Reducing deep-level mine refuge bay compressed air consumption

P de Villiers

orcid.org 0000-0002-8194-2547

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

Supervisor: Dr JC Vosloo

Graduation ceremony: July 2019

Student number: 31551203
Abstract

Title: Reducing deep-level mine refuge bay compressed air consumption

Supervisor: Dr JC Vosloo

School: North-West University, Potchefstroom Campus

Degree: Master of Engineering in Development and Management

Keywords: Compressed air network inefficiencies, deep-level gold mine, refuge bay compressed air consumption, refuge bay, Business process re-engineering

The South African mining industry has been experiencing a difficult time with most local mines operating in unprofitable or marginal conditions. The reason for the dire situations is mainly due to the high operating costs for the South African deep-level gold mines. It is necessary for mines to continuously reduce operating costs by implementing cost-saving initiatives by reducing waste or optimising processes.

One of the most considerable costs for a deep-level gold mine is the electricity costs. Compressed air is supplied to the mines through large compressors which are the single largest consumer of electricity in the mine; second only to a combination of activities grouped into material handling and processing. One of the users of compressed air present in every deep-level gold mine is refuge bays.

It was evident that a need existed to optimise the refuge bay compressed air use. “Rapid Re” business process re-engineering was applied to the South African deep-level mining environment in this dissertation. The methodology aimed at focusing the solution on the technical and the important social aspect of the process.

The application of the adapted Rapid Re-engineering identified the value-adding activity as the valves controlling the flow to the refuge bays. The process was modelled and understood from a technical and social aspect. The inefficiencies of the current process were identified, and goals were set for the solution step. A theoretical benefit was calculated using simulation that resulted in a power reduction of 840 kW. A solution was generated along with a method of implementation based on the goals set out.
Reducing deep-level mine refuge bay compressed air consumption

The solution was implemented on the refuge bays in a deep-level gold mine. 42 refuge bay valves were replaced. The replacement of the valves led to a baseload reduction in power of 962 kW that was estimated to yield R 5.25 million in annual savings. An additional environmental benefit was calculated related to the energy savings achieved by the project. To ensure the year-to-year realisation of the benefit, sustainability methods for the project were put in place.
Acknowledgements

“If I have seen further, it is by standing on the shoulders of giants.” – Isaac Newton

I dedicate this page to all that assisted me in completing this thesis.

Firstly, I want to thank my Mother, Anellie de Villiers, for her sacrifice, support, love and for being my catalyst.

I would also like to sincerely mention the following persons who assisted me in completing this thesis.

- Professor Eddie Mathews and Professor. Marius Kleingeld for providing funding, guidance and support and the opportunity to peruse my master’s degree in engineering.
- My supervisor Doctor Jan Vosloo for his valuable and continued help, guidance, and support.
- CRCED and ETA operations for supporting this research.
- Doctor Charl Cilliers for your continuous care, effort, suggestions and guidance even at short notice and irregular hours. Thank you for the impact on my career and life.
- Doctor Philip Mare for your understanding, motivation, guidance and genuine care and effort for your peers. Thank you for the impact on my career and life.
- Zandalee Slabbert for your motivation, assistance and accepting my divided attention.
- W.R.T.S. Boysen for the continued support and needed distraction.
- My colleagues who helped with the data gathering, project information and problem solving.
- The mining personnel for assisting me in any queries or data.
## Table of contents

### CHAPTER 1: Background

1.1. Preamble .................................................................................................................. 2  
1.2. Deep level mine compressed air systems ................................................................. 5  
1.3. Problem statement and need for the study .............................................................. 12  
1.4. Study objectives ...................................................................................................... 12  
1.5. Overview of dissertation ......................................................................................... 12

### CHAPTER 2: Literature study

2.1. Preamble .................................................................................................................. 15  
2.2. Refuge bay compressed air legislation ................................................................... 15  
2.3. Effect of compressed air leaks in mines and methods for benefit analysis .......... 16  
2.4. Process modelling methods and simulation tools .................................................... 21  
2.5. Problem-solving techniques .................................................................................. 23  
2.6. Project sustainability methods .............................................................................. 28  
2.7. Summary ................................................................................................................ 29

### CHAPTER 3: A Method to optimise refuge bay compressed air consumption

3.1. Preamble .................................................................................................................. 31  
3.2. Constraint identification ......................................................................................... 31  
3.3. Preparation and Identification – Process initiation and process selection .......... 33  
3.4. Vision – Process ideal selection and verification ..................................................... 35  
3.5. Solution ................................................................................................................... 37  
3.6. Transformation – Implementation and validation .................................................... 39  
3.7. Study objectives review ......................................................................................... 41  
3.8. Summary ................................................................................................................ 42

### CHAPTER 4: Case study

4.1. Preamble .................................................................................................................. 45
Reducing deep-level mine refuge bay compressed air consumption

4.2. Constraint identification.............................................................................................................45
4.3. Preparation and identification – Process initiation and process selection..........................48
4.4. Vision– Process ideal selection and verification........................................................................51
4.5. Solution ....................................................................................................................................59
4.6. Transformation – Implementation and validation.................................................................66
4.7. Summary .................................................................................................................................71

CHAPTER 5: Study review and recommendations .................................................................73

5.1. Preamble...................................................................................................................................74
5.2. Study objectives review ..........................................................................................................74
5.3. Study Review and conclusion ...............................................................................................75
5.4. Recommendations ..................................................................................................................78

CHAPTER 6: REFERENCES ............................................................................................................80

Appendix A – Mine compressed air layout..................................................................................84
Appendix B – Simulation layout ....................................................................................................85
Appendix C – Valve replacement schedule ................................................................................86
Appendix D – Electricity monetary equivalent calculations....................................................89
Appendix E – Original valve solution ..........................................................................................93
Appendix F – Refuge bay post implementation audit ...............................................................94
Appendix G - Review of Rapid Re methodology.....................................................................96
List of figures

Figure 1: Gold reserve ranking by country 2017 ................................................................. 2
Figure 2: Differential increases in cost components for 2017 – adapted from ..................... 3
Figure 3: Increase in electricity costs for Sibanye Gold– adapted from ............................... 4
Figure 4: Breakdown of electricity consumption in deep-level gold mines– adapted from .... 5
Figure 5: Multi-stage centrifugal compressor .................................................................. 6
Figure 6: Refuge station standard longitudinal section- developed from ........................... 7
Figure 7: Power savings vs project baseline example - Adapted from ................................. 19
Figure 8: Seven steps of systems methodology – adapted from ....................................... 24
Figure 9: 54 tasks of Rapid Re-engineering divided into the 5 steps– adapted from .............. 26
Figure 10: Adapted Rapid Re-engineering process flow .................................................... 33
Figure 11: Summary of preparation process ...................................................................... 34
Figure 12: Identification process flow ................................................................................ 35
Figure 13: Vison process flow ............................................................................................ 37
Figure 14: Solution step process flow ................................................................................ 39
Figure 15: Transformation process flow ............................................................................. 41
Figure 16: Adapted Rapid Re-engineering process flow ..................................................... 43
Figure 17: Use case diagram for the CA system at Mine A ................................................. 50
Figure 18: Refuge bay compressed air system .................................................................. 51
Figure 19: Refuge bay compressed air process flow ........................................................... 52
Figure 20: Project electrical power consumption baseline ................................................ 54
Figure 21: Simple simulation layout of CA supply - refuge bay configuration .................. 56
Figure 22: Simulated results for optimised flow ................................................................. 57
Figure 23: Simulated results for optimised pressure ........................................................... 58
Figure 24: Simulated results for optimised power ............................................................... 58
Figure 25: Simulated results for mass flow rate of air through various size openings .......... 61
Figure 26: Refuge bay compressed air solution process flow ............................................ 62
Figure 27: 24-hour consumption profile for pre and post project implementation .............. 67
Figure 28: Compressed air layout schematic ..................................................................... 84
Figure 29: Simulation layout schematic ............................................................................ 85
Figure 30 : 2018/2019 Megaflex low and high demand season TOU periods ................. 89
Figure 31: Original valve chosen for solution .................................................................... 93
List of tables

Table 1: Compressed air flow to a refuge chamber ......................................................... 8
Table 2: Financial project evaluation methods ................................................................. 20
Table 3: Simulation tool comparison .................................................................................. 22
Table 4: Comparison of methodologies .............................................................................. 27
Table 5: Project sustainability techniques ........................................................................... 28
Table 6: Project types and characteristics .......................................................................... 31
Table 7: Suggested personnel for Rapid Re assisting team .................................................. 34
Table 8: Consumption/emission factors per kWh produced by Eskom ................................. 40
Table 9: Refuge bay aspects and responsible persons ......................................................... 49
Table 10: Refuge bay compressed air activities and value impact on cost ............................. 53
Table 11: Refuge bay post implementation check list ........................................................... 65
Table 12: Environmental impact of EE reduction ................................................................. 70
Table 13: Mine Schedule for refuge bay valve replacement ................................................. 86
Table 14: High demand season TOU tariff distribution ...................................................... 90
Table 15: EE consumption reduction ................................................................................... 91
Table 16: Total savings cost per week ................................................................................ 92
Table 17: Mine refuge bay post valve implementation audit ................................................ 94
List of equations

Equation 1: Volumetric flow through an orifice ............................................................ 8
Equation 2: Power required for polytropic compression ................................................. 17
Equation 3: Power consumed by the electrical motor ..................................................... 18
Equation 4: Payback period [22] .................................................................................. 20
Equation 5: Net present value [27] .............................................................................. 20
Equation 6: Real discount rate [43] ............................................................................. 39
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISC</td>
<td>All in Sustaining Cost</td>
</tr>
<tr>
<td>BPR</td>
<td>Business process engineering</td>
</tr>
<tr>
<td>CA</td>
<td>Compressed air</td>
</tr>
<tr>
<td>CATWOE</td>
<td>Customers, Actors, Transformation, World, View, Owner, Environmental</td>
</tr>
<tr>
<td>EE</td>
<td>Electrical energy</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>IDEAL</td>
<td>Identify, Define, Explore, Act, Look back</td>
</tr>
<tr>
<td>MSHA</td>
<td>Mine Safety and Health Administration</td>
</tr>
<tr>
<td>MHSC</td>
<td>Mine Health and Safety Act</td>
</tr>
<tr>
<td>NMD</td>
<td>Notified maximum demand</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
</tr>
<tr>
<td>OAN</td>
<td>Optimisation of air network</td>
</tr>
<tr>
<td>PDCA</td>
<td>Plan do check act</td>
</tr>
<tr>
<td>PM</td>
<td>Project manager</td>
</tr>
<tr>
<td>PTB</td>
<td>Process toolbox</td>
</tr>
<tr>
<td>RADR</td>
<td>Risk-Adjusted Discount Rate</td>
</tr>
<tr>
<td>SSM</td>
<td>Soft system methodology</td>
</tr>
<tr>
<td>TOU</td>
<td>Time of use</td>
</tr>
<tr>
<td>UML</td>
<td>Universal Modelling Language</td>
</tr>
<tr>
<td>WACC</td>
<td>Weighted average cost of capital</td>
</tr>
</tbody>
</table>
## Glossary

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Air wolf”</td>
<td>Mine employee dedicated to find compressed air inefficiencies</td>
</tr>
<tr>
<td>“Baseline”</td>
<td>As-is data to be used as reference in calculating project benefit</td>
</tr>
<tr>
<td>“Operational costs”</td>
<td>Cost incurred for production purposes</td>
</tr>
<tr>
<td>“Project sustainability”</td>
<td>The longevity of a project at a constant performance</td>
</tr>
<tr>
<td>“Activity”</td>
<td>Smallest building block of a system</td>
</tr>
<tr>
<td>“Compressed air ring”</td>
<td>Entire network of compressed air in the mine</td>
</tr>
<tr>
<td>“E-learning”</td>
<td>Electronic teaching of various mine safety procedures</td>
</tr>
<tr>
<td>“Process”</td>
<td>Combination of activities to achieve a communal goal</td>
</tr>
<tr>
<td>“Refuge bay/chamber”</td>
<td>Area in the mine for emergency conditions with basic emergency equipment and means of communication to the surface. Chambers have sufficient air and water supply from the main water and compressed air lines of the mine.</td>
</tr>
<tr>
<td>“System”</td>
<td>Combination of processes to achieve a communal goal</td>
</tr>
</tbody>
</table>
CHAPTER 1: Background

This chapter highlights the use of compressed air in mines. The need for initiatives that focus on mine refuge bays and compressed air usage and optimisation is given.
1.1. Preamble

1.1.1. Deep-level mining in South Africa

South Africa has the second largest gold reserve in the world, referring to ore deposits which can be extracted both economically and legally [1]. Gold has boosted the South African economy since its discovery in 1884 [2]. It forms 6.8% of the country’s total gross domestic product (GDP) and employs around 112 200 people [3]. It also contributed to 27% of the country’s exports book in 2017. For each person employed by the mine, two indirect job opportunities are created [3]. Figure 1 illustrates the gold reserve rankings among the top countries in 2017.

![World mine reserves of gold as of 2017](https://www.statista.com/statistics/248991/world-mine-reserves-of-gold-by-country/)

**Figure 1: Gold reserve ranking by country 2017**

South Africa is highly dependent on its commodities; specifically on the export of minerals and metals [4]. Mining dominates the economies of four out of the nine South-African.

During the initial gold rush in 1885 at Witwatersrand, gold could easily be found with a simple bucket and sieve. As the resource diminished, it became necessary to dig deeper to reach the

---

valuable metal. The nature of these mines generates high operating costs due to the depth of the deep-level mines, reaching depths of up to 4 000 meters. Significant infrastructure and support systems are necessary for operation. Implementation and maintenance of these intricate systems are expensive and requires the support of trained employees - all of which have considerable cost implications for the mine.

### 1.1.2. Cost of deep level mining in South Africa

South Africa has the most expensive mines in the world. South Africa has an average All in Sustaining Cost (AISC) of $1,035/oz compared to the global average of $818/oz. The high cost of mining operations puts a considerable strain on South African mines and erodes profitability. In total, mining costs increased by 6% in 2017 [3]. Additionally, there was only a marginal 3.5% increase in commodity prices in 2017 [3]. Figure 2 indicates the rise in costs for different areas of mines.

![Differential increases in cost components for 2017](image)

**Figure 2:** Differential increases in cost components for 2017 – adapted from [3]

The other significant contributor to mining costs is electricity, amounting to 20% of the total gold mining expenditure. The gold sector is responsible for 47% of total electricity usage in

---


the mining industry. Not only does this illustrate the sheer amount of energy needed for its processes, but also the possible opportunity for improvement.

Eskom generates 95% of South Africa’s electricity. Previously, Eskom was the cheapest electricity provider in the world, but now they frequently demand above-inflation price increases. High electricity costs lead to South Africa having the highest production costs with regards to energy. The chamber of mines has expressed their concerns regarding the price increase and further implementation of carbon tax due to its effect on the profitability of the mines. Figure 3 shows an example of the increase in operational electricity costs for Sibanye Gold, a gold mining company in South Africa, from 2007 to 2017.

![Figure 3: Increase in electricity costs for Sibanye Gold– adapted from [5]](image)

The reason for the high electrical intensity is due to the nature of the deep-level mines. Electricity is used to excavate, transport and process the ore from underground. Figure 4 illustrates the electricity consumption breakdown for different processes on deep-level gold mines.

---


Material handling and processing are the leading consumers of electricity, all of which contain numerous sub-processes [1]. Compressed air (CA) is the largest single consumer of electricity. Electricity has a significant correlation to production costs due to its weight in operational costs. With declining production numbers and increasing operational costs and, as of 2017, 75% of these mines are deemed marginal or unprofitable [3].

High operating costs and decreasing production trends create the urgent need for mines to either increase production or reduce current operating costs. The latter can be achieved by continuous improvement in all operations to improve efficiency and production. An ideal place for improvement is a large contributor to operating costs, such as the CA system.

### 1.2. Deep level mine compressed air systems

The South African gold mining industry is a large user of CA due to the nature of its equipment. As previously stated, the largest single user of electricity on gold mines is CA (Figure 4). This intricate network of CA is essential to production because of the use of pneumatic drills in mines. The CA system, however, feeds various other smaller end-users, all of which also present inefficiencies. Improvement of these inefficiencies is vital to the lowering of the current high operating costs of the South African mines. This section will consider the supply and demand aspects of the system, respectively, with a focus on CA optimisation.

**Figure 4: Breakdown of electricity consumption in deep-level gold mines—adapted from [1]**
1.2.1. **Compressed air supply**

A significant use of electrical energy (EE) is attributed to the generation of CA. Compressors are typically located in compressor houses on the surface. These compressors vary in size from 1 MW to 15 MW [6]. On a typical working day, consumption can reach 883 MWh, supplying a flow rate of 30 500 m$^3$/h to 170 000 m$^3$/h at a pressure of approximately 5.5 bar [6], depending on the mine. South African mines mainly make use of multi-stage centrifugal compressors. It has compact size and large operating range [6]. Figure 5 depicts a centrifugal compressor used at a typical gold mine.

