dedicated training sessions required will depend mainly on RDO commitment, since the equipment ergonomics are similar to those of the conventional machine. The mentor fulfilled an important catalytic role in helping them manage the stress and anxiety associated with the unknown equipment. A trainee is deemed capable once they successfully demonstrate the ability to use the equipment for a full shift and apply basic fault-finding tactics with little to no facilitator intervention. The gully RDO was trained to be proficient with a new machine within two days. The RDO was then subjected to a competency validation assessment. This assessment was performed by the mine's trainer assessors, and the RDO was asked to demonstrate all the skills required to safely operate the alternative equipment. Once competent, the trainer proceeded to the next RDO (ADTT Step 4).

ADTT Step 4: Face RDOs equipment transitioning

At this stage of the process, the gully RDO was deemed competent, and the RDO at the bottom of the panel was trained next. This sequence allowed the trainer to focus solely on the RDO at the bottom, while he was next to the gully RDO in case assistance was required. The remaining RDOs continued to use the pneumatic equipment until the RDO in the bottom section was deemed competent.

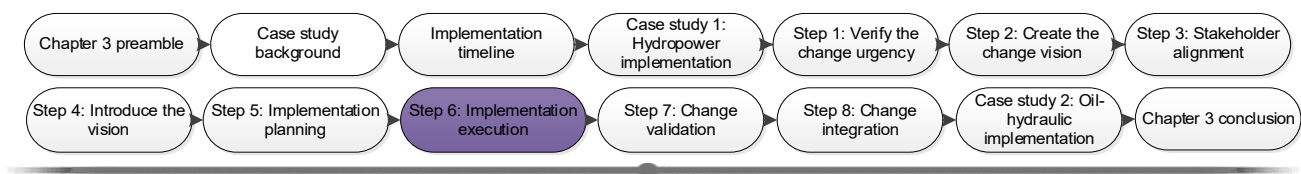
The RDO at the top of the panel followed next. The trainer focused solely on this RDO while monitoring the RDO in the bottom section. By this time, the gully RDO was able to operate the new machine independently. Three training sequences were required since the average face length is around 30 m, and one drill per 15 m of face length was necessary. The additional RDO who was trained formed part of the crew's leave complement.

ADTT Step 5: Roof bolt RDO equipment transitioning

The RDO drilling the roof bolts was trained after the RDOs drilling production holes were deemed competent. Roof bolt support holes were drilled using a dedicated roof bolter RDO. The equipment used to drill roof bolts differed from the drills used on the face and required dedicated focus. Training continued for three days until the roof bolt RDO was deemed competent.

ADTT Step 6: Ancillary equipment transitioning

At this point in the transition process, the RDOs were certified as competent. The stope team members were trained to use the ancillary equipment. The training covered chainsaws, prestressing



pistols, dewatering pumps, and blasthole cleaners. The stope team members were also subjected to a competency assessment to confirm that they know how to safely operate the ancillary equipment.

ADTT end: Crew converted

Finally, the mine's trainer assessors have found all RDOs and stope team members capable of using the new equipment. The crew continued to use the equipment after the training month and did not revert to their old machines. This outcome confirmed that the crew had been converted successfully. The OEM trainer remained at the workplace the following month to provide additional support and refresher training if needed. No lost blasts were recorded during the equipment transition phase. This result validates the usefulness of the equipment transitioning strategy.

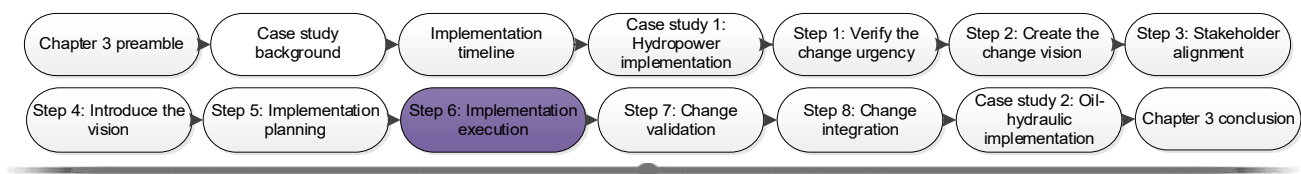
Action 5 – Practical application of the change management methodology (CMM)

The fifth implementation action required the mine management team to apply the change management methodology. To achieve this outcome, the study instituted a weekly change-management meeting. All stakeholders were encouraged to be present, and attendance records were kept. The change management method, as outlined by Figure 2-21 was adopted as the weekly meeting agenda, and the change management strategies were implemented using the following five actions.

CMM Action 1: Promote change willingness

With compressed air machines, end users were equipped with a tool they were familiar with, simple to operate, reliable, and that consistently performed well. The willingness to change increased as the end users began to experience the improved benefits of the alternative technology. To influence this outcome, the following five key actions were executed:

- (1) **Promote the vision:** The vision collectively highlighted the benefits of change and was aimed at fostering stakeholder buy-in. By advocating the change vision weekly, the mine management team had a regular opportunity to positively influence stakeholders' attitudes, beliefs, and feelings toward the change.
- (2) **Prove the change benefits on a small scale:** Stakeholders' attitudes, beliefs, and feelings were further influenced by first demonstrating the change benefits on a small scale. End users experience severe levels of anxiety and stress when they need to operate or use new, unfamiliar technology. Consequently, a gradual approach was necessary to introduce the technology.
- (3) **Change integration:** Once the benefits materialised and the initial end users successfully adopted the technology, it was rolled out to the remaining crews. The technology was first



trialled on a small scale using a single panel. The trial provided practical exposure, which enhanced stakeholder confidence in the alternative technology. This multi-layered approach ensured that end users were adequately equipped to cope with the change, thereby preventing a change shock wave.

(4) Select the correct initial end users and workplace: Previous research suggests that the success of the initial trial strongly depends on the initial end users selected. This study selected a well-ventilated, easily accessible workplace with stable ground conditions as the trial panel. The initial end users were a young, average-performing crew with an approachable mindset. They had little to lose but much to improve. Consequently, selecting the correct workplace and initial end users significantly promoted the willingness to change.

(5) Celebrate short-term wins: Since people tend to sustain their best performance when they know their current efforts are noticed and appreciated, this study intentionally focused on celebrating short-term wins. The short-term wins celebrated are highlighted in [Step 6: Sustain the change momentum by celebrating short-term wins](#).

CMM Action 2: Identify and manage misperceptions

Adverse reactions to the change were initially observed, as it was believed to lead to increased workload, fatigue, and/or job uncertainty. Actual exposure to the ADT's operational and performance parameters, such as operational complexity, reliability, robustness, and drilling speed, was initially unknown to stakeholders. As a result, misperceptions stemming from ignorance instigated resistance to change. The following strategy was used to manage misperceptions by aligning stakeholders' perceptions with the facts. The approach required the following two actions:

(1) Identify false perceptions: The management of misperceptions among all stakeholders must be an agenda item during the weekly change management meetings. To identify potential misperceptions, the mine management team encouraged all stakeholders to share their perceptions. The stakeholders ultimately shared eight perceptions, as listed in Table 3-32.

(2) Use facts to correct false perceptions: The mine management team formulated an in-depth understanding of the false perceptions by analysing the actual data gathered at the trial panel, using [Step 7: Validation of change benefits](#). Facts were formulated and shared with stakeholders to correct misperceptions. Table 3-32 presents an overview of the facts gathered and shared to correct the misperceptions. This approach was successful in managing stakeholder resistance to change, as all crews adopted the hydropower technology.

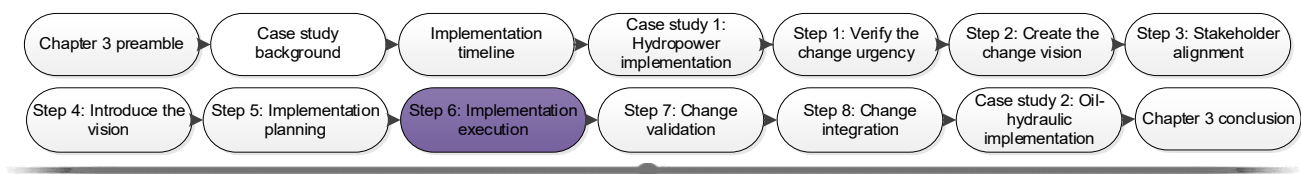
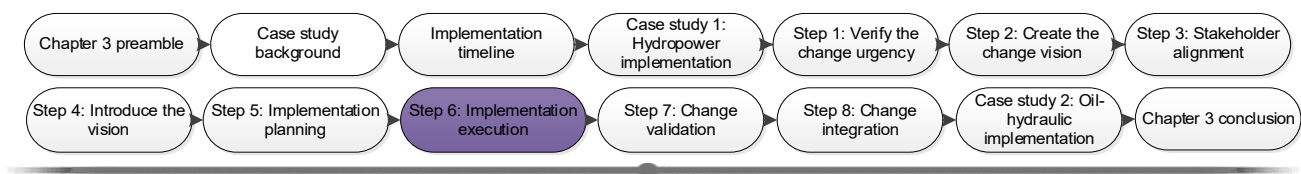


Table 3-32: False perceptions identified versus facts used to manage it

False perceptions identified	Fact(s) used to correct the false perception
(1) The extremely high pressure (180 bar) associated with hydropower drilling systems is a safety risk. This misperception sparked fear among end users about using the equipment.	- Hydropower equipment is designed and manufactured to recognised international standards. - The equipment is fully risk assessed, and the necessary safety valves are incorporated into the system design and configuration to shut off the flow in case of pipe leaks or hose bursts.
(2) Hydropower systems use significantly more water than their compressed air counterparts. This misperception sparked fear among the engineering team that the infrastructure would not be able to sustain the supply and dewatering requirements.	- The actual results gathered from the trial panel confirmed that hydropower uses more water instantaneously. However, it ultimately uses a smaller volume of water as the rock drills drill faster, and the equipment is equipped with auto-shutoff valves when not in use. - The execution of Step 5.2: Infrastructure evaluation assessments focused on identifying and recommending the infrastructure upgrades required. - Step 6: Implementation focused on implementing the required infrastructure upgrades, thereby enabling the water network to support the ADT.
(3) Hydropower will flood the workplaces. This misperception sparked fear among the mining team that an increased influx of water would result in mud rushes.	- This is the exact reason why the implementation standard requires the use of hydropower jet pumps. - The jet pumps enable the crews to pump the water from the strike gully floor into a dedicated draining column routed along the strike and dip direction of the stope.
(4) Hydropower rock drills are unreliable. This misperception sparked fear among the mining and engineering team that reduced rock drill reliability would result in frequent lost blasts.	- The actual results gathered from the trial panel initially confirmed this perception, as the rock drill reliability figures averaged around 221 m drilled per failure. However, the OEM analysed the failures and implemented design changes to improve the equipment's reliability. - Following the implementation, the rock drill reliability improved to 539 m drilled per failure. - Twelve rock drills per crew were allocated based on the failure rate of 539 m/failure and the logistical constraints experienced at the operation. This allowed for four drills to be used, four in transit, and four in the repair shop.
(5) It is impossible to drill a 30 m face with only two RDOs. The mining team feared that the crew would not have enough time to complete the drilling cycle if only two rock drills were used.	- The actual drilling cycle time duration results gathered from the trial panel confirmed that due to the hydropower rock drill's improved performance, the crews managed to finish the 27 m trial panel within 5 hours. - This result highlights an additional benefit, as it confirmed that hydropower provides an effective means to manage RDO absenteeism.



False perceptions identified	Fact(s) used to correct the false perception
(6) The use of only two rock drills on the face will result in crew members being dismissed. The crews feared that the improved rock drill performance would lead to reduced crew size, as some crew members would be dismissed.	- The CSM's historical absenteeism data revealed that the operation's daily RDO absenteeism rate was 7%. - This result highlighted the opportunity to promote improved performance as an effective means to manage RDO absenteeism.
(7) Hydropower equipment is heavier than its compressed air counterparts. The crew initially believed that the increased equipment mass load would contribute to increased levels of fatigue.	- A scale was used inside the trial panel to perform a side-by-side equipment weight comparison. - The results confirmed that the equipment mass load remained unchanged.
(8) The additional heat introduced will result in adverse workplace air temperatures. Since the CSM did not have chilled water to offset the additional heat, the occupational hygiene team feared that the additional heat would cause workplace air temperatures to exceed legal limits, resulting in lost production.	- The actual air temperature data gathered in the trial panel confirmed that: • The wet-bulb air temperature increased by 1.0 °C if the rock drill exhaust water remained uncontrolled. • The wet-bulb air temperature remained unchanged if the rock drill exhaust water was controlled by means of a dump hose installed at the rock drill exhaust port and using the jet pump to remove the water from the workplace. - This result highlighted the importance of complying with the water control standard.

CMM Action 3: Promote an inclusive leadership style

The leadership team's active involvement encouraged stakeholders to feel equipped to cope with the change. Credibility and trust were essential leadership credentials to promote by responding promptly to stakeholder demands. This successful outcome was achieved through interpersonal communication and managerial involvement as follows.

- (1) Promote interpersonal communication and managerial involvement:** Change ownership was advocated through an inclusive leadership style, as highlighted in Figure 3-42. The weekly change management meeting gave each stakeholder a voice, promoting ownership and accountability. Periodic underground visits by the multidisciplinary project team were leveraged as an effective means to underscore that all stakeholders were working together in a collective effort. Adaptive communication was of paramount importance to address the misperceptions highlighted earlier, as some stakeholders responded best to detailed, data-backed explanations or logical arguments. In contrast, others were simply interested in concise, high-level summaries. As shown with the performance curve presented in Figure 3-42, intentional focus was placed on sharing the trial study results. The success stories shared during these sessions reinforced the credibility of the change initiative.

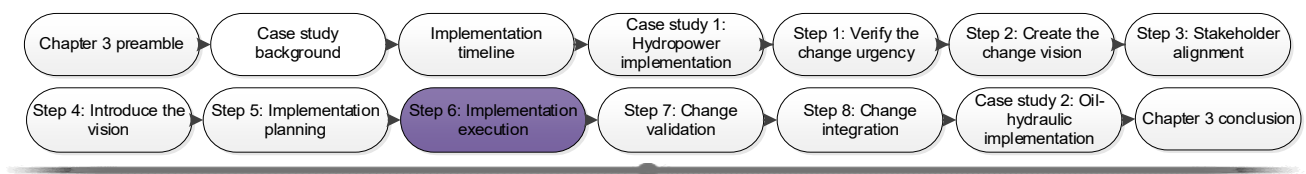


Figure 3-42: Process illustration where trial study results were shared with the stakeholders during one of the weekly change management meetings²¹

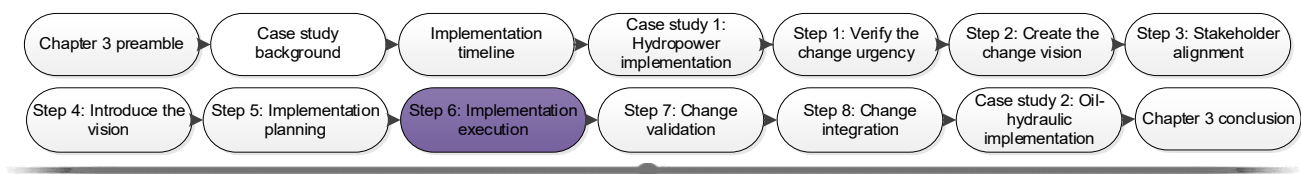
(2) Promote end user support: OEM supplier, engineering, and mining support played an essential role here. Once the crew raised any need or concern, the multidisciplinary team acted swiftly to resolve the highlighted challenges. The end users' trust was earned by addressing the concerns and suggestions raised in a timely manner. The key to success here was keeping the end users positive and motivated. The more the crews were assured that the managerial team would accommodate their needs and address their concerns, the more energy they brought to drive the change. It is, however, important for the mine management team to remain closely involved in the implementation and adoption actions. This enabled them to filter out the stakeholders' actual needs and concerns from poor excuses and commitments for not fulfilling their roles and responsibilities.

CMM Action 4: Manage emotional wellness

(1) Difficulties experienced during the change process triggered frustration, anxiety, and ultimately initial despair: Deliberate composure was needed to prevent impulsive reactions that often lead to poor decisions. Reduced levels of change motivation initially prevailed when employees became negative towards the change. The developed strategy to manage emotional wellness required two actions: introducing and integrating mentors, and avoiding excessive change.

(2) Introduce and integrate mentors: The trial study confirmed that there is no substitute for learning from someone who has already been through the process. This emphasises the importance of recruiting mentors to build alliances and share testimonials. The introduction of one key influencer per crew made it easier to persuade the entire group. The key roles and responsibilities of the mentors were to serve as initial ambassadors and promote the

²¹ B van Rooyen, Personal photograph, "Process illustration where trial study results were shared with the stakeholders during one of the weekly change management meetings", 2024.



technology. Mentors helped alleviate the fear of job loss, as well as stress and anxiety, by advocating for improved benefits.

(3) Stick to the multi-layered sequential method to avoid excessive change: The proposed multi-layered sequential approach was used to gradually introduce ADT. This approach helped manage the stress and anxiety caused by excessive change. Change shock waves were avoided. The mine management team did not deviate from the proposed multi-layered sequential approach, as skipping steps to expedite implementation would have only created illusory progress at the expense of promoting change resistance. A realistic roll-out plan was crucial to managing stakeholder expectations. Paramount to a realistic roll-out plan was the prioritisation of workplaces, from worst performers to best performers. [Step 8.1: Sequential multi-layered approach to expand the change process](#) provides a detailed overview of how the workplaces were successfully prioritised.

CMM Action 5: Align planned and actual change implementation and adoption progress

The stakeholder alignment strategy was used to maintain the urgency for change, promote stakeholder participation, uphold stakeholder accountability, enforce transition strategies, and develop technology support systems. The overarching objectives were to align interests and foster a culture of shared purpose. Weekly progress comparisons to planned objectives reinforced urgency, inspired participation, imposed accountability, and supported transition strategies. The responsibility chart developed in Step 3: Stakeholder alignment was used to reiterate roles and responsibilities. This approach encouraged participation, accountability, and ownership while promoting effective communication.

Step 6.2: Sustain the change momentum by celebrating key change process milestones

The implementation of the change left the crew feeling uncomfortable at first, prompting an automatic response to revert to the old, comfortable way of doing things. To overcome this, the strategy developed to sustain the change momentum was implemented. Crews tend to perform at their best when their current efforts are acknowledged and appreciated. This result emphasises the importance of short-term wins. Acknowledging and celebrating these wins helped to boost morale and energy levels, driving the change. The following change process milestones and short-term wins were celebrated: completing the equipment transition phase and achieving production call.

As illustrated by Figure 3-43, the crew members received their competency certification during the weekly safety meetings. At the same time, illustrated by Figure 3-44, a large notice board was installed at the operation's main gate to publicly recognise the achievements of the best crew, miner, and shift boss.

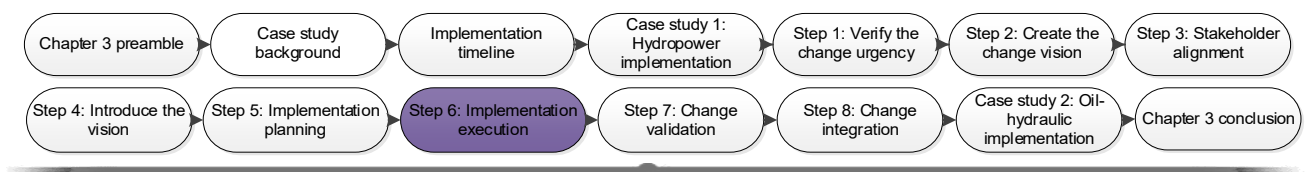


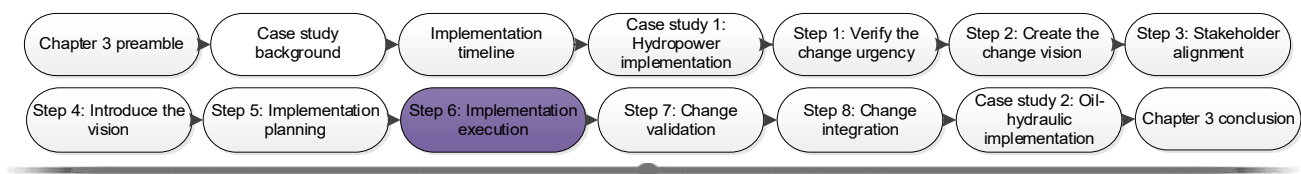
Figure 3-43: Crew members receiving their competency certification²²



Figure 3-44: Celebrating short-term wins – Best crew, miner and shift boss acknowledgement board²³

²² B van Rooyen, Personal collection, "Crew members receiving certification", 2023.

²³ B van Rooyen, Personal collection, "Acknowledgement board", 2025.



Phase 2: Change implementation summary

The main objective of the second phase of the change process was to implement it through Steps 5 and 6. Step 5 focused on implementation planning, while Step 6 facilitated the implementation process. The strategic objectives of the corresponding strategies formulated to achieve this outcome are shown in Table 3-33. The second phase of the change process met the required objectives, confirming that there was no need to revise Steps 5 and 6.

The results discussed in this section validate the following:

- **Implementation Planning:** Step 5.1 guided the mine management team in selecting the best system configuration. The infrastructure evaluation assessments were successfully executed using Step 5.2, and the infrastructure upgrades were successfully formulated. Step 5.3 addressed the necessary updates to the mine's policies, procedures, and standards. The implementation plan formulated in Step 5.4 guided the successful implementation of the alternative technology. Step 5.5 yielded a robust change management strategy that successfully guided the change management process. The equipment transition strategy executed in Step 5.6 successfully guided the equipment transition, with no equipment transition-related lost blasts occurring during this phase of the change process.
- **Implementation execution:** The strategies and corresponding actions formulated under [Step 6.1: Implement the change](#) were successfully used to implement the change since all the crews successfully adopted the ADT. The celebration of small-term wins ([Step 6.2: Sustain the change momentum](#)) sustained the change momentum

The second phase of the change process met the required objectives, confirming that there was no need to revise Steps 5 and 6.

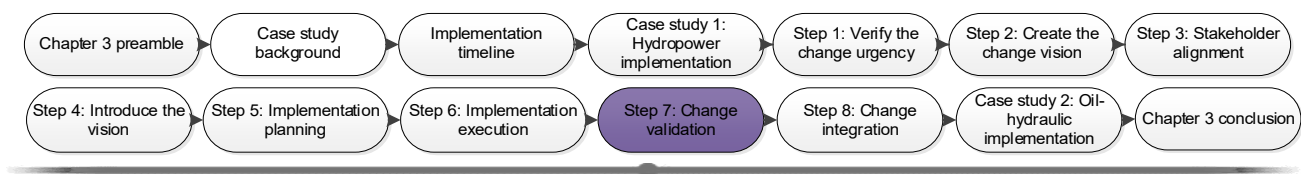


Table 3-33: Objective overview – Step 5 and 6

Method step	Strategy objective	Strategy objective met (or not)
Step 5: Enable implementation and change management	- Provide system selection guidance	✓
	- Assess and recommend upgrades to support infrastructure	✓
	- Recommend updates to policies and procedures	✓
	- Develop an implementation strategy,	✓
	- Maintain stakeholder alignment	✓
	- Encourage stakeholder participation	✓
Step 6: Change implementation	- Implement the change	✓
	- Sustain the change momentum	✓
Legend:	✓ – objective met ✗ – objective not met	

Phase 3: Change benefit validation

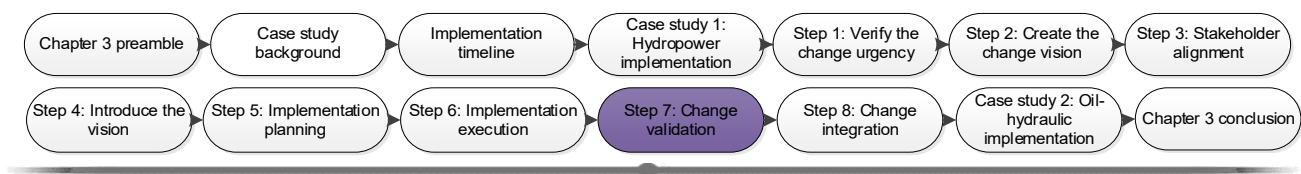
CSM Step 7 of the case study research methodology requires comparing actual and theoretical results to validate the benefits of the change. Phase 3 of the change process focused on this specific requirement. Performance assessments were conducted to evaluate the actual benefits obtained from the small-scale trial. The results were benchmarked against the benefits claimed earlier from a theoretical perspective in [Step 2: Vision creation](#).

Step 7: Assess and validate benefits

The formulated performance assessment strategy was implemented to perform an initial evaluation of the actual benefits of the ADT under the following five strategic focus areas: performance, SHE, reliability, human factors, and techno-economics.

The benefit evaluation assessments were conducted during the small-scale trial phase of the change process. Table 3-34 summarises the trial and baseline environment. Two adjacent working places located in a raise line with stable ground conditions were identified to serve as the compressed air baseline and hydropower trial panel, respectively. This allowed for a homogeneous reef dip angle, reef type, stoping widths, and mining conditions. Care was taken to ensure that crew sizes on the day and night shifts were similar. Trial and baseline measurements were conducted within the same production period, resulting in a total of 69 production days.

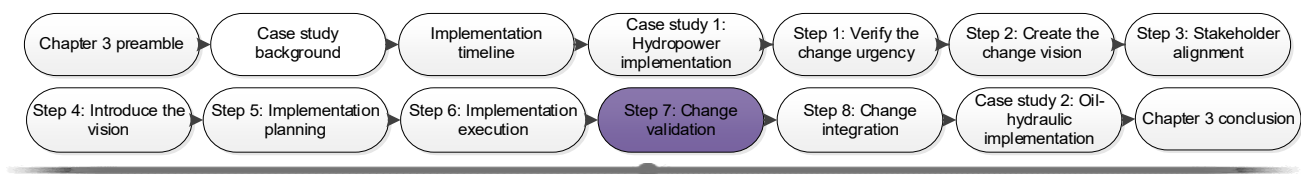
Panel lengths were kept similar to eliminate any advantages associated with shorter face lengths. The blast design and support pattern were similar for both panels to ensure that the total linear metres drilled for production and non-production holes were fairly equivalent. Both panels used 34 mm five-button drill bits. Five rock drills were deployed at the baseline panel, one in the gully and four on the



face. Only three rock drills were used at the trial panel, one in the gully and two on the face. The proximity of the trial and baseline panels enabled daily measurements from both panels.

Table 3-34: Mining, operational and drilling parameters – Trial and compressed air baseline crews

Description	Compressed air baseline crew	Hydropower trial crew
Trial date	01/06/2022–18/09/2022	01/06/2022–18/09/2022
Trial duration	Three months	Three months
Work place name	137L E6 E5	137L E6 E4
Reef dip angle	10°–20°	10°–20°
Reef type	Beatrix Reef	Beatrix Reef
Ground conditions	Good	Good
Crew name	Opel Monza	Ford
Crew size (day shift)	11	11
Working days	69	69
Stoping width	1.09 m	1.09 m
Panel length	25.0 m	25.0 m
Face burden spacing	0.6–0.7 m	0.6–0.7 m
Roof burden spacing	1.5 m	1.5 m
Number of rows drilled	2	2
Drill steel length (face)	1.5 m (1.2 m hole)	1.5 m (1.2 m hole)
Drill steel length (gully)	1.8 m (1.5 m hole)	1.8 m (1.5 m hole)
Drill steel length for roof support	1.8 m (1.5 m hole depth)	1.8 m (1.5 m hole depth)
Drill steel length for siding	1.8 m (1.5 m hole depth)	1.8 m (1.5 m hole depth)
Drill bit	Five button – 34 mm	Five button – 34 mm
Equipment used	4 × Seco215 drills used on face and roof bolts and 1 × Seco215 drill used in gully Face thrust legs: 760 mm; Gully thrust legs: 850 mm – five-point stinger Compressed air diaphragm pump in the gully	2 × hydropower drills used on face, 1 in the gully and 1 drilling support Face thrust legs: 760 mm; Gully thrust legs: 1000 mm – five-point stinger Hydropower jet pump in the gully
Mining cycle overview	Drilling: Handheld rock drills Support: Packs to support the gully shoulder. Elongates and roof bolts to support the hang wall. Cleaning: Face scraper integrated with strike and centre gully scraping.	Drilling: Handheld rock drills Support: Packs to support gully shoulder. Elongates and roof bolts to support the hang wall. Cleaning: Face scraper integrated with strike and centre gully scraping.



Data collection strategy applied

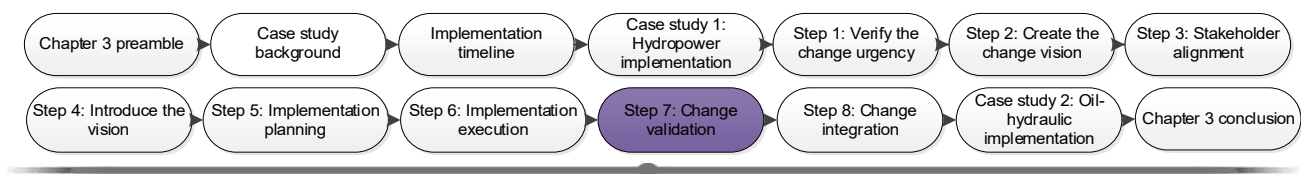
As part of the evaluation strategy, a data collection plan was developed outlining the parameters to be measured. Most of the data were collected through on-site manual measurements over the course of the respective trial period. Where possible, logging devices as listed in Table 3-35 were installed to capture more data points.

Table 3-35: Parameter and equipment breakdown

Parameter	Equipment used	Resolution
Air temperature	Whirling hygrometer, Tinytag2 data loggers	0.1 – 0.5 °C
Airflow	Davis Vane anemometers	1 m
Air pressure	Barometric pressure meter	1 Pa
Water flow	Ultrasonic flow sensors; mechanical flowmeter	0.01 l/s; 0.0005 m ³
Water pressure	WIKA pressure loggers	0.01 Pa
Compressed air pressure	WIKA pressure loggers; mechanical pressure gauge	0.01 Pa; 10 kPa
Compressed air flow	Inline compressed air flowmeter	0.1 kg/s
Energy consumption	Power loggers	±0.5% at rated current
Time studies	Stop watches	1 second
Distance/length	Laser distance meters, tape	1 mm
Noise	Noise dosimeters	< ±0.8 dB
Weight	Manual scale	500 g
Accuracy/socket lengths	Clino ruler	1 mm

Statistical parameters used to evaluate data sufficiency and accuracy

The product performance evaluator accompanied mining crews daily to monitor performance and record measurements. The collected data was analysed to ensure that statistically sound conclusions could be drawn. Since many of the parameters were variable, care was taken to ensure that a representative data sample was collected. The mean value of the defined KPI data population was ultimately used to benchmark the overall impact for each KPI. To signal measurement inconsistency, variability in the collected data was benchmarked using the coefficient of variation, which measures the ratio of the standard deviation to the mean. A coefficient of variance value of less than 20% indicated that the observations cluster closely around the population mean and are deemed consistent [179]. Coefficient of variance values greater than 30% signalled the need for additional data.



Step 7.1: Assess performance

This assessment strategy evaluated the impact of hydropower on drilling performance, production, and utilities. It was found from the literature review that the following five key criteria govern the performance of drilling systems:

- (1) **Collar-to-collar drill rate:** The dataset used to quantify the impact on the collar-to-collar drilling rate consisted of 1 136 data points (holes drilled) to ensure coefficient of variance values smaller than 20%, as shown in Table 3-36. The average collar-to-collar drill rate [hh:mm:ss] improved by 56%, decreasing from 00:12:47 per hole to 00:05:37. This result indicates that due to the improved energy output produced by the hydropower rock drill, the time consumed to drill a blasthole reduced by 56%. Ultimately, this improvement translates into a reduction in the total time consumed to complete the drilling activity, as more fully alluded to next under point (2).

Table 3-36: Face drilling performance summary[#]

Drilling technology	n [–]	CV [%]	$\bar{x}$ [hh:mm:ss]	Impact
Compressed air [*]	506	16	00:12:47	56%
Hydropower	630	18	00:05:37	improvement

^{*} Evaluated at an average in-stope air pressure of 270 kPa

[#] Hole effective length – 1.2 m

- (2) **Drilling shift cycle time:** A total of 48 data points, representing 48 blasting shifts over the three-month trial period, were collected and used to analyse the overall impact on the drilling shift cycle time. The data collected and summarised in Table 3-37, shows that hydropower reduced the face drilling time [hh:mm:ss] by 34% (06:23:00 versus 04:12:00).

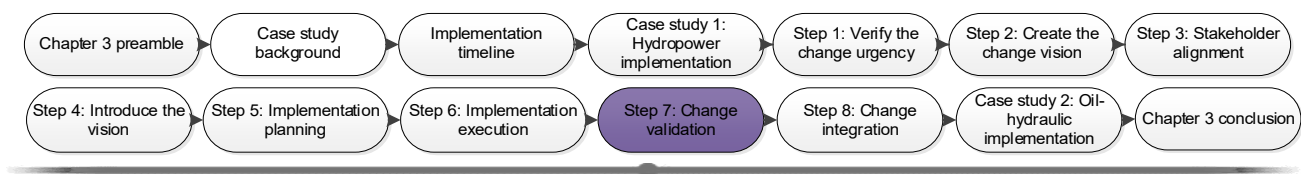
Table 3-37: Hydropower's impact on drilling shift cycle time[#]

Drilling technology	n [–]	CV [%]	$\bar{x}$ [hh:mm:ss]	Impact [#]
Compressed air [*]	24	16	06:23:00	34%
Hydropower	24	17	04:12:00	improvement

^{*} Evaluated at an average in-stope air pressure of 270 kPa

[#] Hole effective length – 1.2 m

- (3) **Production:** The three-month assessment period produced a total of six data points to quantify the overall impact on ore production. To recap, the duration of the trial period was determined by the time required to achieve coefficient of variance values below 20% for all the KPIs. A summary of the data collected is shown in Table 3-38. Improved drilling



performance enabled the hydropower crew to complete the drilling activities on time, ultimately delivering 120% of their monthly call. The compressed air crew achieved only 95% of their monthly call during the three-month trial period.

Table 3-38: Percentage call achieved production comparison

Parameter	Compressed air [%]	Hydro [%]	Impact
Month 1	139	125	14% less
Month 2	83	117	34% improvement
Month 3	65	117	34% improvement
Average	95	120	25% improvement

(4) Water intensity ratio: A mechanical water flowmeter was installed at each panel to accurately record the volume of water used per production month. A summary of the findings is presented in Table 3-39 and was used to calculate the ratio of water consumed to ore generated by each drilling system. Table 3-40 showcases the water intensity ratios and presents the following two important results:

- **Water consumption:** The supply pressure at the compressed air panel was found to be, on average, 12 bar, which is four times higher than the OEM-prescribed requirement [30]. This excessive supply pressure resulted in multiple leaks at the hose joints and couplings. In addition, it is important to note that the rock drills were not fitted with auto-shutoff valves. This simply means that the water did not shut off when the air valve (starter lever) was closed during non-drilling times (i.e. while moving between holes or while resting). In contrast, hydropower has a built-in auto-shutoff advantage and also provides a controlled supply based on user demand using the intelligent VSD controller. Consequently, the hydropower panel used 48% less water (20 700 litres) to drill the same effective panel.
- **Water intensity ratio:** It follows further from the table that the water-to-ore intensity ratio improved by 52%, from 0.59 to 0.31, when using a hydropower drilling system in conjunction with a hydropower jet pump as a dewatering pump.

These two points effectively dispel the myth that hydropower uses more water than compressed-air drilling systems.

