



Analysing the influence of compressed air pressure on gold production

J.A du Preez



orcid.org/0000-0001-8919-9375

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

Supervisor: **Dr J.H Marais**

Graduation: May 2020

Student number: 24931209

Acknowledgements

As author of this dissertation, I would like to express great gratitude to the following parties for the ongoing assistance and support provided during the completion of this study:

- I would like to give thanks to God for providing me with this unique opportunity to further my studies and grow as a person and engineer.
- I want to thank Prof. Eddie Mathews and Prof. Marius Kleingeld for the unique opportunity in completing my post-graduate studies. I would also like to give thanks to Enermanage (Pty) Ltd and its sister companies for its ongoing financial support to complete this study.
- A thank you to my study leader, Dr. Johan Marais, for overseeing the dissertation and providing insight and guidance where needed.
- I would like to thank my mentor, Dr. Jean van Laar, for the continuous advice, insights, and guidance throughout the study.
- I would like to thank the mining personnel for the willingness to provide assistance in any way possible in order to complete this study.
- I would like to thank my co-workers, Dr. Johan Bredenkamp, Mr. Pieter Peach, and Mr. Franco Janse van Rensburg for the advice given when problems unavoidably struck during the writing of the dissertation.
- I want to thank my parents, Dalene du Preez and Peter Albert for the support provided throughout my studies thus far. Without your support it would not have been possible to reach my goals.
- Finally, I want to thank the love in my life, Robyn Buijs, for her continuous love and support throughout the study.

ABSTRACT

Title: Analysing the influence of compressed air pressure on gold production

Author: Jamie du Preez

Supervisor: Dr Johan Marais

School: North-West University Potchefstroom Campus School for Engineering

Degree: Master of Engineering (Mechanical)

Keywords: Compressed air, gold production, Agitation, deep-level mining

Unreliable energy provision in South-Africa led to various high energy-consuming entities searching for new ways to optimise energy distribution. Due to the increasing need for energy saving initiatives on deep-level gold mines, scope exists to implement various optimisation techniques on high energy-consuming systems.

One of the highest energy-consuming systems on deep-level gold mines is the compressed air network. Various studies have been conducted on the optimisation of a deep-level gold mines' compressed air networks, however, most of the studies conducted primarily focused on the shaft's compressed air network energy inefficiencies. Studies which include both optimisation of compressed air on the shaft and the plant are uncommon. A gold plant requires compressed air mainly for instrumentation operation and for agitation purposes in the leaching tanks.

A shared compressed air network between the shaft and the plant usually limits potential for electrical cost savings through control of the pressure setpoints at the shaft throughout the day. The plant receives fluctuating pressures from the shaft compressor house due to its dynamic nature. Fluctuating pressure delivery to agitation leaching tanks may lead to settling of ore within the leaching tanks. The settled ore contains unprocessed amounts of gold which do not progress further than the leaching tanks and is required to be reprocessed with the next batch. **A hypothesis was drawn up which states an increased and non-fluctuating pressure delivery to leaching tanks would have a positive effect on residue quantities in the leaching tanks.** The goal of the study is, therefore, to establish **whether an increased, non-fluctuating pressure delivery will have a positive effect on the residue quantities in leaching tanks and gold production totals.** In addition to potential benefits on the plant, electrical cost savings scope increases significantly on the shaft.

A study conducted on mine A showed the compressed air network was operating inefficiently. The plant used the air supplied from the shaft compressor house for agitation purposes in the leaching tanks. The delivered air pressure fluctuated greatly and may affect the agitation potential of the leaching tanks.

The plant's instrumentation operated on one 90 kW stand-alone compressor. The shaft had to adjust the compressors' setpoint according to the demand needed for plant operation. This hindered lowering the overall setpoint during shaft off-peak mining hours when drilling did not occur. The compressed air network of mine A was thus severely over budget and created a need to investigate different methods of optimisation where both the shaft and the plant could accumulate energy savings and possibly production increases. Various studies focusing on production enhancement techniques were analysed but very few focused on the influence of compressed air agitation pressure on the performance of leaching tanks. **A gap in the literature was thus identified.**

One of the solutions identified was to install a 315kW stand-alone compressor on the plant. The compressor installation enabled the plant to operate their compressed air network independently from the shaft, and adjust the pressures needed for agitation and instrumentation operation. The 90 kW compressor used for instrumentation operation was thus switched off. The main optimisation benefit on the plant's side is concluded as non-fluctuating pressures being delivered to the leaching tanks, which may lower the gold residue quantities trapped in the leaching tanks due to insufficient agitation.

In addition to a decrease in gold residue quantity within leaching tanks, and elimination of fluctuating pressures delivered to the plant, electrical cost savings on both the shaft and plant was achieved. The electrical cost savings on the shaft is calculated as R 3.3 million per annum, while the monetary value of the residue quantity decrease is quantified as R 2.43 million during the 28-day analysis period immediately after compressor installation during the 2018/2019 financial year. An overall verification of whether the consequence of pressure delivery change to the plant is solely responsible for the residue decrease **could not be made** due to various important parameters not being kept constant (due to the industrial-scale of the plant) throughout the study.

TABLE OF CONTENTS

Acknowledgements	ii
Abstract.....	iii
Table of Contents	v
List of Figures.....	vi
List of Tables	ix
List of Equations	x
List of Abbreviations	xi
List of symbols.....	xiii
Glossary	xiv
1 Background and Literature review.....	2
1.1 Preamble	2
1.2 Technical Background	2
1.3 Compressed air consumption in the gold mining sector	6
1.4 Literature study	12
1.5 Need for the study	39
1.6 Study objectives	40
1.7 Hypothesis.....	40
1.8 Study outline	40
2 Methodology	43
2.1 Preamble	43
2.2 Strategy approach identification	44
2.3 Parameter identification	45
2.4 Data collection	47
2.5 Solution optimisation	51
2.6 Implementation	52
2.7 Data analysis	52
2.8 Conclusion	57
3 Results and interpretation.....	59
3.1 Preamble	59
3.2 Case study background	59
3.3 Results analysis	64
3.4 Conclusion	78
4 Conclusions and recommendations.....	80
4.1 Preamble	80
4.2 Overview of the study	80
4.3 Recommendations	83
5 Bibliography	84
Appendix A	93
Appendix B	97

LIST OF FIGURES

Figure 1: Contributing sectors to South African GDP in 2017 [1]	2
Figure 2: Top 8 global gold producing countries [3][5]	3
Figure 3: Global gold production comparison to South African gold production [3][5]	4
Figure 4: Compressor demand and supply diagram [28]	7
Figure 5: Diagram of a typical gold plant [34]	10
Figure 6: Diagram of an isolated CIP process [50]	18
Figure 7: Influence of grind size on leaching recovery [50]	19
Figure 8: Closed reactor system consisting of permeable silicone tubing [56]	23
Figure 9: Graph of NaCN consumption vs gold recovery [59]	29
Figure 10: Graph of the PSD of the analysed material [33]	32
Figure 11: Graph of the screen analysis from the ball mill cyclone overflow [33]	33
Figure 12: Graph of the settling rates for the BMCO, SMCO and TF systems [61]	34
Figure 13: Graph of the average settling velocities for the BMCO, SMCO and TF systems [61]	34
Figure 14: Graph of the grind analysis of the mill feed [33]	36
Figure 15: Graph of deflocculation trends after testing [33]	37
Figure 16: Graph of the reduction in settling velocities after deflocculant addition [33]	37
Figure 17: Simplified flowchart of methodology development	43
Figure 18: Flowchart of strategy approach step in methodology	44
Figure 19: Flowchart for data collection step in methodology	47
Figure 20: Portable pressure logger [74]	48
Figure 21: Portable calcium photometer [75]	49
Figure 22: Portable cyanide meter [76]	49
Figure 23: Portable pH value meter [77]	49
Figure 24: Data collection flowchart	50
Figure 25: Solution optimisation flowchart	51
Figure 26: Improvement quantification flowchart	57
Figure 27: Shared shaft and plant compressed air network pressure delivery to leaching tanks	60
Figure 28: Shaft compressor energy profile after energy initiative identification	60
Figure 29: Shared shaft and plant compressed air delivery layout	62
Figure 30: Proposed separate shaft and plant compressed air layout	62
Figure 31: Mine A shaft compressor performance profile after project implementation	63
Figure 32: Comparison graph of pressure delivery to leaching tanks	64
Figure 33: Comparison graph of gold production and grade before and after project implementation	65

Figure 34: Comparison graph of residue quantities and grade before and after project implementation	66
Figure 35: Graph of leaching recovery before and after project implementation	67
Figure 36: Comparison graph of ore tonnes hoisted and treated before and after project implementation	68
Figure 37: Graph of the relation of ore treated to gold produced before and after project implementation	69
Figure 38: Comparison graph of mills' running time and ore tonnes treated before and after project implementation	70
Figure 39: Graph of cyanide addition in leaching tanks before and after project implementation	71
Figure 40: Comparison graph of pH level and lime addition before and after project implementation	72
Figure 41: Comparison graph of leaching recovery and pressure delivery before and after project implementation	73
Figure 42: Comparison graph of pressure delivery and gold grade before and after project implementation	73
Figure 43: Comparison graph of pressure delivery and gold production before and after project implementation	74
Figure 44: Comparison graph of pressure delivery and residue quantity before and after project implementation	75
Figure 45: Comparison graph of pressure delivery and residue grade before and after project implementation	75
Figure 46: Rand vs Dollar gold price comparison [7].....	93
Figure 47: Breakdown of a gold mine's input expenses [9][10]	93
Figure 48: Yearly Eskom tariff increases and Eskom revenue as % of mining GDP [11]	94
Figure 49: Electricity usage breakdown on a gold mine [13]	94
Figure 50: Average global gold reserve grade [15] [16].....	95
Figure 51: Average gold grade recovery of South African gold mines [17].....	95
Figure 52: Various targeted reefs at gold mines [23].....	96
Figure 53: Regression analysis graph of residue quantity vs gold production	96
Figure 54: Graph of copper concentration during a reaction with thiosulfate [59].....	98
Figure 55: Graph of gold leaching rate and mixed potential as a function of time [59]	99
Figure 56 : The proposed mechanism for the reaction between copper (II)-thiosulfate [59]	99
Figure 57: Graph of the gold leaching rate as a function of time [59].....	100
Figure 58: Graph of copper and thiosulfate concentrations as a function of time [59].....	101
Figure 59: Graph of the gold leaching rate with and without sparging [59].....	102
Figure 60: Graph of the gold leaching rate in the presence of disulfate [59].....	102

Figure 61: Mechanically agitated cyanide leaching tank [67]	104
Figure 62: Compressed air-agitated cyanide leaching reactor [67]	104
Figure 63: Gas sparger located below the lower impeller of a mechanically agitated reactor [70]	105
Figure 64: Graph of the performance of the gas dispersion chamber [67]	106
Figure 65: Corrugated tank bottom structure [67]	107
Figure 66: Different types of tank bottom structures and vertical fluid velocity of each [67].....	107
Figure 67: Fluid velocities at 85 mm from tank bottom of the different tank types [67].....	108
Figure 68: Transparent leaching tank setup showing suspension cloud height [67].....	108
Figure 69: Reactor equipped with measuring probes [67]	109

LIST OF TABLES

Table 1: Literature review study relevance.....	12
Table 2: Results of the atomic absorption method used to quantify gold concentration [56].....	25
Table 3: H ₂ O ₂ feed during the testing period [59].....	28
Table 4: Average percentage gold feeds and recoveries before and after pre-oxidation with H ₂ O ₂ [59]	28
Table 5: Measurements of the agitation tank taken for agitation efficiency analysis [33]	35
Table 6: Table comparing the shortcomings of the listed studies from literature.....	39
Table 7: Statistical analysis table.....	53
Table 8: Compressor specifications	63
Table 9: Summary of the results obtained	76
Table 10: Summary of the results obtained	81
Table 11: Results from the torque table power requirement test [67].....	109
Table 12: Comparison of annual expenses of a CIP reactor train with two different carbon attrition rates [67].....	111

LIST OF EQUATIONS

Equation 1: Cathode half-reaction [45][42]	11
Equation 2: Anode half-reaction [45][42].....	11
Equation 3: Empirical equation for volumetric flow of air [29]	15
Equation 4: The Elsner equation, leaching of gold [50][51].....	18
Equation 5: Ion pair adsorbed onto activated carbon [50]	21
Equation 6: Gold cyanide complex #1 [56]	22
Equation 7: Gold cyanide complex #2 [56]	22
Equation 8: Gold cyanide complex #3 [56]	22
Equation 9: Oxidation state of gold in the aurocomplex [56].....	23
Equation 10: Reduction half reaction [56].....	23
Equation 11: Hydrogen peroxide oxidising sulphides to form sulphates [59].....	26
Equation 12: Hydrogen peroxide oxidising sulphides to form sulphates [59].....	26
Equation 13: Spontaneous decomposition of hydrogen peroxide [59]	27
Equation 14: Gold leaching recovery formula [78][79].....	48
Equation 15: Copper-thiosulfate oxidising reaction [60].....	98
Equation 16: Carbon fines proportion as a function of mixer energy transference [73].....	110

LIST OF ABBREVIATIONS

Abbreviation	Description
SA	South Africa
GDP	Gross Domestic Product
NERSA	National Energy Regulator of SA
KPI	Key Performance Indicator
CIP	Carbon In Pulp
DO	Dissolved Oxygen
SAG	Semi Autogenous Grinding
MCO	Mill Cyclone Overflow product
BMCO	Ball Mill Cyclone Overflow product
TF	Pre-leach Thickener Feed
PSD	Particle Size Distribution
SMCO	Sag Mill Cyclone Overflow product
CIL	Carbon In Leach
CFD	Computational Fluid Dynamics

ANNs Artificial Neural Networks

RPM Revolutions Per Minute

PPM Parts Per Million

SG Specific Gravity

CFM Cubic Feet per Minute

LIST OF SYMBOLS

Symbol	Description	Units
V_f	Volumetric flow rate	m^3/hr
NL	Number of air leaks	<i>dimensionless</i>
T_i	Atmospheric air temperature	$^{\circ}C$
P_1	System air pressure	kPa
P_i	Atmospheric pressure	kPa
C_1	Isentropic sonic volumetric flow constant	$m/s K^{0.5}$
C_2	Conversion constant	s/h
C_d	Isentropic coefficient of discharge for square edged orifice	-
D	Leak diameter	mm
hf	Conversion constant	$10^6 mm^2/m^2$
M^{n+}	Appropriate metal ion	-
H_{grade}	Gold grade of the slurry sent to the CIP process	g/t
R_{grade}	Gold grade of the ore settled at the bottom of the leaching tanks	g/t

GLOSSARY

<i>"Adsorption"</i>	Process by which a solid holds molecules of gas or liquid as a thin film
<i>"Baseline"</i>	Data reference point used for future comparison
<i>"Bottle roll test"</i>	Assessment conducted to establish the potential gold recovery of an ore sample
<i>"Blasting"</i>	The process of using explosives to break large rock bodies into smaller pieces for excavation
<i>"Chute"</i>	A sloping channel or slide for sending ore to a lower level
<i>"Cleaning/Sweeping"</i>	Process of collecting all the blasted rock from the stopes and loading it into the hoppers
<i>"Compressor house"</i>	Building containing all the compressors and compressor auxiliaries
<i>"Energy intensive"</i>	Process requiring a significant amount of energy
<i>"Gold diggings"</i>	Colloquial term for gold rush locations
<i>"Gold grade"</i>	Term used to define the proportion of metal in the ore
<i>"Gross Domestic Product"</i>	Monetary measure of the market value of all the goods and services produced in a specific time period
<i>"Leaching"</i>	Process of extracting a soluble constituent from a solid by means of a solvent
<i>"Mining off-peak period"</i>	Periods excluding mine-drilling activities

"Narrow reef"	Ore deposit with a narrow distribution range, usually mined through conventional mining techniques
"Operational costs"	Cost inquired for production purposes
"Ore pass"	Transporting tunnel for material from one level to another
"Pachuca tank"	Cylindrical tank with a conical bottom
"Peak mining period"	Periods pertaining to mine drilling time
"Pneumatic equipment"	Equipment operating by means of gas or compressed air
"Raise"	Incline development at the stope
"Reef"	A vein of ore in the earth containing gold
"Rock face"	Furthest point of development/mining which is drilled and blasted
"SCADA"	Control system architecture using computer networks and graphical interface to store and display data
"Shaft"	A vertical opening giving access to various levels
"Skip"	Large container used to hoist the blasted rock to surface
"Stope"	Mining site containing the rock face
"Validation"	Process used to ensure the obtained results accurately address the problem statement

"Verification"

Process of ensuring the developed solution strategy is accurate and can be used

1. Background and Literature review

This chapter provides a broad introduction and literature review of the study. Background of the study assists in describing the problem that is researched. Energy usage and utilisation in the gold mining sector will be discussed in this chapter. The gold production process will be thoroughly described, and shortcomings of the process will be identified. Thereafter, the aim and the expected outcome of the study will be provided.

“There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things.” - Niccolo Machiavelli

1 Background and Literature review

1.1 Preamble

The first chapter serves as the introduction to the dissertation. It will provide an insight into what the uses of compressed air are in the gold mining industry, and the limitations of a shared shaft-plant compressed air network.

1.2 Technical Background

South African Gross Domestic Product

South Africa (SA) is a country rich in natural minerals, which makes the mining sector one of the key contributors to the Gross Domestic Product (GDP). Mining contributes to approximately 8% of SA's GDP [1]. Figure 1 shows a breakdown of the key economic sectors in SA.

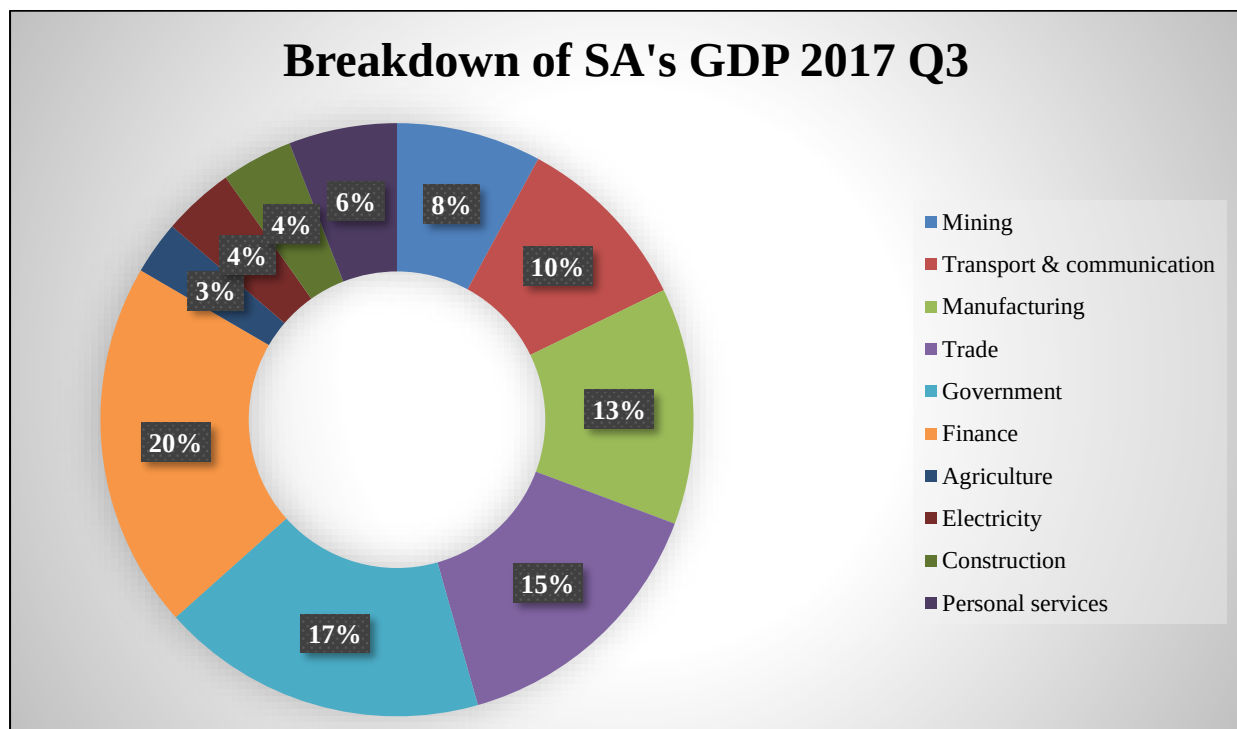


Figure 1: Contributing sectors to South African GDP in 2017 [1]

SA's mining sector populates a noteworthy percentage of the world production and reserves, and accounts to an estimated worth of R 20.3 trillion [1]. In terms of world rankings, SA has the fifth largest mining sector [1].

Gold mining

Gold was discovered in the late 19th century which led to the founding of numerous towns and cities such as the metropolitan city of Johannesburg around the gold diggings [2]. According to the Reuters' latest gold survey, SA was the 8th largest gold producer in 2017 [3] [4]. The graph containing the top 8 gold producing countries of 2017 is shown in Figure 2.

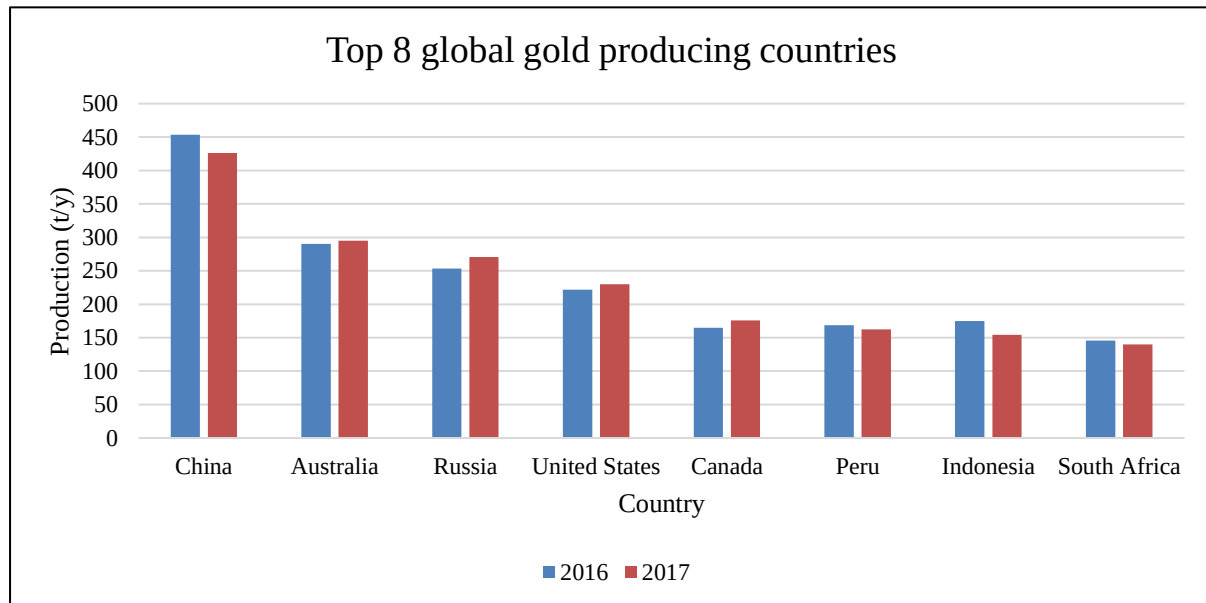


Figure 2: Top 8 global gold producing countries [3] [5]

The overall global production trends increased by approximately 800 tonnes during the past decade [3]. When considering SA's production, it issued a decline in yearly production totals. Mines from across the world are under financial pressure due to different factors, unique to certain reasons. SA is one such country and is under strain due to various profit-constricting factors. The gold industry is, therefore, classified as a price taker, meaning it cannot control the price of its product. It is set by the market driven by a supply and demand philosophy [4]. Cost increases are inversely proportional to production increases. As a result, 75% of gold mines operating in SA are unprofitable [4]. A graph comparing global and South African production is shown in Figure 3.

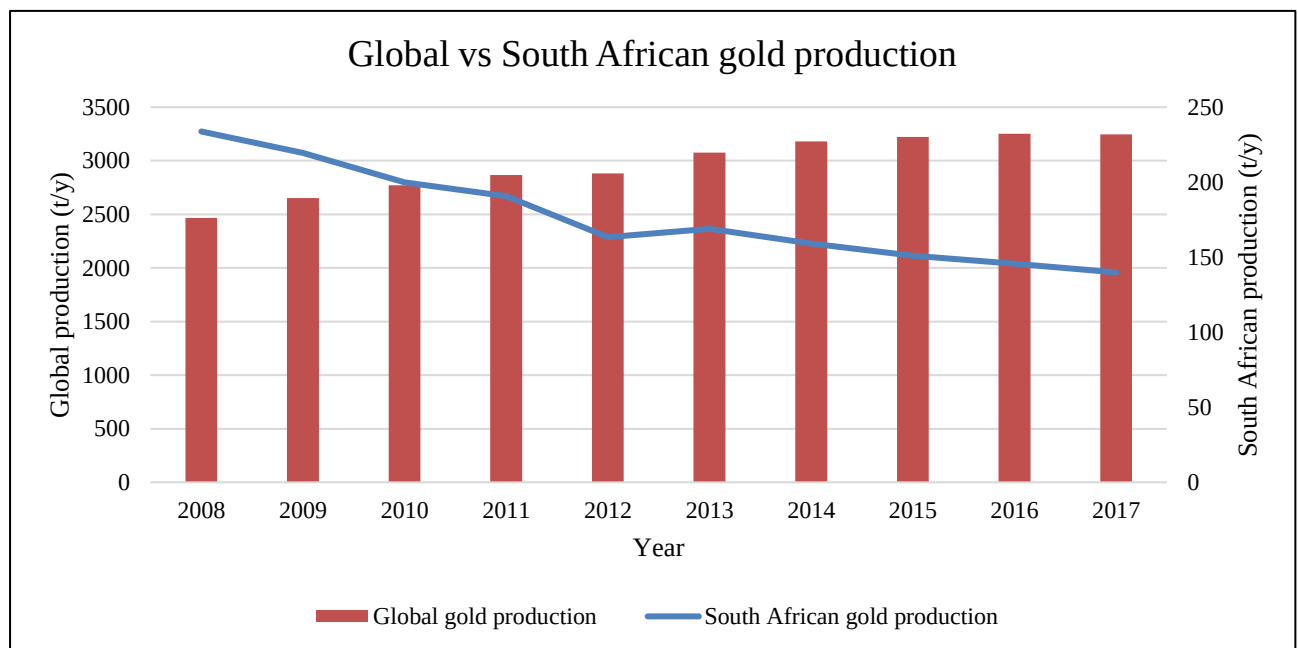


Figure 3: Global gold production comparison to South African gold production [3] [5]

Over the past decade, the gold mining sector in SA experienced prolific financial strain. Economically, it became increasingly strenuous to produce a yearly production rise. There are numerous factors that feature in dwindling production figures. A substantial amount of research has been done on the contributing factors of economic strain on the mining industry. According to the Southern African Journal of Mining and Metallurgy, the contributing factors (some unique to SA) are [6]:

- Gold price volatility – Recent economic decline in industrial powerhouse countries, especially China and the United States, has influenced global economic conditions [6]. Strategic planning in South African companies became more challenging due to gold's influence on revenue, cash flow and mineral asset values [6]. Figure 46 in Appendix A portrays a steady decline in gold price value compared to the dollar over the last five years [7].
- Escalating cost of production – The relationship between ore grade and energy consumption per unit metal is exponential [8]. A lower ore grade would therefore require greater energy consumption due to increased consumables during mining and processing of ore. Inflation, economic instability and rising electricity cost are also prolific contributors to increased production cost. Figure 47 in Appendix A displays a typical breakdown of a gold mine's expenses [9][10]. Figure 48 in Appendix A portrays the yearly Eskom electricity tariff increases as approved by the National Energy Regulator of SA (NERSA), and Eskom mining revenue as percentage of GDP [11][12]. To illustrate the contribution of compressed air to a gold mine's electricity usage, Figure 49 was added to Appendix A [13].

- Declining gold resource grade – Gold mining commenced over a century ago resulting in depleted higher-grade deposits, exposing more abundant lower grade ore [6]. One of the most common identification methods of gold grade is the bottle roll test. These are industry standard tests assessing the recovery possible through cyanide leaching and provides information regarding expected recovery rates, reagent costs, and addition rates [14]. Figures 50 and 51 in Appendix A portrays the decline in global average ore grade and South African ore grade over the past decade [15][16][17].
- Depth and mining method - Eight of the top ten deepest mines in the world are situated in the North-Western region of SA [18]. According to [6], the ability to mine deeper than normal in SA is due to a lower geothermal gradient compared to the rest of the world, which on average increases with 30°C per km [19]. Deep-level mines need to sustain a working environment which is life-sustaining, determined at a maximum temperature of 28°C wet bulb and 29.5°C dry bulb [20], and thus consists of extensive ventilation and refrigeration to cool the working environment [6].
- Insufficient hoisting – The hoisting of ore directly influences the profitability of the. If less ore is hoisted, less ore is processed into the gold end-product. Various factors contribute to sub-par hoisting and may differ in each mining operation [21].
- Varying gold grades - Differences in ore grade can occur frequently and can be attributed to various factors. The location where mining activities take place underground has a huge effect on what the resulting ore grade will amass to [22]. Figure 52 in Appendix A illustrates typical mining locations on a targeted reef, which can differ according to planning preferences [22].
- Gold production¹ – All the above-mentioned factors have an influence on gold production. These factors are mostly relevant to the accumulation of ore and not the processing of the ore into the high value end-product. The gold processing plant may have various production constricting factors which limit the amount of ore being processed and ultimately the amount of gold being produced. Some of the restrictions on a gold plant include empty silos due to sub-

¹ Jan Roos, Plant manager at Mine A, 2019/03/15, Details available upon request at jdupreez@rems2.com due to confidentiality

par hoisting, low gold grade, re-milling due to differing mill entry particle size, faulty equipment and fluctuating compressed air delivery.

All the above-mentioned factors have forced South African mining entities to adapt their yearly budget to include vast financial season increases [23].

1.3 Compressed air consumption in the gold mining sector

When considering all the above-mentioned problems individually, each would have its own unique challenges in attempts to rectify the problem at hand. The main conclusion which can be drawn from the accumulated information is that mines need to be financially driven and realise cost savings or production enhancement opportunities wherever possible. One strategy to be followed is the identification of inefficiencies within high energy-consuming systems and low performing production-related systems. In this document, solutions to an inefficient compressed air network will be discussed and applied. Compressed air networks are regarded as one of the most inefficient high energy-consuming systems on deep-level gold mines [24]. Compressed air is commonly used on deep-level gold mines for [25][26]:

- Pneumatic tools (compressed air is used as a source of energy),
- Pneumatic loading boxes,
- Refuge chamber pressurisation,
- Blasting (compressed air is used in the process of blasting),
- Cleaning/sweeping (compressed air is used for cleaning after blasting),
- Workshop service air,
- Ventilation,
- Pneumatic conveying, and
- Processing plant (compressed air is used for agitation and instrumentation purposes).

Compressed air systems often consist of various inefficiencies. A few of the most common inefficiencies identified include [27]:

1. Inappropriate use - Applying compressed air to processes which can be done using alternative sources of energy [27].
2. Compressed air leaks - Common problem areas linked to leaks are pipe disconnects, pipe joints, flanges, and thread sealants [27].
3. Increased demand due to excessive system pressure - Additional compressed air used due to higher than normal pressures needed to run equipment properly [27].

4. Maintenance neglect - Proper compressor maintenance can cut energy expenditure by approximately 1%. A few important components of a compressed air system to be maintained includes the following [27]:
 - Filters - Air filters need to be changed regularly to ensure proper air quality and optimum performance [27].
 - Condensate drains - These drains are installed to remove excess amounts of condensates from a compressed air system. Compressed air wastage can occur if a condensate drain is stuck open. Drains should be monitored frequently as they open directly to the compressed air lines [27].
 - Cooling water quality - Frequent water analyses should be conducted to determine any treatment needs [27].
5. Effective control of the supply and demand sides of a compressed air system - The supply and demand system are important contributors to running an effective compressed air system [27]. The difference between the supply and demand side of a compressed air system should be fully understood. Figure 4 describes the relationship between the demand and supply side of a compressed air system.

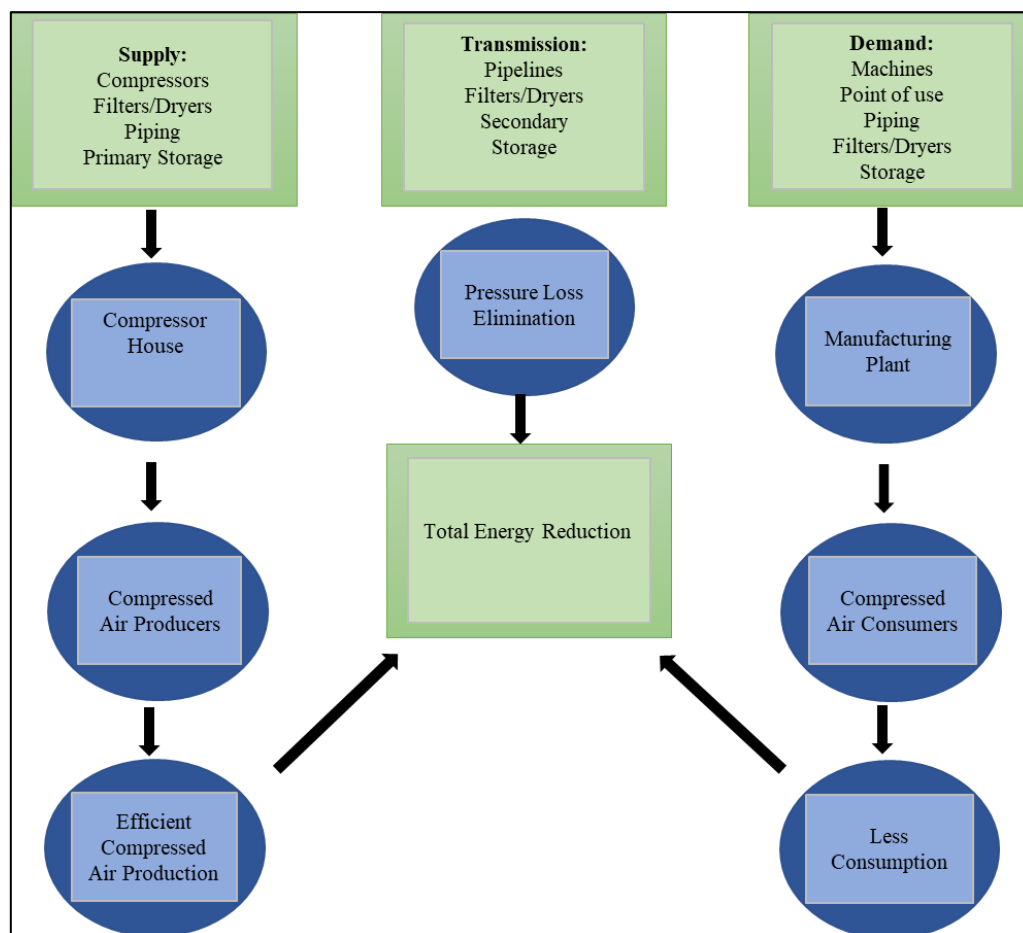


Figure 4: Compressor demand and supply diagram [27]

The supply side of the compressed air system would typically consist of [27]:

- The air compressor,
- The aftercooler,
- The dryer,
- Automatic drains, and
- Receiver tanks.

The demand side of the compressed air system would consist of [27]:

- The piping distribution system,
- Loading profile, and
- Air treatment.

The demand side of the compressed air system effectively controls the amount of compressed air being distributed to the various end users. Therefore, if the demand side of the compressed air system needs an increased amount of compressed air, the supply side would have to match the need the demand side requires. The demand of a compressed air system on a gold mine is typically increased by [27][28]:

- Peak drilling, sweeping or loading periods,
- Mismanagement of compressed air,
- Compressed air leaks, and
- Compressed air supply to a secondary system, typically the nearby gold plant.

Most gold shaft-plant operations in SA share the same compressed air network. The plant requires a constant supply of compressed air, whereas the shaft operates on a more dynamic delivery system [25]. Due to the dynamic nature of the shaft's compressed air system, the plant usually receives fluctuating pressures from the compressor house. The compressed air originating from the shaft compressor house is primarily used for agitation purposes in the leaching tanks and equipment operation [29]. The fluctuating pressures received from the shaft compressor house induces a tendency for the settling of ore at the bottom of the leaching tanks if the minimum superficial gas velocity is not consistently provided [30][31]. When working with commercial scale Pachuca tanks, tank height is an essential part of the operation efficiency due to better agitation within higher tanks [31]. Taking into consideration the beforementioned financial state SA's mining sector is in, limiting and correctly utilising the supply of compressed air is essential. A shared network may, therefore, limit the shaft's opportunities to decrease their compressed air demand.

Gold plant compressed air usage

The treatment of gold ore through cyanidation is the most widely used process of extraction. Cyanidation may consist of the following operations [32]:

- Air-agitated tank leaching,
- Heap leaching,
- Carbon adsorption recovery, and
- Zinc precipitation recovery.

Agitation in a leaching tank is an important part of this process and needs to be constantly monitored to ensure the key parameters are at the correct specified values. Upon entering the agitation tanks, the ore is already reduced to an approximate size so that 80% of the total ore can pass through a 74-micron screen [32]. The ore entering the agitation tank is mixed with a ratio of water to cyanide solution and combined with other chemicals needed for extraction [32]. It is by means of agitation with compressed air that the solution of water, cyanide, and slurry remain suspended [32].

On most gold mines in SA, the shaft compressor house supplies compressed air to the plant for instrumentation and agitation purposes. In numerous cases, the pressure supplied to the plant is insufficient due to a few contributing factors³:

- Pressure drops occurring from the shaft to the plant due to distance or leaks in the compressed air line.
- The dynamic nature of the shaft's compressed air network does not always correlate with the static nature of the plant's network. The shaft's compressed air demand may differ from the plant's demand, which contributes to varying pressures being delivered to the plant. These varying pressures may contribute to the settling of ore in the leaching tanks.

If the pressure supplied is not enough, inefficient agitation can occur which leads to siltation of ore particles that accumulate at the bottom of the leaching tanks [33]. These settled particles are known as residues. Bottle roll tests are conducted on residues to determine the potential gold recovery of these unprocessed ore masses [14]. The accumulated particles increase with every batch of ore entering the agitation tanks. This adds up to a substantial amount of ore not being processed. The correct quantity of supplied compressed air is, therefore, needed to ensure financial loss due to unprocessed ore is avoided.

³ Jan Roos, Plant manager Mine A, 2019/03/14, Details available upon request at jdupreez@rems2.com due to confidentiality

Key performance indicators of gold processing

The gold production process, done on the gold processing plant, is an intricate system which needs to be monitored carefully. Each contributing aspect of the overall process can be individually analysed and isolated to fully optimise the gold production [34]. Figure 5 is a drawing of a typical gold plant.