![Multi-stage centrifugal compressor](image)

Figure 5: Multi-stage centrifugal compressor

These compressors are connected to pipes feeding the substantial network underground. The pipes form a closed system sometimes referred to as a “compressed air ring” [1]. Appendix A shows a simplified layout of a South African deep-level gold mega mine, with three shafts and three points of supply for the CA system.

1.2.2. **Compressed air demand**

On the end of the sizeable CA ring mentioned in the previous section, are the various end-users. The most important of these are pneumatic drills. In gold mining, pneumatic drills are used to drill the holes to load charges for blasting [7]. Typically, more than one type of drill is used in a mine; some are used for development and others are used in working areas [7]. Other users of CA include pneumatic loaders, pneumatic cylinders, processing plants, and refuge bays.

---

Given this broad array of users, there exists ample opportunity for waste reduction. Reduction in waste benefits electricity usage, as well as the pressure delivery to the other users.

1.2.3. Optimisation of compressed air use in refuge bays

Refuge bays are areas underground that are used during cases of emergency. These areas are equipped with a phone for communication, a bathroom area, and basic emergency equipment [8]. Should an emergency occur, mine employees are instructed apply their self-respirators and move to their closest refuge chamber. The employees are expected to remain in these areas until fetched [16].

The typical setup of the refuge chamber CA supply is a tie-off from the main CA supply through the chamber wall. Inside the chamber, the pipe is fitted with a valve, followed by a muffler. Figure 6 shows a longitudinal section of a refuge bay.

These valves are constantly open to a certain degree, as each refuge bay needs a constant flow of air that considers the size of the refuge chamber [8]. The flow of CA to refuge bays is not regulated. From personal observation, it is sometimes used by mine personnel for self-cooling purposes, leading to a fully opened valve. Using Equation 1 and given that the compressed air tie in for refuge chambers are typically 50 mm in diameter, Table 1 displays the compressed air usages at various levels of valve positions for one refuge chamber in the mine.
Equation 1: Volumetric flow through an orifice

\[ Q = C \times Ao \times \sqrt{\frac{2 \times \Delta P}{\rho}} \]

Where:

\( Q \) = Air Flow Rate (m\(^3\)/s)
\( C \) = Discharge Coefficient (0.7)
\( Ao \) = Area of orifice (m\(^2\))
\( \Delta P \) = Pressure difference before and after orifice (Pa)
\( \rho \) = Density of air (kg/m\(^3\))

The CA line pressure was assumed to be 400 kPa, and the outlet barometric pressure was assumed to be constant at 114 kPa. The temperature was assumed to be 25 °C, rendering an air density of 4.66 kg/m\(^3\). The discharge coefficient was assumed to be 0.7. The area of the orifice is calculated as 0.00196 m\(^2\).

<table>
<thead>
<tr>
<th>Valve Position</th>
<th>Area (m(^2))</th>
<th>Volumetric Flow (m(^3)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25%</td>
<td>0.000491</td>
<td>0.12</td>
</tr>
<tr>
<td>50%</td>
<td>0.000982</td>
<td>0.24</td>
</tr>
<tr>
<td>75%</td>
<td>0.001473</td>
<td>0.36</td>
</tr>
<tr>
<td>100%</td>
<td>0.001963</td>
<td>0.48</td>
</tr>
</tbody>
</table>

A constant fully open valve will essentially have the same effect as a relatively large leak in the system. The overall system pressure is reduced, which negatively affects important end-users such as pneumatic drills [9]. Consequently, compressor output requirements are increased to meet the same demand, affecting electricity consumption [10]. The optimisation of CA usage in refuge bays will lead to a cost-effective solution to reduce waste and improve drilling efficiency.
1.2.4. Previous studies on compressed air in refuge bays

It is evident that the reduction of CA use in refuge bays will result in improvement of operation costs and CA ring pressure. In this section, the previous research done on CA in refuge bays is reviewed. To align the relevance of the reviewed literature to the focus of this study, the research was based solely on studies performed on CA consumption in refuge chambers. The most relevant studies found are as follows:

Study A (2017) [11]:

Title : Experimental study of the gas leakage and optimised supply of oxygen in coal mine refuge chamber

Authors : Shao, Hao; Li, Peng Fei; Shi, Xu Mao

Overview : This study focuses on the leakage rate of underground refuge chambers. The CO\textsubscript{2} and O\textsubscript{2} concentration variation laws with no oxygen supply were obtained experimentally. The effects of an air purification system in the refuge chambers were observed and proven to be beneficial to CO\textsubscript{2} and O\textsubscript{2} concentrations. The study also concluded that the oxygen supply should be adjusted dynamically according to the human need.

Shortcomings & Recommendations : The study focuses only on refuge chambers, with a limited supply of oxygen to the chamber, unlike the chambers found in deep-level South African gold mines. The focus was placed on the oxygen concentration in the refuge chambers, and the minimum needed for ventilation.

Study B (2017) [12]:

Title : Experimental air curtain solution for refuge alternatives in underground mines

Author : Wang, Shu
Overview: The study tested the effectivity of using air curtains to seal and ventilate refuge chambers in underground mines. Through experiments and simulation, various configurations of the air curtain were evaluated. The study found that a two-sided configuration equipped with a baffle side exposed to the harmful gasses can support an air curtain for 3.5 minutes with a 40litre oxygen cylinder at 0.1 – 0.2 MPa.

Shortcomings & Recommendations: The study focused on refuge chambers that make use of oxygen containers for its supply. The air curtain has a relatively large consumption rate. The sealing efficiency of the CA curtain maximised at 41%. Given that the refuge bay doors in the current deep level mine close off the entrance of a refuge bay, 41% efficiency is not as effective as current practices.

Study C (2015) [13]:

Title: Study and analysis of human survival parameters in mine refuge station

Author: Zhe, Y

Overview: The study evaluated the life-support techniques of a refuge chamber and tested the clinical emergency response of participants. The study concluded that the minimum supply rate for survival in the refuge chamber is 0.067 m³/min air.

Shortcomings & Recommendations: In the testing condition, a particular refuge bay type was used. The test facility differs from deep-level refuge chambers found in South Africa. This test facility included an air purifier and ice storage unit, amongst other equipment not found in a typical South African refuge chamber.

Study D (2017) [14]:

Title: Simulating operational improvements on mine CA systems
Overview: The study identifies the inefficiencies on South African deep-level gold mines and the benefit of improving the systems in terms of energy savings. A CA system was modelled using simulation software. The study simulated that a reduction in air consumption in refuge bays could lead to a 0.9 MW power reduction on compressor consumption. The study ultimately shows that simulation could help efficiency and profitability in the mining industry.

Shortcomings & Recommendations: The study proves that simulation can be used to model refuge bay consumption optimisation but does not have a practical implementation test. The flow to the refuge bays in the simulation was set to 0 kg/s.

Three of the studies reviewed above focused on refuge bays that are dissimilar to those found in a South African deep-level gold mine. The reason for this is that the refuge chambers are not designed for an ultra-deep level mine. The typical South African deep level mine has refuge bay that are simply holes in the haulage or repurposed storerooms underground and rarely has any built-in additional walling. The method of supplying oxygen to the refuge chamber varies to that seen in a typical gold mine in South Africa as can be seen in figure 6.

Study D is a study closely related to the problem identified in this chapter, however, it lacks practical implementation. Additionally, it simulated zero flow to the refuge chamber, which should not be the case in order to have a pressurised chamber.

Furthermore, the studies above do not include the social aspect of refuge chambers in reference to South Africa. It is essential that the solution to the problem at hand should be safe and easily useable for a typical deep-level mine employee of South Africa. Unions have a large say in the South African mining industry [15]. The Unions constantly fight for safer working environments for all the mine employees [15]. Unions can cause a significant loss in production (such as through mass strikes) if they should feel that certain aspects of a system are unsafe [15].

The need exists to investigate and improve on the CA use in refuge chambers of a deep-level gold mine in South Africa and simultaneously adhering to mine safety regulation.
1.3. Problem statement and need for the study

Deep-level gold mines consist of integrated systems that are expensive to operate. Replacement or redesigning of entire parts is not feasible for marginal mines. The outdated nature of the systems could only lead to even worse production figures in the future. Therefore, a more cost-effective and optimised way of using the current infrastructure is needed to reduce operational costs.

One of the most cost-intensive systems in a deep-level gold mine in is the CA system, in terms of operational costs. One of these end-users that is easily overlooked by mines is refuge bays. When considering a single refuge bay, wastage is relatively small. However, the cumulative effect from numerous refuge bays in a mine will amount to notable losses. A holistic approach with regards to refuge bay CA optimisation is necessary as a method to continuously improve the system.

1.4. Study objectives

To optimise the usage of compressed air in refuge bays, the following goals will be addressed in the dissertation:

- Identify techniques to reduce CA refuge bay consumption.
- Investigate current refuge chamber CA supply design.
- Redesign and implement new refuge chamber CA supply configurations.
- Quantify the impact of optimisation of energy savings.

1.5. Overview of dissertation

A summary of each section in the dissertation is as follows:

Chapter 1

Chapter 1 provides a synopsis of the current situation of gold mining in South Africa. The gold mining sectors reserves, and high operating costs are discussed. A breakdown of the CA as one of the most significant contributors to costs is reviewed. From the identification of CA users, a need is identified to optimise CA use in refuge bays. Previous studies are considered related to refuge bay compressed air use, and the study objectives are provided.
Chapter 2

Chapter 2 investigates current refuge bay legislation with the addition of regulations from the Canadian Ministry of labour. In order to quantify the impact of the project and compressed air reduction, other studies that were done on CA in deep-level gold mines are reviewed. Methods to quantify a theoretical and actual benefit is identified. Simulation packages are reviewed, and the ideal option is chosen for the study. A method to financially analyse the project benefit is reviewed and selected, along with the identification of possible benefits through emissions and water and coal consumption. Various problem-solving methodologies for the study are evaluated, and Rapid Re-engineering is chosen as the most ideal of the reviewed methodologies. Finally, literature of sustainability methods is reviewed to identify applicable methods for the study.

Chapter 3

Rapid Re-engineering is adapted to a deep-level gold mine environment. First, the main project constraints are identified. The Rapid Re process is then initiated by a combined first two steps of Identification and Preparation. This is followed by the vision, solution, and transformation steps to complete the process.

Chapter 4

A deep-level gold mine located in South Africa is used as a case study to test the improvement of refuge bay CA consumption. The adapted Rapid Re-engineering process is applied to the mine, and the results are analysed and discussed.

Chapter 5

This chapter concludes the study by comparing the study outcome to the objectives set out for the study. Recommendations are made for further studies on the matter.
CHAPTER 2: Literature study

Refuge bay legislation is discussed. A problem-solving methodology is selected along with the review of various supporting tools. Methods to ensure the longevity of the project is investigated.
2.1. Preamble

This chapter reviews the literature to support the process of finding a solution to the problem identified in the first chapter. In this chapter, the refuge bay legislation is investigated to ensure that each aspect of the project adheres to laws regarding refuge bays in deep-level gold mines, specifically in South Africa. Various problem-solving methods are evaluated to ensure that the most applicable one is chosen for the identified problem environment. Based on the problem-solving method chosen in this chapter, research is conducted on methods to assist the problem-solving method such as simulating tools, financial analysis and benefit quantification. Finally, methods to ensure the longevity of the project are investigated.

2.2. Refuge bay compressed air legislation

In the mining industry, refuge bay construction is based on the legislation for safety in the mine [16]. A wide variety of refuge bays exist in the mining industry depending on the mine. For this study, only deep-level gold mines’ refuge bays are considered. To redesign the CA system, one must ensure the correct legislation is adhered to with regards to the CA in refuge bays. South African mining adheres to the Mine Health and Safety Act (MHSC) No. 29 of 1996 [17]. All refuge bay-related regulation is summarised as follow:

- The employer of the mine must ensure that readily accessible refuge bays are provided underground.
- Refuge bays should be located within the limits of the self-contained self-rescuers in use at the mine$^8$.
- Based on the number of persons likely to be present in the area, the employer should ensure that every refuge bay complies with the following criteria:
  - Sufficient size;
  - supplied with sufficient air supply;
  - sufficient supply of potable water;
  - sufficient ablution facilities;
  - sufficient illumination;
  - sufficient first aid equipment;

$^8$ A self-rescuer is a portable oxygen device providing limited air when the surrounding air is unbreathable [45]
- sufficient means to communicate verbally with surface operations;
- located in a safe area not close to combustible material storage in such an area;
- constructed so that toxic gasses will not enter refuge bay;
- equipped with an escape route plan indicating current position and way to the surface;
- information regarding emergency procedures and emergency phone numbers; and
- methods of identifying the chamber from the outside, even in low visibility.

- Inspection of the refuge bay should take place every 30 days by an appointed employee and every 90 days by a person that holds an Intermediate Certificate in Mine Environmental Control.

The MSCH ensures the safety of the mine employees but fails to supply specifications to any of the regulations given, specifically the CA supply pressure and flow needed for the refuge bay.

The Canada is one of the world’s largest gold producers and currently holds eighth place in gold reserve ranking in the world\(^9\). Canada’s Ministry of labour provides information for guidance for inspectors when assessing underground refuge chambers [18].

According to the information set out by the requirements for underground refuge stations, the flow to a refuge chamber should be 7,645 litres of air per eight hours per person occupying the chamber [18]. In order to improve on the current CA supply methodology, these regulations should be adhered to in the solution generation.

### 2.3. Effect of compressed air leaks in mines and methods for benefit analysis

#### 2.3.1. Quantifying compressed air leaks

The CA feed into the refuge chamber could be viewed as a “leak” in the CA system, since air escapes the system continuously. To simulate and quantify the effect of these leaks in the mine, it is necessary to have proper methods to do so and understand the impact of CA leaks on the mines’ electrical power consumption. In this section, studies are researched to find methods of quantifying and understanding leaks in the CA system.

Study I (2011)[19]:

Title : Integrating various energy saving initiatives on compressed air systems of typical South African gold mines

Author : Jaco-Albert Snyman

Overview : The study focussed on methods to reduce the requirement of compressed air in industry to have a positive effect on electricity consumption. The study aims to combine efforts to improve compressed air supply efficiency and reduce compressed air waste. Results indicated that savings can be doubled by combining different methods of reducing energy usage of compressed air.

Shortcomings & Recommendations : This study did not include the social aspects of the solutions implemented. Training and savings procedures could lead to further savings.

The study uses an equation to determine the power required for the compression of air based on the mass flow rate of the air being compressed.

Equation 2: Power required for polytropic compression

\[ W_c = \dot{m} \frac{nRT_1}{n-1} \left[ \left( \frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \]

Where:

\( W_c \) Work input [kW] required to compress gas.

\( \dot{m} \) Mass flow rate [kg/s] of the gas being compressed.

\( n \) Polytropic exponent.

\( R \) Universal gas constant taken as 0.287 kJ/kg-K.

\( T_1 \) Inlet temperature [K].
Absolute pressure [kPa].

To adjust for the efficiency of the compressors the following equation is used:

**Equation 3: Power consumed by the electrical motor**

\[
W_m = \frac{W_c}{n_c n_m}
\]

Where:

- \( W_m \) Power [kW] consumed by the electrical motor
- \( W_c \) Power [kW] required to compress the air.
- \( n_c \) Compressor efficiency
- \( n_m \) Electrical motor efficiency

The study provides a method to determining the effect of the “leaks” in the refuge bays. The equation is ideal for simulating the benefit from the project by assuming similar characteristics for each refuge bay discharge.

**Study II (2007) [20]:**

- **Title**: Investigating the effects of different DSM strategies on a compressed air ring
- **Author**: J.W. Lodewyckx
- **Overview**: The study focusses on the demand side of the CA system. Demand side management strategies are proposed to reduce energy consumption from the compressors. Substantial savings are released through the reduction of CA energy consumption.
- **Shortcomings & Recommendations**: This does not include savings from leak management in the mining system, as the focus is on the demand of the CA. It is suggested to focus on CA waste in the CA network underground in future studies.
Although the study focuses on demand-side management of the CA, it uses a simple method to determine the benefit of the implemented project. Lodewyckx makes use of a 24-hour profile that displays the electrical power consumption of a mine. These 24-hour profiles are ideal to compare projects that have a baseload reduction effect. The effect will easily be seen on the 24-hour consumption profile.