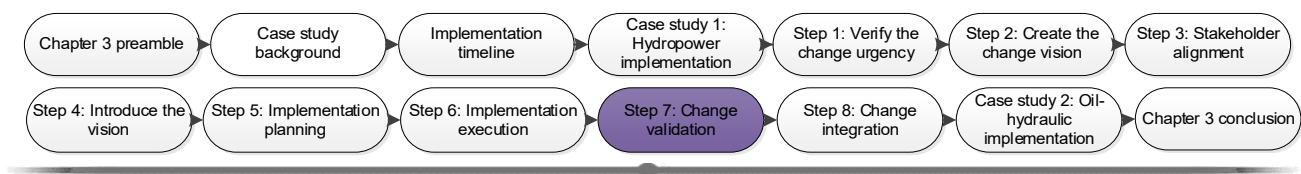


Table 3-39: Three-monthly water consumption

Drilling technology	n [–]	CV [%]	$\bar{x}$ [tonne] [#]	Impact
Compressed air	3	16	1 470.50	52%
Hydropower	3	18	1 150.05	improvement

[#] This is the trial average amount of water to drill the gully, siding, support and ± 25 m face of ± 1.1 m stoping width

Table 3-40: Water intensity ratio comparison

Parameter	Unit	Compressed air	Hydro	Impact
Production per month ^{**}	[Tonne]	2 482	3 723	–
Water per tonne of ore – Total (actual)	[Tonne/tonne]	0.59	0.31	52% reduction

^{**} Tonnages collected from survey data.

(5) Electricity intensity ratio: The electrical energy usage measurement results are shown in Table 3-41. The electrical energy consumed by the compressed air panel was derived from the compressed air consumed using Equation 2-26 and Equation 2-27. These data points were translated into an overall effective kWh per tonne mined, as seen in Table 3-42. The following important points are noteworthy from Table 3-42:

- The energy consumed to energise the rock drills was 98.1% less compared to compressed air. This result indicates that the hydropower system consumed 98.1% less electricity. The in-stope measurements confirmed that the compressed air valves were not closed after drilling was completed. This contributed to the energy consumed during both the non-drilling and drilling periods. Compressed air was generated on surface using a 3.5 MW compressor, resulting in an overall energy intensity ratio of 146 kWh/tonne of ore generated. The intelligent VSD controller enabled the hydropower system to consume energy only when there was end-user demand, and it consumed only 3.5 kWh/tonne.
- The energy consumed to dewater the service water used to drill reduced by 21.6%.
- An overall reduction in energy intensity ratio of 97.6% was quantified.

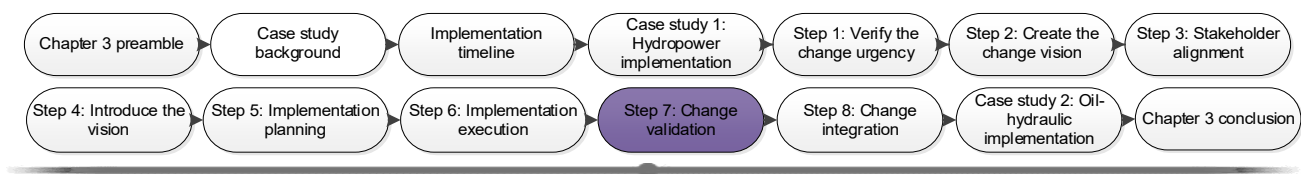


Table 3-41: Three-monthly electricity consumption per mining activity

Activity	Drilling technology	n [–]	CV [%]	$\bar{x}$ [kWh]	Impact
Drilling	Compressed air	3	18	354 370	98.1% reduction
	Hydropower	3	16	6 701	
Dewatering	Compressed air	3	19	8 083	21.6% reduction
	Hydropower	3	20	6 329	

Table 3-42: Electricity intensity ratio

Parameter	Unit	Compressed air	Hydro	Impact
Three-month production achieved	[Tonne]	2 482	3 723	50% improvement
Electricity used per tonne of rock	[kWh/tonne]	146	3.5	97.6% improvement

Step 7.2: Assess SHE

This specific key performance area (KPA) assessment focused on understanding the impact of hydropower on SHE by considering the following as presented in Table 3-43:

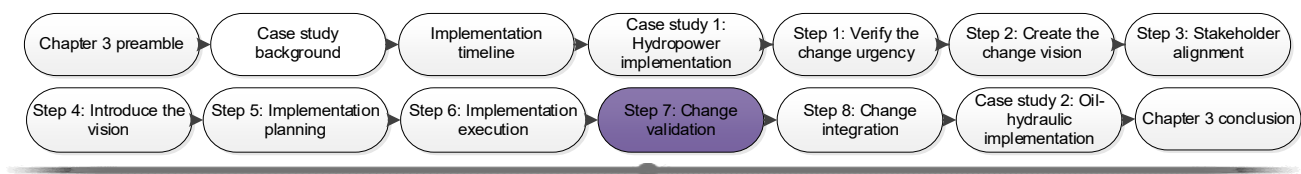
- (1) Noise:** The sound pressure level could not be measured due to the presence of compressed air open ends near the drills. Although it would have been ideal to obtain actual sound-pressure measurements at the CSM, the objective was to determine what change in TWA noise exposure could be expected. Consequently, the sound pressure levels produced by each rock drill type were obtained from the literature and used to calculate the change in daily noise exposure based on the actual drilling shift durations. Philips *et al.* [51] published sound pressure measurements for both compressed air and hydropower rock drills. The corresponding TWA exposures shown in Table 3-43 were ascertained using Equation 2-16. TWA noise exposure was reduced by 8.5 dB(A), confirming that hydropower RDOs are exposed to less noise over a normalised eight-hour working shift.

Table 3-43: Daily noise exposure

Rock drill	Sound pressure level [#] [dB(A)]	Exposure time* [hours]	Noise exposure [%]	TWA [dB(A)]	Impact
S215	104.4	6.4	587.4	102.8	8.5 dB(A) reduction
Hydropower	98.9	4.2	180.3	94.3	

[#] Rock drill sound pressure levels adopted from [51].

* Per shift based on the sample mean value reported in Table 3-37.



(2) Vibration: The daily exposure of a person to vibration was ascertained using Equation 2-20 to normalise the vibration magnitude to actual exposure time over an eight-hour base period. The rock drills' vibration magnitude could not be physically measured since no service provider was willing to expose delicate measuring equipment to the harsh underground environment. Alternatively, vibration magnitudes from published literature, as proposed in Table 2-7 were used to estimate the impact on vibration.

Following Equation 2-20 and the vibration magnitude guidance provided in Table 2-7, the TWA vibration exposure for each RDO was calculated. As indicated by Table 3-44, the TWA vibration exposure was estimated to have increased by 2.9 m/s^2 . This result was expected because hydropower drills exert greater percussive force on the drill steel, which elevates vibration levels. As a remedial action, the solid steel handles were replaced with rubber handles to act as vibration dampers (refer to Step 7.4 for a detailed summary relating to this topic). It is always more effective to reduce a hazard at the source using engineering solutions rather than relying on personal protection equipment to protect workers [51].

Table 3-44: Daily vibration exposure

Rock drill	Magnitude [m/s^2]	Exposure time* [hours]	TWA vibration exposure [m/s^2]	Impact
S215	21.9	6.4	19.6	2.9 m/s^2 increase
Hydropower	31.0	4.2	22.5	

* Per shift based on the sample mean value reported in Table 3-37

(3) Heat load: Figure 2-29 shows a simplified energy balance for the trial setup based on the heat-load calculation method described earlier. The pressure generation unit used a 75 kW motor with a VSD to drive the positive-displacement pump. A power logger was installed to monitor the motor's actual power consumption during the trial. Table 3-45 shows that 38.7 kW was added to the water by the hydropower system, compared to only 15 kW for the compressed air counterpart. The worst-case scenario was considered with three drills running simultaneously, which is peak drilling. Although the motor is rated at 75 kW, peak drilling only consumed 50.4 kW. The hydropower panel's heat load increased by 50.4 kW when the water was not controlled, while only 11.7 kW was liberated into the occupational environment when the water was controlled.

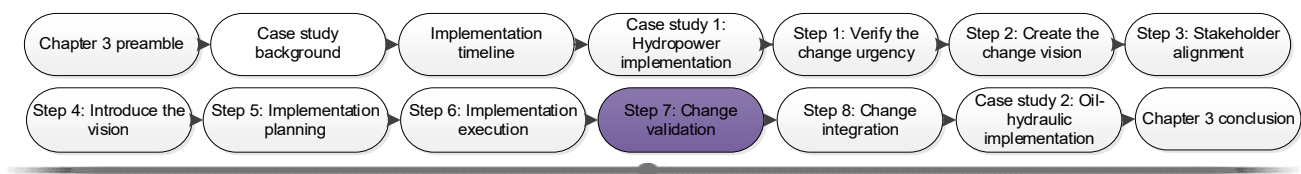


Table 3-45: Water temperature summary

Ref.	Parameter	Compressed air	Hydropower
C	Manifold inlet water temperature [°C]	26.4	26.6
E	Water temperature in strike gully [°C]	29.4	30.8
-	Delta (C-E) [°C]	3.0	4.2
-	Total flow rate through running drills [l/s]	1.2	2.2
-	Maximum heat added/removed [kW]	15.0	38.7

(4) Ambient wet-bulb temperature change: An important parameter monitored was the air temperature before and during drilling to quantify the impact of the added heat load. The hydropower and compressed air rock drills deployed are illustrated in Figure 3-45 and Figure 3-46, respectively. Table 3-46 shows the change in the wet-bulb temperature before and during drilling. The in-stope air temperature measurements showed a 0.5 °C reduction in wet-bulb temperature when the drills were in use. This was due to the expansion of the compressed air at the outlet port of the Seco 215 drills. Figure 3-46 shows the ice formation on one of the rock drills. Removing the compressed air drills from the panel will increase the overall wet-bulb temperature inside the panel by 0.5 °C. This result aligns with the theoretical estimate that the compressed air drills will provide cooling.

From the results presented in Table 3-46, the air wet-bulb temperature increased by 0.5 °C when 50.4 kW was added to the occupational environment. This result aligns with the results published by Seabell [31]. Seabell's model predicted that the corresponding wet-bulb temperature may increase to as high as 0.6 °C per panel when hydropower is introduced.

To mitigate this undesired result, water controls were enforced. The air-to-water contact area was minimised by installing a jet pump in the gully to remove the hot water from the workplace. Further optimisation was achieved by installing a dump hose on the rock drill's exhaust port. Instead of spraying the water uncontrollably into the air, as depicted in Figure 3-45, the hose enabled the rock drills to dump the water onto the footwall in a controlled manner. This approach further reduced the air-to-water contact area. As a result, the temperature recordings revealed no increase in temperature before or during the drilling shift if water controls were in place. This highlights the importance of in-stope water control when using hydropower drilling systems.

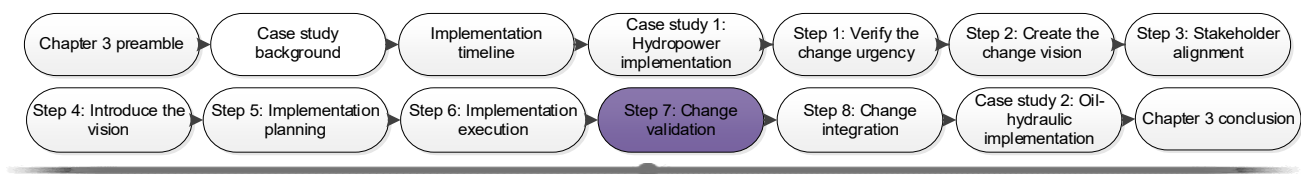


Table 3-46: Wet-bulb temperature before and during drilling

KPI	Unit	S215	Micro-hydropower	Impact
Localised temperature change while drilling	[°C]	0.5 decrease	0.5 increase if not controlled - No change if water is properly controlled	1.0 increase if water is not controlled 0.5 increase if water is controlled correctly.



Figure 3-45: Dump hose to be connected to the drill's exhaust port²⁴



Figure 3-46: Frost formation near the outlet port²⁵

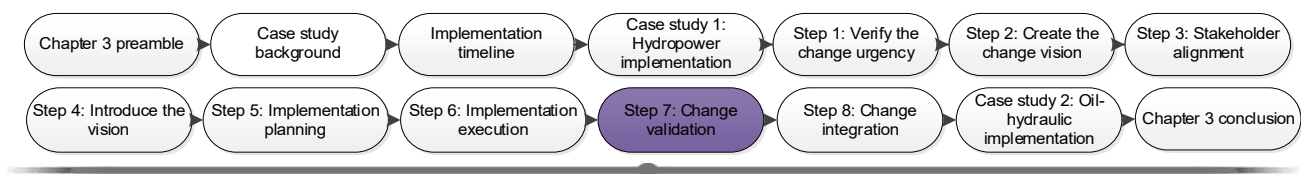
- (5) **Mud rushes and other water related safety risks:** An important parameter monitored here was the water related risks introduced following the implementation of the hydropower trial crew. The evaluation strategy applicable here called for tracking the number of hydropower related injuries, workplaces flooded, and mud rushes.

Effectiveness of isolation valves - Four hose failures were recorded, but the combined excessive flow and isolation valves effectively isolated the flow once the hose failures occurred. Consequently, no flooded workplaces or hydropower related injuries were recorded. The hydropower system's ability to isolate the water flow after the drilling shift is complete is an advantage worth highlighting. In contrast, the compressed air panel's isolation valves were frequently left open after the drilling shift, resulting in water flowing to the tips.

Mud rushes - An effective dewatering network, as recommended by [Section 2.5, Step 7.2](#), was implemented at the hydropower panel. The jet pump positioned in the strike gully was effectively used to prevent water from entering the tip. As a result, no mud rushes were

²⁴ B van Rooyen, Personal collection, "Dump hose", 2022.

²⁵ B van Rooyen, Personal collection, "Frost formation", 2022.



recorded during the trial phase discussed in this section. The same result was observed at the compressed air panel's tip. Although no mud rushes occurred, water indeed flowed into the tips due to valves left open.

These results highlight the following important points:

- The water related risks accompanying hydropower can be managed effectively, and
- The water controls incorporated into the hydropower system design presents an effective means to prevent water from entering the tips during non-production times.

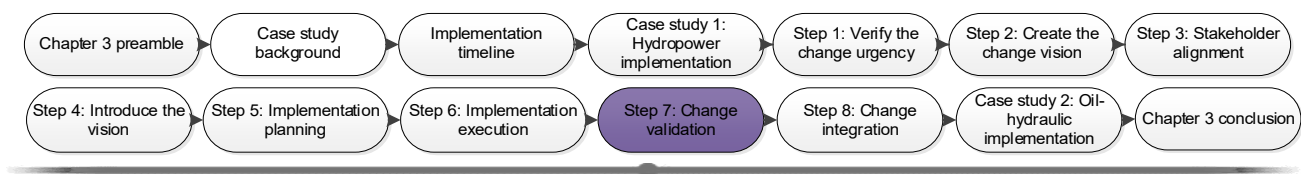
Step 7.3: Assess mine suitability

The key objective of the mine worthiness assessment was to evaluate the overall suitability of the alternative equipment in terms of functionality and reliability. The assessment first evaluated whether all the required key mining activities could be fulfilled with the new equipment. Secondly, we need to understand the equipment's lifespan until failure.

(1) Functionality: Table 3-47 summarises the equipment functions required to complete a narrow reef mining cycle as more fully set out in [Section 1.2](#). From Table 3-47, water-hydraulic equipment was found to be fully interchangeable with its compressed air counterpart.

Table 3-47: Equipment flexibility

Activity	Function required	Amenability
Drilling	Face drilling	Yes
	Gully drilling	Yes
	Rigging hole drilling	Yes
	Pin hole drilling	Yes
	Footwall ripping	Yes
	Support hole drilling	Yes
Support	Prestressing of: - Prestressing plates - Jackpods - Hydraulic props - Matt packs	Yes
	Chainsaw	Yes
Blasting	Blasthole cleaning	Yes
	Emulsion loader	Yes
Cleaning	Sweepings	Yes
	Waterjet	Yes
Other	Dewatering pump	Yes
	Atomisers	Yes
	Hoist	Yes



Activity	Function required	Amenability
	Watering down	Yes

(2) Reliability: The trial duration allowed for reliability data to be collected for the rock drill, thrust leg, and pressure generation unit motor.

- **Rock drills and thrust legs:** Table 3-48 presents an overview of the rock drill and thrust leg reliability findings. The linear metres drilled were ascertained using Equation 2-31. Thirty hydro-powered rock drills and 26 thrust legs failed during the trial period. This corresponds to MTBFs of 221 and 254 linear metres for the drills and legs, respectively. When compared with the compressed air panel, regressions of 71% and 66% were observed for the rock drills and thrust legs, respectively. The compressed air rock drills lasted roughly 20 drilling shifts, compared to only six for the hydropower rock drill. Hence, for roll-out planning purposes, the operation will require a minimum of three hydropower rock drills for every compressed air rock drill removed from production to ensure the same level of rock drill availability. [Section 3.5 – Results discussion](#) provides an overview of how this challenge was resolved.
- **Pressure generation unit's motor:** The motor failed after 526 running hours. Only one failure occurred.

Table 3-48: Reliability results overview

Drilling technology	Equipment type	n [–]	CV [%]	$\bar{x}$ [m]	Impact
Rock drill	Compressed air	6	5	750	71% reduction
	Hydropower	30	11	221	
Thrust leg	Compressed air	6	5	750	66% reduction
	Hydropower	26	15	254	

Step 7.4: Assess human factors

The human factor assessments focused on understanding end users' experiences when using the hydropower system. The assessment KPIs included fatigue, morale, and willingness to adopt. Table 3-49 presents the important results.

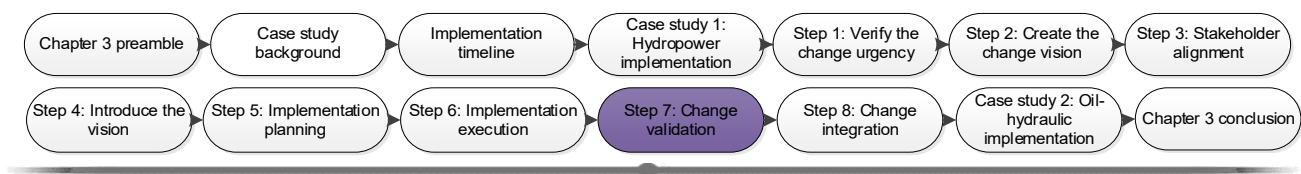


Table 3-49: Human factor key observations

Human factors	KPI	Operators' response
Fatigue	Did the technology help reduce operator fatigue?	Yes, the enhanced performance of hydropower enabled us to complete the drilling shift with only two rock drills on the face. This allowed us to achieve RDO redundancy and enabled them to manage fatigue and absenteeism. Key note: Although not directly mentioned by the RDOs here, due to the reduced rock drill reliability, the need to carry 3 times more rock drills up and down the raise contributed to unnecessary fatigue. This might lead to unwanted change resistance if not managed effectively. Refer to Section 3.5 – Results discussion for recommendations to manage this aspect.
Morale	Did the technology help to improve the overall team morale?	Yes, the technology boosted our morale because it is quieter, faster, cleaner, and offers improved performance.
Adoption willingness	Would you like to adopt the technology?	Yes, the new technology transformed their world, and they would like to continue using hydropower.

(1) Operator fatigue: Operator fatigue was confirmed by the operators to be a function of drilling activity duration, RDO availability, equipment mass load, and ergonomics.

- **Drilling shift duration and operator availability:** The crew highlighted that the enhanced performance provided by hydropower enabled them to complete the drilling shift using only two rock drills on the face. This enabled them to achieve RDO redundancy and manage fatigue and absenteeism.
- **Equipment mass load and ergonomics:** The hydropower drill assembly was found to weigh the same as the compressed air counterpart. Ergonomically, the rock drills and pusher legs are comparable to the compressed air units. The agronomical similarities and reduced mass loading motivated RDOs to confirm that the equipment did not contribute additional fatigue.

Overall, the operators confirmed that hydropower enabled them to manage their fatigue.

(2) Operator morale: The crew affirmed that the technology boosted their morale since it is quieter, faster, cleaner, and offers improved performance. As mentioned earlier, the improved performance allowed them to drill the face using only two operators. This helped the crew manage fatigue by allowing operators to rest on a rotational basis. When comparing Figure 3-47 and Figure 3-48, the grease-free hydropower RDO clearly stands out.

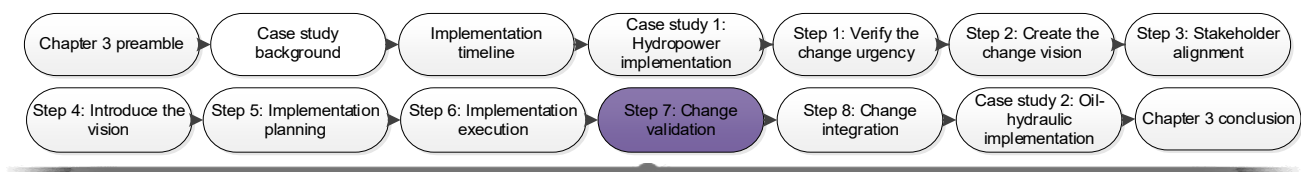


Figure 3-47: Compressed air RDO full of grease²⁶

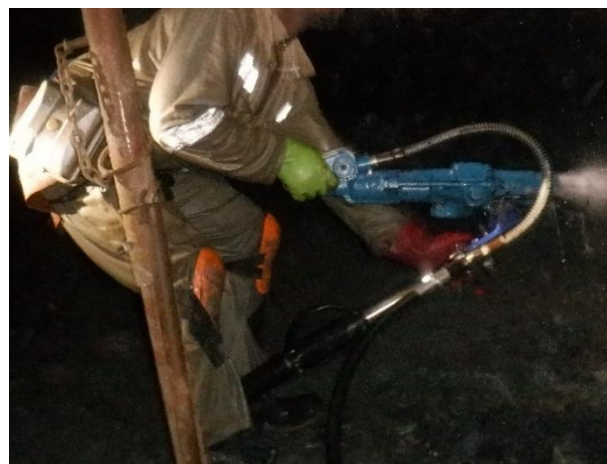


Figure 3-48: Grease-free hydropower RDO²⁷

- (3) **Environmental contamination:** As highlighted in [Section 1.2](#), an oiler is filled with grease to lubricate the compressed air rock drill. A mixture of oil, air, and water formed a dense layer of fog inside the panel while drilling, reducing the overall visibility and air quality, as depicted in Figure 3-49. Due to the absence of grease in the hydropower drilling systems, visibility improved, as illustrated in Figure 3-50.
- (4) **Adoption willingness:** The crew was asked whether they would like to continue using the technology when the trial period lapsed. They indicated that the new technology has transformed their world and that they would like to continue using hydropower.



Figure 3-49: Compressed air panel – Impaired visibility and grease contamination on footwall²⁸



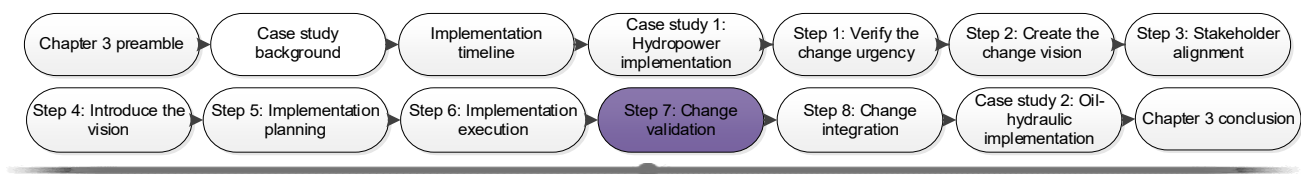
Figure 3-50: Hydropower panel – Clear mist-free occupational environment²⁹

²⁶ B van Rooyen, Personal collection, “RDO with grease”, 2022.

²⁷ B van Rooyen, Personal collection, “Grease-free RDO”, 2022.

²⁸ B van Rooyen, Personal collection, “Impaired visibility”, 2022.

²⁹ B van Rooyen, Personal collection, “Clear mist-free environment”, 2022.



Step 7.5: Assess techno-economic aspects

The purpose of the techno-economic assessment was to specifically benchmark the performance and corresponding cost of the implemented technologies. This specific KPA assessment considered the cost of acquiring and operating a hydropower drilling system, as well as the ROI. The KPI data collected included capex, opex, and ROI.

(1) **Capex:** The capital outlay required to equip the crew with a modern hydropower drilling system was R1.4 million (USD79 407). This value included the pressure generation unit, rock drills, ancillary equipment, and the reticulation network.

(2) **Opex:** The five opex cost categories considered are shown in Table 3-50, and comprised the following as noted from Table 3-50:

- **Electricity cost to generate rock drill motive energy:** It follows from the energy intensity ratios reported in Table 3-42, the compressed air workplace consumed 143 kWh/tonne compared to 3.5 kWh/tonne for hydropower. The corresponding cost to energise the rock drills reduced from R236 (USD13.44) per tonne to R3.00 (USD0.17) per tonne, based on the energy tariff of R1.65 (USD0.09) at the time.
- **Electricity cost to dewater:** It follows from the dewatering energy intensity ratios reported in Table 3-41 that the cost to dewater the water consumed by the compressed air panel equated to R5.31 (USD0.30). In contrast, the hydropower drilling system consumed less water, and the dewatering cost amounted to only R2.82 (USD0.16)
- **OEM labour:** OEM labour to maintain the compressor was included in the maintenance rate, and no monthly retainer was payable. In contrast, OEM labour was deployed daily to maintain the hydropower system, at a cost of R8.00 (USD0.45) per tonne.
- **Maintenance:** The data collected considered the costs of maintaining the drills, ancillary equipment, and the pressure generation unit. Hydropower drilling equipment was noted to be less reliable (see Table 3-48) and was serviced more frequently. These figures included the life-cycle maintenance of the pressure-generation units.
- **Damaged equipment replacement cost:** The equipment damages experienced at the hydropower panel amounted to R2.00 (USD0.11) per tonne. The dataset's coefficient of variation exceeded 20% because damaged components and their replacement costs varied. No equipment damage was recorded for the compressed air drilling system.

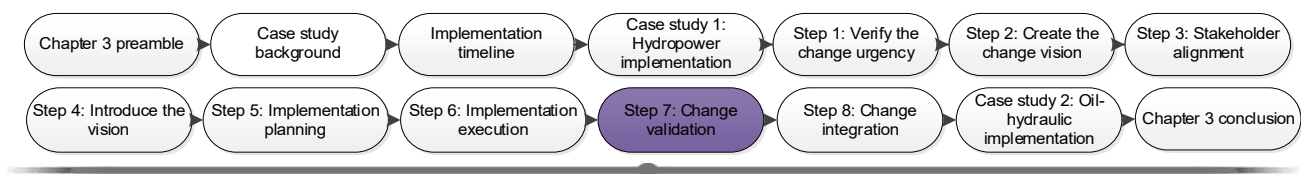


Table 3-50: OPEX cost summary per drilling technology type

Opex type	Drilling technology	n [–]	CV [%]	$\bar{x}$ [R]	$\bar{x}$ [USD]	Impact
Rock drill motive energy	Compressed air	3	31	236	13.44	98% reduction
	Hydropower	3	16	3.00	0.17	
Dewatering energy	Compressed air	3	19	5.31	0.3	46% reduction
	Hydropower	3	20	2.82	0.16	
OEM labour	Compressed air	0	–	–	–	–
	Hydropower	3	10	8.00	0.45	
Maintenance	Compressed air	3	15	8.78	0.5	495% increase
	Hydropower	3	0	43.50	2.48	
Equipment damages	Compressed air	0	–	–	–	–
	Hydropower	3	35	2.00	0.11	
Grand total	Compressed air	3	–	250	13.75	76% reduction
	Hydropower	3	–	59.32	3.26	

(3) ROI: The ROI was evaluated using Equation 2-32, and the result is shown in Table 3-51. The initial capital outlay required to equip the crew with a micro-hydropower drilling system was R1.4 million. An average monthly profit estimate was obtained from the shaft's financial manager. The estimate accounted for the production generated, operational expenses, labour, and shaft infrastructure overheads. The hydropower panel generated an ROI of 129%, indicating that the capital required to acquire the equipment needed was recovered within the first production month.

Table 3-51: Initial capital cost vs monthly ROI per panel

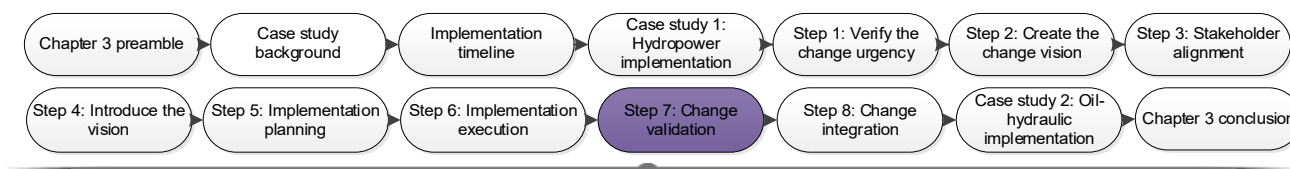
System type	Tonnage	Monthly profit	Capex	ROI
Micro	1 241	R1 806 210	R1 400 000	129%

Step 7.6: Validate change benefits

KPA 1: Performance validation

The five performance KPIs are validated below. A benchmark comparison between the theoretical and actual performance KPIs is outlined in Table 3-52. The following important observations are highlighted:

(1) Drill rate: The theoretical drill rate predicted an improvement of 100%. The actual trial drill rate results, however, confirmed a 56% improvement. This means that the improvement in the drill rate was initially overestimated by 44%. The vast discrepancy was primarily due to the hydropower drill rate being estimated from the literature to be the same. However, the exact



rock drill used and the rock hardness were unknown. This result highlights the importance of using actual tests during specific operations to confirm the actual improvement. They contribute the actual hydropower drill rates for the Beatrix Reef type to the industry.

(2) Drilling cycle time: The theoretical and actual drill cycle times correlate within 4%, validating the process used to estimate the theoretical drill cycle impact.

(3) Production: The production improvement correlated within 8%. This result validates the strategy used to formulate the theoretical estimate.

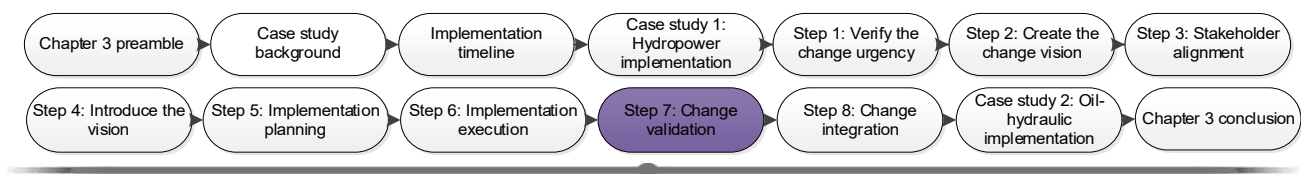
(4) Water intensity ratio: The actual water-to-ore ratio confirmed a 52% reduction in water usage, and the improvement was initially overestimated by 21%. This vast discrepancy is mainly since the theoretical estimate was based on the shaft's overall water-to-tonne ratio and included all wastage along the flow path. The actual result was limited to what the panel itself consumed. It is important to note that the automatic shut-off valves incorporated into the hydropower technology will also only reduce water wastage between the pressure generation unit and the panel. However, the strategy proposed in Step 2 to estimate the water intensity ratio remains relevant, as mines seldom have flowmeters installed near workplaces.

(5) Energy intensity ratio: It can be concluded from the energy intensity ratios presented below that the actual and theoretical results correlate within 1.6%. This result validates the strategy used to formulate the theoretical estimate.

Performance KPA overall validation outcome: The validation results presented in Table 3-52 and discussed above have successfully validated the actual results achieved and the theoretical strategies used to formulate the initial performance-impact estimates.

Table 3-52: KPA 1 – Performance validation

Parameter	Result type	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Drill rate [min/1.2 m hole]	Theoretical	00:10:08	00:04:11	100% improvement
	Actual	00:12:47	00:05:37	56% improvement
Drilling cycle time [142 holes]	Theoretical	08:00:00	04:57:00	38% improvement
	Actual	06:23:00	04:12:00	34% improvement
Production [% call achieved]	Theoretical	82%	100%	18% improvement
	Actual	95%	120%	25% improvement
Water intensity ratio [tonne water/tonne ore]	Theoretical	1.5	0.41	73% reduction
	Actual	0.59	0.31	52% reduction
Energy intensity ratio [kWh/tonne]	Theoretical	120	5.16	96% reduction
	Actual	146	3.5	97.6% improvement



KPA 2: SHE validation

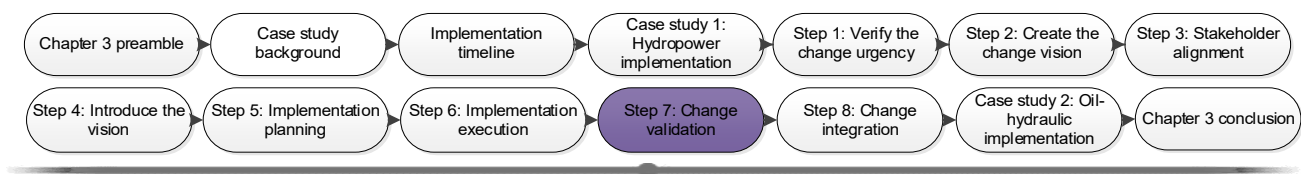
The three SHE KPIs are validated below. A benchmark comparison between the theoretical and actual SHE KPIs is outlined in Table 3-53. The following important observations are highlighted.

- (1) **Noise exposure:** The actual noise benefit correlated 100% with the theoretical estimate.
- (2) **Vibration exposure:** Vibration exposure correlated within 4% but was underestimated from a theoretical perspective, as the actual exposure time was higher than what was initially estimated.
- (3) **Heat load and occupational environmental temperature:** The actual temperature measurements confirmed that the temperature within the occupational environment will increase following the implementation of hydropower. The actual measurements demonstrated that the temperature of a compressed air panel decreases by 0.5 °C when the drills are operational. At the same time, the hydropower panel showed a 1 °C increase when the drills were in operation if the water was not controlled. This adverse result can be limited to 0.5 °C if the water is controlled. This result confirms the importance of in-stope water control.
- (4) **Mud rushes and other water related safety risks:** The water controls associated with hydro drilling systems present a reduced risk to mud rushes, and effective means to manage water related safety risks.

SHE KPA overall validation outcome: Table 3-53 shows that the theoretical estimates correlate within 4% of the actual results. This outcome validates the SHE strategies used to formulate the theoretical predictions and confirms the benefits advocated during Step 4: Introduce the vision.

Table 3-53: KPA 2 – SHE validation

Parameter	Type	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Noise exposure (TWA) [dB(A)]	Theoretical	103.8	95.4	8% reduction
	Actual	102.8	94.3	8% reduction
Vibrations exposure (TWA) [m²/s]	Theoretical	21.9	24.4	11% increase
	Actual	19.6	22.4	14% increase
Occupational environmental temperature [°C]	Theoretical	Provides localised cooling.	Additional electrical load might increase the heat load.	Expected to increase.
	Actual	0.5 decrease while drilling	+0.5 (wet-bulb) if not controlled; no change if water is properly controlled.	1.0 increase if water is not controlled; 0.5 increase if water is controlled correctly.



Parameter	Type	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Mud rushes and other water related safety risks	Theoretical	Lack of water controls associated with compressed air drilling systems presents an elevated risk to mud rushes.	Water controls associated with hydro drilling systems presents a reduced risk to mud rushes.	Risk expected to increase
	Actual	No mud rushes or water related safety risks. However, water did enter the tip.	No mud rushes or water related safety incidents recorded	Risk was effectively managed

KPA 3: Mine suitability validation

The two mine suitability KPIs are validated next. A benchmark comparison between the theoretical and actual mine suitability KPIs is outlined in Table 3-54. The following important observations are highlighted:

- (1) **Reliability:** The initial rock drill reliability predicted a 38% regression. Actual measurements confirmed a 71% regression, indicating this KPI was initially underestimated by 33%. This important result indicates that the initial rock drill fleet size was underplanned by 33%. The actual outcome enabled the mine management team to revise the rock drill fleet required to sustain uninterrupted production. This vast discrepancy existed because the theoretical estimates were based on literature from an operation that has used hydropower drills since the 1990s. The crews there were well-versed in the overall machine care standards. At the same time, the results obtained represent the training period. They are expected to improve as the crews become more conversant with the equipment's operational standards.
- (2) **Functionality:** All the required equipment functions were tested during the trial to confirm their functionality. The results presented in Table 3-47 have shown that the hydropower equipment managed to perform all the tasks required. These actual results confirmed the theoretical prediction that equipment functionality would remain unchanged.