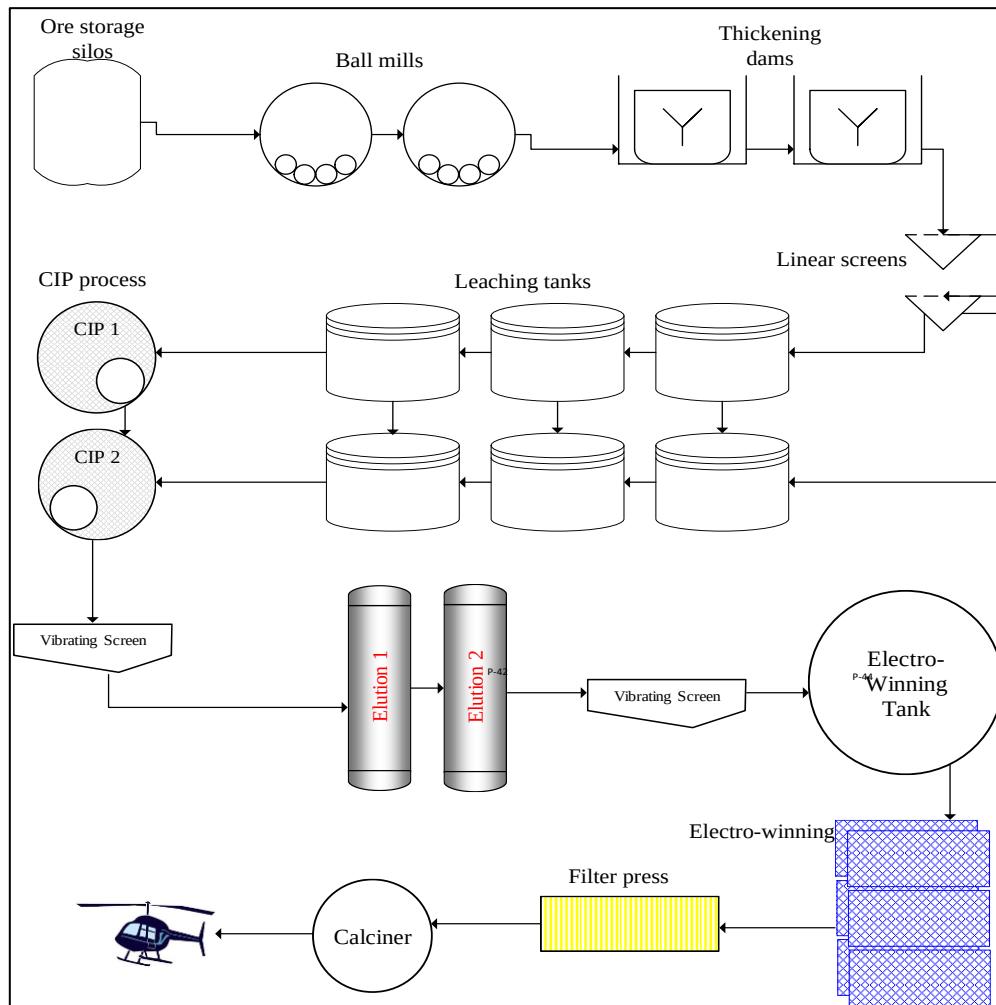


Figure 5: Diagram of a typical gold plant [34]

The first step of gold plant processing is the feeding of ore into the ball mills where it is crushed into the right sized ore [35][36]. The preferred size of ore particles exiting the ball mills differs on each plant. The particles larger than the preferred size are sent back to the mills for re-milling after being separated by linear screens [35] [36]. The ore that passed through the linear screens is sent to thickening dams. The purpose of the thickening dams is to remove portions of the liquid made up from pulp or slime which consists of finely divided solids and liquids [37][38]. Flocculants, which assist in the separation of liquids and solids, are added to the dams in predetermined concentrations. The solids are allowed enough time to settle, while the liquids at the top of the slurry are decanted. The settled solids are discharged, and the operation is repeated until enough liquids have been removed from the pulp

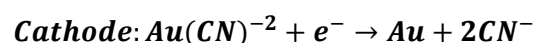
[37][38]. The slurry discharged from the thickening dams is sent to a set of vibrating screens to allow the passing of solids being sent to the leaching tanks [37][38].

In the air-agitated leaching tanks, the ore received from the thickeners is mixed with an aqueous cyanide solution. The slurry entering the leaching tanks is agitated by means of air injectors, which increases the cyanide and oxygen contact time with the slurry [39]. The solution forms a gold cyanide complex through oxidation by using a cyanide complexation [40]. The process is repeated by means of transporting the slurry through a series of parallel placed leaching tanks. The slurry exits the leaching tanks' processing phase and enters the first CIP (Carbon-In-Pulp) processing tank [39]. The CIP process can be described as the sequential leach, then adsorption of gold from its ore surface [39]. The leaching phase takes place in the agitation leaching tanks and the adsorption phase takes place in the CIP tanks. The solution flows through several agitation tanks containing activated carbon. The activated carbon flows counter-current to the pulp [39]. Gold is absorbed onto the surface of the activated carbon and the barren pulp is then separated by screens from the carbon loaded with gold [39][41]. The gold loaded pulp exits the CIP process and is sent to vibrating screens. The pulp is sent to a holding vessel after which it enters the elution process [41].

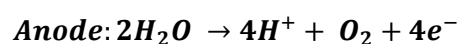
The elution process is essentially the reverse process of the adsorption process. The loaded carbon is washed with HCL acid prior to entering elution [42]. The elution process consists of several elution columns heated to high temperatures of approximately 130°C [42]. During elution, water is drawn from a portable water tank and pumped through a heat exchanger before entering the column [42]. Water flows up the column, transporting with it the gold that was freed into the solution [42]. The gold-containing (pregnant) solution flows out of the column through an inline filter and heat exchanger to the eluate tank. The process is repeated until a desired barren carbon assay is reached (typically -30g Au/ton) [43].

The eluates containing gold and silver is sent to the electrowinning process. Electrowinning is an attractive method used to recover gold from concentrated solutions by applying a voltage across electrodes immersed in the concentrated solutions [44][45][42]. The rectifier's positive terminal is connected to the anode, where the oxidation reaction occurs and electrons are generated. The cathode is connected to the negative terminal of the rectifier and the generated electrons are consumed at this terminal [45][42]. The reduction reaction therefore results in the deposit of metal on the cathode. The chemical half-reactions taking place during this process are the following:

Equation 1: Cathode half-reaction [45][42]



Equation 2: Anode half-reaction [45][42]



In cyanide solutions, the presence of gold is a stable auro-cyanide complex anion with a high cathodic potential [44]. High extraction efficiencies can be achieved at an increased eluate temperature of approximately 70°C, which increases ionic activity [45] [42]. The limit of the electrolyte operating in the electrowinning cell can be operated at a maximum upper limit of 90°C [45][42].

The key performance indicators, adapted from the Visual KPI process [46], for a gold processing plant can be identified as:

- Throughput/Production values,
- Downtime management,
- Equipment maintenance,
- Waste stream and cycle time management,
- Cyanide addition management, and
- Recovery monitoring.

The continuous goal of a gold plant is to increase the throughput and ultimately increase the amount of gold being produced. Various recovery-enhancing techniques can be applied; however, these techniques are rarely successful due to the uniqueness of each gold processing plant.

1.4 Literature study

Introduction

The literature study focuses on theoretical and practical applications, as well as subsidiary information required to successfully address the formulated problem statement found in this chapter. The start of the literature study will focus on the key performance indicators (KPI's) and key parameters when considering the gold production process on the plant. The latter part of the literature study will focus on various studies already conducted to enhance production and list the shortcomings of these studies. Some of the studies were conducted on pilot-scale plants and may assist if the study is to be repeated on a non-industrial scale. Information required to directly address the problem statement at hand will be analysed and used to formulate solutions. A table indicating the contribution of each included study is shown in Table 1.

Table 1: Literature review study relevance

Study	Contribution
Study nr. 1	This study proposes the idea to separate the shaft and plant compressed air network which is one of the main principles of this dissertation.

Study	Contribution
Study nr. 2	In order to analyse the performance of a leaching operation on a plant, it is important to understand the basic operation of a leaching unit. The study explains the important parameters to consider and provides a broad description of the leaching operation.
Studies 3 - 7	The listed studies contain production enhancement techniques that have been previously researched. By listing the techniques, it emphasizes the need for a study to be conducted on the influence of compressed air on the gold production and residue quantities. This dissertation will then either attempt to prove or falsify the forecast result formulated at the end of Chapter 1.
Study nr. 3	The technique entails enhancing production by using natural occurring bacteria to recover gold from ore. It is listed due to its relevance by releasing ore by using an additional, less expensive extraction method.
Study nr.4	The enhancing technique discussed entails adding sulphide to gold bearing ore due to increased oxygen consumption with injected air. The study was added due to its relevance to oxygen addition (in either the form of air or pure oxygen) being manipulated in attempt to enhance gold production.
Study nr. 5	The study was added due to its relevance to oxygen addition. The study did however contain some unnecessary information (included in the summary aid in results conclusion) and was placed in Appendix B.

Study	Contribution
Study nr 6.	The main focus of the study was to analyse the causative effects of siltation at the bottom of leaching tanks. This dissertation entails the analysis of the residue amount (settled ore) at the bottom of the leaching tanks. The study concludes what the main causative factors of siltation are.
Study nr 7.	The study focuses on oxygen addition and performance analyses of different leaching tank types. Dispersion within the tank types are analysed and can be used to determine optimal dispersion for agitation within leaching tanks. It was placed in Appendix B due to certain unnecessary information which is also required to successfully conclude the results of the study.

Each of the listed studies contributes to the dissertation and can aid when replicating the study on a pilot-scale plant. By considering each of the techniques within a pilot-scale plant, production enhancement studies can be conducted and continuously optimised.

Study 1: Separation of the shaft and plant compressed air network

The stimulus for the current study to be conducted was triggered by [29]. The concept of the study consisted of an investigation to separate the shared shaft and plant compressed air network. By allocating a dedicated compressor for high pressure components, the network pressure use can be lowered while the plant is still supplied with high pressure [29]. The energy consumption of the compressor network is reduced due to a reduced system pressure. Electrical energy savings are due to a lower discharge pressure and a decrease in distance air must be transferred through the pipe [29]. Energy savings are achieved on the shaft's side, and operational benefits may result at the process plants [29]. Various factors have been identified which contribute to the achieved energy savings.

Pressure losses resulting from compressed air line friction

Air flowing through a pipe over certain distances will be subjected to pressure losses as a result of friction (friction quantity depends on the distance air must travel) [29]. Other minor losses also need to be accounted for. Minor losses include pressure decreases from bends, t-pieces, reductions and valves [47]. The total pressure loss can ultimately be calculated if airflow speed, system pressure, pipe wall roughness, and pipe lengths are known [29]. Turbulent flow is to be assumed in these systems.

Airflow losses through compressed air leaks

Compressed air losses caused by air leaks in the line can be determined if the actual size, number of leaks and system pressure at every leak position is known [29]. An empirical formula is used for each network, as each network consists of its own characteristics [29]. The airflow, in cm³/hr, through a leak of known size is given by Equation 3 below.

Equation 3: Empirical equation for volumetric flow of air [29]

$$V_f = \frac{NL \times (T_i + 273) \times \frac{P_1}{P_i} \times C_1 \times C_2 \times C_d \times \pi D^2 / 4}{C_3 \times \sqrt{T_1 + 273}}$$

Where the variables are defined as:

- Volumetric airflow rate - V_f (m³/hr),
- Number of air leaks in the line – NL (dimensionless unit),
- Atmospheric air temperature – T_i (°C),
- System air pressure - P_1 (kPa),
- Atmospheric pressure - P_i (kPa),
- Isentropic sonic volumetric flow constant - C_1 (7.3587 m/s $K^{0.5}$),
- Conversion constant - C_2 (3 600 s/h),
- Isentropic coefficient of discharge (square edged orifice) - C_d (0.8),
- Leak diameter - D (mm), and
- Conversion constant - C_3 (10⁶ mm²/m²).

It can be seen from the formula, if the pressure P_1 is lowered, the airflow through the leak will decrease. A decrease in air lost through leaks will require less air to be generated, resulting in energy savings [29].

Energy savings due to a decrease in pressure demand

Energy savings is obtained by controlling the mass and pressure of compressed air being delivered to a system [29]. Every system is designed according to a predetermined flow and pressure [29][48]. By lowering the discharge pressure of the compressor to match the requirement of the largest air consumer, the power consumption is effectively reduced. A general estimation of a compressor's power consumption is a 1% improvement for every 14 kPa decrease in supply pressure [49].

Installation of a plant stand-alone compressor

Prior to compressor installation on the plant, an investigation needs to be conducted to identify the pressure and airflow requirements, air quality, and existing infrastructure [29]. Compressed air on gold plants is primarily used for agitation of leaching tanks, slurry tanks, and operation of pneumatic equipment. Agitation in leaching tanks is generally efficient at 380 kPa, however, exceptions may include very high leaching tanks (>20 m), or slurries with a relative density higher than 1.56 (dimensionless unit) [29]. Pneumatic equipment pressure requirement averages 500 kPa at lower flowrates [29]. The compressor can be used for both pneumatic equipment operation and required agitation. It is more cost-effective to design a compressor for a high pressure at a lower flow rate [29]. A higher volume of compressed air (used for agitation) can still be recovered from the existing compressed air network [29]. Although an additional compressor will be added to the network, the sum of actual resulting energy use will still be less than before the pressure is decreased [29]. This is due to the plant compressor being installed close to the equipment and leaching tanks to which it supplies compressed air. Stand-alone units can easily be installed on a flat surface by a qualified artisan [29].

Case study

Simulations were done on a case study which was implemented [29]. On the site, the gold plant required a constant non-fluctuating high pressure of 500 kPa. The entire compressed air network, including two mining shafts, needs to be supplied at the specified pressure to ensure the plant receives 500 kPa [29].

The air supplied to the gold plant can be separated from the main compressed air supply by installing a dedicated plant stand-alone compressor with an additionally installed air dryer [29]. The pressure supply from the main compressors can be set to deliver a 420 kPa setpoint. This is a 16% reduction from 500 kPa [29]. As previously mentioned, each 14 kPa decrease results in a 1% power saving. Therefore, with an 80 kPa decrease, a 5.7% power reduction is expected [29]. This results in an 807 kW power saving, which excludes the savings gained from reduced line losses and leaks.

The average baseline power consumption of the project was determined at 14.1 MW for the combined power of all the compressors before implementation [29]. The simulated and actual test results indicated an average 1 MW saving. The supplementary 200 kW saving can be allocated to the decreased line losses and leaks. It specified that a 160 kW stand-alone compressor should be enough to supply 500 kPa air to the plant [29]. Even with the 160 kW compressor added to the energy profile, a saving of 20.2 MWh per day is expected [29]. The installation cost of the compressor, averaging at R 900 000, would be paid back in three months when using the 2012/2013 Eskom Mega Flex Tariff structure [29].

Summary of the study

Compressors are large consuming entities on deep-level gold mines, and by reducing the pressure demand, electrical cost savings can be obtained. The initiative of installing dedicated plant compressors is feasible and cost-effective, with a short payback period when controlled optimally.

The case study was done with the sole purpose to obtain electrical cost savings, primarily directed at the shaft. The study neglected to investigate the influence of pressure delivery changes on the agitation in the leaching tanks, which is an essential part of processing gold ore. The study conducted in this dissertation will thus investigate the influence pressure delivery changes has on the production of gold, and the amount of residue left behind in the leaching tanks.

Before an investigation into the operation of leaching tanks is launched, it is imperative to establish how leaching tanks are designed and which parameters most affect the leaching operation.

Study 2: The process design of gold leaching and carbon-in-pulp circuits***Introduction***

Assuming gold ore sent to the mills has been effectively milled to ensure maximum release of gold, the circuits affecting the success of the entire plant operation the most will be the leaching and carbon-in-pulp circuits [50]. The reagent and utility operating costs associated with leaching, adsorption, elution, and regeneration processes would typically contribute to 15% of the total operating cost [50]. These specified plant areas signify the primary gold recovery process, which means the technical and operational efficiencies will have a substantial effect on the overall plant efficiencies [50]. The objective during the design of these plant sections is to develop a design providing maximum technical and economic efficiency, which is adaptable to potential unforeseen changes to ore throughput, mineralogical characteristics and ore head grade [50].

Process overview and description

The CIP process is a well-established process in the South African (SA) mining industry which strengthens the study need for mining operation efficiency in SA [51]. A block flow diagram of the CIP process up until the residue disposal can be seen in Figure 6.

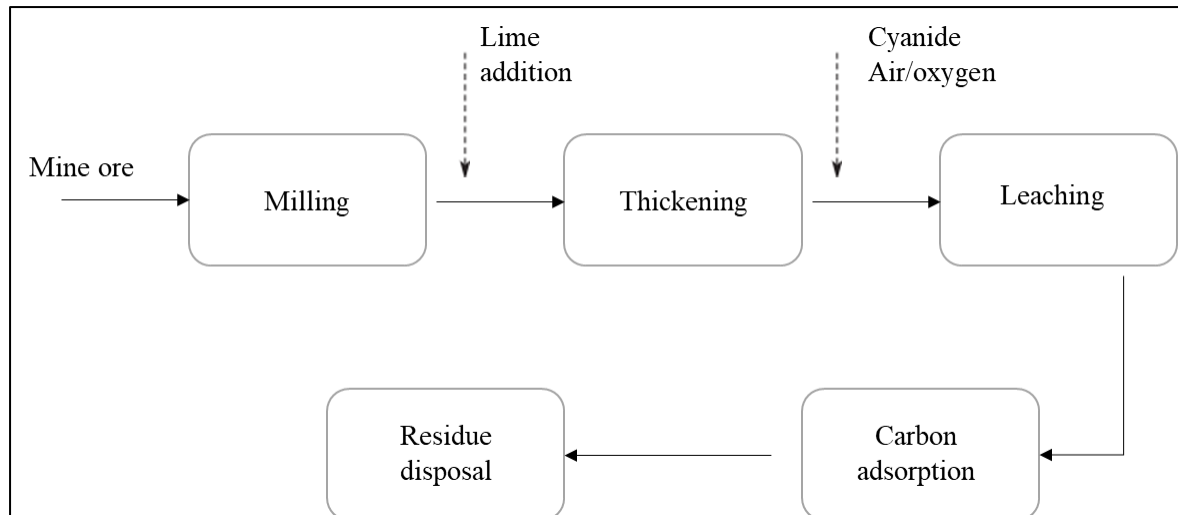
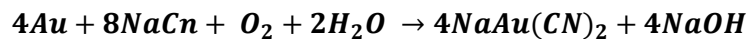


Figure 6: Diagram of an isolated CIP process [50]

After milling, the pulp is diluted, and thickening is used to increase the pulp densities to roughly 50% solids by mass [50]. The thickening process assists in reducing the required leaching plant size, as well as the number of required leaching reagents [50]. Lime, in the form of Calcium oxide (CaO), is added before leaching commences to adjust the pH level to range from 9.5-11 [50]. This is done to ensure minimum loss of cyanide as hydrogen cyanide (HCN). Leaching of gold is presented by Equation 4.

Equation 4: The Elsner equation, leaching of gold [50][51]



The slurry in the leaching tanks is agitated either by means of air agitation or mechanical agitation. Air agitation is an indication of an old plant and is not used as often anymore [50]. Some mines do still use air agitation and parameters are adjusted accordingly. Proceeding the leaching process, the pulp is passed over feed screens to ensure the removal of tramp material such as wood chips, plastics, and grit larger than 0.6 mm [50]. After the pre-screening of the feed, the pulp flows through a cascade of well-mixed adsorption tanks, usually 6-8 tanks [50]. Typical practice convention is having a mean pulp residence time of an hour each. Tanks are air-agitated, leaving each batch at a carbon concentration of 10-25 g of carbon per litre of pulp (0.5-1.2% of carbon volume) [50].

Carbon is retained in each reactor by means of screens, with approximate aperture size of 0.6-0.8 mm, allowing pulp to flow through and out of the reactor while retaining carbon. The gold aurocyanide complex in the aqueous phase is readily absorbed onto the activated carbon. Upon leaving the last tank in the adsorption cascade, the pulp's gold concentration in the aqueous phase is typically between 0.001 and 0.02 ppm [50]. It is regarded that a 0.01-0.005 ppm is a practical, achievable value for most operating plants [50]. It has been noted that a small amount of leaching takes place in the CIP reactors.

This is due to an additional residence time of the pulp in a leaching suitable environment and adds an economic benefit to the process [50].

Leaching parameters

There are various parameters influencing the leaching performance. According to [52], the most important parameters affecting the leaching process performance are:

- Lime addition – Added to create an aqueous environment with pH 9.5 – 11, in order to minimise cyanide lost by conversion to hydrogen cyanide (HCN). A CaO content of 150 – 200 ppm is normally added. The lime addition rate to achieve the desired pH will depend on the pulp properties. Typically used rates differ from 700 – 1500 g/t of 100% CaO equivalent [52].
- Grind size – The influence of grind size on the residue value obtained is shown in Figure 7. The curve shape and position are dependent on ore type [52].

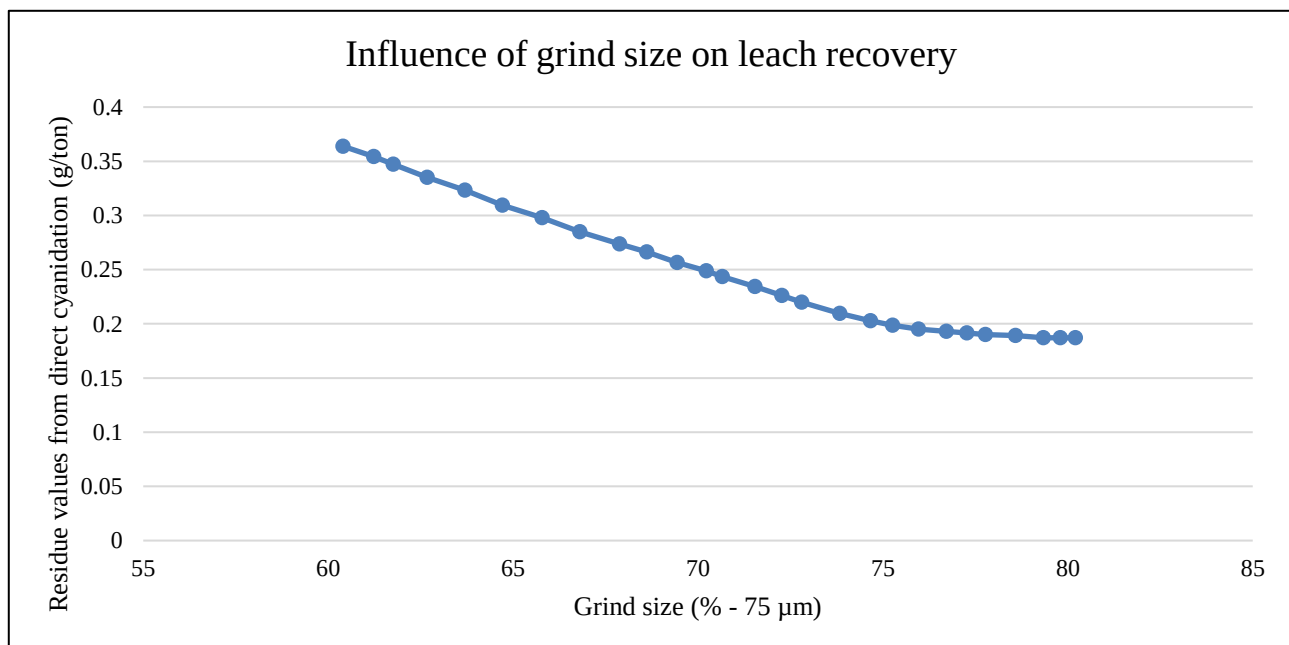


Figure 7: Influence of grind size on leaching recovery [50]

- Cyanide consumption – Many components in a typical processed ore consume cyanide via side reactions [50]. In addition to side reactions, cyanide is also lost through hydrolysis [50]. In order to achieve effective leaching, cyanide concentration, expressed as 100% NaCN, needs to be maintained at minimum level. The minimum level is typically 120 ppm in the last leaching vessel [50]. To obtain the specified concentration in the last leaching vessel, a typical initial concentration would range from 200 – 250 ppm [50]. Actual cyanide consumption rates will differ from one ore type to another, however, typical rates range from 150 – 550 g/t of 100% NaCN equivalent [50].

- Oxygen demand – Oxygen is a crucial leaching reagent as pulps may contain organic and inorganic components which may consume oxygen, and effectively reduce the overall leaching efficiency [50]. The use of air-agitated Pachuca tanks have an added advantage due to oxygen nearly always being enough due to vast quantities of air being used for agitation purposes [50].
- Agitation – Due to certain mechanisms in gold leaching, certain minimum agitation rates are required. There have been reported cases where agitation at low rates have resulted in poor leach recoveries [50]. Good mixing characteristics in a Pachuca tank entails maintaining a sufficient pressure in the tank [53]. Oxygen dissolves better at higher pressures and therefore maintaining a higher pressure may aid in delivering a higher a leaching recovery [53]. In cases where air agitation is used as primary form of mixing, it is essential to maintain optimum operating pressure (may differ according to plant size and demand) to ensure an efficient leaching recovery.
- Residence time – Varying residence leaching times will be required depending on whether the treated ore is a low-grade material or high-grade material. Typical residence times vary from 12 – 48 hours [50].
- Pulp density – Pulp density affects viscosity by considerable amounts and influences gold leaching. It is shown that pulp densities being too high, as well as densities being too low, can negatively impact leaching performance [50]. Overly-dense pulps hinder mass transfer whilst diluted pulps may result in a loss of ore residence time and high reagent addition rates [50]. A compromise between the effects must be achieved and a w/s (water/solids) ratio of 1 – 1.1 has been proved to be effective [50].

Various models have been developed to assist in obtaining the parameters needed for a specific plant operation [54]. The primary objective of model development and fitting is to calculate the minimum residence time required to obtain economically-optimal leach recovery. Modelling such scenarios are difficult due to batch leaching data being noisy and inconsistent toward the end stages of the leach [50].

Parameters affecting adsorption

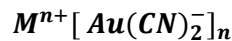
The fundamental physical and chemical parameters of adsorption play a vital role in the CIP process as it occurs sequentially after the leaching process. The equilibrium capacity of activated carbon for the adsorption of gold is affected by, but not limited to the following [55]:

- Temperature,
- The raw material nature used in the manufacturing of the carbon,
- The activation condition used during carbon manufacture,
- The pH value,

- The free cyanide and spectator ions concentration. Free cyanide examples include Ca^{2+} , Na^+ and K^+ ,
- The influence of organic solvents such as acetone, ethanol and acetonitrile, and
- The influence of organic and inorganic foulants such as xanthates and calcium carbonates.

Gold adsorbs onto the activated carbon as the ion pair showed in Equation 5:

Equation 5: Ion pair adsorbed onto activated carbon [50]



Where:

- M^{n+} represents the appropriate metal ion such as Ca^{2+} , Na^{2+} or K^+ . The aurocyanide is only transformed into AuCN or metallic gold by high temperatures, a strong acid, or a combination of both parameters.

Parameters affecting the kinetics of adsorption include [50]:

- Carbon particle size. The smaller the carbon particle size, the higher the adsorption rate.
- Temperature.
- The surface coarseness of the carbon, affecting the film transfer coefficient for adsorption.
- The internal surface and pore diffusion properties, which will be affected by the physico-chemical properties of the carbon, which in turn is influenced by raw material properties.
- The in-pulp agitation degree in where the adsorption is taking place. Adsorption in industrial applications is restricted by film transfer. It is, therefore, expected that an increase in agitation efficiency will lead to improved adsorption rates.
- Oxygen concentration in the pulp.
- The pH of solution. The lower the pH, the stronger adsorption will take place.

Conclusion

Due to the complexity and interactive nature of these discussed processes, a good understanding of the factors influencing the processing steps is essential. Developed process engineering methodologies can be used to establish an appropriately designed and cost-effective plant.

Various production enhancement techniques have been investigated in the past to aid and assist in enhancing plant profitability. This dissertation will attempt to prove whether higher and more constant delivery pressure to leaching tanks (for agitation purposes) can be used as one such technique.

1.4.1 Recovery enhancement techniques

Various studies to enhance production of gold through the optimisation of a variety of the systems and parameters contributing to the cyanidation process were investigated to strengthen the need for the study.

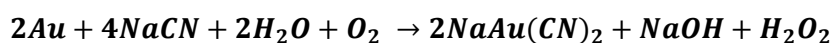
Study 3: Biological gold recovery from gold-cyanide solutions

The concept of biological recovery consists of using naturally occurring soil microorganisms to recover gold from ore. Microbes are used to release gold cations from aurocyanide complexes, after which the gold is captured on iron and zinc electron donors [56]. Cyanide can be produced by a variety of bacteria, fungi and algae. These species release substantial amounts of inorganic cyanide upon decay. HCN is a colourless gas with a weak almond odour, where sodium and potassium cyanide are both white solids. The aforementioned cyanide compounds' uses include [56]:

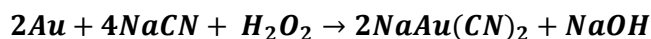
- Electroplating,
- Metallurgy,
- Chemical production,
- Photographic development,
- Plastic manufacturing,
- Ship fumigation, and
- Mining processes such as gold ore processing.

Stable ferricyanides and less stable free cyanides are present in the effluents of gold milling operations. In addition to the aforementioned compounds, thiocyanates (CNS^-) are normally present post-dissolution of metal sulphides. As the cyanide comes into contact with the milled gold ore, it dissolves the gold and forms gold cyanide complexes according to the following equations [56]:

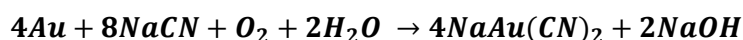
Equation 6: Gold cyanide complex #1 [56]



Equation 7: Gold cyanide complex #2 [56]



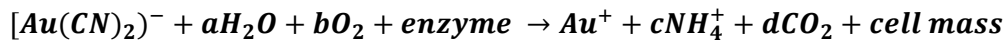
Equation 8: Gold cyanide complex #3 [56]



Oxygen is needed for the dissolution of gold, as can be seen from all three dissolution complexes above. The major mechanism of gold is considered as the first complex, whereas the second complex is seen as minor. The dissolution rate depends on various factors including cyanide concentration, pH, and temperature. The addition of biological treatment of cyanides have previously been successfully applied

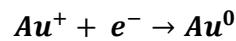
to various industrial processes [56]. The complexes above will be biologically altered when adding microorganisms to the gold cyanide reactions, as the organisms possess an enhanced capacity to break down free and metal cyanides. The study, therefore, relied on the developed hypothesis that the CN^- can be degraded by the added bacteria. The aurocomplex decomposition is believed to result in the release of Au^+ since the oxidation state of gold in the aurocomplex is:

Equation 9: Oxidation state of gold in the aurocomplex [56]



The gold ion should vigorously seek an electron, due to its galvanic properties, from close surroundings and be stabilised to its metallic form according to Equation 10 below.

Equation 10: Reduction half reaction [56]



Iron and zinc are placed low on the galvanic series and can be used as appropriate electron donors, where the reduction reaction takes place and the metal gold can plate the donor's surface [56]. The goal of the study was, therefore, to investigate the recovery of gold from pregnant solutions using cyanide degrading microorganisms [56].

The success of microorganisms degrading cyanide solutions was determined by altering the pH level normally found in milling operations from the typical 10-12 pH level, to a level of 8. This was due to the microorganisms preferring a lower pH than found in normal milling operations [56]. In order to provide oxygen to the aerobic organisms, a closed reactor system consisting of permeable silicone tubing to supply molecular oxygen was used. A visual depiction of the system can be seen in Figure 8.

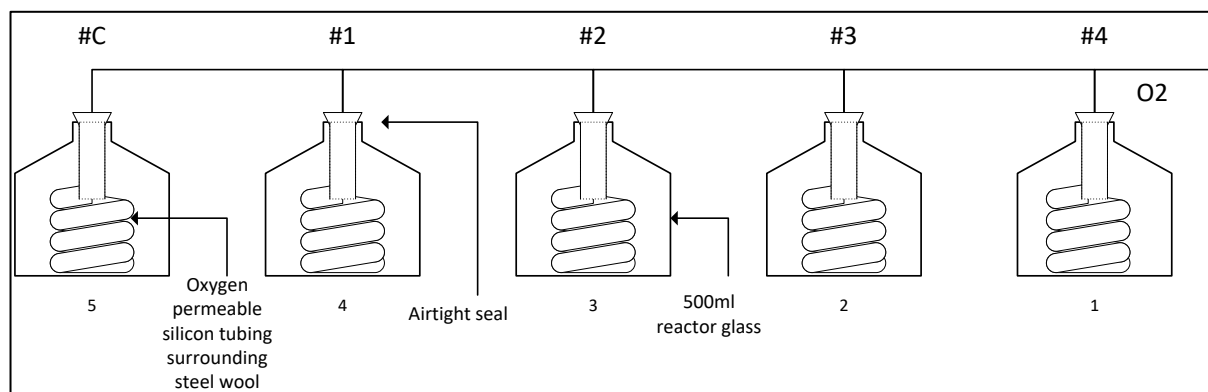


Figure 8: Closed reactor system consisting of permeable silicone tubing [56]

The five Erlenmeyer flasks with rubber stoppers were used as “reactors” for the microbial enrichment experiments. The reactors were labelled 1-4 and “C”, which represented the abiotic control reactor. Glass ports were added to the stoppers to connect the silicon tubing [56]. Reactor #3 had 1.5 m of silicone tubing compared to the other reactor which only had 1 m of tubing. This was done to determine whether the silicone amount had an effect on gold recovery. Both ends of tubing were connected to the glass ports within the reactor. A series setup was chosen to accompany aeration system flow [56]. Soil from Fort Knox gold mine tailings was collected and used within the reactors. The soil chosen had to fulfil the following criteria [56]:

- Soil must be exposed to cyanides for a prolonged period of time.
- Soil must have some biological activity indications.

Upon assessing the plants close to the selection spot, it was determined that biological activity is present [56]. Soil was also obtained from the Ryan Lode mine, F-heap leachate pond. The F-heap was known to have been exposed to cyanide for many years and when analysed indicated biological activity. All except two vessels were inoculated with both soil types collected. All the reactors were buffered with a dibasic potassium phosphate, controlled up to a pH of 8, and was fed with a cyanide solution to uphold the CN^- level between the specified limit of 30 and 80 mg/L CN^- [56]. It was observed that the reactors containing only the Ryan Lode soil displayed cyanide degradation rates of ranging from 0.8- 1.3 mg/L.h. The concentration of ammonia (nitrogen) was thoroughly monitored during the enrichment period. When the $\text{NH}_3\text{-N}$ concentration reached 90-100 mg/L, volumes within each reactor were halved and replaced with tap water to prevent potential ammonium poisoning of the biomass [56].

A hypothesis test was performed where a reactor vessel was treated with gold pregnant solution rather than a barren cyanide solution. A steel wool strand was suspended in the reactor for three days before extraction from the container [56]. The suspended strand was compared to a strand of steel wool not exposed to a gold pregnant solution. The strand exposed to the pregnant solution was coated with gold. The enrichment contained microorganisms that were both cyanide degraders and cyanide tolerant. After the hypothesis tests were conducted, the experimental procedure began [56].

Experimental procedure

After a successful cyanide degrading microbial enrichment in all five prepared vessels, reactor #C was dosed with 1.04g of sodium azide (NaN_3) with sole objective to kill microbiota for abiotic control purposes [56]. The remaining reactors were left unsterilised. The bottom soil was removed from reactor #2 preceding the experiment to eradicate additionally added surface available for gold precipitation. The soil was also removed to determine if it is essential as a growth substrate or supply of nutrients. Marble-sized bundles of steel wool packets, suspended within the liquid phase, were added to the vessels to provide an electron donor for the gold cation [56]. For 21 days, the reactors' pH were

monitored and buffered to values of 8-8.5 with potassium phosphate dibasic solution when the pH dropped below this level. The reactors were fed with a total of 2-4 mL of gold pregnant solution, depending on the specific reactor's concentration during this period [56].

After 21 days, the experiment was ended, steel wool from each reactor was removed and dissolved in a known volume of aqua regia for analysis (mixture of concentrated nitric acid and hydrochloric acids used to purify gold [57] [58]), and an atomic absorption method was used to quantify the concentration of gold. Table 2 portrays the results of the experiments.

Results

Table 2: Results of the atomic absorption method used to quantify gold concentration [56]

Experiments					
Reactor	Volume (L)	Pregnant solution added (mL)	Pregnant solution gold concentration (mg/L)	Total gold added (mg)	Total recovered gold
#1	0.5	4	9037.39	36.15	42.97
#2	0.5	3	9037.39	27.11	31.47
#3	0.5	4	9037.39	36.15	40.95
#4	0.5	2	9037.39	18.07	23.53
#C	0.5	3	9037.39	27.11	31.24

The mass balance shows that approximately 20% more gold was recovered than added in all the reactors. An explanation may be the “background” soil used as an inoculate in each vessel. The reactor (#2), where the soil was removed, also shows a 10% increase in gold added. The control reactor (#C), showed an increase in gold added, however, no bacteria were active to release the gold from the cyanide solution [56]. While little gold was recovered on the steel wool and some solids remained in the reactor, most of the added gold remained in liquid phase. Approximately 1.4 mg (4%) of the recovered gold was associated with the soil. The gold recovered on the steel ranged between 2.9 - 12.5% due to the strength of the microbial enrichment. The silicon tubing surface area did not influence the recovery due to the results from reactor #3 not differing significantly from the reactor #1 and #4 [56]. The cyanide concentration was undetectable prior to the completion of the experiments which led to the conclusion that the gold may be complexed in biomass or another organic form.

Conclusion

Naturally occurring cyanide degrading bacteria is more commonly found in soil from sites exposed to high concentrations of cyanides for prolonged periods of time. It was observed that the reactors with soil from the Ryan Lode heap (which was in operation from 1987-1990) grew biomass at higher rates than soil taken from the Fort Knox heap (since 1996) [56]. The results show that enhancing gold recovery, and ultimately production, through carefully controlled bioleaching processes is possible. The process needs to be carefully monitored to ensure the key performance parameters, such as the pH of the solution, operate at the correct values. This production enhancing technique is difficult to implement on a large scale and is not as commonly used in industry.

Study 4: Improvements in gold ore cyanidation by pre-oxidation with hydrogen peroxide

The presence of sulphide minerals in gold ore cyanidation is known to cause increased oxygen consumption supplied within the injected air. This results in dissolved oxygen (DO) starvation for oxidative leaching of gold and would reduce the maximum amount of gold recovery attainable from the processed ore. The presence of sulphides leads to added consumption of cyanide leaching agents, which adds to production costs [59]. Sulphide containing gold ore may be pre-treated, preceding cyanidation, by adding an oxidation step. This step entails conversion of the sulphides into oxides. The treatment leads to a DO consumption reduction, reduction in cyanide during the cyanidation step, and is hypothesised to improve gold recovery [59].

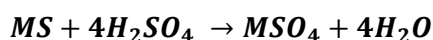
A study was conducted on AngloGold Ashanti's Serra Grande gold plant to establish if improvements in gold recovery were possible by addressing the leaching kinetics. The leaching circuit consisted of three in-series tanks for an alkaline pre-oxidation leaching step using compressed air and lime, followed by tanks 4-14, which are aerated and mechanically agitated and used for cyanidation purposes. The ore feeding the leaching tanks averaged a gold grade of 1.7 g/t. A main oxygen consuming parameter was established as the sulphide mineral pyrrhotite (FeS) at 2.5% w/w [59]. Pre-treatment aims to improve the oxygenation along the cyanidation circuit, with the end goal of improving gold recovery.

A dosing system consists of a centrifugal pump for fast and efficient hydrogen peroxide (H₂O₂) delivery, which is diluted with water at a 1:10 ratio [59]. H₂O₂ is an aqueous liquid oxidant with a redox potential of 1.8 V, which is higher than oxygen at 1.2 V [59]. It can oxidise sulphides found in a gold ore slurry according to Equation 11 and Equation 12.

Equation 11: Hydrogen peroxide oxidising sulphides to form sulphates [59]

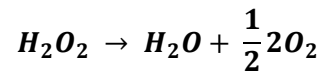


Equation 12: Hydrogen peroxide oxidising sulphides to form sulphates [59]



H₂O₂ can decompose spontaneously into water and oxygen according to Equation 13.

Equation 13: Spontaneous decomposition of hydrogen peroxide [59]



Before conducting the experiments, a few process parameters needed to be identified, and trial tests had to be run in order to obtain accurate results through constant monitoring of the correct parameters.

1. **Process parameters survey prior to H₂O₂ pre-oxidation trial** - The ore feeding the leaching circuit was examined for a period of five days to determine the oxygen uptake rate. DO, pH, and cyanide were also measured before and during the trial testing. Probes and equipment were used in unison with ordinary calibration procedures. The H₂O₂ addition was found to reduce the pH slightly (less than 0.3) at the end of the pre-oxidation time. The lime dosage was altered to ensure the pH was kept at 10.5. The operating range chosen for the H₂O₂ feed was based on the results of the trial tests [59].
2. **Dissolved oxygen and NaCN profiles monitoring** – Tanks 1,2, and 3 were only used for pre-oxidation. The results showed that the DO profile is classified as “low” in tanks 1 – 3, fluctuating between 0.5 – 1 ppm. Sodium cyanide (NaCN) was first introduced in tank 4 averaging at a normal 250 - 400 ppm when measured. The very low DO content of tanks 1-3 indicates insufficient oxidation in the tanks [59].
3. **Industrial-trial settings** – The H₂O₂ supply method consisted of a 50% H₂O₂ solution (diluted at 1:10 with water) being pumped into the pre-oxidation tanks using a dosing skid in combination with a centrifugal pump and flow meter. H₂O₂ dilution with water was done in the main feed pipe, which split equally into three in-series tanks [59]. A monitoring schedule for the following parameters was set up for each documented shift [59]:
 - Flow rates of H₂O₂ in L/hr,
 - Concentration of the DO in all tanks,
 - Concentration of the NaCN (ppm),
 - Gold leach feed content (g Au/t),
 - Gold content of solid tailings (g Au/t), and
 - NaCN consumption.