At first, a baseline pressure profile is drawn up. The baseline displays the average consumption the mine will experience from its compressors during each part of the day. The baseline is compared to the post-implementation 24-hour profile. Based on the difference between the baseline power consumption and the post-project implementation consumption, the benefit is calculated. The reduction of power consumption can be converted to monetary equivalent based on the mine’s electricity costing structure per kilowatt-hour consumed. Figure 7 is an example of baseline versus post project implementation:

![Shaft compressed air system](image)

**Figure 7: Power savings vs project baseline example - Adapted from [20]**

### 2.3.2. Financial evaluation tools

To test the financial feasibility of a solution in the project, an appropriate tool must be used. It is important to evaluate the financial aspect of the projects in a mining environment due to the financial strain of the mines, and thus requires the contemplation of the project benefit and capital expenditure [21]. The financial evaluation tools give an insight into the possible benefit that the project might have, a worthwhile indicator if the project should proceed. In addition to
this, the methods allow for the evaluation of the project post-implementation. Table 2 summarises four project evaluation methods.

Table 2: Financial project evaluation methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Summary</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback period [22]</td>
<td>This indicates the time it takes to repay the cost of the project using the benefit that the project delivers.</td>
<td>- Payback period length</td>
</tr>
<tr>
<td>Ratio Methods [23], [24]</td>
<td>Indicates the ratio between two sides of the projects.</td>
<td>- Cost benefit ratio</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Return on investment</td>
</tr>
<tr>
<td>Net present value (NPV) [25]</td>
<td>The sum of net annual cash flows discounted based on the time value of money.</td>
<td>- NPV factor</td>
</tr>
<tr>
<td>Internal Rate of return (IRR) [26]</td>
<td>The discount rate that makes the NPV value equal to zero (net cash flow equal to zero).</td>
<td>- Internal Rate of return (IRR)</td>
</tr>
</tbody>
</table>

The chosen evaluation method deemed as the best-fit is based on the type of project and the project environment. The financial pressure of mines causes the mine to limit their capital expenditure on new projects and a rather short payback period can be expected. Therefore, the payback period evaluation would be ideal. Payback period calculation is given as follows:

Equation 4: Payback period [22]

\[
\text{Payback period} = \frac{\text{Expenses}}{\text{Income/period}}
\]

As an added perspective on the project performance, the second suggested evaluation method will be net present value. The project lifetime will continue until the mine closes; therefore, the life-of-mine will be used for NPV calculations. The formula for NPV is as follows:

Equation 5: Net present value [27]

\[
NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t}
\]

Where:
\[ R_t \quad \text{Net cash flow for period } t \]
\[ i \quad \text{Discount rate} \]
\[ t \quad \text{Time of the cash flow} \]
\[ N \quad \text{Number of cash flows} \]

In addition to the power reduction of the project, environmental benefit will also be realised by reducing the EE consumption [28]. There will be an impact on the amount of water and coal used to generate the electricity and a reduction in emissions such as CO\(_2\) [28]. This should be taken into account when determining the project benefit.

### 2.4. Process modelling methods and simulation tools

#### 2.4.1. Digital modelling and simulation

As proven by Friedenstein [14], simulation software can be used as a tool to simulate deep-level mine refuge bays and their CA consumption. By simulating the solution, a replica of full-scale implementation can be witnessed without any risk, if the simulation is accurate. A variety of simulation tools are available. This section will review and choose an appropriate tool for simulation.

**Process toolbox (PTB) [29]**

Process toolbox is a thermal hydraulic simulation package that is used to simulate mine systems, such as the CA, refrigeration or the water network. This package can determine the optimal use of equipment by incorporating all the components into a system. Doing so, the system inefficiencies can accurately be determined. The package can be used to determine the possible cost savings for inefficiency solutions. PTB has a relatively easy-to-use interface that enables simple drag and drop functions for system components. It has been used in a closely-related study by simulating CA use in refuge bays [14].

**Flownex [1]**

The simulation tool can be used for simulating both compressible gasses and incompressible liquids. Given the size of the deep-level gold mine, the package offers limited size simulation in their demo version. Although the tool offers various uses of mining systems, the tool is a costly product.
**KYPIPE** [30]

KYPIPE is a simulating tool to solve steady-state flows for pipe distribution systems. The package is mainly used for liquids and gasses, given a constant density. The product facilitates various components in a pipe system, such as valves, flow meters and storage tanks. The product is more suited for hydraulic systems.

**AIRMaster+** [31]

The AIRMaster+ is a software that can be used to determine energy use and potential energy savings. The tool provides a simple way to set up a baseline for the current system, and furthermore, gives the opportunity to evaluate the energy and monetary savings from the project. The software uses a systematic approach and assesses the supply-side performance of the CA system.

### 2.4.2. Simulation tool selection

The various simulation packages each have their advantages and disadvantages. The ideal package for the CA system is one that will best accommodate the deep-level mine CA environment. Table 3 compares each of these packages.

<table>
<thead>
<tr>
<th>Simulation Tool</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process Toolbox (PTB)</td>
<td>• Proven in other CA projects in mines [1],[20], [29]</td>
<td>• Input data needed for all components</td>
</tr>
<tr>
<td></td>
<td>• User-friendly</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can determine the project benefit</td>
<td></td>
</tr>
<tr>
<td>Flownex</td>
<td>• Proof to be used in mining environment</td>
<td>• Expensive</td>
</tr>
<tr>
<td></td>
<td>• Quality, accurate simulations</td>
<td></td>
</tr>
<tr>
<td>KYPIPE</td>
<td>• Accommodates various pipe components</td>
<td>• Not ideal for gas application</td>
</tr>
<tr>
<td></td>
<td>• Accurate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• User friendly</td>
<td></td>
</tr>
<tr>
<td>AIRmaster+</td>
<td>• Provides savings calculation</td>
<td>• Intervals are 1 hour apart</td>
</tr>
<tr>
<td></td>
<td>• Provides 24-hour profiles</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Proven in mining environment [32]</td>
<td></td>
</tr>
</tbody>
</table>

Based on Table 3, PTB is chosen as the best-suited simulation tool for the project. The tool has proven results from previous studies done in similar environments [20] [1] [6] [29]. A large benefit the simulation tool adds is the ability to determine the benefit of an implemented...
project. Once the benefit is realised, a financial analysis can be conducted to measure the performance from various perspectives of the project.

2.5. Problem-solving techniques

2.5.1. Introduction

As discussed in Chapter 1, a deep level mine consists of various intricate networks. All these networks work together to operate the large mining system and ultimately remove gold from the ground. Given the sheer size of the system, it is essential to consider all aspects when altering any part of the system. Developing a methodology might be subject to the limitation of the developer’s perspective and knowledge. Therefore, a generic problem-solving methodology is chosen and adapted to the conditions of the project environment.

Additionally, the problem-solving methodology should be moderately easy to adapt to the project environment without too much alteration to the problem-solving method. In this section, some problem-solving methodologies are reviewed, after which one of them will be chosen.

2.5.2. Project environment

In an attempt to select an appropriate methodology, the project environment should be defined in order to select the methodology that is most applicable. In this section, the important aspects of the problem will be highlighted.

- The focus of this study is based on the CA use in refuge bays that are in deep-level gold mines in South Africa. As one of the users of CA in the mine, altering the use will affect the other users of CA. Therefore, the problem should include a holistic approach to problem-solving.
- The problem identified is mainly mechanically based but does include human interaction which is the leading cause of waste in the process. The methodology should address the technical and human aspect of the problem.
- The methodology must have a majority focus on the solution and implementation step, and less focus on problem identification.
- Given the pressure on the mines outlined in Chapter 1, the methodology should have a rapid approach to problem-solving.
2.5.3. Review of problem-solving methodologies

In this section, four problem-solving methodologies are reviewed and evaluated based on the needs identified in the previous section. A short description of each methodology is given, as well as their implementation steps.

**Soft systems methodology (SSM) [33]:**

The methodology is a systems approach to solving business management problems and is typically used for complex problems. The methodology assists in identifying how entities interact and then determines the best course of action [34]. It is based on organisational modelling which means that everything is part of an interconnected whole. The methodology consists of seven steps to achieve the solution, as shown in Figure 8. These steps are as follow:

1. Start with the problem and its environment.
2. Define the problem and build a rich picture of the problem.
3. Do a root cause analysis and identify the root cause.
4. Construct conceptual models of the human activity systems.
5. Compare the models with real-world.
6. Define changes that are both desirable and feasible.
7. Implement solutions to improve the problematic situation.

![Figure 8: Seven steps of systems methodology – adapted from [33]](image-url)
SSM is a comprehensive approach to problem-solving that considers human interaction. The seven steps of the methodology each have a sub-tool to help achieve the goal of the step, such as the rich picture method and human activity systems.

Much focus is placed on the identification of the root cause of the problem by use of root cause techniques such as CATWOE (Customers actors transformation world view owner environmental) [34]. There is less detail when it comes to the implementation and validation steps, and little focus placed on methodologies to implement it.

**Plan Do Check Act (PDCA):**

As part of continuous organisational improvement or Kaizen, the PDCA cycle is used as a methodology to continuously improve processes and solve problems [35]. The idea of the methodology is to continuously improve various parts of a system. The most important step of the cycle is the “act” step. The “act” step sets up the next iteration of the cycle to build on the previous improvement. The methodology does not assist in methods to achieve the goals of each step and leaves room for the user’s interpretation [35].

The PDCA steps can be interpreted as follow:

1. Plan - Set objectives to achieve a solution
2. Do - Implementation of the plan
3. Check – Analyse the results and determine the benefit
4. Act – Act on the improvement of the previous steps and ensure the changes are sustainable

The PDCA focuses less on the problem identification as required by this project. The methodology has a rapid implementation period and ensures the sustainability of the project after it is implemented.

The methodology does not consider the human factor of the project and does not specify any methodology to perform steps. The number of goals that need to be identified for each goal might lead to the project taking longer than expected. The methodology offers limited assistance with regards to the execution of the problem-solving.
“Rapid Re” Business process re-engineering [36]:

The Rapid Re-engineering methodology is designed to rapidly produce substantial results: typically, within six months to a year. The methodology is designed so that minimal additional methodologies are necessary. As seen in Figure 9, the methodology consists of 54 tasks divided into five stages of the Rapid Re-engineering process to assist in performing the steps. Before implementation, the methodology considers the project environment by identifying the constraints of the project beforehand. The steps of Rapid Re-engineering are as follows:

1. Preparation – Initiate the re-engineering process and identify the need for the project.
2. Identification – Identify the process to be re-engineered to fulfil the need for the project and develop a model of the system.
3. Vision – Analyse the identified process and model the as-is process. Identify the cause of waste and suggest an ideal solution.
5. Transformation – Implement solution and measure the benefit.

Figure 9: 54 tasks of Rapid Re-engineering divided into the 5 steps – adapted from [36]

The methodology considers the technical as well as the social design. It is business-oriented, where a lot of the tasks do not apply to the mining environment. The re-engineering process...
will completely replace one of the systems, and without proper testing, might have a negative impact on the system.

**IDEAL problem solving**[37]

IDEAL is an acronym for Identify, Define, Explore, Act and Look back. The Identify step is the problem identification phase, and the goal is to determine the root cause for the problem. The Define step is used to define the process as-is. All information regarding the problem area is gathered and analysed. The problem is to be defined in one sentence and revised until it represents the project goal. In the Ideal step, an ideal solution is formulated from all persons influenced by the problem: determine what will be necessary to implement the chosen solution. During the Action step, the solution is implemented. The Look back step is to evaluate the impact of the solution, as well as the effect of problem-solving in the organisation.

### 2.5.4. Selection of problem-solving methodology

To select the most suitable solution to the problem, consider Table 4 below, which investigates each of the solutions within the different project environment characteristics.

<table>
<thead>
<tr>
<th>Methodology</th>
<th>Holistic approach</th>
<th>Address technical and social aspect</th>
<th>Focus on solution benefit</th>
<th>Rapid problem-solving</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSM</td>
<td>Yes</td>
<td>Yes</td>
<td>Not in much detail</td>
<td>Not specifically</td>
</tr>
<tr>
<td>PDCA</td>
<td>Yes</td>
<td>Not specifically</td>
<td>More focus on next project preparation</td>
<td>Yes</td>
</tr>
<tr>
<td>Rapid Re BPR</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes, detailed tasks to achieve and report on benefits</td>
<td>Yes</td>
</tr>
<tr>
<td>IDEAL</td>
<td>Yes</td>
<td>Not specifically</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

By careful consideration of Table 4, it is evident that the Rapid Re-engineering process is the most suitable for this project. The problem-solving methodology has a holistic approach, addresses the technical and social aspect of the problem, is focused on the solution development
and can be implemented in rapid fashion. Appendix G is a detailed review of the problem-solving methodology.

### 2.6. Project sustainability methods

Sustainability in the perspective of this project is the longevity of the solution to ensure the benefit is observed year to year. To continuously improve the institution and its processes, implemented projects should remain sustained to build on them for cumulative improvement [38]. If proper sustainability of the project is not witnessed, the malfunction of the solution might lead to a zero or negative effect on the system [38]. Table 5 summarises various strategies found in studies to assist in ensuring the longevity of the solution applicable to the deep-level mining environment.

#### Table 5: Project sustainability techniques

<table>
<thead>
<tr>
<th>Study</th>
<th>Method</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wang, Xia [38]</td>
<td>Maintenance to ensure the optimal functioning of implemented retrofits in energy efficiency projects.</td>
<td>Maintenance is classified into two parts: Corrective maintenance (CM) or preventative maintenance (PM). CM fixes the system when broken whereas PM is actions to prevent the malfunction of the system.</td>
</tr>
<tr>
<td>de Coning [39]</td>
<td>Team dedicated to follow up on CA inefficiency.</td>
<td>The study suggests the use of an Air wolf team which travels the mine in search of CA leaks and repairs them. A similar team can be used for other purposes to monitor conditions and proper working of the implemented solution.</td>
</tr>
<tr>
<td>Berry, Harrel [40, 41]</td>
<td>Communicate the project to key staff.</td>
<td>Communicate the project and the possible benefit to all levels of staff to get them on board with the project. Train staff that will be in contact with the system and the proper operating procedure.</td>
</tr>
<tr>
<td>Harrel [41]</td>
<td>Analyse data for setback in optimal operation.</td>
<td>By data analysis of performance indicators such as electricity consumption, one can see if the initial project improvement is still realised.</td>
</tr>
</tbody>
</table>

From Table 5, a combined strategy could be developed. Initially, project communication is essential. Most importantly, the individuals interacting with the system that is altered should
be informed before and continuously after the alteration. After implementation, Air wolf teams can be assigned to fix CA leaks and at the same time, ensure the altered refuge chambers are operating correctly. Any reduction from savings observed from the data should trigger an audit on the implemented projects. These sustainability methods will be incorporated into the implementation step developed in Chapter 3.

2.7. Summary

In this chapter, various topics were researched to provide a background as well as methods to achieve the objectives of this study. As the refuge bays are there for the goal of keeping workers safe during emergencies, the regulations of the refuge bays were reviewed to ensure that all specifications are adhered to during solution generations.

A suitable simulation tool, Process Toolbox, was chosen to use in the problem-solving process. Given that the CA in the refuge bay resembles a large leak, previous studies containing similar problems were revised, along with methodologies on cost calculation.

An appropriate methodology was necessary to evaluate the financial benefit of the project. Out of the four methodologies, payback period and net present value evaluations were deemed best fit for the project environment.

Various problem-solving techniques were identified and reviewed. Rapid Re-engineering was chosen as the methodology to solve the need for this study. Finally, methods to ensure the sustainability of the project were researched.

The chapter reviewed various ways to achieve the outlined objectives set out in Chapter 1. Methodology’s and auxiliary methodologies were identified for use in the quest to understand, redesign and implement new refuge chamber CA supply configuration and quantify the benefit realised from it.
CHAPTER 3:  A Method to optimise refuge bay compressed air consumption

Rapid Re-engineering is applied and adapted in reference to refuge bays in a deep-level gold mine.
3.1. Preamble

This chapter will adapt Rapid Re-engineering to a deep-level gold mine. The typical process is broken up into two parts to put more focus on the project constraints. Firstly, the constraint identification where the goal is to determine the constraints for the rest of the project. The second part is the implementation of the Rapid Re steps. Each step has objectives to achieve to complete the stage. There is a certain input from the previous stages. The input allows the objectives to be met in the step. Each stage has an output as a product of the objectives in the step. After each section, a summary of the entire section process is given in an image to illustrate the adapted version of the step.

3.2. Constraint identification

Out of the original categories of constraints seen in Appendix G, only four were seen as applicable to the study. The primary goal is to identify the constraints in the project environment in order to regulate the Rapid Re steps [36]. The focus on the constraints for the project will ensure that the change to the intricate CA system of the mine is done in an appropriate way, without causing ignorant problems in the system. Throughout the implementation, the project should continuously refer to the constraints identified in this section.

3.2.1. Define the type of project to be re-engineered

In this step, the type of project needs to be chosen, and the constraints for the appropriate type should be identified. Three types of projects are identified in the original Rapid Re process under the types of projects to be engineered. Table 5 summarises each of the project types and their respective characteristics.