Mine suitability KPA overall validation outcome: The reliability validation results presented in Table 3-54 confirmed two important points: the hydropower rock drill fleet needed to be expanded by 33% and the hydropower equipment provides all the functions required to serve as a replacement.

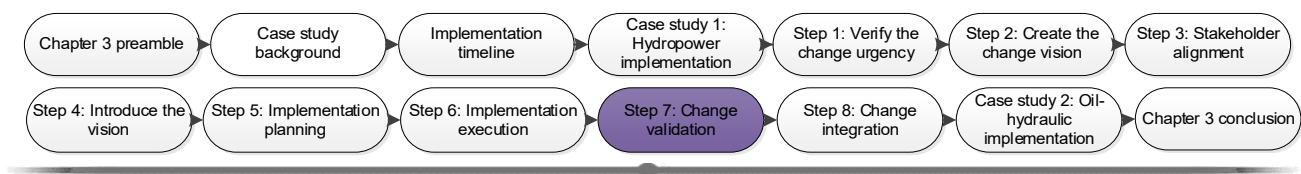


Table 3-54: KPA 3 – Mine suitability validation

Parameter	Type	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Reliability [m/failure]	Theoretical	800	500	38% regression
	Actual	750	221	71% reduction
Functionality	Theoretical	Remains unchanged. Hydropower does offer ancillary equipment.		No change
	Actual	Remains unchanged. Hydropower does offer ancillary equipment.		No change

KPA 4: Human factors validation

The three human factor KPIs are validated below. A benchmark comparison between the theoretical and actual human factor KPIs is outlined in Table 3-55. The following important observations are highlighted:

- (1) **Mass load:** The mass load results presented correlated 100%, which confirms the actual result measured.
- (2) **Ergonomics:** The equipment remained unchanged, as handheld rock drills use thrust legs. As a result, ergonomics remained unchanged.
- (3) **Environmental contamination:** Hydropower does not make use of oil or grease to lubricate the rock drill. The absence of oil or grease eliminated the environmental contamination that the crew had previously been exposed to.

Human factors KPA overall validation outcome: The human factors validation results presented in Table 3-55 confirmed three important points: (1) the rock drill assembly mass load remained the same, (2) equipment ergonomics remained unchanged, and (3) the environmental conditions improved due to the absence of oil and grease.

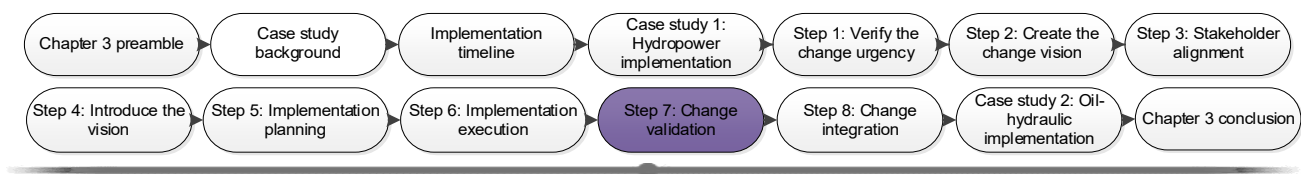


Table 3-55: KPA 4 – Human factors validation

Parameter	Type	Pneumatic	Hydropower	Validated benefit
Rock drill assembly mass load [kg]	Theoretical	39	39	No weight increase
	Actual	39	39	No weight increase
Ergonomics	Theoretical	Handheld rock drill and thrust leg	Handheld rock drill and thrust leg	No operational changes
	Actual	Handheld rock drill and thrust leg	Handheld rock drill and thrust leg	No operational changes
Environmental contamination [–]	Theoretical	Present due to the presence of oil particles in the air	Hydropower does not use oil or grease	Expected to improve
	Actual	Present due to the presence of oil particles in the air	Hydropower does not use oil or grease	Actual improvement noted

KPA 5: Techno-economics validation

The two techno-economical KPIs are validated below. A benchmark comparison between the theoretical and actual techno-economical KPIs is outlined in Table 3-56. The following important observations are highlighted:

- (1) **Opex:** Initial estimates of the opex reduction were underestimated by 35%. The actual compressed air measurements revealed that the baseline panel used more compressed air than initially estimated.
- (2) **Revenue generated:** This KPI was underestimated by 7%. The actual production achieved resulted in a 25% improvement over the theoretical 18% estimate. This achievement, however, was obtained from a single panel, and caution should be exercised. It may decrease when a full raise is converted, as material and ore movement may become the next bottleneck, as alluded to in [Section 2.4: ADTT Step 2: Introduce the downstream impact of face advance improvement initiatives](#).
- (3) **ROI:** The ROI calculation equated to 129%. This result clearly shows that the capital outlay required is recovered within the first month of production.

Techno-economical KPA overall validation outcome: The techno-economical validation results presented in Table 3-56 confirmed three important points: (i) the operational cost shows a potential saving of 71% if all the panels are converted to hydropower (mining without compressed air), (ii) revenue generated improved by 25%, and (iii) the capital outlay required to purchase the hydropower equipment is typically recovered within the first month.

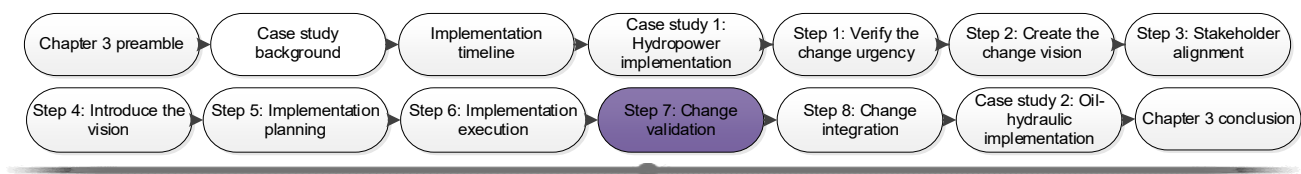


Table 3-56: KPA 5 – Techno-economics validation

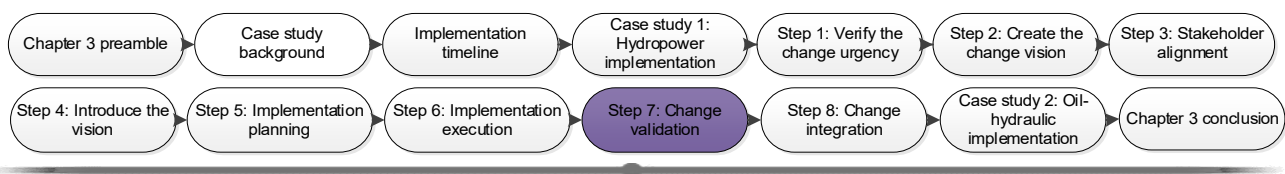
Parameter	Type	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Opex [R/T]	Theoretical	136	80	41% reduction
	Actual	250	59	76% reduction
Revenue generated [%]	Theoretical	–18	+18	18% improvement
	Actual	–5	+20	25% improvement
ROI [%]	Actual	–	129	–

Step 7.6: Update vision board

Step 7 presented an opportunity to collect data to inform the decision-making processes related to success and expansion. The validation strategy was used to evaluate the overall readiness of hydropower drilling technology to function as an ADT by confirming the theoretical change benefits highlighted in [Step 2: Change vision](#). Table 3-57 presents an overview of the validated results. It represents the updated vision board used to advocate the change benefits to the remaining crews.

Table 3-57: Updated vision board containing the validated change benefits

Focus area	Parameter	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Performance	Drill rate [min/1.2 m hole]	00:12:47	00:05:37	56% improvement
	Drilling cycle time [142 holes]	06:23:00 (three operators)	04:12:00 (two operators)	34% improvement
	Production [% call achieved]	95	120	25% improvement
	Water intensity ratio [tonne water/ tonne ore]	0.59	0.31	52% improvement
	Electrical intensity ratio [kWh/tonne]	146	3.5	97.6 improvement
SHE	Noise level [dB(A)]	102.8	94.3	8% reduction
	Vibrations level [m/s ²]	19.6	22.4	14% increase
	Occupational environmental wet- bulb temperature [°C]	–0.5	+0.5 if not controlled - No change if water is controlled properly	1°C increase if water is not controlled 0.5°C increase if water is controlled correctly
Mine worthiness	Reliability [m/failure]	750	221	71% regression



Focus area	Parameter	Pneumatic @ 270 kPa	Hydropower	Validated benefit
Human factors	Mass load [kg]	39	39	No weight increase
	Ergonomics	Handheld rock drill and thrust leg	Handheld rock drill and thrust leg	No operational changes
Techno-economics	Opex [R/T]	250	59	76% reduction
	Revenue generated [% call achieved]	95	120	25% improvement
	ROI	–	129%	–

Phase 3: Change benefit validation summary

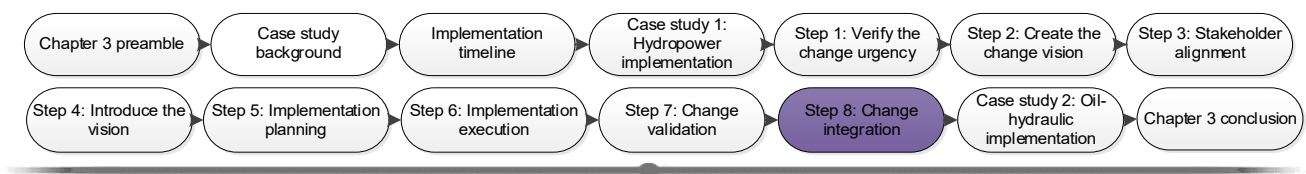
Phase 3 focused on validating the benefits of the change to confirm the ADT's overall readiness to replace compressed air drilling systems at the CSM. The results presented in Steps 7.1 to 7.5 successfully confirmed the benefits of the change and validated the usefulness of the formulated strategies for assessing these benefits when implementing an ADT. Table 3-58 presents an overview of strategic objectives formulated in [Section 1.8](#), which were successfully met.

Table 3-58: Objective overview – Step 7

Method step	Strategy objective	Strategy objective met
Step 7: Change benefit validation	Assess the technology's overall readiness to function as a replacement to the compressed air system.	✓
	Validate the change benefits.	✓
Legend:	✓ – objective met ✗ – objective not met	

Phase 4: Change integration

As the final phase, Phase 4 focused on executing the strategies required to integrate the change with the remaining crews, using Step 8. It follows from [Section 1.7](#) that failure to integrate the change generally results from organisational shock waves when excessive change is applied, or when the change benefits fail to materialise during large-scale roll-outs. To remedy this, Step 8.1 was used to sequentially expand the change to the remaining crews. Step 8.2 analysed the change results and formulated and implemented continuous improvement initiatives as catalysts to materialise the change benefits.



Step 8: Ensure change integration and continuous improvement

Step 8.1: Follow a sequential multi-layered approach to expand the change process

Action 1: Prioritise crew to establish the roll-out plan

PME Step 1: Total travel time, entry examination, face preparation, and charge-up time studies:

The travel time, entry examination time, and face preparation durations for each crew were quantified first. Travel times were derived from the mine's MPL system. Since the MPL beacons were only installed up to the cross-cuts, manual studies were conducted in the three mining sections to quantify entry examination and face preparation durations, as well as in-stope compressed air pressures. These times varied between crews due to differences in crew locality, stoping widths, face length, and blast design. The compressed air pressures were used to estimate the duration of the drilling activity.

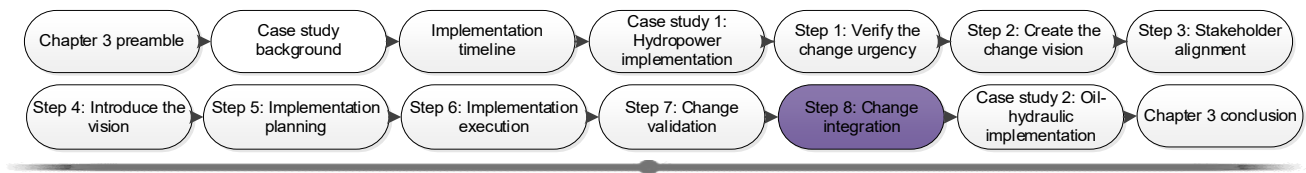
Ultimately, the shift time deficits were calculated by subtracting the available shift time from the drilling shift duration. As shown in Table 3-61, shift time deficits were ranked from largest (Crew 1) to smallest (Crew 26) to prioritise the crews from first to last on the roll-out schedule.

PME Step 2: Collar-to-collar drill rate study: The CSM's average collar-to-collar compressed air drill rates ($\bar{x}$) at various compressed air pressures (260–380 kPa) are presented in Table 3-59. The dataset was gathered from 1 203 holes (1.2 m deep), and data integrity was assured by collecting data at a specific compressed air pressure until the coefficient of variation fell below the 20% threshold. The data was collected using the process defined in [Step 7.1: Performance assessment strategy](#).

Table 3-59: Collar-to-collar drill rate study results at various compressed air pressures

In-stope pressure [kPa]	260	270	290	300	310	330	340	360	370	380
$\bar{x}$ [mm:ss]	07:29	07:07	06:28	06:11	05:55	05:27	05:14	04:51	04:41	04:31
n [–]	125	120	115	118	125	138	105	115	129	113
CV [–]	18	19	15	17	12	18	10	15	19	15

PME Step 3: Establishment of the drill rate performance curve: The collar-to-collar drill rate data presented in Table 3-59 was translated into a graph using Microsoft Excel™, as illustrated in Figure 3-51. The curve, however, only accounts for drill rates within the 260–380 kPa pressure range, as these were the only available pressures from which to gather data. To overcome this shortcoming, the regression line describing the dataset was obtained using Microsoft Excel™'s trendline function.



$$Predicted_Drill_{rate} = 8.2958 \times (x)^{-1.327} \quad \text{Equation 3-1}$$

where:

- $Predicted_{Drill_{rate}}$ – Compressed air drill rate
 x – In-stope compressed air pressure

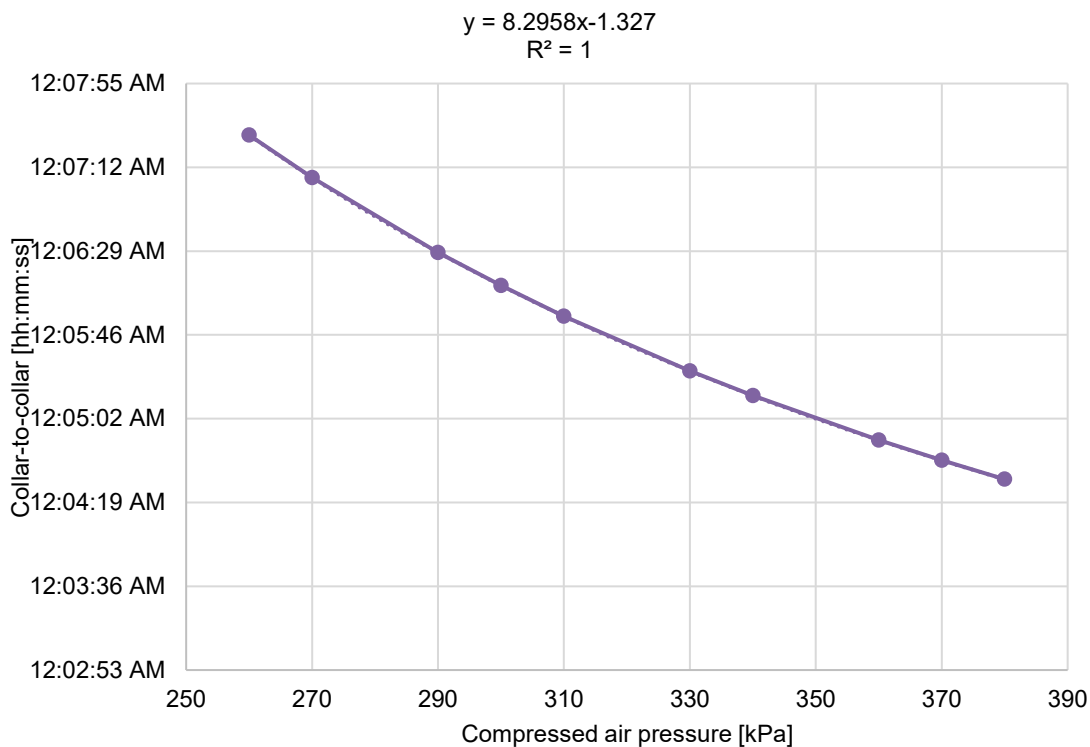


Figure 3-51: CSM collar-to-collar drill rate performance curve

PME Step 4: Performance equation validation: The equation describing the line was validated by ensuring that the R^2 exceeded the 0.70 threshold and equated to 1.0, indicating a perfect fit. As a second validation measure, Equation 3-1 was used to predict the previously measured drill rates at the corresponding pressures. The AME calculation presented in Table 3-60 shows the variance to be less than 1%, confirming the validity of the performance curve equation.

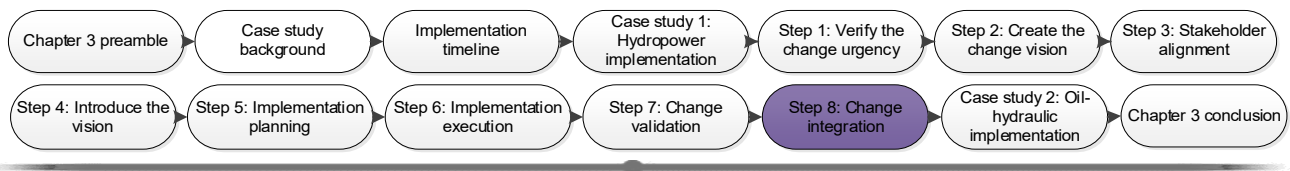


Table 3-60: Performance curve equation validation results

In-stope pressure [kPa]	260	270	290	300	310	330	340	360	370	380
Measured [mm:ss]	07:29	07:07	06:28	06:11	05:55	05:27	05:14	04:51	04:41	04:31
Predicted [mm:ss]	07:27	07:06	06:27	06:10	05:54	05:26	05:13	04:51	04:40	04:30
AME [%]	0.27%	0.27%	0.27%	0.28%	0.28%	0.28%	0.28%	0.28%	0.29%	0.29%

PME Step 5: Establish the holistic performance curve: Equation 3-1 was used to produce the holistic performance curve for pressures ranging from 240 kPa to 480 kPa, as illustrated in Figure 3-52. This curve describes the compressed air drill rates at the CSM. It was specifically developed for the CSM's operational parameters, such as drill bit size, drill steel length, and rock properties. The key point to note is the inflection point positioned at 355 kPa. All crews experiencing compressed air pressures below 355 kPa will experience an improvement when converting to hydropower, and should be converted. At the same time, compressed air will outperform hydropower at all crews mining with compressed air pressures above 355 kPa, and should not be converted.

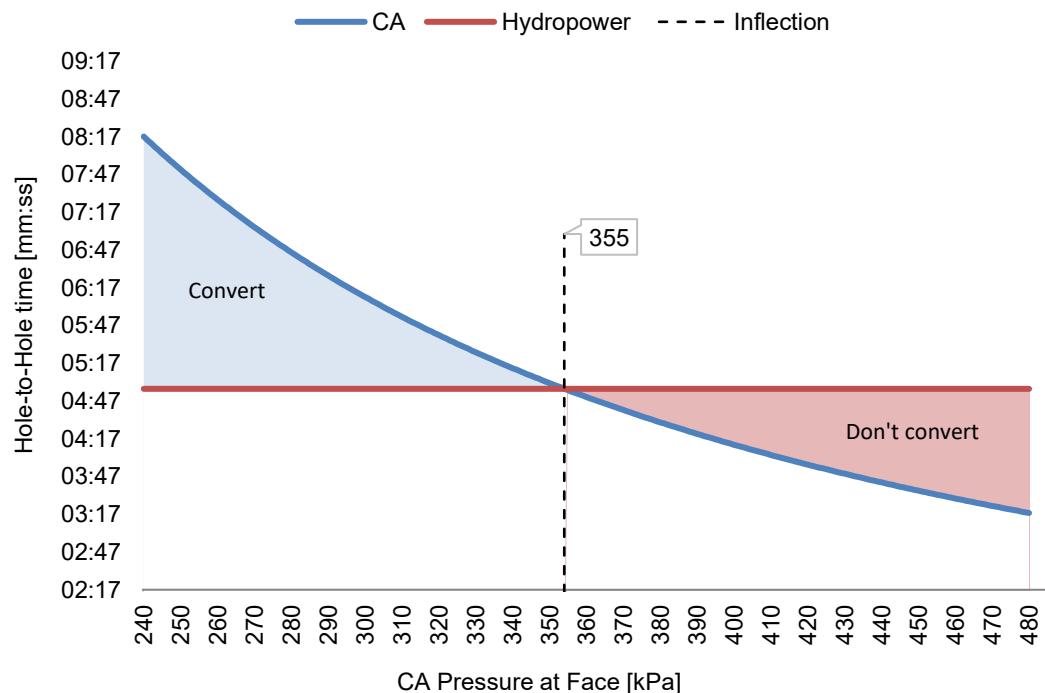
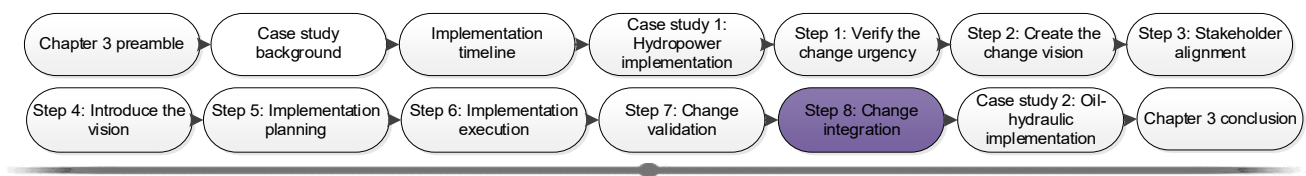


Figure 3-52: Site-specific holistic performance curve



PME Step 6: Establish the roll-out plan: The compressed air pressures at the faces during peak drilling measured 260 kPa, 280 kPa, and 300 kPa for sections A, B, and C, respectively. Based on the in-stope compressed air pressures, it was established that none of the crews mined above 355 kPa, and all crews had to be converted.

The time study data gathered for each of the three mining sections were used to estimate the travel time, entry examination time, face preparation, and charge-up durations. The drilling activity duration was estimated using the measured in-stope pressures and Equation 3-1. The crews were prioritised according to the shift time deficit to establish the roll-out plan, as shown in Table 3-61. As expected, the crew with the longest travel time and the lowest compressed air pressure was prioritised as the first crew to be converted, while the crew closest to the shaft, with the highest pressure, was the last to be converted.

Action 2: Sequential change process expansion

First implementation iteration (April 2022 to August 2022)

To recap, the initial micro stope system, used to prove the concept and demonstrate benefits, was installed and commissioned in April 2022, following the steering guidance provided in Step 6. A one-month training period followed, during which the transition strategy was used to sequentially introduce the equipment. All operators were assessed as competent at the end of May 2022. The three-month trial period to validate the performance benefits spanned from June 2022 to August 2022. To validate the change benefits, the assessment results (Step 7) were benchmarked against the theoretical change benefits captured in Step 2. The actual results correlated with the theoretical results, confirming that the change benefits had materialised. The theoretical change vision was updated to reflect the validated actual change benefits.

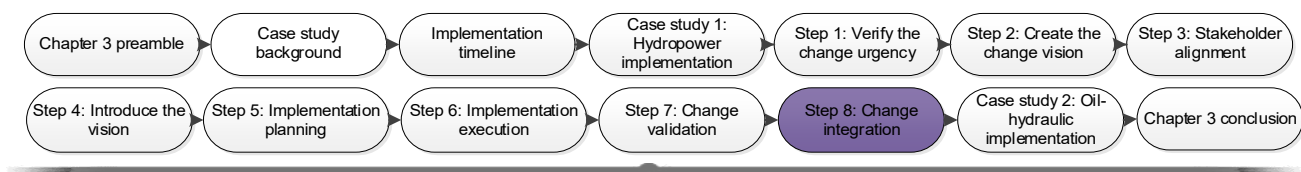


Table 3-61: CSM roll-out plan

Section	Crew	Total travel time	Entry examination and face preparation	Drilling activity duration	Charge-up duration	Drilling shift duration	Available shift time	Shift time deficit
		[hh:mm:ss]						
A – 260 kPa	Crew 1	03:58	00:40	05:53:42	01:30:00	12:01:42	08:00:00	04:01:42
	Crew 2	03:58	00:40	05:28:07	01:30:00	11:36:07	08:00:00	03:36:07
	Crew 3	03:58	00:40	05:06:52	01:30:00	11:14:52	08:00:00	03:14:53
	Crew 4	03:58	00:40	05:06:52	01:30:00	11:14:53	08:00:00	03:14:53
	Crew 5	03:58	00:40	04:45:37	01:30:00	10:53:38	08:00:00	02:53:38
	Crew 6	03:58	00:40	04:35:00	01:30:00	10:43:00	08:00:00	02:43:00
	Crew 7	03:58	00:40	04:35:00	01:30:00	10:43:00	08:00:00	02:43:00
	Crew 8	03:58	00:40	04:35:00	01:30:00	10:43:00	08:00:00	02:43:00
	Crew 9	03:58	00:40	04:35:00	01:30:00	10:43:00	08:00:00	02:43:00
	Crew 10	03:58	00:40	04:35:00	01:30:00	10:43:00	08:00:00	02:43:00
B – 280 kPa	Crew 11	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 12	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 13	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 14	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 15	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 16	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 17	03:30	00:35	04:16:40	01:30:00	09:51:40	08:00:00	01:51:40
	Crew 18	03:30	00:35	04:16:40	01:00:00	09:21:40	08:00:00	01:21:40
C – 300 kPa	Crew 19	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 20	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 21	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 22	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 23	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 24	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 25	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22
	Crew 26	03:00	00:35	04:02:22	01:00:00	08:37:22	08:00:00	00:37:22

Second method iteration (September 2022 to August 2023)

Step 8.1 – Implement: A second layer of the change process was applied from September 2022 to August 2023 to convert the first seven high-priority crews listed in the roll-out plan (Crews 1 to 7, Table 3-61). At the end of August 2023, eight crews adopted the micro-hydropower system (MHS), as shown in Table 3-62.

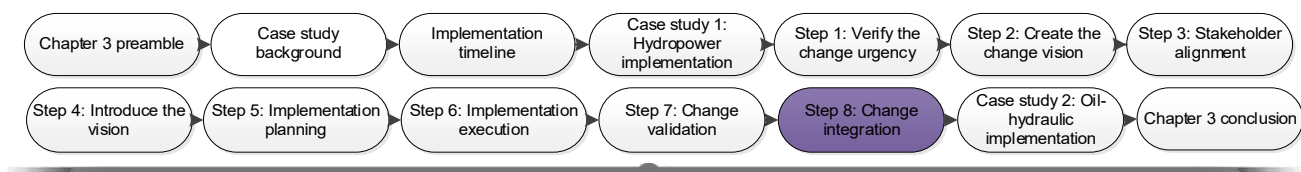


Table 3-62: Conversion matrix – first five crews (five method iterations)

#	Crews	Apr-22	May-22	Jun-22	Jul-22	Aug-22	Sep-22	Oct-22	Nov-22	Dec-22	Jan-23	Feb-23	Mar-23	Apr-23	May-23	Jun-23	Jul-23	Aug-23
1		MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
2	First iteration						MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
3											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
4											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
5											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
6											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
7	Second iteration										MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
8											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
9											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
10											MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS

LHS: localised hydropower system; MHS: micro-hydropower system

Step 8.2 – Optimise: At the end of August 2023, there was performance data for 17 months, which was used to develop the initial version of the continuous improvement strategy (CIS).

Production achieved: The production results were analysed, and a production performance curve was developed, as illustrated in Figure 3-53. Production performance, expressed as the percentage of calls achieved, is shown on the primary y-axis, while the number of lost blasts is represented on the secondary y-axis. Production achieved by the micro-hydropower crews over this period averaged 98% per crew. This correlates to a 16% improvement in production compared to the compressed air baseline. However, only four crews achieved the production target of 100%. The irregular performance and the high number of lost blasts highlighted the need for further optimisation.

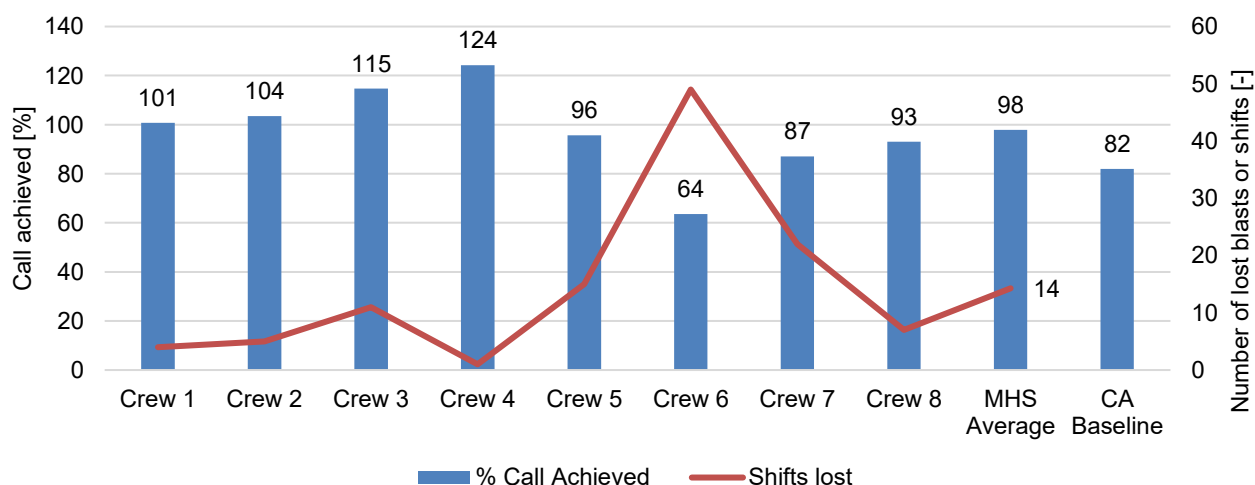
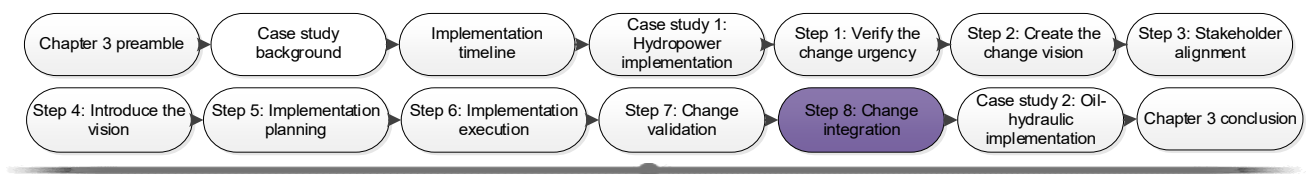


Figure 3-53: Microsystems – Production vs call achieved and number of lost blasts (Sept '22–Aug '23)

Pareto analysis: The lost blast data was analysed, and the Pareto curve was developed. Figure 3-54 shows the problem categories on the x-axis and the number of lost blasts on the primary y-axis. The overall contribution of each category is shown on the secondary y-axis. The data used to develop the



Pareto graph were collected from two different and independent sources: (1) the mine booking system and (2) the OEM supplier's daily performance reports. Reasons booked were correlated between the sources and aligned when discrepancies existed. The curve shows that the top 80% contributors to the production loss included:

- Crew moves resulted in 63 lost blasts and contributed to 55% of the total lost blasts. To recall, micro hydropower systems were implemented at this stage of the hydropower conversion. Equipping a compressed air raise is straightforward, where only reticulation, drills and ancillaries are needed. The complexity involved with equipping a raise with micro hydropower was underestimated. Moving the 1.3-tonne pressure-generation units up the raise and into the working places with chain blocks proved exceptionally challenging. A level bed of sufficient depth must be blasted to accommodate the pressure-generation unit. This result indicated that the initiatives implemented to address this problem category might reduce the number of lost blasts by 55%.
- Motor failures and shortage of electricity contributed a further 9% each.
- Shortage of water caused an additional 7%.

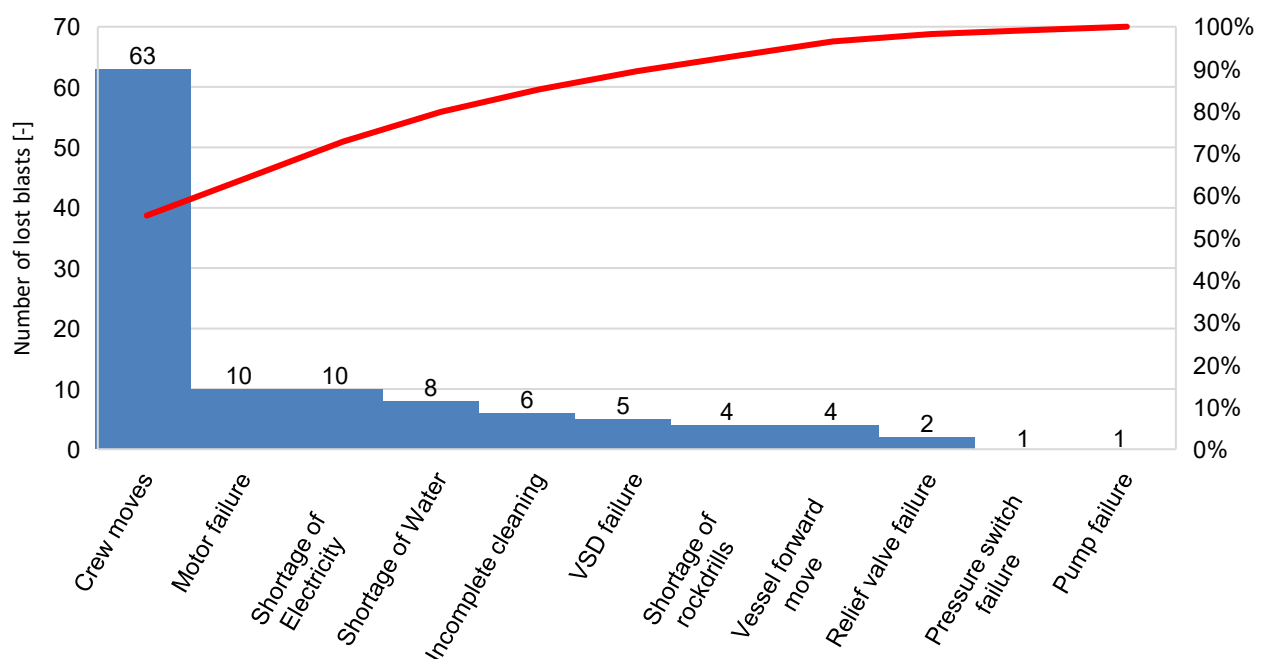
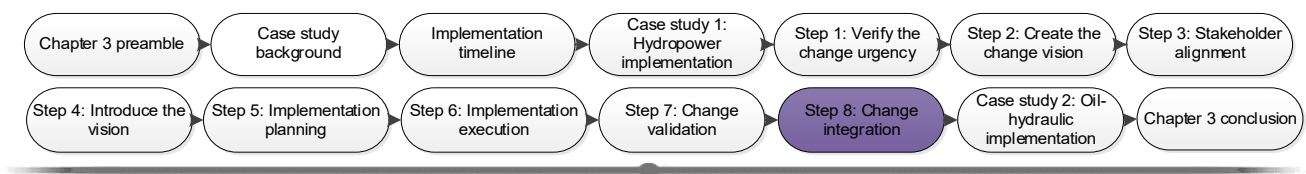


Figure 3-54: Microsystems – Pareto analysis (Sept '22–Aug '23)

Identification and implementation of improvement initiatives: The root causes behind the three main problem categories were investigated using the study's proposed continuous improvement methodology (refer to Figure 2-41). As shown in Table 3-63, the following improvement initiatives were identified and implemented:



(1) Crew moves: It was found that the substantial number of lost blasts due to crew moves was driven by two factors, namely the limited availability of equipping crews and the extensive effort and resources required to move the equipment between workplaces. To alleviate these constraints, an additional equipping crew was added for each section, and one additional drilling system was acquired for each mining section. This was since, on average, one crew per section per month needed to be accommodated at that time, which enabled the new workplace to be equipped before the required crew moved. It follows from [Section 1.4](#) that localised hydropower systems enable crew moves to be executed in a timely manner. As a result, a conscious decision was made to implement localised hydropower systems in raises where four or more panels are clustered on the same raise line.