Results

The industrial-scale tests commenced with a base feed of 45 L/hr of H₂O₂ solution, diluted with water prior to distribution to the three pre-oxidation tanks. Throughout the entire measurement period of five

months, only the three pre-oxidation tanks were exposed to direct injection of H_2O_2 solution. The H_2O_2 flow rates were determined according to Table 3.

Table 3: H_2O_2 feed during the testing period [59]

<i>H_2O_2 feed during testing period</i>		
Period (days)	Flow rate (L/hr)	Average DO in tanks 1, 2 and 3 (ppm)
Prior to pre-oxidation	0	<1
1 - 15	45	2.9
16 - 21	55	4.2
22 - 32	80	8
33 - 150	60	7.2

After cost evaluation of different H_2O_2 rates, a fixed dosing rate of 60 L/hr was chosen at day 32. The dosing rate corresponds to a value of 0.24 kg of 100% H_2O_2 per ton of dry ore. Faster and more efficient oxidation of cyanide-consuming sulphidic species were noted due to higher levels of DO and H_2O_2 in the pre-oxidation tanks [59]. The species used cyanide as a complexing agent and was inactivated in the first tanks of the circuit (Tanks 1-3), resulting in reduced NaCN consumption compared to historic data from the previous three years. During the five-month period prior to the industrial tests, the average cyanide consumption was measured as 0.52 kg/t and fell to 0.4 kg/t during the peroxide pre-oxidation trial [59]. The NaCN consumption underwent a reduction of approximately 23%. Table 4 shows the gold ore feeds and recoveries prior to and during the industrial test phase, where the last mentioned was month 6-10 [53].

Table 4: Average percentage gold feeds and recoveries before and after pre-oxidation with H_2O_2 [59]

Average % gold feeds and recoveries before and after pre-oxidation with H_2O_2			
Month	% Gold ore feed	% Gold leach residue	Recovery (%)
1	3.17	0.323	89.8
2	3.56	0.238	93.3

Average % gold feeds and recoveries before and after pre-oxidation with H_2O_2

3	3.09	0.273	91.2
4	3.01	0.277	90.8
5	3.54	0.297	91.6
6	3.27	0.258	92.1
7	3.34	0.276	91.7
8	3.25	0.224	93.1
9	3.61	0.275	92.4
10	3.83	0.271	92.9

A combined graph of the NaCN consumption and gold recovery is portrayed in Figure 9.

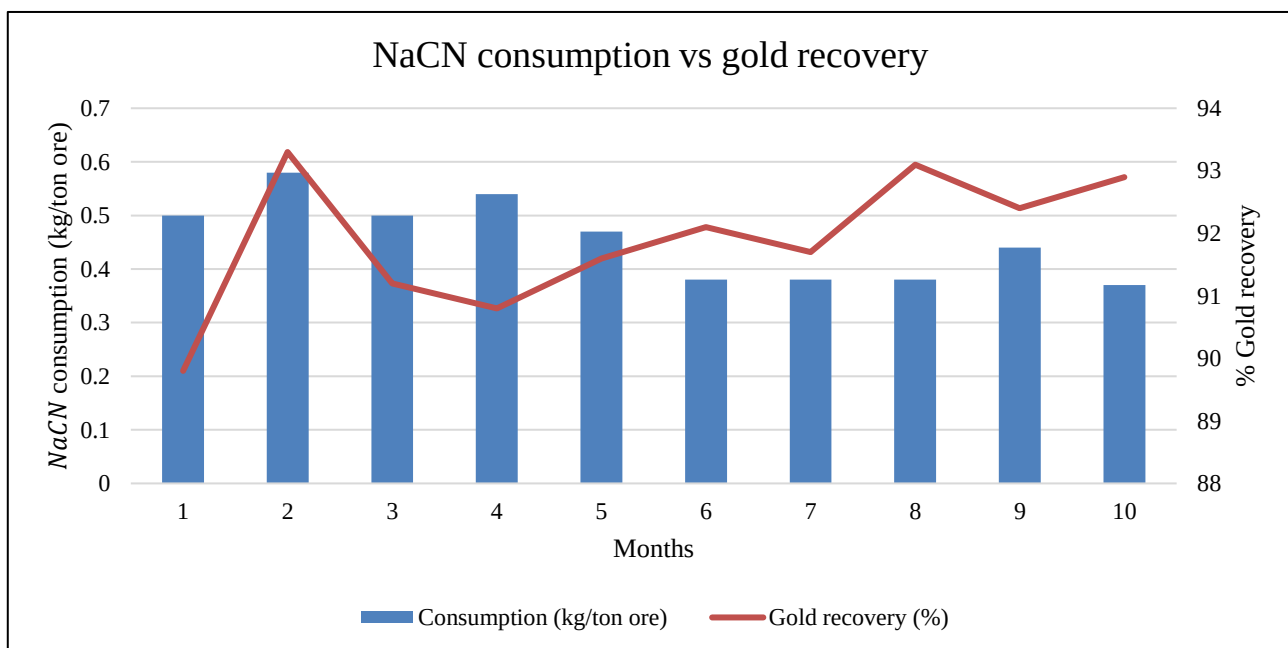


Figure 9: Graph of NaCN consumption vs gold recovery [59]

Despite unavoidable variations in metal recovery, which can be allocated to changes in the physical characteristics of the ore being fed to the leaching unit, the average gold recovery increased from 91.3% to 92.5%. The cost of adding peroxide is more than offset by the reduced NaCN consumption. A

diagnostic analysis of tailings portrayed a reduction in the gold content amenable to cyanidation from an average of 0.144 g/t (prior to pre-oxidation) to 0.107 g/t (after pre-oxidation) [59].

Conclusion

The effect of adding a 50% diluted H_2O_2 solution to a slurry of sulphide-containing gold ore (2.5% w/w FeS) had the following results:

- Increases in the average concentration of DO in the pre-oxidation tanks from 1 – 7.2 ppm [59].
- Reduced NaCN consumption in the circuit from an average of 0.52 kg/t ore to 0.40 kg/ton ore. Decreased NaCN can have substantial financial benefits considering the price of cyanide used in the industry [59].
- An average metallurgical recovery increase from 91.3 to 92.5 % [59].

Study 5: The importance of controlling oxygen addition during the thiosulfate leaching of ores

This study is mentioned in the literature review due to its relevance to oxygen addition, which is added in the case of agitation by means of using compressed air [60]. The study was conducted to enhance production and was used in Table 7 as comparison. Various other aspects covered in the study had too little relevance to the research conducted in this dissertation to be summarised in the literature. The summary of the study can be viewed in Appendix A [60][86][87][88].

Study 6: Gold losses due to silt formation in gold leaching tanks

Siltation involves accumulation of sediment materials over time, which can occur in closed systems such as leaching tanks [33]. Particle size analysis, slurry settling rates, and agitation efficiency analysis were used to identify contributory factors of siltation. The mitigation measures were determined by deflocculation tests and grinding analysis [33].

Most mineral extraction processes start with comminution to release the mineral of interest. Comminution is the progressive size reduction of an ore to a suitable size range to extract the mineral from the worthless gangue, or shorten the reagent travel distance during the leaching process. Most plants operate on a high tonnage throughput principle and leaching is consequently conducted at pulp densities in excess of 50% solids instead of conventional values of 40% and 45% [33]. The classifier overflow material is prepared for leaching by passing through a thickener to obtain a suitable feed density of 50% solids. The thickening process requires flocculants which may have a carry-over effect causing settling or siltation within the leaching tanks. Coarse materials present in circuits affect particle suspension due to the smaller surface area and higher drag forces of the particles in a turbulent flow regime [33]. The effects cause the particles to gravitate to the bottom of a containing vessel due to gravitational forces. Significant amounts of ore accumulate at the bottom of the leaching and is lost for further processing [33]. Coarse gold particles present in leaching tanks gravitate towards the bottom of

the tank due to the beforementioned drag forces and get locked up in the already silted material [33]. Some locked up coarse gold materials can possess a head grade as high as 53 g/t [33]. The causative factors of silt formation in the Carbon-in-Leach tanks of the Tarkwa Gold fields plant in Ghana was investigated [33].

Resources and methods

The samples used in the study were Semi Autogenous Grinding (SAG), mill cyclone overflow product (MCO), ball mill feed (BMF), ball mill cyclone overflow product (BMCO), pre-leach thickener feed (TF), leach feed, and silt material collected from the processing plant of Gold Fields Ghana [33]. The dimensions of the tank from which the silt material was collected is 17.1 x 15.8m (height x diameter).

A settling rate test, deflocculation test, screen-, agitator efficiency- and grind analyses were conducted to determine the results of the study.

Screen analysis

Wet-screening was done on four randomly selected silt material samples to calculate the particle size distribution (PSD) of the materials. The screen test used was constructed according to the Tyler series, with 6700 μm as the coarsest screen aperture size, whereas 106 μm was the lowest [33]. Overflow samples from a ball mill cyclone composited over a two-week period, was wet-screened using the 106 μm aperture size screen to determine the percentage passing [33].

Settling rate test

Settling rate tests were done on the SAG and ball mill cyclone overflow samples [33]. The thickener feed was placed in a graduated 1000 ml cylinder for 40 minutes and monitored for a slurry boundary change in 30-second intervals [33]. Settling velocities, together with a standard sample milled to 80% passing 106 μm were determined [33].

Agitation efficiency analysis

Measurements from fresh and a worn-out agitator blades were taken using specially designed engineering tape. A visual observation was done in a drained tank containing the accumulated silt material [33].

Grind analysis

Samples of ball mill feed, consisting of the SAG mill cyclone underflow and ball mill cyclone underflow, milled at 65% pulp represented the milling pulp density of the plant [33]. The samples were milled for periods of 5, 10, 15 and 20 minutes [33]. The initial passing percentage of the 106 μm aperture from the ball mill sample was estimated using wet screening. The final milled products used were wet screened and a 106 μm passing percentage was estimated [33].

Deflocculation test

A kilogram dry weight of a leach feed sample, having a PSD (particle size distribution) of (+220 μm - 75 μm), was pulped to 56% to get material with similar pulp densities to the plant material. 60-minute settling tests were done without flocculation and slurry boundary changes noted every two minutes [33]. This served as a control boundary for the following experiment, which was replicated using a caustic deflocculant at various concentrations for a specified period of 60 minutes. The slurry boundary was monitored in intervals of two minutes [33].

Results and discussion

Screen analysis of the silt material

The PSD of the silt material was analysed and can be seen in Figure 10.

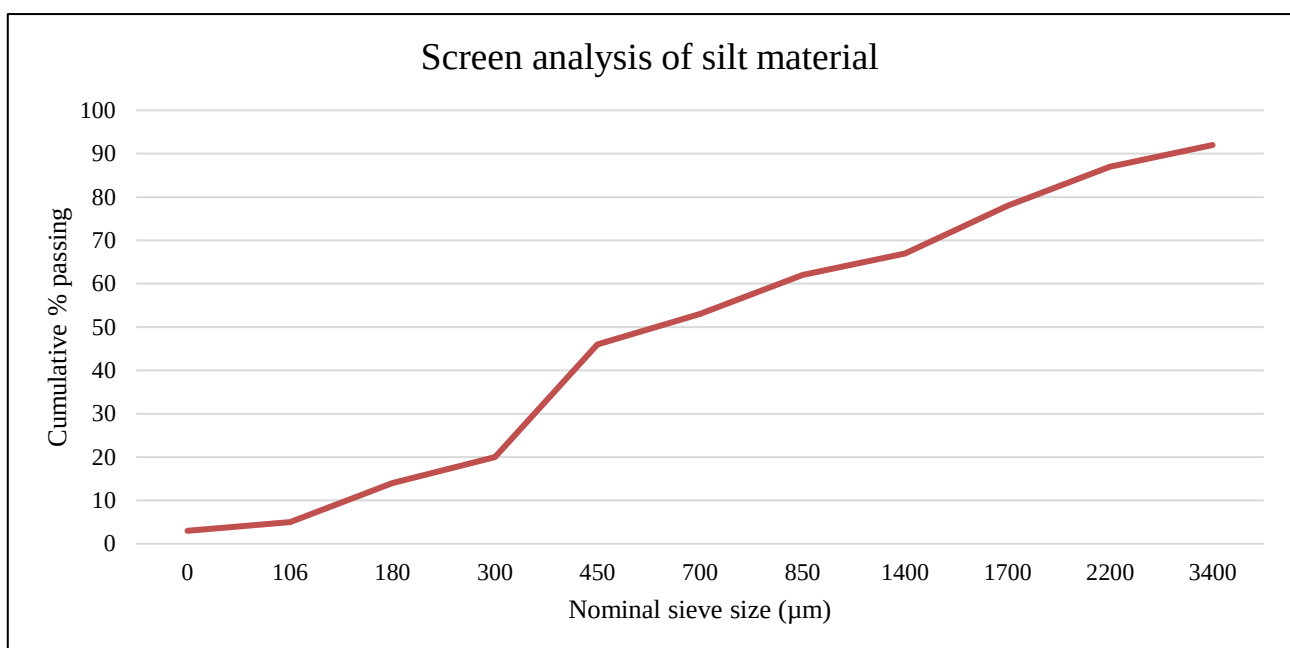


Figure 10: Graph of the PSD of the analysed material [33]

The results reflect the numerous size ranges of particles in the silt material processes. The coarse nature of the particles indicates the poor grinding process [33]. The 80% passing size of the material was estimated at 1700 μm , which is relatively higher than the reference design size range of 106 μm for leaching operation [33]. The silt material particle size ranging above 106 μm is estimated at 94%. The coarser particles may impact particle suspension negatively, thus reducing the agitation efficiency due to high drag forces, causing high settling velocities leading to siltation [33].

Screen analysis of the ball mill cyclone overflow

Proceeding a 14-day testing period, the passing percentage of the 106 μm aperture for the ball mill cyclone overflow indicated 67% of the feed particles had sizes less than the reference size of 106 μm . The value obtained was less than the specified design size, defined as 80% passing 106 μm [33]. The

results show that only two out of the fourteen samples taken, were within the design leach feed. Due to increased particle size in the leaching tanks, unnecessary pressure is placed on agitators creating suspension inefficiencies and enhanced feed particle siltation [33]. The obtained results are shown in Figure 11.

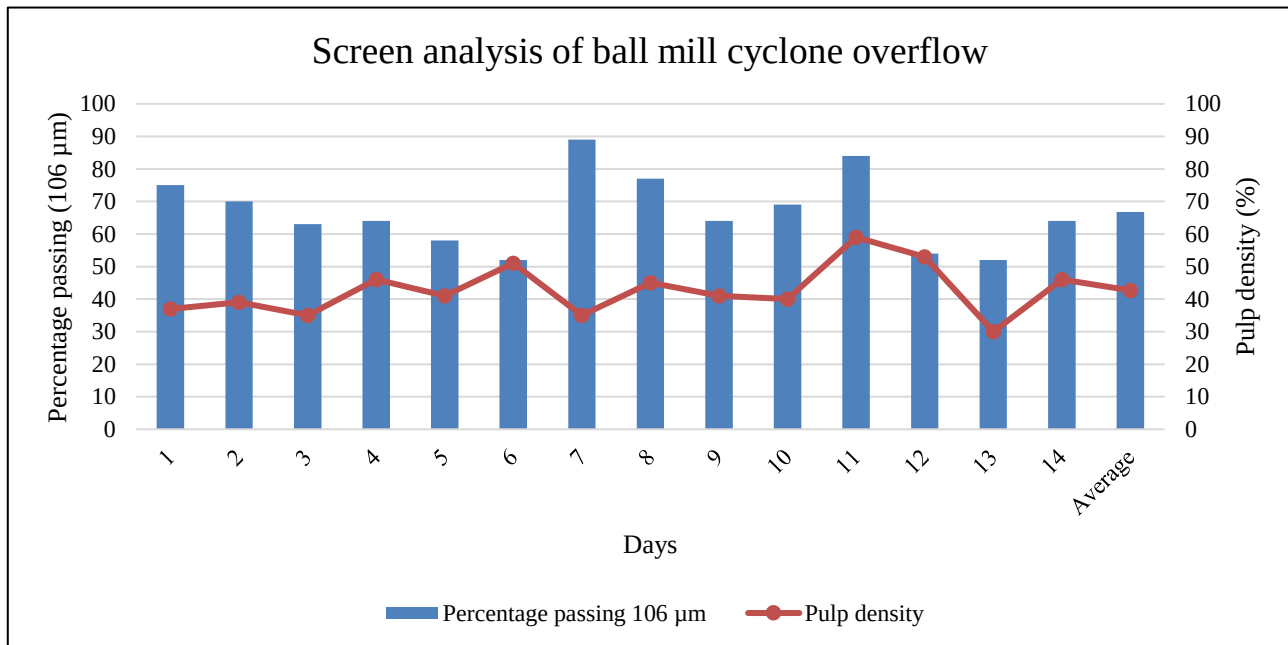


Figure 11: Graph of the screen analysis from the ball mill cyclone overflow [33]

The abrasive nature of the cyclone overflow can be allocated to numerous factors which includes the following [61]:

1. Short residence time of materials fed into the ball mill due to decreased gold grade or gold prices, causing management to resort to high tonnage processing with a constant residence time to meet target tonnages [61].
2. Ineffective classification by cyclones due to high feed tonnages and cyclone pressures, which on occasion can exceed plant design values [61].
3. In cases of severe wear, the mill liners can also affect grinding efficiency [61].

Settling rate test

The settling rate test consisted of investigating the relation of settling velocity and particle siltation in the BMCO, TF, and SMCO. The average settling velocity of all investigated systems was high compared to the standard feed particle size with 80% passing 106 µm. The results were monitored over a two-hour period and the results obtained can be seen in Figure 12.

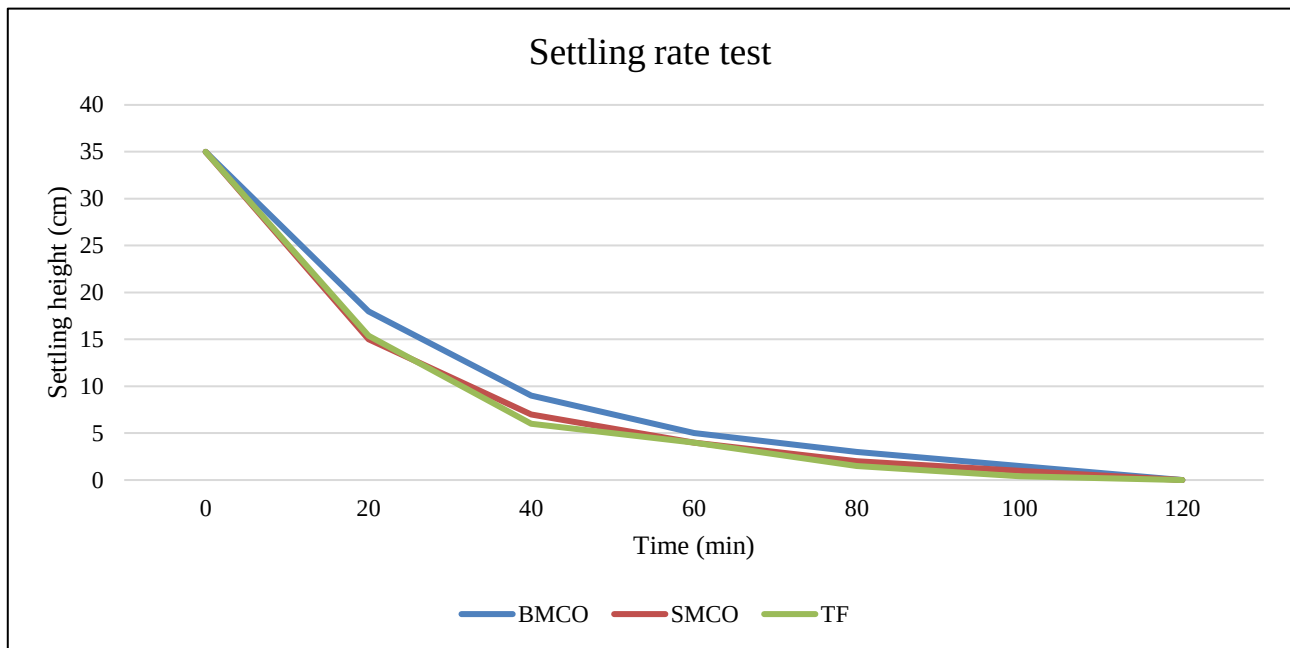


Figure 12: Graph of the settling rates for the BMCO, SMCO and TF systems [61]

The settling velocity of the BMCO was the highest, followed by the SMCO and the TF. The BMCO settling velocity was due to the coarse nature of the particles with a 67% 106 μm passing rate. Settling is enhanced to the higher drag force present in the particles [62]. The SMCO was expected to show low settling velocities, but showed a high settling velocity irrespective of the 94% 106 μm passing size. This may be due to high pH values documented at the milling unit, further inducing negative charge densities and revoking the repulsive forces causing them to sediment at a faster rate [63]. The TF is a mixture of BMCO and SMCO and showed a higher than expected settling velocity, due to flocculation, producing interparticle polymer bonds, creating higher drag forces. The results are shown in Figure 13.

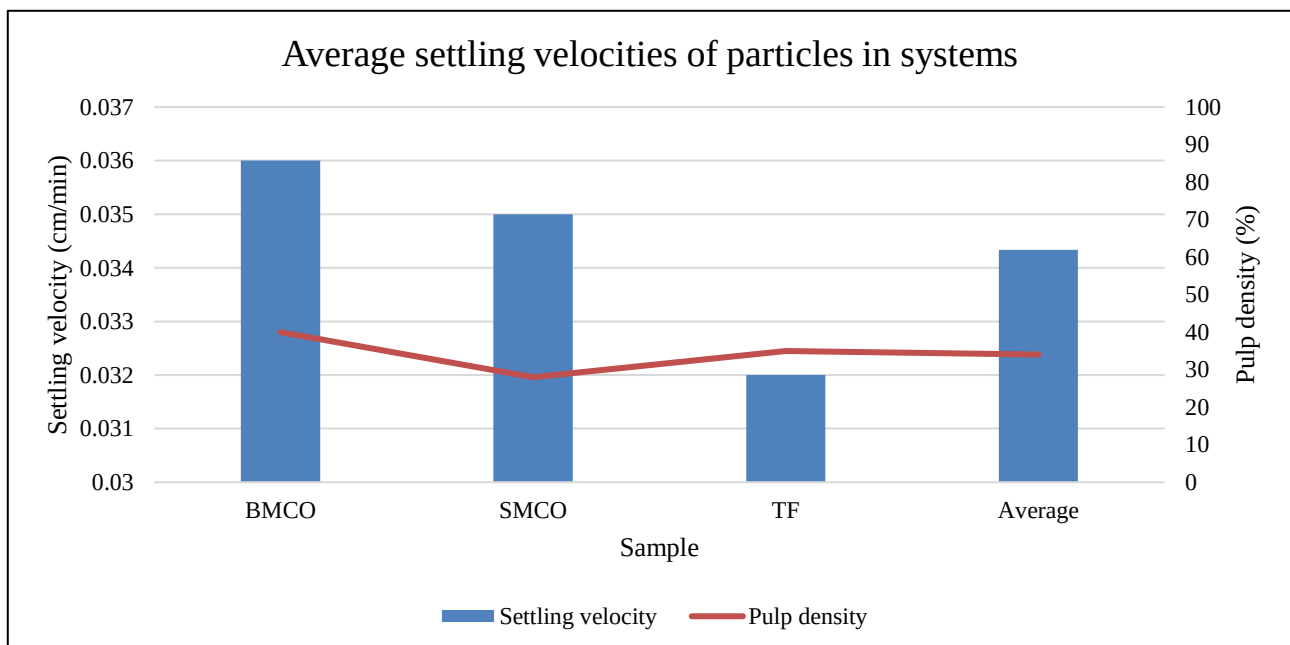


Figure 13: Graph of the average settling velocities for the BMCO, SMCO and TF systems [61]

When sending high drag force material to leaching tanks, it is prone to create more agitation inefficiencies which can lead to siltation.

Agitation efficiency analysis

The off-bottom distance of the agitator was measured as 5.8 m. For maximum off-bottom suspension of solids, the impeller location of 33% of the impeller diameter can be used [33]. The impeller diameter measurement at the plant chosen for the study was 5.2 m. Literature recommends it to be 1.7 m, but the off-bottom was measured as 5.8 m [33]. The off-bottom is approximately three times more than it should be, affecting the mixing efficiency. By reducing the distribution of axial and radial forces introduced into the slurry by agitation means, some areas may be unmixed [33]. Feed particles consisting of higher settling velocities located below the required off-bottom distance are prone to settling, leading to siltation at the bottom of the tanks [33]. The other measured parameters are shown in Table 5.

Table 5: Measurements of the agitation tank taken for agitation efficiency analysis [33]

Measurements taken from agitation tank	
Parameters	Measurements (m)
Off-bottom distance of agitator	5.8
Diameter of the leaching tank	15.8
Height of the leaching tank	17.1
Freeboard of the leaching tank	0.6
Length of fresh agitator blade	2.6
Length of the worn-out agitator blade	2.3
Perimeter of the fresh agitator blade	6.6
Perimeter of the worn-out agitator blade	5
% wear of the agitator blade	24.3

Agitators tend to wear with time due to friction cause by feed material, reagents, and chemicals added to the tank. It is, therefore, crucial to monitor the wearing rate of impellers to ensure agitation efficiency is not significantly reduced [33].

Grind analysis

The initial 106 μm passing percentage of the circulating load at time zero was 13%. From the results it can be seen the passing percentage increased with time. The effect of the grinding residence time on mill product was investigated and results can be seen in Figure 14.

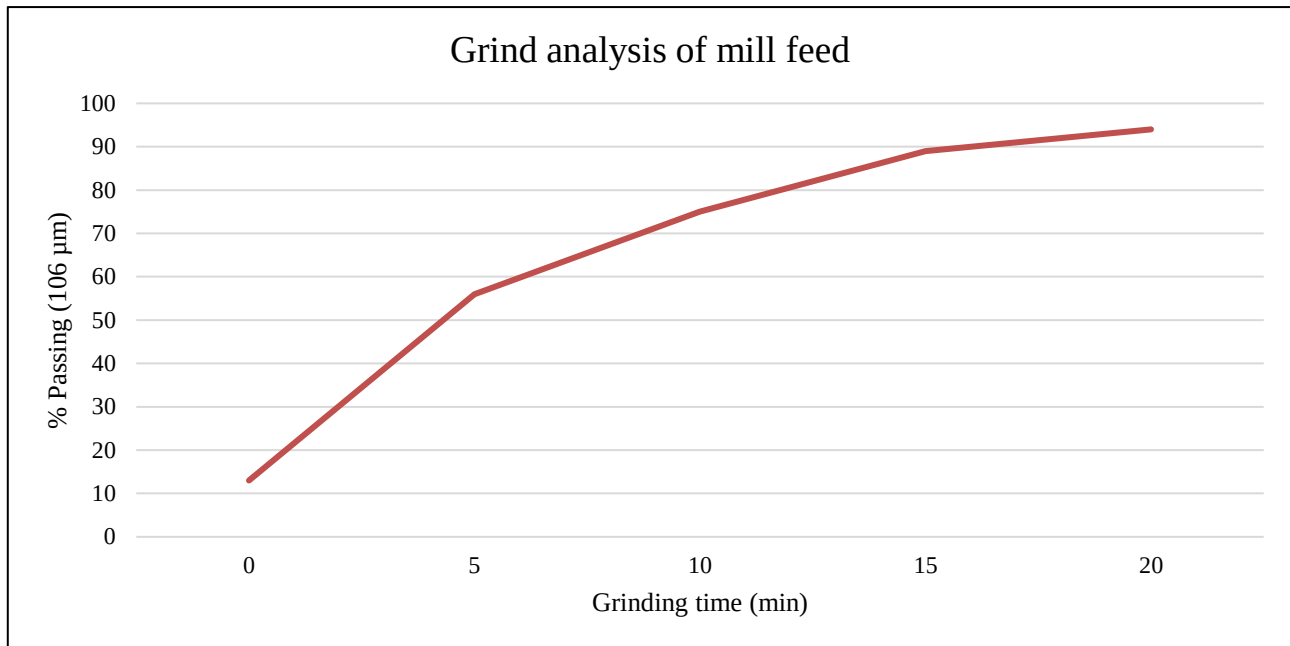


Figure 14: Graph of the grind analysis of the mill feed [33]

The trend observed is similar to research from [64]. The mill feed achieves maximum abrasion and impact from coarser feeds, steel balls, and liners causing reduction in particle size and an increase in particle breakdown efficiency [33]. Interpolation was used between 10 and 15 minutes to estimate the required time needed for 80% 106 µm passing [33]. The required time was estimated at 12 minutes and 22 seconds. Increasing the grinding time results in finer products and having lower drag forces. This would enhance particle suspension at an optimum pH level by the agitator in the absence of mechanical failure [33].

Deflocculation test

The deflocculation tests portrayed a decrease in settling velocities of the leach feed when adding caustic deflocculant [33]. This occurs due to a steric repulsion between the particles, which is created by the deflocculant, breaking the polymer bonds between the flocculants and feed particles. The deflocculant increases the zeta potential of the particles, which results in a decrease in attractive forces and an increase in repulsive forces [65]. This is due to the presence of the sodium ion in the deflocculant. The double electrical layer between the particles increases by being attracted to the negatively charged feed particles, creating repulsion between neighbouring particles [65].

This keeps the particles in a state of suspension. The settling curves obtained after the deflocculation tests can be seen in Figure 15.

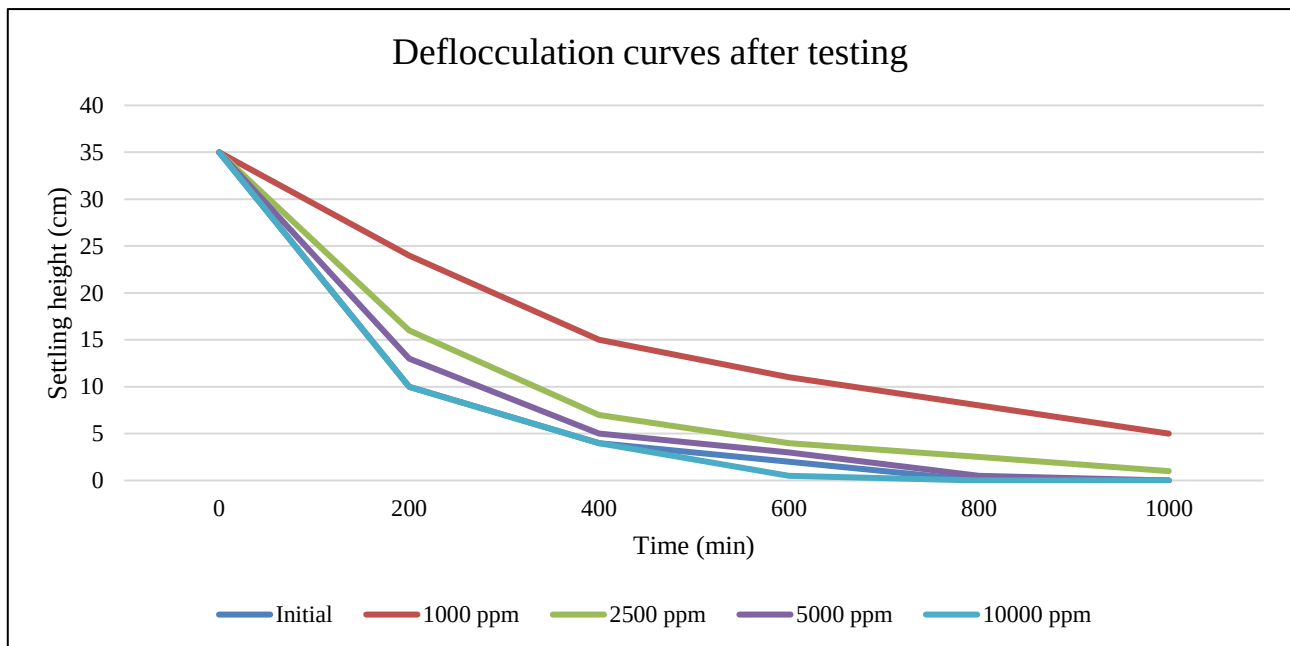


Figure 15: Graph of the deflocculation trends after testing [33]

Settling velocity reduced by 71% at 1000 ppm, with the velocity reduction decreasing with an increase in concentration [33]. The 10000 ppm sample settling velocity reduced by 14% due to higher solid percentage and deflocculant concentration leading to an overlapping and superimposition of the zeta potential of neighbouring particles [66]. The results obtained can be seen in Figure 16.

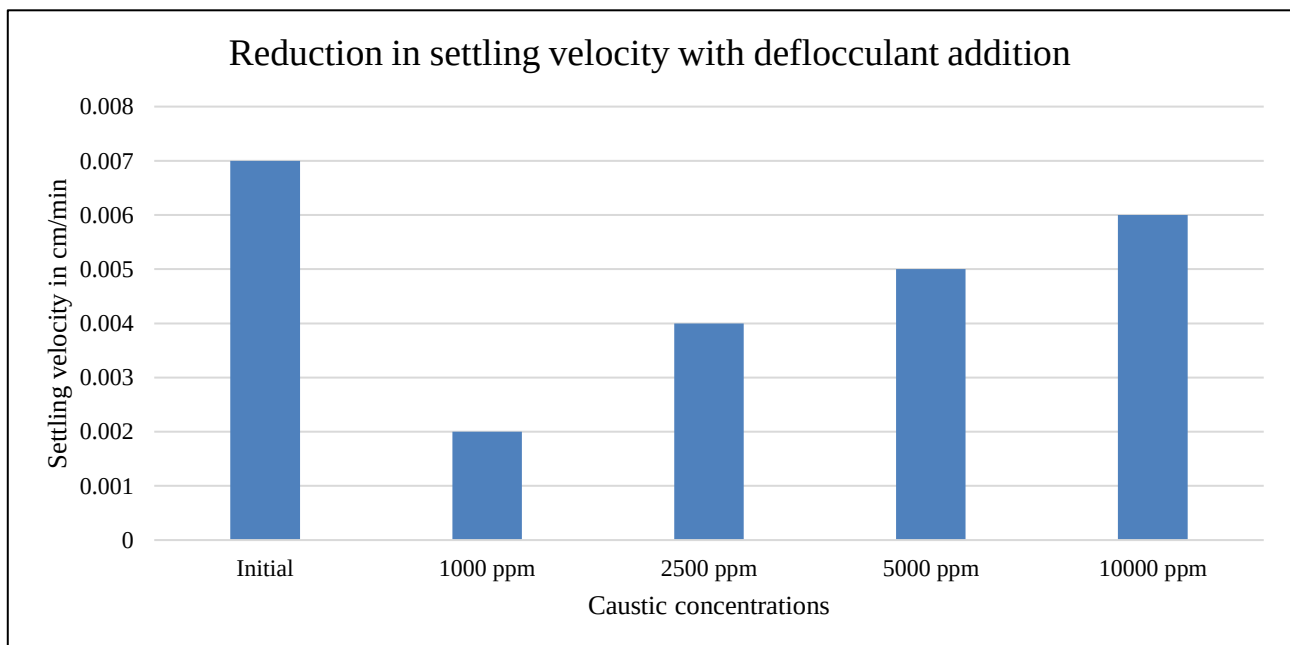


Figure 16: Graph of reduction in settling velocities after deflocculant addition [33]

Conclusion

From the investigations it can be concluded the major factors of siltation are [33]:

1. Inefficient milling and classification,
2. High settling velocities, and
3. Agitation inefficiencies.

The average passing percentage for the BMCO was 67% for the 106 μm aperture instead of the 80% design specification [33]. The average settling velocity was estimated as 5.67×10^{-6} m/s. The agitator efficiency was assessed by referring to its off-bottom distance, which was 5.8 m, three times higher than the distance specified in literature [33]. A drastic decrease in settling velocity, when caustic deflocculant was used, occurred at a 1000 ppm. Deflocculation and finer grinding can, therefore, be considered as the main mitigating factors considering the causative factors of siltation.

Study 7: Improving the process performance of gold cyanide leaching reactors

This study is included in literature review due to its relevance to oxygen addition in the form of compressed air, energy requirements due to different tank bottoms, gold loss due to the performance of the different tank bottoms and gas dispersion within the tank for efficient suspension of solids. The study was conducted to enhance production and minimise gold loss and was used as comparison in Table 7 Other aspects covered in the study had too little relevance to include the summary in the literature survey. The full summary of the study can be viewed in Appendix A [41][67][68][69][70][71][72][73].

Shortcomings of each study

Each study considered in this section added valuable contributions to the initiative researched in this dissertation. Each listed study provided an in-depth analysis of previous methods used to enhance production efficiency. By combining all the attributes in each study, efficiency on a gold plant can be substantially increased. The value of the studies to this dissertation, however, aims to identify the different approaches to efficiency enhancement and recognise the gap in literature. The value and shortcomings of each study is listed in Table 6.

Table 6: Table comparing the shortcomings of the listed studies from literature

Study	Gold mines	Production enhancement	Leaching	Compressed air influence	Plant specific	Siltation & settling
Study nr. 1 [29]	X			X		
Study nr.2 [50]	X		X		X	X
Study nr. 3 [56]	X	X			X	
Study nr. 4 [59]	X	X			X	
Study nr. 5 [60]	X	X	X		X	
Study nr. 6 [33]		X	X		X	X
Study nr. 7 [67]		X	X		X	X

1.5 Need for the study

The mining industry has been under continuous financial strain over the past couple of decades. One of the contributing factors of declining mine profitability is the constant rising energy tariffs implemented by Eskom. Various techniques can be applied to lighten the financial load placed on deep-level gold mines situated in SA. One such technique is to decrease energy consumption on large energy-consuming systems through implementation of energy saving initiatives. It is also critical to constantly attempt to increase production on the gold plant.

Various investigations to maximise production output on a gold plant have been conducted. The cyanidation extraction method is the most commonly used and requires compressed air delivery to leaching tanks for agitation purposes. Due to a shared compressed air network between the plant and the shafts on gold mines, fluctuating pressures are delivered to the leaching tanks. This could lead to an excessive amount of settled ore at the bottom of the leaching tanks, which accumulates as residue and contains unprocessed gold-containing ore. Very few studies have comprehensively investigated the influence of compressed air pressure on agitation efficiency. It is expected that an increased, non-fluctuating pressure delivery would allow for better agitation of ore in the leaching tanks, decreasing the amount of ore settled at the bottom of the tanks. The production and residue amounts need to be compared with normalised ore grades and treated tonnes quantities to determine the actual validity of non-fluctuating pressure delivery.

1.6 Study objectives

The study objectives will consist of the following:

- Identify and evaluate the compressed air network inefficiencies of a shared compressed air network between the shaft and plant.
- Develop a methodology to successfully determine the effects of a non-fluctuating, increased pressure delivery to the leaching tanks.
- Evaluate the effects of mentioned pressure delivery on gold production, gold grades, and residue quantities.
- Determine the important uncontrolled variables within the CIP process which may affect the results of the study. Identifying these parameters will also assist in replicating the study on a pilot-scale plant.
- Quantify the effect of the separate shaft and plant compressed air network.

1.7 Hypothesis

It is hypothesised that an increased pressure delivery to the leaching tanks will initially decrease the residue quantities in the leaching tanks and possibly increase gold production. After the initial respective decrease and increase, the profile is expected to stabilise due to the settled ore at the bottom of the tanks being processed and exiting the leaching tanks for further processing.

1.8 Study outline

The chapters contained in this study can be summarised as follows:

Chapter 1

This chapter introduces the study being conducted and contains information regarding the financial state of deep-level gold mines in SA. The challenges the South African mining sector are confronted with are discussed in this chapter and solutions to the problems are provided. Previous studies done on production enhancement strategies were analysed, and shortcomings of each were listed in order to validate the study being conducted in this document.

Chapter 2

Chapter 2 portrays the development of the research methodology used throughout the study. The methodology primarily entails identifying, evaluating, and addressing the effect of altering compressed air supply pressure on the production output of gold.

Chapter 3

Chapter 3 contains the developed research methodology application to an industrial-scale case study. A solution implementation strategy was analysed to ensure all identified objectives of the study were met. The results obtained from the solution strategy are discussed in this chapter.