<table>
<thead>
<tr>
<th>Project type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Once-off</td>
<td>• No return to project</td>
</tr>
<tr>
<td></td>
<td>• Not replicated</td>
</tr>
<tr>
<td></td>
<td>• Goals are project specific</td>
</tr>
<tr>
<td>Part of similar projects</td>
<td>• Generic approach</td>
</tr>
<tr>
<td></td>
<td>• Easily adaptable solution</td>
</tr>
<tr>
<td></td>
<td>• Efficient implementation</td>
</tr>
<tr>
<td>Pilot project</td>
<td>• Sufficient proof of concept</td>
</tr>
<tr>
<td></td>
<td>• Test of new concept</td>
</tr>
<tr>
<td></td>
<td>• Possibly small scale</td>
</tr>
</tbody>
</table>
After the appropriate project type is chosen, the project-specific constraints are determined based on the project type. The constraints align the project to the project type boundaries. Typically, in the mining environment, a pilot project is done only when the cost of the pilot project is low. Deep-level mines in South Africa are similar in operation in terms of CA usage for operations [42], therefore, a once-off project can be done if the problem is site-specific. Otherwise the project should be designed as a part of similar projects.

3.2.2. Define scope for the project

The scope of the project should be determined to define the project boundaries. Various boundaries are already identified for this project thus far and the redesign process should stay within these boundaries. As stated in Chapter 1, the project will focus on CA use in refuge bays located in deep-level gold mines. The scope should be further defined to a narrower focus if necessary.

3.2.3. Determine the role players in the BPR process

In this section, the constraints for the role players of the project are defined. These constraints are generic and can be applied to the deep-level mining environment. In summary of what is stated in same section of Appendix G, the constraints for the project role players are as follow:

- Both external and internal employees to the refuge bay CA configuration should be represented;
- Persons should have the capacity for the project – still in line with their daily responsibilities on the mine.

3.2.4. Management’s expectations of the project

In this section, the constraints according to the mining management are defined. Management for the refuge bay CA system will fall under the management of the services engineer who will sign off the project implementation.

It must be determined if the management views the project as an experiment or gains oriented. If the project is only an experiment, the constraint will require the project to produce useful data on the performance of the solution, including the output. The output is not necessarily a benefit contributor, but always a learning exercise. For a financially stressed mine, a benefit-oriented project will be preferred.
If the focus is on the gains of the project, the project constraint should ensure that the project yields a positive result. Therefore, ample proof should be given that the project will work before implementation. Given that the CA can be simulated [14], an experimental project can easily be done in software to test before implementation. The constraints regarding the aim of the project should be defined after selection of the type of project.

Management should define the level of financial freedom with regards to available capital for the project. The financial freedom is not necessarily a set amount but could be a payback period or benefit. Typically, the mine will require a short payback period with little to no capital expenditure due to the financial stress on the mine [1]. An expected timeline should be given for the project; therefore, the allowed duration is also regarded as a constraint.

The management should decide the magnitude of change of the project. The amount of change the solution can bring to the organisation might have a large impact on other parts of the system. All the above-mentioned constraints form the project constraints. If all constraints are agreed upon, the implementation of the Rapid Re process can start.

3.3. Preparation and Identification – Process initiation and process selection

In Chapter 1, the need for the project was identified with the necessary process to focus on for re-engineering. Seeing as the preparation and identification steps are typically used for this purpose, the steps will be combined. In the combined step, the goals of the first two steps not yet met will be achieved. In this section, each of the BPR steps will be reviewed with regards to deep-level mining. The adapted Rapid Re steps are shown in Figure 10.

![Figure 10: Adapted Rapid Re-engineering process flow](image)

3.3.1. Preparation

The first part of preparation is to have a need for improvement as an input for the step. The need for this study is outlined in Chapter 1 as the need for operational improvement in CA usage in refuge bays to reduce operational costs. The other inputs for the preparation step are the permission of management. The project constraints identified in the first part are given as an input to align each of the Rapid Re steps.
The team to assist in the problem solving should be from outside and inside the refuge bay CA configuration. Typically, a team is assembled to solve the problem [36]. This document will follow the problem-solving process with the assistance of the chosen team members. Since the process to be redesigned is already chosen, the suggested persons to form part of the BPR assisting team is summarised in Table 7.

Table 7: Suggested personnel for Rapid Re assisting team

<table>
<thead>
<tr>
<th>Refuge bay aspect</th>
<th>Person of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project funding, guidance, permission</td>
<td>Services engineer</td>
</tr>
<tr>
<td>Health and safety</td>
<td>Occupational hygienist</td>
</tr>
<tr>
<td>CA tie-off configuration</td>
<td>Head of instrumentation/Mechanical foreman</td>
</tr>
</tbody>
</table>

In a deep-level gold mine, the mine is broken up into sections. The sizes of these sections vary from mine to mine. In each section, an allocated mechanical foreman takes charge of mechanical maintenance and improvement. The mechanical foreman will most likely facilitate the implementation of any new configuration or the head of instrumentation. Above the mechanical foreman is the services engineer in charge of all services for the shaft. The services engineer will most likely give advice and mentoring for the project along with permission with regards to budget expenditure and any changes to the system. Finally, the occupational hygienist is part of the team to ensure that all changes adhere to the regulations of refuge bays.

The identification step can be initiated if the need for the study is clear and agreed upon by management, the constraints for the project adhered to, and the appropriate mining personnel is identified. Figure 11 displays a summary of the preparation step process.
### 3.3.2. Identification

The input for this step is the project constraints to align the step. Typically, this step is used to identify the process to be re-engineered [36]. Therefore, the need for re-engineering identified in the preparation step is given to identify a process motivated by the project need.

The end-user and the needs of the end-user should be identified. In this study, the end user is the CA users in the mine. Exact need specifications are not necessary at this stage.

The next goal is to identify the processes that make up the CA system of the project. The definition of each process should include the role in the CA system as well as the place of the refuge bay with regards to the other processes in the system. Universal modelling language (UML) can be used to achieve this goal, such as a use case diagram. The use case diagram documents the influence on all the different parts of the system in which it operates. This way, any post-project activities can make informed decisions on any alterations.

If the system is modelled with reference to the refuge chambers the Vision step can commence. Figure 12 displays the process flow of the Identification step.

![Identification process flow](image)

**Figure 12: Identification process flow**

### 3.4. Vision – Process ideal selection and verification

In the Vision step, the ideal process is envisioned. The ideal process is the optimal part of the process that will be altered according to the project’s constraints and desired performance. The refuge bay CA configuration needs to be understood as-is, the important part to alter should be chosen, and then the ideal is developed based on the identified performance driver.
3.4.1. Understand the as-is process

The standard operating procedure should be explained, and it is essential to determine which part’s deviations are causing waste. The deviation should be improvement points for the ideal developed later in this step. In a deep-level gold mine, the systems are integrated. It is essential to understand the process relative to the rest of the mining system as well.

3.4.2. Identify the most valuable activity

Each of the activities in the process adds value to the primary goal of the system. The most valuable activity in the CA refuge bay system that contributes to the project goal must be identified. Ultimately, the value-adding activity will be the focus of redesign to ensure the correct part is altered for the most substantial project impact.

3.4.3. Determine performance drivers

In addition to the value-adding activity, the performance indicator of the refuge bay CA configuration should be identified. The performance indicator is the data used to indicate project performance and improvement. The need for this study is to reduce electrical power consumption by reducing CA usage. Therefore, the electrical power consumption of the compressors is used as a performance indicator.

3.4.4. Baseline performance

As part of the as-is analysis, define the current process performance in terms of the electrical power consumption. The baseline is derived from a period with regular mining activity. For the compressors, the baseline should comprise of a typical 24-hour compressor electrical power consumption graph, as seen in Section 2.3.

3.4.5. Develop ideal

The ideal is given in the form of goals to be met by the solution step to ensure the current problems in the refuge bay CA configuration are solved or improved. The ideal is envisioned, but no specific solution is decided upon yet. The ideal is given rather as a set of goals to be met in the solution step. Goals from both the social and technical perspective are needed for the solution.
3.4.6. Verification and possible benefit

The possible benefit is determined to test the feasibility and the worth of the project at an early stage, and then reported to the project participants. The benefit is the compressor electrical power reduction, provided that all the vision goals in the ideal are met.

The theoretical benefit is calculated by determining the effect of the implementation. The effect can be calculated mathematically, by simulation or through a small-scale implementation. For this project, simulation will be used, as it is a proven method for refuge by CA consumption [14].

The theoretical benefit will serve as the verification for the ideal. The result of the project verification will identify a theoretical benefit. In this study, the verification is done utilising PTB simulation.

If the reduction in electrical power renders a result that would make the project worthwhile, the Rapid Re process may continue. The design process can commence if a clear understanding is given of what the process consists of and what the ideal would be for a new solution. Figure 13 summarises the vision process flow.

3.5. Solution

In the solution step, a combined technical and social solution is developed from the goals defined in the Vision step. Each of the goals should be addressed in the appropriate part of the solution. Along with this solution, implementation planning must be done. Finally, the solution should be combined. Given the cost of the solution, the financial feasibility of the project can be determined for approval before implementation.
3.5.1. **Technical solution**

This section aims to address goals that form part of the technical side of the solution that can improve the refuge chamber CA configuration as-is. If there are any changes to the relationships with other processes in the CA system, these relationships need to be redefined. In the harsh underground mining environment, electronic equipment does not last long. Analogue equipment and parts would be more feasible in the environment.

3.5.2. **Social solution**

The social design considers the part of the solution that deals with the employees that engage with the process. The social design must ensure to adhere to the MHSC, and furthermore, ensure the general safety of employees in its use.

3.5.3. **Combined solution**

The two parts of the solutions must be combined and adequately described. The combined solutions should be adapted to adhere to the constraints of the project. The new project process flow must be defined for simple description of how the new configuration operates.

3.5.4. **Financial evaluation**

The financial evaluation is done as a final test of the feasibility of the project before full implementation can commence. As discussed in section 2.3.2, the payback period and NPV financial evaluation tools are used for this study.

The first tool is the payback period. The method is straightforward by simply determining the amount of time it would take the project to pay back the initial investment through annual project benefit [21]. The NPV evaluation would allow for a long-term evaluation of the project’s benefit. The NPV formula is as follows: The period of each cash flow will be taken annually, as the savings for the project are determined in terms of annual savings. The company’s weighted average cost of capital (WACC) is used as the company’s discount rate [43]. The NPV will be calculated over a number of year and the time-value of money should be considered. To compensate for the effect of inflation, A real discount rate should be calculated and used. The real discount rate used in Equation 5 will then be calculated as follows:
Equation 6: Real discount rate [43]

\[
\text{Real Discount Rate} = \frac{(1 + \text{Nominal Discount Rate})}{(1 + \text{Inflation Rate})} - 1
\]

The number of periods in the evaluation should be chosen based on the life of the mine that the project is implemented on, since the project is assumed to run indefinitely until the mine closes.

3.5.5. Implementation plan

After achieving vision goals, an implementation plan should be devised for the solution. The implementation plan should address and explain any disruption to processes outside of the refuge bay when the solution is implemented.

Should the project seem financially beneficial and the implementation plan is agreed upon by the mine, the project can continue to implementation. Figure 14 illustrates the process flow of the solution step.

3.6. Transformation – Implementation and validation

3.6.1. Small-scale implementation

It is recommended to implement and test the solution in a small-scale implementation if it is uncertain what the outcome of the solution might deliver. A simulation can replace the small implementation project in a low-risk manner since no expenditure is needed for its development and tests if done in-house. After the pilot test, any refinement is made if necessary, and the transition should commence.
3.6.2. Full-scale implementation

A full-scale implementation on the refuge chambers can start as planned. Implementation should be followed by monitoring the configured refuge bays. It is vital to ensure the implementation facilitates the technical as well as the social side of the solution. A post-implementation audit on each of the refuge chambers will ensure the BPR team is informed of the successful project implementation. The initial effect in a real-life refuge bay set-up can also be communicated to the BPR team. The affected individuals that will operate or work closely with the redesigned solution should receive proper training. The mining personnel receives annual training that should include the use of the new refuge bays. A simple, easy to remember method must be devised for training.

3.6.3. Project benefit

After implementation of the project, the project benefit to the system can be evaluated. The benefit is calculated by comparing the post-implementation data with the baseline, in terms of electrical power consumption. Given this benefit, along with the actual costs of the project, a final financial evaluation must be executed as an indicator of project success and communicated to the members of the BPR team.

In order to validate the results of project, reduction in electrical power consumptions can be compared to the simulation results. The actual payback period and NPV of the project can be determined for the project. In addition to the monetary benefit of the project, some benefit in terms of the environment will also be realised, since there will be a reduction in electricity consumption. Electricity causes an indirect pollution from the mine due to the waste it causes to supply the electricity [28]. The factors are based on the 2017/2018 figures were calculated based on total electricity sales by Eskom. These factors can be used to determine the indirect effect by reducing electricity consumption of the mine. Table 8 lists the factors for each of the items that will be focused on in this thesis.

<table>
<thead>
<tr>
<th>Indirect consumption/emission</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.54 kg/kWh</td>
</tr>
<tr>
<td>Water</td>
<td>1.30 l/kWh</td>
</tr>
</tbody>
</table>
### 3.6.4. Model new system

The new system model must be completed to illustrate the new refuge bay CA process in the larger scheme of things. System modelling will assist in seeing who the change will affect after the redesign. If the solution has little or no effect on the system, a new model is not necessary.

### 3.6.5. Project sustainability

Section 2.6 discusses various methods to maintain the benefit of a project after implementation. In the current mining environment, project benefit should remain constant several years after implementation to build on previous projects as part of continuous improvement. A combination of these strategies should be used to ensure the project benefit will be realised year to year. Figure 15 shows a summarised flow of the transformation process.

---

<table>
<thead>
<tr>
<th>Particulate emissions</th>
<th>0.27 g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2 emissions</td>
<td>0.97 kg/kWh</td>
</tr>
</tbody>
</table>

---

#### Figure 15: Transformation process flow

---

### 3.7. Study objectives review

Before application of the developed methodology, the study objectives are reviewed to ensure the methodology will be successful in executing all the objectives. The study objectives found in section 1.4 are posed as questions.
Were techniques identified to reduce CA refuge bay consumption?

- Yes, Rapid Re-engineering was chosen as the problem-solving methodology in Section 2.5.4. The tool is supported by PTB for simulation of the system, chosen in Section 2.4, and UML to model the system, chosen in Section 3.3.2.

Will the current refuge bay design be investigated and understood?

- Yes, Section 3.4.1 is used to understand the process as-is where the refuge bay design is investigated and understood.

Will the refuge chamber CA configuration be redesigned?

- Yes, Section 3.5 (solution step) is used to redesign the current configuration based on findings in Section 3.4 (Vision).

Will the impact of the new design be quantified?

- Yes, Section 3.6.3 determines the project benefit along with the quantification after implementation.

From the answers above, it is evident that the objectives of the study will be met with the implementation of the adapted tool.

3.8. Summary

Rapid Re-engineering was adapted to be applied to a deep-level gold mine. The majority of the redesign process is generic and can be interpreted by the person managing the implementation.

First, the constraints to consider are reviewed before attempting the re-engineering process. The constraints are then used as guidelines throughout the next part. The second part is the adapted Rapid Re methodology and starts with preparation where a team is identified to meet the need identified in Chapter 1. The identification step models the process to be redesigned relative to the other parts of the compressed air system.

In the Vision step, the process as-is should be understood, and a new process is envisioned. The Solution step generates a solution from a technical and social perspective based on the Vision goals. Finally, the solution is implemented in the transformation step should an initial
simulation prove the concept to be beneficial. The success and impact of the implemented project are measured and reported both in terms of electrical power and environmental impact. Finally, sustainability measures for the project are implemented to ensure longevity.

The chapter summarises the inputs needed for each step, the objectives of each step, and which output is expected. The adapted process ensures all the objectives of the thesis will be met through implementation. The final adapted process flow of Rapid Re-engineering is illustrated in Figure 16 below.

Figure 16: Adapted Rapid Re-engineering process flow
CHAPTER 4: Case study

Application of refuge bay optimisation to a deep-level South African mine
4.1. Preamble

This chapter focuses on the application of the adapted Rapid Re-engineering on a practical case study. The main aim of this chapter is to meet the goals of the study and at the same time test the adapted Rapid Re methodology on a deep-level gold mine. The application, results and interpretation are discussed in detail.

4.1.1. Case study – Mine A introduction

Due to confidentiality agreements, the mine used for this case study will be referred to as Mine A. Mine A is a deep-level gold mine located 90 kilometres from Johannesburg, South-Africa. It is situated in the West Witwatersrand basin. The mine mines from the Ventersdorp Contact Reef. Mine A is a relatively large gold mine comprising of a vertical and sub-vertical shaft reaching a depth of approximately 3 400 meters. Due to its sheer size, the mine hosts many refuge bays. This mine is an ideal candidate for this study since the number of refuge bays increases the impact of the waste reduction in refuge bays.