(2) Shortage of electricity: This problem category was driven by electrical overloads resulting in trip-outs due to excessive demand. The infrastructure upgrades required were evaluated using Step 5.2. The electrical supply was initially fed from two mini-substations, located on 129L and 121L. Four panels were fed from 121L, and six from 129L. The failure analysis revealed that overload trip-outs generally occurred when the strike gully and centre gully winches were used in conjunction with the pressure generation units. To balance the supply load, the number of panels needed to be split equally per level, and an additional mini-substation had to be installed at 129L to supply the winches, in accordance with the infrastructure upgrades recommended in Step 5.2. These recommendations were implemented to address this problem category.

(3) Shortage of water: The required infrastructure upgrades were evaluated earlier in Step 5.2. To recap, the recommended upgrades were as follows: level PRVs and service water supply columns, upgraded from four to six inches. At the time of the analysis, none of these upgrades had been implemented, and the operations team was recommended to expedite execution. The service water supply columns were upgraded first, followed by the level PRVs.

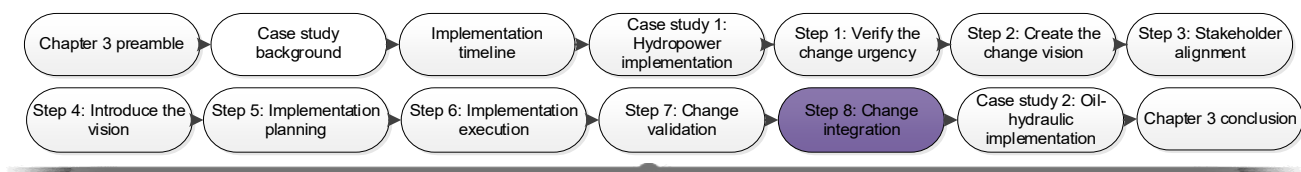


Table 3-63: Improvement initiatives identified and implemented (Sept '22–Aug '23)

Problem category	Root cause(s) identified	Improvement initiative identified and implemented
Crew moves	- Limited availability of equipping crews. - Extensive effort and resources required to move the equipment.	- Workplaces were equipped prior to crew moves. This required one additional equipping crew per mining section and one floating vessel. To reduce the equipping time required, a decision was made to implement localised hydropower drilling systems at raises with four or more panels clustered together.
Shortage of electricity	- Supply network infrastructure constraints.	- The required infrastructure upgrades were re-evaluated by means of reiteration of Step 5. - The supply load was split, where the bottom five panels were fed from 129L and the top five panels from 121L. An additional mini-sub was added.
Shortage of water	- Supply network infrastructure constraints. - Failure to implement the proposed infrastructure upgrades as proposed by Step 5.2 within time.	- Proposed water network infrastructure upgrades to be implemented.

Third method iteration (September 2023 to May 2024)

Step 8.1 – Implement: A third layer of the change process was applied from September 2023 to May 2024 to implement three additional micro-hydropower systems and convert seven compressed air crews to hydropower using a localised hydropower system. As shown in Table 3-64, 18 crews adopted the ADT at the end of May 2024.

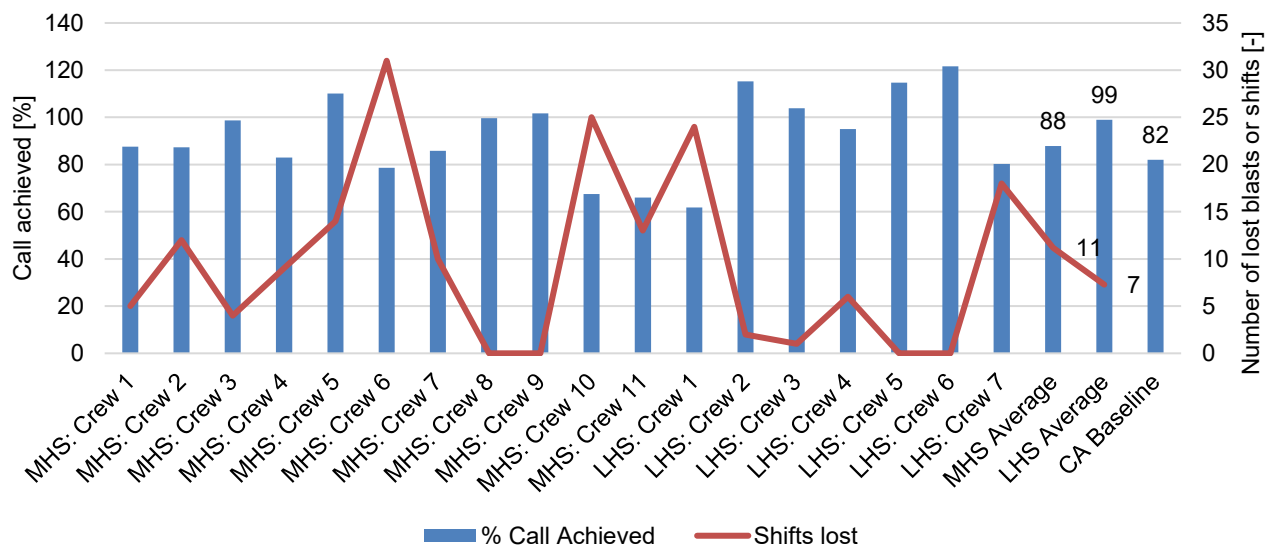
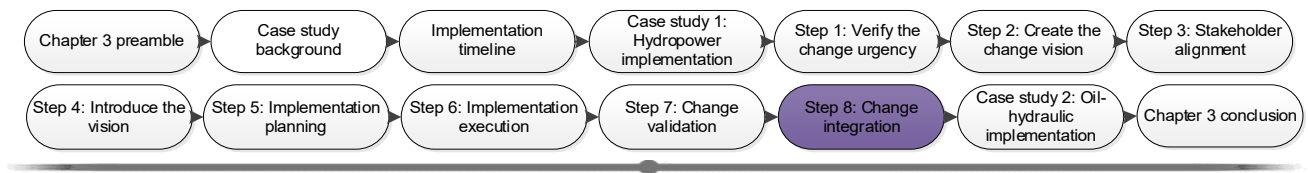


Figure 3-55: Third method iteration – Call achieved vs the number of lost blasts (Sept ‘23–May ‘24)

Pareto analysis: The Pareto curves are depicted in Figure 3-56 and Figure 3-57 for the micro and localised systems, respectively. The following key problem categories were identified from the curves: incomplete cleaning, water shortages, and motor failures, which accounted for 80% of the lost blasts experienced by the micro-hydropower system crews. A shortage of rock drills, incomplete cleaning, and a shortage of support resulted in 80% of the lost blasts being recorded at the localised hydropower crews.

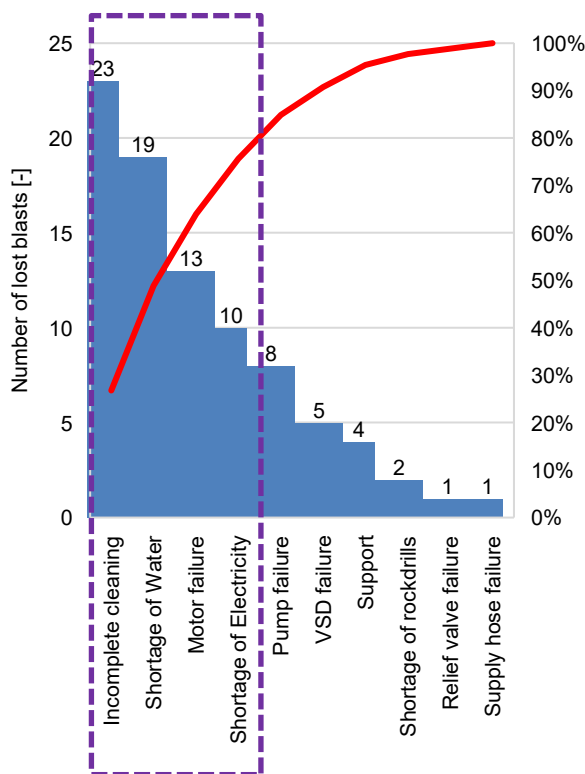
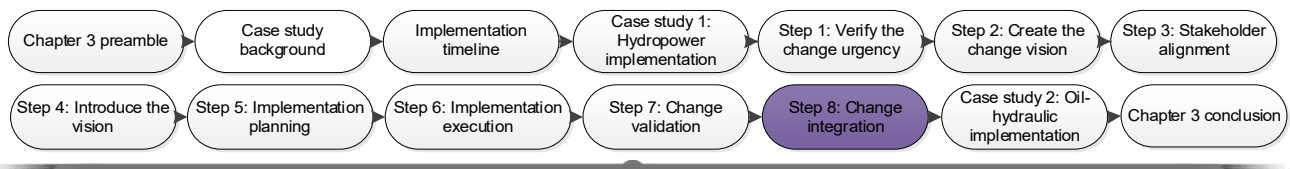


Figure 3-56: Microsystems – Pareto analysis (Aug '23–May '24)

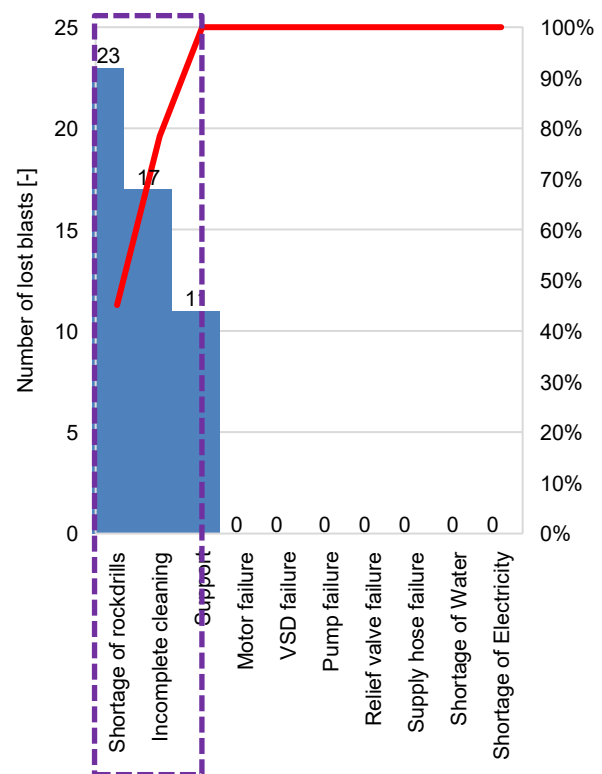
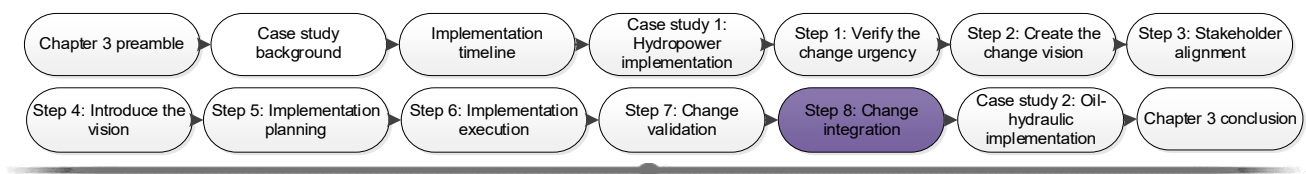


Figure 3-57: Localised systems – Pareto analysis (Aug '23–May '24)

Identification and implementation of improvement initiatives: The root causes behind the four main problem categories were investigated using the study-proposed CIS.

(1) Incomplete cleaning: Underground time and motion studies were conducted to analyse and identify the root causes of the problem category. Cleaning operations were analysed on 10 panels. On average, the cleaning time required to move 95 tonnes per panel from the face into the time was estimated to be 360 minutes (as per Equation B-6). The studies revealed that only 240 minutes were effectively used to scrape ore into the ore passes. The remaining 120 minutes presented opportunities for improvement. The time spent repairing rope breaks was 20 minutes, while 45 minutes were lost due to ineffective scraping. It was found that all the scrapers were blunt, reducing their effectiveness to as low as 50%. Due to unplanned locomotive breakdowns, 30 minutes were lost, and ore passes were filled up. The full ore passes caused the advance strike gullies to become blocked due to insufficient gully depth. As a result, the following improvement initiatives were implemented:

- **Scraper bucket and winch rope condition monitoring:** Rope breaks and ineffective scraping were addressed by implementing a scraper bucket and winch rope condition



monitoring programme. A managerial instruction was issued requiring shift bosses to report biweekly on the condition of scraper buckets and winch ropes.

- **Gully depth to mine standard:** Gullies were redeveloped to meet mine standards to ensure sufficient capacity.
- **Lithium locomotive battery upgrade:** Lead acid locomotive batteries were upgraded to lithium. This initiative reduced charging time and increased operational capacity between charges.

(2) Shortage of water: Micro-hydropower systems require low-pressure service water pipes to be reticulated into the stope. This proved to be a significant challenge, as scraper buckets frequently collided with the pipes. It became especially problematic at shallow gullies. This resulted in severe water leaks. Isolation valves were installed only up to the cross-cut level. This meant that the water supply to all panels had to be isolated in events where water leaks had to be repaired. The following changes were implemented to resolve these challenges:

- **Additional isolation valves:** Isolation valves were installed at each strike gully breakaway.
- **Pipe routing:** As far as practically possible, pipes were routed adjacent to the gullies along the first line of packs.
- **Gullies to comply with mine standard:** Shallow gullies were redeveloped to meet mine standards.

(3) Motor failure: Six motor failure data points existed at the time, which were used to develop the reliability curve for this specific component. The number of operational shifts between failures and the time required to replace the motors are depicted in Figure 3-58. On average, the data shows that motors can be expected to last 270 operational shifts, allowing for two shifts to replace faulty motors. The main causes of failure were found to be water penetration and overheating. These challenges presented the following improvement opportunities:

- **Electrical connection boxes:** Cable compression glands were installed at all connection points, and the connection boxes were sealed.
- **Force fan pre-use inspections:** Emphasis was placed on conducting daily pre-use inspections of force fans to ensure operational compliance.

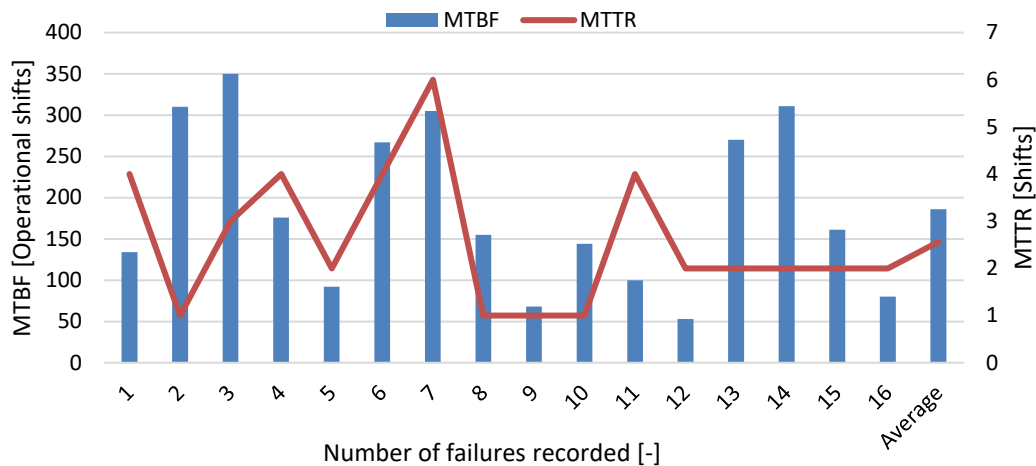
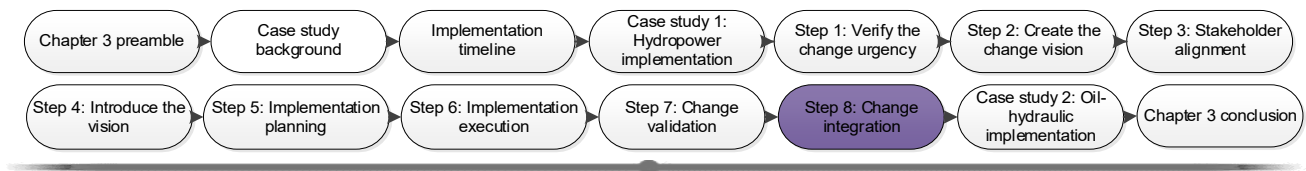


Figure 3-58: Microsystems – Motor MTBF and MTTR curve (Sept '23–May '24)

(4) **Shortage of electricity:** Similar to water, the electrical shortages were caused by cables that were damaged by scraper buckets. The following remedial measures were implemented:

- **Cable routing:** As far as practically possible, cables were routed adjacent to gullies
- **Gullies to comply with mine standard:** Shallow gullies were redeveloped to comply with the mine standard.

(5) **Shortage of rock drills:** The rock drill shortages were caused by premature rock drill failures. On average, the rock drills lasted only 62% of the targeted MTBF, as illustrated in Figure 3-59. This result highlights the importance of involving the OEM in the transformation journey. Following several consultation sessions, the OEM identified limitations in the rock drill design and proposed replacing the rock drills with an improved version.

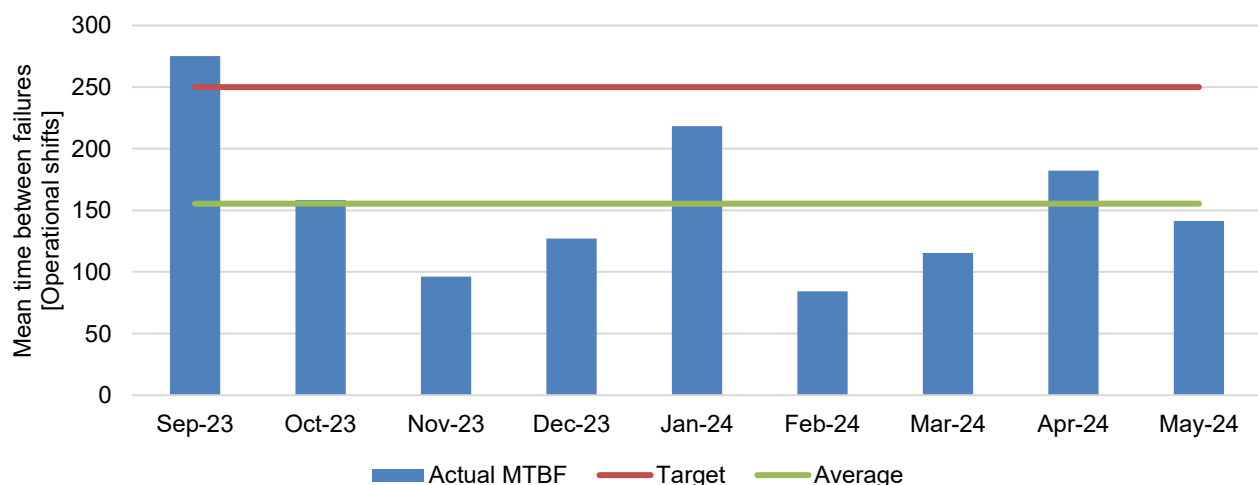
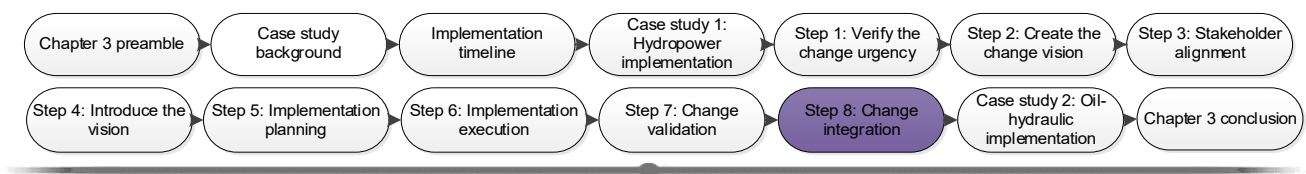


Figure 3-59: Rock drill reliability overview – Sept '23–May '24



Fourth method iteration (June 2024 – July 2025)

Step 8.1 – Implementation: A fourth method iteration was applied to convert the remaining crews, with the last two crews converted in November 2024, as shown in Table 3-65. A second localised hydropower system was implemented. It was concluded that the method developed in this study successfully achieved its objective of serving as an implementation and change management methodology, as all crews adopted hydropower as an alternative technology.

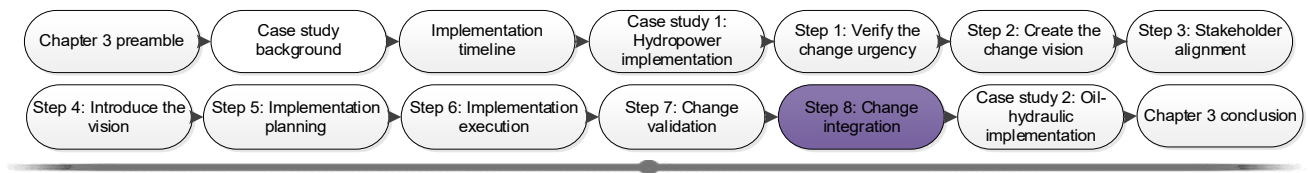
Table 3-65: Conversion matrix – Fourth method iteration

# Crews	Apr-23	May-23	Jun-23	Jul-23	Aug-23	Sep-23	Oct-23	Nov-23	Dec-23	Jan-24	Feb-24	Mar-24	Apr-24	May-24	Jun-24	Jul-24	Aug-24	Sep-24	Oct-24	Nov-24	Dec-24
1	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
2	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
3	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
4	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
5	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
6	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
7	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
8	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
9	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
10	Third iteration					MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
11						MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
12						MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS	MHS
13						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
14						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
15						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
16						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
17						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
18						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
19						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
20	Fourth iteration					LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
21						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
22						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
23						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
24						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
25						LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS	LHS
26																			MHS	MHS	
27																			MHS	MHS	

LHS: localised hydropower system; MHS: micro-hydropower system

Step 8.2 – Optimisation: The continuous performance improvement strategy developed during the third method iteration was implemented from June 2024 to July 2025. Twelve months of performance results, as illustrated in Figure 3-60, were gathered and analysed.

Production achieved: Following the implementation of the proposed improvement initiatives, the performance of the micro-hydropower system crews increased from 88% to 93%. At the same time, the performance of the localised hydropower system crews improved from 99% to 106%. When compared to the compressed air baseline, it is evident that the CSM made a strategically sound decision to implement hydropower as an ADT. The 7% performance shortfall from the micro-



hydropower system called for an additional iteration of the performance improvement strategy, as showcased next.

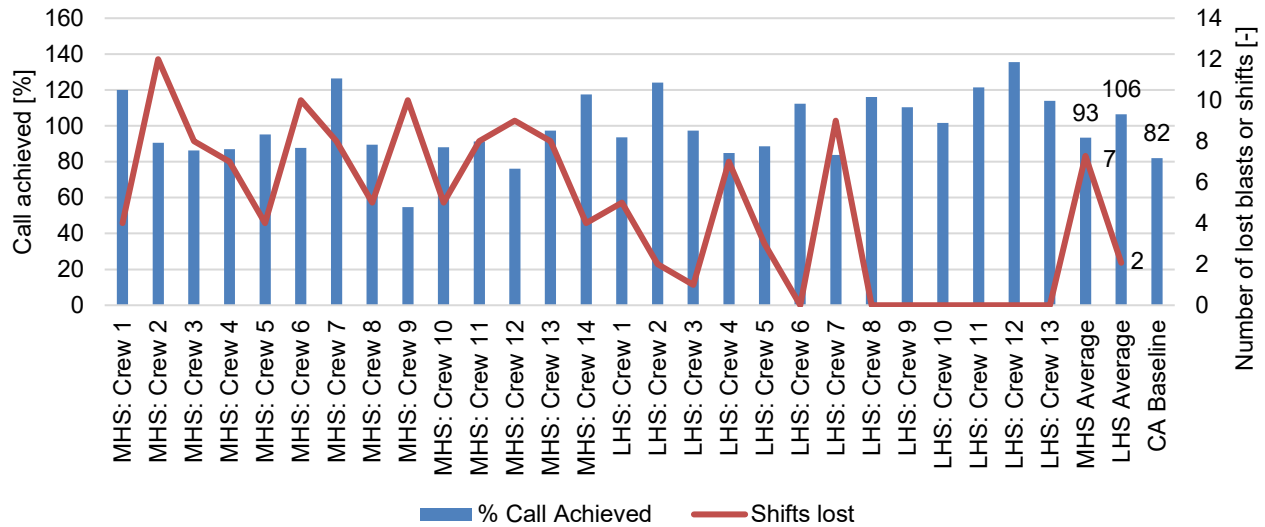


Figure 3-60: Fourth method iteration – Call achieved vs the number of lost blasts (Jun '24–Jul '25)

Pareto analysis: The Pareto curve representing the lost blast data for June 2024 to July 2025 for micro-hydropower systems is shown in Figure 3-61. The following four key problem categories were identified: motor failures, pump failures, incomplete cleaning, and VSD failures.

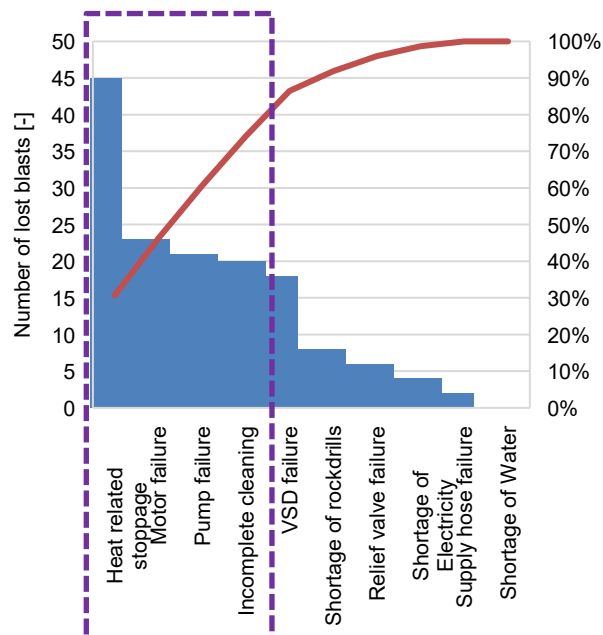
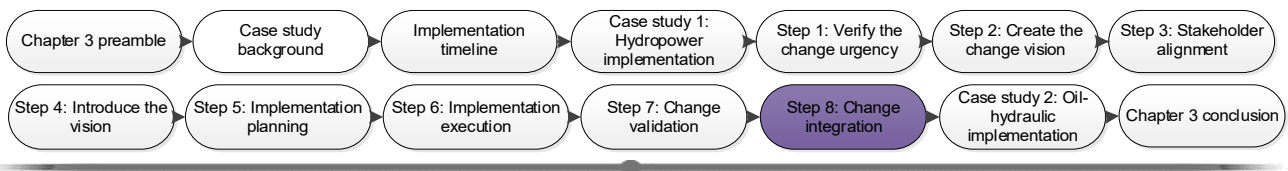
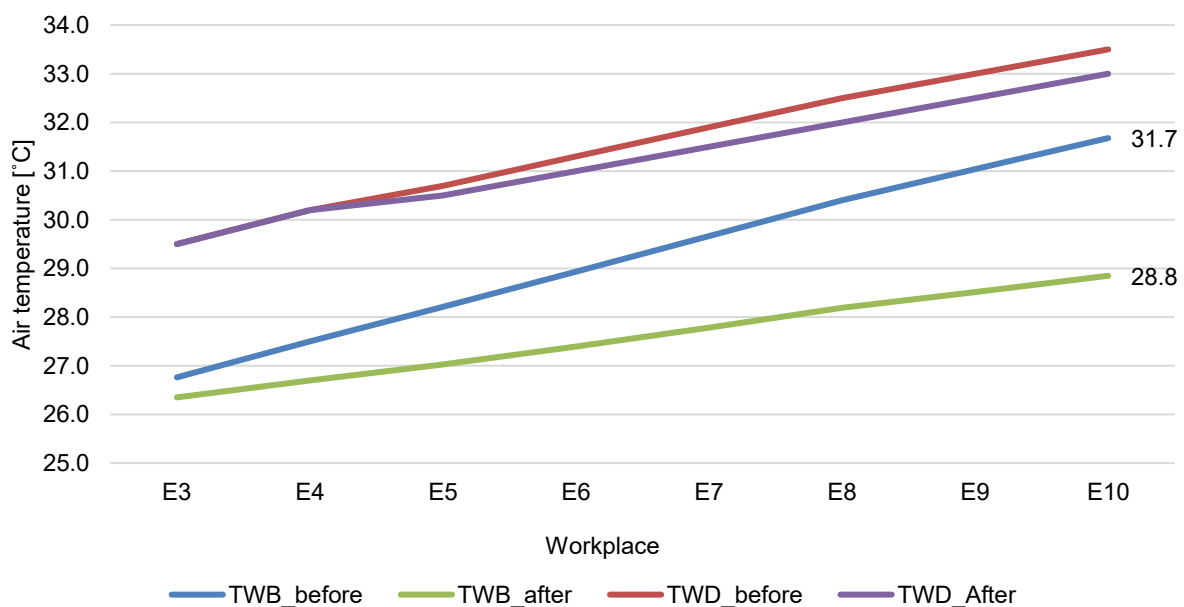


Figure 3-61: Microsystems – Pareto analysis (Jun '24–Jul '25)



(1) Heat-related stoppages: At the CSM, as a precautionary measure, workers are stopped from advancing the face at 31.5 °C wet-bulb. This is done to ensure workers are not exposed to 32.5 °C when they must fix vent controls, etc. It was confirmed in Step 7.2 that the occupational environmental temperature increases by 1.0 °C per panel if the water is not controlled to the new mine standard. Figure 3-62 presents an overview of the heat map for this specific section. If no water controls were in place, air entered the stope at 26.5 °C (wet-bulb) and returned at 31.7 °C (wet-bulb) after removing heat from eight workplaces. At the same time, after the water controls were implemented and adhered to, the rejected wet-bulb temperature reduced to 28.8 °C. This result highlights the importance of in-stope water control in mitigating heat-related stoppages.

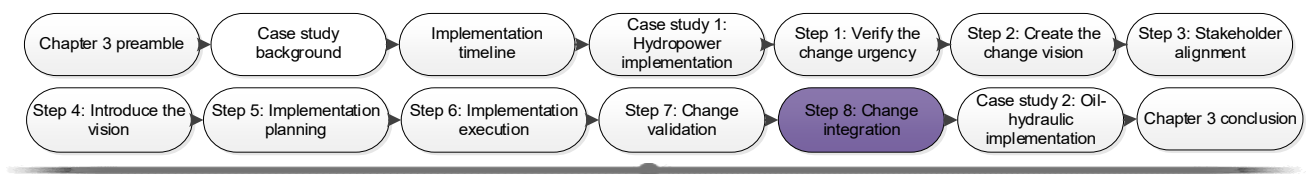


TWB: Temperate wet bulb.

Figure 3-62: Workplace temperature changes before and after installation of dedicated draining columns

(2) Motor failures: Most of the micro-hydropower systems were due for refurbishment during this period. Several units were returned to the mine as faulty after refurbishment. Further investigation revealed that the OEM lacked the facilities to test the equipment after refurbishment. As a result, the motors were found to be down to earth upon commissioning after being rewound during the refurbishment process. This highlighted the following improvement opportunities:

- **OEM testing facility:** The OEM was requested to invest in a generator capable of generating the voltage and current required to test the equipment after refurbishment.



- **OEM supplier to only use new motors:** An additional agreement was reached with the OEM supplier to replace old motors with new units during the refurbishment process.

(3) Pump failures: Several pump failures were recorded during the first four operational shifts following refurbishment. Failure data describing 12 pump failures and replacement times were collected, as illustrated in Figure 3-63. It can be estimated from the data that the pumps lasted, on average, 160 shifts and required two shifts to replace. Failures were driven by high oil temperatures, pump head failure, and/or oil leaks. Similar to the electric motors, several refurbished units were returned to the mine due to faulty pumps. During an OEM consultation session, it was established that the pressure generation units were only tested for 10 minutes after refurbishment. The OEM supplier was requested to institute the following two corrective measures:

- **OEM supplier requested to institute a quality assurance programme:** A request was extended to the OEM to run the units for at least 22 hours to allow for sufficient quality assessment. This was based on an average running duration of 5.5 hours per operational shift.
- **OEM supplier requested to have sufficient spare pumps readily available on-site:** Figure 3-63 presents an overview of the motor failure rate data collected. The data confirmed that motors last an average of 160 shifts, and at least two shifts are required to replace faulty units. This is 18 shifts less than what the OEM supplier claimed. To minimise downtime, the OEM was requested to establish a preventive maintenance strategy in which pumps are replaced after 160 operational shifts.

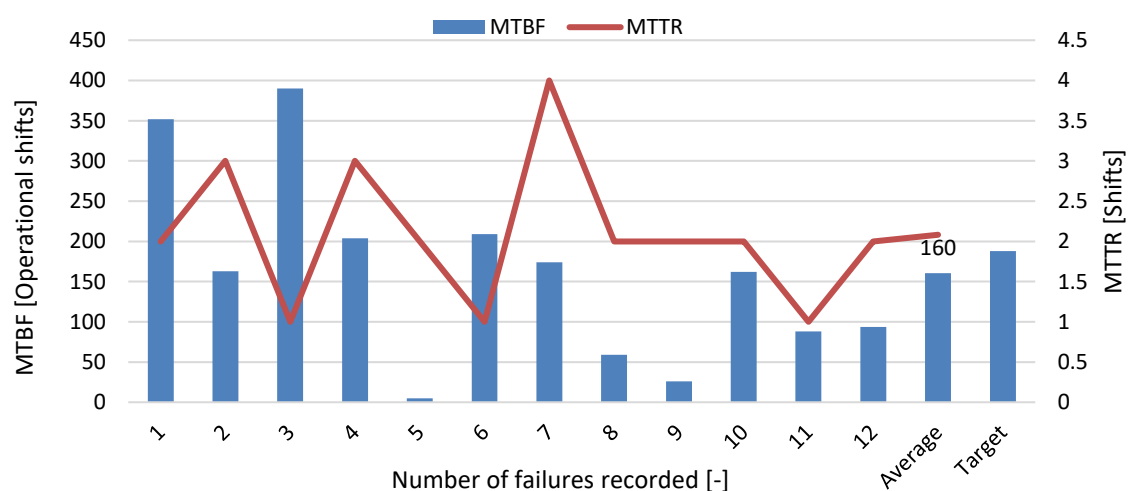
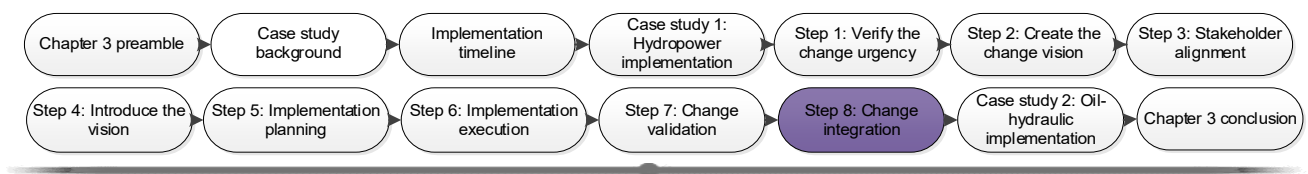


Figure 3-63: Microsystems – Pump MTBF and MTTR curve (Sept '24–Jul '25)



(4) Incomplete cleaning: The available time to clean the panels remained a significant challenge, with the key driver identified as late blasting. It is worth mentioning that the development crews were not converted to hydropower. Slow drilling due to insufficient compressed air pressure delayed completion of the drilling activity within the available shift time. Consequently, the development drilling cycles were stretched, resulting in delayed blasting. A reduction in the face time available to clean the panels resulted since the re-entry period remained non-negotiable. To alleviate the slow drilling constraint, capital was requested for the FY26 financial year to convert the development crews. The improved drilling performance offered by hydropower will enable the development crews to complete drilling on time, allowing the mine to blast earlier.