Chapter 4

The results of the study are concluded in this chapter and compared to the identified objectives. The problem statement is addressed, and an overall conclusion regarding the study is made. Recommendations for further studies conducted on the subject will be addressed in the final chapter.

2. Methodology

This chapter focuses on the development of an investigation and solution strategy by using the research conducted in the preceding chapter. The methods used for the development of each step and how it will be implemented on a gold plant will be discussed. The main objective of the methodology chapter is to ensure the correct procedure is followed to enable the correct outcome of the study is obtained.

“Behind every method lies a belief. Researchers must have a theory of reality and of how that reality might surrender itself to their knowledge-seeking efforts. These epistemological fundamentals are subject to debate but not to ultimate proof.” - Shoshana Zuboff

2 Methodology

2.1 Preamble

This chapter provides a generic description of the methodology developed for this study and explains why the developed method is best suited to identify and resolve excessive settling of ore at the bottom of leaching tanks due to fluctuating pressures. The method of choice depends on various factors, specifically the nature of the research and the constraints of the study field. Figure 17 illustrates a simplified methodology layout.

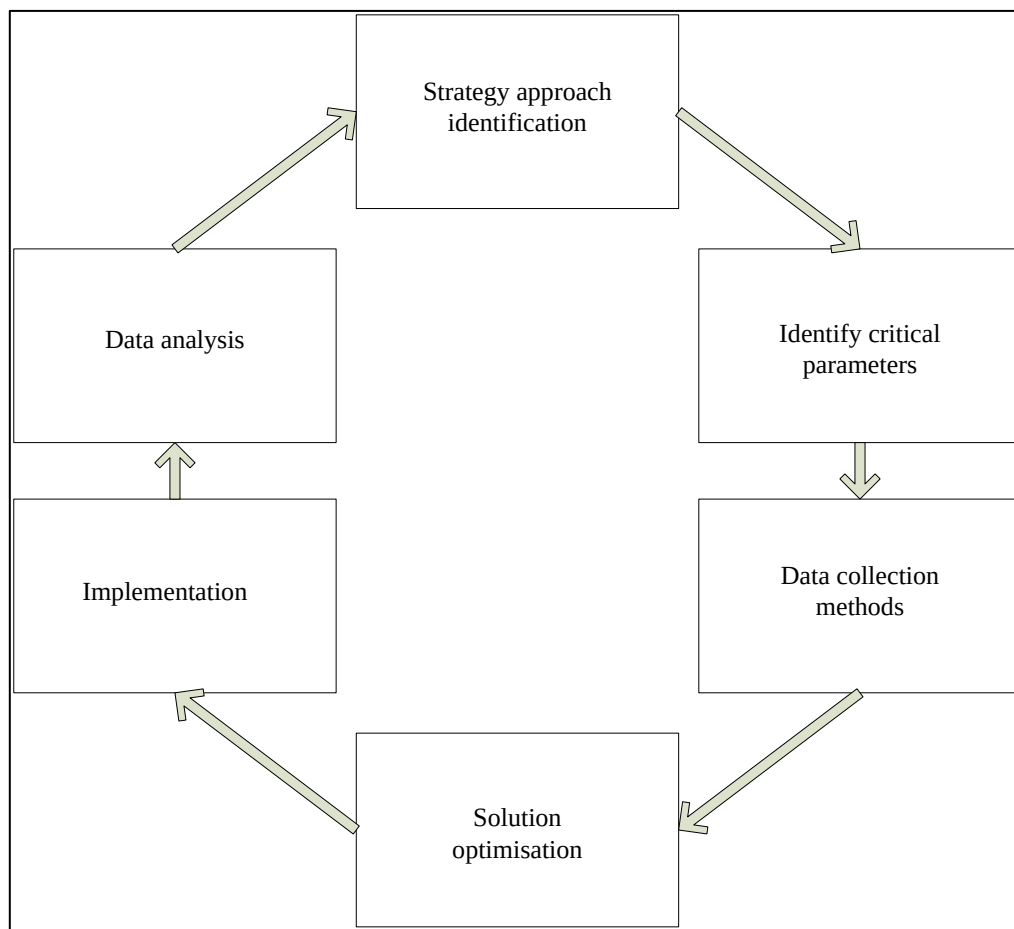


Figure 17: Simplified flowchart of methodology development

The first step of the methodology is to identify the strategy to confirm or disprove the hypothesis formulated in Chapter 1. Critical influential parameters need to be identified to accurately determine whether the consequence of change affected the production and residue quantities of gold. Various data collection methods need to be identified to obtain the relevant data required for analysis. Study-specific analysis techniques need to be selected and appropriately used to obtain accurate results. The obtained results are then interpreted, and a conclusion is made regarding the validity of the study. Techniques for solution optimisation are identified and suggested. Each of the steps in Figure 17 will be discussed in detail in the following sections.

2.2 Strategy approach identification

Various approaches can be used to conduct experimental procedures to deliver valuable results. An industrial-scale plant setup can be used as a testing ground for experiments to be conducted. This serves as the ideal testing ground due to it being where the actual processing of gold takes place for distribution. Various environmental and operational conditions play a role in the process which adds to the “real-world” validity of the study.

Simulations can be used to determine whether the consequence of change positively influences production and residue quantities before a change is considered. Boundaries and ideal values can be provided for ideal operations which may assist in optimising the operation strategy. Simulations may not always provide accurate results and need to be verified by conducting tests on industrial-scale plants.

Erecting pilot plants to conduct experimental procedures is another strategy approach which enables the complete control over influential variables. Obtained results need to be verified by conducting tests on industrial-scale plants. A simplified flowchart for strategy selection is shown in Figure 18.

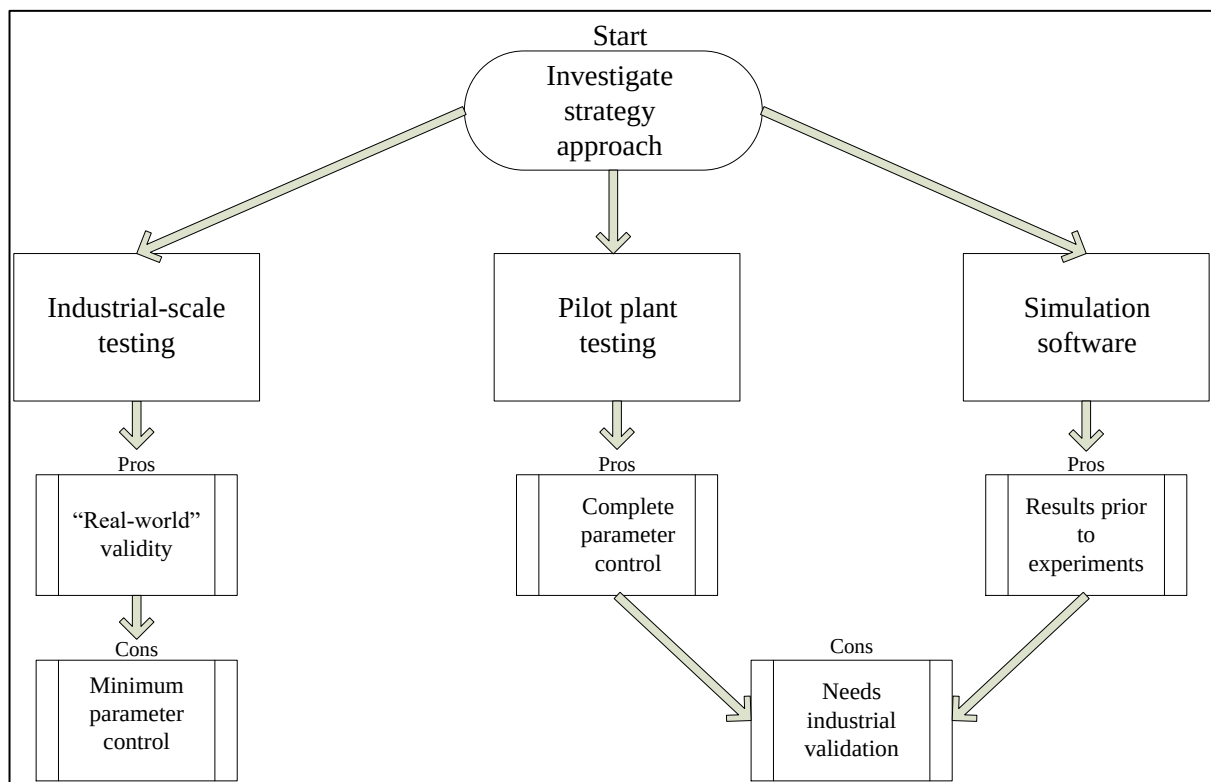


Figure 18: Flowchart of strategy approach step in methodology

All three listed approaches can be used, with the validation step ending in industrial-scale plant testing for most accurate results. Methods can be combined for increased accuracy or scope determination before actual experiments are conducted. The selected strategy approach should ultimately be chosen according to the available infrastructure for the investigation.

2.3 Parameter identification

The performance of leaching tanks is influenced by a variety of variables. These variables need to be identified to ensure the relevant information is readily available for use. The variables need to be listed according to independent, dependent, and controlled/uncontrolled variables. The parameters identified for monitoring are summarised as follows:

Independent variable

Pressure delivery to leaching tanks is chosen as the single independent variable due to the investigation analysing the influence of pressure delivery on residue quantities and production of gold.

Dependent variables

The dependent variables are the target variables analysed due to the consequence of change. The dependent variables are listed as⁴ [50]:

- Gold production – The production of gold ultimately determines the profitability of the plant as the quantity of gold produced is converted into a monetary value.
- Gold residue quantities – Residues indicates gold bearing ore quantity which have not yet been processed and is left behind in leaching tanks. The ore undergoes bottle roll tests to determine the amount of gold locked in the ore.
- Leaching recovery – The leaching recovery indicates the actual metal extraction within the tanks, comparing it to the residue grade of the gold bearing ore left behind in the tanks.
- Production grade – The production grade refers to the gold grade of the total gold produced. A higher grade would indicate a more effective recovery process.
- Residue grade – The grade allocated to the residue is the grade the unprocessed ore quantities left behind in leaching tanks possess. A lower residue grade would indicate a more effective recovery process.

These variables will be analysed over a chosen time period before and after the pressure delivery change to the leaching tanks occurred, in order to establish the effect of altering the independent variable.

Controlled/uncontrolled parameters

These parameters can be listed as controlled or uncontrolled according to the chosen strategy approach. The parameters can be controlled or uncontrolled in either of the listed approaches, depending on the available resources and infrastructure.

⁴ Jan Roos, Plant manager at Mine A, 2019/03/15, Details available upon request at jdupreez@rem2.com due to confidentiality

The parameters are listed as:

- Ore tonnes hoisted by the shaft (specific to mining environment) – Differing quantities of ore may be hoisted by the shaft which may affect the amount of ore being processed by the plant, leading to differing production values.
- Ore tonnes treated by the plant – The plant may have silos filled up to avoid losses when the shaft is not hoisting ore. In some cases, plant's may not have ore stored to avoid standing when the shaft is not hoisting ore.
- Ratio of ore treated to gold produced – The ratio of ore treated to gold produced may differ due to gold grades of hoisted ore varying.
- Operational mills' running time – The running times of the mills may differ on a day to day basis, depending on the scheduling of maintenance by plant personnel (or unforeseen events).
- Cyanide addition in leaching tanks – Cyanide addition may differ on industrial-scale plants due to the optimal cyanide addition being calculated by monitoring the response of leachable gold losses determined by daily laboratory tests.
- Lime addition – In order to continuously adjust the pH of the slurry entering the thickening dams (to minimise the cyanide lost by conversion to HCN gas), CaO needs to be added in varying concentrations.
- pH levels in thickening dams – The pH levels in the thickening dams are controlled by lime addition.

The above listed variables were classified as the most influential on the performance of leaching tanks by Stange [50]. The investigation can, therefore, be simplified without affecting the accuracy of the results by listing only the most influential parameters to be monitored.

2.4 Data collection

Characterising a network primarily entails data collecting and effective data clarification. The initial step for data collecting on a plant is to identify the different existing data sources. This will establish whether the designated measuring locations are being monitored through a dynamic control system, or whether manual measurements need to be taken to acquire the relevant data for analysis. Establishment of measuring points is key in obtaining the correct data values. All the variables listed in the previous section need to be monitored for a successful investigation. On industrial-scale plants, the data is usually documented in certain specified time intervals and stored on a Supervisory Control and Data Acquisition System (SCADA). This enables quick and effective acquisition of data. Figure 19 shows the important measuring points for a generic gold production process if a central SCADA system is not used or is offline.

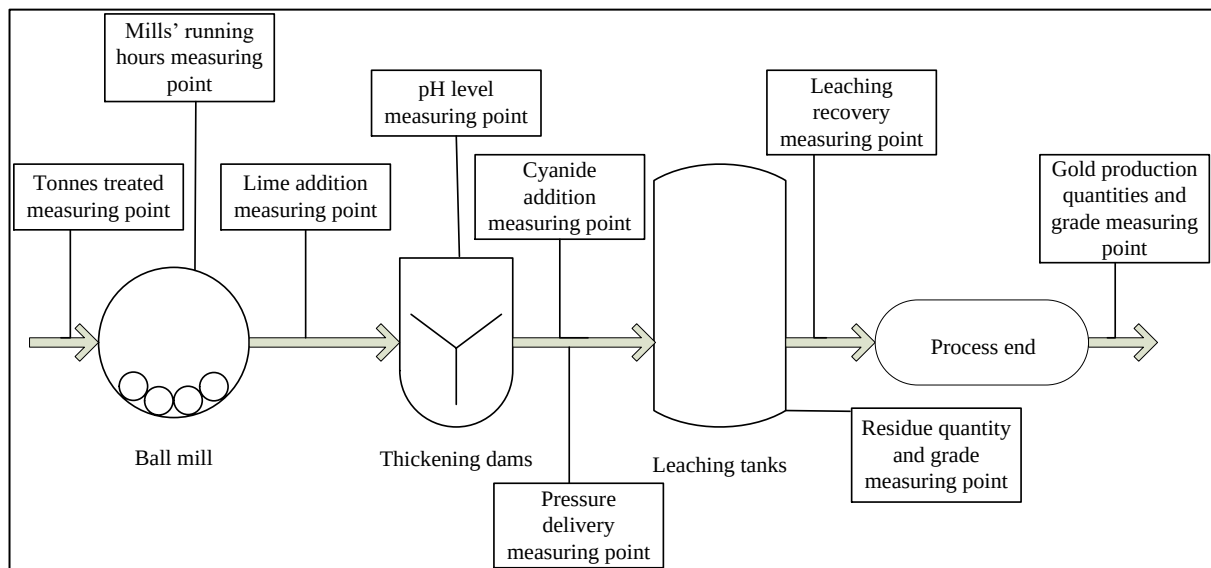


Figure 19: Flowchart for data collection step in methodology

It is important to take note of instruments sensitive to some line disturbances, especially flowmeters downstream of a valve. Manual measuring entails using portable measuring equipment. The measurements requiring portable equipment are:

- Pressure delivery – The compressed air being delivered to the tanks can be measured for flow and pressure by using a portable compressed air pressure logger [74].
- Lime addition – The lime added to the leaching tanks can be measured by a portable calcium photometer which measures the CaO in the line to the thickening dams [75].
- Cyanide addition – The cyanide added in the line to the leaching tanks can be measured by a hydrogen cyanide detector [76].
- The pH value- The pH can be measured in the thickening dams by a portable pH meter [77].

The gold residue and production grade measurements need to be conducted by bottle roll tests, which are usually analysed by on-site or independent laboratories to indicate the gold grade. Gold and residue quantities are mere values which can be weighed to obtain a result. Mills' running hours can be calculated according to a running status meter on the mills or be physically documented. Leaching recovery is a calculation done between the head grade and residue grade according to Equation 14.

Equation 14: Gold leaching recovery equation adapted from [78][79]

$$\frac{(Hgrade - Rgrade)}{Hgrade} \times 100$$

Where:

- *Hgrade*- The gold grade of the slurry sent to the CIP process.
- *Rgrade* – The gold grade of the ore settled at the bottom of the leaching tanks.

The abovementioned portable equipment is visually shown in Figures 20 to Figure 23.



Figure 20: Portable pressure logger [74]



Figure 21: Portable calcium photometer [75]



Figure 22: Portable cyanide meter [76]



Figure 23: Portable pH value meter [77]

The portable measuring equipment listed is suggested approved equipment and is entirely user-preference based.

Limitations of instruments should be listed and understood to obtain accurate data. An appropriate time period should be selected during which the study will be conducted. The decision should be made based on results accuracy and possible unforeseen circumstances during operation (most applicable to industrial-scale operations.) The hypothesis in Chapter 1 predicts an initial decrease in residue quantities, after which a stabilising period will follow. The investigation period should allow sufficient time for the hypothesis (non-fluctuating increased pressure delivery will have a positive influence on residue quantities and gold production) to be confirmed or disproved. A prolonged time period may result in a bigger standard deviation of monitored values, or operational changes which may influence results accuracy. Figure 24 shows a flowchart of how the data collection step should be approached to aid in the understanding of the complete system, as well as the completion of the investigation.

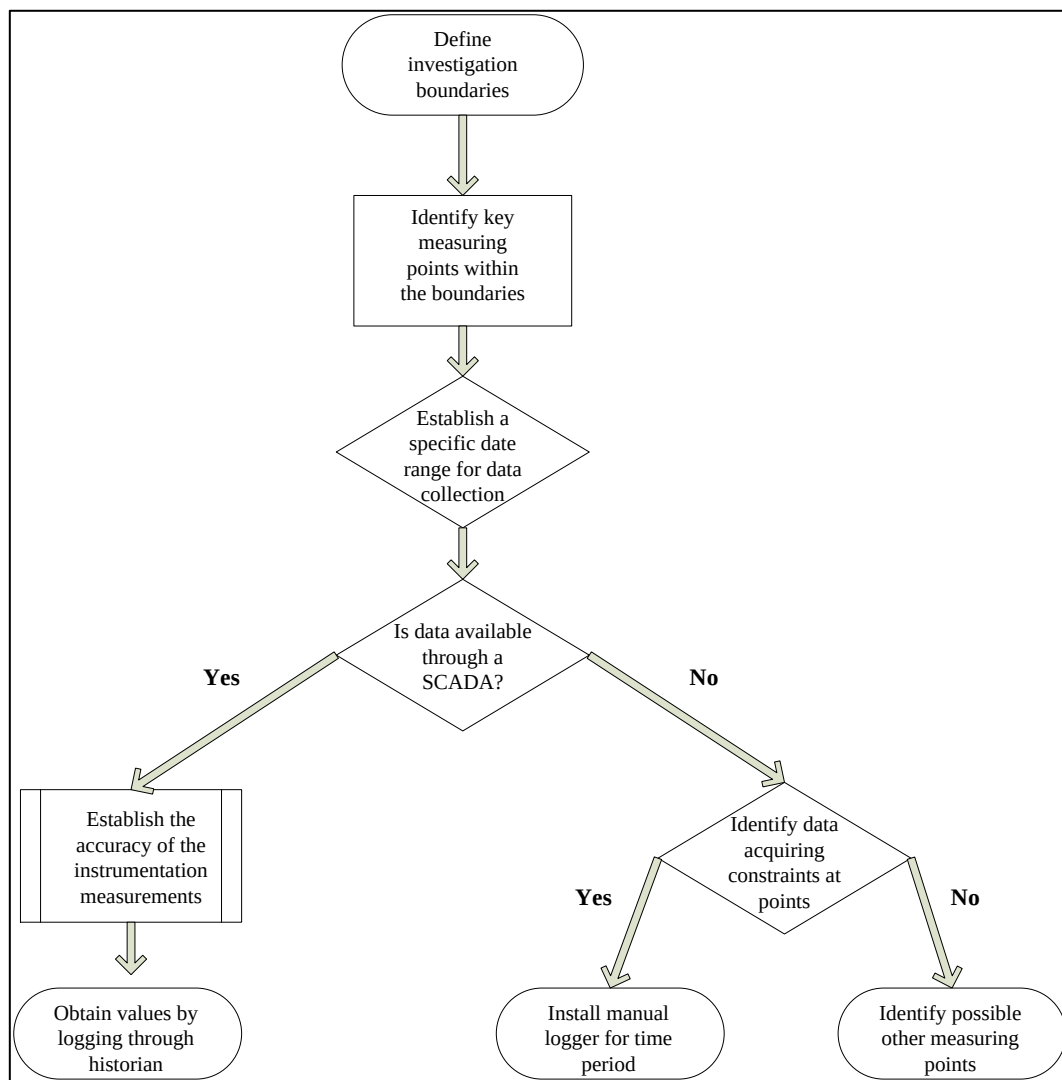


Figure 24: Data collection flowchart

Once all the measuring points have been established and relevant data collected, data analysis can commence to establish the trends over time and quantify the impact after the change in system operation has occurred.

2.5 Solution optimisation

This step entails the revision of the preceding developed steps in the methodology. The step is considered important so as to include probable new information or list possible solutions to unforeseen events that came to light while developing and executing the previous methodology steps. This ensures an optimised methodology is used when implementation is executed. A flowchart of the solution optimisation steps is shown in Figure 25.

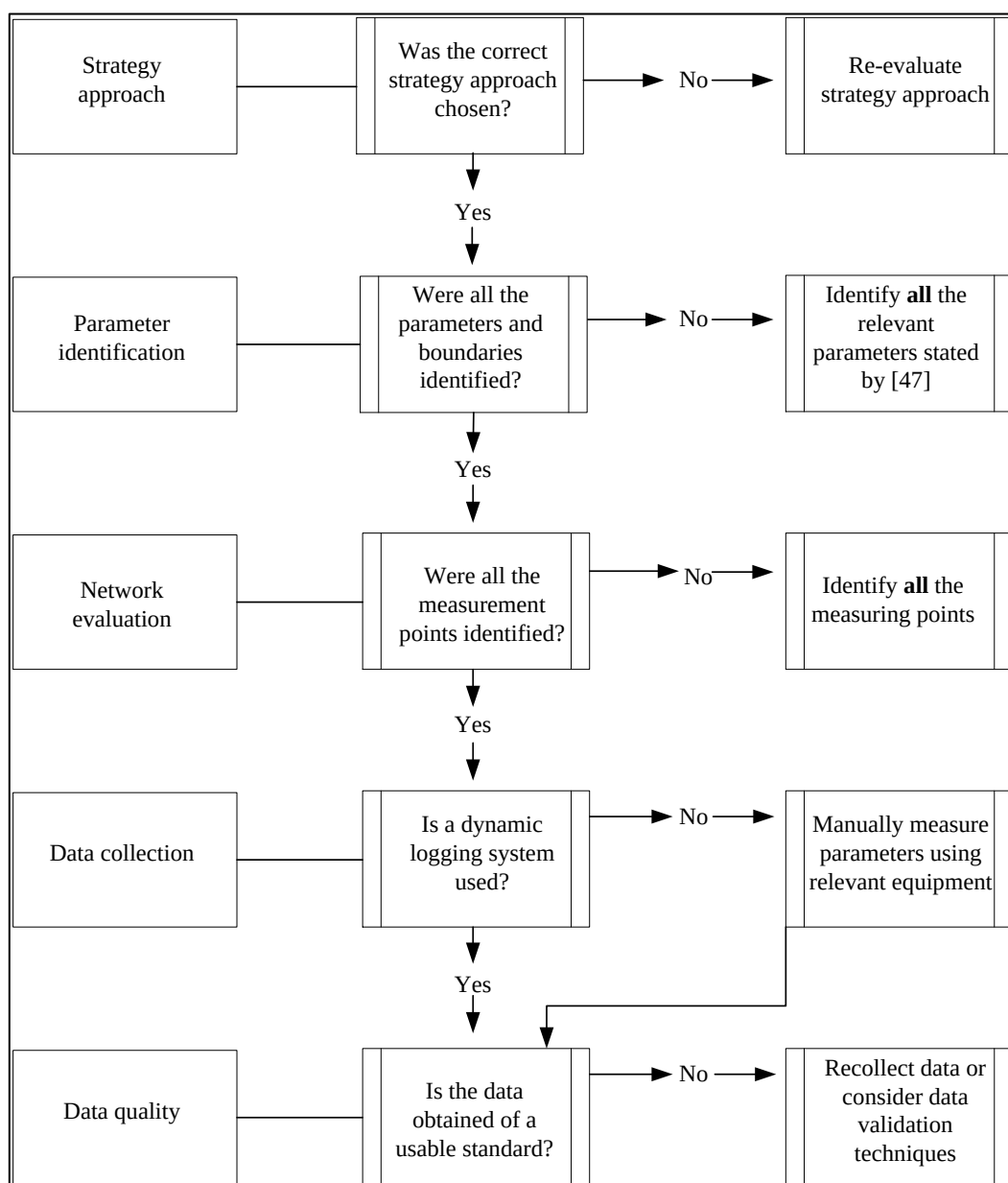


Figure 25: Solution optimisation flowchart

After the solution strategy optimisation, the designed strategy can be implemented.

2.6 Implementation

The implementation process of the methodology consists of several steps. The steps are developed with the focus of addressing the chosen objectives for the study. The steps are discussed in the following sections.

Attainment

Acquisition of required infrastructure, equipment, and parts for the study should be done in advance to ensure delays are kept to a minimum. Delivery periods on some essential equipment may take several months. It is therefore important to ensure all the equipment, infrastructure, and parts be obtained prior to the actual implementation.

Resource allocation

Industrial-scale operations are complex operations with many unforeseen events which need to be dealt with promptly. Ensuring workers are properly informed of scheduled work during allocated downtime for repairs is essential to avail required personnel during key project times. Resource distribution on industrial-scale operations is usually poorly managed which may lead to project delays.

A resource breakdown, containing each individual worker's specific responsibility, should be constructed. This enables deliverables to be divided amongst smaller broken-down tasks, which combine to form part of the detailed project planning. The plan should be continuously revised and updated to ensure project progress remains up to date.

Installation procedures

Procedures to install loggers and equipment to obtain data values need to be done correctly to ensure accurate data measurements. Loggers and equipment installed for a prolonged period of time need to be regularly inspected to ensure quality data for analysis.

2.7 Data analysis

The collected data will be monitored over an allocated time period after which conclusions can be drawn regarding the behaviour of the data trends. The chosen statistical analysis methods focus on daily average values over the chosen time period. Average values give a good indication regarding the behaviour of different variables over time, and the correlations they have with one another. A table explaining the analysis strategy is shown in Table 7.

Table 7: Statistical analysis table

Statistical analysis method	
Variable type	Independent variable: - Pressure delivery to leaching tanks: Knowing the pressure delivery to the leaching tanks can assist in drawing a conclusion if non-fluctuating, higher pressure delivery aids in reducing the residue value within the leaching tanks.
Descriptive analysis	- Average pressures (daily, before, and after), - Pressure ranges before and after, and - Pressure frequency ranges.
Inferential analysis	Correlations: - Pressure vs time, - Pressure vs production, - Pressure vs ore grade, - Pressure vs residue grade, - Pressure vs residue quantity, and - Pressure vs leach recovery.
Visual trends and discussion	Visual trends and discussion to occur in Chapter 3.
Variable type	Dependent variables: - Production of gold: The production of gold indicates the profitability of the plant. Comparing the values before and after the pressure delivery change assists in drawing conclusions to the statements made in this dissertation. - Residue and production grades: A lower residue grade and a higher

	production grade is preferred within leaching tanks. Lower residue grades would assist in obtaining a more efficient operation. - Residue quantities: High residue quantities indicate a lot of ore entering the tanks remain within the tanks and does not progress to the next step in the gold process. The remaining residue then have to be re-treated. A gold processing plant therefore aims for lower residue quantities within leaching tanks. - Leaching recovery: The leaching recovery is determined by comparing the gold grade of the residue and the ore quantities progressing to the elution columns. A higher leaching recovery percentage would indicate a more efficient operation
Descriptive analysis	- Daily production averages, - Daily production and residue grade averages, - Production variability ranges, - Daily residue quantities, and - Leaching recovery averages. -
Inferential analysis	Correlations: - Production vs time, - Residue quantities vs time, - Production grade vs time, - Residue grade vs time, - Treated ore vs time, - Production vs residue quantity,

	- Production vs residue grade, - Production vs ore grade, - Production vs treated ore tonnes, and - Treated ore and gold produced ratio.
Variable type	Uncontrolled/controlled variables: - Treated ore: Treated ore quantities differ on a daily basis on an industrial-scale plant. Knowing the quantities of ore treated may assist in explaining higher or lower production values. - Hoisted ore: The hoisted ore tonnes originating from the shaft also differs regularly. Knowing the ore quantities hoisted may assist in explaining higher or lower production values. - Mills' running time: The first step in the gold production process is ore feed to the mills. Knowing mills running times may assist in explaining higher or lower production values. - Cyanide addition in tanks: Cyanidation is used as a metal extraction method within the gold process. Knowing the added cyanide values may assist in obtaining leaching recovery and possibly gold production values trends. - Lime addition: CaO is added in the gold process to limit the amount of cyanide lost by conversion to HCN. Knowing the added lime values may assist in production and leaching recovery trends.

Descriptive analysis	- Treated ore averages, - Treated ore ranges, - Daily cyanide addition averages, - Daily lime addition averages, - Milling hours daily totals, and - Hoisted tonnes totals.
Inferential analysis	- Treated ore vs time, - Hoisted tonnes vs time, - Milling hours vs time, - Treated tonnes vs milling hours, - Hoisted tonnes vs milling hours, and - Treated tonnes vs hoisted tonnes.

It is important to note, **if full control over the uncontrolled/controlled variables is obtainable, these values should be kept constant while manipulating only the independent variable** to acquire the best possible results. To simplify data analysis, visual trends should be used to easily identify a change in behaviour of the different variables. After the data is analysed, the outcome of the data needs to be evaluated to establish the success of the investigation.

Quantifying the improvements

After the data is analysed and conclusions regarding different trends can be drawn, the implemented solution strategy needs to be quantified to determine the actual impact.

Quantification of improvements includes the improvements in the daily profiles of the variables investigated. In order to successfully evaluate the impact of the implemented solution, it is important to identify parameters which may have influenced the results of the study (particularly on industrial-scale operations.) To ensure accuracy of results, normalised values must be compared to results where needed. The flowchart in Figure 26 illustrates the quantification steps.

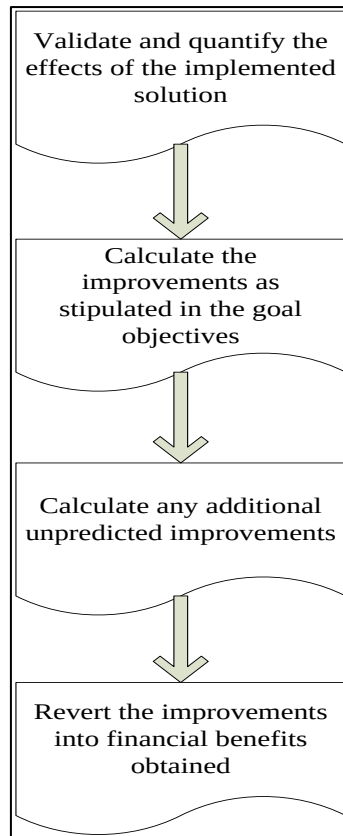


Figure 26: Improvement quantification flowchart

The improvements will be quantified by analysing the quantity of possible residue reduction and production increases over the chosen time period. The gold price upon completion of the study will be used to translate the quantity into a monetary value.

2.8 Conclusion

After all the relevant variables are plotted and distinct correlations are made, conclusions can be made regarding the relationships of the variables with one another. The validity of the study can, therefore, be made through analysis of the results. Chapter 3 will discuss the results delivered in extended detail from which the conclusions will follow.

3. Results & Implementation

In this chapter, the methodology developed in Chapter 2 is validated by using the results obtained when implementing the developed methodology on a South African gold plant. This case study will be used to determine whether the system change in the gold process will have a positive effect on production and residue in the gold plant.

“I don’t take on a project unless I know the end result is going to make me happy. If I can’t give 100 percent to something, I choose not to do it because it is difficult to have so many pots on the fire at one time.” – Johnny Weir

3 Results and interpretation

3.1 Preamble

This chapter focuses on the results obtained after the solution strategy was implemented. The main objective of the study is to determine whether an increased, non-fluctuating pressure delivery would have a positive impact on the production of gold and the residue quantities in the leaching tanks.

3.2 Case study background

General information

The developed methodology was implemented and tested on the shared compressed air ring of Mine A situated in the Gauteng province of SA. The mine is located near the northern rim of the Witwatersrand Basin. The operation focuses primarily on narrow-reef conventional mining of the South Reef. Mine A had 3073 employees and 669 contractors for the 2018 financial year [80]. Mine A achieved an average gold grade of 4.47 g/t for the past three financial years [80]. The low ore grade consequently means high volumes of ore need to be extracted and processed to ensure a safe profit margin.

In addition to high volumes of ore needed to be hoisted for profitability, energy savings investigations can be launched to accumulate electrical cost savings. Electrical cost savings initiatives entail holistic, comprehensive investigations. All systems influenced by a change in the configuration of the system, need to be analysed to quantify the effects it has on these systems.

Compressed air electrical cost savings investigation

An initial preceding study was conducted on the compressed air use of mine A. The goal of the study was to reduce the compressed air use on mine A due to continuous financial strain from rising energy tariffs placed on the mine. Like most gold operations situated in SA, the shaft and the plant's compressed air network was shared.

The surface setpoint of the compressors was chosen as 600 kPa during the day when mining activities took place. The plant's minimum pressure setpoint was determined at 430 kPa, to ensure sufficient pressure for agitation purposes. The graph in Figure 27 portrays a pressure profile of the compressed air supplied to the plant in January 2019. The pressure delivery increased due to the commissioning of a stand-alone compressor on the 31st of January operating at a higher, non-fluctuating pressure. Pressure fluctuation can be observed throughout the month.

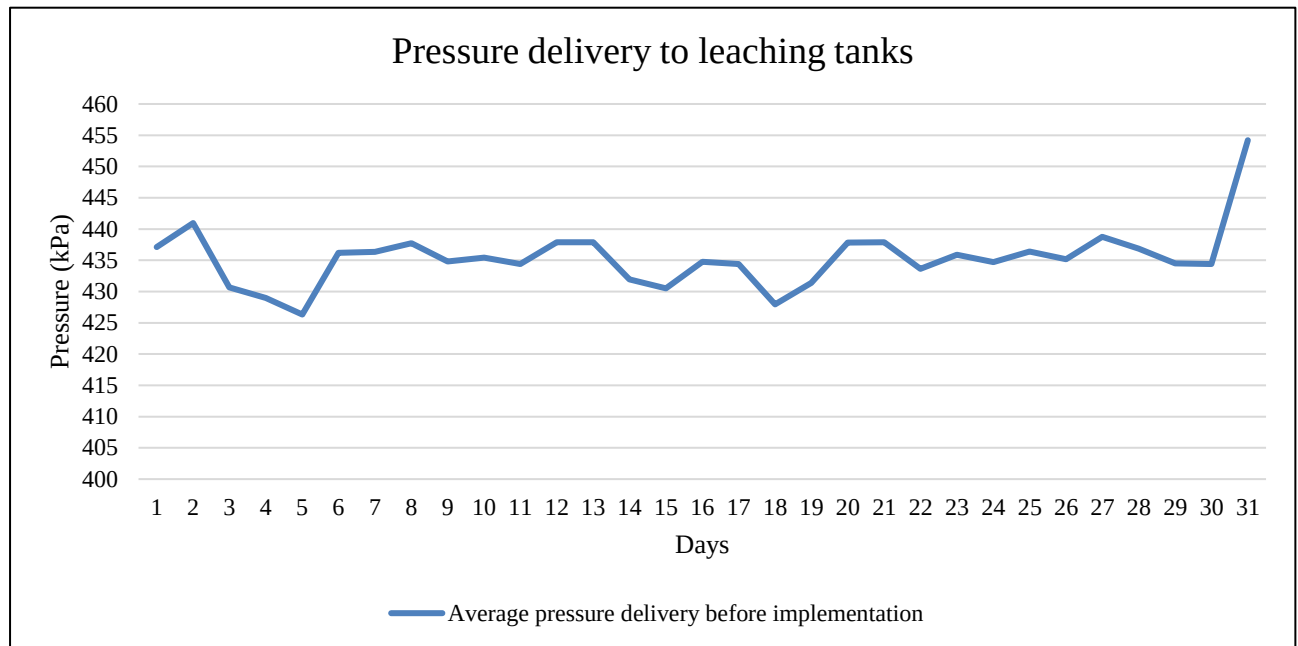


Figure 27: Shared shaft and plant compressed air network pressure delivery to leaching tanks

An electricity cost saving initiative was identified on the shaft which required the surface pressure setpoint of the shaft to be lowered to 350 kPa during the weekday off-peak mining hours of 16:00-21:00. Extraction of pressure setpoint data was not yet available at time of writing. The initiative entailed altering the setpoint in the mining off-peak times to obtain electrical cost savings. Due to the minimum required setpoint of the plant, the surface pressure setpoint could not be set lower than 450 kPa, thus limiting the scope for electrical cost savings (pressure drops compensated for.) Figure 28 shows the shaft compressor energy profile after initiative identification.

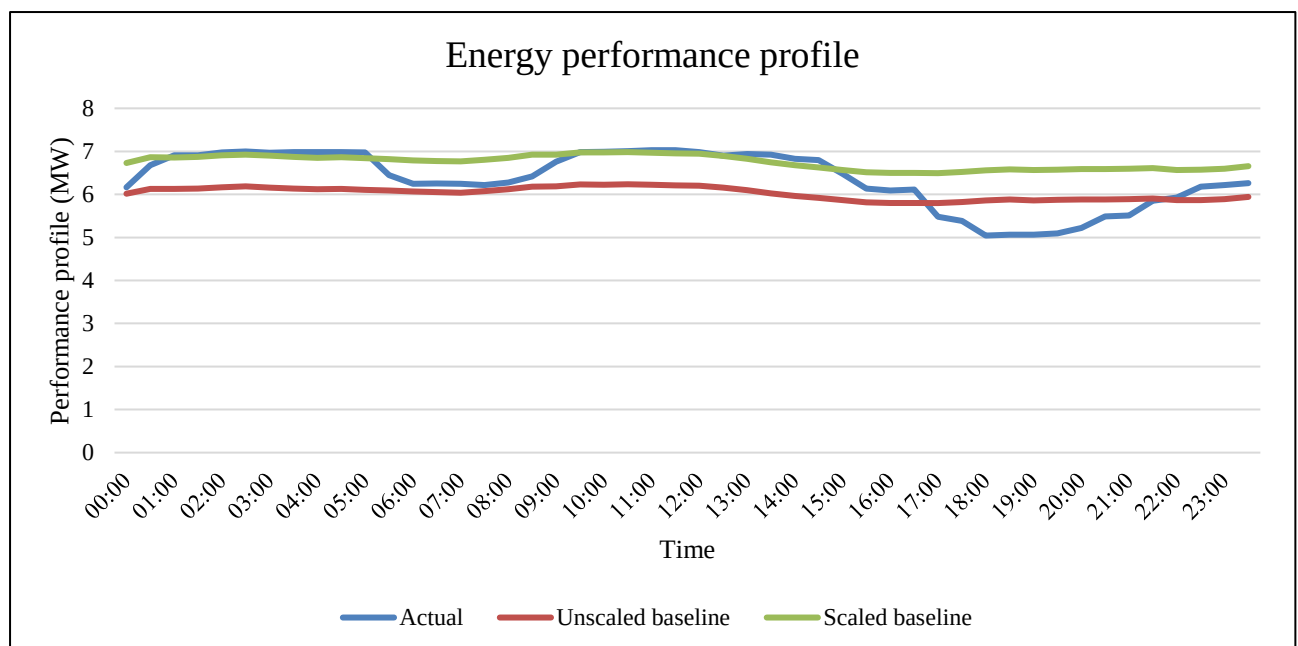


Figure 28: Shaft compressor energy profile after energy initiative identification

Electricity cost savings were limited, and fluctuating pressures delivered to the plant were still a constant point of concern.

A further investigation was launched on mine A to address both the limited electricity cost savings scope, and the fluctuating pressures supplied to the plant. The following solutions were identified:

- Purchasing a stand-alone compressor for the plant, and
- Installing a shaft bypass control valve.

Feasibility studies were conducted on both solutions and conclusions could be drawn from the results. The shaft bypass valve installation had a lower capital investment amount and a slightly shorter payback period than the purchase of a stand-alone compressor, but did not directly address the problem of fluctuating pressures being delivered to the plant. The stand-alone compressor had a slightly longer payback period but provided a solution to both problems at hand. The option of stand-alone compressor installation was chosen.