Mine A currently mines on levels 98 to 113. The mine practices sequential grid mining, which is an upside-down Christmas tree configuration, in order to direct seismic stresses from working areas into virgin rock areas. The mine has an ore grade of 7 g/t in the total mineral reserves, with an estimated 959 000 oz gold available in the reserves. Currently, the mine is contributing to 12% of the total group production.

The Department of Mineral Resources and Water and Sanitation conducts annual performance audits on Mine A to verify compliance with the Mine Health and Safety act 29 of 1996 amongst others. The audit will include refuge bay regulations according to Chapter 16 of this legislation.

The cash operating costs for Mine A has increased by 17.45% since FY14. The all-in sustaining costs are 1 342 US$/oz compared to the global average of 818 US$/oz. The high operating costs of mine A drives the need for operational improvement on CA usage.

4.2. Constraint identification

As stated in Chapter 3, the goal of this process is to identify the environment and its constraints of the project before attempting to redesign the CA process of the refuge bays in Mine A. The constraints are constantly referred to throughout implementation.
4.2.1. Define the type of project to be re-engineered

Mine A forms part of a group of mines. Successful implementation on Mine A could lead to the project being replicated on other mines in the group. Redesigning as part of a series of similar projects will allow ease of implementation on other mines in the group.

Therefore, the type of project is defined as part of a series of similar projects. Subsequently, the application should be well-documented to be easily adapted to the next mine if it proves to be successful. The generic approach allows for the variation in deep-level mines. The redesign process should be simple to implement and versatile. The cost of the new design should be limited so that it can be applied to any deep level mine, regardless of their financial situation. Summarised, the constraints regarding the type of project are as follow:

- Process redesign, implementation and results should be well documented;
- The new design should be versatile enough to be implemented on any deep-level gold mine with variations in refuge bay configuration;
- The new design should be easy to implement on a deep-level gold mine to reduce implementation cost, and installation should not necessarily have to be done by a product expert;
- The new design should be low cost to minimise project capital expenditure.

4.2.2. Define the scope for the project

The scope of the project is limited to the CA usage in refuge bays and will not focus on the supply of the CA to the refuge bay. In summary, the constraints regarding the scope of the project are as follow:

- The focus of the redesign is based on the CA use in refuge bays; supply to the refuge bay is neglected as part of the redesign.

4.2.3. Determine the role-players in the Rapid Re process

Chapter 3 outlines the role-player specific constraints in the redesign process. The role-player constraints of this redesign process needed no further adapting to Mine A. The constraints regarding the role-players were as follow:
• Both external and internal employees to the refuge bay CA configuration should be represented;
• Persons should have the capacity for the project – still in-line with their daily responsibilities.

4.2.4. Management’s expectations of the project

The project should have an experiment orientation, or it should be based on benefit. Due to the financial needs of Mine A, the project will focus on the benefit when redesigning the process. This means that the redesign process should give an expected output that is relatively accurate and of worth to the mine.

The financial budget constraint is an important one for this study since the need in Chapter 1 is devised from the financial problem in the mines. The low cost of the project is already stated in previous constraints. Should the solution require capital, Mine A requires the payback period of the project to be less than a year.

Mine A has no set requirement for the timeline, but since it forms part of continuous improvement, the project should be implemented as soon as possible to continue with other initiatives. For this project, a timeline of fewer than 12 months was accepted by Mine A.

Since the project was limited to a relatively small scope, the change in the entire system was minimal, however, the effect can result in a possible significant impact. Therefore, the project change should be communicated to the proper role-players after execution. In summary, the following constraints were identified regarding management’s expectations:

• The project is benefit-orientated and should aim to maximise the project benefit;
• the project should have proof that some benefit will come from the solution by means of verification;
• a payback period of less than a year for the project;
• a timeline of fewer than twelve months for the entire project;
• change should be properly communicated to the appropriate parties.

These constrains is used to align each of the steps throughout the methodology. The complete project constraints for Mine A is as follows:

• Process redesign, implementation and results should be well documented.
• The new design should be versatile enough to be implemented on any deep-level gold mine with variations in refuge bay configuration.
• The new design should be easy to implement on a deep-level gold mine to reduce implementation costs and installation should not necessarily have to be done by a product expert.
• The new design should be low cost to minimise project capital expenditure.
• The focus of the redesign should be based on the CA use in refuge bays; supply to the refuge bay is neglected as part of the redesign.
• Both external and internal employees to the refuge bay CA configuration should be represented.
• Persons should have the capacity for the project – still in line with their daily responsibilities.
• The project is benefit-orientated and should aim to maximise the project benefit.
• The project should have proof that some benefit will come from the solution by means of verification.
• A payback period of less than a year is expected for the project.
• Timeline of fewer than twelve months for the entire project.
• Change should be properly communicated to the appropriate parties.

4.3. Preparation and identification – Process initiation and process selection

This section is the initiation of the Rapid Re process and part two of the methodology. Throughout each of the steps, the constraints were referred to as they were met.

The need for the study was outlined in Chapter 1 as the necessity for a reduction of operational costs, with a specific focus on the reduction of CA, as this is one of the highest observed costs. The process to be redesigned is the CA configuration in refuge bays. The choice of this process ensured that the project adhered to the following constraint:

• The focus of the redesign should be based on the CA use in refuge bays; supply to the refuge bay is neglected as part of the redesign.

Typically, the BPR team will consist of various people of different expertise. For this project, the team consists of everyone assisting in the redesign process, and not a team in the
traditional sense. The reason for this was that there was no need for the team to identify the process to be redesigned.

As stated in Chapter 3, three persons were of interest with regards to the CA in refuge bays. The persons of interest and their respective roles in the BPR process is discussed in Table 9. The names of the persons were omitted for privacy purposes. This completed the desired output for the Preparation step.

<table>
<thead>
<tr>
<th>Refuge bay aspect</th>
<th>Person of interest</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project funding, guidance, permission</td>
<td>Services engineer</td>
<td>Knowledgeable on the generation and supply of CA to the mine</td>
</tr>
<tr>
<td>Health and safety</td>
<td>Occupational hygienist</td>
<td>Knowledgeable on the regulations and standards in Mine A refuge chamber</td>
</tr>
<tr>
<td>CA tie-off configuration</td>
<td>Head of instrumentation</td>
<td>Knowledgeable on the equipment used to transfer CA to the chamber from the main line</td>
</tr>
</tbody>
</table>

Each of the chosen persons has a variety of responsibilities and expertise. Each of the participants gives their inputs on the redesign process from their experienced point of view. Although not external to the process, they were external to certain aspects of the redesign. Since the persons chosen was not be permanently engaged in the project, the following constraint for the project was adhered to:

- Both external and internal employees to the refuge bay CA configuration should be represented.
- Persons should have the capacity for the project – still in line with their daily responsibilities.

The needs of the end-users of CA were defined as constant CA supply at a pressure of at least 4.5 Bar. The processes that make up the system were then defined by use of a use-case diagram to show the intended functionality and environment. Without describing how the system does it, the use-case describes how it transpires. It was based on the interactions and relationships of individual use-cases.
Figure 17: Use case diagram for the CA system at Mine A

Figure 17 depicts the CA system in Mine A, which consists of five compressors. The installed capacity is four 4.8 MW compressors and one 2 MW compressor supplying all mining activities with CA. All the CA users is represented on the right-hand side of the diagram. They have a direct link between each of the use-cases represented by the ovals. The effect of the activities is indicated by use of association lines. Should one activity include the other, it represents that the base-case (direction of arrowhead) cannot occur without the included case. For example, the air cannot be compressed without consuming electricity.

As visible in Figure 17, the refuge bays have a direct influence on the pressurised line which influences electricity consumption. This also affected all other processes dependant on the CA pressure. The use-case diagram ensured that the project partly conformed to the following constraint:

- Process redesign, implementation and results should be well documented.
Based on findings in Chapter 1, the refuge bay process in the CA system was chosen as the redesigned process. This completed all the desired outputs for the identification step.

4.4. Vision– Process ideal selection and verification

In this step, the current process was understood, and improvements were suggested. The goals to mitigate any current problems were clearly set out, and the theoretical impact was evaluated.

It is important to understand the structure of the process of the refuge bay in Mine A. This study focused on the implementation of the project on active levels. The active levels in Mine A were levels 98 to 113. Figure 18 displays a typical CA system in refuge bays in Mine A. Note that this also depicts the scope of the redesign process.

![Figure 18: Refuge bay compressed air system](image)

4.4.1. Understand the as-is process

The process starts at the main CA line and feeds air into the refuge bay tie-off. According to the MHSC regulations, the refuge bay should be at a higher pressure than the haulage outside of the refuge bay. The pressure delivered by the compressors in Mine A is typically between 4 and 6 Bar.

The pressurised air flows through the line until it is met with a whistle. The whistle is opened in emergency situations to inform rescue workers that the refuge bay is occupied. This whistle, if present, is typically opened by a wire that can be operated from within the refuge bay.

The air continues through the line and the wall of the refuge chamber. Inside the chamber, the air flows to a valve. Typically, ball valves were used in Mine A for this purpose. Under
emergency conditions, the miners were instructed to open the valve fully. The open valve ventilates the chamber and assists with temperature control. Under normal circumstances, the employees were instructed to keep the valve open at 25%. The chamber will keep constant pressure.

Finally, the air proceeds to the end of the line fitted with a muffler. The muffler reduces the sound made by the CA escaping. Employees should not be exposed to noise louder than 85 dB for an extended period, according to the MHSC [17]. The CA enters the chamber and completes the process. The standard operating procedure is depicted in Figure 19.

Figure 19: Refuge bay compressed air process flow
4.4.2. Cause of waste

Although the above mentioned standard operating procedure was communicated to employees, it was not always followed. Refuge bays that were in relatively hot areas is used as cooling down chambers. Workers fully opened the CA valve to bring down the chambers’ ambient air temperature. This form of waste could be mitigated by ensuring the proper ventilation and cooling of working areas and therefore falls outside of the scope of this project.

As seen in Figure 19, the employees should keep the valve open at 25% during non-emergency situations. Each employee might have had their own perspective of 25% open. Opening the valve at 35% would lead to waste, and 15% might be deemed insufficient by regulations.

Due to the high humidity in Mine A, most metallic-based parts are subjected to rust. Over a period of non-use, the valve might not be able to open any more or might break, which leads to an uncontrolled leak. These problems should be addressed in the redesigned solution.

4.4.3. Identify the most valuable activity

The highest value-adding activity of the process should be identified and become the focus of redesign. This ensured the maximum impact for the redesign process. In this context, the value referred to the cost implication to the mine with regards to CA. Table 10 evaluates each part according to their value in terms of cost.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Value impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emergency whistle</td>
<td>Low – only in use in emergencies. Has little effect on cost.</td>
</tr>
<tr>
<td>Refuge bay valve</td>
<td>High – always in use, controls the consumption</td>
</tr>
<tr>
<td>Air muffler</td>
<td>Low – always in use, does not affect consumption cost</td>
</tr>
</tbody>
</table>

It can be concluded that the valve that controls the flow of CA was the most important activity of the process, in terms of consumption cost.
4.4.4. **Determine performance drivers**

Since the need for this study was to reduce CA to the reduce the electrical power consumption, the power consumption (MW) of the compressors at Mine A were used as a performance indicator.

4.4.5. **Baseline performance**

The baseline for the project was set up by determining the usage profiles for three months prior to implementation. The baseline for the project is October 2017 to January 2018. December 2017 was omitted from the baseline due to irregular consumption data, as the production decreases with the holiday season. Figure 20 illustrates the baseline for this project.

![Project baseline - Electrical energy consumption](image)

**Figure 20: Project electrical power consumption baseline**

The profile illustrates the average of the three baseline months. Since refuge bay consumption was continuous, the baseline was expected to reduce in baseload, and the usage profile would have remained the same.

4.4.6. **Develop ideal**

The ideal is formed out of the goal of the process redesign, the constraints of the project, and the current inefficiencies to be remedied. The goal of the refuge bay CA process is to pressurise the chamber and supply the chamber with fresh air.
According to Canadian regulations, the flow to the chamber must be equivalent to 7645 litres of air per person per 8 hours, or 0.27 litres per second per person [18]. The refuge bays in the production levels have a capacity range from 60 to 100 persons. By avoiding numerous solutions for each refuge bay capacity, the largest capacity was used as a guideline.

The refuge bays had to have a higher pressure than the haulage in which it is located. As Mine A is a deep-level gold mine, the barometric pressure of each level differs. In order to maintain an outward flow of air, the barometric pressure outside of the chamber had to be lower than the pressure inside of the chamber. This was controlled by having a constant flow into the chamber that is higher than what is flowing out of the chamber. For example, if the door of the refuge bay was closed, the flow into the chamber had to be larger than the flow through leaks. Therefore, CA had to constantly flow into the chamber in non-emergency conditions.

**Vision goal 1:** The flow of the solutions should allow for 27 litres per second for 100 persons in emergency conditions. There should be a constant flow into the chamber in non-emergency conditions.

The leading cause of inefficiencies is due to the human interaction with the process. The ideal solution limits the necessity of human interaction. Ideally, humans would have only interacted with the system in case of emergencies. Furthermore, the waste occurring from varying valve open states had to be mitigated, and flow should be controlled.

**Vision goal 2:** Reduce human interaction to only emergency situations and control compressed air flow to the system mechanically.

The valves were subject to oxidation, causing rust to form and ultimately render the valves ineffective. The solution had to prevent damage by ambient conditions to the valves.

**Vision goal 3:** The material of the solution should be resistant to oxidation.

The following project constraints had an impact on the design of the solution:

- The new design should be versatile enough to be implemented on any deep-level gold mine with variations in refuge bay configuration.
- The new design should be easy to implement on a deep-level gold mine to reduce implementation cost, and installation should not necessarily have to be done by a product expert.
The new design should be low cost to minimise project capital expenditure. Each of the constraints should have been be adhered to in the redesign process.

Vision goal 4: Adhere to pre-determined constraints of the project.

Four goals were outlined for the ideal process. The final step for the Vision step was to determine the theoretical benefit of the project.

4.4.7. Verification and possible benefit

The solution should attempt to maximise output since it is benefit-oriented. Seeing as the benefit is the reduction in baseload power and its monetary equivalence, the performance indicator was chosen as the electrical power consumed.

In order to witness the impact of the project on all the refuge chambers, a simulation of the CA system was set up. The purpose of the simulation was to illustrate the project benefits to Mine A personnel before recommending any implementations. The layout of the simulation can be found in Appendix B. Figure 21 is a simplified simulation layout for a refuge chamber connected to a CA supply.

The simulated model was verified to ensure the accuracy of the simulation. The verification was done by performing a small-scale test on the refuge bays in Mine A. The test was done by closing the valves of all the refuge bays in a specific area and observing the effect on the CA line. The predicted results were compared to the simulated results, and the simulation model yielded an accuracy of 98%.

The simulation model measured three aspects of the system – CA flow, CA line pressure, and compressor power consumption. The flow to Mine A was simulated, and the results from the simulation gave a 6158 m³/h reduction of air consumption. As seen in Figure 23, the pressure delivered to the mine increased the optimised simulation. With an increase of pressure, the flow to the level also increased. This effect is illustrated in Figure 22 by observing the higher flow during the drilling period. High flow will allow for an improved
service delivery for drilling practices. As for the rest of the day, the flow was reduced, thereby reducing flows through leaks and other forms of waste in the system. Figure 22 illustrates the 24-hour profile for flow reduction versus the baseline flow.

![Baseline vs. Optimised Flow](image)

**Figure 22: Simulated results for optimised flow**

Though the benefit of power reduction is the focus of the project, there is some benefits on the production side through increased drilling pressure [1]. The simulation resulted in a 15 kPa increase in pressure during the drilling shift. This effect is desirable during the drilling shift since the maximum possible pressure for drilling penetration rate is preferable [1].

At the time of the simulation, the mine supply pressure profiles were not yet optimised. The effect of this can be seen on the baseline between 13:00 and 14:00 in Figure 23, where the supply pressure to the mine was still at a maximum. At 14:00, control was applied, and the supply pressure is suddenly reduced. The oversupply of CA pressure leads to waste in the system.

Although a lower pressure is not ideal for drilling as shown in the simulated pressure, the time between 13:00 and 14:00 is outside of the drilling period. A drilling period pressure benefit of 15 kPa is still seen before 13:00, verifying the effect the project will have on the system in terms of pressure. Figure 23 illustrates the optimised line pressure.
Case study

Figure 23: Simulated results for optimised pressure

The performance indicator, power consumption, had a reasonably significant benefit, with a simulated 840 kW in possible savings. An overall reduction in power consumption was observed through simulation. At 13:00, the simulated and baseline values were the same, because high power consumption was simulated by assuming the drilling would continue to 13:00. The CA consumption in the baseline reduces from 11:00, as the drilling in the mine decreases in reality. Although the mine enforces maximum pressure supply until 14:00, the actual flow consumption reduces, whereas the simulation assumes a constant flow consumption. This was simply an indicator of the conservative approach taken in the simulation. Benefits determined from the simulation might be more when implemented in real-life. Figure 24 illustrates the optimised power consumption profile versus the baseline consumption.