(5) VSD failures: Eight VSD failure data points and the corresponding replacement times were collected, as illustrated by Figure 3-64. When compared to the operational target, VSDs, on average, lasted longer than expected. Failures ultimately occurred due to non-functional force cooling fans.

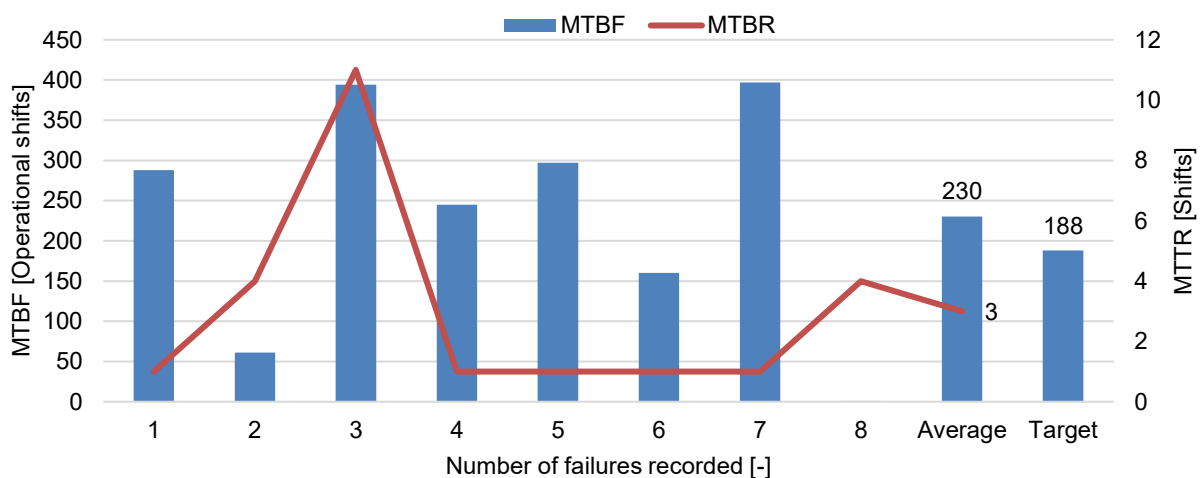
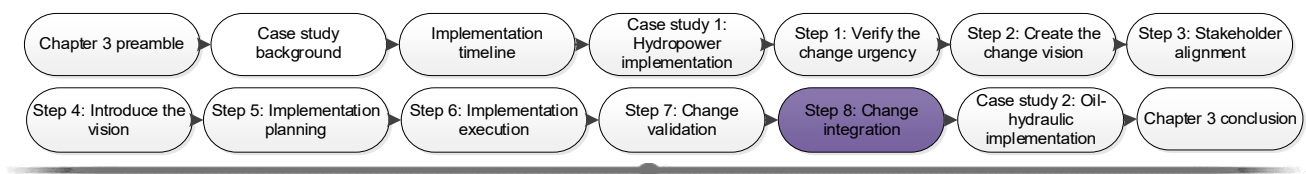


Figure 3-64: Microsystems – Variable speed drives' MTBF and MTBR curves (Sept '24–Jul '25)



3.5. Case study 1: Results discussion

This section includes a detailed discussion on the following seven key result categories:

(1) System performance

Figure 3-65 compares the CSM's historical compressed air performance with the performance enabled by the alternative drilling system. The CSM's production performance improved by 17% following the implementation and adoption of hydropower. It is evident from Figure 3-65 that the mine's overall performance deficit to target reduced from 17.2% to 1% after the implementation of hydropower. Moreover, this improvement corresponds to an increase in revenue of R720 million.

However, it is important to note that the overall performance result was achieved by executing a combination of performance improvement strategies, rather than solely by the alternative technology itself. An overview of these specific performance improvement strategies is discussed next.

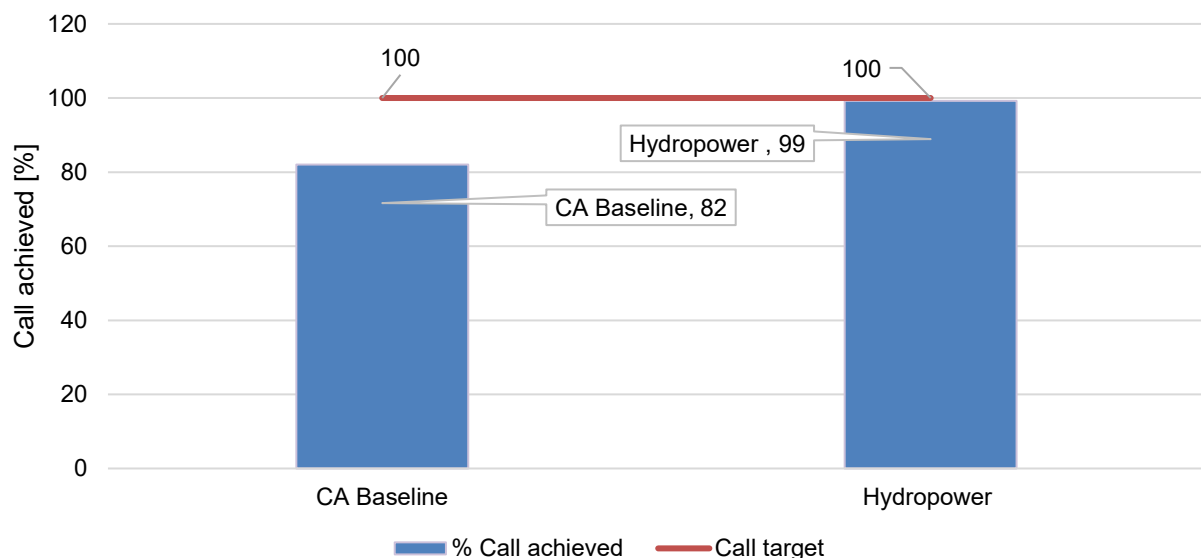
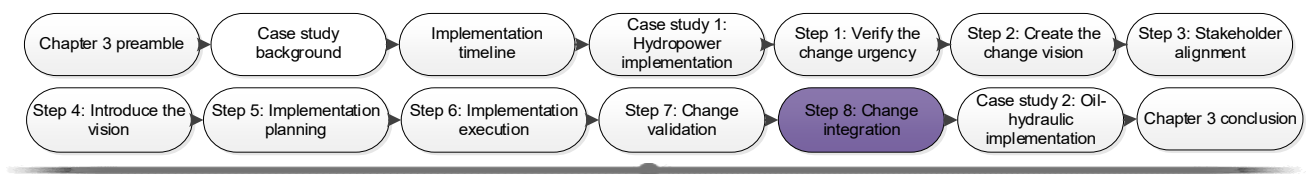


Figure 3-65: Compressed air (FY'20) vs hydropower performance comparison (FY'25)

(2) Continuous performance improvement

This section highlights the importance of integrating a continuous improvement strategy. Figure 3-66 illustrates the variance in performance over the implementation lifespan. Hydropower enabled the initial crew to achieve a production performance of 114%. With only one crew converted, the supporting network (including water, electricity, ore movement, and materials) managed to provide the additional water, electricity, and materials needed without interruptions.



However, following the conversion of an additional seven crews under the second method integration, equipment-related implementation constraints reduced the achieved production to 98%. The third method iteration converted 13 more crews, who only managed to achieve 93.5% of the production call. With 77% of the total stoping crew converted, the support network became severely strained. Shortages of water and electricity validated the need for critical network upgrades as predicted by the simulation models. Ore movement challenges highlighted the need for improvement initiatives related to ore logistics. The data on hydropower equipment failures provided sufficient information to develop a preventive maintenance strategy.

The improvement strategies were implemented during the fourth and final method iteration. Water pipe sizes and flow-control valves were upgraded to meet the increased demand. Electrical cables and mini substations were upgraded to meet load-flow requirements. The rerouting of services on Reef Horizon and the development of gullies to standardise minimised scraper bucket related damages. Fragmentation-improvement initiatives, combined with lithium-locomotive batteries, improved ore logistics. Ultimately, production improved to 99%, with all 27 crews converted to hydropower.

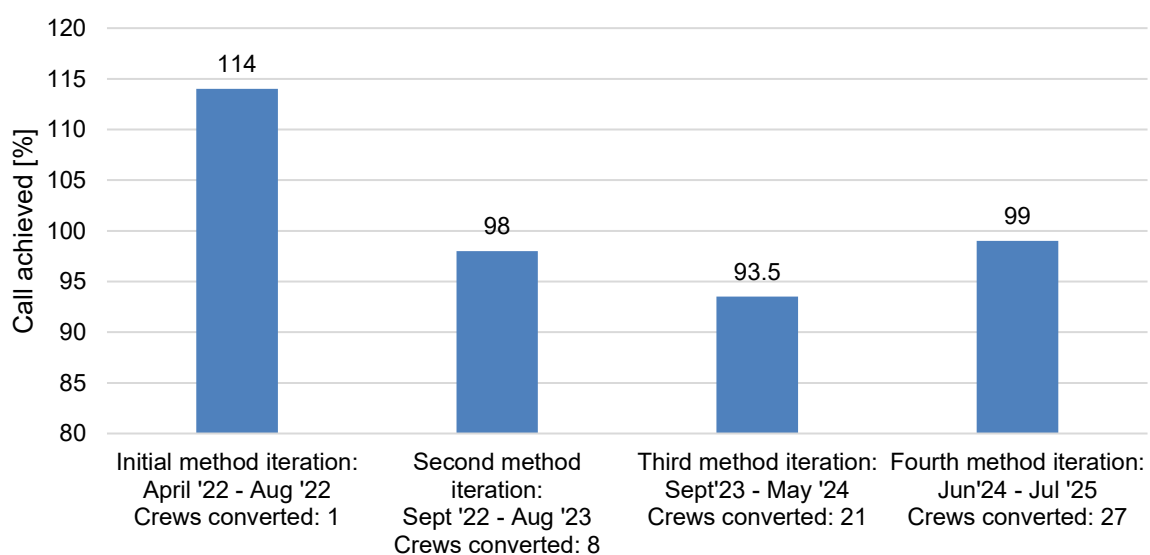
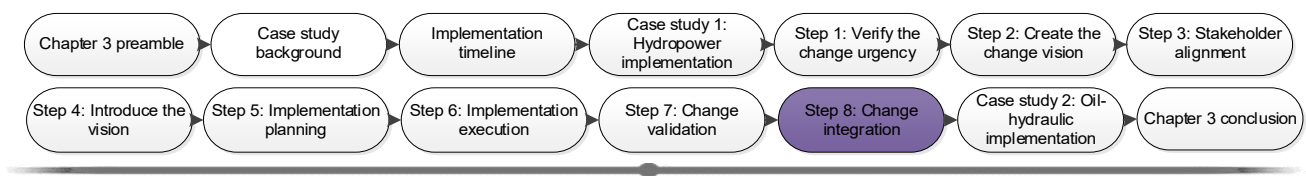


Figure 3-66: Production performance variances showcased over the implementation lifespan

Summary of the required production improvement initiatives

Improvement area #1 – Crew moves: Specifically relevant to micro-hydropower systems, one additional drilling equipment suite per active raise line has been introduced to facilitate crew moves without incurring production losses. The additional equipment suite provided the flexibility to equip the new workplace before the old workplace's production ground was depleted, allowing the crew to



start mining upon arrival. Localised hydropower systems, in contrast, allowed for crew moves with relative ease by simply extending the hydropower pipes to the new workplaces, provided that the workplace was located within the same raise line.

Improvement area #2 – Shortage of water and electricity: The importance of evaluating the capabilities of the electrical and water networks to support the ADT using simulation software should be noted. As predicted by the digital modelling, the CSM's base-case installed infrastructure was insufficient to support the hydropower drilling systems. Shortages of water and electricity were addressed by implementing the infrastructure upgrades recommended by the model. Cable and pipe routing, as well as gully development to standard, were also equally important. To prevent damage related to scraper buckets, cables and pipes should be routed along the gully shoulders as close to the hanging wall as practically possible.

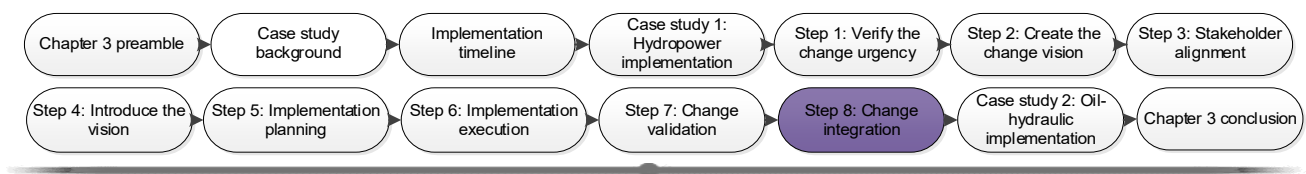
Improvement area #3 – Continuous equipment development: Lost production due to equipment-related failures was effectively minimised by:

1. developing and implementing a preventative maintenance strategy, and
2. forming a strategic partnership with the EOMs to enable continuous equipment development.

Preventative maintenance strategies rely heavily on accurate equipment reliability data, which may be unavailable initially. As a result, OEM-supplied data may be used as initial estimates. The actual failure data presented earlier have shown some discrepancies. This highlights the importance of implementing a data collection plan to gather actual failure data to refine the preventive maintenance plan. Based on the refurbishment and/or replacement intervals recommended by the preventative maintenance plan, pump and VSD failures were minimised effectively.

The initial premature rock drill failures highlighted the importance of forming strategic partnerships with the OEMs. Actual performance and reliability data were made available to OEMs, enabling continuous refinement of the implemented technology. Figure 3-67 presents an overview of the rock drill reliability trend during the CSM implementation phase. At first, the average reliability of the initial version of the rock drill (Mark I) was calculated during the trial phase as 221 m/failure.

However, the reliability reduced to as low as 104 m/failure (01/06/2024). The data was shared with the OEM supplier and further development work was requested. Failure modes were analysed, and it was found that a material change in the rotating mechanism's pawl springs was the main failure driver. The springs were redesigned, leading to the development of the Mark II rock drill. A first batch of Mark II rock drills was deployed in September 2024 and monitored for four months. The reliability of the Mark II version improved to 334 m/failure. However, a significant reliability shortfall between a hydro and a compressed-air drill persisted (334 vs 750 m/failure). The OEM supplier was challenged



to further improve the rock drill. Ultimately, the rotating mechanism was completely redesigned, and Mark III was launched in November 2024. Mark III's reliability improved to 539 m/failure.

The findings presented here highlight the importance of:

- ✓ Establishing a continuous improvement programme,
- ✓ Meticulous collection of performance and failure data, and
- ✓ Sharing the data with the EOM suppliers to enable continuous product development over time.

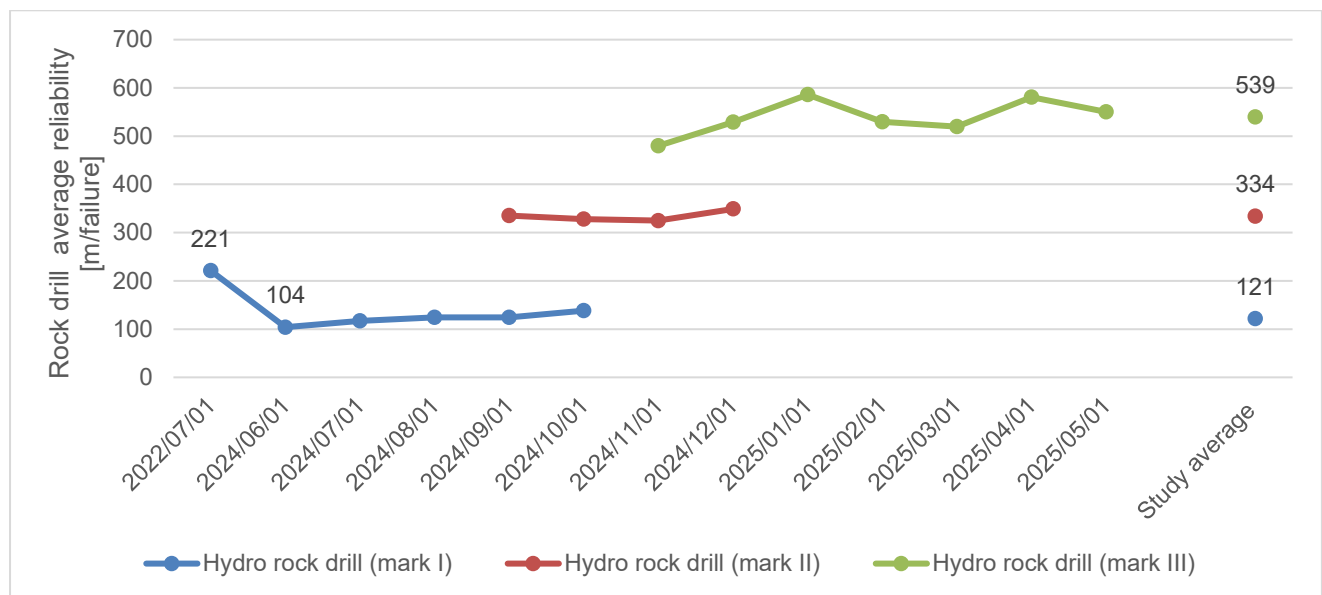
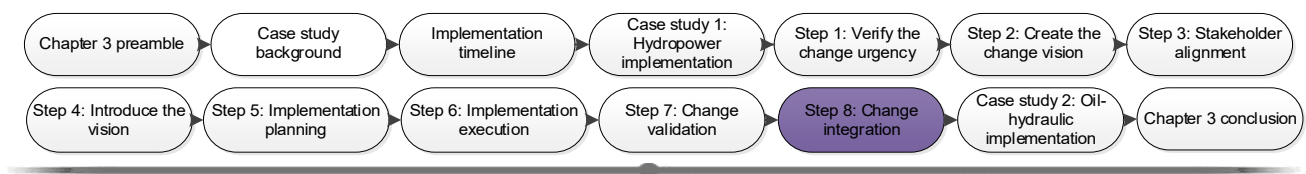


Figure 3-67: Rock drill reliability improvement trend

Improvement area #4 – Heat-related stoppages: The introduction of pressure generation units into the stopes increased the temperature by 0.6 °C per panel. This adverse effect was minimised through the following two initiatives:

- **Initiative #1 – In-stope water control:** To minimise the air-to-water contact time, the following water control measures were implemented:
 - ✓ All the drills were fitted with dump hoses.
 - ✓ All the strike gullies were equipped with dewatering pumps.
 - ✓ Dedicated draining columns were installed to reticulate dewatering water from the strike gully, down the raise, and into a simple pump located in the cross-cut.
- **Initiative #2 – Strategic placement of pressure generation units:** As far as practically possible, pressure generation units must be positioned in the return airway of the raise line. This prevents the cool intake air from becoming contaminated by the heat radiating from the units.
 Note to mine management teams - Underground mobile refrigeration plants, or surface bulk air



cooler upgrades, may be needed to offset the heat load introduced, especially when hosting multiple panels in long raises

(3) *Mud rushes and other water related safety risks*

This section presents a holistic (macro level) reflection on the initiatives implemented to manage the water related safety risks associated with the implementation of hydropower.

Initiative #1 – Water controls

The trial results confirmed the effectiveness of the water controls implemented on a micro level to manage the water related safety risks. Strike gully jet pumps were implemented in all the strike gullies, as illustrated in Figure 3-68. High-density polyethylene HDPE pipes (50 mm) were used to reticulate the water from the strike gullies into the 100 mm drain column positioned in the centre gully. The water was discharged directly into the spindle pump sump located in the cross-cuts.

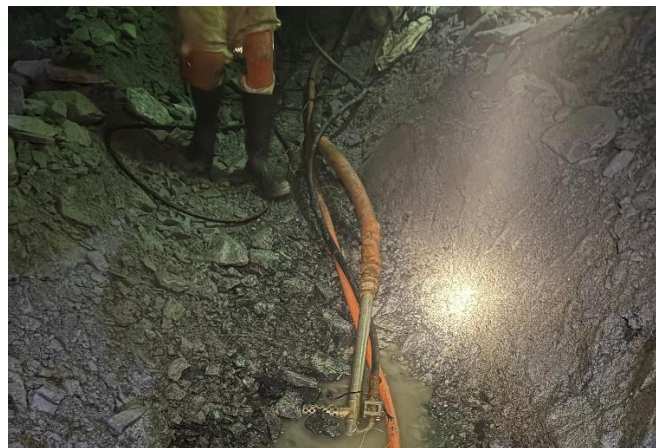


Figure 3-68: CSM – jet pump deployment in a strike gully³⁰

Additionally, due to hydropower's built-in auto-shutoff technology, the volume of water used to produce the fragmented ore was significantly reduced, as illustrated in Figure 3-69 and Figure 3-70. Localised hydropower systems showed a 76% reduction in the water-intensity ratio compared to the historical compressed-air baseline operations of FY20. In contrast, micro-hydropower systems showed a 53% reduction, which highlights an important drawback of these systems. The micro-hydropower system's configuration allows low-pressure service water to be reticulated into the raised line, whereas a localised hydropower system eliminates this need.

³⁰ B van Rooyen, Personal collection, "Jet pump deployment in strike gully", 2025.

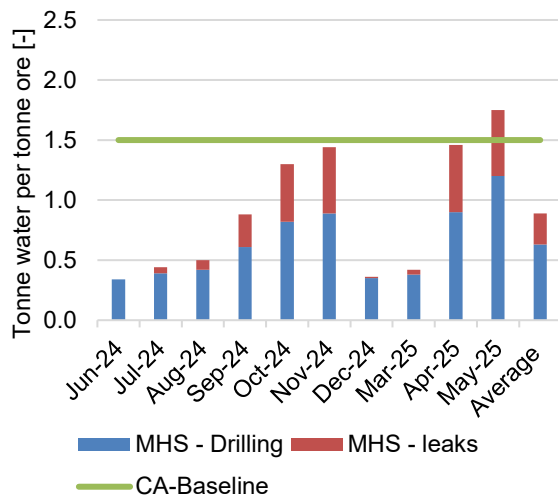
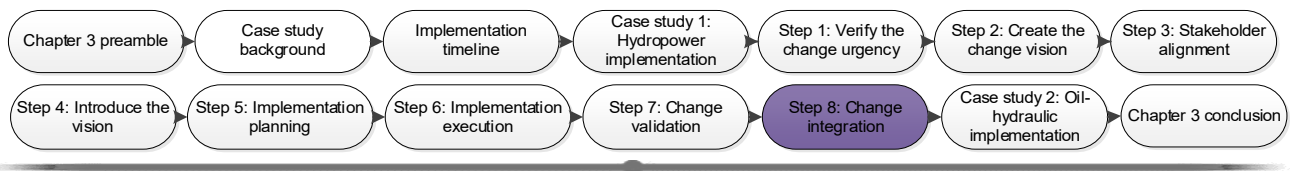


Figure 3-69: Water intensity ratio for micro-hydropower system

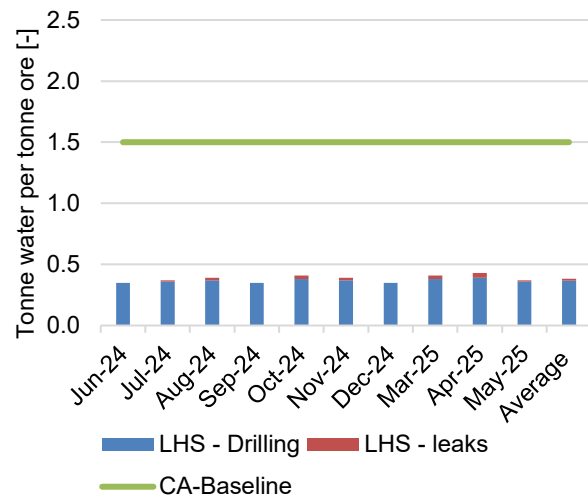


Figure 3-70: Water intensity ratio for localised hydropower system

Initiative #2 – Box front radial doors

To recall from the guidance provided in Section 2.5, Step 7.2, the stope layout can be adjusted to allow for sumps in the raise, or if not possible, box fronts with slotted doors may be installed to prevent water from accumulating in the boxes. It was not possible to alter the stope layouts at the CSM, and also impractical to replace the box front radial doors due to production pressure.

Instead, the following effective solution was implemented at each box front radial door. It follows from Figure 3-71 that low-flow leaks formed over time at the connections of the high-pressure pipe. The leaks were small enough to go undetected by the excessive-flow control valves. These pipes are routed along the centre gully, and water from these leaks did enter the tips when the leaks were not attended to timeously. As illustrated in Figure 3-72, to prevent mud rushes from forming, the corners of the box front radial doors were slightly rounded to allow the water to flow out of the boxes. No mud rushes were recorded during the study implementation phase.

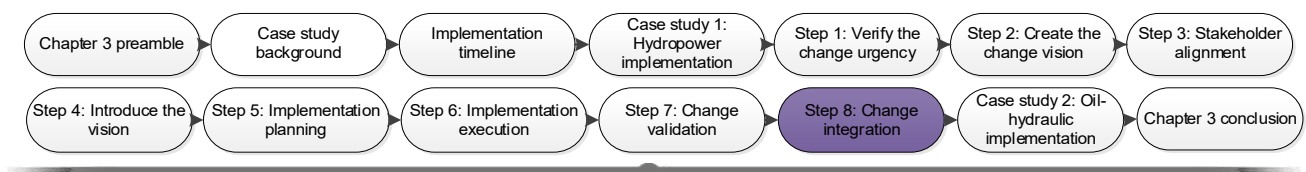


Figure 3-71: Hydropower high-pressure pipe connection leak³¹



Figure 3-72: CSM – box front radial door³²

The results presented in this section confirmed the following two important points:

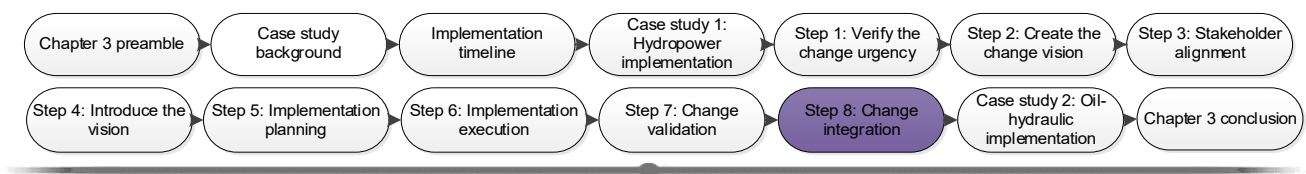
- ✓ No water-related injuries were recorded over the duration of this study, and the combined flow and isolation valves safely isolated the flow when the hose busted, and
- ✓ No mud rush incidents were recorded over the duration of this study, confirming the effectiveness of the dewatering strategies implemented.

(4) Compressor energy cost

The background provided in Chapter 1 highlights the need for mining operations to reduce energy consumption, given South Africa's low-energy availability factor. ADTs present an opportunity to meet this need. The results obtained from the performance evaluation assessments (Step 7.1) confirmed a 98% reduction in energy consumption when using hydropower to drill the blastholes. Step 7.3 further confirmed that hydropower ancillary equipment existed, and tests confirmed the functionality required to perform all ancillary activities required to complete a narrow reef gold mining cycle. This confirms that narrow reef gold mining is possible without compressed air. As a result, it was initially anticipated that the CSM's overall compressed energy consumption would decrease once all the stoping crews were converted to hydropower. However, as shown in Figure 3-73, the CSM's compressor energy consumption did not decrease. Since the mine's development section was not converted, the entire compressed air network had to remain pressurised. The cost savings opportunity loss here equates to R51 million per annum. This result highlights the following key points:

³¹ B van Rooyen, Personal collection, "Hydropower high-pressure pipe connection leak", 2025.

³² B van Rooyen, Personal collection, "CSM - box front radial door", 2025.



- The implementation of an alternative drilling system should be driven by the need for improved production rather than by compressed air energy savings.
- Compressed air energy savings are only possible once the mine has been fully converted to hydropower (including stoping, development, and box holes).

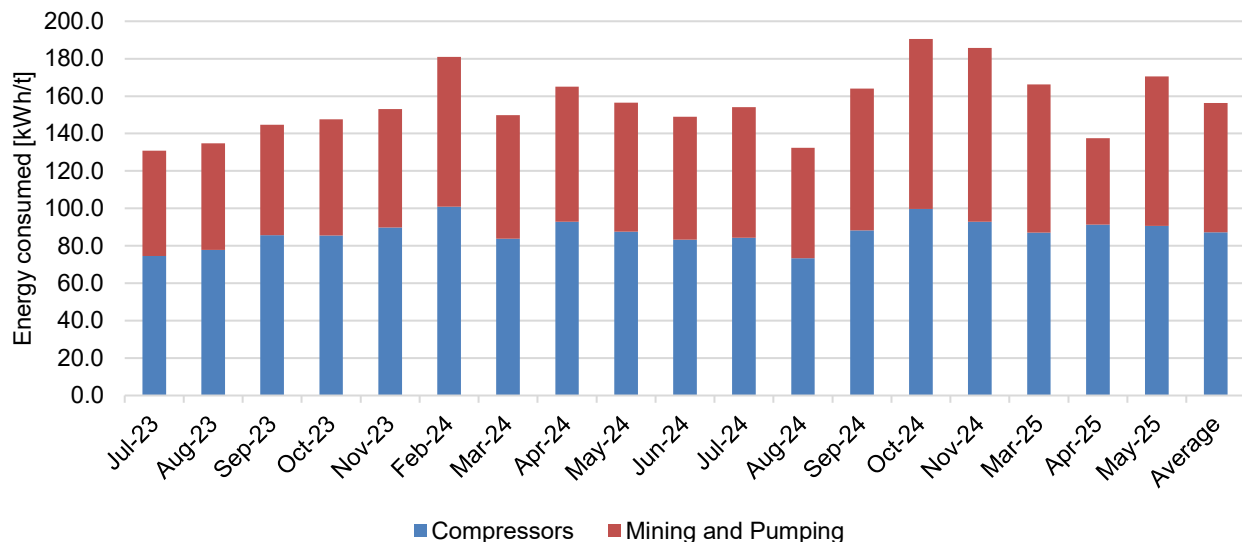


Figure 3-73: Energy consumed – Compressors

(5) Cost

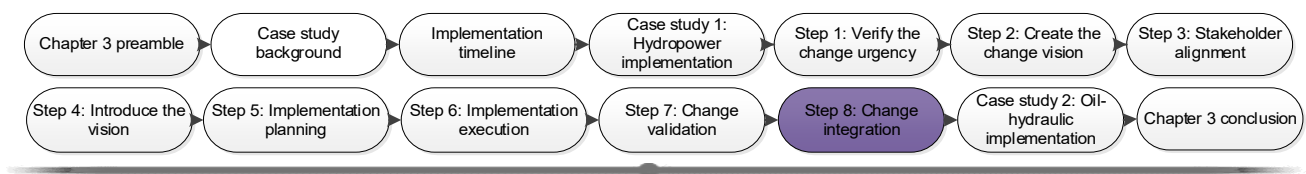
Capex

The capital outlay required to equip the crew with a micro-hydropower drilling system at the time was R1.42 million (USD79 407) and R1.08 million (USD60 364). As indicated earlier, the additional monthly tonnes generated by the hydropower trial crew translated to an additional revenue stream generated of R10.8 million (USD617 093). This result indicates that the required capital outlay was recovered in less than one production month.

Opex

Overall, the hydropower crew's operational cost was 71% more cost-effective than the compressed air panel. The following important points are highlighted from Figure 3-74:

- When benchmarked against compressed air, hydropower consumed 98% less energy to energise the rock drills. Consequently, the cost to energise the rock drills reduced from R236.00 (USD13.44) per tonne to R3.00 (USD0.17) per tonne. This result highlights a significant opportunity to reduce the mine's overall electricity bill should all the crews convert to hydropower.



- An additional electrical cost saving materialised from the reduced water consumption offered by the hydropower drilling systems. This resulted in a dewatering cost reduction of 42%, from R5.31 (USD0.30) to R2.82 (USD0.16).
- OEM labour to maintain the compressor was included in the maintenance rate, and no monthly retainer was payable. On the contrary, OEM labour was deployed daily to maintain the hydropower system, at a cost of R8.00 (USD0.45) per tonne.
- The hydropower equipment was more costly to maintain at R43.50 (USD2.48) per tonne, compared to R8.78 (USD0.50). This vast cost difference was mainly due to the need for three times as many hydropower rock drills and to the high cost of the service kits' engineering materials.
- Equipment replacement costs were charged for hydropower systems. Equipment damages were caused by scraper winches, which amounted to R2 (USD0.11) per tonne.

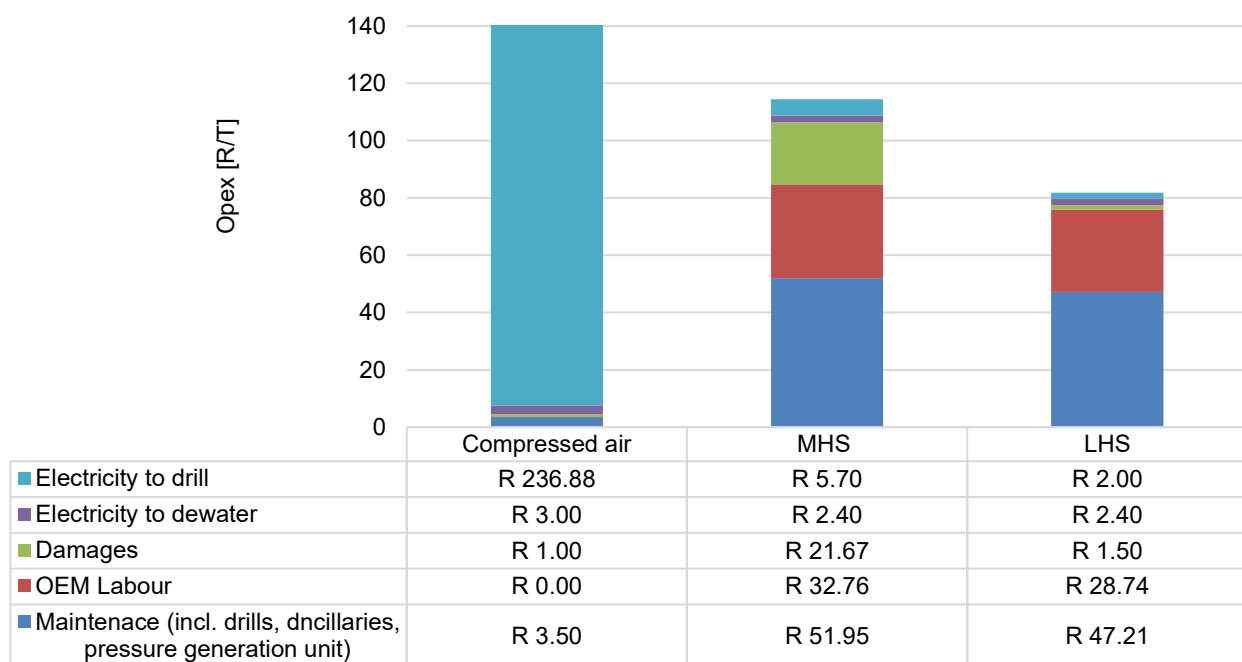


Figure 3-74: Operating cost summary

(6) Technical implementation and operating challenges

Several technical challenges must be addressed when implementing and operating micro-hydropower systems. Table 3-66 provides an overview of recommended strategies to overcome the technical challenges associated with hydropower systems as identified during the study.