The shaft surface pressure setpoint is predicted to be adjusted to 350 kPa and expose greater scope for compressor peak clipping during the off-peak mining periods after implementation. In addition to solving the problem of fluctuating pressures delivered to the agitation tanks, electrical cost savings increased on the shaft. Improved agitation in the leaching tanks can be beneficial to the overall end residue quantity of gold, as it might directly address the problem of ore settling at the bottom of leaching tanks.

The effect of altering the delivery pressure of compressed air to the leaching tanks was neglected in the investigation conducted on the shaft of mine A. The results after project implementation will be discussed in detail in this Chapter. Potential leaching, residue, and gold production benefits due to higher and non-fluctuating pressure delivery will be investigated in this study. This study was, therefore, conducted to assist in obtaining a conclusion for the plant manager who identified the initial problem of fluctuating pressure delivery⁵.

Mine A compressed air network investigation

The electrical cost savings, accumulated by the peak clipping initiative, was limited. The most feasible option of installing a dedicated plant compressor was selected after a comprehensive investigation, which primarily focused on the shaft. A simplified layout of the operational compressed air network before project implementation is shown in Figure 29.

⁵ Jan Roos, Plant manager Mine, 2019/03/05, Details available upon request at jdupreez@rems2.com due to confidentiality

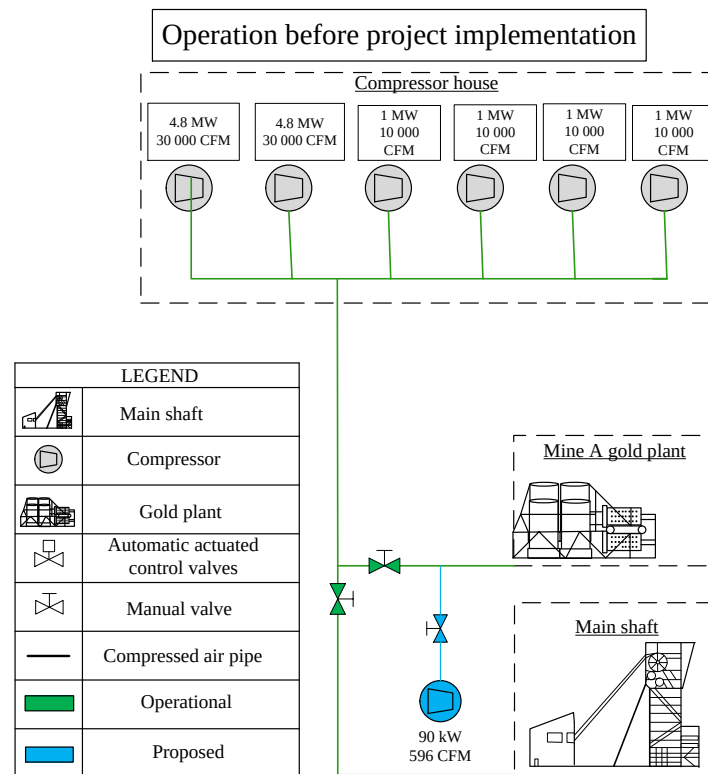


Figure 29: Shared plant and shaft compressed air delivery layout

The proposed solution entailed installing a dedicated plant compressor to supply the plant with compressed air. The supplied air will primarily be used for pneumatic equipment and for agitation purposes in the leaching tanks. Operation after compressor installation is shown in Figure 30.

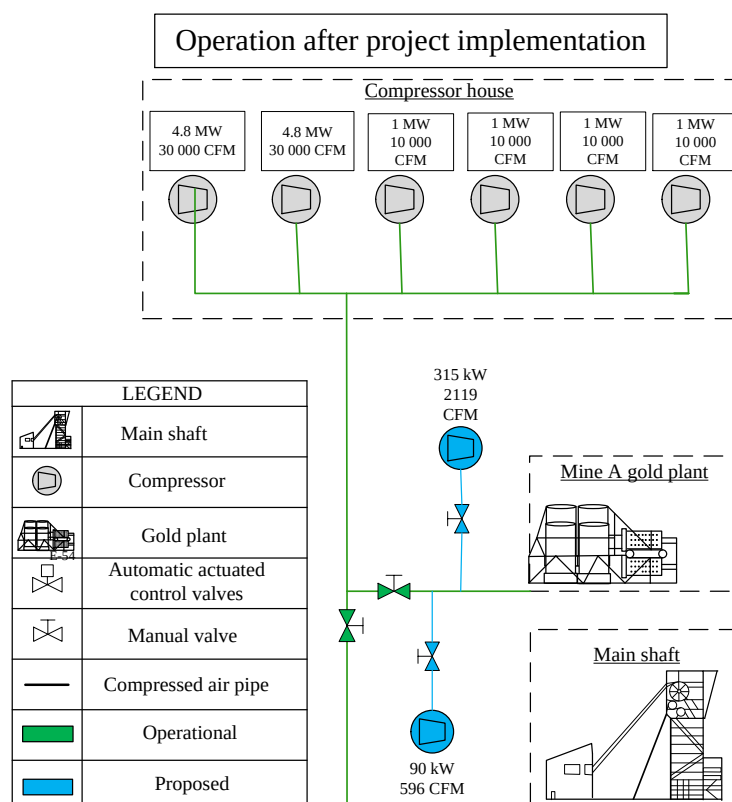


Figure 30: Proposed separate shaft and plant compressed air layout

Once the shaft and plant compressed air network was separated, the shaft compressors could lower their setpoint to 350 kPa and obtain additional electrical cost savings through means of peak clipping in the peak Eskom tariff periods. The specifications of the compressor installed on the plant is shown in Table 8.

Table 8: Compressor specifications

Specification	Value
Rated Motor Power	315 kW
Pressure	750 kPa
Flow	2119 CFM
Supply Voltage	3-Phase, 525 V
Cooling	Air cooled

The loading- and offloading pressure was set at 500 kPa and 550 kPa, respectively. Figure 34 shows a comparative energy profile before the compressor installation. The shaft compressed air performance profile after compressor installation is shown in Figure 31.

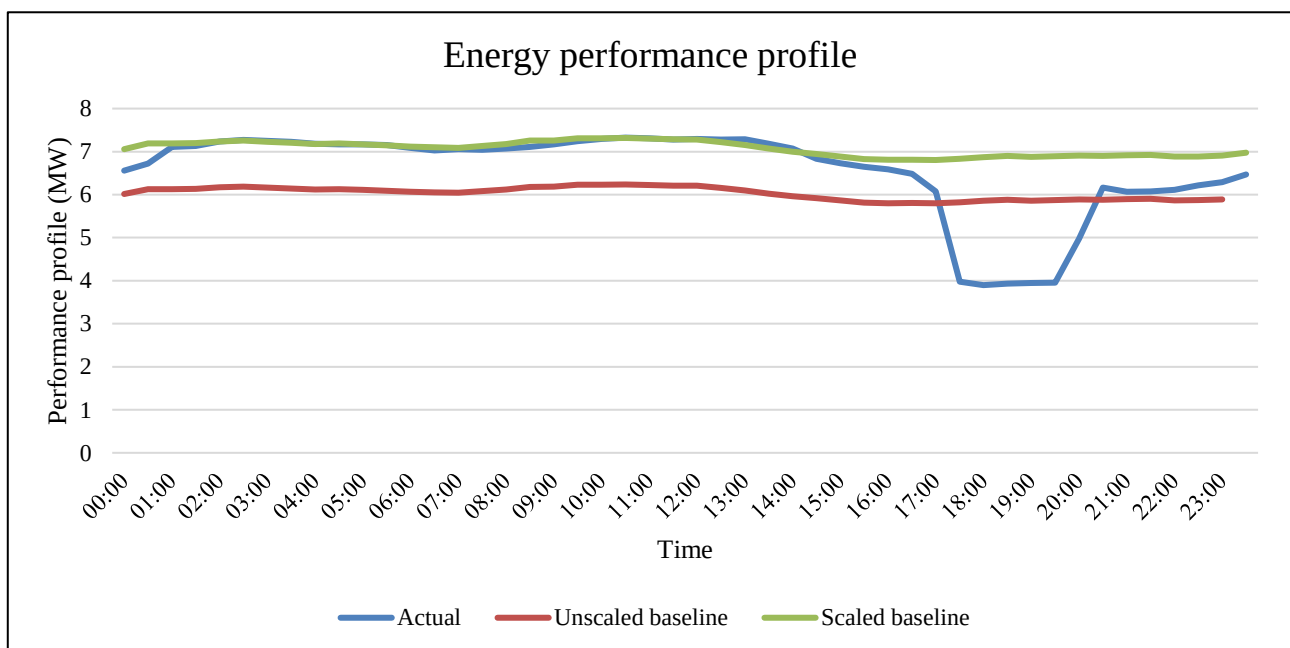


Figure 31: Mine A shaft compressor performance profile after project implementation

The electrical cost savings is estimated at R 3.3 million per annum if the control philosophy persists. The 90 kW compressor at the plant was also switched off, but the electrical cost savings were offset due to the usage of the 315 kW compressor.

The pressure profile of the plant changed after the installation of the standalone compressor. The pressure profile comparison before and after project implementation is shown in Figure 32.

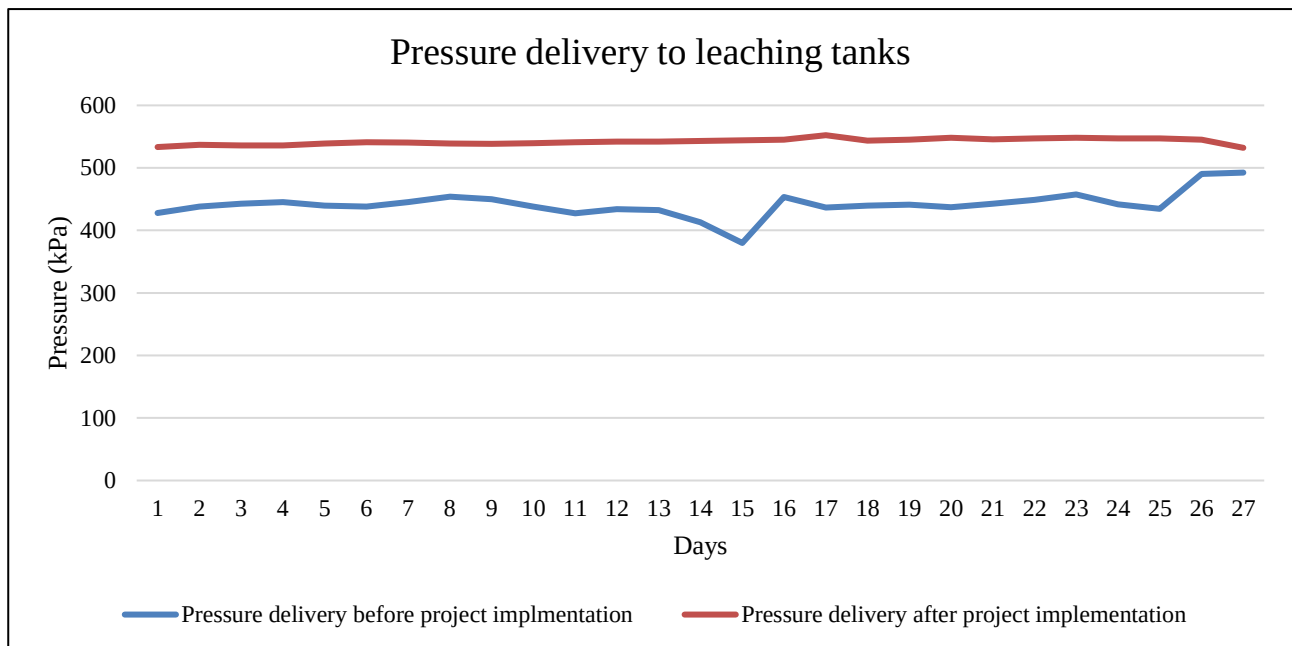


Figure 32: Comparison graph of the pressure delivery to leaching tanks

The installation of the plant compressor had an approximate pressure change of 100 kPa. The effects of the higher, less-fluctuating pressure delivery will be analysed. Conclusions determining whether the hypothesis was formulated correctly will be made by implementing the data analysis techniques discussed in Chapter 2.

3.3 Results analysis

Before any variable can be compared to one another, each variable listed in Chapter 2 will be analysed over a time period. By analysing each variable over an allocated time period, trends indicating changes can be established and a base can be obtained from which the hypothesis can either be verified or falsified. Trends analysis over an allocated time period is known as a temporal change analysis. As previously mentioned, the primary variables to be analysed are the independent variable, dependent variables, and uncontrolled variables.

Independent variable

The independent variable in this study was chosen as the pressure delivery to the leaching tanks. The monitoring period was chosen as four weeks before and after project implementation. The period was chosen strategically to minimise the effects of uncontrolled variables and unforeseen events, but also allow sufficient time for conclusions to be made.

It can clearly be seen from Figure 32 that the pressure changed significantly at the end of January 2019 when the dedicated plant compressor was commissioned. A distinct time period was, therefore, established for when the hypothesised changes are expected to occur.

Dependent variables

Various dependent variables have been established during the study, however, only the main variables used to indicate the efficiency and profitability of the plant will be chosen to obtain results. The selected dependent variables are:

- Gold production quantities and grade,
- Gold residue quantities and grade, and
- Leaching recovery.

Gold production and grade

To establish the trends of these variables, each were analysed and monitored over the specified eight-week period. The period was chosen to minimise the chance of unforeseen events, as well as allow enough time for conclusions to be made. The Gold grade is determined by the quantity of gold obtained per processed ton of ore [81], while gold production is a mere quantity to be measured in kilograms. The lagging/ storage effects of gold were considered during the determination of analysis period length. Gold production and grade are the main parameters used to determine the profitability of a gold plant. A graph showing the trends on Mine A's total gold production and grade during the analysis period is shown in Figure 33.

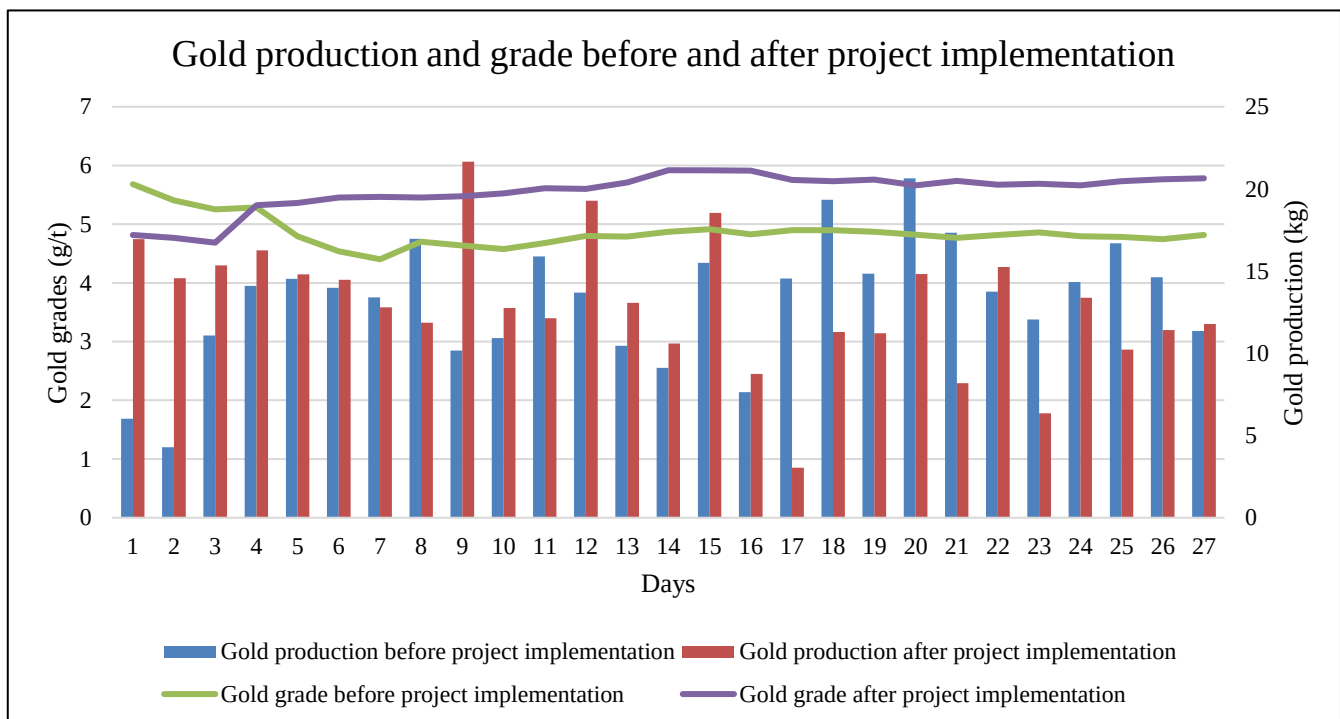


Figure 33: Comparison graph of gold production and grade before and after project implementation

The graph portrays a slight overall decline in total production. A minor initial production increase can be seen after project implementation, followed by an overall decline over the remaining analysis time. The average daily gold production before project implementation was 13.12 kg and 12.99 kg after

implementation. The overall gold production declined by 1.8%. The overall gold grade increased after project implementation. This may be caused by a variety of factors including ore mining location, tonnes treated, and cyanide addition. The influence of pressure delivery will be concluded in the latter part of Chapter 3. The total average gold grade rose by 14.28%.

Residue quantities and grade

Residues contain gold which settled at the bottom of the leaching tanks. A more efficient operation would contain less residue quantities. A graph portraying the trends of the residue quantities and grade is shown in Figure 34.

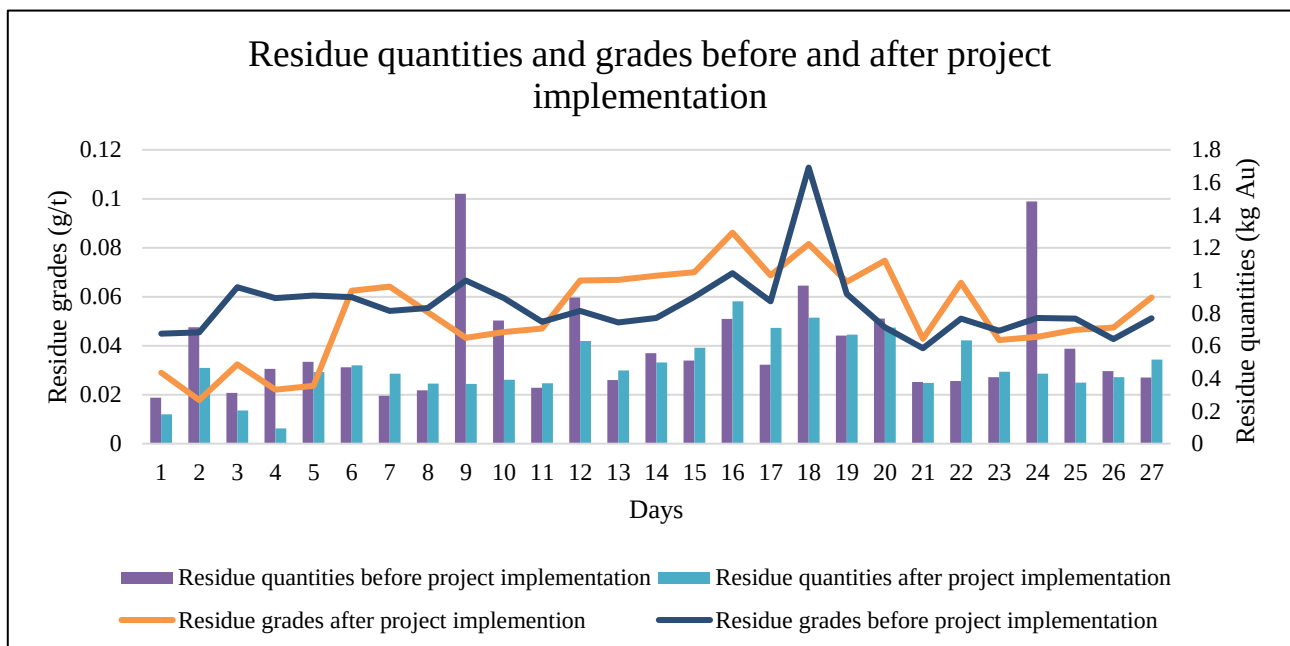


Figure 34: Comparison graph of residue quantities and grades before and after project implementation

The trend observed is an initial decline in residue quantity and grade, followed by a fluctuating profile compared to the period before compressor installation. A clear correlation between residue quantities' variables cannot be concluded from the graphs. A regression analysis was conducted, and the results obtained were inconclusive. The graph of the regression analysis can be viewed in Appendix A in Figure 53. The residue quantity shows a decrease of 19.97%, while the residue grade shows a decline of 5.14% after project implementation.

Leaching recovery

As previously mentioned, leaching is a physico-chemical process where minerals in rock masses go through dissolution under percolating water and anion/cation exchange [82]. Leaching recovery in the leaching tanks gives a good indication of whether a leaching operation operates efficiently. The leaching recovery temporal change analysis is shown below in Figure 35.

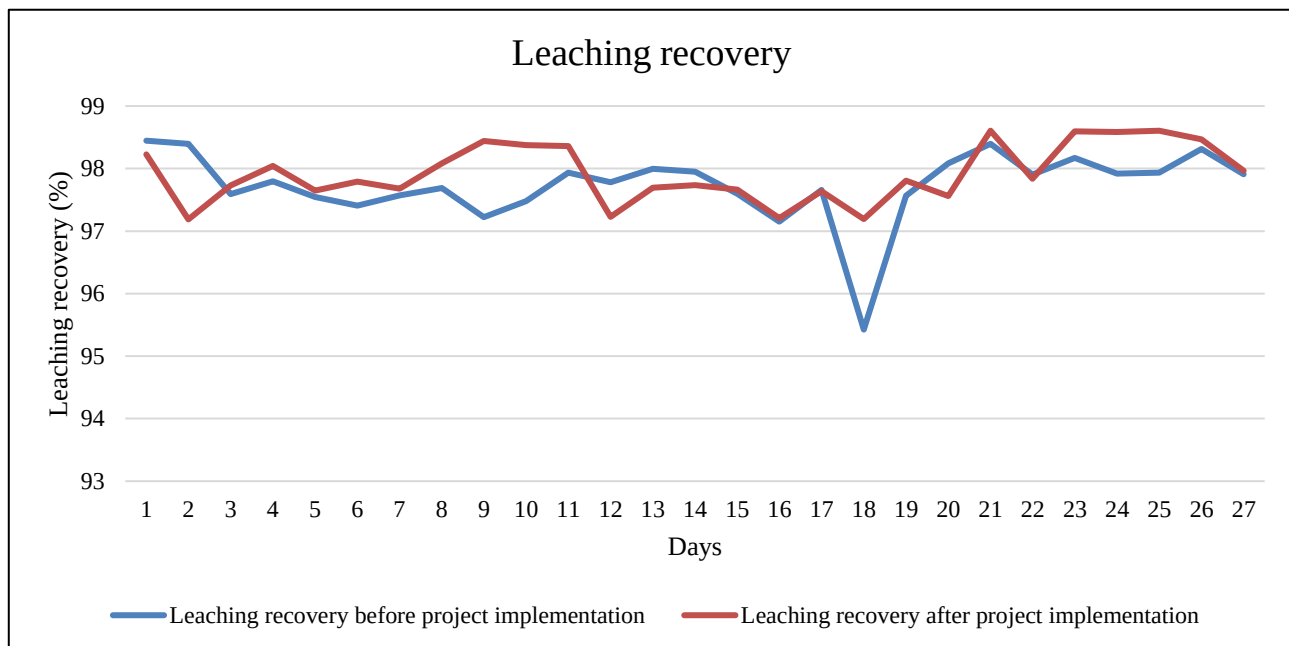


Figure 35: Graph of leaching recovery before and after project implementation

The leaching recovery rate is determined by Equation 15. The leaching recovery in the tanks portrays an average increase of 0.2% after project implementation. This value holds relevance to the study due to leaching recovery directly linking to gold production values. Bottle roll tests of the residue and production ore quantities are done by the on-site laboratory on the gold plant.

Uncontrolled variables

Conducting a study on an industrial-scale plant may come with a wide variety of uncontrolled variables. These variables are chosen as uncontrolled due to the nature of operation. A gold plant operates on the principle of maximising production and can suffer from unforeseen circumstances which may affect overall performance of other identified variables, as well as the end results of the study. It can also be used as an advantage to simulate various scenarios which can be bypassed by using mathematical models or scaling factors. The presence and importance of the uncontrolled variables, therefore, needs to be noted and taken into consideration when analysing results. Numerous uncontrolled variables have been identified during the study. After vigilant consideration, the primary variables chosen are:

- Ore hoisted,
- Ore treated,
- Mills' running time,
- Cyanide addition,
- Lime addition, and
- pH level.

Ore hoisted and treated

The shaft is responsible to accumulate ore and send it to the plant for processing. Not all the ore hoisted each month is processed, and is, therefore, stored in silos for later processing. It is important to distinguish between the quantities hoisted and treated. The temporal change graph for the ore hoisted and treated is shown in Figure 36.

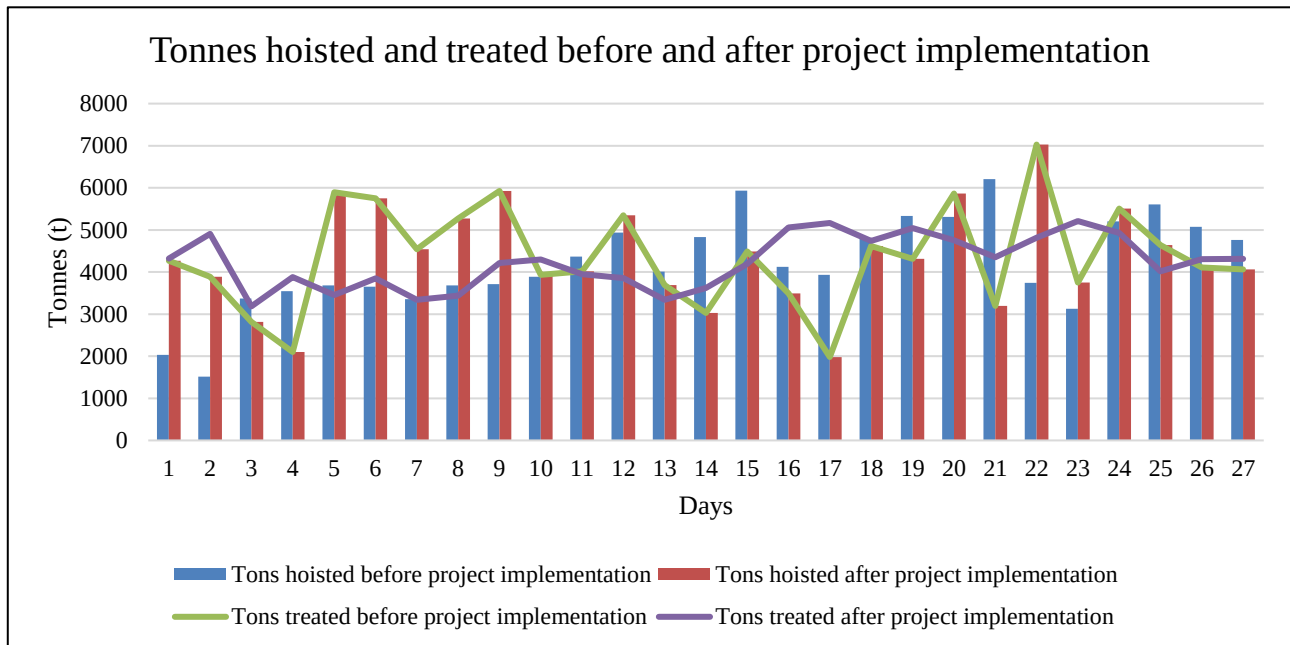


Figure 36: Comparison graph of ore tonnes hoisted and treated before and after project implementation

The general trend during the analysis period shows a 2.07% increase in tonnes hoisted and 1.24% decrease in tonnes treated. A directly proportional relationship is observed between the ore hoisted and treated. This may result in less overall gold production but can still deliver valid results when data is normalised. In order to normalise the gold production, a relation between the treated ore and the gold produced was developed. The relation is an indication of whether the processing operation is efficient and provides additional information on possible changes in production efficiency. A graph portraying the monthly ore treated in relation to the gold produced is shown in Figure 37.

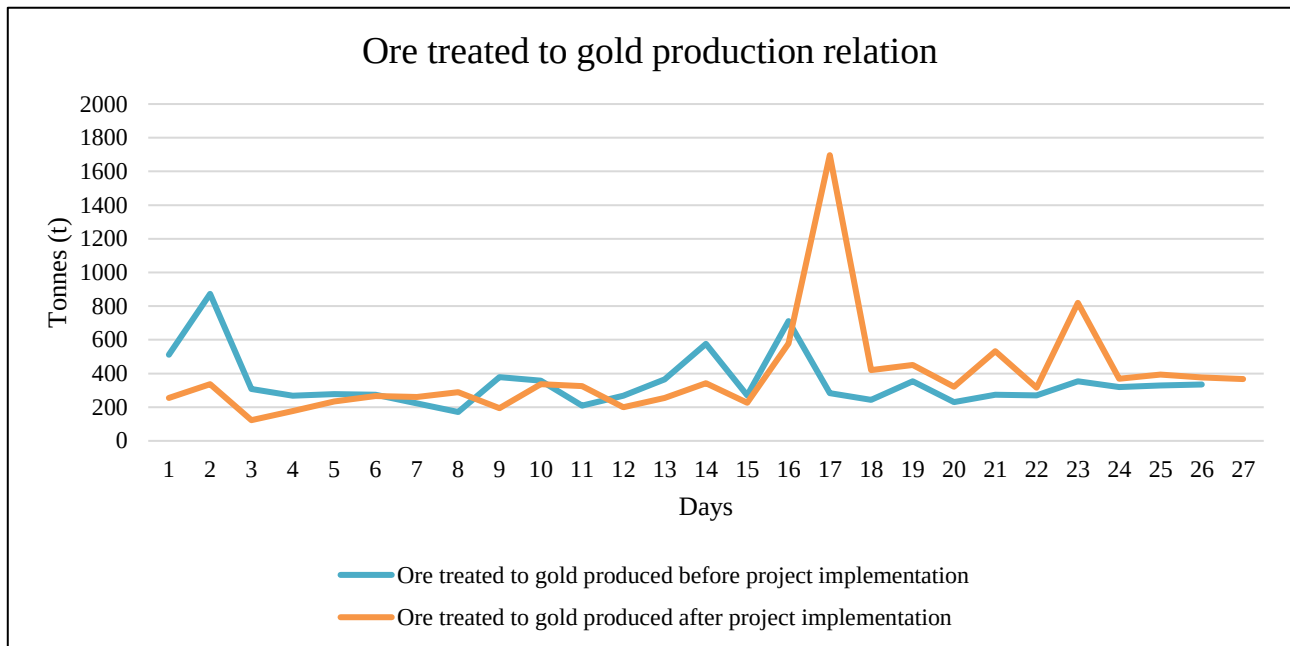


Figure 37: Graph of the relation of ore treated to gold produced before and after project implementation

A higher order relation would indicate a less efficient operation and a lower relation would indicate a more efficient operation. After project implementation the tonnes treated per kg of gold produced increased by 13.06%. The higher relation indicates a less efficient operation due to more ore having to be processed per kg of gold produced.

Mills' running time

The mills situated on a processing plant ultimately regulate the throughput of the plant on any given operational day. An analysis was done to establish whether the total amount of milling hours differs significantly before and after the project implementation. A total of four mills are in operation at a time and run for varying hours of the day due to realigning and scheduled maintenance [35]. The aim of the mills analysis was to determine if there were any notable irregularities before and after project implementation (which could influence the obtained results). A graph portraying the mills' running time and tonnes treated before and after implementation is shown in Figure 38.

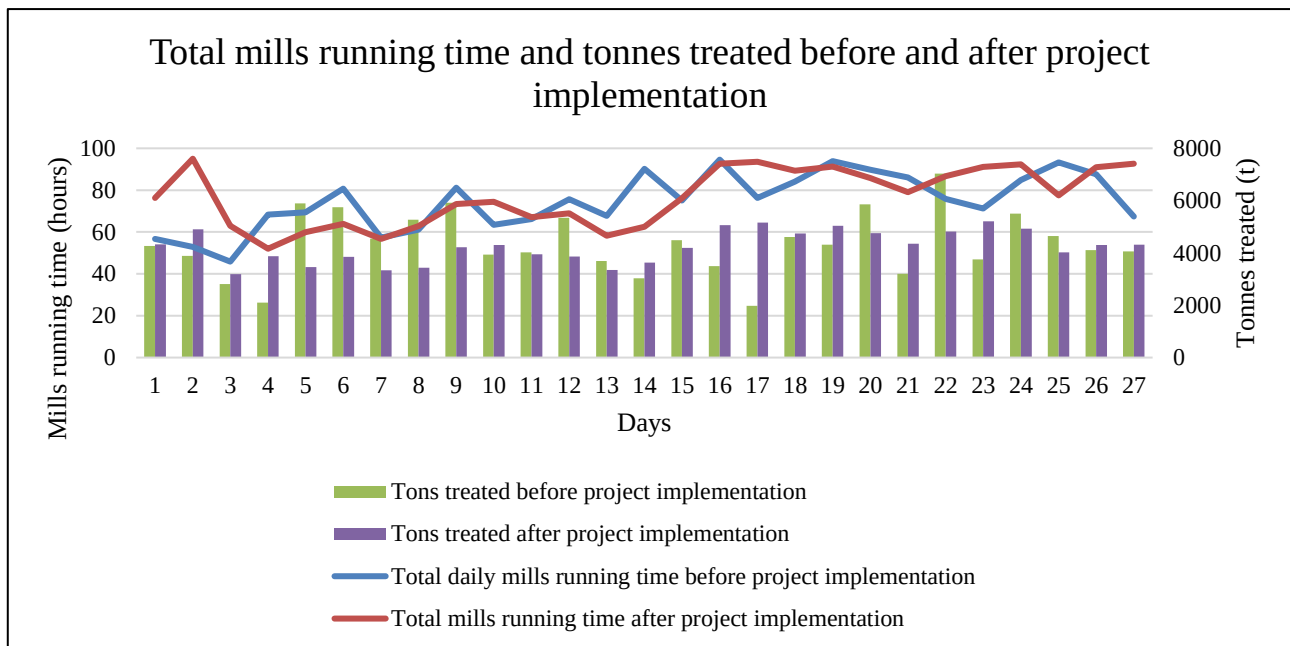


Figure 38: Comparison graph of mills' running time and ore tonnes treated before and after project implementation

The graph shows no significant irregularities in operation before and after the project implementation, which supports the conclusion of normal operation. A 2.82% increase in mills' running time is observed. When compared to the size of the industrial operation, this can be seen as negligible.

Cyanide addition

Cyanidation distribution strategies are usually empirically selected along cascading leaching tanks [83]. Cyanide distribution, therefore, needs to be determined optimally in order to maintain the best compromise between the two antagonistic effects, gold recovery and cyanide consumption [83]. The temporal change analysis for cyanide addition in leaching tanks is shown in Figure 39.

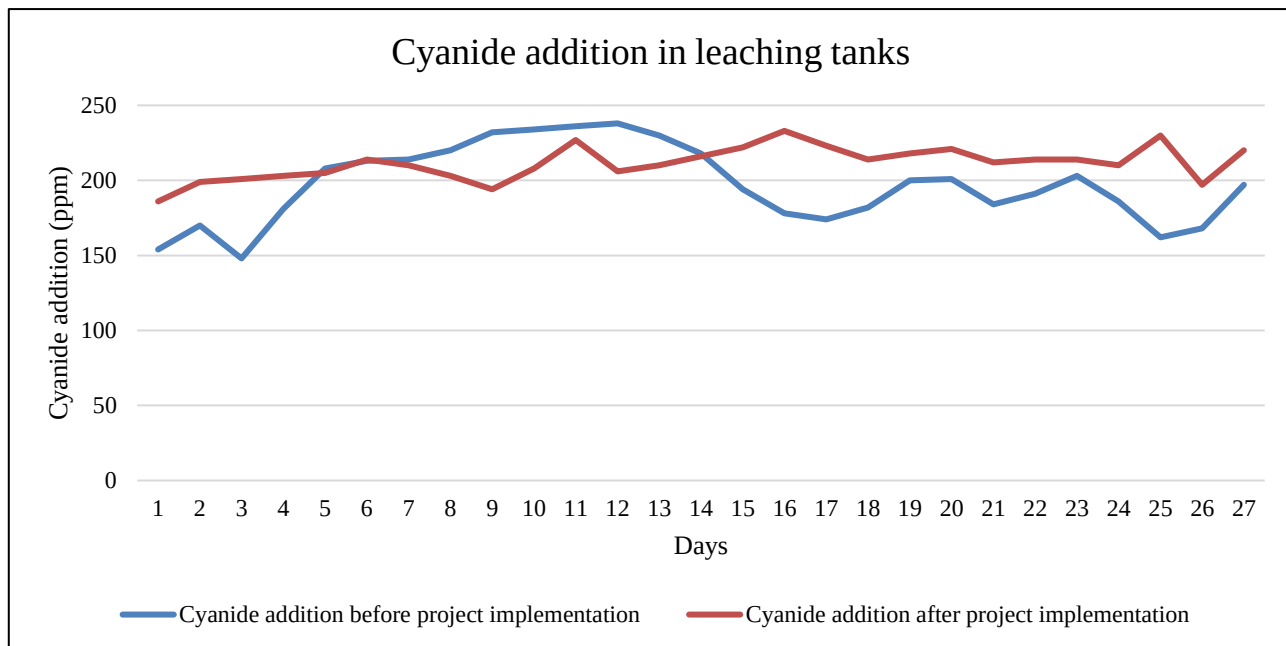


Figure 39: Graph of cyanide addition in leaching tanks before and after project implementation

The graph portrays a 7.41% increase in cyanide addition after the project implementation. Higher cyanide addition does not necessarily reflect on increased leaching rate [84]. All the uncontrolled variables listed influence gold production and residue quantities. It was, therefore, important to establish if there were any severe irregularities during the analysis period.

Lime addition and pH level

Lime, in the form of Calcium oxide (CaO), is added in the thickening dams to establish an aqueous environment at a pH of 9.5 to 11, to minimise cyanide lost by conversion to hydrogen cyanide (HCN) gas [50]. A CaO content of 150-200 ppm is normally required to achieve the desired pH level. The graph portraying the lime addition and pH levels over the analysis period is shown in Figure 40.

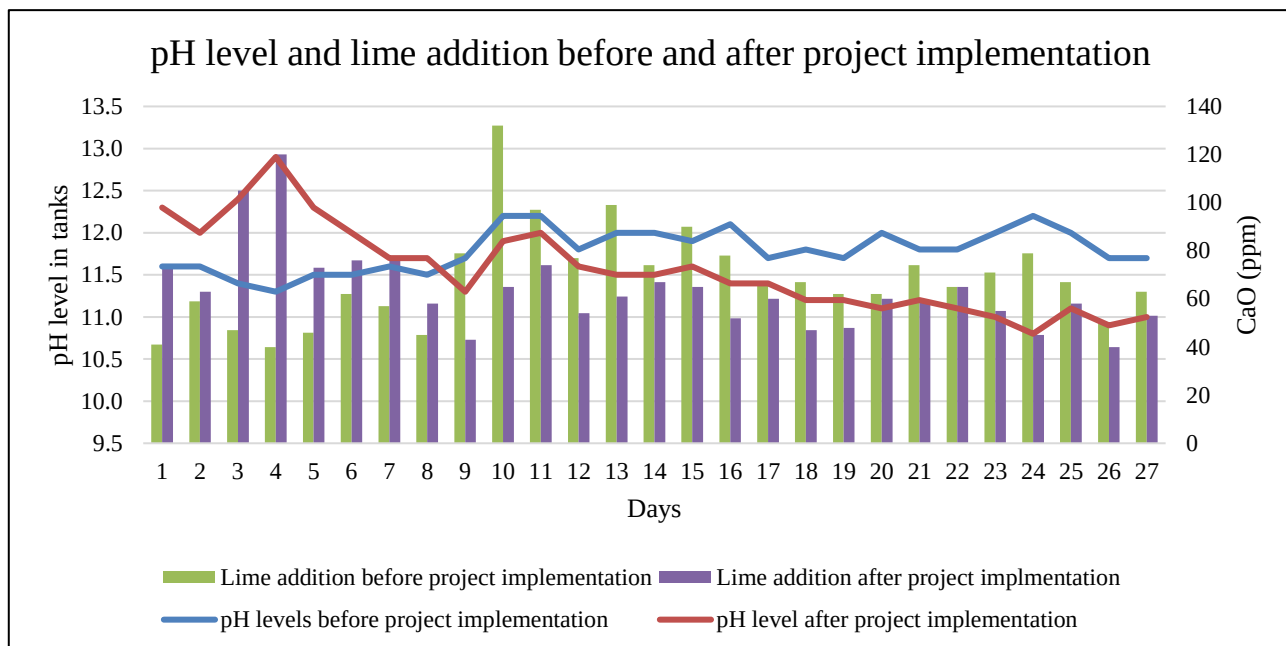


Figure 40: Comparison graph of pH level and lime addition before and after project implementation

Lime addition and pH level shows a directly proportional relationship. Lime addition increased by 7.24% and the pH level decreased by 1.69% before and after project implementation.