Figure 24: Simulated results for optimised power
The benefit of the proposed project proved worthwhile for implementation. The monetary interpretation of the savings amounted to R5.1 million annually for Mine A. The positive result in possible benefit ensured the project adhered to the following constraints:

- The project is benefit-orientated and should aim to maximise the project benefit.
- The project should have proof that some benefit will come from the solution by means of verification.

4.5. Solution

The solution generation has two parallel aspects - the technical and the social solution. These two aspects were combined into a final solution. The solution will indicate the cost of the project. The cost was compared to the benefit, and financially analysed. The value-adding activity was the valve of the line. In order to mitigate the current wastage, the chosen valve had to meet all the goals set out by the process ideal. To ensure all the goals were met, each goal was addressed individually.

4.5.1. Technical solution

Vision goal 1: The flow of the solutions should allow for 27 litres per second for 100 persons in emergency conditions. There should be a constant flow into the chamber in non-emergency conditions.

The goal was met by ensuring the valve, if opened fully, will deliver the required airflow. The size of the opening determines the flow of the valve. Volumetric flow through an orifice is given by Equations 1.

**Equation 1: Volumetric flow through an orifice**

\[ Q = C \times Ao \times \sqrt{\frac{2 \times \Delta P}{\rho}} \]

The CA line pressure was assumed to be 400 kPa, and the outlet barometric pressure was assumed to be constant at 114 kPa. The temperature was assumed to be 25 °C, rendering an air density of 4.66 kg/m³. The discharge coefficient was assumed to be 0.7. Given a flow of 27 l/s, solving for Ao, the equation renders 11.84 mm. Therefore, if fully opened, the orifice will need to be at least 11.84 mm in diameter.
Vision goal 3: The material of the solution should be resistant to oxidation.

To prevent the oxidation of the valve, the valve should be galvanised, or a stainless-steel valve can be used. The exact life cycle of the solution is outside of the scope of the study.

4.5.2. Social solution

Vision goal 2: Reduce human interaction to only emergency situations and control compressed air flow to the system mechanically.

To prevent human interaction, the initial state without any interaction had to deliver the base flow required by the refuge bay in non-emergency conditions. To prevent the uncertainty of precisely where the valve was regarded as 25% open, a standard state should have been apparent.

The goal was achieved by deciding on a crack valve. A crack valve is a standard ball valve which contains a hole in the ball. The hole allowed for a predetermined amount of air to escape when in a closed position. Removing the 25% open state, it limited the use of a human to only an emergency condition. All refuge bay valves could be left in a closed position unless in the case of an emergency.

The size of the crack valve was dependant on the refuge bay leaks. The only area where air can leak out of the refuge chamber is at the door, as it is assumed that the refuge chamber wall is sealed. The typical refuge chamber door is 0.6 m x 1.5 m. It was assumed that the door will have a 1 mm opening along the entire length of the door except where the hinges are located, rendering an area of 0.0035 m². Using Equation 1, and a pressure differential of 100 Pa between the chamber and the haulage, a mass flow rate of 0.0127 kg/s was assumed to escape the chamber.

To ensure that the chosen crack size would be sufficient to pressurise the chamber, three scenarios were simulated. The supply pressure was varied in each of the scenarios based on Mine A’s pressure profile (400 kPa, 500 kPa and 600kPa). Each of the scenarios for a crack size ranging from 4 mm to 16 mm in intervals of 2 mm were simulated. Figure 25 illustrates the simulated mass flow rates through the various size openings.
Since compressed air will be constantly escaping through the crack, the smallest crack diameter is preferable. The smallest necessary crack diameter, to build up pressure in the chamber, is 0.0127 kg/s as determined above. From figure 25 above, the smallest crack diameter that will at least allow for 0.0127 kg/s mass flow rate is 4mm.

4.5.3. Combined solution

Finally, the suggested solution was found to be stainless steel or galvanised valve with a crack when in a closed position. The valve should have an opening of no less than 11.84 mm when in an open position, and a crack with 4 mm diameter when in a closed position. The new solution will have an altered process flow, as illustrated in Figure 26.
The suggested solution will allow for the valve to be continuously closed and easily visible if open, with constant optimal leaking CA. In emergency conditions, the valve should be opened fully. The material of the valve will ensure the longevity of the valves’ condition.

- The new design should be versatile enough to be implemented on any deep-level gold mine with variations in refuge bay configuration.

Although the standard practice for Mine A is to have a 50 mm tie-off into refuge bays, the size might vary. The uncertainty was mitigated by merely using South African standard size valves. If there is any variation in inlet pipe size, an adapter can be used.

- The new design should be easy to implement on a deep-level gold mine to reduce implementation cost and installation should not necessarily have to be done by a product expert.
In Mine A, there is a valve at the tie-off. The tie-off allows for easy close-off of air to replace the old valve.

- The new design should be low cost to minimise project capital expenditure.

To ensure the lowest costs, the cheapest option will be chosen. The payback period should also be less than a year.

The original valve chosen was a two-piece stainless-steel ball valve. The selected size was the 15 mm or ½ inch diameter. The design specifications of the valve can be seen in Appendix E. The supplying company then altered the ball valve by drilling a hole (diameter of 4mm) into the ball.

4.5.4. Financial evaluation

The price of the valve chosen determines the cost of implementation. On the active production levels, Mine A has 68 refuge bays to be refitted with the new valve. Since the installation of these valves' forms part of the regular duties of the mechanics underground in the form of maintenance, no attention was given to the expenditure on installation wages. This left only the expense of the valve itself.

Mine A ordered 75 units of the altered ball valve at a price of R2,391.33 per unit. The total costs amounted to R204,458.72 including tax. Given this expense for the project, the financial evaluation could be done to evaluate the financial feasibility of the project. Given a theoretical saving of R5.11 million a year, the payback period for the project would be as shown in Error! Reference source not found. below.

**Equation 4: Payback period**

\[ \text{Payback period} = \frac{\text{Expenses}}{\text{Income/period}} \]

\[ \text{Income} = \frac{\text{R5.11 mil}}{12 \text{ Months}} = \text{R0.43 mil/month} \]

\[ \text{Expenses} = \text{R0.21 mil} \]

\[ \frac{\text{R0.21 mil}}{\text{R0.43 mil/month}} = 0.48 \text{ Months} \]
Once the project has been implemented, it will be paid off within one month of implementation. The short payback period ensures the project adheres to the following constraint:

- A payback period of less than a year;

Knowing that the project payback period was in line with the requirements, the NPV could be determined. An NPV larger than zero represents a beneficial project. As of 2018, Mine A has a life-of-mine of 5 years. Therefore, the number of cash flows will be taken as 5. The company under which Mine A operates has a WACC of 7.25%, as of December 2017. The South African inflation rate as of December 2017, was 4.4%.\(^\text{10}\) The real discount rate was determined as follows:

**Equation 6: Real discount rate**

\[
\text{Real Discount Rate} = \frac{(1 + \text{Nominal Discount Rate}) \div (1 + \text{Inflation Rate}) - 1}{(1 + i)^t}
\]

\[
\text{Real Discount Rate} = \frac{(1 + 7.25\%) \div (1 + 4.4\%) - 1}{(1 + 2.73\%)} = 2.73\%
\]

Finally, the NPV of the project can be determined using Equation 5.

**Equation 5: Net present value [27]**

\[
NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t}
\]

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real cash flows (R-million)</td>
<td>5.11</td>
<td>5.11</td>
<td>5.11</td>
<td>5.11</td>
<td>5.11</td>
<td></td>
</tr>
<tr>
<td>Present value discount rate @ 2.73% Real</td>
<td>1.03</td>
<td>1.06</td>
<td>1.08</td>
<td>1.11</td>
<td>1.14</td>
<td></td>
</tr>
<tr>
<td>Present value of cash flows (R-million)</td>
<td>4.97</td>
<td>4.84</td>
<td>4.71</td>
<td>4.59</td>
<td>4.47</td>
<td>23.58</td>
</tr>
</tbody>
</table>

NPV = R23.58 mil – R0.21 mil = R23.37 mil > 0 – Project should continue

---

The electricity price change year-to-year was disregarded from the calculations due to the uncertainty of the annual electricity increase from Eskom. If incorporated, the evaluations results would only improve and would therefore have no effect on the evaluation outcome.

It was evident that the project would deliver considerable benefit if implemented with positive results on both financial evaluations. The positive result was due to the low cost of the new design by merely keeping the focus of redesign small and straightforward.

4.5.5. Implementation plan

The final step before implementation of the project was the method of implementation. The implementation of the project was to be done within six months, according to the following constraint:

- Timeline of six months for the entire project.

The start of implementation was February 2018 and should last for five months or less. The valves were to be purchased by Mine A before implementation. These valves were then to be scheduled for installation. After installation was completed, an audit was to be done to ensure that all valves were successfully installed, as well as an audit on the impact of the valve on the refuge chamber. The audit was to be compared based on the newly modelled process.

For a system in a non-emergency state, the valve should be fully closed, allowing for the slight leak through the crack in the valve. The pressure of the refuge chamber should be higher than that of the area outside of the chamber, and if the valve was opened fully, sufficient air should be flowing through a hole larger than 11.84 mm. The operating procedure was summarised into Table 11 for post-implementation auditing.

<table>
<thead>
<tr>
<th>Location of refuge bay</th>
<th>Refuge bay number</th>
<th>Valve replaced</th>
<th>Pressure inside chamber (hPa)</th>
<th>Pressure outside chamber (hPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example</td>
<td>Example</td>
<td>Yes</td>
<td>1136</td>
<td>1135</td>
<td>Example</td>
</tr>
</tbody>
</table>
Once it was confirmed that all valves were replaced, the impact of the project could be determined by the post-implementation power consumption data from the mine. The consumption was to be compared to the previously set up baseline to illustrate the benefit achieved.

4.6. Transformation – Implementation and validation

The final step of the Rapid Re-engineering process is the transformation step. This step was the actual implementation of the project designed in the previous section.

4.6.1. Small-scale implementation

As per Chapter 3, a pilot project was suggested to test the implementation of the project. To speed up the process of implementation, the pilot project was not done. The simulation set up in the previous section had an accuracy of 98% and proved adequate as proof of concept. Additionally, the change being implemented to the system was relatively small, therefore having little risk in the case of failure.

4.6.2. Full-scale implementation

The project was implemented in February 2018 until March 2018. In total, 49 refuge bays were altered with the new valve. Appendix C illustrates the location and implementation dates of the valves. The variation from the previously stated 68 potential chambers was due to some refuge bays that were not operational or closed off, or some that were never built. Appendix F shows the result of the post-implementation audit results.

As part of the BPR team, the occupational hygienist was constantly informed of the development of the project. In terms of safety for employees, the occupational hygienist did not raise any concerns after implementation of the project.

The occupational hygienist conducts constant checks on sound levels underground to ensure it adheres to the mine safety regulations. No concerns were raised after the implementation of the solution.
4.6.3. **Project benefit**

The post-implementation period was from April 2018 to June 2018. Figure 27 illustrates the comparison of the 24-hour consumption profile for pre-and post-project implementation.

![Project base-line vs. Post-implementation power consumption](image)

**Figure 27: 24-hour consumption profile for pre and post project implementation**

As seen in Figure 27, there was a visible reduction in power consumption before and after the project implementation. The average decrease in power amounts to 1215 kW. The project was not the only one implemented that would affect the CA power reduction of Mine A. During this period, an optimisation of air network (OAN) project was implemented. This project focused on the supply management of CA by optimising the CA pressure delivered to each level. The effect of the project can be seen at 17:30, 20:30, and 07:30, where the consumption sharply declines or inclines to meet the demand in that period. Notice that the effect of the refuge bay project can be seen by the reduction in the overall baseload of the consumption, since the refuge bays consume the same amount the entire day.

The average reduction in the baseload during the drilling period (08:00 to 11:30) between the baseline and post-implementation data was 962 kW. It was assumed that only the refuge chamber project was in effect during this period since the OAN project would not apply set-point control during this period to ensure maximum supply pressure. The average reduction was assumed to be the same throughout the entire day.

The 962 kW observed was 15% higher than the theoretical benefit determined by the simulation of 840 kW. The reason for the inaccuracy of the benefit might be due to other
projects that were done by the mine to reduce CA consumption between the period of the simulation setup and the implementation of the two above-mentioned projects. The implementation of the projects and possible benefit thereof, can create a compressed air savings culture on the mine leading to better compressed air leak and waste management. It could also have been due to some inaccuracies in the simulation and variation in refuge bays to the simulated refuge bay.

Typically, Mine A used ball valves with a 15 mm diameter orifice before project implementation. Given that the air is initially compressed at 500 kPa and 20 degrees Celsius, Equation 1 amounts to 0.107 kg/s mass flow rate with an air density of 1.204 kg/m³. Using Equation 2 and 3, the mass flow rate amounts to 27.49 kW per refuge bay.

Given the new size of the crack valve solution the mass flow rate is 0.00583 kg/s at the same conditions. The mass flow leads to a power usage of 1.95 kW per refuge bay. The difference in power consumption is 25.53 kW. Multiplied by the 49 altered refuge bays, the total reduction in power is 1251 kW. This amount is fairly larger than the adjusted savings seen above. The reason could be that the calculation assumes that all refuge bay was fully open before being altered. Furthermore, the line pressure is assumed at a constant 500 kPa which is not the case in a typical gold mine where pressure supply varies. This further validates that the project did indeed have a positive benefit on the mine electricity costs.

To determine the monetary equivalent of the calculated benefit, the consumption profile was used to determine the electricity costs according to each consumption period. The calculation of the monetary equivalent of the savings can be found in Appendix D.

As seen in Appendix D, the total savings from the project were R5.25 million annually. Using the actual costs and savings of the project, a final financial evaluation was done. The actual cost of implementation was set to R204 458.72. The actual payback period of the project was determined by once again considering Equation 4.

**Equation 4: Payback period**

\[
\text{Payback period} = \frac{\text{Expenses}}{\text{Income/period}}
\]

\[
\text{Income} = \frac{R5.25 \text{ mil}}{12 \text{ Months}} = R0.53 \text{ mil/ month}
\]
Case study

\[ Expenses = R0.21 \text{ mil} \]

\[ \frac{R0.21 \text{ mil}}{R0.53 \text{ mil/month}} = 0.39 \text{ Months} \]

The payback period indicated a positive period that was acceptable with the mine’s one-year payback policy. The next evaluation was the NVP evaluation. Similar to the evaluation done pre-implementation in section 4.5.4, the variables of Error! Reference source not found. have the following values:

- Life-of-mine is 5 years.
- WACC is 7.25\%, yielding a Real discount rate of 2.73\% given an average annual inflation of 4.4\%.
- Electricity cost increase year-to-year was disregarded for the evaluation.

The actual NPV of the project can be determined using Equation 5.

**Equation 5: Net present value**[27]

\[
NPV(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1 + i)^t}
\]

<table>
<thead>
<tr>
<th>Year</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real cash flows (R-million)</td>
<td>5.25</td>
<td>5.25</td>
<td>5.25</td>
<td>5.25</td>
<td>5.25</td>
</tr>
<tr>
<td>Present value discount rate @ 2.73% Real</td>
<td>1.03</td>
<td>1.06</td>
<td>1.08</td>
<td>1.11</td>
<td>1.14</td>
</tr>
<tr>
<td>Present value of cash flows (R-million)</td>
<td>5.11</td>
<td>4.97</td>
<td>4.84</td>
<td>4.71</td>
<td>4.59</td>
</tr>
</tbody>
</table>

NPV = R24.23 mil – R0.21 mil = R24.02 mil > 0 – Project was beneficial

Ultimately, the project proved to be beneficial in both financial evaluations. The results of the post-implementation analysis ensured the project adhered to the following constraints:

- The project was benefit-orientated and should aim to maximise the project benefit.
- A payback period of less than a year for the project.

As discussed in section 3.6.4, the reduction of electrical energy will lead to further indirect benefits in terms of environmental benefit through a reduction in water and coal use, as well as a reduction of emissions. A saving of 962 kW results in an annual EE reduction of 8.43
GWh. Table 12 displays the environmental impact and added benefit of the EE reduction achieved by the project.