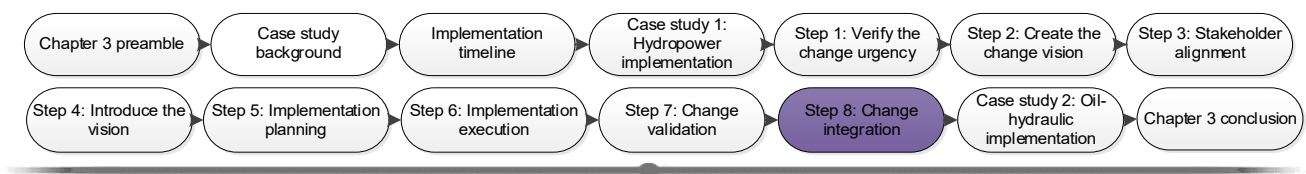
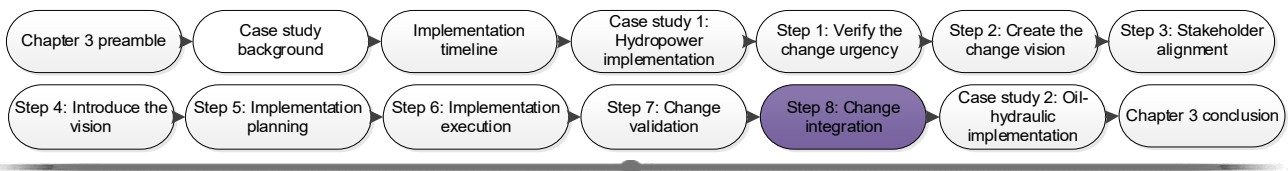


Table 3-66: Overview of technical barriers associated with hydropower systems

Hydropower system type	Technical barrier	Description	Overcoming strategy
Micro	Crew moves	Lost production due to lengthy crew moves. Crews must remove their system from the old workplace before it can be transported to and installed at the new workplace.	One float system per five operational systems is recommended to minimise lost production due to crew moves. The float system is used to equip the new workplace before the crew arrives.
Localised and micro	Heat load	Failure to control the additional heat load introduced by the system will adversely affect stope intake temperatures.	Position: As far practically possible (i.e. return airways on every level), pressure generation units should be positioned on the return side of the raise. Water control: Discharge water needs to be manned as follows: - All drills need to be fitted with dump hoses. - All strike gullies need to be equipped with dewatering pumps. - Dedicated draining columns must be installed to reticulate dewatering water from the strike gully, down the raise, and into a simple pump in the cross-cut.
Micro	Equipment damages	Additional operational cost due to damage claims.	- Ensure rigger crews are adequately trained to transport the heavy equipment. - To prevent fall of ground damage, ensure power pack cubbies are placed in an area with solid hanging wall conditions and adequate support as per mine standards.
Localised and micro	Equipment failure	Failure to replace the faulty pump, motors, and critical electrical control within the failure shift.	Ensure enough spare motors are kept in the underground store to sustain production.
Localised and micro	Electrical load	Failure to proactively plan for the additional electrical load introduced.	Conduct load flow simulations to ensure that mini substations, switchgear, and cables are sized correctly to handle the additional load.

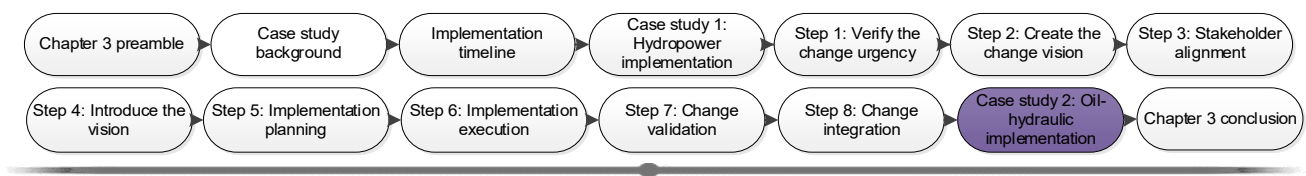


Hydropower system type	Technical barrier	Description	Overcoming strategy
Localised and micro	Service water supply	Failure to proactively design for service water requirements.	Conduct thermo-hydraulic transient state simulations to ensure that the water supply network can sustain the design requirement of 3.5 l/s per power pack at 6 bar dynamic pressure.
Localised and micro	Water demand	Failure to control end user water demand will result in low-pressure trip-outs.	Control end user water demand by equipping the panels with only one rock drill per 15 m of face length and limit the number of manifold ports to four.
Localised and micro	Equipment maintenance	Failure to retrieve equipment due for maintenance.	It is recommended that equipment be issued to crews only on a one-to-one exchange ratio. This arrangement will force them to return the equipment in need of service.
Localised and micro	Equipment reliability	Equipment less reliable compared to compressed air.	Two hydropower rock drills are needed for every compressed air rock drill removed from service to ensure the same level of equipment availability. A strategic partnership between the mine and the OEM supplier is needed to ensure data is shared to enable continuous product improvement.

(7) Recommendations towards the system optimum configuration

This section alludes to the system-type recommendations and provides mine management teams with steering guidance in selecting the most suitable drilling system.

The techno-economic assessment results showed that localised hydropower systems cost less to acquire and operate while generating more profit than micro-hydropower systems. It is, therefore, the recommended system type if the production panels are clustered together in the same raise line. Situations exist where it is not practically possible to place pressure generation units in the cross-cuts when mining isolated blocks of ground or using handheld machines to develop raises, ore passes, and travelling ways. Micro-hydropower systems are then fit for purpose and are recommended.



3.6. Case study 2: Failure to implement oil-hydraulic handheld drilling technology

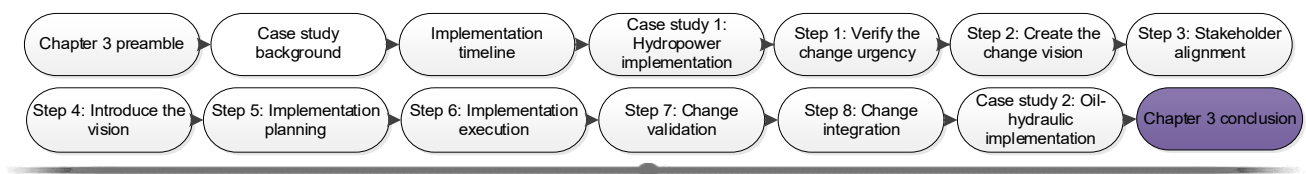
Oil-hydraulic handheld drilling technology was prioritised as the most suitable ADT in Step 1. However, the performance, cost, and reliability data used to configure the selection process were adopted from a case study conducted in a platinum mine, as no published data from a gold mine was available. The mine management team adopted oil-hydraulic equipment as their first choice and attempted to implement it.

A single end user trial was conducted initially to validate the benefits on a small scale. Poor equipment reliability resulted in the first trial being halted within the first month. The reliability concerns were shared with the OEM, and second-generation equipment was imported from Sweden. The implementation of the second-generation equipment took place in May 2021, after which the second trial attempt commenced in June 2021. Regrettably, the equipment reliability challenges persisted, and the second trial attempt was halted in July 2021. Key findings are highlighted as follows:

- **Production:** Over the two-month trial period, the crew managed to blast the panel only once using only the oil-hydraulic drilling equipment. However, the platinum data indicated that steady monthly production was achieved.
- **Health and safety:** The platinum data showed no adverse effects on environmental temperatures. The wet-bulb temperature at the test panel, however, increased by 1.0 °C after introducing the new drills.
- **Mine suitability:** The platinum data reported high levels of reliability, whereas the equipment failed within five shifts in the test panel.

As a result, the theoretical benefits could not be successfully validated using actual results, and the study's proposed method guided the mine management team to terminate the initiative. This result validates the method's ability to prevent large-scale roll-outs of unsuitable technology. It prevented the mine from committing to the R51.34 million capital outlay required to convert the entire mine. Furthermore, the substantial discrepancies observed between the theoretical data used and the actual data collected underscore the need for reliable, unbiased performance and cost data to support sound decision-making. At the time of the trial, the OEM claimed that changes were made to improve the drill's performance and reliability. However, the results of the trial indicated the opposite. The study result provides an additional data point to the mining industry that the drill's performance and reliability remain technical barriers to be resolved.

The method for implementing hydropower was thoroughly reviewed, leading to a successful transformation effort, as previously mentioned.



3.7. Conclusion - Overall outcome of the validation process

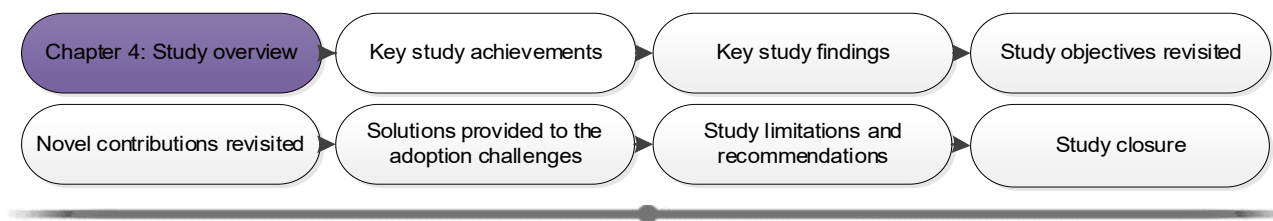
The overarching objective of this study was to develop an implementation and change-management methodology for introducing ADTs into mature compressed-air-driven narrow-reef mines. Previous failures to introduce new technologies into underground mines were studied, and 14 key failure drivers were identified. These failure drivers were adopted as study objectives. Corresponding strategies were formulated during the method development process to address these failure drivers. At the end of the development process, the novel methodology was subjected to a verification process to confirm that the required strategies were incorporated to address each failure driver.

Following the verification process, it was necessary to demonstrate the method's validity through a case study. A mature compressed air-driven system in need of an alternative drilling method was identified as the case-study mine, and the method was used to convert all stoping crews to hydropower drilling systems in an iterative manner. As a first iteration, the OEM's potential benefits were validated on a small scale by implementing the change with a single crew. The validation assessment strategies incorporated into the method successfully validated the benefits of the hydropower drilling system. Following the successful validation of the change benefits on a small scale, four additional method iterations were employed to integrate the proposed change with the remaining stoping crews.

The proposed methodology for assessing the capability of electrical and water infrastructure highlighted the need for critical infrastructure updates and was used to successfully recommend key upgrades. Following the second method iteration, when eight crews were converted, the model predictions were validated as lost blasts were recorded due to water and electricity shortages. The proposed infrastructure upgrades were implemented, successfully addressing the water and electricity shortages. This outcome validates the proposed methodology for assessing the capability of the electrical and water network to support the ADT.

Several system constraints, including incomplete cleaning and a shortage of support materials, emerged after the second method iteration, and the need for continuous improvement was evident. The proposed improvement strategy integrated into the method was used to analyse implementation results, identify improvement opportunities, and implement several improvement strategies. These improvement strategies ultimately enabled the crews to harness the full potential of the hydropower drilling systems.

Ultimately, all the stoping crews at the operation adopted hydropower drilling systems, which proves the method's validity.



4. CONCLUSION AND RECOMMENDATIONS

4.1. Overview of the study

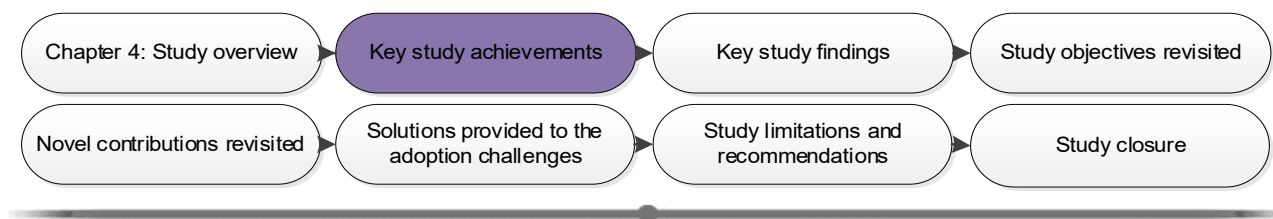
Chapter 1 provided sufficient background on compressed air handheld drilling systems to define the problem and highlight the urgency for mature gold mines to consider ADTs. The literature review revealed that implementation and change management strategies are currently lacking, which has been identified as a reason for the reluctance to adopt ADTs, despite compelling theoretical evidence of the improved benefits they offer. This highlighted the need for this study to develop an implementation and change-management methodology to introduce and integrate ADTs into mature compressed-air gold mines. Eighteen failure drivers identified in the literature review were used to define the method's objectives. This study used a case study research methodology to address the study's need.

Based on the study objectives defined in Chapter 1, Chapter 2 focused on developing a unique implementation and change management methodology to introduce alternative handheld drills into mature compressed air mines. A verification process was used to confirm that the method included the necessary strategies to address the study objectives. The case study implementation described in Chapter 3 validates the newly developed method using a mature narrow reef gold mine. Two case studies were used to achieve this outcome.

The first case study demonstrated that the proposed methodology successfully converted all stoping crews to hydropower. As the method suggests, the change process was first tested at a small scale, with the alternative's actual benefits evaluated using only one crew. The results were compared with theoretical claims in prior literature, and the findings were consistent. As a result, the theoretical benefits were validated, and the change process was extended to the remaining crews. Several downstream operational challenges, such as cleaning, support, and materials, emerged following the improvement in face advance and highlighted the importance of having a continuous improvement strategy. The strategy developed in this study was used to analyse change results and identify and implement improvement initiatives to address these bottlenecks.

The second case study has demonstrated how the proposed method successfully flagged a particular oil-hydraulic alternative as an incompatible drilling solution for the CSM. This critical result prevented the mine from committing to a capital outlay of R51.34 million.

In this final chapter, the study concludes by first providing an overview of the key achievements and results. The study objectives and novel contributions are revisited, and the solutions provided to the

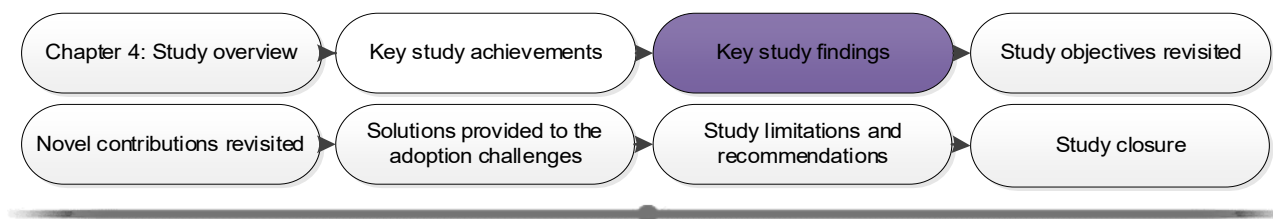


change resistance drivers highlighted earlier in Chapter 1 by general managers are emphasised. Important study limitations and recommendations worth considering are discussed.

4.2. Key study achievements

This section highlights the following five key achievements to demonstrate the value added by this study:

- **Successes achieved in managing change resistance:** The CSM successfully converted all the stoping crews to an alternative drilling system. This result is remarkable, as it is the first mine in the history of South Africa's narrow reef gold mining to achieve this outcome.
- **Successes achieved with the infrastructure evaluation assessment methodology** include early detection of critical process constraints, contributing to a proactive blast management strategy. The infrastructure evaluation assessment methodology used at the onset of the change process successfully highlighted key water and electrical infrastructure upgrades required to support the ADT. The successful early detection of these infrastructure upgrades enabled the mine management team to proactively budget for and implement the upgrades before the constraints resulted in significant lost blasts.
- **Successes achieved with the transition strategy:** The greatest risk of severe financial losses (R1.7 million per lost blast) lies within the equipment transition phase. The unique transition strategy enabled the crews to switch to the new equipment without encountering a single lost blast during the transition phase. This result showcases successful transitions to ensure business continuity during equipment transitions.
- **Successes achieved with the continuous improvement strategy:** The results discussion session highlighted the additional process constraints that surfaced after the new drills were introduced. The unique continuous improvement strategy developed by this study was implemented at the CSM. The improvement strategy guided the mine management team in resolving the identified process constraints. Ultimately, extracting the maximum benefits of the alternative. The introduction of an alternative drilling system at the CSM, followed by continuous improvement initiatives, enabled the operation to increase production by 18%. This correlates to an additional revenue stream generated of R 760 million per annum.
- **Successes achieved due to the implementation of an ADT at the CSM:** The successful implementation and adoption of hydropower as an ADT was the key production enabler to the operation's transformation from making losses to becoming a profitable operation. As a result,



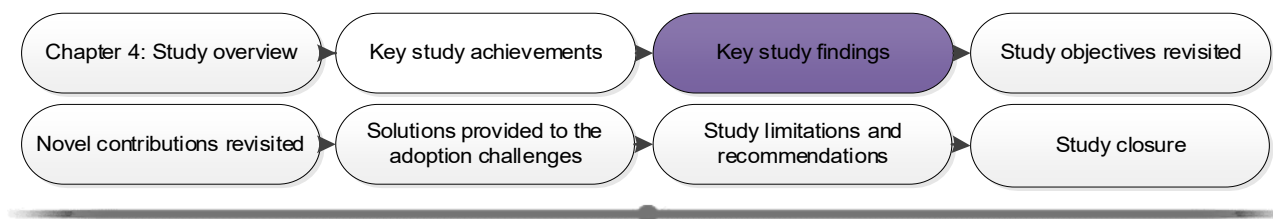
the proposed implementation and change management methodology was a catalyst in successfully securing the jobs of 1 800 full-time labourers, and more than 200 contractors.

4.3. Key study findings

The trial study results confirmed that modern hydropower handheld drilling systems offer improved operational benefits compared with compressed air-driven drilling systems. The results obtained validated the following important points:

KPA #1 – Performance

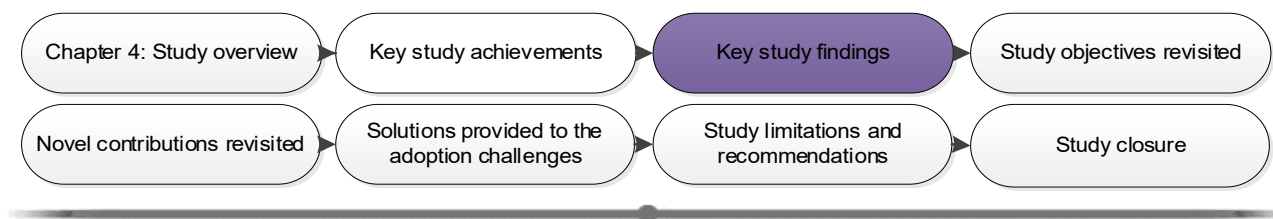
- **Drilling rate:** The drill rate improved by 56%, which reduced the hydropower crew's time to complete the drilling activity by 34%.
- **Production achieved:** The improved drilling performance enabled the hydropower crew to complete the drilling activity as required, ultimately delivering 120% of their monthly call (Table 3-38). The compressed air crew achieved only 95% of their monthly call over the three-month trial period. The ore generated comparison presented in Table 3-38 demonstrated that the hydropower crew managed to cumulatively generate 1 241 more tonnes over the three-month trial period. The operations recovery grade at the time was 4.6 g/tonne. This means that the extra tonnes generated translated into an additional 5.7 kg of gold produced. At a gold price of USD108 262/kg, the additional tonnes translated to an additional revenue stream generated of USD617 093 (R10.8 million)
- **Water intensity ratio:** It follows further that the water-to-ore intensity ratio improved by 52%, from 0.52 to 0.31, when using a hydropower drilling system in conjunction with a hydropower jet pump as a dewatering pump. The supply pressure at the compressed air panel was 12 bar on average, which is four times greater than the OEM-prescribed requirement [30], [48]. This excessive supply pressure resulted in multiple leaks at the hose joints and couplings. Additionally, it is worth noting that the rock drills were not equipped with auto-shutoff valves. This means that the water did not shut off when the air valve (starter lever) was closed during non-drilling times (i.e., when moving between holes or while resting). On the contrary, auto-shutoff is a built-in advantage of hydropower. This result effectively dispels the century-old myth that hydropower uses more water than compressed air drilling systems.
- **Electrical energy intensity ratio:** The following important points are noteworthy. The energy consumed by the hydropower drilling system to energise the rock drills was 98.1% less. This



result indicates that the hydropower system consumed 98.1% less electricity. The energy consumed to dewater the service water used for drilling was reduced by 21.6%. An overall reduction in energy intensity ratio of 98% was quantified, with only 3.5 kWh/tonne consumed by the hydropower panel compared to 146 kWh/tonne used by the compressed air panel. Compressed air was generated on the surface using a 3.5 MW compressor, resulting in an overall energy intensity ratio of 146 kWh per tonne of ore generated. The baseline crew failed to close the compressed air valves at the end of the drilling shift, resulting in a constant demand on the compressor for 24 hours. On the contrary, the hydropower panel only consumed energy when the system was in use and consumed only 3.5 kWh per tonne. This result confirms that hydropower drilling technologies present a unique opportunity to significantly reduce the mine's compressor energy consumption during the drilling shift if fully converted to hydropower.

KPA #2 – Safety, health and occupational environment

- **Noise:** The TWA noise exposure data presented in Table 3-43 indicates an 8.9 dB(A) reduction. This means that hydropower RDOs are exposed to less noise over a normalised eight-hour working shift. This is yet another advantage of the 34% reduction in drilling shift time reported earlier.
- **Vibration:** Exposure (TWA) to vibration was estimated to increase by 2.9 m/s^2 . This was mainly driven by the increased amount of percussive energy applied to the drill steel, resulting in higher vibration amplitudes than in less energetic compressed air-driven rock drills.
- **Heat load:** Detailed heat load calculations revealed that compressed air drills added 15 kW to the occupational environment. In comparison, hydropower adds 50.4 kW when the exhaust water is sprayed into the air and accumulated in the strike gully. As a remedial action, a dump hose was installed at the water outlet. This initiative reduced the heat liberated to only 11.7 kW. The corresponding changes in air temperature in the occupational environment were as follows:
 - A 1.0°C increase per panel if the rock drill exhausted water was not controlled.
 - No changes were observed before and during the drilling shift when the water was controlled by dumping it onto the footwall through a hose connected to the rock drill's exhaust port and removing the water from the panel using a pump installed in the strike gully.
 - A 0.5°C decrease per panel in air temperature when using a compressed air rock drill.



- **Environmental contamination:** The hydropower crew affirmed that the technology boosted their morale since it is less noisy, faster, cleaner, and offers improved performance. When comparing Figure 3-47 and Figure 3-48, the grease-free hydropower RDO clearly stands out.

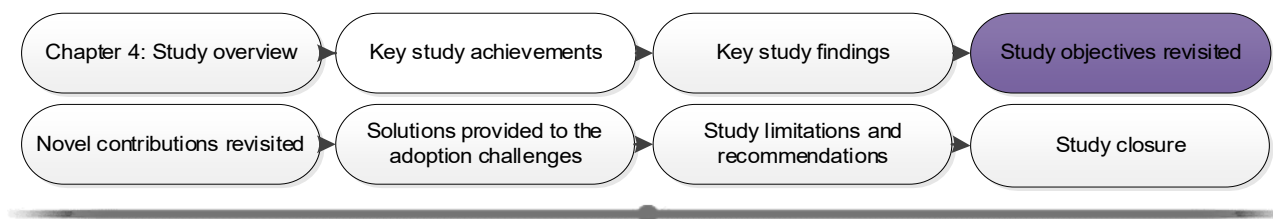
KPA #3 – Mine suitability

The objective of this KPA was to provide answers to the following two critical suitability requirements:

- **Functionality:** The required equipment functions, as listed, were tested, and it was found that hydropower alternatives are available to provide all the necessary activity functions. This means that mining is possible without compressed air.
- **Reliability:** The initial reliability data collected during the trial phase are shown in Table 3-48. At that time compressed air rock drills lasted roughly 20 drilling shifts, compared to only six per hydropower rock drill. A continuous improvement program was launched to improve the rock drill reliability. Figure 3-67 presents an overview of the reliability trend over time and shows that the reliability improved from 221 to 539 m/failure. This result corresponds to roughly 15 days' worth of drilling. Although still shy from 20 days, the result highlights the importance of forming strategic partnerships with the EOM suppliers to enable continuous product development. For roll-out planning purposes, the operation will require a minimum of two hydropower rock drill assemblies for every compressed air rock drill assembly removed from production to ensure the same level of rock drill availability.

KPA #4 – Cost

- **Capex:** The capital outlay required to equip the crew with a modern hydropower drilling system at the time was R1.4 million (USD79 407). As indicated earlier, the additional tonnes generated by the hydropower crew translated to an additional revenue stream generated of R10.8 million (USD617 093). This result indicates that the capital outlay was recovered in less than one month of production.
- **Opex:** Overall, the hydropower crew's operational cost was 71% more cost-effective than that of the compressed air panel. The following important points are highlighted from Figure 3-74:
 - When benchmarked against compressed air, hydropower consumed 98% less energy to energise the rock drills. Consequently, the cost to energise the rock drills reduced from R236 (USD13.44) per tonne to R3.00 (USD0.17) per tonne. This result highlights a



significant opportunity to reduce the mine's overall electricity bill should all the crews convert to hydropower.

- An additional electrical cost saving materialised from the reduced water consumption offered by the hydropower drilling systems. This resulted in a 42% reduction in dewatering costs, from R5.31 (USD0.30) to R2.82 (USD0.16) per tonne ore mined.
- OEM labour to maintain the compressor was included in the maintenance rate, and no monthly retainer was payable. On the contrary, OEM labour was deployed daily to maintain the hydropower system, at a cost of R8.00 (USD0.45) per tonne.
- The hydropower equipment was more costly to maintain at R43.50 (USD2.48) per tonne, compared to R8.78 (USD0.50). This significant cost difference was primarily driven by the fact that three times more hydropower rock drills were required, and the service kits consisted of expensive engineering materials.
- Equipment replacement costs were charged for hydropower systems. Equipment damage was caused by scraper winches, and amounted to R2.00 (USD0.11) per tonne.

4.4. Meeting the study objectives

Past failures were analysed in Chapter 1 to identify hidden drivers of failure, risks, and opportunities that had previously been overlooked or underestimated. In total, 18 failure drivers were identified and used as strategic objectives to formulate the study-specific method. The verification process outlined in Chapter 2 aimed to verify that all the required strategies to address the corresponding objectives were incorporated into the method. The overall verification result presented in Table 2-38 confirmed that the required strategies were incorporated into the method. At the same time, the method validation process applied in Chapter 3 aimed to confirm that the strategies developed have successfully addressed the failure drivers. As shown in Table 4-1, all the objectives were successfully verified and validated. The overall successful adoption of an ADT at the CSM further substantiates that the study objectives were met.

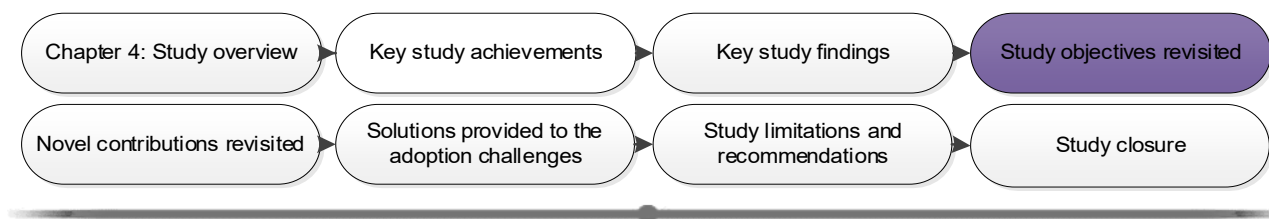
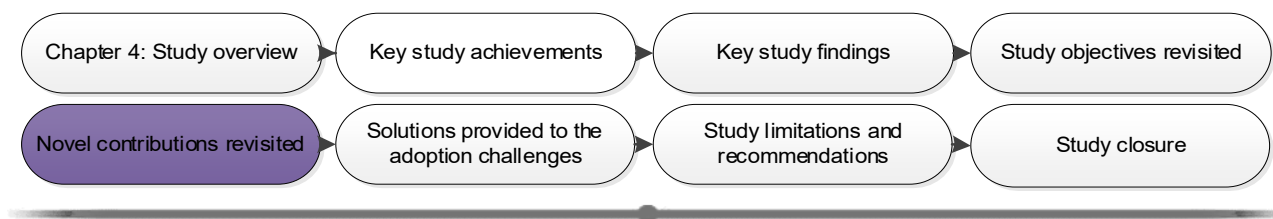


Table 4-1: Study objectives revisited

Failure driver (FD)	FD #	Method objectives	Chapter 2 verification: Objective addressed?	Chapter 3 validation: Objective met?	Method reference
HRD1: Passive leadership style	1	- Promote an active leadership style.	✓	✓	Step 3
HRD2: False perceptions	2	- Rectify misperceptions by means of factual information.	✓	✓	Step 3
HRD3: Change unwillingness	3	- Promote change willingness by ensuring the need for change is clear to all stakeholders.	✓	✓	Step 3
HRD4: Emotional wellness	4	- Promote emotional wellness.	✓	✓	Step 3 Step 8
SFD1: Lack of urgency	5	- Establish a definite sense of urgency.	✓	✓	Step 1 Step 3
SFD2: Unclear vision of benefits	6	- Highlight the change benefits to all stakeholders.	✓	✓	Step 2
SFD3: Exclusion of critical role players	7	- Perform a conscientious stakeholder analysis to identify all role players.	✓	✓	Step 3
SFD4: Incorrect initial end user and/or workplace selection	8	- Provide clear strategic guidance to end user selection.	✓	✓	Step 3 Step 5.
SFD5: Lack of stakeholder participation and accountability	9	- Define and track stakeholder roles and responsibilities.	✓	✓	Step 3 Step 4 Step 5
SFD6: Incorrect selection of alternative technology	10	- Provide alternative technology selection guidance based on the operations' geotechnical environment.	✓	✓	Step 2 Step 5 Step 7
SFD7: No updates to policies and procedures	11	- Highlight critical change updates to policies and procedures.	✓	✓	Step 5
SFD8: Change support from senior management	12	- Provide change support guidance to senior management.	✓	✓	Step 6 step 7

Failure driver (FD)	FD #	Method objectives	Chapter 2 verification: Objective addressed?	Chapter 3 validation: Objective met?	Method reference
SFD9: Stakeholder misalignment	13	- Provide a strategy to align stakeholders and maintain alignment.	✓	✓	Step 4
SFD10: Transition strategy	14	- Adequate transfer of knowledge, skill, policies, and procedures during the training phase. - Provide a transition (implementation) strategy.	✓	✓	Step 3 Step 5
SFD11: Technology support systems	15	- Assess and integrate technology support systems.	✓	✓	Step 3 Step 5
SFD12: Technology readiness	16	- Provide a strategy to assess the technologies' fit-for-purpose to operate as replacement. - Technology must be fully functional, simple and reliable with little/no changes required. Mature technologies are preferable.	✓	✓	Step 7
SFD13: Vision/benefits did not materialise	17	- Provide a strategy to continuously monitor change benefits as highlighted by means of the vision.	✓	✓	Step 5 Step 7
SFD14: Shock waves caused by excessive change	18	- Consist of a progressive and gradual approach to introduce the change.	✓	✓	Step 3 Step 5 Step 8
Legend:		✓ – objective met ✗ – objective not met			



4.5. Novel contributions revisited

Five novel contributions were formulated in Chapter 1 based on the problem statement, study needs, and objectives. These contributions are revisited here to confirm if the intended outcome was successfully achieved.

Novel contribution #1

The development of an implementation and change management methodology to integrate alternative handheld drilling technologies in existing compressed air mines.

State-of-the-art and shortcomings of existing methods

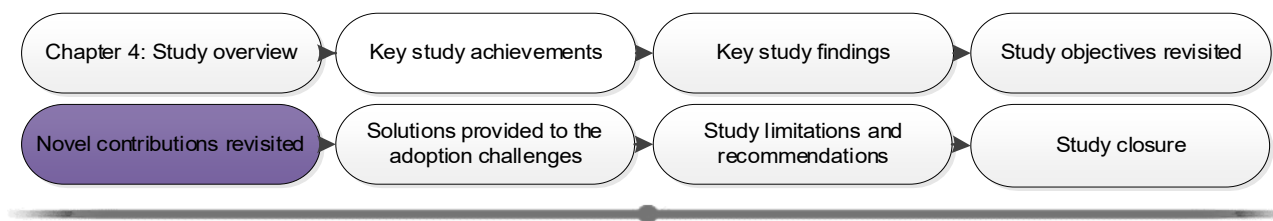
The analysis of past failures showed that transformation efforts frequently fail without an implementation and change management strategy to guide the change process. Due to the limited application of ADTs in mature, deep-level gold mines, published implementation and change management strategies for ADTs appear to be non-existent.

What was accomplished by this study?

An implementation strategy was developed to guide mining companies through the process of integrating ADTs in existing compressed air mines. The primary objective was to simplify the complexities (failure drivers, [Section 1.7, Part A and B](#)) associated with implementing and adopting an ADT into a comprehensive implementation and change management strategy. The new method was put to the test at a case-study mine and guided the mine management team in successfully converting all stopping crews to an ADT. This overall result validated the usefulness of the new method.

What was the outcome of this contribution?

The first contribution delivered a step-by-step, pragmatic implementation and change management strategy for alternative handheld drilling technologies in existing compressed air mines, addressing the implementation and change management challenges highlighted in [Chapter 1](#). The successful validation demonstrates that the proposed method is practical and compatible with real-world case studies.



Novel contribution #2

The development of a multi-criteria decision-making methodology to select the most suitable ADT based on the mine's unique operational parameters.

State-of-the-art and shortcomings of existing methods

Past analyses of failures revealed that some change initiatives were doomed to fail from the start due to the incorrect selection of the technology to be implemented. Due to the limited application of ADTs in mature, deep-level gold mines, published methodologies for selecting the best-fit-for-purpose ADT based on operation-specific requirements appear to be non-existent.

What was accomplished by this study?

A selection methodology was to be developed to guide mining companies in selecting the best-fit-for-purpose ADT from commercially available options. Real-world applications have demonstrated that the method enables mine management teams to configure selection criteria based on their operational needs. The case study's specifically configured selection criteria were successfully used to select the best-fit-for-purpose alternative.

What was the outcome of this contribution?

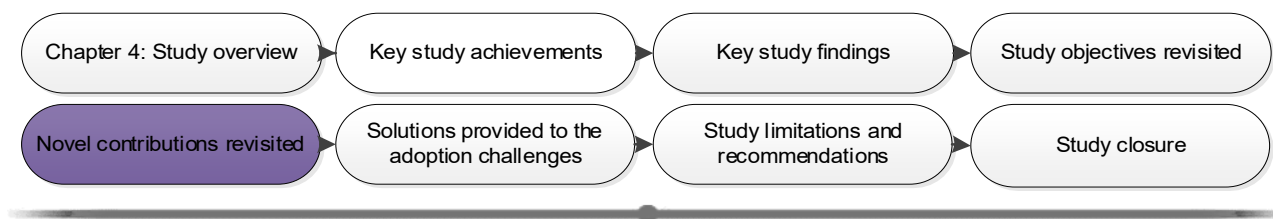
The second contribution delivered a step-by-step, pragmatic selection methodology. This methodology enabled the mine management team to minimise resistance to change by selecting the most suitable alternative technology based on their operational specifications.