Inferential analysis

After analysing the specified parameters' trends over the total analysis period, the parameters need to be compared to one another. The independent variable, which is the change induced in the system, is the primary variable to which dependent and uncontrolled variables need to be compared to. Correlations can be made after which conclusions are used to validate the study. Pressure delivery is chosen as the primarily comparative variable in the study.

Pressure delivery and leaching recovery

The leaching recovery showed a 0.2% increase over the allocated analysis period. A graph portraying the daily pressure and leaching recovery trends is shown in Figure 41.

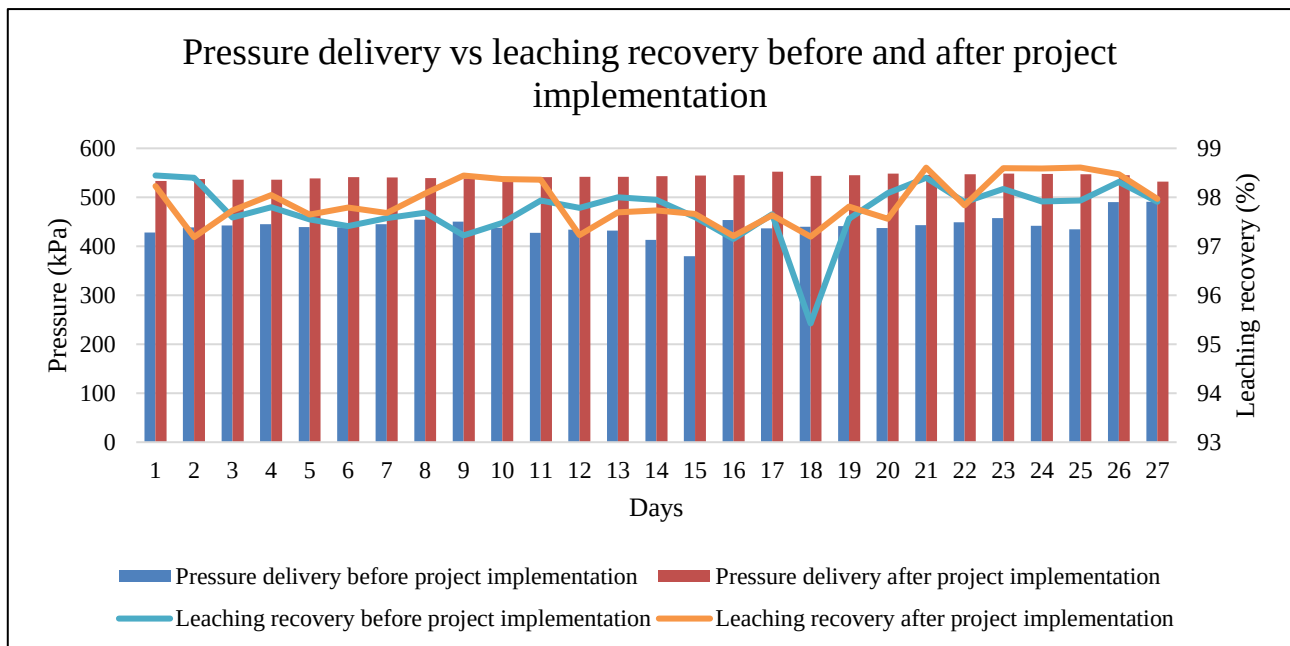


Figure 41: Comparison graph of leaching recovery and pressure delivery before and after project implementation

The graph shows a slight directly proportional relationship between leaching recovery and pressure delivery, but a definitive conclusion regarding the two parameters cannot be made due to the large-scale nature of operation and the number of uncontrolled parameters present.

Pressure delivery and production gold grade

An analysis to determine the pressure delivery relation to gold grade was conducted and is visually shown in Figure 42.

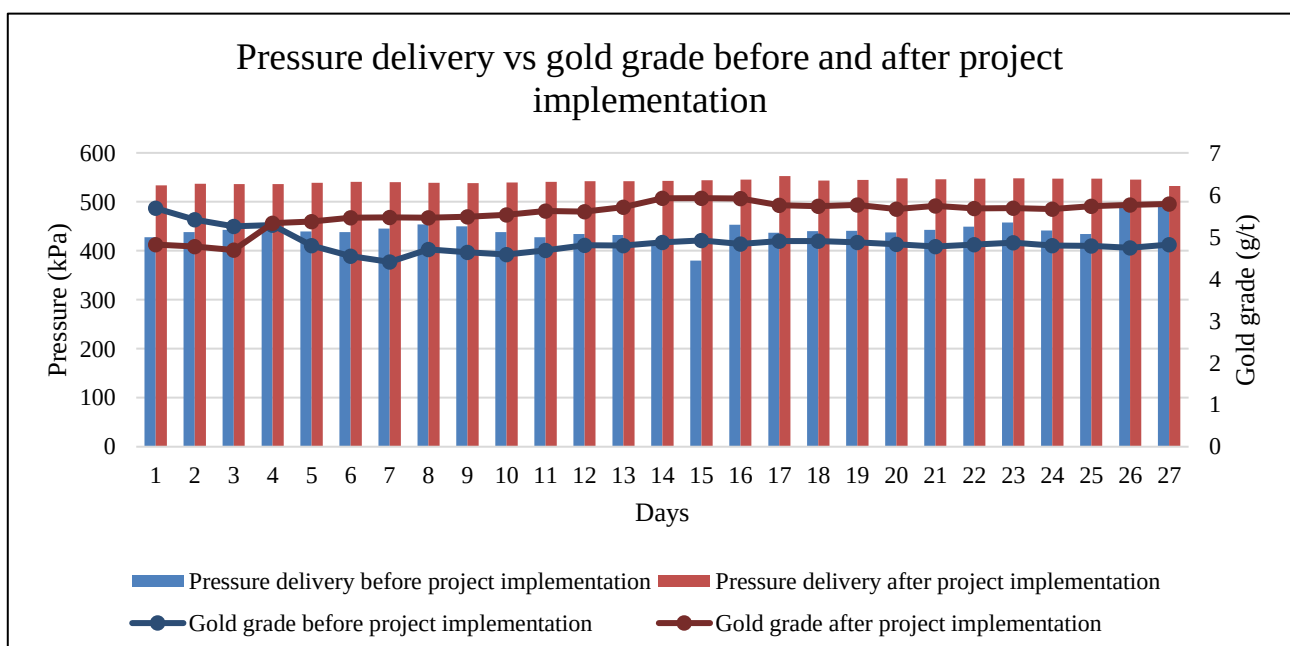


Figure 42: Comparison graph of pressure delivery and gold grade before and after project implementation

When considering the analysis independently, pressure shows a directly proportional relation to gold grade as the gold grade improved by 14.28% after the project was implemented. As previously mentioned, various parameters influence gold grade and may affect the accuracy of the results.

Pressure delivery and gold production

Figure 43 shows a graph of gold production and pressure delivery.

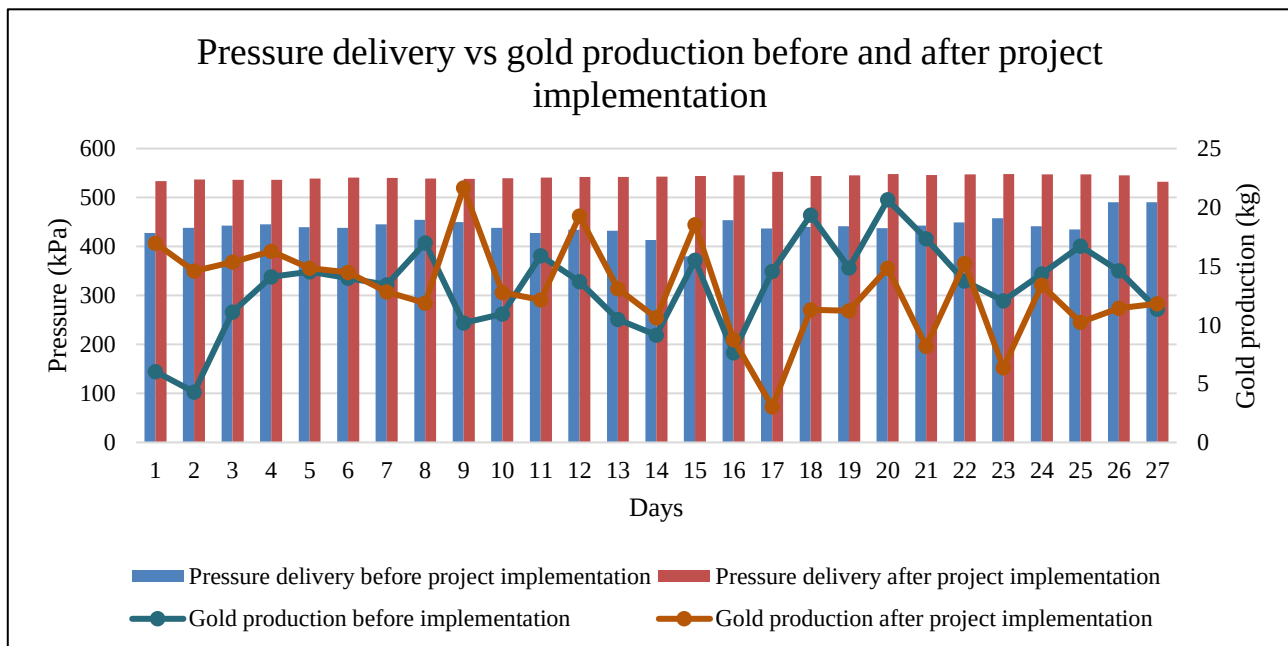


Figure 43: Comparison graph of pressure delivery and gold production before and after project implementation

As previously mentioned, gold production showed an overall decrease before and after implementation. The other end objective of the study was to establish whether less gold will be lost in the process, accumulating as residue at the bottom of leaching tanks.

Pressure delivery, residue quantity, and grade

It has already been established residue grade and residue production quantities share a directly proportional relation. A relation with the independent variable needs to be established to support results validation. Figure 44 shows a graph portraying the relationship between pressure delivery and residue quantity.

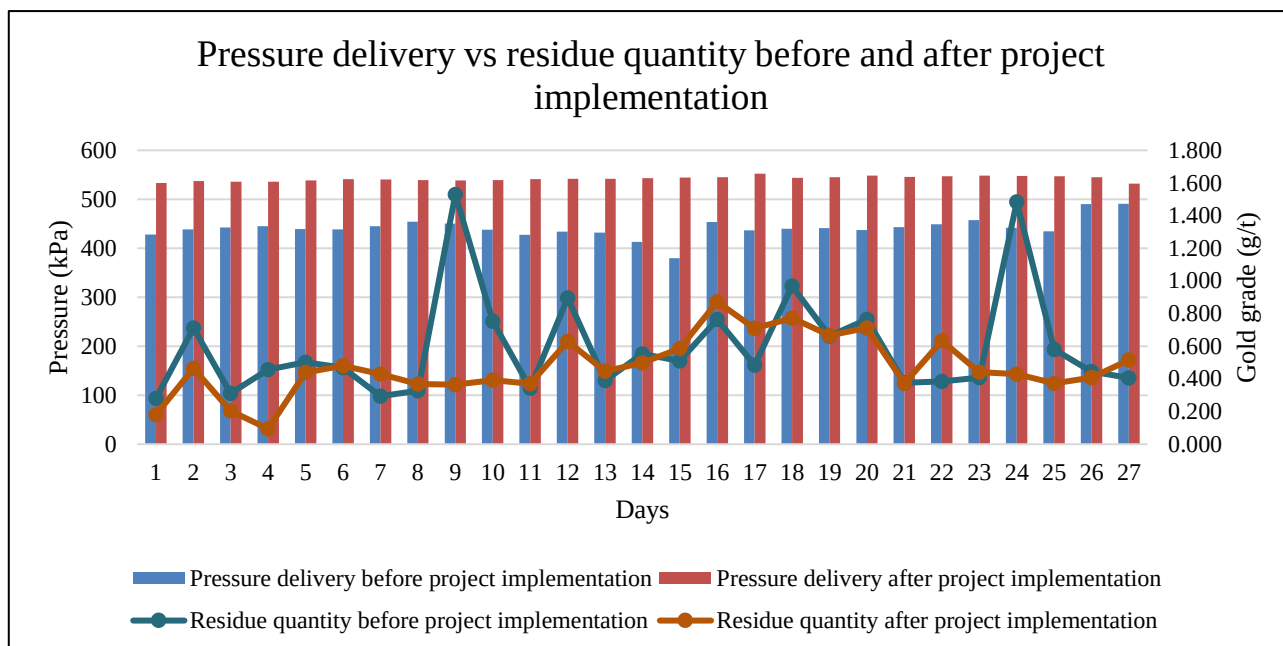


Figure 44: Comparison graph of pressure delivery and residue quantity before and after project implementation

The residue quantity decreased by 19.97 % after project implementation. This shows an inversely proportional relation when considering the parameters showed on the graph in isolation. Figure 45 contains a graph of pressure delivery and residue grade.

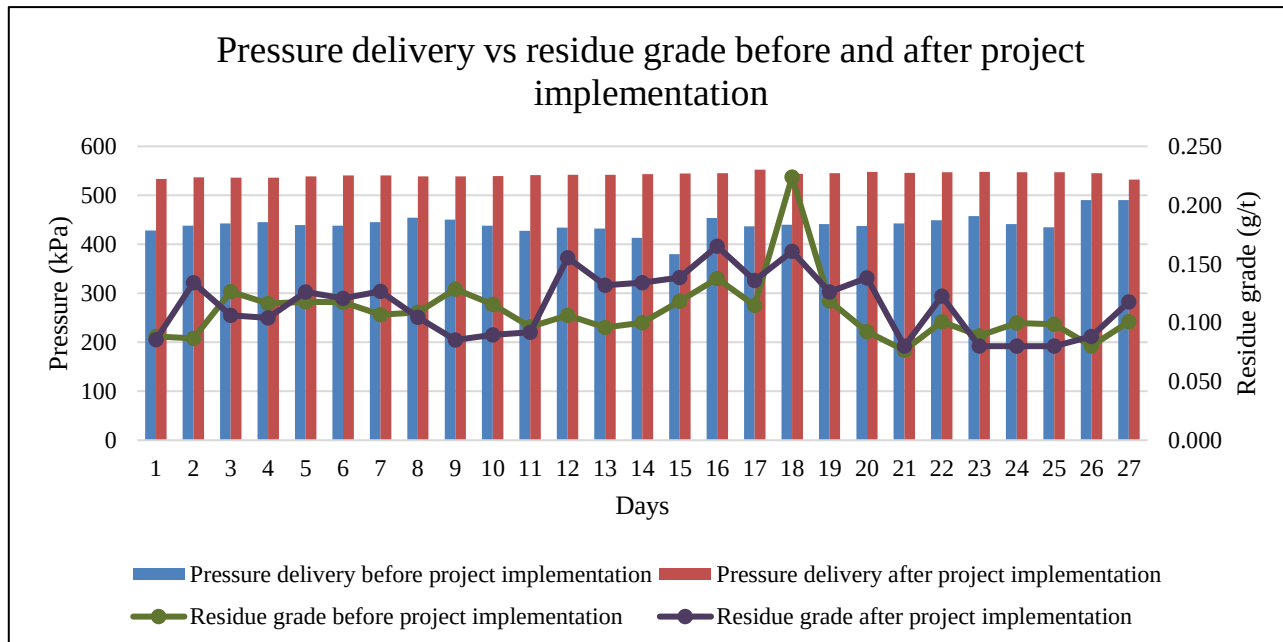


Figure 45: Comparison graph of pressure delivery and residue grade before and after project implementation

The graph indicates a 5.15 % reduction in residue grade after project implementation. The parameters listed in the graphs above all play a crucial role in the processing of gold ore to pure gold.

A summary of the results, differences, and standard deviations before and after implementation is shown below in Table 9.

Table 9: Summary of the results obtained

Variable	Average quantity before project implementation	Average quantity after project implementation	Standard deviation before project implementation	Standard deviation after project implementation	Average quantity difference	
Pressure delivery (kPa)	441.87	542.27	18.81	4.74	22.72%	increase
Gold production (kg)	13.23	12.99	3.70	3.86	1.81%	decrease
Gold residue quantity (kg Au)	0.59	0.48	0.32	0.18	19.97%	decrease
Gold production grade (g/t)	4.86	5.55	0.26	0.32	14.28%	increase
Residue grade (g/t)	0.06	0.05	0.03	0.02	5.15%	decrease
Leach recovery (%)	97.73	97.92	0.56	0.45	0.19%	increase
Tonnes hoisted (tonnes)	4211.95	4300.09	1077.12	1185.83	2.07%	increase
Tonnes treated (tonnes)	4135.05	4085.51	723.92	603.98	1.20%	decrease
Ore treated : gold produced ratio	347.38	392.75	155.17	287.72	13.06%	increase
Mills' running time (hr)	75.00	77.00	13.12	13.56	2.82%	increase
Cyanide addition (ppm)	197.00	211.00	25.34	10.89	7.41%	increase
Lime addition (ppm)	69.00	64.00	19.74	17.10	7.25%	decrease
pH level (pH)	11.80	11.60	0.25	0.51	1.69%	decrease

The results of the analysed parameters can be explained as follows:

- Pressure delivery – After the installation of the stand-alone compressor, the average pressure delivered increased by 22.72%. The standard deviation decrease substantiates that fluctuating pressures are no longer evident in the leaching tanks. The leaching tank conditions have changed and the dependent variable results will indicate whether the consequence of change had a positive or negative effect on the leaching system.
- Gold production – The overall gold production over the analysis period decreased. The standard deviation of daily gold produced did not portray a vigorous difference. It can therefore be assumed that no unforeseen events occurred during the analysis period. Various factors may have contributed to the decrease and were also listed in the table above.

- Residue quantity – The residue quantity decreased after the consequence of change occurred. The standard deviation showed a slight decrease after compressor installation. Taking into account the diminutive quantity of daily residue gold, the decrease does hold some relevance. The residue quantity decrease is a positive result but cannot be solely attribute to a pressure delivery increase.
- Gold production grade – The gold production grade portrayed an increase after the pressure delivery increase. The standard deviation between the two periods differs minutely. A higher gold production grade is beneficial to a gold plant.
- Residue grade – The residue grade after installation decreased slightly, while the standard deviation showed little change. A lower residue grade is beneficial to a gold plant as it is an indication of an efficient leaching operation.
- Leaching recovery – The leaching recovery after installation portrayed a slight increase. The standard deviation decreased slightly, which can indicate a slightly more consistent operation. A gold plant continuously attempts to enhance leaching recovery to increase production. A leaching recovery increase is therefore beneficial for operation.
- Tonnes hoisted – The tonnes hoisted by the shaft portrayed in increase. Taking into account the large-scale operation linked with hoisting, the standard deviation portrayed only a slight increase. The shaft continuously aims to achieve the hoisting targets set out by management and an increase in tonnes hoisted is therefore a positive result.
- Tonnes treated – The tonnes treated by the plant and hoisted the shaft are rarely the same value. The tonnes treated showed a decrease, which conclusively may lead to a production output decrease. The standard deviation value decreased and a conclusion of unforeseen events influencing the gold ore tonnes treated remains inconclusive.
- Ore treated : Gold produced ratio – The ore treated per kg of gold produced increased after compressor installation. The standard deviation also increased after installation. No exact conclusions can be drawn from the relation increase, but it can be logically concluded that treating more tonnes per kg of gold produced is not beneficial towards production.
- Mills' running time – The mills' running time increased and the standard deviation showed an insignificant decrease. Various factors such as maintenance scheduling, mills realignment and possible equipment failures can influence a mill's daily running time. It can therefore be concluded that an increase in mills' running time (taking shutdowns for maintenance into account), can be beneficial for plant operation.
- Cyanide addition – Cyanide addition increased after a change in the pressure delivery and showed a decrease in standard deviation. Adding more cyanide for extraction in leaching tanks adds to cyanide procurements costs and may increase the cyanide risk management activity. It is however inconclusive if cyanide addition affects gold production or residue quantities.

- Lime addition – Lime added proceeding compressor installation portrayed a decrease, while the standard deviation did not differ greatly when comparing the two analysis periods. Lime is added to prevent substantial loss of cyanide by conversion to HCN [50]. A decreased lime addition may indicate a good operating pH level. It is, however, inconclusive if lime addition influences gold production and residue quantities.
- pH level – The pH level after compressor installation decreased, while the standard deviation increased slightly. According to [50], a sufficient operating pH levels fluctuates from 9.5 – 11. The average daily value after compressor installation is closer to the desired operating range, which benefits the plant.

3.4 Conclusion

Taking the above parameters into consideration, a clear conclusion cannot accurately be drawn as to whether the consequence of non-fluctuating, higher pressure delivery to the leaching tanks directly caused the decrease in residue quantity. It can, however, be seen on the graphs that the gold residue quantities and grades decreased significantly directly after project implementation. The gold production and production grades increased significantly directly after project implementation. All these parameters stabilised after a period of approximately 4-5 days after project implementation. This refers to the hypothesis formulated in Chapter 1, which predicts a sudden decrease in residue quantities and an increase in production, followed by a stabilised profile. The results obtained portray a positive influence on residue quantities in leaching tanks which **verifies the hypothesis**. When considering all the various uncontrolled parameters listed, an overall conclusion regarding the positive influence of pressure delivery in leaching tanks cannot be accurately made.

In addition to rectifying the problem of fluctuating pressures being delivered to the plant, electrical cost savings were realised on the shaft. The electrical cost savings obtained accumulated to R 3.3 million per annum if the prescribed control philosophy is maintained on the shaft. When analysing the gold **residue quantity decrease in isolation** and not considering the critical parameters influencing the results, the residue quantity decrease adds up to R 2.43 million of gold not settled at the bottom of the tanks (when using the gold price from 28 August 2019 [85]). This value was obtained by multiplying the residue quantity decrease for the period (3.21 kg) with the per kg gold price of 28 August 2019. The study objectives set out for the study were addressed and conclusions could be drawn from the results. The successful results could not be allocated entirely to the consequence of change (pressure delivery) due to uncontrolled variables not being kept constant throughout the study.

4. Conclusion

The final chapter of this dissertation is a conclusion to the study. A procedure overview and the obtained results will be given. The results will be evaluated to determine the success of the developed system and establish whether the objectives formulated in Chapter 1 were reached. Recommendations for future work will be given to ensure follow-up studies are as accurate and successful as possible.

“People do not like to think. If one thinks, one must reach conclusions which are not always pleasant.”
– Helen Keller

4 Conclusions and recommendations

4.1 Preamble

This chapter serves as the conclusion to the dissertation and summarises the preceding chapters. The problem statement will be discussed followed by the literature review assessment. The chosen methodology will be mentioned, and conclusions will be drawn stating whether the methods chosen were successful to the nature of the study. The implementation of the developed methods will be revisited to determine the validation of the study. Recommendations for future research work will be given to increase accuracy of future studies.

4.2 Overview of the study

The initial motivation for the study was triggered by the dwindling status of the South African gold mining industry. The decline is caused by a variety of factors such as:

- Gold price volatility,
- Escalating costs of production,
- Declining gold resource grade,
- Depth and mining method, and
- Gold production.

To reduce the cost of production, it is essential for gold mines to ensure optimal operation and utilise production enhancement possibilities. High energy-consuming systems, such as the compressed air system, should be targeted and optimised to reduce energy consumption at a time when electricity prices are at a record high. The compressed air system is regarded as one of the most inefficient systems on a gold mine and directly affects production. Electrical cost savings initiatives and production enhancement possibilities are, therefore, essential in the attempts to optimise a compressed air system. Insufficient agitation caused by fluctuating pressure delivery leads to settling of ore at the bottom of leaching tanks. An increased, non-fluctuating pressure delivery was observed after project implementation. To optimise the system and the directly linked production, the following objectives were developed:

- Identify and evaluate the network inefficiencies of a shared compressed air network between the shaft and plant.
- Develop a methodology to successfully determine the effects of a non-fluctuating, increased pressure delivery to the leaching tanks.
- Evaluate the effects of mentioned pressure delivery on gold production, gold grades, and residue quantities.

- Determine the important uncontrolled/controlled variables within the CIP process which may affect the results of the study. Identifying these parameters will assist when replicating the study on a pilot-scale plant.
- Quantify the effect of the separate shaft and plant compressed air network.

To have a better understanding of the research objectives, Chapter 1 gave an overview of typical gold plant operation and the various uses for compressed air on the plant. Typical gold production enhancement techniques were discussed with special focus placed on leaching tanks. Previous studies were listed and analysed to ensure recognised work had been done on production enhancement possibilities.

From the performed literature review, essential leaching operation parameters were identified, and a methodology was developed accordingly. The methodology specifically focused on determining the correlation between the variables most essential in the leaching process. The process data after project implementation was compared to the values before the commissioning of the stand-alone compressor. A four-week period before and after project implementation was chosen to minimise the occurrence of unforeseen events and environmental conditions, while still allowing sufficient time for data results to be relevant. The hypothesis formulated predicted a decrease in the residue quantity accumulated at the bottom of the leaching tanks. The summary of results is shown in Table 10.

Table 11: Summary of the results obtained

Variable	Average quantity before project implementation	Average quantity after project implementation	Standard deviation before project implementation	Standard deviation after project implementation	Average quantity difference	
Pressure delivery (kPa)	441.87	542.27	18.81	4.74	22.72%	increase
Gold production (kg)	13.23	12.99	3.70	3.86	1.81%	decrease
Gold residue quantity (kg Au)	0.59	0.48	0.32	0.18	19.97%	decrease
Gold production grade (g/t)	4.86	5.55	0.26	0.32	14.28%	increase
Residue grade (g/t)	0.06	0.05	0.03	0.02	5.15%	decrease
Leach recovery (%)	97.73	97.92	0.56	0.45	0.19%	increase
Tonnes hoisted (tonnes)	4211.95	4300.09	1077.12	1185.83	2.07%	increase
Tonnes treated (tonnes)	4135.05	4085.51	723.92	603.98	1.20%	decrease
Ore treated: gold produced ratio	347.38	392.75	155.17	287.72	13.06%	increase
Mills' running time (hr)	75.00	77.00	13.12	13.56	2.82%	increase

Variable	Average quantity before project implementation	Average quantity after project implementation	Standard deviation before project implementation	Standard deviation after project implementation	Average quantity difference	
Cyanide addition (ppm)	197.00	211.00	25.34	10.89	7.41%	increase
Lime addition (ppm)	69.00	64.00	19.74	17.10	7.25%	decrease
pH level (pH)	11.80	11.60	0.25	0.51	1.69%	decrease

Considering the objectives set out for the study, the benefits of a split shaft and plant compressed air network were identified. A methodology to determine the effects of non-fluctuating increased pressure delivery to the leaching tanks was developed and data for the various parameters were compared before and after the project implementation. The effects of the change in pressure delivery on gold production, gold grades, leaching recovery, and residue quantities were analysed. Due to the industrial nature of the plant, the uncontrolled variables listed as most influential to the CIP process are:

- Tonnes treated,
- Tonnes hoisted,
- Mills' running time,
- Cyanide addition,
- Lime addition, and
- pH level.

All the above-mentioned values were not kept constant throughout the study and affected the accuracy of the results obtained. From the standard deviation data analysis, it can be seen that pressure fluctuated significantly less after implementation, while other parameters did not indicate a significant fluctuation after implementation. The observed fluctuation remained influential on the results. The residue quantity values compared before and after the project implementation decreased by 19.97%, while the leaching recovery increased by 0.2%. It can, however, **not be solely allocated to the change in pressure delivery** due to the listed uncontrolled variables not being constant throughout the study. Therefore, although the residue quantity before and after implementation portrays a decrease, it cannot solely be attributed to the pressure delivery change. The treated tonnes decreased which may explain the decrease in gold production. The overall decrease in residue quantity before and after implementation is 3.21 kg. When considering the results **in isolation** and portraying the obtained decrease to rand value, using the gold price from 28 August 2019 (R 758 380 p/kg) [85], the decrease of gold left in process four weeks after implementation was R 2.43 million. The added benefit from the electrical cost savings on the shaft was determined as R 3.3 million.

The hypothesis formulated in Chapter 1 is verified when analysing the residue quantities in isolation. The goal of the study, however, was to establish if the pressure delivery change would have a positive effect on production and residue quantities. The accuracy of the results on the plant were affected by the differing uncontrolled parameters and a clear conclusion as to whether the change in pressure delivery positively affected residue quantities and production could **not** be made; however, most results after implementation indicate positive results.

4.3 Recommendations

The recommendations for further studies are summarised as follows:

- The most influential uncontrolled variables affecting the leaching performance such as tonnes treated, tonnes hoisted, mills' running time, cyanide addition, lime addition, and pH level were not kept constant throughout the study. This may have influenced the accuracy of the results obtained, even though correlations on how the different parameters influence one another were made. Simulations can be used to determine the values of parameters if changed.
- It is recommended an identical study be conducted on a pilot-scale plant or controlled environment where control of parameters can easily be manipulated. All the uncontrolled parameters should be kept constant while only changing the pressure delivery (the independent variable.) Accurate results can, therefore, be obtained due to the isolation of change.
- Focus can also be placed on the most efficient size ore should be grinded to. Once an efficient ore size is achieved, where maximum contact area with cyanide addition is established, an optimal residence time can be calculated within the leaching tanks. This may further increase leaching recovery and add to the efficiency of the CIP process.
- Efficiency of plant and shaft compressed air networks can be investigated in other industries by using the implemented methodology.

5 Bibliography

- [1] Brand South Africa, "South Africa's key economic sectors," 2 January 2018. [Online]. Available: <https://www.brandsouthafrica.com/investments-immigration/business/investing/economic-sectors-agricultural>. [Accessed 26 February 2019].
- [2] Minerals council South Africa, "Key facts and figures of gold," 1 February 2019. [Online]. Available: <https://www.mineralscouncil.org.za/sa-mining/gold>. [Accessed 1 March 2019].
- [3] Thomson Reuters, "GFMS Gold survey," Thomson Reuters, London, 2018.
- [4] This is gold, "The state of the gold mining industry," This is gold, Johannesburg, 2018.
- [5] D. Nell, "Optimising production through improving the efficiency of mine compressed air networks with limited infrastructure," North-West University, Potchefstroom, 2018.
- [6] P. Neingo and T. Tholana, "Trends in productivity in the South African gold mining industry," *The Journal of the Southern African institute of Mining and Metallurgy*, vol. 116, no. March, pp. 283-290, 2016.
- [7] Gold price.org, "Gold price the past ten years," Gold price, 5 March 2019. [Online]. Available: <https://goldprice.org/gold-price-history.html>. [Accessed 6 March 2019].
- [8] J. Muller and H. Frimmel, "Numerical analysis of historic gold production cycles and implications for future sub-cycles," *The open geology journal*, vol. 4, no. January, pp. 29-34, 2010.
- [9] Minerals council of South Africa, "Facts and figures 2017," Minerals council of South Africa, Johannesburg, 2018.
- [10] Eskom, "Eskom, System adequacy reports," Eskom, 30 October 2018. [Online]. Available: <http://www.eskom.co.za/Whatweredoing/SupplyStatus/Pages/SupplyStatusT.aspx>. [Accessed 25 March 2019].
- [11] T. Niselow and L. Omarjee, "Eskom tariff hikes: Is there a light at the end of the tunnel?," News 24, Financials 24, 7 March 2019. [Online]. Available:

- <https://www.fin24.com/Economy/Eskom/eskom-tariff-hikes-is-there-light-at-the-end-of-the-tunnel-20190307>. [Accessed 3 April 2019].
- [12] A. Slabbert, “Eskom tariff increase to cost SA 5 000 jobs,” Moneyweb, 31 March 2016. [Online]. Available: <https://www.moneyweb.co.za/news/south-africa/eskom-tariff-increase-to-cost-sa-5-000-jobs/>. [Accessed 3 April 2019].
- [13] J. Bredenkamp, “An integrated energy management strategy for the deep-level gold mining industry,” Ph.D Thesis, Dept. Mech. Eng. North-West university, Potchefstroom, 2016.
- [14] M. Cetin, A. Emre, U. Atalay and K. Buyuktanur, “Bottle roll testing for cyanidation of gold ores: Problems related to standardised procedures on difficult to process ores,” in *World congress on Mechanical, Chemical and material engineering*, Rome, Italy, 2017.
- [15] S. Bogner, “Intact gold acquires historic high-grade gold project with 75000oz in BC,” Stockhouse, 23 September 2016. [Online]. Available: <https://stockhouse.com/opinion/independent-reports/2016/09/23/intact-gold-acquires-historic-high-grade-gold-project-with-75000-oz-bc>. [Accessed 19 June 2019].
- [16] J. Muller and H. Frimmel, “Numerical analysis of historic gold production cycles and implications for future sub-cycles,” *The open geology journal*, vol. 4, pp. 29-34, 2010.
- [17] C. Musingwini, “Introduction of specialisation in the mine planning and optimisation within the Master's degree,” in *Proceedings of the 6th international platinum conference*, Johannesburg, 2014.
- [18] Mining Technology, “The top ten deepest mines in the world,” Verdict media Limited, 11 September 2013. [Online]. Available: <https://www.mining-technology.com/features/feature-top-ten-deepest-mines-world-south-africa/>. [Accessed 03 May 2019].
- [19] K. Saemundsson, G. Axelsson and B. Steingrímsson, “Geothermal systems in global perspective,” in *Short course on surface exploration for geothermal resources*, Ahuachapan, El Salvador, 2009.
- [20] F. du Toit, Intermediate certificate in mine environmental control, Johannesburg: The mine ventilation society of South Africa, 2019.

- [21] Stantec, “Increase mine productivity through better shaft and hoist operation,” Stantec, 10 September 2017. [Online]. Available: <http://www.mining.com/sc/increase-mine-productivity-better-shaft-hoist-operation/>. [Accessed 08 May 2019].
- [22] M. Splaine and J. D. C. Browner, “The effect of head grade on recovery efficiency in a gold-reduction plant,” *JOURNAL OF THE SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY*, no. 1, p. 11, 1982.
- [23] Gold fields, “Integrated Annual Report 2014,” Gold fields, Johannesburg, 2014.
- [24] J. de la Vergne, *Hard Rock Miner's Handbook*, Edmonton: Stantec Consulting, January 2014.
- [25] J. Bredenkamp, “Reconfiguring mining compressed air networks for cost savings,” North-West University, Potchefstroom, 2013.
- [26] Quincy compressor, “Compressed air usage in the mining industry,” Quincy compressor, 25 January 2019. [Online]. Available: <https://www.quincycompressor.com/industries/mining/>. [Accessed 17 May 2019].
- [27] Stowe, Michael L., “Compressed air basics,” American institute of chemical engineers, Raleigh, North Carolina, 2017.
- [28] E. Arfalk, “Energy savings checklist for your compressed air system,” 1 March 2015. [Online]. Available: <http://www.thecompressedairblog.com/energy-savings-checklist-for-your-compressed-air-system>. [Accessed 24 May 2019].
- [29] H. Joubert, J. van Rensburg and G. Bolt, “Dedicated process plant compressors save energy,” *E+C Spot on*, no. April, p. 4, 2013.
- [30] H. Le Roux, “Aerator is tested on gold mine,” 12 March 2004. [Online]. Available: <https://www.engineeringnews.co.za/print-version/aerator-is-tested-on-goldmine-2004-03-12>. [Accessed 08 September 2019].
- [31] C. J. Hallet, “Oxygen mass transfer in Pachuca tanks,” University of London, London, England, 1981.

- [32] Denver Mineral Engineers, “Gold mining process development,” 20 January 2019. [Online]. Available: <https://www.denvermineral.com/gold-mining-process-development/>. [Accessed 17 May 2019].
- [33] O. Abaka-Wood, G. Ofori-Sarpong and R. Amankwah, “Siltation of ore particles in leaching tanks: Causative factors and mitigation measures,” *Ghana Mining journal*, vol. 16, no. 2, pp. 51-57, 2016.
- [34] Anglo American, “Gold mining & processing in South Africa,” AngloGold Ashanti, Johannesburg, 2008.
- [35] D. Michaud, “Ball mills,” 911 Metallurgist, 13 February 2017. [Online]. Available: <https://www.911metallurgist.com/blog/ball-mill>. [Accessed 24 September 2019].
- [36] M. Alamouti, B. Rezai and M. Noaparast, “Grindig Circuit at Mouteh Gold Mine,” *AUT Journal of Mineral Engineering*, vol. 42, no. 2, pp. 71-76, 2011.
- [37] 911 Metallurgist , “How a thickener works,” 911 Metallurgist, 22 January 2017. [Online]. Available: <https://www.911metallurgist.com/blog/how-a-thickener-works>. [Accessed 08 June 2019].
- [38] B. Gladman, S. Usher and P. Scales,”Understanding the thickening process,” *Dept. of Chemical and Biomolecular Engineering, University of Melbourne*, p. 23, 2006.
- [39] J. O. Marsden and I. C. House, *The chemistry of gold extraction*, Littleton, Colorado: Society for Mining, Metallurgy and Exploration, Inc., 2006.
- [40] UKEssays, “Agitation leaching Theory and practice biology essay,” 1 November 2018. [Online]. Available: <https://www.ukessays.com/essays/biology/agitation-leaching-theory-and-practice-biology-essay.php?vref=1>. [Accessed 8 June 2019].
- [41] J. Marsden and C. House, *The Chemistry of gold extraction 2nd Edition*, Littleton, CO: Society for Mining, Metallurgy and Exploration Inc., 2006.
- [42] A. I. Lunga, “Optimizing the operating conditions of gold elution and electrowinning for Tau Lekoa stream at Kopanang gold plant,” University of Witwatersrand, Johannesburg, 2006.

- [43] A. Stone, “Development of the continuous elution process for extraction of gold from carbon,” in *Development of the continuous elution process for extraction of gold from carbon*, Las Vegas, Nevada, 1989.
- [44] J. Steyn and R. Sandenbergh, “A study of the influence of copper on the gold electrowinning process,” *The Journal of The South African Institute of Mining and Metallurgy*, no. April, pp. 177-182, 2004.
- [45] Kemix, “Electrowinning cells,” Kemix, 10 January 2015. [Online]. Available: http://www.kemix.com/kemix_products_electrowinning.html. [Accessed 08 June 2019].
- [46] OSI Soft, “Visual KPI,” OSI Soft, 15 January 2019. [Online]. Available: <https://www.osisoft.com/marketplace/solution-detail/?id=a2K1I0000001XhHUAU>. [Accessed 8 June 2019].
- [47] S. Khaleefa Ali, H. Hamad, “Study of pressure losses in piping systems,” *International Journal of Science and Research*, vol. 8, no June, pp. 1816-1819, 2019.
- [48] J. Lodewyckx, “Investigating the effects of different DSM strategies on a compressed air ring, M.Eng Dissertation,” North West university, Potchefstroom, South africa, 2007.
- [49] W. Booysen, M. Kleingeld and J. van Rensburg, “Optimising compressor control strategies for maximum energy savings,” *Energize*, no. July, pp. 65-68, 2009.
- [50] W. Stange, “The process design of gold leaching and carbon-in-pulp circuits,” *The South African institute of ming and metallurgy*, vol. January, pp. 14-26, 1999.
- [51] P. Laxen, “Carbon-in-pulp processes in South Africa,” *Hydrometallurgy*, vol. 13, pp 169-192, 1984.
- [52] G. Young, “The extraction metallurgy of gold in South Africa,” *South African institute of mining and metallurgy*, 1987.
- [53] J. Schubert, I. Barker and C. Swartz,”Performance evaluation of a corbon-in-pulp plant by dynamic simulation,” *Journal of the South African Institute of Mining and Metallurgy*, vol. 93, no. 11/12, pp 293-299, 1993.