<table>
<thead>
<tr>
<th>Indirect consumption/emission</th>
<th>Factor</th>
<th>Amount reduced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>0.54 kg/kWh</td>
<td>4.55 kt</td>
</tr>
<tr>
<td>Water</td>
<td>1.30 l/kWh</td>
<td>10.96 Ml</td>
</tr>
<tr>
<td>Particulate emissions</td>
<td>0.27 g/kWh</td>
<td>2.28 t</td>
</tr>
<tr>
<td>CO2 emissions</td>
<td>0.97 kg/kWh</td>
<td>8.34 kt</td>
</tr>
</tbody>
</table>

4.6.4. Project sustainability

As part of the social redesign, the human factor was limited to only emergencies. However, the employees will still follow the old process flow where the valve should be left open at 25%. In order to prevent this, the training was adjusted. At Mine A, all mine employees must attend an e-learning course annually. The course includes all safety practices of the mine, including refuge bay operations. The refuge bay operation was requested to be updated to the new process flow. In order to simplify the operation and ease explanation, the following acronym was devised for the employees:

C – Closed

U - Until

E – Emergency

Referring to the valve in the refuge chamber, it should remain closed until the event of an emergency, in which case the valve should be fully opened.

The method mentioned above should be communicated to the e-learning staff at Mine A. As previously mentioned, the mine is broken up into sections. In charge of the sections are the mine captains. In order to ensure the instant delivery of the new system, the new process flow should be communicated to them. The mine captain, in turn, will communicate to the
shift bosses who will then finally communicate to the workers. The communication to the workers ensures the project adheres to the following constraint:

- Change should be appropriately communicated to the appropriate parties.

Furthermore, as part of the mining safety meetings, the refuge bay is brought up as a vital part of the safety system in the mine, and staff is to be encouraged to continuously ensure the proper condition of all its components. This will lead to the correction of a malfunctioning valve.

Should the mine foremen realise an increase in CA consumption in the level, an audit can be done to ensure all retrofitted valves work correctly. As part of the current maintenance plan for each mining level, the valves of the refuge bays were suggested to form part of the schedule to the mine. This will help ensure the proper operation and usage of the valves.

4.7. Summary

In this chapter, Rapid Re-engineering was applied to a deep-level gold mine in South Africa. The chapter gave a brief overview of Mine A to illustrate the mine for the reader. Based on the need that was identified in Chapter 1, the re-engineering process was initiated by the preparation and identification steps.

The vision step attempted to understand the process to be re-engineered and identify the current inefficiencies in the project. The baseline consumption of the project was devised. The ideal project was envisioned, and goals that represent the ideal were developed. Given the ideal process, the solution could be designed. After determining how each goal was to be met, a crack valve was chosen that met all the requirements. Given the solution, the theoretical benefit for the project could be determined.

Finally, project implementation was done. The benefit could be calculated based on the predetermined baseline. The calculated benefit was monetised based on the reduction of electrical energy reduction, and the total project benefit was determined to be R5.25 million annually. After the actual benefit was determined, a financial evaluation was done A payback period of 0.39 months was determined and an NPV of R 24.42 million was calculated. The evaluation tools indicated that the project proved to be beneficial in the short and long term.
In addition, the calculated reduction in coal, water and emissions were determined due to the reduced energy consumption.

Throughout the implementation of the adapted methodology, the project constraints were continuously recalled and adhered to. The overall re-engineering proved to be successful and delivered a positive impact on the electricity consumption of the CA in Mine A.
CHAPTER 5: Study review and recommendations

This chapter summarises the key findings and addresses the study objectives. It provides further recommendations.
5.1. Preamble

The study objectives were specifically addressed. The study is reviewed and summarises the main findings by addressing each chapter in reference to the objectives of this study.

5.2. Study objectives review

This section will specifically address each of the objectives of the study. Each of the objectives were stated as a question that is identical to those posed in Section 3.7.

Were techniques identified to reduce CA refuge bay consumption?

- Yes, Rapid Re-engineering was chosen as the problem-solving methodology in Section 2.5.4. The tool is supported by PTB for simulation of the system, chosen in Section 2.4, and UML to model the system, chosen in Section 3.3.2. Various other methods with regards to financial evaluation and benefit quantification were also identified in Chapter 2.

Was the current refuge bay design investigated and understood?

- Yes, Section 4.4.1 was used to understand the process as-is where the refuge bay design was being investigated and understood.

Was the refuge chamber CA configuration redesigned?

- Yes, Section 4.5 (solution step) is used to redesign the current configuration based on findings in Section 3.4 (Vision). These steps forms part of the Rapid Re methodology identified as part of the first objective.

Was the impact of the new design quantified?

- Yes, section 4.5.4 quantifies the project benefit before implementation (theoretical) to verify the project. Section 4.6.3 quantifies and evaluates the post-implementation project benefit.

All objectives set out for the study were achieved. The following section will review the study with reference to the study objectives.
5.3. Study Review and conclusion

South Africa has the second largest gold reserve in the world, giving it the potential to be the largest gold producer in the world. Gold has a significant positive effect on the South-African economy and employment. The nature of the ultra-deep mines leads to high operating costs. South African mines have some of the highest operating costs in the world, rendering mines marginal or unprofitable. Electricity is one of the most significant contributors to the operating costs of gold mines, and South Africa has some of the largest production costs with regards to energy in the world. Electricity is widely-use on the mine for operations, and the largest single user of electricity on mines is CA. Given high operating costs, a reduction in operating cost is needed for South African mines.

The mine compressors have various end-users of CA. One of these end-users- refuge chambers that use CA for ventilation and positive pressure inside the chamber- are often overlooked for optimisation initiatives. Waste occurs in the chamber when valves are left fully open or when valves are broken, and the CA flows through an open end. A review on the literature on CA use in refuge bays indicated that studies that focus on CA in refuge bays do not have similar constructions and equipment as a typical South-African deep-level gold mine. Thus, there is a need for a comprehensive study on the CA optimisation of a South African deep-level mine refuge chamber and implementation of a feasible, low-cost solution. To achieve this, the following objectives were formulated:

- Identify techniques to reduce CA refuge bay consumption.
- Investigate current refuge chamber CA supply design.
- Redesign and implement new refuge chamber CA supply configuration.
- Quantify the impact of optimisation of energy savings.

To assist in the problem-solving of the objectives mentioned above, a review of relevant literature is conducted. A review is done on the South African mining regulation with regards to refuge bays. With the assistance of the Canadian mine refuge bay regulation, the necessary flow to the refuge chamber is determined.

To assist in quantifying the benefit of the solution objective, two studies are reviewed. The first is to determine the effect of a leak in the CA system on the power consumption of the compressors. This method assisted in pre-implementation benefit identification. The second
study used a 24-hour profile comparison against a pre-implementation baseline. This method was used to assist in post-implementation benefit identification.

In order to solve the problem as identified in the review, four problem-solving methodologies were suggested. First, the problem-solving environment was identified, after which a review and comparisons of the problem-solving methodologies were conducted. Rapid Re-engineering was chosen as the best fit for the problem environment.

It is needed to simulate a solution before implementation to determine the benefit and feasibility of the projects. Simulation packages are reviewed and the most applicable, Process toolbox, was chosen for this study.

Methods to financially analyse the project are reviewed to use after the project benefit is determined. Net present value analysis and payback period were chosen as the most effective for the deep-level mining environment. Project sustainability methods are researched in the literature to ensure the project benefits after implementation are realised year to year. This achieved the first goal of the study by identifying a problem-solving technique to solve the problem, along with various auxiliary tools.

Once the means were determined to meet the study objectives, Rapid Re was adapted for the deep-level mining environment. The methodology was divided into two steps. The first step was used to identify the constraints of the project in terms of the type of project, the scope for the project, the role-players in the process and managements’ expectation of the project. The second step was the implementation of the Rapid Re process. Each step was reviewed in terms of deep-level mining. Each step is summarised by input, output, and process objectives for each step.

The developed Rapid Re process was applied to a South African deep-level gold mine. A short description of the mine was given, including its CA system. The first part of the process identified the constraints of the project. With the alignment of the project constraints, the Rapid Re process was implemented.

The Rapid Re process was initiated with the combined preparation and identification steps. A BPR team was devised, and the as-is CA system was modelled. The chosen process was reiterated from Chapter 1 as the CA usage in the refuge bays.
In the vision step, the process chosen was understood, and the cause of waste in the as-is system was identified. The most valuable activity of the as-is process was identified as the refuge bay CA valve. The performance driver for the study was chosen as the electricity consumption of the mine compressors. A baseline was set up as the benchmark for current performance. To guide the solution generation, four goals were set up for the solution of the process to improve on the as-is process and meet mine regulations. Given the goals identified, the theoretical benefit was determined through simulation on PTB and rendered a possible benefit of 840 kW. The vision step completed the second objective of the study by investigating and understanding the current CA refuge bay supply design.

With the alignment of the four vision goals, the solution was initiated. First, the technical solution was devised adhering to three of the four vision goals, followed by the social solution which was devised, adhering to the last vision goal. The four solutions to the vision goals was combined. The combined solution was chosen as a ball valve with a 4-mm hole allowing air to pass through, building pressure in the chamber continually. The hole removes the human factor in non-emergency conditions. The ball valve was to be made from stainless steel to prevent oxidation. In emergency conditions, the valve had a large enough orifice to ensure the occupied chamber will be adequately ventilated. With the final solution, a financial analysis is done rendering positive results for both the cost benefit analysis and payback period. The implementation plan was devised. The solution step partly completed the third objective of the study by redesigning the refuge chamber CA supply configuration through a problem-solving methodology.

The solution was implemented on Mine A from February 2018 to March 2018. Replacing the pilot project, the simulation done in the vision step was seen as sufficient proof of concept before implementation. The project benefit realised a 962 kW reduction in power usage, equivalent to R5.25 million in annual savings. To indicate the reduction in flow of compressed air to refuge chambers, the theoretical flows are calculated for pre and post solution implementation. The calculation indicated a 1251 kW theoretical reduction in compressed air flow if the pre solution valves was assumed to be fully open. The payback period was 0.39 months and had an NPV of R24.02 million, proving the substantial benefit of the project. The reduction in water, coal and emissions was calculated related to the 8.43 GWh EE reduction. To ensure the project benefit is realised year after year, project sustainability methods were devised and implemented on the mine. The implementation step completed the second part of
the third and fourth objectives of the study. The solution was implemented on mine A, and the electrical power reduction of the project were quantified, which will help with the financial situation of Mine A.

5.4. Recommendations

Due to the financial pressure of the mines and little capital available for projects, a wider variety of solutions could not be considered, and the scope of the redesign was set as small as possible. Even if not feasible in terms of capital availability, the more expensive option could be considered given the benefit that was ultimately realised.

Current refuge chambers in deep-level mines are simply holes made in the rock. Various other refuge chamber designs are seen across the world. Possible redesign of the entire chamber could be investigated.

If capital allows, pressure loggers can be installed at various points on each level. The drop-in pressure observed from each logger could be monitored and raise an alert when too high. This will help identify when refuge bay use is high outside of emergency conditions. Additionally, it will assist in the consumption monitoring of other CA activities.

Since the valves are only to be altered in emergency conditions, a seal can be placed on valves that will set off an alert when broken, should capital allow for it. This seal should discourage any employee from opening a refuge chamber valve unnecessarily.

The adapted Raid Re process should be applied to various mines part of the group to test the effect on various deep-level gold mines.

Mines benefit from data from underground activities to make an informed decision on mitigating waste and improving the system. A project such as the one implemented in this study benefits the mine substantially, and even more similar projects will ensure continuous improvement of the mine. Data loggers such as flow meters and pressure meters will allow at the very least the services of the mine to operate at an optimal rate.

After implementation, it was noticed that refuge chambers are in a bad state in some cases. Should a refuge chamber door not seal properly, then the airflow into the chamber is pure waste since no pressure can build up. The effect of dysfunctional refuge chamber door should be investigated to reduce waste and improve safety even more.
The as-is state of the refuge chambers should be documented before solution implementation. This will allow for more accurate project benefit calculation.

The usage of the chambers should be monitored continuously after implementation. Changes to training should be made if the usage of the valve are not done properly.

Further study on the life cycle of the new solution can be done to and any build-up inside of the altered valve or deterioration of the valve would be addressed in time with a maintenance schedule based on the results.
CHAPTER 6: REFERENCES

List of references.
REFERENCES


REFERENCES


[35] A. Prashar, “Adopting PDCA (Plan-Do-Check-Act) cycle for energy optimization in energy-


Appendix A – Mine compressed air layout

Figure 28: Compressed air layout schematic
Appendix B – Simulation layout

Figure 29: Simulation layout schematic
## Appendix C – Valve replacement schedule

Table 13: Mine Schedule for refuge bay valve replacement

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Refuge bay no</th>
<th>Section</th>
<th>Tel No</th>
<th>Actual completion Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>102-Conn No 2</td>
<td>R 241</td>
<td>NM</td>
<td>2881</td>
<td>2018/02/04</td>
</tr>
<tr>
<td>102</td>
<td>102-Conn x/c 36</td>
<td>R 289</td>
<td>NM</td>
<td>7609</td>
<td>2018/02/04</td>
</tr>
<tr>
<td>102</td>
<td>102-Conn No 6</td>
<td>R 334</td>
<td>NM</td>
<td>2509</td>
<td>2018/02/04</td>
</tr>
<tr>
<td>113</td>
<td>113-Conn No 5</td>
<td>R 304</td>
<td>KM</td>
<td>7808</td>
<td>2018/02/11</td>
</tr>
<tr>
<td>113</td>
<td>113 Conn No 10</td>
<td>R 335</td>
<td>KM</td>
<td>2842</td>
<td>2018/02/11</td>
</tr>
<tr>
<td>113</td>
<td>113- x/c 32</td>
<td>R 341</td>
<td>RE</td>
<td>2869</td>
<td>2018/02/19</td>
</tr>
<tr>
<td>102</td>
<td>102-Conn x/c 38</td>
<td>R 307</td>
<td>MF</td>
<td>1004</td>
<td>2018/02/20</td>
</tr>
<tr>
<td>113</td>
<td>113-x/c 28</td>
<td>R 359</td>
<td>DEV</td>
<td></td>
<td>2018/02/20</td>
</tr>
<tr>
<td>105</td>
<td>105-Conn No 30</td>
<td>R 375</td>
<td>NM</td>
<td>7313</td>
<td>2018/02/20</td>
</tr>
<tr>
<td>113</td>
<td>113-x/c 34</td>
<td>R 343</td>
<td>KM</td>
<td>2845</td>
<td>2018/02/20</td>
</tr>
<tr>
<td>113</td>
<td>113-x/c 35</td>
<td>R 344</td>
<td>KM</td>
<td>2851</td>
<td>2018/02/21</td>
</tr>
<tr>
<td>113</td>
<td>113-x/c 36</td>
<td>R 345</td>
<td>KM</td>
<td>8812</td>
<td>2018/02/21</td>
</tr>
<tr>
<td>113</td>
<td>113-Conn x/c 40</td>
<td>R 379</td>
<td>RE</td>
<td>2869</td>
<td>2018/02/22</td>
</tr>
<tr>
<td>105</td>
<td>105-Conn x/c 31</td>
<td>R 322</td>
<td>NM</td>
<td>2522</td>
<td>2018/02/25</td>
</tr>
<tr>
<td>105</td>
<td>105-Conn No 24</td>
<td>R 374</td>
<td>NM</td>
<td>2519</td>
<td>2018/02/25</td>
</tr>
<tr>
<td>109</td>
<td>109-Conn No 02</td>
<td>R 303</td>
<td>KM</td>
<td>7613</td>
<td>2018/02/25</td>
</tr>
<tr>
<td>Level</td>
<td>Description</td>
<td>Refuge bay no</td>
<td>Section</td>
<td>Tel No</td>
<td>Actual completion Date</td>
</tr>
<tr>
<td>-------</td>
<td>---------------------</td>
<td>---------------</td>
<td>---------</td>
<td>--------</td>
<td>------------------------</td>
</tr>
<tr>
<td>109</td>
<td>109-Conn No 09</td>
<td>R327</td>
<td>KM</td>
<td>2822</td>
<td>2018/02/25</td>
</tr>
<tr>
<td>105</td>
<td>105-Conn x/c 26</td>
<td>R 364</td>
<td>NM</td>
<td></td>
<td>2018/02/27</td>
</tr>
<tr>
<td>105</td>
<td>105-Conn No 27</td>
<td>R 366</td>
<td>NM</td>
<td>2520</td>
<td>2018/02/27</td>
</tr>
<tr>
<td>105</td>
<td>105-x/c 20</td>
<td></td>
<td></td>
<td></td>
<td>2018/02/27</td>
</tr>
<tr>
<td>102</td>
<td>102-Conn X/C 42</td>
<td>R 333</td>
<td>FH</td>
<td>2508</td>
<td>2018/03/01</td>
</tr>
<tr>
<td>102</td>
<td>102-41 CONN X/C</td>
<td>R 319</td>
<td>NM</td>
<td>2867</td>
<td>2018/03/01</td>
</tr>
<tr>
<td>105</td>
<td>105 Conn 5</td>
<td>R 270</td>
<td>NM</td>
<td>2218</td>
<td>2018/03/01</td>
</tr>
<tr>
<td>105</td>
<td>105-33 Conn X/c</td>
<td>R 306</td>
<td>NM</td>
<td>2858</td>
<td>2018/03/01</td>
</tr>
<tr>
<td>105</td>
<td>105-22 Conn x/c</td>
<td>R 353</td>
<td>MF</td>
<td>8506</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>105</td>
<td>105-22 X/c</td>
<td>R 381</td>
<td>MF</td>
<td></td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109 Hlg Sth Conn 7</td>
<td>R 234</td>
<td>KM</td>
<td>7000</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109-39 Conn</td>
<td>R 337</td>
<td>KM</td>
<td>2875</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>105</td>
<td>105-23 x/c</td>
<td>R 324</td>
<td>WK</td>
<td>NEW</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>105</td>
<td>105-28 Conn</td>
<td>R 332</td>
<td>WK</td>
<td>7313</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109-35 CONN</td>
<td>R 336</td>
<td>WK</td>
<td>2822</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109-31 CONN W</td>
<td>R 338</td>
<td>WK</td>
<td>2897</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109-30 X/C</td>
<td>R 346</td>
<td>WK</td>
<td>2898</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109-28 conn</td>
<td>R 383</td>
<td>WK</td>
<td>2817</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>109</td>
<td>109-29</td>
<td>R384</td>
<td>WK</td>
<td>2817</td>
<td>2018/03/04</td>
</tr>
<tr>
<td>Level</td>
<td>Description</td>
<td>Refuge bay no</td>
<td>Section</td>
<td>Tel No</td>
<td>Actual completion Date</td>
</tr>
<tr>
<td>------</td>
<td>----------------------</td>
<td>---------------</td>
<td>---------</td>
<td>--------</td>
<td>-------------------------</td>
</tr>
<tr>
<td>98</td>
<td>98-21 conn X/C</td>
<td>R 371</td>
<td>FH</td>
<td>2205</td>
<td>2018/03/07</td>
</tr>
<tr>
<td>98</td>
<td>98-23 conn X/C</td>
<td>R 372</td>
<td>FH</td>
<td>2854</td>
<td>2018/03/07</td>
</tr>
<tr>
<td>98</td>
<td>98-18 HLGE</td>
<td>R 295</td>
<td>NM</td>
<td></td>
<td>2018/03/07</td>
</tr>
<tr>
<td>98</td>
<td>98 Sth Hlg Conn</td>
<td>R 382</td>
<td>NM</td>
<td>2204</td>
<td>2018/03/07</td>
</tr>
<tr>
<td>102</td>
<td>102-31 CONN</td>
<td>R 308</td>
<td>BB</td>
<td>2510</td>
<td>2018/03/11</td>
</tr>
<tr>
<td>102</td>
<td>102-27 conn</td>
<td>R 329</td>
<td>BB</td>
<td>7811</td>
<td>2018/03/11</td>
</tr>
<tr>
<td>102</td>
<td>102-19 X/Cut</td>
<td>R 378</td>
<td>BB</td>
<td>8511</td>
<td>2018/03/11</td>
</tr>
<tr>
<td>98</td>
<td>98-20 conn X/C</td>
<td>R 204</td>
<td>FH</td>
<td>2205</td>
<td>2018/03/11</td>
</tr>
<tr>
<td>98</td>
<td>98-26 CONN X/C</td>
<td>R 133</td>
<td>NM</td>
<td>7814</td>
<td>2018/03/11</td>
</tr>
<tr>
<td>113</td>
<td>113-33 X/C</td>
<td>R 342</td>
<td>RE</td>
<td>2842</td>
<td>2018/03/12</td>
</tr>
<tr>
<td>113</td>
<td>113-31 x/c</td>
<td>R 356</td>
<td>RE</td>
<td>2826</td>
<td>2018/03/12</td>
</tr>
<tr>
<td>105</td>
<td>105-21 X/c</td>
<td>R 380</td>
<td>EM</td>
<td></td>
<td>2018/03/12</td>
</tr>
<tr>
<td>113</td>
<td>113-28 x/cut</td>
<td></td>
<td></td>
<td></td>
<td>2018/03/18</td>
</tr>
<tr>
<td>102</td>
<td>102-19 Hlg</td>
<td>R 207</td>
<td>BB</td>
<td>7811</td>
<td>2018/03/11</td>
</tr>
</tbody>
</table>
Appendix D – Electricity monetary equivalent calculations