Novel contribution #3

Development of a methodology to assess the capability of the mine's water and electrical networks to support the ADT.

State-of-the-art and shortcomings of existing methods

One of the failure drivers identified highlighted that technology implementation efforts frequently fail when engineering services, such as water and electricity, are insufficient to support the ADT. Published literature on methods to assess whether the mine's water and electrical networks will be capable of supporting the ADT could not be found.



What was done by this study?

A methodology for evaluating infrastructure was developed. The method is versatile enough to serve as a framework for guiding the assessment process of both water and electrical networks. A practical case study was conducted to validate the new assessment method.

What was the outcome of this contribution?

This contribution provides a multi-purpose method to assess the support capability of water and electrical networks and, if necessary, evaluate the feasibility of proposed design upgrades. The method was successfully used to evaluate the support capabilities of the water and electrical networks at the CSM. Both networks were found to be insufficient to support the ADT, and the recommended design changes were first verified using the digital models before being implemented. The implemented design changes validated the model predictions and enabled the mine's service networks to support the alternative drilling system.

Novel contribution #4

Development of a benefit validation strategy for ADTs.

State-of-the-art and shortcomings of existing methods

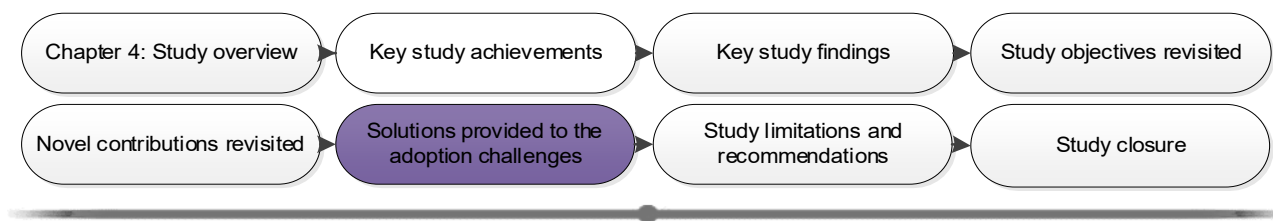
All the studies reviewed were conducted by biased sources, such as OEM design engineers and/or OEM directors. Mine management teams tend to question the transparency and credibility of the data if biased sources are involved in evaluating the studies. Consequently, mining companies fail to select and implement alternative technologies. None of the studies reviewed presented a strategy to validate the actual benefits offered by the ADT.

What was accomplished by this study?

A benefit assessment strategy was developed. The strategy was used to assess and validate the ADT's theoretical benefits claimed under the following KPAs: performance, health and safety, mine suitability, human factors, and techno-economics.

What was the outcome of this contribution?

This contribution provided a benefit validation strategy to confirm the advantages of ADT before committing to large-scale roll-outs. The results obtained contributed unbiased cost and performance data for the industry to use when selecting an alternative drilling system.



Novel contribution #5

Development of a continuous improvement strategy to enable the benefits of ADTs after implementation.

State-of-the-art and shortcomings of existing methods

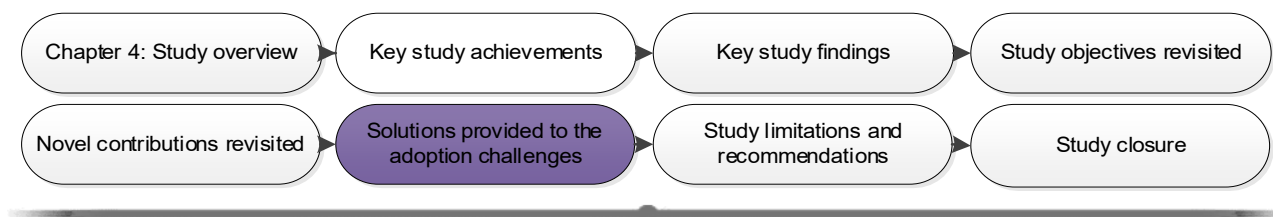
It follows from the literature review ([Section 1.7, Part C](#)) that transformation efforts generally fail when the benefits do not materialise following large-scale roll-outs. Continuous improvement strategies aim to identify operational constraints and implement ongoing efforts to maximise the technology's benefits. None of the studies reviewed presented a continuous improvement strategy to enhance system effectiveness following the implementation of ADTs.

What was accomplished by this study?

A continuous improvement strategy was developed to identify operational constraints and implement incremental changes to improve the overall effectiveness of alternative drilling systems. The newly developed strategy was implemented and tested using a real-world case study.

What was the outcome of this contribution?

This contribution yielded a strategy that enabled the case study mine to identify operational constraints and implement incremental changes to realise the intended benefits of the ADT. The improvement initiatives identified and implemented using the proposed improvement strategy enabled an 18% increase in production.



4.6. Adoption challenges highlighted by the general managers revisited

The fundamental adoption challenges of new technology in South Africa's narrow reef gold mines, as highlighted by the general managers, were reported in [Section 1.5](#). The purpose of this section is to reflect on what this study has done to address the adoption challenges related to ADTs.

Challenge 1: Change resistance

Resistance to change was highlighted as a notable challenge, including:

"The workforce has used compressed air handheld drills for the past century. Several humanistic resistance drivers will prevent the introduction and adoption of an alternative drill." – **General Manager Mine A**

"Of all areas to introduce change, narrow reef stopes are the most difficult. All previous efforts to introduce alternative drilling technology over the past 30 years resulted in disappointing failures." – **General Manager Mine C**

"My on-shaft team is not geared up to handle transformation efforts as complex as converting a mine from conventional drilling to an alternative." – **General Manager Mine D**

Solution provided: This study used the case study research methodology to develop and validate a unique pragmatic approach to implementing alternative handheld drilling technologies in mature, deep-level, narrow reef gold mines. The agile method enables mine management to implement and integrate the alternative drilling system through eight well-crafted, pragmatic steps.

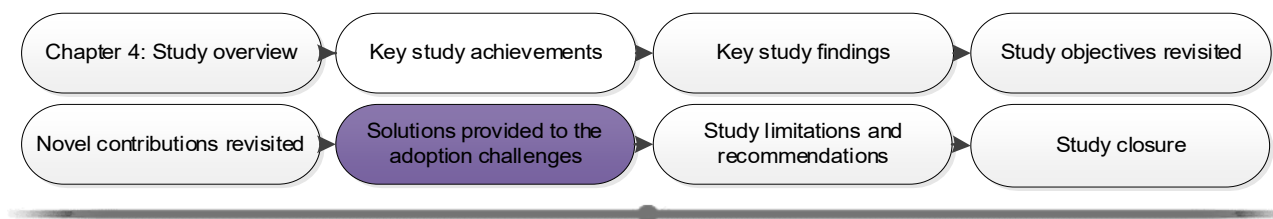
Challenge 2: The lack of independently verified cost and performance data of hydropower drilling systems

The lack of independently verified cost and performance data emerged as a significant adoption challenge. The general managers highlighted the following:

"Alternative drilling technology is way more expensive to acquire and operate. We cannot afford it." – **General Manager Mine F**

"First convince me with reliable and consistent performance and corresponding cost data, independent from what the OEM supplier claims, then I'll consider it." – **General Manager Mine I**

"Where do I start? Which system configuration is best, localised or micro in-stope applications? How do I prioritise workplaces during the implementation phase?" – **General Manager Mine E**



Solution provided: The study yielded independently verified cost and performance data for hydropower drilling technologies. These findings will guide mine management teams in selecting and implementing the most appropriate system configuration based on the operations’ geotechnical parameters. The unbiased performance and cost data provided compelling evidence that hydropower is a cost-effective and reliable alternative solution. Furthermore, the study provided future researchers with a generic method for conducting techno-economic assessments of ADTs, highlighting the key parameters to consider.

Challenge 3: Workplace prioritisation, and equipment transitioning

It was further uncovered in [Section 1.7](#) that initiatives to implement alternative technologies also fail to commence due to the lack of a strategy for prioritising workplaces during the implementation phase. Once implementation commences, transformation efforts frequently fail due to lost blast encountered during the equipment transition phase.

“How do I prioritise workplaces during roll-out?” – General Manager Mine E

“We cannot afford the severe production losses associated with the implementation and transformation phase when introducing alternative drilling technology.” – General Manager Mine B

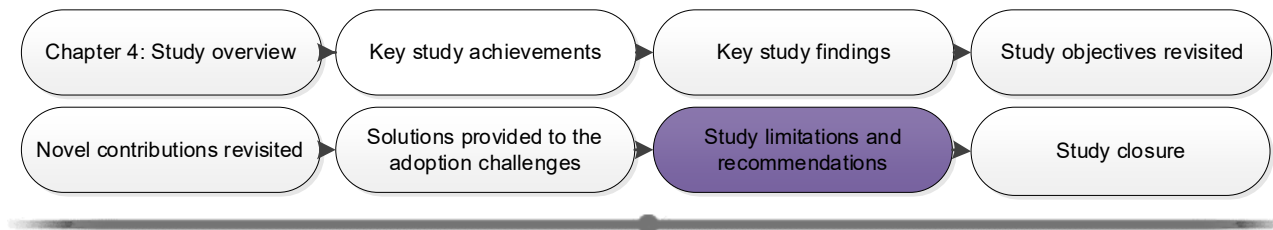
Solution provided: To prioritise the crews during the implementation phase, a strategy was developed to benchmark each crew’s actual drilling shift duration against the available shift time. An equipment transition strategy was developed to guide the crews through the equipment transition phase. The unique approach proposed provides the necessary redundancy to prevent the occurrence of lost blasts during this critical phase of the implementation process.

Challenge 4: Inadequate water and electrical infrastructure to support the alternative

Critical design changes to the mine’s water and electrical infrastructure might be required to support the alternative drilling system, as noted:

“Hydropower uses three times more water. Ore passes, cross-cuts, and return water dams will flood. Furthermore, our electrical network will become unstable when moving the pressure generation units underground.” – **General Manager Mine G**

Solution provided: The study provided a generic methodology for assessing existing water and electrical infrastructure using simulation software packages. The results section provides a detailed example of how to apply the method when assessing the capabilities of water and electrical infrastructure. Additionally, best practice design guidelines were provided.



4.7. Study limitations and recommendations

Macro level heat load study

[Chapter 1, Section 1.5](#) created awareness about the adverse impact ATDs will have on the mine's heat load. The study confirmed that the wet-bulb temperature might increase up to 1.0 °C per panel when the rock drill exhausted water is not controlled. As a result, the implementation of alternative drilling technologies may result in heat-related production losses. This concern is especially relevant to mines hosting multiple panels in long raise lines.

Limitation: This study only considered the heat load impact on a micro level (single panel). Additional work is required to evaluate the overall macro (entire mine) heat load impact when introducing ATDs. Practical recommendations are needed to overcome the induced heat load challenges, especially in mines with limited return airways.

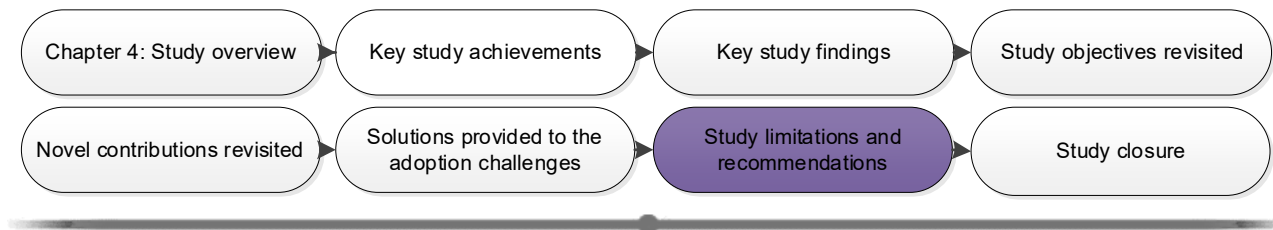
Recommendation: Nell contributed a pragmatic approach to determine the heat loads of existing deep level gold mines [214], [218]. It is recommended to use Nell's method (or any other applicable method) to evaluate the overall heat load impact when introducing ATDs to conventional mines. Practical recommendations to overcome the heat load challenges need to be formulated (i.e. bulk air cooler upgrades, introduction of mobile underground refrigeration plants, etc.). Seabell's work on this topic yielded a simulation method to evaluate the heat load impact per raise line [31]. Seabell's method can be used to validate the solutions recommended.

Hydropower equipment reliability

The continuous development of the compressed air rock drill over the past century has resulted in a robust and reliable tool. This study highlighted reliability shortcomings in ATDs that require additional product development to resolve.

Limitation: The results presented in [Chapter 3, Section 3.5](#) highlighted that hydropower and oil-hydraulic alternatives need additional product development to enable comparable levels of equipment reliability and availability.

Recommendation: An interconnected multidisciplinary partnership between the mining industry and OEM suppliers is recommended to enhance equipment reliability and availability. A continuous development program of ADTs is needed to achieve this outcome. Mining companies that implement ADTs are recommended to meticulously track equipment performance, reliability and failure modes.



The data must be made available to OEM suppliers to ensure that additional research and development yields cost-effective solutions to the identified challenges.

Compressor energy savings

[Chapter 3, Section 3.5](#) highlighted a notable cost savings opportunity loss (R 51million per annum) since the conversion of all stopping crews at the CSM did not yield any compressor electrical cost savings.

Limitation: The reduction in compressor electricity costs was prevented because the development section of the CSM was not converted to hydropower due to capital constraints. As a result, the compressed air network remained pressurised, and electrical cost savings did not materialise.

Recommendation: To enable compressor energy cost savings, the following two critical actions need to be executed:

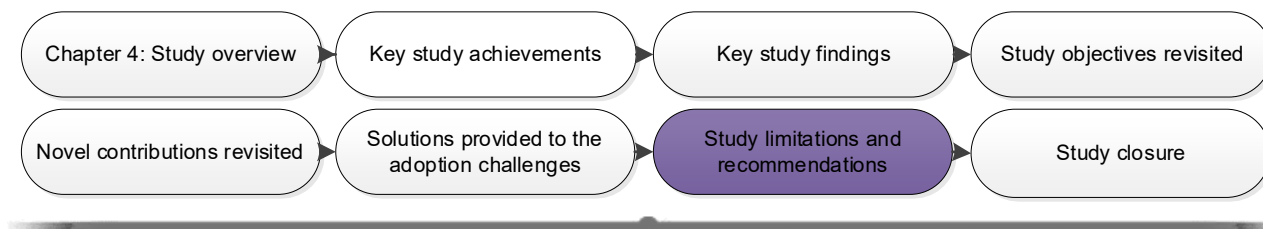
- The proposed methodology should be used to iteratively convert all development crews at the CSM.
- Furthermore, all other compressed air users (i. e. box front and other pneumatic actuators, mud agitation, and refuge bays etc.) need to be converted to an alternative solution.

Benefit tracking at the CSM

The scope of this study was the implementation and adoption of hydropower drilling systems by all stopping crews at the CSM.

Limitation: Benefits were tracked throughout the change process, but only for a six-month period during which all stopping crews used hydropower drilling systems. Unbiased performance, cost and reliability data for development hydropower crews are unknown. An extension of the benefit tracking process will contribute additional performance, reliability and cost data to the industry.

Recommendation: The proposed methodology should be used to convert all development crews at the CSM. Furthermore, it is important to track the benefits of the purely hydropower shaft for at least a year to obtain an accurate reflection of the improvement in production at reduced operating costs.



Hydropower adoption in platinum group metals

The annual worldwide production of platinum group metals (PGM) is around 450–460 metric tonnes, with the largest producers being South Africa and Russia, followed by the United States, Canada, Zimbabwe, Australia, and others [115]. The South African-based Bushveld mafic–ultramafic intrusion covers an area of 66 000 km² and hosts two PGM reefs (the Merensky Reef and Upper Group 2 Reef), with average thicknesses varying from 0.5 m to a maximum of 3.0 m.

Limitation: Mature PGM operations also use compressed air-powered handheld drills to mine the orebody and may face the same compressed air efficiency challenges as at the CSM. As a result, the PGM mining industry currently lacks credible performance and cost data on hydropower drilling systems in platinum mines³³.

Recommendation: The recommendation is to apply the method to convert PGM mines that require an alternative drilling system to hydropower. Such a study will yield valuable techno-economical results for the PGM mining sector.

Hydropower water recirculation

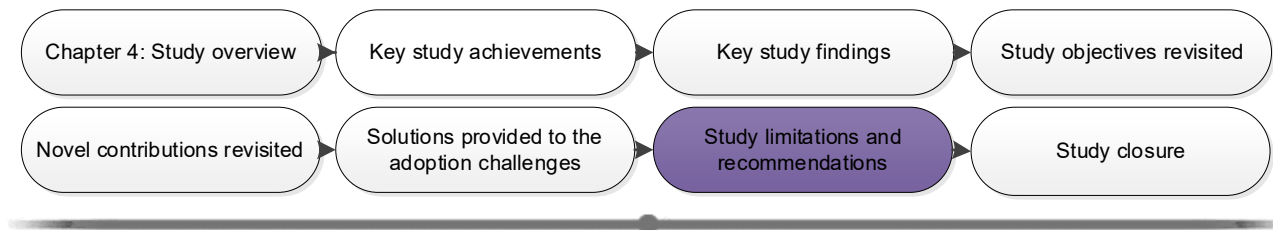
South Africa is a water-scarce country, highlighting the need to save water. The opportunity exists to further reduce the water consumed by hydropower drilling systems by applying recirculation technology [48]. This entails connecting a recirculation hose to the rock drill's discharge port, which directs the water into a reservoir. Water from the reservoir is then reintroduced into the system to energise the rock drills. A theoretical study compiled by Fraser [48] indicated the possibility of recirculating up to 65% of the water.

Limitation: The equipment used to recirculate hydropower exhaust water was not included in the equipment suite implemented and adopted at the CSM.

³³ Although Northam is a hydropower mine, the last hydropower publication made available by the mine dates back to 2000. Peter Fraser from HPE published a few articles on the different system configurations suitable for PGM mines, however, adoption remains remarkably limited.

Implala Platinum implemented hydro in 2022 one raise at 12 and 10 shafts, respectively. Today in 2026, the roll-out remains limited to these two raises due to no clear face advance benefit. Predominantly, since the technology was applied in winze panels mining below step over, without ensuring the dewatering infrastructure was adequately set up, frequent flooding disabled optimum performance.

The most recent performance data was published by one of the OEMs in 2022. Cost was not covered. Thus unbiased published performance vs cost data of hydropower in platinum mines remain unknown to date.



Recommendation: It is recommended to use the proposed methodology to implement ADT and conduct a trial of a recirculation hydropower drilling system. Recommended parameters of significance to evaluate during the trial include:

- Collar-to-collar drill rates (since the additional recirculation hoses might impact drill manoeuvrability and drilling speed due to possible back-pressure),
- Water quality (water quality might be compromised since the water will not pass through the settles, and the abrasive suspended solids might adversely affect equipment reliability),
- Water temperature (since the recirculation of water might increase water temperatures above legal limits), and
- Water intensity ratio (to quantify the overall benefit of recirculation).

Flat end development drill rigs

In addition to in-stope drill guides, flat end development drill rigs are used to replace handheld drilling of blastholes in flat development ends.

Limitation: The literature review revealed no existing methods to foster the change process when implementing drill rigs at development ends. The proposed method is limited to handheld drilling.

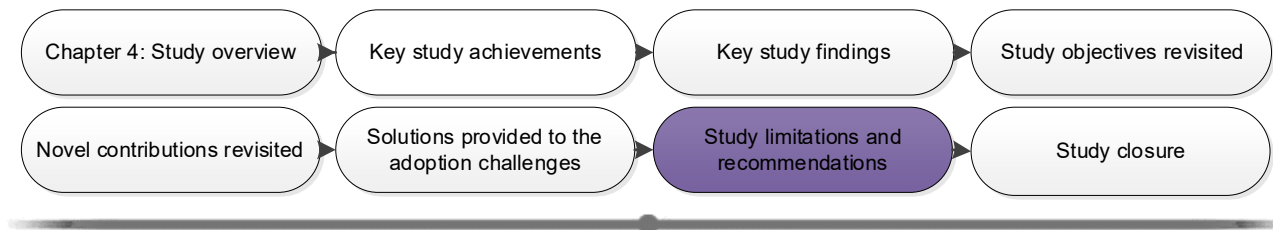
Recommendation: The recommendation is to refine the proposed method to make it applicable to development rigs. This will entail conducting a detailed literature review to identify the failure drivers associated with the adoption of development rigs and to derive strategies to address them. The implementation of a practical case study is needed to validate the developed method.

Drill cycle face time optimisation

An opportunity exists to further optimise the drilling cycle face time at the CSM.

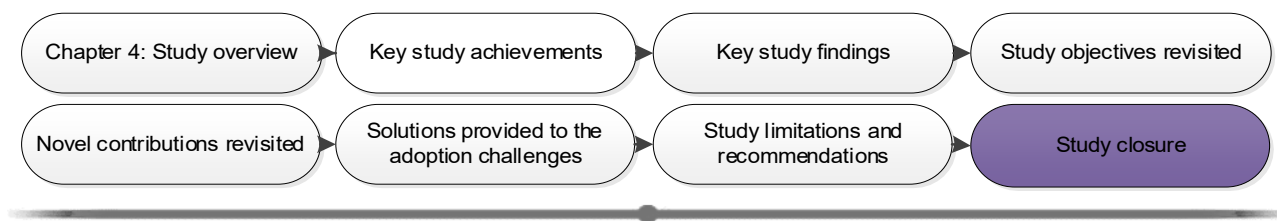
Limitation: To recall from [Section 3.5](#), the number of RDOs drilling blastholes per 30m face length at the CSM were limited to two. This resulted in an average face drilling cycle time of 04:12:00 [hh:mm:ss]. Even though it improved from 06:23:00, an opportunity may exist to further reduce it by adding an additional face drilling RDO.

Recommendation: The pressure generation units used at the CSM were originally designed to serve one RDO per 15 m face length to optimise capital costs. This restricted installed pressure generation capacity limited the number of RDOs to be deployed. The recommendation here is to study the overall techno-economic impact offered by reducing the face length per RDO to 10 m. Although the initiative will yield reduced face drilling cycle times, the addition impacts the following critical areas adversely:



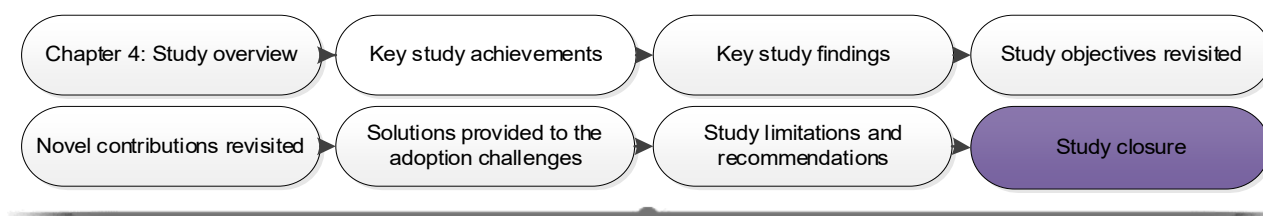
- Pressure generation infrastructure upgrades will be required
- Rock drill fleet size needs to be increased
- Water and electrical infrastructure upgrades may be required
- More electricity will be consumed to energise the rock drills, and dewatering pumps.

The cost should be compared to the benefit offered by reduced face time. If the face time presents a critical production constraint, the benefit might outweigh the cost by far. However, it is paramount to also account for the gully drilling cycle since the gully drilling cycle (only one RDO drilling) might present the next bottle neck. Such constraint may in turn outweigh the benefit offered the additional face drilling RDO.



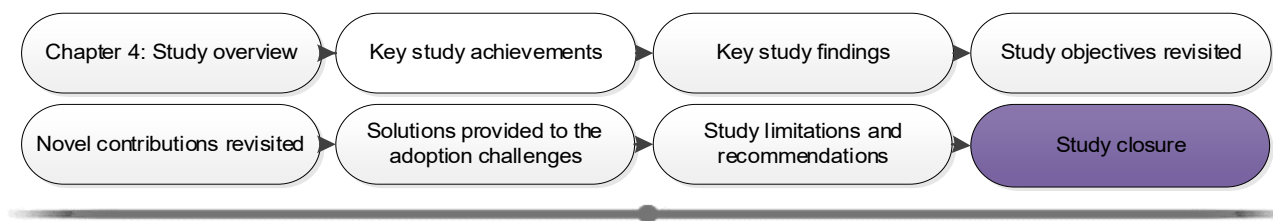
4.8. Study closure

This chapter concluded the document by providing an overview of this study. Furthermore, it was stated how the objectives of the study were met, the expected novel contributions were revisited, and recommendations were provided for further studies.

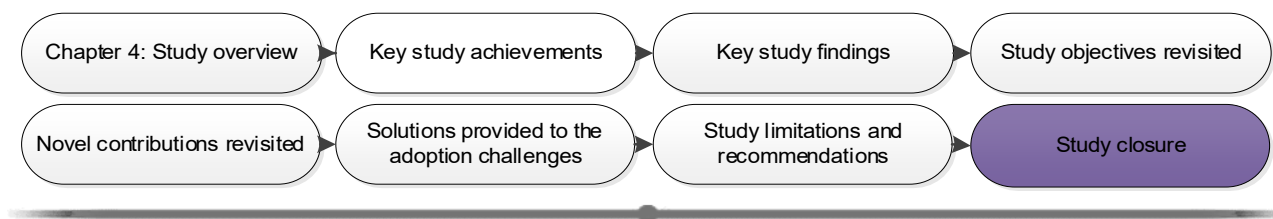


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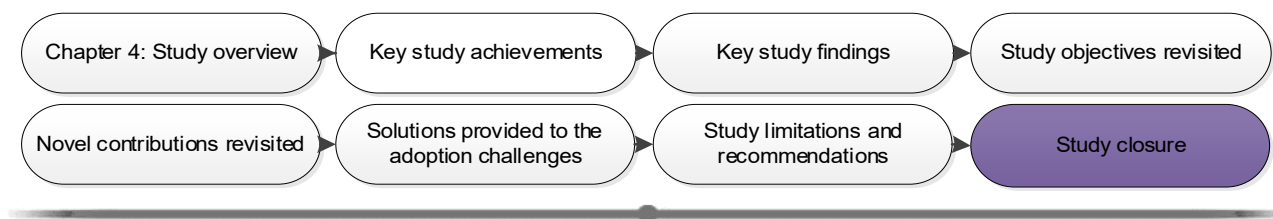
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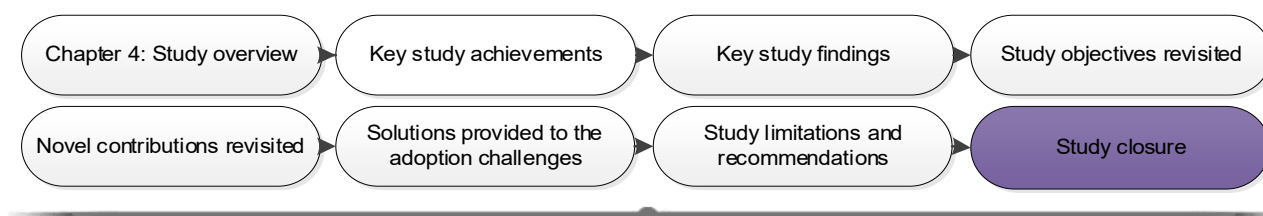
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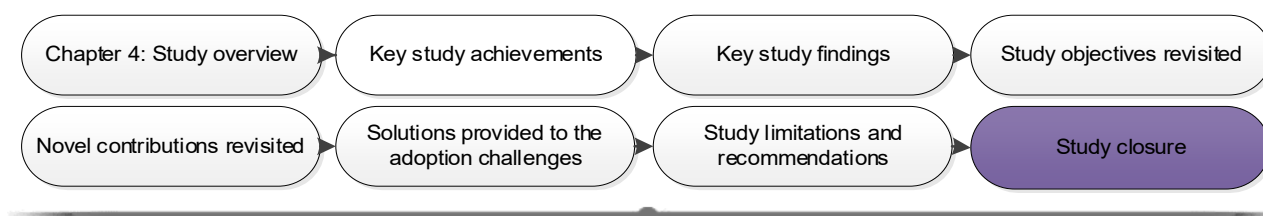


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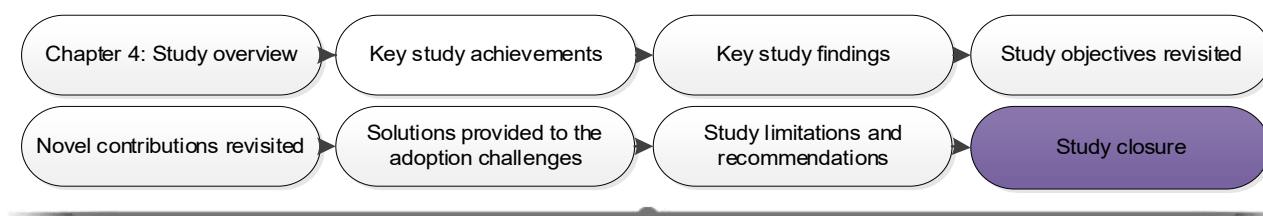
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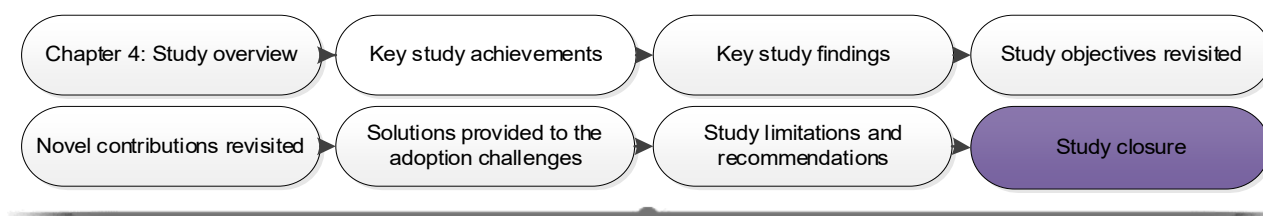


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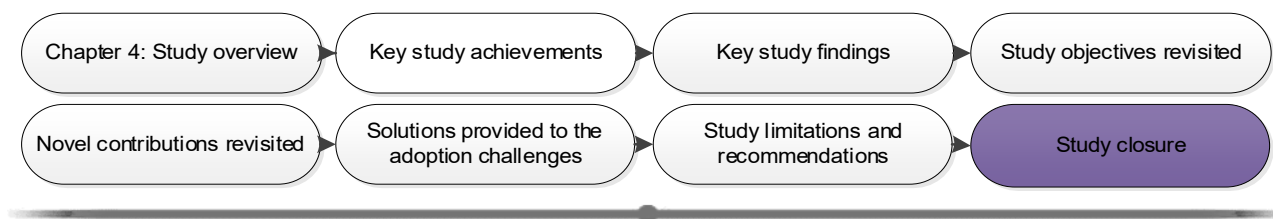
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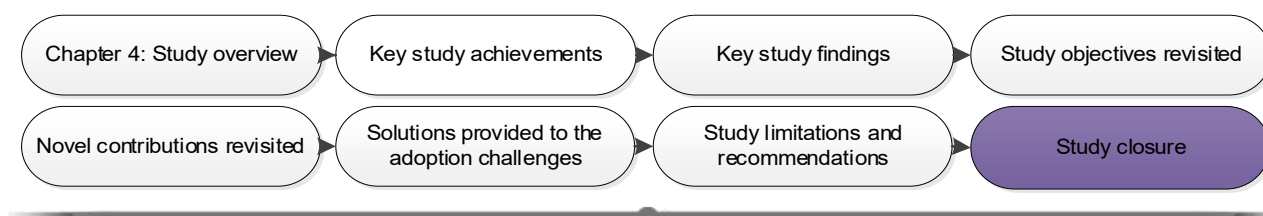


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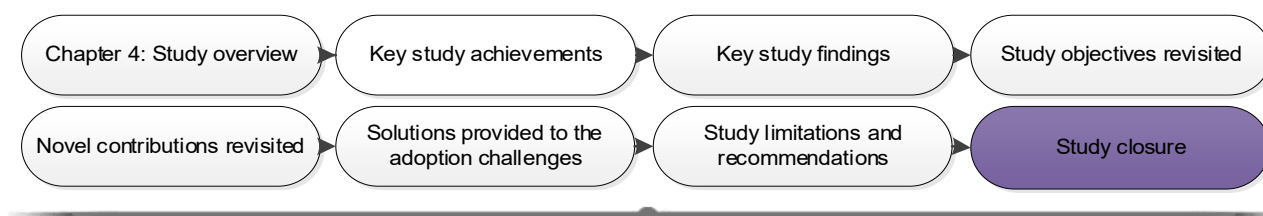


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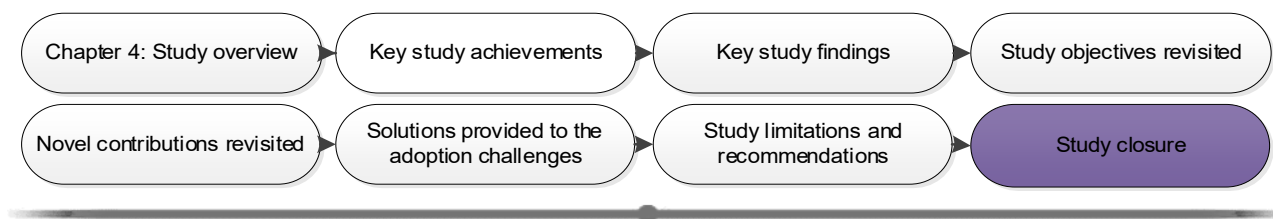
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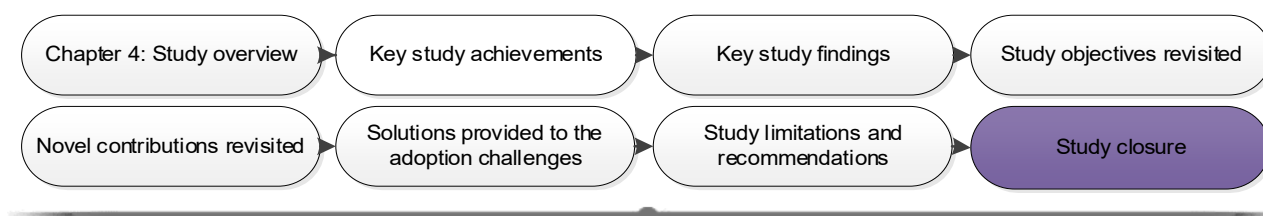