- [54] L. Woollacott, W. Stange and R. King, “Towards more effective simulation of CIP-CIL processes, Part 1: The modelling of adsorption and leaching,” *Journal of the South African institute of mining and metallurgy*, no. October, 1990.
- [55] P. Bailey, “Application of activated carbon to gold recovery,” in *Extractive metallurgy of gold in South Africa*, Johannesburg, South African Institute of mining and Metallurgy, 1989, p. Chapter 9.
- [56] T. Aitimbitov, D. White and I. Seth, “Biological gold recovery from gold-cyanide solutions,” *International journal of mineral processing*, vol. 76, no. 2005, pp. 33-42, 2004.
- [57] 911 Metallurgist, “How to use Aqua regia to purify gold,” 911 Metallurgist, 15 January 2017. [Online]. Available: <https://www.911metallurgist.com/blog/how-to-use-aqua-regia-to-purify-gold>. [Accessed 19 June 2019].
- [58] M. Dehchenari, S. Hosseinpour, R. Ali, N. Iran and M. Mehdipour, “Simple method for extracting gold from electrical and electronic wastes using hydrometallurgical process,” *Environmental Health Engineering and Management Journal*, vol. 4, 2017.
- [59] O. Nunan, I. Viana, G. Peixoto, H. Ernesto, D. Verster, J. Pereira, J. Bonfatti and L. Teixeira, “Improvements in gold ore cyanidation by pre-oxidation with hydrogen peroxide,” *Journal for Minerals engineering*, vol. 108, no. February, pp. 67-70, 2017.
- [60] M. Jeffrey, P. Breuer and C. Chu, “The importance of controlling oxygen addition during the thiosulfate leaching of gold ores,” *International Journal of Mineral Processing*, vol. 72, no. 2003, pp. 323-330, 2003.
- [61] K. Konadu, G. Abaka-Wood and G. Ofirisarpong, “Gold losses due to silt formation in leaching tanks,” in *Proceeding of the 3rd UMaT Biennial International Mining and Mineral conference*, 2014.
- [62] D. Walsh, “A study of the factors suspected influencing the settling velocity of fine gold particles,” University of Alaska, Fairbanks Alaska, 1988.
- [63] B. Ersoy, “Effect of pH and Polymer Charge Densities on Settling Rate Turbidity of Natural Stone Suspensions,” *International Journal of Mineral Processing*, pp. 207-216, 2004.

- [64] J. Song, F. Wang, X. Li, L. Zhao and W. Li, “Influence of ball milling parameters on the refined effect of quartz sand,” in *Second International Conference on Materials, Mechatronics and Automation Lecture Notes in Information Technology*, 2012.
- [65] M. Larsson, A. Hill and J. Duffy, “Suspension stability: Why particle size, Zea Potential and Rheology are important,” *Annual Transactions of the Nordic Rheology Society*, vol. 20, no. 2012, p. 6 pp, 2012.
- [66] Schwarz and Zchimmer, “Mechanisms of action of deflocculants and dispersants in ceramic bodies,” Ceramics, GmbH & Co, Lahnstein, Germany, 2009.
- [67] M. Latva-Kokko, R. T. Hirsi and J. Tiuhonen, “Improving the process performance of gold cyanide leaching reactors,” in *World gold conference*, 2015.
- [68] L. Michaud, “911 Metallurgist: Pachuka Tank,” 911 Metallurgist, 11 June 2016. [Online]. Available: <https://www.911metallurgist.com/blog/pachuca-tanks>. [Accessed 9 July 2019].
- [69] S. Mehrotra and R. Shekhar, “Studies on particle suspension in air-agitated Pachuca tanks,” *Processing of fines*, vol. 2, pp. 345-361, 2000.
- [70] M. R. T. Latva-Kokko and J. Vaarno, “Stirred tank reactor,” Outotec, 2014.
- [71] C. M.W, “Solids suspension behaviour in profiled bottom and flat bottom mixing tanks,” *Chemical Engineering Science*, vol. 40, no. 3, pp. 385-392, 1985.
- [72] H. Van Dam, “Durability of gold recovery carbons, testing methods and results,” *Engineering and Mining Journal*, vol. 1994, no. August, pp. 34-35, 1994.
- [73] M. Coetzee and F. Cloete, “A comparison of axial flow impellers with inclined blade turbines in a baffled mixer,” *Journal of the South African Institute of Mining and Metallurgy*, vol. 89, no. 4, pp. 99-109, 1989.
- [74] Direct industry, “Kimo manufacturers,” Direct industry, [Online]. Available: <http://www.directindustry.com/tab/kimo.html?suggest=694a5158387871577466666374723353383476506a773d3d>. [Accessed 31 10 2019].

- [75] Hanna Instruments, “Calcium and magnesium poertable photometer,” Hanna instruments, [Online]. Available: <https://hannainst.com/hi96752-calcium-and-magnesium-portable-photometer.html>. [Accessed 31 10 2019].
- [76] B&W Technologies , “Amazon- Technologies,” B&W Technologies, [Online]. Available: <https://www.amazon.ca/Technologies-GAXT-Z-DL-GasAlert-Hydrogen-Measuring/dp/B00ANVCG4O>. [Accessed 31 10 2019].
- [77] Selectech, “pH portable meter,” Selectech, [Online]. Available: <https://selectech.co.za/product/ph-portable-meter-sensodirect-ph300/>. [Accessed 31 10 2019].
- [78] D. Michaud, “Cyanide bottle roll leach test,” 911 Metallurgist, 24 June 2015. [Online]. Available: <https://www.911metallurgist.com/blog/bottle-roll-leach-test-leaching-procedures>. [Accessed 13 September 2019].
- [79] P. Fu, Z. Li and Z. Bian, “Recovery of Gold and Iron from Cyanide Tailings with a Combined Direct Reduction Roasting and Leaching Process,” *Metals*, p. 13, vol. 8, no. 561, 2018.
- [80] Harmony Gold, “Operations FY 18,” Harmony gold mining company Ltd., Johannesburg, 2018.
- [81] N. Lioudis, “What does the grade of a gold mine refer to Investopedia,” Investopedia, 25 June 2019. [Online]. Available: <https://www.investopedia.com/ask/answers/022315/what-does-grade-gold-mine-refer.asp>. [Accessed 19 September 2019].
- [82] C. Zanbank, “Heap leaching technique in mining,” Euromines, Turkey, 2012.
- [83] L. de Andrade Lima and D. Hodouin, “Simulation study of the optimal distribution of cyanide,” *Minerals Engineering*, vol. 19, no. January, pp. 1319-1327, 2006.
- [84] Y. Kianinia, M. Khalesi Reza, M. Abdollahy and G. Hefter, “Predicting cyanide consumption in gold leaching: A kinetic and thermodyanic approach,” *Minerals*, vol. 8, no. 110, p. 19, 2018.
- [85] GoldHub, “Gold prices,” Goldhub, 4 November 2019. [Online]. Available: <https://www.gold.org/goldhub/data/gold-prices>. [Accessed 6 November 2019].
- [86] P. Breuer and M. Jeffrey, “Copper catalysed oxidation by oxygen in gold leach solutions,” *Journal of minerals engineering*, vol. 16, no. 1, pp. 21-30, 2003.

- [87] J. Byerley and S. Fouda, “Activation of copper (II) amine complexes by molecular oxygen for the oxidation of thiosulfate ions,” *Journal of the chemical society*, no. 1975, pp. 1329-1338, 1975.
- [88] C. Chu, P. Breuer and M. Jeffrey, “The impact of thiosulfate oxidation products on the oxidation of gold in ammonia thiosulfate solutions,” *Journal of minerals engineering*, vol. 16, no. 3, pp. 265-271, 2002.

APPENDIX A

The Figures in Appendix A were added to provide additional background information on factors contributing to dwindling production, both globally, and in SA. The factors are summarised in bullet form on Page 4-6 in Chapter 1. Gold price decline – The graph in Figure 46 illustrates a decline in gold price compared to the Dollar value, but illustrates an increase compared to Rand value.

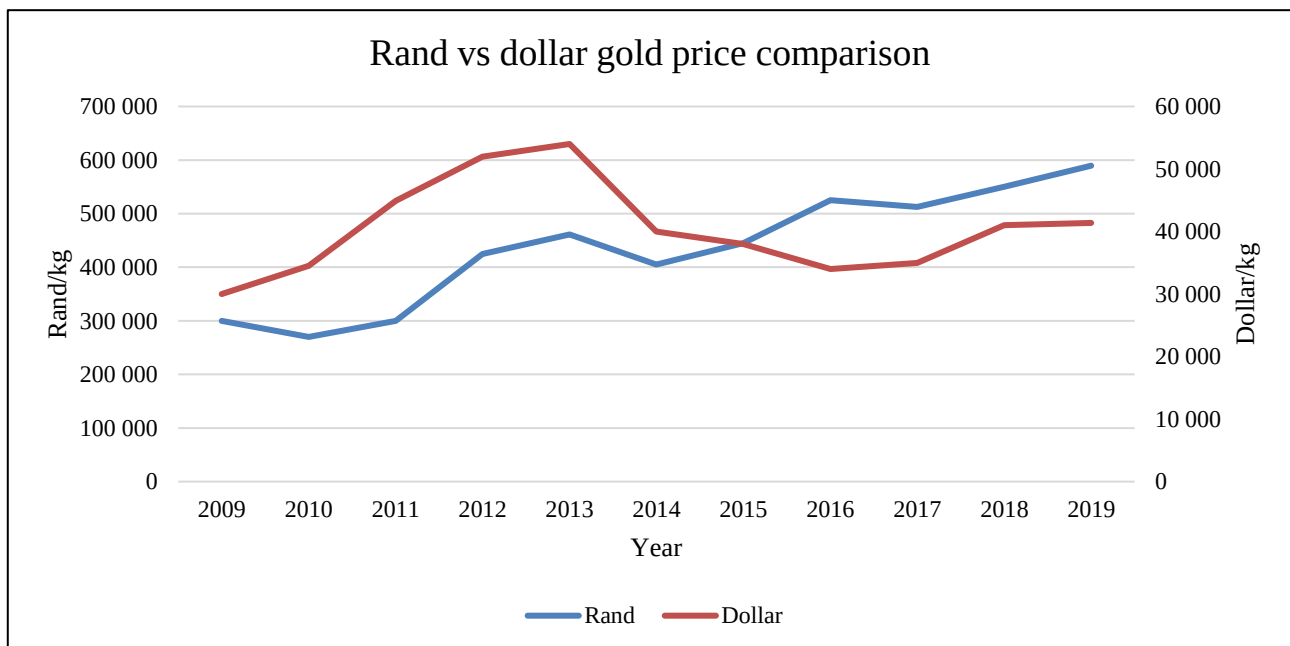


Figure 46: Rand vs dollar gold price comparison [7]

Mine expenses breakdown – The graph in Figure 47 illustrates the percentage electricity contributes to a deep-level gold mine's total expense.

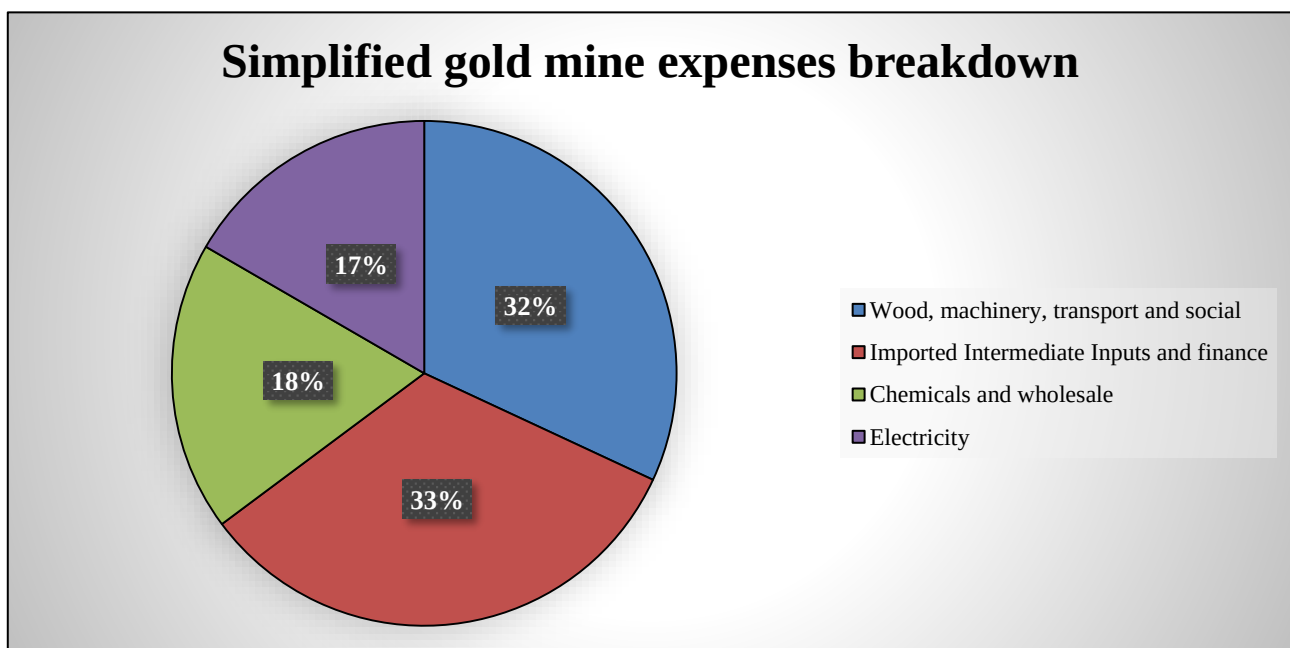


Figure 47: Breakdown of a gold mine's input expenses [9][10]

Eskom tariff increases and mining GDP percentage – The graph in Figure 48 illustrates the yearly Eskom tariff increase and Eskom revenue as percentage of total mining GDP.

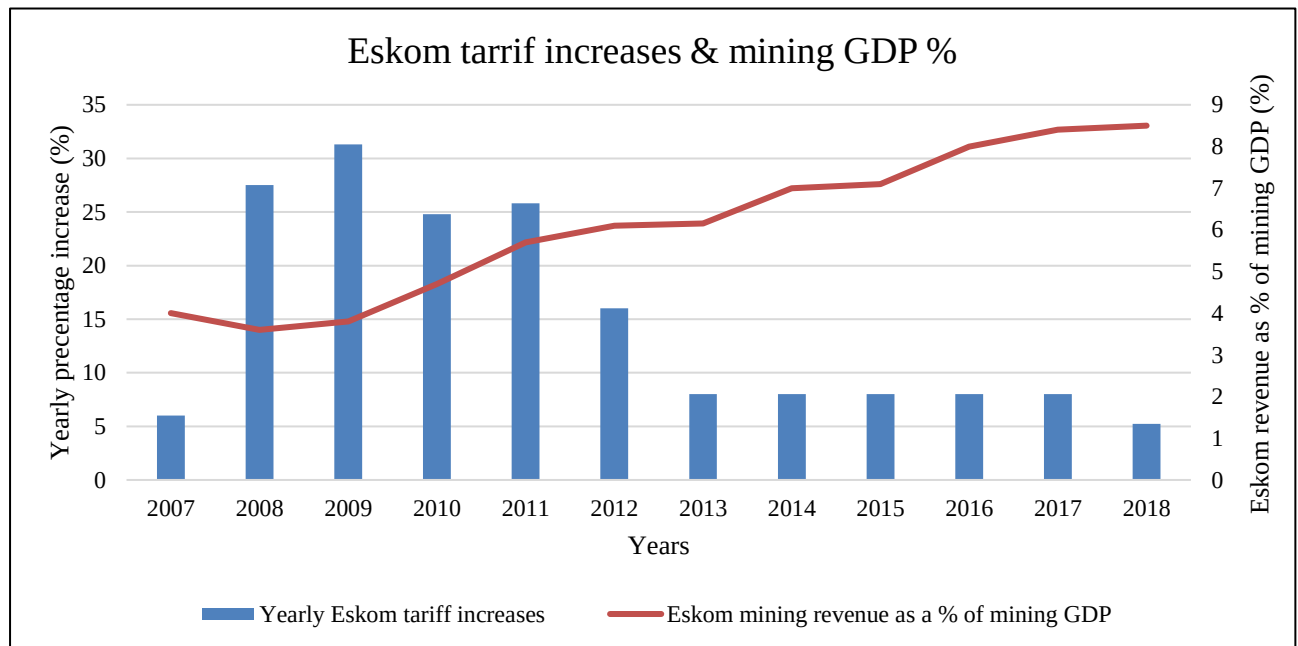


Figure 48: Yearly Eskom tariff increases and Eskom revenue as % of mining GDP [11][12]

Electricity usage breakdown – The graph in Figure 49 illustrates the breakdown of a deep-level mine's electricity usage.

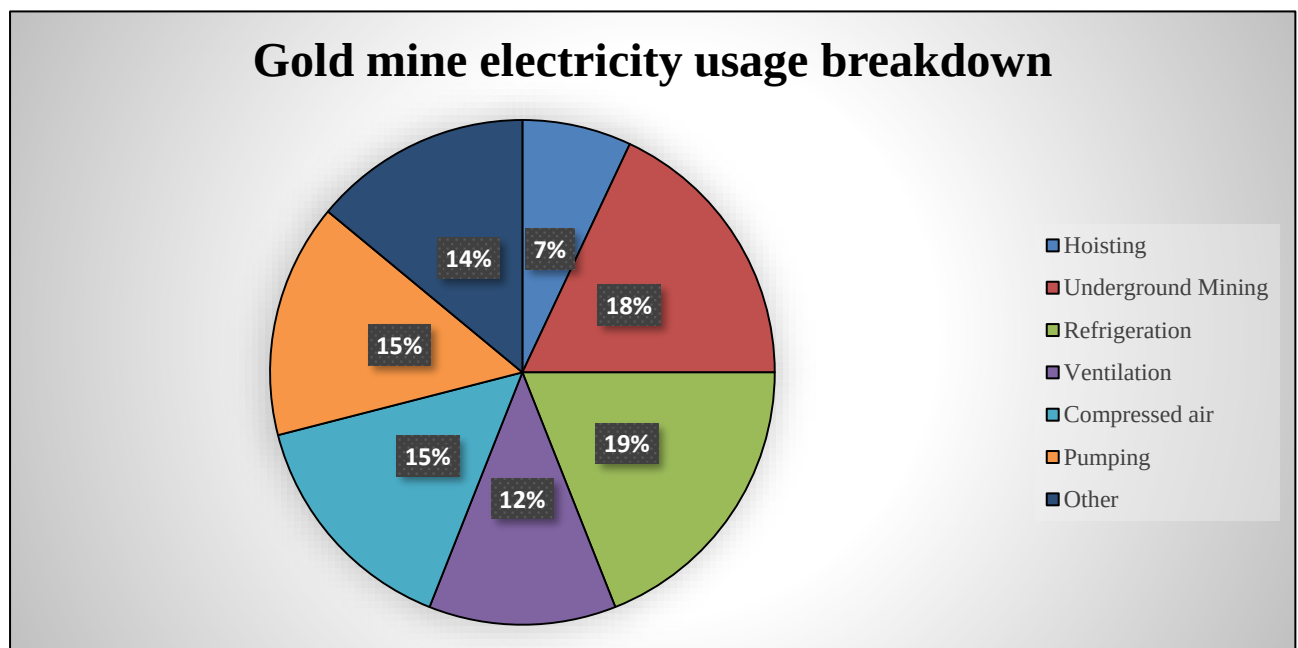


Figure 49: Electricity usage breakdown on a gold mine [13]

Global resource grade decline – The graph in Figure 50 illustrates the decline in global average gold grade.

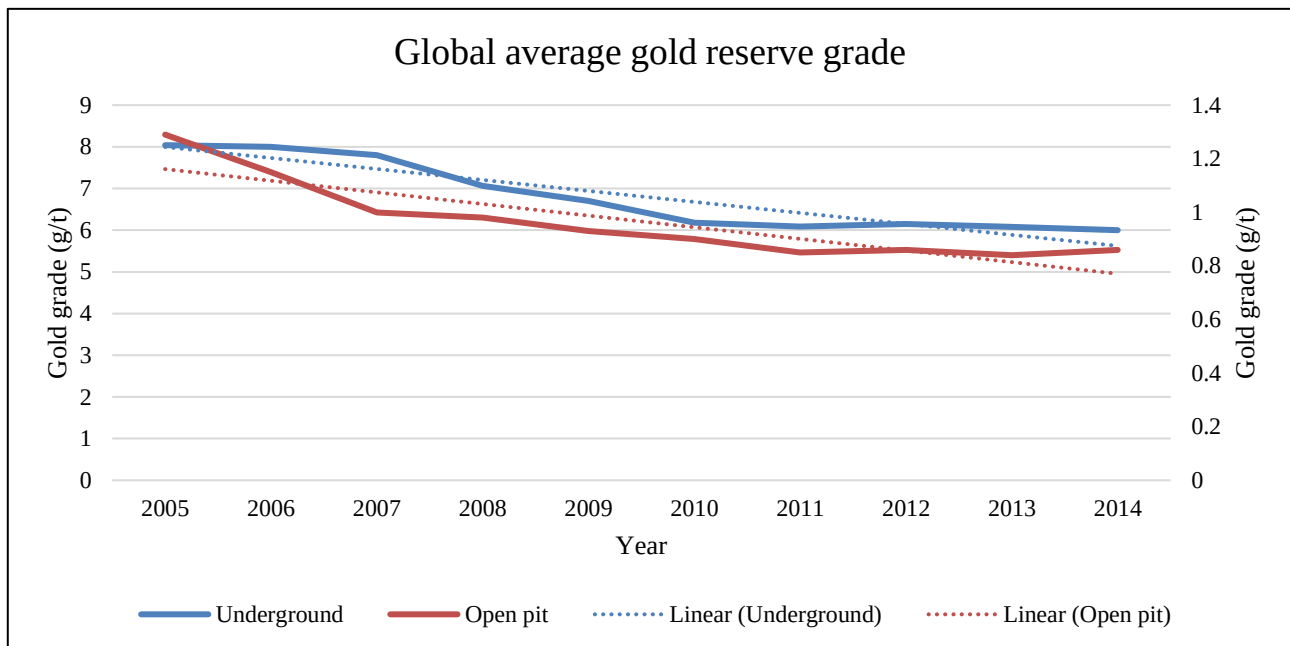


Figure 50: Average global gold reserve grade [15][16]

South African resource grade decline – The graph in Figure 51 indicates the average value of South African gold grade on deep-level gold mines over the past decade.

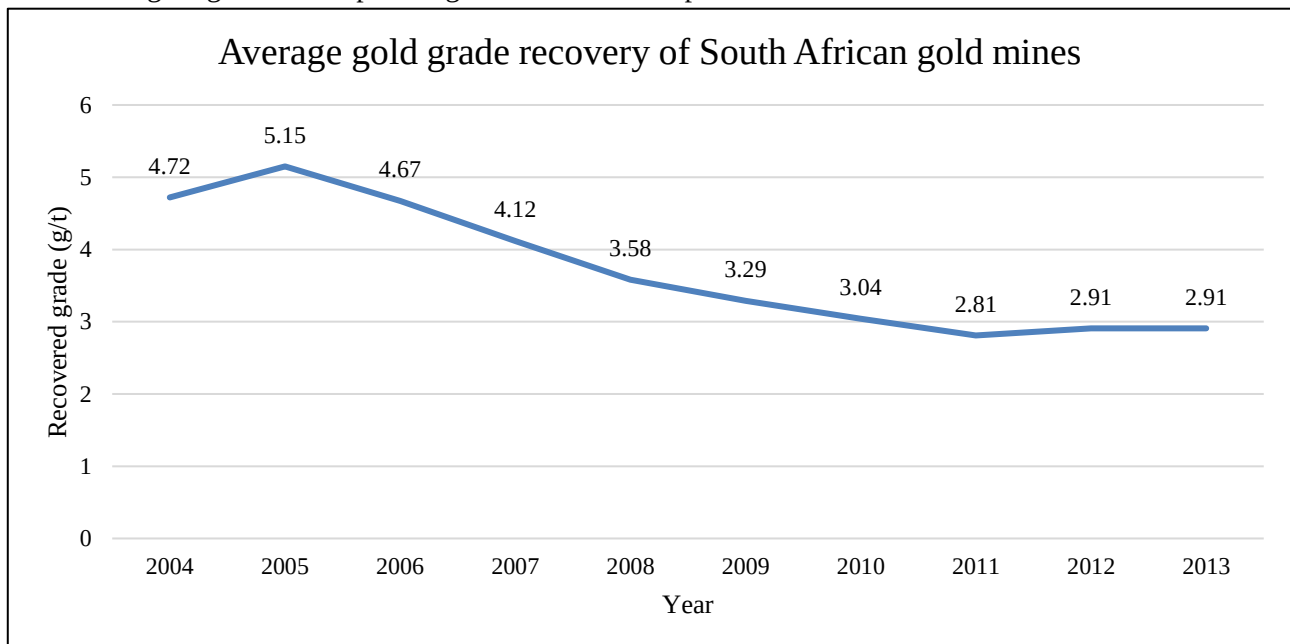


Figure 51: Average gold grade recovery of South African gold mines [17]

Targeted reefs on a typical gold mine – Figure 52 illustrates the typical different mining locations on a gold reef. The obtained gold grade may differ depending on location as explained on Page 5.

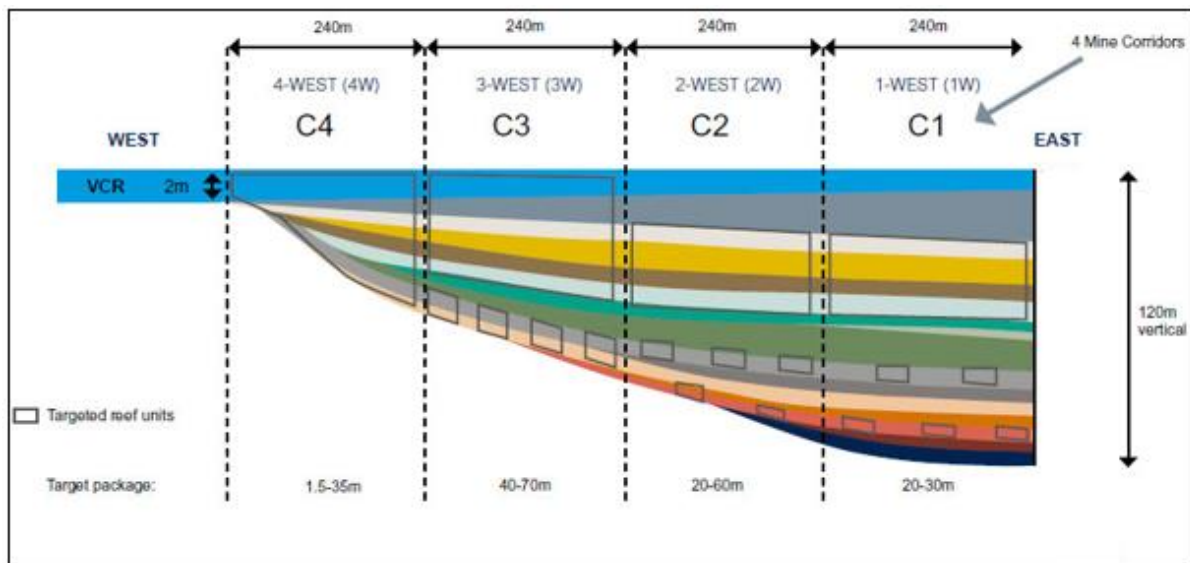


Figure 52: Various targeted reefs at gold mines [23]

Figure 53 illustrates the regression analysis done of residue quantity vs gold production.

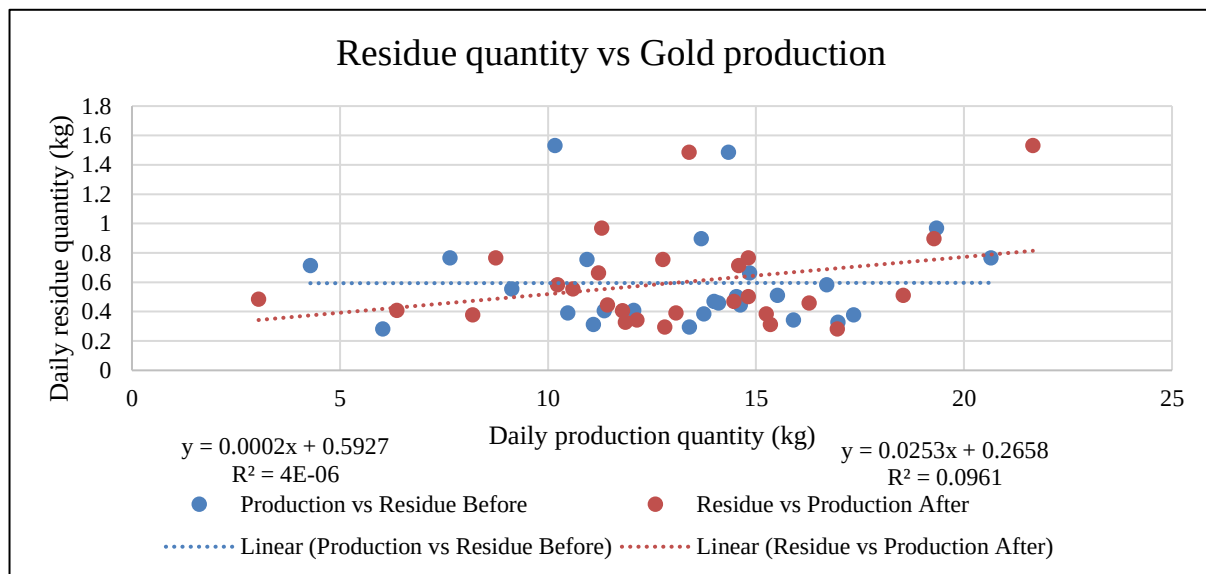


Figure 53: Regression analysis graph of residue quantity vs gold production

The regression analysis results does not indicate any clear correlation between residue quantity and gold production. Linear, power, exponential and polynomial trendlines were used for an attempted usable correlation. The scale of the operation rendered the achievement of a distinct correlation very difficult and led to the regression analysis being inconclusive. A regression analysis of the data can be replicated on a pilot-scale plant where possible correlations may emerge. Refer to Page 66 for more information.

APPENDIX B

The Importance of controlling oxygen-addition during the thiosulfate leaching of ores

The study entails using a copper-ammonia thiosulfate system for gold leaching enhancement purposes. Solutions containing copper, ammonia and thiosulfates have continuous chemical changes due to the homogenous reaction between copper and the thiosulfate [60]. It is known that the gold leaching rate decreases as the reaction between copper and thiosulfate progresses. The use of oxygen, to re-oxidise the copper, to increase the leaching rate of gold will be investigated [60]. The cyanidation method of gold extraction is one of the most common methods used for hydrometallurgical recovery of gold. Due to the toxicity of cyanide, investigations for alternative lixivants were launched. In order to use thiosulfate as an alternative lixiviant, the fundamental aspects of a thiosulfate leaching system need to be properly understood [60]. During the study, the fundamental issues regarding thiosulfate leaching of gold is addressed. The role oxygen plays in the regeneration of copper will be the focus point [60].

Experimental procedure

The experiments were done using solutions prepared from analytical grade reagents and distilled water. The experimental temperature was kept at 30°C, while the solutions consisted of 0.2 M sodium thiosulfate, 0.4 M ammonia and 10 mM copper [60]. The pH of the solution remained primarily consistent throughout the experiments at 11.4. In each case, the ammonia was mixed with the copper before addition to the thiosulfate solution. A rotating electrochemical quartz crystal microbalance at a rotational speed of 300 rpm was used during the experiments [60]. A UV – VIS spectrophotometer was used to monitor the copper-amine complex. The gold powder used was prepared by means of reductive precipitation of gold from a gold chloride solution using sodium disulfate. 5mg of gold with 100ml of solution was used for the powder leaching experiments [60]. Therefore, after the leaching process is complete, the solution will contain 50 ppm of gold. Roasted gold ore consisting of 80-90 g/t of gold was used for the ore leaching experiments [54]. A 30 g portion of solid was mixed with 70 ml of solution, and solution assays were performed at frequent time intervals using the AAS. An enclosed reactor was used for both the ore leaching and powder leaching experiments, where agitation was supplied by a 500 rpm magnetic stirrer [60].

Results and discussion

Three parameters were evaluated during the analysis of the results. These parameters are [60]:

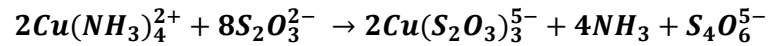
1. The interaction of the solution chemistry and gold leaching effects in the absence of oxygen.

2. The minimising of the copper-thiosulfate rate.
3. Solution chemistry and leaching effects in the presence of oxygen.

The interaction of solution chemistry and gold leaching in the absence of oxygen

Copper oxidises thiosulfate according to Equation 15 below:

Equation 15: Copper-thiosulfate oxidising reaction [60]



The absence of ammonia renders the reaction to be rapid, with the copper being consumed in only a few seconds of mixing with the thiosulfate [54]. When ammonia is present, the reduction of copper by the thiosulfate is significantly slower. The copper concentration profile in the presence and absence of ammonia can be seen in Figure 54. Oxygen was excluded from the experiments [60].

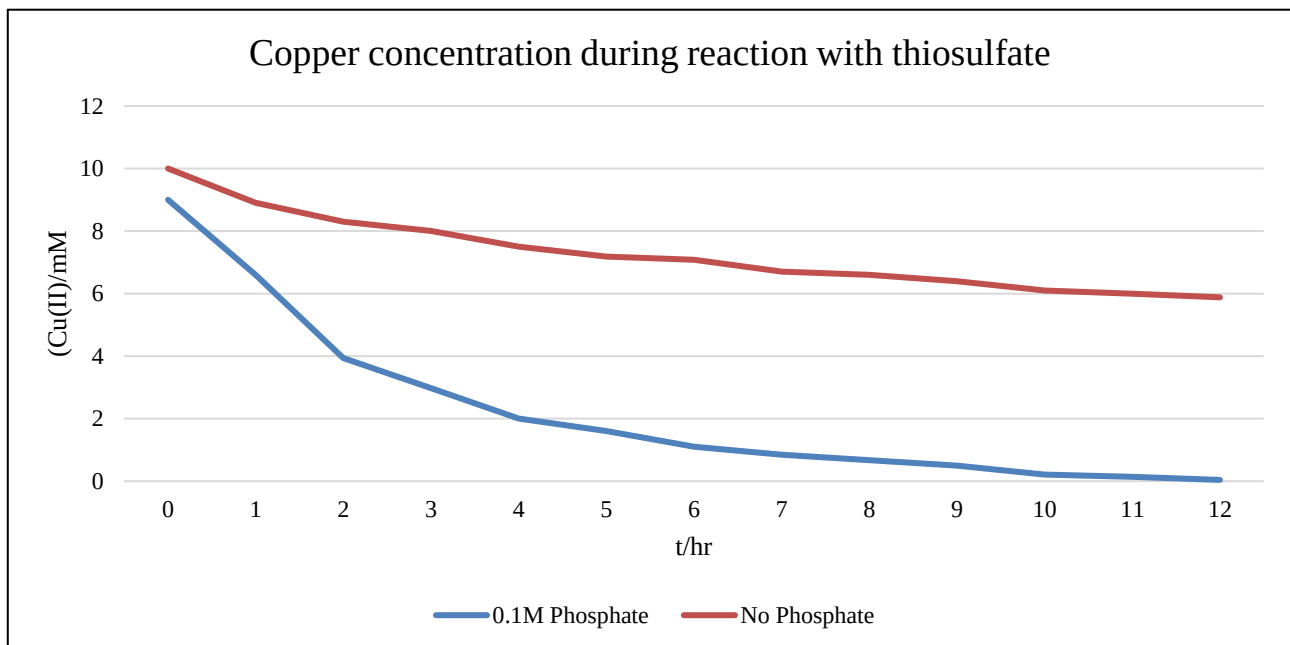


Figure 54: Graph of copper concentration during a reaction with thiosulfate [60]

The decrease in thiosulfate is not essential, since the thiosulfate was in substantial excess of copper. The decrease in copper influences the rate of gold leaching, as copper is used as the oxidant. The effect the decrease in copper has on gold leaching can be seen in Figure 55, where leaching rate and mixed potential is indicated as a function of time.

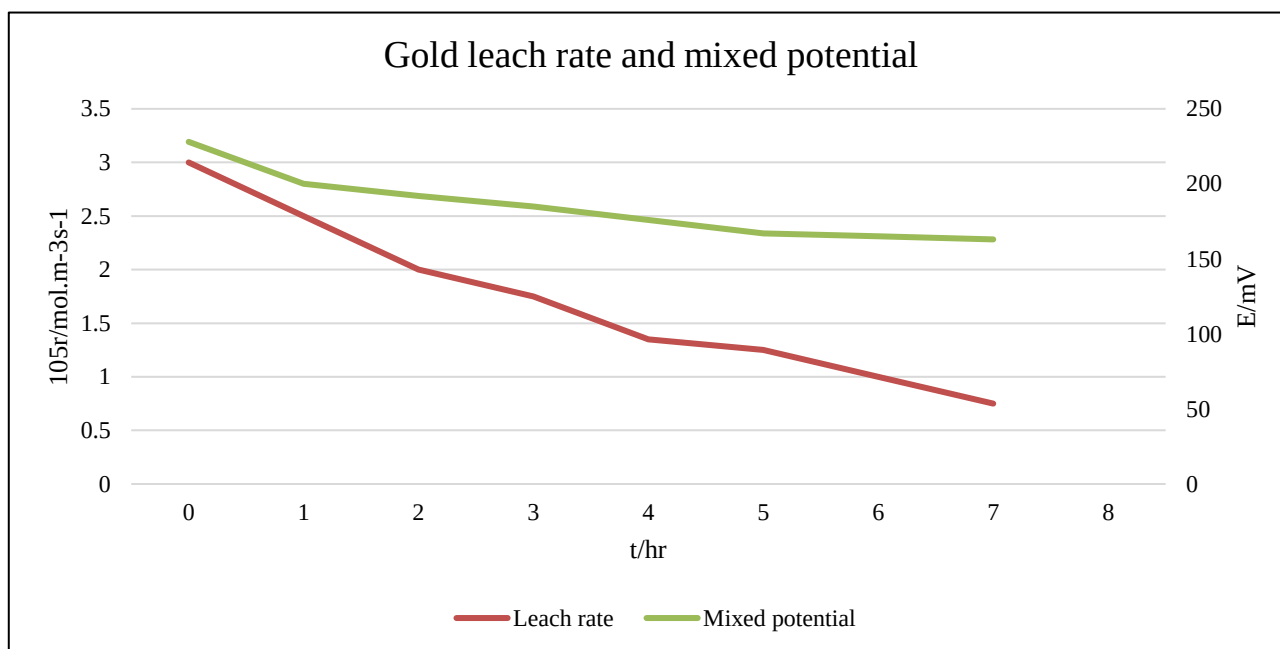


Figure 55: Graph of gold leaching rate and mixed potential as a function of time [60]

The initial potential is 227mV and decreases as copper reacts with the thiosulfate to decrease the potential to 165mV after 6 hours. The gold leaching rate is decreased to a third of what it initially was. Leaching should not be done under these conditions as good leaching kinetics are only observed for a limited time [60]. The reaction rate of copper and thiosulfate needs to be addressed.

Minimising the reaction rate between copper and thiosulfate

The reaction between copper and thiosulfate is an inner coordination sphere reaction [60]. For thiosulfate oxidation to occur, bonding to an axial site is required. The proposed mechanism for the reaction between copper (II)-thiosulfate in the conducted experiments is shown in Figure 56.

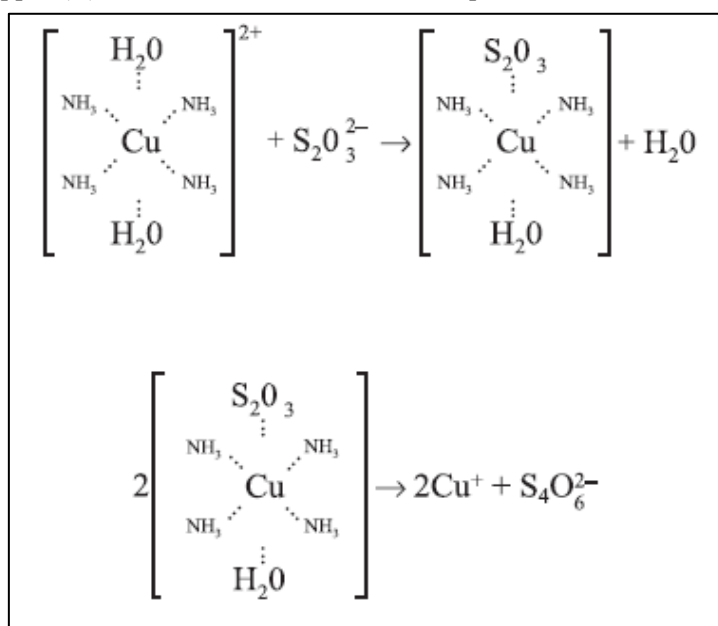


Figure 56: The proposed mechanism for the reaction between copper (II)-thiosulfate [60]

An axial site can also be coordinated by using other anions such as chloride, sulfate, and phosphate. Phosphate has been found to reduce the rate of copper reduction as can be seen in Figure 62 above. Leaching tests were carried out in the solution containing 0.1 M phosphate [60]. The results from the leaching tests can be seen in Figure 57.