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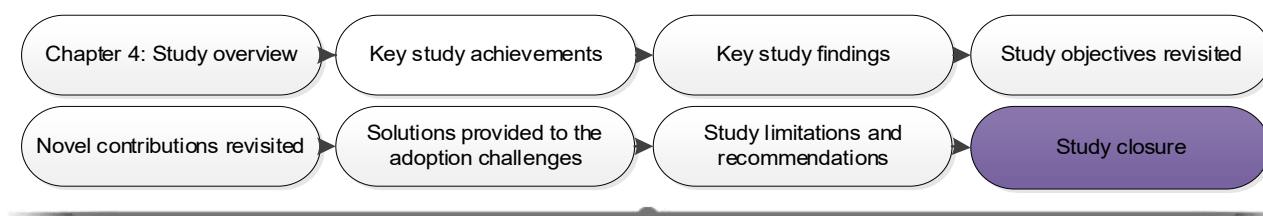
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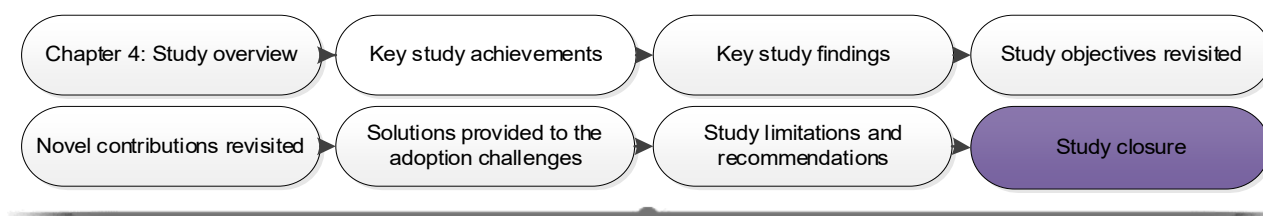
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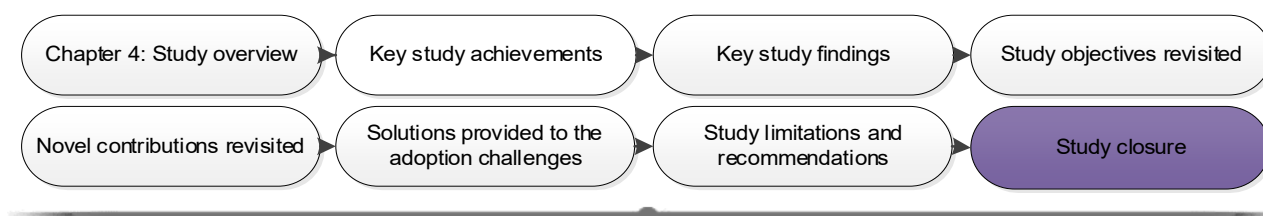


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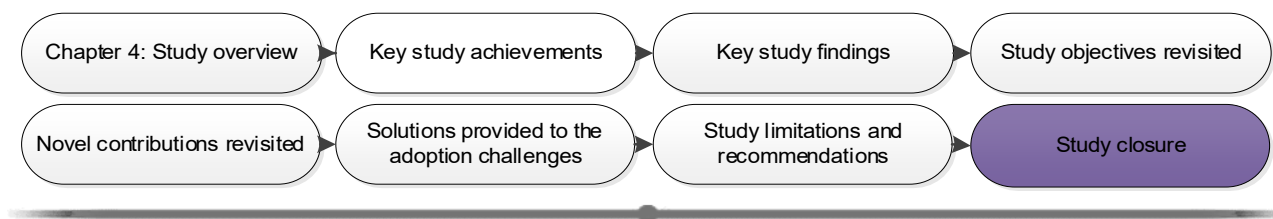


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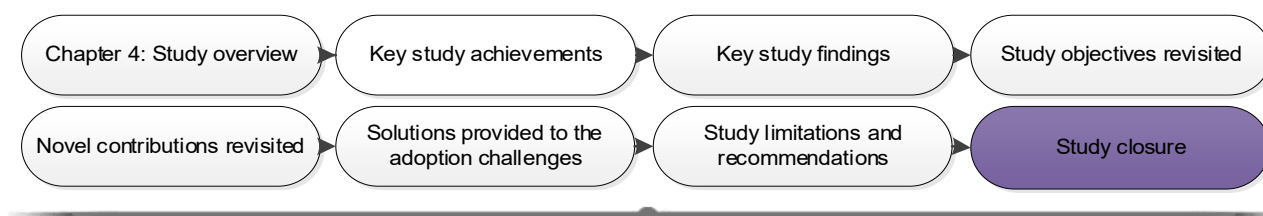


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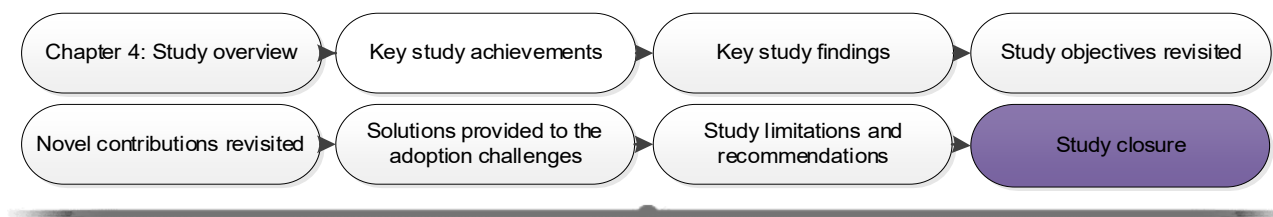


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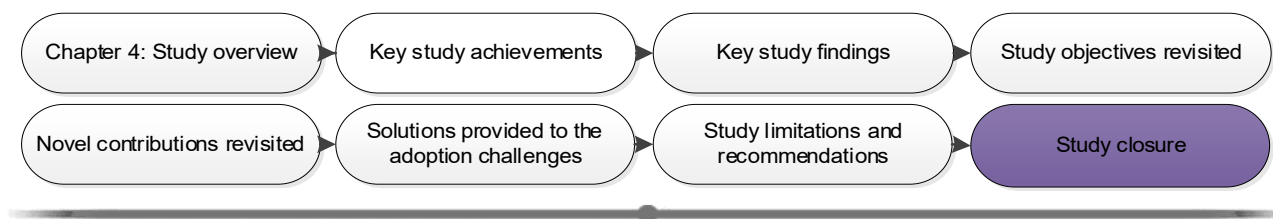
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APPENDIX A – CRITICAL REFERENCES

Table A-0-1 shows the references used to support the humanistic failure drivers illustrated in Figure 1-21. The references used to support the systemic failure drivers are shown in Table A-0-2.

Table A-0-1: References to humanistic failure drivers

Year	Title of study	Ref.
2017	Proactive personality and job satisfaction: The mediating effects of self-efficacy and work engagement in teachers	[104]
2015	Unlocking the black box: Exploring the link between perceive organizational support and resistance to change	[91]
2019	The effect of organizational resilience and CEO's narcissism on project success: Organizational risk as mediating variable	[90]
2021	Encountering Covid-19 and perceived stress and the role of a health climate among medical workers	[89]
2020	Change engagement, change resources, and change demands: A model for positive employee orientations to organizational change	[94]
2017	The relationship between universal network perceptions and dyadic network perceptions and their effect on employees' behavioural reactions to organizational change	[95]
2020	Understanding the individual's reactions to the organizational change: A multidimensional approach	[101]
2016	The impact of power distance orientation on recipients' reactions to participatory versus programmatic change communication	[92]
2021	Employee coping with organizational change in the face of a pandemic: The role of transparent internal communication	[82]
2014	The effects of authentic leadership on strategic internal communication and employee-organization relationships	[83]
2009	Leader creativity as a predictor of leading change in organizations	[87]
2020	A fuzzy Delphi analytic job demands-resources model to rank factors influencing open innovation	[84]
2012	The impact of leadership, management, and HRM on employee reactions to organizational change	[88]
2002	Technology and knowledge transfer: Good practice guidelines	[85]
2012	A dependence-regulation account of psychological distancing in response to major organizational change	[102]
2006	Changes at work and employee reactions: Organizational elements, job insecurity, and short-term stress as predictors for employee health and safety	[59]
2010	A positive approach to stress, resistance, and organizational change	[58]
2021	Effect of open-mindedness and humble behaviour on innovation: mediator role of learning	[57]
2016	Transformational leadership and change related voice behaviour	[109]
2016	Employee voice behaviour revisited: its forms and antecedents	[98]
1989	Predicting exit, voice, loyalty, and neglect	[99]
2008	A dispositional approach to employability: Development of a measure and test of implications for employee reactions to organizational change	[86]
2011	Researching sensitively without sensitizing: Using a card sort in a concurrent mixed methods design to research trust and distrust	[97]

Year	Title of study	Ref.
2015	Overcoming resistance to change in engineering and construction: Change management factors for owner organizations	[81]
2013	An approach for evaluating the functional and non-functional change factors of web service using Finite State Machine	[105]
2017	Employees' reactions to IT-enabled process innovations in the age of data analytics in healthcare	[107]
2020	Employees' emotional reactions to digitally enabled work events	[93]
2012	Technology changes at work and employee reactions: The role of leader behaviour	[106]
2016	The reasons behind change recipients' behavioural reactions: A longitudinal investigation	[108]

Table A-0-2: References to systemic failure drivers

Year	Title of study	Ref.
1996	The introduction of man-tracking surveillance systems	[5]
1970	Dry drilling in gold mines	[5]
1984	The development of a hydraulic backfilling system for a deep-level gold mine	[219]
1976	The introduction of an impact ripper for mining soft reefs on a continuous basis	[19]
1995	The introduction of cement backfill systems in Western Deep Levels	[220]
1988	The introduction of electronic delay detonation technology	[221]
2021	Low-cost Internet of Things (IoT) for monitoring and optimising mining small-scale trucks and surface mining shovels	[222]
1973	Early attempts to mechanize and automate short wall coal faces	[205]
2002	Rollout of stope drilling systems in SA mines: A review of successes and failures, and the way forward	[14]
2000	The introduction of electric handheld drills	[55]
1973	The introduction of hydraulic rock props	[215]
1978	Mechanical rock cutters	[15]
1978	Mechanical rock-breaking hammer	[19]
1988	Wheeled or 'tank tracked' multi-boom rigs	[9]
1999	Single boom stope jig on mono rail	[56]
1998	Rock splitting using non-explosive 'propellants'	[56]
2017	Low-profile electro-hydraulic drill rigs	[76]
2003	Centralised hydropower	[71]
1975	Blast-on reciprocating flight conveyors	[19]
2006	Mining by rock cutting in narrow reefs	[15]

APPENDIX B – ADDITIONAL INFORMATION ON STEP 1: STRATEGY DEVELOPMENT

The literature review ([Section 1.7](#)) indicates that change initiatives frequently fail when the urgency for change remains unverified. Verification is crucial to ensure that the correct production constraint earmarked for change is identified. As a result, the method objectives listed in Table 1-5 called for a strategy to verify the change urgency. The main aim of the change urgency verification strategy is to prevent the operation from implementing ADTs misleadingly in cases where the drilling cycle might not actually be the main bottleneck. As part of their role profile, the first person expected to acknowledge that change is needed at a mining operation is the shaft general manager. Step 1 provides the shaft general manager with a strategy to verify the urgency of the change.

Strategy development overview

S1.1: Activity benchmarking

This is done by comparing the time duration benchmark and the actual and theoretical shift cycle activities. The following ten activities of significance were identified from a study completed by Steward [121]:

- Day shift travels down the mine and to the workplaces;
- Day shift entry examination and face preparation;
- Drilling and support;
- Charging up;
- Day shift travel time out;
- Blast and re-entry period;
- Night shift travel in;
- Night shift entry examination and watering down;
- Cleaning; and
- Night shift travel out.

Data collection strategy

1.1.A: Actual shift cycle activity duration study

Table B-0-1 showcases the proposed strategy for evaluating the actual shift cycle duration. When selecting a panel to study, the following selection criteria are paramount. The panel needs to be located at an average distance from the shaft. Panels that are abnormally close to or far from the shaft will skew the results. Also, the panels need to represent the shaft's average mining conditions in terms of face length, stoping width, gully distances, and ground conditions.

Table B-0-1: Proposed strategy to evaluate the actual shift cycle duration

Activity	Recommended evaluation strategy
(1) Day shift travels down the mine and to the workplaces:	To record the time taken by day shift to travel from surface to the workplace: - Start the time recording at surface when the cage is about to go down. - Travel with the crew to the waiting place of their workplace. - Stop the recording once arrived.
(2) Day shift entry examination and face preparation:	To record the time taken to conduct the entry examination and face preparation: - Start the time recording once the crew start to enter the workplace - The crew will examine the workplace. Once declared safe, stope team members will start to prepare the face, while the RDOs will start to assemble their machines. - Stop the recording once the face is fully prepared for drilling to commence.
(3) Drilling and support:	To record the time taken to drill and support the panel: - Start the time recording once RDOs start drilling. - Be sure to record the panel's face length, stoping width, as well as the blast and support design as these parameters will be used to calculate the theoretical time required. - Support installation and drilling of production and non-production holes usually happen in paralleled. - Stop the time recording once these activities are completed.
(4) Charging up:	To record the time taken to charge the production holes with explosives: - Start the time recording once the miner and miner's assistant start to charge the holes. - Be sure to record the number of holes charged. - Stop the time recording once all holes are charged up.
(5) Day shift travel time out:	To record the time taken by day shift to travel from the workplace to surface: - Start the time recording once the miner and miner's assistant leave the panel. - Stop the recording once the cage stops on surface.
(6) Blast and re-entry period:	The time allocated to the blast and re-entry period is available from the daily reports generated by the centralised blasting system.
(7) Night shift travels in:	To record the time taken by night shift to travel from surface to the workplace: - Start the time recording at surface when the cage is about to go down. - Travel with the crew to the waiting place of their workplace. - Stop the recording once arrived.
(8) Night shift entry examination and watering down:	To record the time taken to conduct entry examination and winch preparation: - Start the time recording once the crew start to enter the workplace. - The crew will examine the workplace. Once declared safe, stope team members will water down the ore and start to prepare the scraper winches. - Stop the recording once the winches are all fully prepared.

Activity	Recommended evaluation strategy
(9) Cleaning:	To record the time taken to clean the panel: - The time recording starts when the winches become operational. - It is paramount to record the number of winch rope breaks since it will be used to calculate the theoretical time required to clean the panel. - Stop the recording once the winch drivers stop the winches at the end of the shift.
(10) Night shift travels out:	To record the time taken by night shift to travel from the workplace to surface: - Start the time recording once winch drivers leave the panel. - Stop the recording once the team arrives on surface.

Data sample size: Four blasts represent roughly half of a gold mine's monthly face advance cycles [6], [12], [25], [49]. Data collected over the span of four blasts should be sufficient to represent the actual time required by each activity.

1.1.B: Theoretical shift cycle activity duration study

The theoretical shift cycle times are calculated using the following formulas.

Travel times: Travel time in and out of the mine is governed by the mode of transport deployed at the operation, including walking, carriages, lift shafts, and chairlifts. The total travel time is typically a function of the sum of the time required by each transport mode, as expressed by Equation B-1, where travel distances can be obtained from the mine survey department. Recommended travel rates are provided in Table B-0-2.

$$Travel\ time = Travel_{rate} \times Travel_{distance} \quad \text{Equation B-1}$$

$Travel_{rate}$ *Time duration to travel one kilometer [min/km]*

$Travel_{distance}$ *Distance to travel [km]*

Table B-0-2: Travel rate of various underground transport modes

Transport mode	Travel rate [min/km]	Source
Walking	9.0	Manual time studies performed
Carriages	5.0	
Chair lifts	3.0	
Lift shafts	3.3	

Entry examination and face preparation (EEFP): The total EEFP time required is a function of the face length examined and prepared. It is given by Equation B-2. Entry examination and preparation rates for day and night shift examinations could not be obtained from the literature. Instead, data was

gathered during various entry examinations at different face lengths at an underground gold mine. The data suggested that the activity of examinations and face preparations are typically performed at a rate of:

- Four minutes per metre of face length (day shift examination and preparation), and
- Two minutes per metre of face length (night shift examination and preparation).

$$EEFP = \text{Examination \& preparation}_{\text{rate}} \times \text{Travel}_{\text{distance}} \quad \text{Equation B-2}$$

Drilling and support cycle: Production and non-production holes need to be drilled. Holes drilled to gain face advance are considered production holes. Rigging and support holes are non-production holes. Two areas need to be drilled: the face and the gully. Equation B-3 is used to calculate the total time required to complete the drilling cycle for each area. The total linear metres to be drilled are simply the product of the hole depth and the number of respective holes. Drill rates are available from the rock drill performance specification at the applied pressure as measured in the panel. The number of holes drilled per operator in the area of the face generally exceeds the number of gully holes. Therefore, the drilling cycle will be dominated by the face drilling component.

$$\text{Drill cycle time (DCT)} = \frac{LMD \times DR}{NOD} \quad \text{Equation B-3}$$

where:

- DCT – Drill cycle time [min]
- LMD – Total linear metres drilled [m]
- DR – Drill rate [m/min]
- NOD – Number of drills deployed [–]

To prevent the excavation from collapsing, support has to be installed. This consists of a combination of two components: roof bolts and timber support. The installation of components is covered under the drilling component. The timber support cycle time is calculated using Equation B-4. It is governed by the number of support units to be installed and the installation rate. Two types of timber support units are generally utilised: packs and elongates.

$$\text{Support cycle time} = \frac{EN_{\text{units}}}{ESR} + \frac{PN_{\text{units}}}{PSR} \quad \text{Equation B-4}$$

where:

- EN_{units} – Number of elongate units [–]
- ESR – Elongate installation rate [units/hour]
- PN_{units} – Number of pack support units [–]
- PSR – Pack installation rate [units/hour]

Charging up: The time required to charge a production hole is governed by the number of production holes and the charge-up rate (Equation B-5). The charge rate is defined as the time required to clean and fill the hole with explosives.

$$\text{Charge}_{\text{up}} \text{ cycle time} = \frac{HN_{\text{units}}}{HCR} \quad \text{Equation B-5}$$

where:

- HN_{units} – Number of holes to be charged [–]
- HCR – Hole cleaning and charge rate [Holes/hour]

Cleaning: Rock movement in conventional mining layouts consists of a number of integrated processes [42], [197]. As illustrated in Figure B-0-1, the movement of rock through a narrow reef stope consists of four basic processes: face to the strike gully (FCR), strike gully to the centre raise (SCR), raise to the ore pass (DCR), and finally, ore tramming. The overall cleaning cycle time is given by Equation B-6.

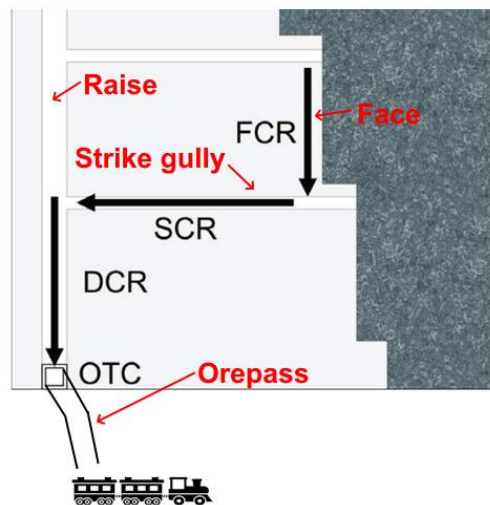


Figure B-0-1: Ore movement segments through a narrow reef stope (Adapted from [197])

$$\text{Cleaning cycle time (CCT)} = \frac{Qa}{CR} \quad \text{Equation B-6}$$

where:

- CCT – Cleaning cycle time [h]
- Qa – Volume of fragmented ore generated per blast [m^3]
- CR – Scraper cleaning rate [m^3/h]

Rupprecht [197] studied fragmented ore movement on the reef horizon and presented an equation to calculate the cleaning rates associated with each in-stope segment (Equation B-7). It is a function of the scraper bucket size, bucket fill factor, scraper trip efficiency and the number of trips per hour.

$$CR = Qa \times Ff \times N \times \eta \quad \text{Equation B-7}$$

where:

CR	– Scraper cleaning rate [m ³ /h]
Qa	– Scraper bucket capacity [m ³]
Ff	– Bucket fill factor [%]
N	– Trips per hour
η	– Scraping efficiency [%]

The number of trips per hour is given by Equation B-8. It is simply the product of the winch speed, scraping distance, and time lost to rope break repairs.

$$N = \frac{3\,600}{\left(\frac{D_t}{WR_s} + T_{\text{tip}} + T_{\text{fill}} + T_{\text{repairs}}\right)} \quad \text{Equation B-8}$$

where:

N	– Trips per hour [–]
3 600	– Hour to seconds conversion factor [s]
D_t	– Scraper bucket distance travelled (forward and reverse)
WR_s	– Winch rope speed [m/s]
T_{fill}	– Bucket fill time [s]
T_{tip}	– Bucket tip time [s]
T_{repairs}	– Rope break repair time [s]

Waterjet face cleaning

Some mines have water jets to assist in cleaning the face. Assume a face cleaning rate between 20 t/h and 30 t/h for mines using water jet assisted face cleaning [29]. This is only relevant when the strike or centre gully cleaning rate exceeds the face cleaning rate; otherwise, the cleaning cycle is constrained by the strike or centre gully [197].

Data collection plan: The proposed data collection plan is outlined in

Table B-0-3.

Table B-0-3: Shift cycle time and motion study

Shift cycle component	Data collection strategy
(1) Day shift travels in	- Depends on travel distance and modes of transport. - Evaluated by means of Equation B-1.
(2) Entry examination and face preparation	- Depend on travel distance, face length, and stoping width. - Ascertained by Equation B-2.
(3) Drilling, support, and charging up	- Depends on the face length and stoping width. - Evaluated by means of: • Drilling – Equation B-3. • Support – Equation B-4.
(4) Charging up	- Depends on the number of holes to be charged. - Evaluated by means of: • Charging up – Equation B-5.
(5) Day shift travels out	- Unique per operation. - Depends on travel distance and means used to travel. - Evaluated by means of a time study.
(6) Blast and re-entry	Requirement per law [125]: - Two hours (centralised blasting). - Three hours (non-centralised). - Alternatively, until all fire heads measuring blasting fumes have been cleared.
(7) Night shift travels in	- Depends on travel distance and means of traveling. - Governed by the re-entry time. - Evaluated by means of Equation B-1.
(8) Entry examination and watering down	- Unique per operation. - Depends on travel distance, face length, and stoping width. - Evaluated by means of Equation B-2.
(9) Cleaning	Evaluated by means of: - Time required to clean: Equation B-6.
(10) Night shift travel out	- Depends on travel distance and means of traveling. - Evaluated by means of Equation B-1.

1.1.C: Activity benchmarking

Figure B-0-2 presents a visual representation of the nine shift activities in order of events within a 24-hour mining cycle. The inner ring represents the theoretical baseline time required to complete each activity. The outer ring illustrates the actual time taken. The circular representation will clearly illustrate the time phasing effect on consecutive activities when those activities start to deviate from the theoretical baseline. For example, an increase in the drilling and support cycle will consequently delay the remaining activities, ultimately reducing the time available to clean the face.

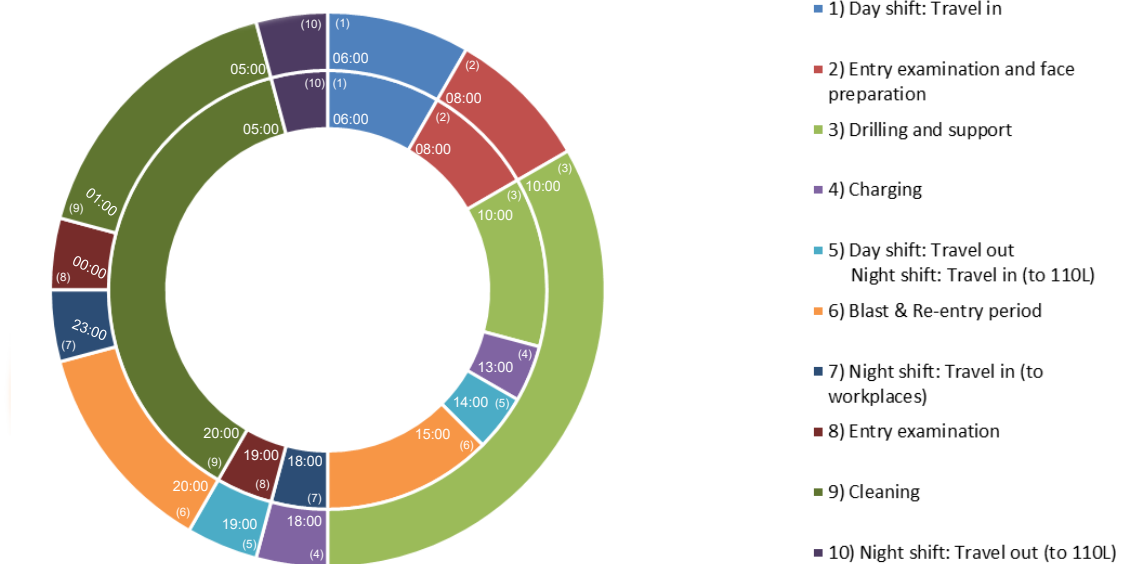


Figure B-0-2: Actual vs theoretical shift cycle components

APPENDIX C – PROPOSED IMPLEMENTATION PLAN

[Step 5.4](#) focused on developing an implementation plan template to be used by mine management teams when implementing an ADT. The proposed template is shown in Table C-0-1.

Table C-0-1: Implementation plan

Task group	Task breakdown	Actionable items	Responsible person	Timeline
Step 1: Verify the change urgency	1.1: Benchmark activities	1.1.A: Actual time to complete the mining cycle	Shaft general manager	Once-off: start date/ end date
		1.1.B: Theoretical time to complete the mining cycle	Shaft general manager	Once-off: start date/ end date
		1.1.C: Benchmark actual vs theoretical to verify the change urgency	Shaft general manager	Once-off: start date/ end date
	1.2: Analyse lost blasts	1.2.A: Non-drilling-related lost blasts	Shaft general manager	Once-off: start date/ end date
		1.2.B: Drilling-related lost blasts	Shaft general manager	Once-off: start date/ end date
		1.1.C: Non-drilling-related vs drilling-related lost blasts comparison	Shaft general manager	Once-off: start date/ end date
Step 2: Create the change vision	2.1: Select the alternative	2.1.A: Review alternatives available	Shaft general manager	Once-off: start date/ end date
		2.1.B: Select most appropriate fit based on the selection guidance provided	Shaft general manager	Once-off: start date/ end date
	2.2: Create the vision board highlighting the benefits	2.2.A: Performance	Shaft general manager	Once-off: start date/ end date
		2.2.B: Safety, health and environment	Shaft general manager	Once-off: start date/ end date
		2.2.C: Mine worthiness	Shaft general manager	Once-off: start date/ end date
		2.2.D: Human factors	Shaft general manager	Once-off: start date/ end date
		2.2.E: Techno-economics	Shaft general manager	Once-off: start date/ end date

Task group	Task breakdown	Actionable items	Responsible person	Timeline
Step 3: Develop a change management strategy	3.1: Promote change willingness	3.1.A: Promote the vision	Shaft general manager	Recurring: weekly
		3.1.B: Prove the change benefits on a small scale	All stakeholders	Recurring: weekly
		3.1.C: Select the correct initial end user and workplace	Shaft mine manager, shaft surveying department, shaft project engineer, OEM supplier	Recurring: weekly
		3.1.D: Celebrate small-term wins	All stakeholders	Recurring: weekly
	3.2: Identify and manage false perceptions	3.2.A: Identify false perceptions	Shaft project engineer	Recurring: weekly
		3.2.B: Correct false perceptions though facts	Shaft project engineer	Recurring: weekly
	3.3: Promote an inclusive leadership style	3.3.A: Promote interpersonal communication and managerial involvement	Shaft project engineer	Recurring: weekly
		3.3.B: Promote end user support	Shaft project engineer	Recurring: weekly
	3.4: Manage emotional wellness	3.4.A: Introduce and integrate mentors	Human resources leader	Recurring: weekly
		3.4.B: Stick to the multi-layered sequential method to avoid excessive change	All stakeholders	Recurring: Weekly
	3.5: Define roles and responsibilities	3.5.A: Identify stakeholders	Shaft project engineer	Recurring: weekly
		3.5.B: Develop the responsibility chart	Shaft project engineer	Recurring: weekly
		3.5.C: Use the RACI chart to define roles and responsibilities	Shaft project engineer	Recurring: weekly
	3.6: Align planned with actual change implementation progress	Facilitate weekly meetings to align actual vs planned progress using the implementation plan as reference	All stakeholders	Recurring: weekly
Step 4: Communicate the vision	4.1: Introduce the vision	Share the vision during a mass meeting	Shaft general manager	Recurring: start date/ end date
	4.2: Introduce the equipment	Demonstrate the equipment	All stakeholders	Recurring: start date/ end date

Task group	Task breakdown	Actionable items	Responsible person	Timeline
	4.3: Seek stakeholder approval	Obtain stakeholder approval	All stakeholders	Recurring: start date/ end date
Step 5: Enable implementation and change management	5.1: Supplier engagement on implementation scope	5.1.A: Verify end users' mining parameters	Shaft mine manager, shaft surveying department, shaft project engineer, supplier	Recurring: start date/ end date
		5.1.B: Select system type	Shaft mine manager, shaft surveying department, shaft project engineer, supplier	Recurring: start date/ end date
		5.1.C: Obtain water and electricity requirements	Shaft simulation engineer, shaft project engineer, supplier	Recurring: start date/ end date
	5.1: Supplier engagement on commercial arrangements	5.1.D: Purchase option	Shaft financial manager, supplier	Recurring: start date/ end date
		5.1.E: Maintenance option	Shaft financial manager, shaft engineering manager, supplier	Recurring: start date/ end date
		5.1.F: Quotation and lead time	Shaft financial manager, shaft project engineer, supplier	Recurring: start date/ end date
		5.1.G: Supplier contract and order number	Shaft financial manager, Group legal representative, supplier	Recurring: start date/ end date
	5.2: Infrastructure evaluation assessments – Electrical and water networks	5.2.A: Simulation package selection	Shaft simulation engineer	Once-off: start date/ end date
		5.2.B: One-line diagram development	Shaft simulation engineer	Once-off: start date/ end date
		5.2.C: One-line diagram-to-digital twin translation to create base model	Shaft simulation engineer	Once-off: start date/ end date
		5.2.D: Base model verification	Shaft simulation engineer	Once-off: start date/ end date
		5.2.E: Evaluate the operational change's impact on base model	Shaft simulation engineer	Once-off: start date/ end date

Task group	Task breakdown	Actionable items	Responsible person	Timeline
		5.2.F: Propose design changes required to support the operational change	Shaft simulation engineer, shaft engineering manager	Once-off: start date/ end date
	5.3: Updates to policies, procedures, and standards	5.3.A: Updates to policies	Shaft risk manager, shaft financial manager, human resources leader, shaft organised labour	Once-off: start date/ end date
		5.3.B: Updates to procedures and standards	Shaft risk manager, shaft mine manager, shaft organised labour	Once-off: start date/ end date
	5.4: Plan the implementation	Define and configure the case study-specific implementation plan	Shaft project engineer	Recurring: start date/ end date
Step 6: Implement the change and sustain the change momentum	6.1: Implement the change	6.1.A: Change management	All stakeholders	Recurring: start date/ end date
		6.1.B: Labour engagements	Human resources leader	Recurring: start date/ end date
		6.1.C: Infrastructure upgrades	Shaft simulation engineer, shaft engineering manager	Recurring: start date/ end date
		6.1.D: Equipping	Shaft project engineer, shaft mine manager, supplier	Recurring: start date/ end date
		6.1.E: System commissioning	Shaft project engineer, shaft mine manager, supplier	Recurring: start date/ end date
		6.1.F: Equipment transition	Shaft project engineer, supplier	Recurring: start date/ end date
	6.2: Sustain the change momentum	6.2.A: Identify key project milestones	Shaft project engineer	Recurring: start date/ end date
		6.2.B: Celebrate key project milestones	All stakeholders	Recurring: start date/ end date
Step 7: Do continuous	7.1: Assess performance	7.1.A: Collar-to-collar drill rate	Product performance evaluator	Recurring: start date/ end date

Task group	Task breakdown	Actionable items	Responsible person	Timeline
performance assessments		7.1.B: Face advance rate	Product performance evaluator	Recurring: start date/ end date
		7.1.C: Production	Product performance evaluator, shaft surveying department	Recurring: start date/ end date
		7.1.D: Water intensity ratio	Product performance evaluator	Recurring: start date/ end date
		7.1.E: Electrical intensity ratio	Product performance evaluator	Recurring: start date/ end date
	7.2: Assess safety, health and environment	7.2.A: Noise	Product performance evaluator, shaft occupational hygienist	Recurring: start date/ end date
		7.2.B: Vibration	Product performance evaluator, shaft occupational hygienist	Recurring: start date/ end date
		7.2.C: Heat load	Product performance evaluator, shaft occupational hygienist	Recurring: start date/ end date
		7.2.D: Ambient wet-bulb temperature change	Product performance evaluator, shaft occupational hygienist	Recurring: start date/ end date
		7.2.E: Environmental contamination	Product performance evaluator, shaft occupational hygienist	Recurring: start date/ end date
	7.3: Assess mine worthiness	7.3.A: Functionality	Product performance evaluator, shaft mine manager	Recurring: start date/ end date
		7.3.B: Reliability	Product performance evaluator, shaft engineering manager	Recurring: start date/ end date
	7.4: Assess human factors	7.4.A: Fatigue	Product performance evaluator, shaft mine manager	Recurring: start date/ end date

Task group	Task breakdown	Actionable items	Responsible person	Timeline
		7.4.B: Morale	Product performance evaluator, shaft mine manager	Recurring: start date/ end date
	7.5: Assess techno-economic factors	7.5.A: Capex	Product performance evaluator, shaft financial manager	Recurring: start date/ end date
		7.5.B: Opex	Product performance evaluator, shaft financial manager	Recurring: start date/ end date
		7.5.C: ROI	Product performance evaluator, shaft financial manager	Recurring: start date/ end date
Step 8: Verify the change benefits and sequentially expand the change process	8.1: Verify the vision	Verify and expand the initial vision board	Product performance evaluator, shaft project engineer	Recurring: start date/ end date
	8.2: Sequentially expand the change process	Apply a second layer of the method to reapply the change process to the next crew	All stakeholders	Recurring: start date/ end date

APPENDIX D – ARTICLE STATUS CONFIRMATION (AS OF 30/05/2026)

Article 1: B. van Rooyen, J. H. van Laar, J. C. Vosloo, "A techno-economic assessment of micro versus localised hydropower drilling systems for mature deep-level gold mines", Accepted for publication at the *Journal of Mining Technology*:

From: peter.dowd@adelaide.edu.au

To: bertusvanrooyen1@gmail.com

Subject: Mining Technology - Decision on Manuscript ID MTG-26-0019.R1

Body: 21-May-2026

Dear Mr. van Rooyen:

It is a pleasure to accept your manuscript entitled "A techno-economical assessment of micro vs localised hydropower drilling systems for deep-level gold mines" in its current form for publication in Mining Technology. The comments of the reviewers who reviewed your manuscript are included at the foot of this letter.

Please note that you must sign a license for us to publish your article. You will soon receive an email from Sage Journals: Licensing & Payment with a link to sign an appropriate license in the next few days.

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Thank you for your fine contribution. On behalf of the Editors of Mining Technology, we look forward to your continued contributions to the Journal.

Sincerely,
Dr. Peter Dowd
Mining Technology
peter.dowd@adelaide.edu.au

Reviewers' Comments to Author:

Comments to the Author

The authors have addressed my comments and paper is much improved.

Article 2: B. van Rooyen, J. H. van Laar, J. C. Vosloo, "A deep dive into modern hydropower handheld drilling systems' impact on production, cost, health and safety", Accepted for peer review at the *Journal of the Southern African Institute of Mining and Metallurgy*:

From: pen-bounces@emnuvens.com.br

To: bertusvanrooyen1@gmail.com

Subject: Journal of the Southern African Institute of Mining and Metallurgy - Editor Decision

Body: 09-April-2026

The following email was sent to Bertus Van Rooyen from Journal of the Southern African Institute of Mining and Metallurgy regarding **A deep dive into modern hydropower handheld drilling systems' impact on production, health, safety, and cost**.

You are receiving a copy of this notification because you are identified as an author of the submission. Any instructions in the message below are intended for the submitting author, Bertus Van Rooyen, and no action is required of you at this time.

Bertus Van Rooyen, Jean van Laar, Jan Vosloo:

We have reached a decision regarding your submission, "A deep dive into modern hydropower handheld drilling systems' impact on production, health, safety, and cost".

Our decision is to: Send to Review