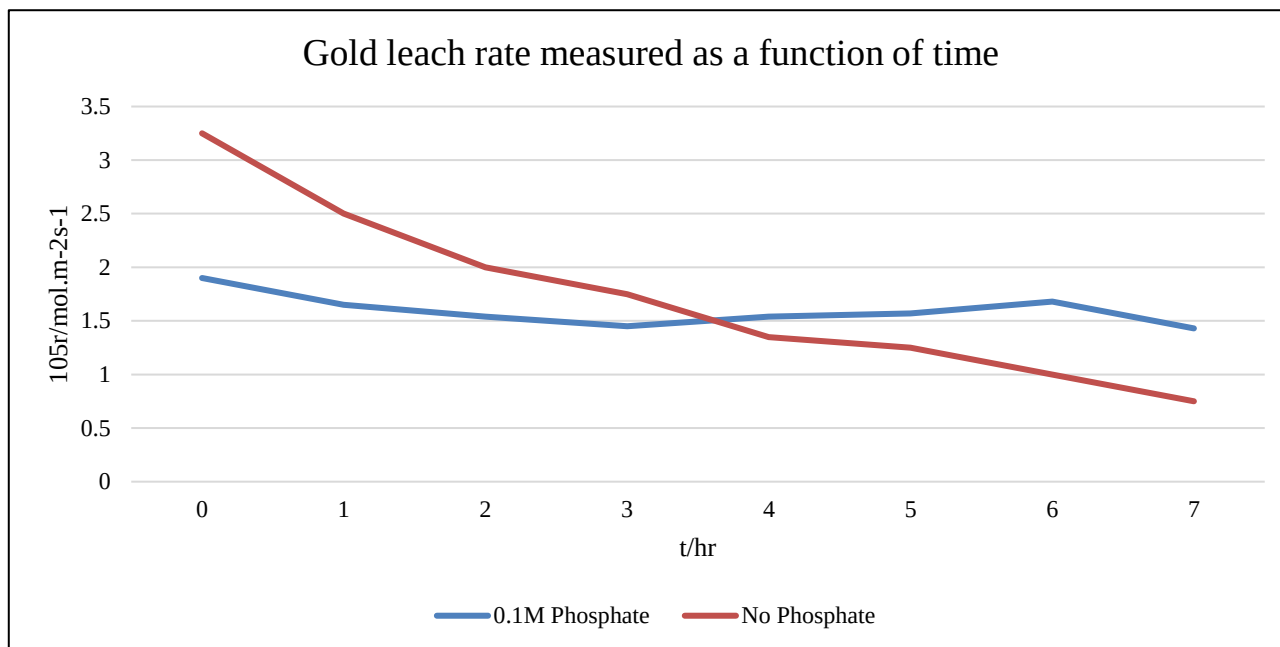


Figure 57: Graph of the gold leaching rate as a function of time [60]

The initial rate in the phosphate containing solution is lower than in the absence of phosphate. The results are due to the copper ion's reduction potential decreasing as the ion is stabilised. The gold leach in the phosphate containing solution is relatively stable as a function of time when compared to the solution without phosphate. After a period of 6 hours, the leaching rate in the phosphate solution was much higher than the solution in without phosphate.

Solution chemistry and leaching in the presence of oxygen

Recent studies have been conducted into the oxidation of thiosulfate by oxygen in the presence of ammonia [86]. This study had three major outcomes relevant to the study being conducted:

1. Even though oxygen oxidises copper (I) to copper (II) in thiosulfate solutions, a substantial proportion of copper exists as copper (I) [60].
2. The thiosulfate oxidation rate is directly proportional to the oxygen flowrate [60].
3. The steady-state copper (II) concentration is not significantly affected by the oxygen flowrates [60].

The copper (II) concentration and thiosulfate oxidation rates are imperative for gold leaching in thiosulfate solutions. Low flowrates of air will be used since the increasing flowrates of air does not increase the copper (II) concentration of the leaching solution, but increases the rate of thiosulfate oxidation [60]. Figure 58 shows the thiosulfate profiles for a solution sparged with 32 cm³/min of air.

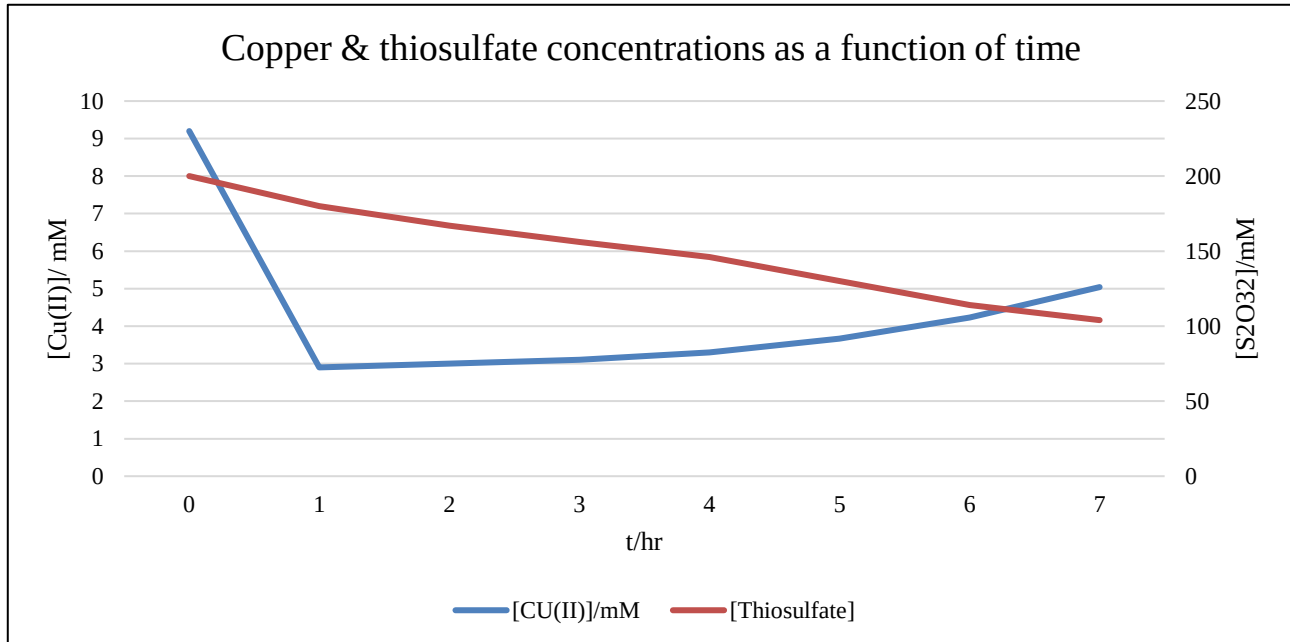


Figure 58: Graph of copper and thiosulfate concentrations as a function of time [60]

The copper (II) concentration initially decreases rapidly, more rapid than in the absence of oxygen. The copper (II) concentration is regenerated in the presence of oxygen by means of oxidation of copper (I) to copper (II). As shown in Figure 58, the copper (II) concentration approaches a steady concentration of 2.9 mM. The undesired reaction consuming copper (II) is matched by the regeneration of copper (II) [54]. The thiosulfate concentration decreases by approximately 20% in just over 2 hours.

The copper (II) concentrations starts to increase after 2.5 hours due to the decrease of thiosulfate concentrations [60]. Adding oxygen does have some value, due to the copper (II) concentration being higher than for solutions without sparging taking place [60]. Leach experiments were conducted using the aerated solutions. The results can be seen in Figure 59.

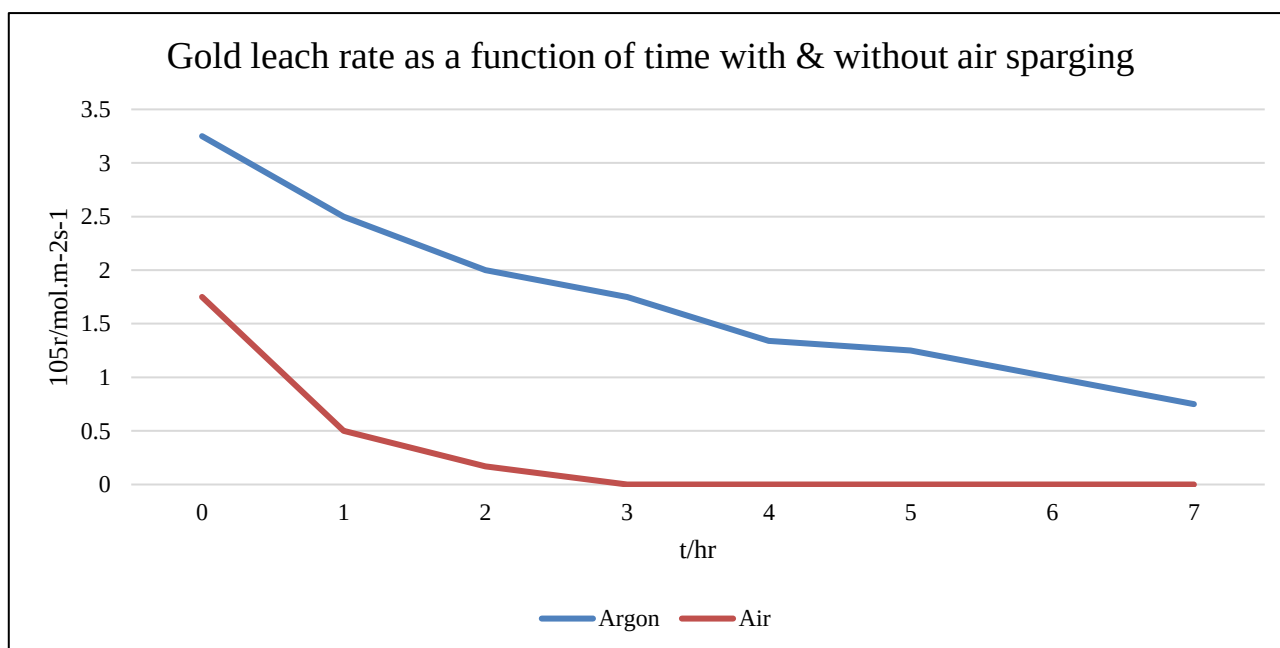


Figure 59: Graph of the gold leaching rate with and without air sparging [60]

Gold leaching in the presence of oxygen is initially high, but severely affected after 1 hour. It cannot solely be allocated to the decrease in thiosulfate concentration. Major products from oxidation of thiosulfate by oxygen in solutions containing copper and ammonia are trithionate and sulfate, while tetrathionate and disulfate were suggested to be classified as intermediate species [87].

Recent studies show that although trithionate and tetrathionate have little effect on the leaching process, as the presence of disulfate ($S_2O_5^{2-}$) affects the oxidation of gold in thiosulfate solutions [88]. Additional experiments were conducted where amounts of disulfite were added to freshly prepared thiosulfate solution in the absence of oxygen [60]. The results can be seen in Figure 60.

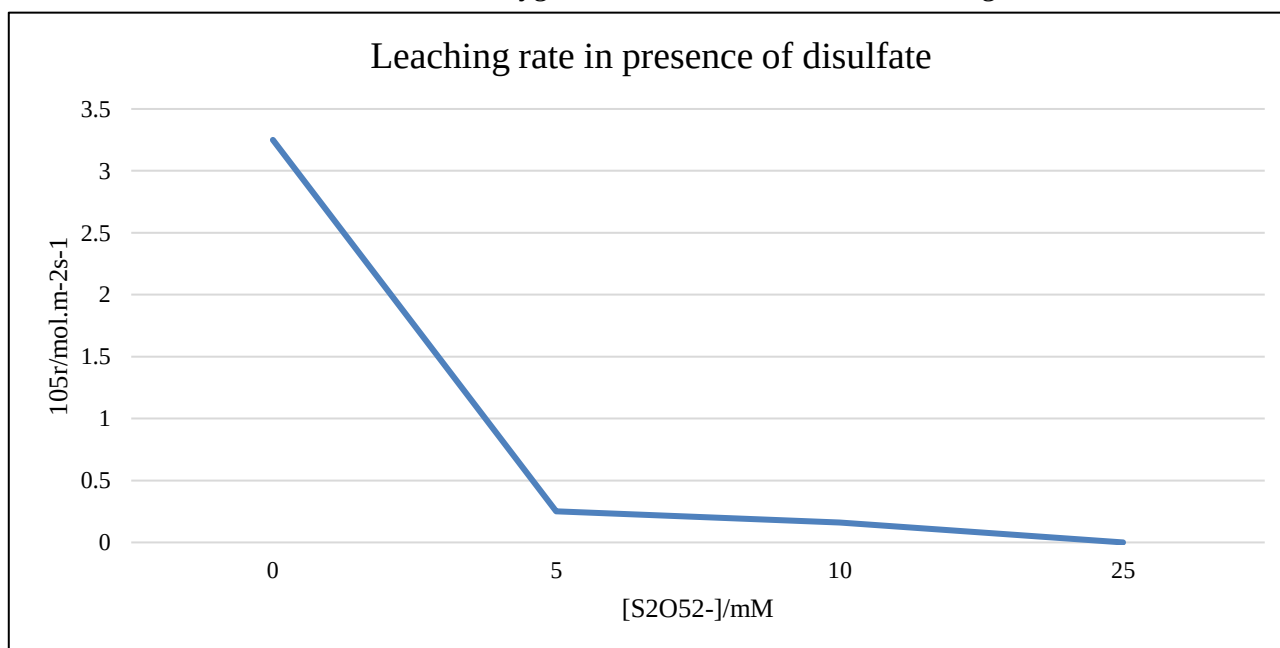


Figure 60: Graph of the gold leaching rate in the presence of disulfate [60]

The results obtained are consistent with disulfite being formed as a result of the copper (II) catalysed oxidation of thiosulfate by oxygen, and the disulphide hindering the gold leaching reaction [60].

Conclusion

The gold thiosulfate leaching system is considered complex due to solution chemistry and leaching kinetics interacting strongly with one another. Gold leaching kinetics are good when either phosphate is used to slow down the reaction between copper (II) and thiosulfate, or a mixture of 2% oxygen and 98% nitrogen is used to re-oxidise copper (I) to copper (II) [60]. When the experiments were carried out using air, poor kinetics were obtained [60]. Leaching studies show a similar trend when excess oxygen is added to a pulp. The experiments were hindered by the fact that the ore was reactive towards copper (II) and shows an optimum air addition rate does exist [60].

Improving the process performance of gold cyanide leaching reactors

Gold cyanide leaching is classified as the prevailing method for solubilising and recovering gold [67]. The CIP and carbon in leach (CIL) are the processes used for gold recovery. To avoid gold and carbon losses due to attrition of activated carbon, low mixing power inputs and shear rates are preferred in CIP and CIL reactors [67]. Due to the difficulty in obtaining efficient gas dispersion and suspension of coarse gold particles with low mixing power input, many industrial leaching reactors operate at low oxygen utilisation [67]. These reactors, therefore, suffer from sanding of solids at the bottom of the reactor. Low oxygen utilisation efficiency increases operational costs due to the air feed being high. The high gas or feed, therefore, decreases the solids suspension in the reactor, which can lead to an effective reactor volume decrease and thus also the residence time of coarse gold particles [67].

Conventional gold cyanide leaching reactor

Gold cyanide leaching reactors are normally large, approximately an average of 5000 m³, due to a low concentration of gold present in ore and a long residence time needed for gold to dissolve [67]. A typical reactor configuration consists of two downward pumping hydrofoil impellers used as mechanical agitation. Hydrofoil impellers generate a highly axial flow pattern for a low power draw [67]. The lowest capital cost and annual operating expenses for a reactor are achieved by minimising the power and torque requirements [67]. The reactor design can also have some drawbacks. The strong correlation between particle size and required mixing power for solids suspension can make it difficult to achieve homogenous suspension [67].

An occasional small increase in feed solids particle size can lead to siltation of solids at the bottom of the reactor. A typical mechanically agitated reactor can be seen in Figure 61.

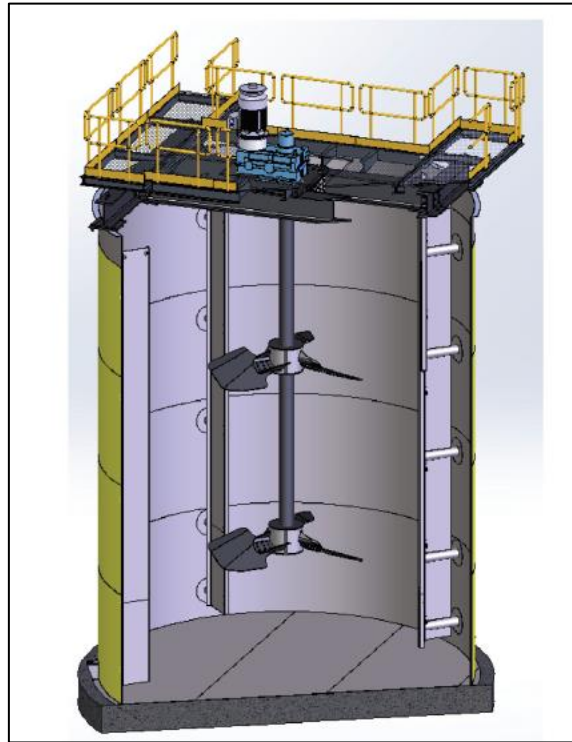


Figure 61: Mechanically agitated cyanide leaching reactor [67]

In some tanks, dispersion columns are placed in the reactors to agitate the slurry by means of compressed air. A visual representation of an air-agitated leaching is seen in Figure 62.

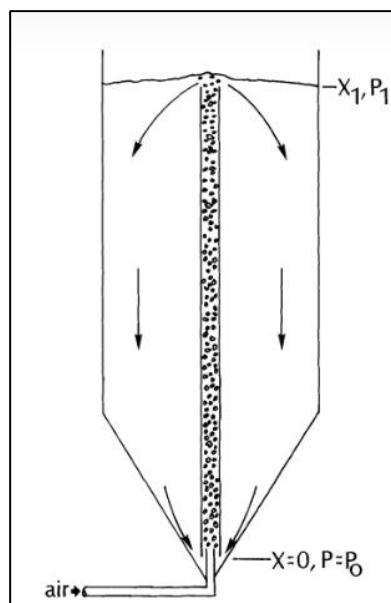


Figure 62: Compressed air agitated cyanide leaching tank [67]

To agitate the slurry and restrict particle settling in the tank, air is dispersed at the base of the tank from the cone's centre [68][69].

Air is freely allowed to rise in a free two-phase flow jet to the surface to enable a natural circulation pattern. To assess the performance of a typical gold cyanide leaching reactor, various parameters such as effective reactor volume, agitation efficiency, capital costs, and operational expenses need to be assessed.

Gas to liquid mass transfer

One gas dispersion property improvement strategy would be to implement a special gas dispersion chamber such as in [70]. The mechanical gas sparger is located below the lower main impeller as seen in Figure 63 within a mechanically agitated reactor.

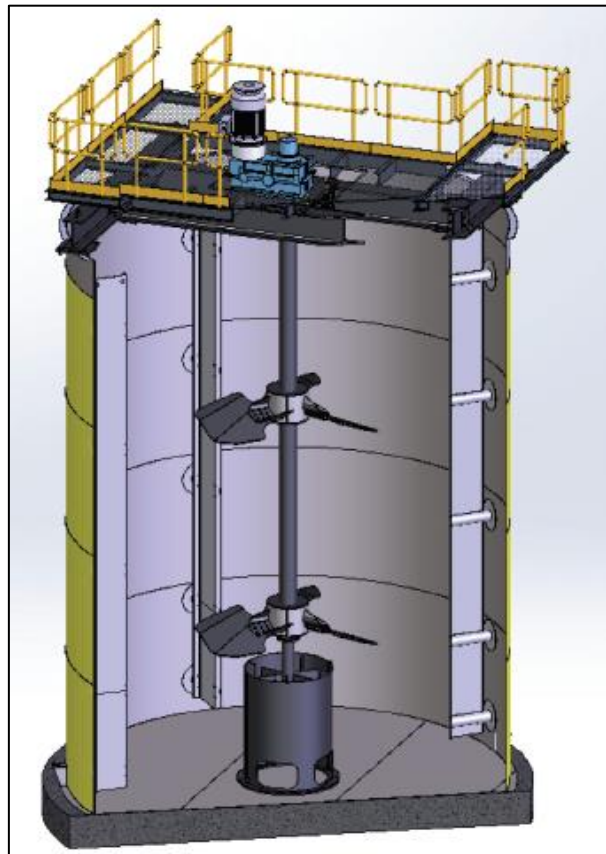


Figure 63: Gas sparger located below the lower impeller of a mechanically agitated reactor [70]

The gas fed through the sparging chamber is dispersed into fine bubbles prior to entering the main circulation inside the reactor. The location of the chamber was chosen to minimise the effect on solids suspension induced by the impellers [67]. Due to the rising gas bubbles and macro flow pattern inside the reactor, activated carbon particles do not travel extensively through the dispersion chamber which does not significantly increase the attrition of activated carbon [67].

The performance of the gas dispersion chamber was evaluated by oxygen utilisation efficiency measurements. The results can be seen in Figure 64.

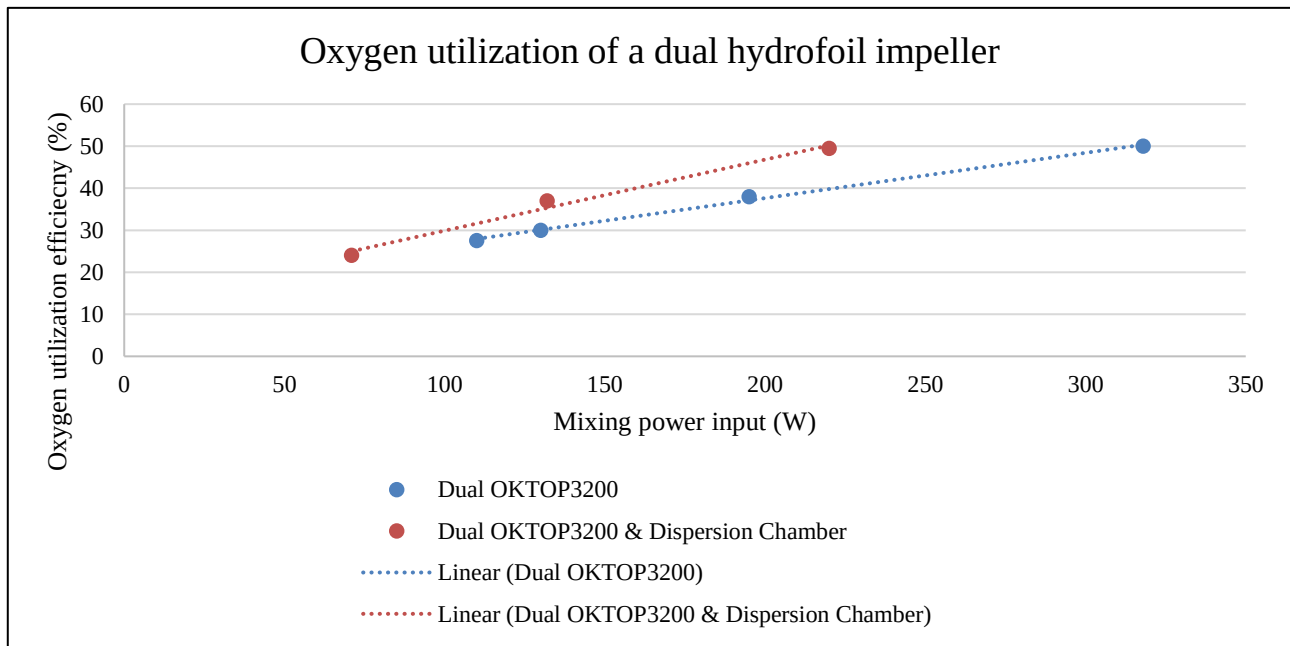


Figure 64: Graph of the performance of the gas dispersion chamber [67]

The experiments were conducted in a cylindrical transparent reactor with a 780 mm diameter and effective volume of 373 L. The reactor was furnished with four baffles and agitated with a dual Outotec3200 impeller [61]. The air feed was 2.4 Nm³/hr, which accumulates to the same superficial gas velocity (0.14 cm/s) as an air feed of 400 Nm³/hr to a full-scale cyanide leaching reactor with a 10 m diameter [67]. It was concluded that a power mixing intensity increase of 38% would be needed for the reactor without the dispersion chamber to obtain the same oxygen utilisation as the reactor with the dispersion chamber [67].

Solids suspension

The agitator configuration and impeller type for the gold cyanide leaching reactor has already been optimised for solids suspension for minimum power requirements. It may, therefore, seem that little room for improvement exists. Tank geometry can influence the solids suspension of a mixing tank, especially the tank bottom shape. It has been previously suggested by [71] that a cone and fillet tank bottom structure be used with a square pitch propeller. A similar approach was used in this study to further improve solids suspension.

CFD Modelling

The performance of the different tank bottom types was evaluated by means of single phase CFD (Computational Fluid Dynamics) modelling. Calculations were used to suit a cylindrical reactor consisting of an 8.5 m diameter. The rotational speed of the 3.5 m diameter impeller was 32 rpm [67]. An example of a corrugated tank bottom structure is shown in Figure 65.

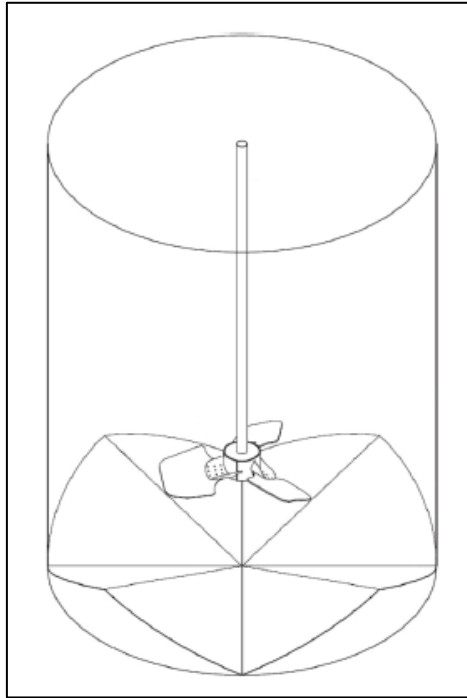


Figure 65: Corrugated tank bottom structure [67]

The different types of tank bottom structures investigated were the flat, conventional dished and the corrugated tanks. The comparison between the vertical fluid velocities of the different tank structures are shown in Figure 66.

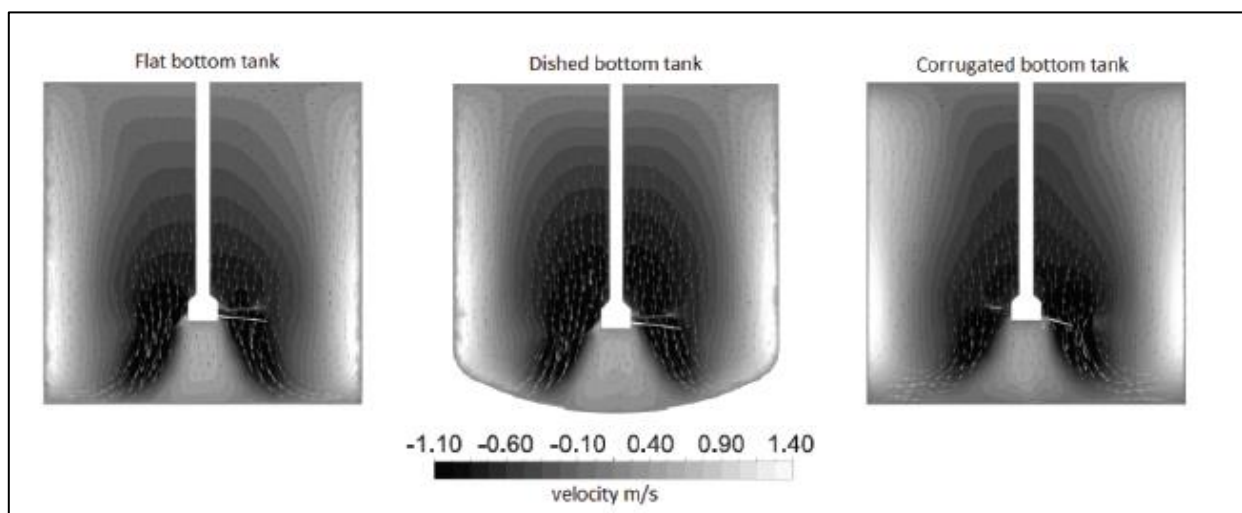


Figure 66: Different types of tank bottom structures and vertical fluid velocity of each [67]

The corrugated tank bottom structure portrays the rising flow velocities at a higher level in the upper half of the tank compared to the remaining two tank structures. A second comparison showing the fluid velocities of the different tank types at 85 mm from tank bottom is shown in Figure 67.

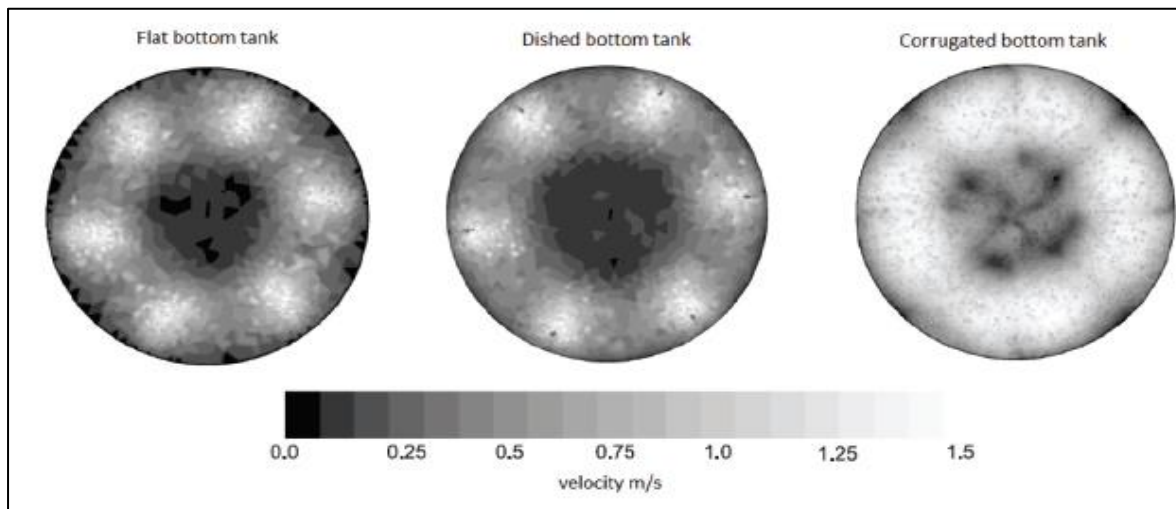


Figure 67: Fluid velocities at 85 mm from tank bottom of the different tank types [67]

The corrugated tank structure portrays an average fluid velocity of approximately 1.3 m/s near the tank bottom. This value is significantly higher than the average velocities of less than 0.8 m/s obtained by the flat and dished bottom structures [67].

Experimental testing

Additional testing was done to verify the performance of the corrugated tank bottom structure. Lab-scale sized leaching reactors consisting of an OKTOP3200 axially downward pumping hydrofoil impeller with a 145 mm diameter was used. Tank 1 had the flat bottom, tank 2 had the dished bottom, and tank 3 had the corrugated bottom [67]. All tanks had a diameter of 362 mm and were loaded with 37.3 L quartz sand in slurry water [67]. Due to the difference in tank bottom structures, each tank's surface height differed. The solid content of the test slurry was 400 g/l and particle diameter ranged from 125-185 μm . The transparent leaching tank setup showing suspension cloud height attached to a torque table can be seen in Figure 68.

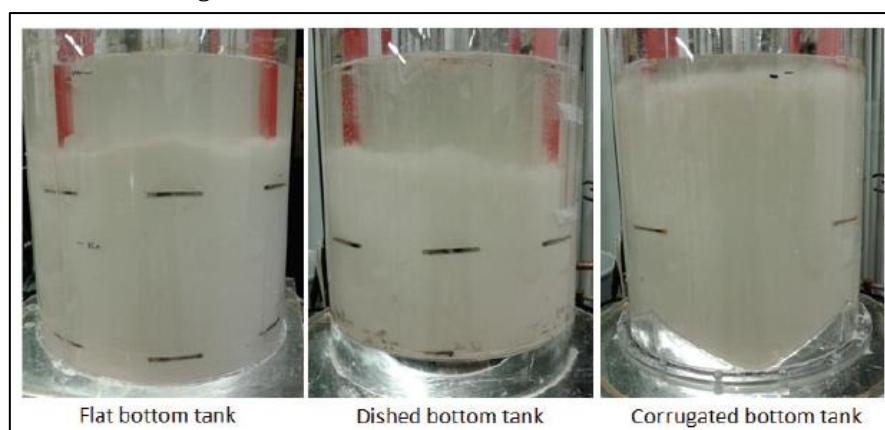


Figure 68: Transparent leaching tank setup showing suspension cloud height [67]

The torque table was used to establish the required absorbed mixing power required for complete off-bottom-and uniform suspension of sand slurry. The results obtained is shown in Table 11.

Table 11: Results from the torque table power requirement test [67]

Off-bottom suspension	Flat bottom	Dished bottom	Corrugated bottom
RPM	330	390	285
W (mixing power)	5.37	8.87	3.46
Uniform suspension	Flat bottom	Dished bottom	Corrugated bottom
RPM	490	500	350
W (mixing power)	17.6	18.7	6.41

The mixing power required to provide a uniform solids suspension was 64% less in the corrugated tank bottom compared to the flat bottom tank. The performance of the dished bottom tank structure had the lowest efficiency, which may be due to a stagnant region directly below the impeller [67].

Continuous suspension level measurement and mixing control

The PSD and solids concentration have strong effects on suspension degrees. Considering a continuous industrial operation, these parameters may fluctuate. A measurement technology was developed for continuous monitoring and control of solids suspension inside a leaching tank. The measurement is made using electrical impedance tomography using probes integrated into the reactor. Slurry cloud height and the settled layer of solids at the bottom of the tank is measured using the probe [67]. A visual representation of a reactor equipped with the measuring probes can be seen in Figure 69.

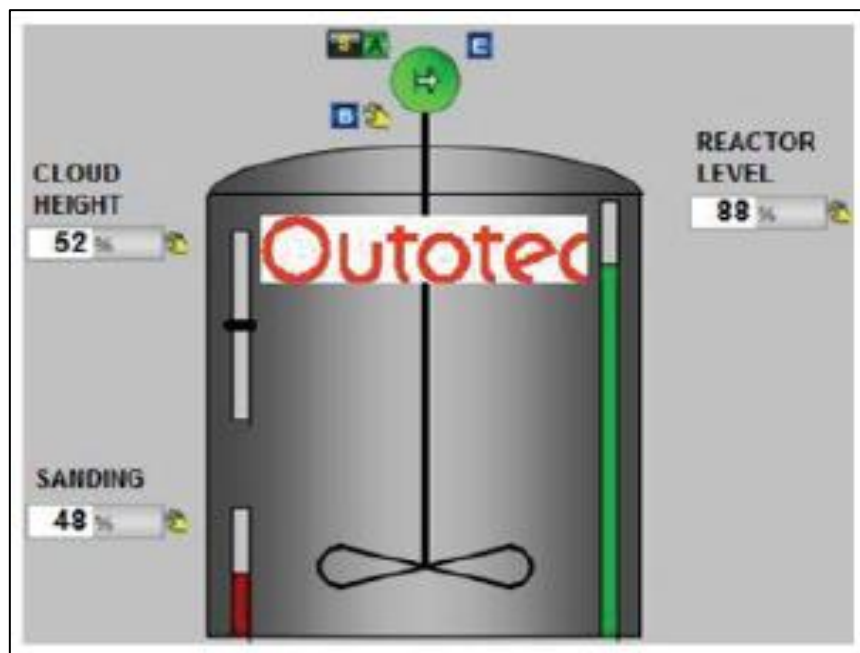


Figure 69: Reactor equipped with measuring probes [67]

By continuously monitoring suspension level and settling layer thickness, the mixing power intensity can be controlled and dynamically optimised [67].

Attrition of activated carbon

Attrition of activated carbon causes gold and carbon losses in CIP and CIL systems [61]. The typical attrition values in CIP and CIL systems are approximated to be 40-60 g carbon per ton of ore [41]. Gold loading predominantly takes place on the outer shell of carbon particles which leads to abrasion fines having a relatively high gold content [72]. Considering the financial aspect of the two elements at hand, gold losses are considered more serious. According to [73], the proportion of carbon fines (X) is correlated with the total energy amount transferred to the suspension by the mixer (E) after the initial conditioning phase. The carbon fines portion as a function of mixer energy transference is shown in Equation 16.

Equation 16: Carbon fines proportion as a function of mixer energy transference [73]

$$X = 0.056E^{0.6}$$

Based on the abovementioned correlation, the 64% reduction in mixing power input, which could be obtained with the corrugated tank bottom structure, could lead to 46% lower attrition of activated carbon compared to conventional reactor design [67]. Based on the dispersion chamber tests conducted in the study, the effect of increasing the mixing energy on carbon attrition was significantly higher when sand particles were present in the slurry [67].

Gold and carbon losses due to the attrition of activated carbon

To evaluate the financial impact of carbon attrition, a dynamic carbon management model was developed and used to establish gold and carbon losses for two attrition rates in a CIP process. The attrition rates used were 60 g/t and 32 g/t of ore [67]. Attrition effects were calculated for a six reactor CIP train, where each reactor was measured to be 1500 m³. The slurry flow was 350 m³/hr with a 45% solid content [67]. The specific gravity (SG) of the solution was 1 kg/L and the solids was 3.5 kg/L, leading to an adsorbed flowrate of 284 m³/hr. The activated carbon concentration in each reactor was 5 g/L, which accumulates to a total of 45 t of carbon in the train at the beginning of the process. Approximately 95% weight of carbon was transferred in 6 hours each day. The loaded carbon contained 2714 g gold per ton of carbon, while the regenerated carbon contained 20 g/t [67]. In addition to gold loading on the retained carbon, the retention time of the pulverised carbon in the system was also considered [67]. Table 12, showing the comparison of annual expenses of a CIP reactor train with two different carbon attrition rates, is shown below [67].

Table 12: Comparison of annual expenses of a CIP reactor train with two different carbon attrition rates [67]

Carbon attrition	32.5 g/t		60g/t	
	Value \$ million		Value \$ million	
Gold loss	35 kg	1.35	64 kg	2.47
Activated carbon loss	60 t	0.06	111 t	0.11
Mixing energy consumption	2592 MWh	0.13	7200 MWh	0.36
Total value		1.54		2.94

The annual production of gold without any carbon attrition would be 4 984 kg. The loss of gold with the pulverized carbon in the system was taken into account in gold loading [67]. The loss of gold with the pulverised carbon at a 60 g/t attrition rate would be 64 kg/annum, decreasing to 35 kg/annum with a 32.5 g/ attrition rate. The carbon losses for 60 g/t and 32.5 g/t, would be 111 t/annum and 60 t/annum respectively [67].

Conclusion

The performance of cyanide leaching reactors can be improved significantly by implementing the optimisation techniques discussed above. Economic savings can be achieved due to reduced operating costs, combined with a reduction in gold and carbon losses [67]. When considering gas dispersion chamber reactors, oxygen utilisation efficiency can be improved without a major increase in carbon attrition rate [61]. This may lead to the use of air instead of oxygen in some applications, which further reduces operating costs. The mixing power requirements, which are directly linked to gold loss by carbon attrition, can be greatly reduced by using the novel corrugated tank bottom structure [67]. Lastly, the mixing power requirements can be further optimised by continuous monitoring of the slurry suspension level [67].