Mine A is supplied by Eskom, South Africa’s largest electricity provider. The tariffs offered by Eskom are based on the distance the mine is from the electricity supply and the voltage requirements. Further transmission tariffs are also added based on the location of the mine [44]. The tariffs are also dependant on the time of year. The year is broken into low demand (Jun – Aug) and high demand (Sep–May) periods [44]. The tariffs are then further dependant on the time of day and are referred to as Time of Use Structures (TOU). Eskom identifies three parts of the day; peak, off-peak, and standard [44]. Each of which has its tariff due based on nationwide pressure on the power grid. These TOU structures encourage users to shift consumption away from peak periods. Mine A falls under the Megaflex TOU structure. Megaflex tariffs are allocated to users with notified maximum demand (NMD) larger than 1 MVA [44]. Figure 30 illustrates the TOU periods for a Mega flex user in the high and low demand season.

![Figure 30: 2018/2019 Megaflex low and high demand season TOU periods](image)

The post-implementation of the project falls within the tariff period of the 2018/2019 year. Therefore, the 2018/2018 Megaflex tariffs will be used to calculate electricity costs. Mine A falls in the transmission zone of ≤300km. Additionally, Mine A has a voltage profile of ≥500V and <66kV. The baseline was set put from October to January, and the post-implementation results were taken from April to June. Therefore, the high demand period tariffs (Sep–May) will be used for calculations.
The location of the mine calculates transmission tariffs [R/kVA/m]. Since the consumption reduction of the compressors will not have an effect on the transmission costs, it will be neglected for this cost calculation. Additional charges are allocated based on the consumers NMD. The production rate of the mine mainly determines the NMD. The reduction in compressor electricity consumption is considered not to influence the NMD, and these tariffs are neglected for this cost calculation.

The calculation is done by taking the hourly baseline consumption data and multiplying it with the tariff for the corresponding hour. The post-implementation hourly data is then multiplied by the corresponding tariff. Finally, the difference in costs can be determined. Table 14 indicates the tariffs set out for Eskom based on the characteristics mentioned above of Mine A. All costs are VAT excluded.

Table 14: High demand season TOU tariff distribution [44]

<table>
<thead>
<tr>
<th>Hour of the day</th>
<th>High demand tariff (c/kWh)</th>
<th>High demand tariff (c/kWh)</th>
<th>High demand tariff (c/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weekday</td>
<td>Saturday</td>
<td>Sunday</td>
</tr>
<tr>
<td>1</td>
<td>44.48</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>2</td>
<td>44.48</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>3</td>
<td>44.48</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>4</td>
<td>44.48</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>5</td>
<td>44.48</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>6</td>
<td>101.87</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>7</td>
<td>101.87</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>8</td>
<td>101.87</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>9</td>
<td>70.12</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>10</td>
<td>70.12</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>11</td>
<td>70.12</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>12</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>13</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>14</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>15</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>16</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>17</td>
<td>101.87</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>18</td>
<td>101.87</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>19</td>
<td>70.12</td>
<td>70.12</td>
<td>44.48</td>
</tr>
<tr>
<td>20</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>21</td>
<td>70.12</td>
<td>44.48</td>
<td>44.48</td>
</tr>
<tr>
<td>22</td>
<td>44.48</td>
<td>44.48</td>
<td>44.48</td>
</tr>
</tbody>
</table>
To determine the savings of the project, the consumption is determined by taking the assumed reduction in consumption pre-and post-project implementation for weekdays, Saturdays and Sundays separately. The findings are summarised in Table 15.

Table 15: EE consumption reduction

<table>
<thead>
<tr>
<th>Hour of the day</th>
<th>Consumption benefit (kWh)</th>
<th>Consumption benefit (kWh)</th>
<th>Consumption benefit (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Weekday</td>
<td>Saturday</td>
<td>Sunday</td>
</tr>
<tr>
<td>1</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>2</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>3</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>4</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>5</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>6</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>7</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>8</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>9</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>10</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>11</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>12</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>13</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>14</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>15</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>16</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>17</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>18</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>19</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>20</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>21</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>22</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>23</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
<tr>
<td>24</td>
<td>962</td>
<td>962</td>
<td>962</td>
</tr>
</tbody>
</table>

To determine the cost benefit, the reduction in energy is multiplied by the tariff for the corresponding period. The costs are seen in Table 16.
### Table 16: Total savings cost per week

<table>
<thead>
<tr>
<th>Hour of the day</th>
<th>Weekday</th>
<th>Saturday</th>
<th>Sunday</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>2</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>3</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>4</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>5</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>6</td>
<td>4899.95</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>7</td>
<td>4899.95</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>8</td>
<td>4899.95</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>9</td>
<td>3372.77</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>10</td>
<td>3372.77</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>11</td>
<td>3372.77</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>12</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>13</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>14</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>15</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>16</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>17</td>
<td>4899.95</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>18</td>
<td>4899.95</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>19</td>
<td>3372.77</td>
<td>674.55</td>
<td>427.90</td>
</tr>
<tr>
<td>20</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>21</td>
<td>3372.77</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>22</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>23</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td>24</td>
<td>2139.49</td>
<td>427.90</td>
<td>427.90</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>78716.13</td>
<td>11996.14</td>
<td>10269.54</td>
</tr>
<tr>
<td><strong>Nett</strong></td>
<td>R 100,981.81</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

From Table 16, it is evident that R100 981.81 is saved in electricity costs per week. This amounts to a total saving of R R5,251,054.30 annually.
Appendix E – Original valve solution

Figure 31: Original valve chosen for solution
## Appendix F – Refuge bay post implementation audit

**Table 17: Mine refuge bay post valve implementation audit**

<table>
<thead>
<tr>
<th>Location of Refuge Bay</th>
<th>Refuge Bay No</th>
<th>Valve Replaced</th>
<th>Pressure outside RB (hPa)</th>
<th>Pressure inside RB (hPa)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>98 HLGE</td>
<td>144</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door Open</td>
</tr>
<tr>
<td>98 Sth Hlg Conn</td>
<td>382</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door open</td>
</tr>
<tr>
<td>98-18 HLGE</td>
<td>295</td>
<td>Yes</td>
<td>1136.2</td>
<td>1137</td>
<td></td>
</tr>
<tr>
<td>98-20 conn X/C</td>
<td>204</td>
<td>Yes</td>
<td>1144.3</td>
<td>1144</td>
<td></td>
</tr>
<tr>
<td>98-21 conn X/C</td>
<td>371</td>
<td>Yes</td>
<td>1146</td>
<td>1146</td>
<td></td>
</tr>
<tr>
<td>98-23 conn X/C</td>
<td>372</td>
<td>Yes</td>
<td>1144.5</td>
<td>1145.5</td>
<td></td>
</tr>
<tr>
<td>98-26 CONN X/C</td>
<td>133</td>
<td>Yes</td>
<td>1152.6</td>
<td>1153.4</td>
<td></td>
</tr>
<tr>
<td>98-27 X/C</td>
<td>285</td>
<td>Yes</td>
<td>1146.7</td>
<td>1147</td>
<td></td>
</tr>
<tr>
<td>98-29 CONN X/C</td>
<td>139</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door open</td>
</tr>
<tr>
<td>98-33 CONN X/C</td>
<td>310</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door open, not sealed</td>
</tr>
<tr>
<td>102-19 Hlg</td>
<td>207</td>
<td>Yes</td>
<td>1143</td>
<td>1143.7</td>
<td></td>
</tr>
<tr>
<td>102-21 X/C</td>
<td>352</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door broken</td>
</tr>
<tr>
<td>102-24 Conn X/C</td>
<td>378</td>
<td>Yes</td>
<td>1145.9</td>
<td>1145.7</td>
<td></td>
</tr>
<tr>
<td>102-27 conn</td>
<td>329</td>
<td>Yes</td>
<td>1149</td>
<td>1149.7</td>
<td></td>
</tr>
<tr>
<td>102-31 CONN</td>
<td>308</td>
<td>Yes</td>
<td>1146.3</td>
<td>1146.3</td>
<td></td>
</tr>
<tr>
<td>102-33 CONN</td>
<td>290</td>
<td>Yes</td>
<td>1147.5</td>
<td>1147.7</td>
<td></td>
</tr>
<tr>
<td>102-CONN 6</td>
<td>334</td>
<td>Yes</td>
<td>1153.8</td>
<td>1154</td>
<td></td>
</tr>
<tr>
<td>102-CONN 2</td>
<td>241</td>
<td>Yes</td>
<td>1160.5</td>
<td>1160.8</td>
<td></td>
</tr>
<tr>
<td>105-20 X/C</td>
<td>380</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door open, used as waiting place</td>
</tr>
<tr>
<td>105-22 X/c</td>
<td>381</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door open, flooded</td>
</tr>
<tr>
<td>105-22 Conn x/c</td>
<td>353</td>
<td>Yes</td>
<td>1160.4</td>
<td>1160</td>
<td></td>
</tr>
<tr>
<td>105-23 x/c</td>
<td>324</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>105-24 Conn</td>
<td>374</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Door open, valve fully open</td>
</tr>
<tr>
<td>105-27 conn x/c</td>
<td>366</td>
<td>Yes</td>
<td>1166</td>
<td>1165.3</td>
<td>Pipe before valve full of holes</td>
</tr>
<tr>
<td>105-30 Conn</td>
<td>375</td>
<td>Yes</td>
<td>1166</td>
<td>1166</td>
<td></td>
</tr>
<tr>
<td>105-31 CONN X/C</td>
<td>322</td>
<td>Yes</td>
<td>1166</td>
<td>1166.5</td>
<td></td>
</tr>
<tr>
<td>105-33 Conn X/c</td>
<td>306</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Not sealing properly</td>
</tr>
<tr>
<td>105-37 Conn X/cut</td>
<td>348</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Under construction</td>
</tr>
<tr>
<td>105-41 x/c</td>
<td>351</td>
<td>Yes</td>
<td>1165.5</td>
<td>1165.5</td>
<td></td>
</tr>
<tr>
<td>105 conn 2</td>
<td>232</td>
<td>Yes</td>
<td>1173.8</td>
<td>1173.8</td>
<td></td>
</tr>
<tr>
<td>109 Hlg Sth Conn 7</td>
<td>234</td>
<td>Yes</td>
<td>NA</td>
<td>NA</td>
<td>Flooded, door leaking</td>
</tr>
<tr>
<td>109-28 conn</td>
<td>383</td>
<td>Yes</td>
<td>1164</td>
<td>1163.7</td>
<td>Drilling at RB entrance</td>
</tr>
</tbody>
</table>
Some discrepancies are found in the audit done on the refuge bays. Two major reasons for this was the possible inaccuracy of the equipment used and methodology inconsistency in measurement. In a few cases the refuge chamber doors were completely broken, as this post-audit sheet was sent to the appropriate parties, it is expected that the mine personal would attend to defective refuge chambers.
Appendix G - Review of Rapid Re methodology

Rapid Re-engineering has a rapid approach to problem-solving (6 months to a year). The developers intended the methodology to be used without the help of trained consultants. The Methodology is broken up into two parts. The first is the project set-up, where the constraints of the project are determined. The second is the Rapid Re process steps. This section will give an overview of the methodology.

**Constraint identification** [36]

**Define the type of project to be re-engineered**

The project manager should decide if the project is a once-off, a pilot, or part of a series of similar projects. The type of project will help align the BPR process concerning its goals and re-engineering.

**Once-off**

If the project is a once-off project, the process should cater to ensure there will be no need to return to the project. All focus and goals should be project specific. The project has a one-time execution to achieve a unique goal.

**Series of similar projects**

If the project is part of a series of similar projects, a more generic approach should be followed in the design process that can quickly adapt to changing project variables. It will have an easily adaptable implementation that coincides with a continuous improvement culture. The redesign should be efficient and straightforward.

**Pilot project**

A pilot project should have a detailed design with enough proof of concept before implementation. A project redesigned in this manner would mean completely redesigning the entire process as a method of trying a new concept.

**Define scope for the project**

The scope of the project plan is outlined once the nature of the project is determined. The PM should consider the boundaries of the project, such as company-wide, section-wide or a narrower focus. The scope of the project might only reach certain areas but will influence processes and employees further down the line.
Determine the role players in the BPR process
Role players should be represented from both internal and external areas of the system to ensure that the system understanding is represented, as well as the creative ignorance of a person external to the system.

Each area that the project will influence needs to be represented. Every person should have the capacity to take part in the project. The project should not cause a waste of employees’ time with projects that are not in line with their daily duties and responsibilities.

Determine the role, if any, for consultants
Management should decide if consultants are necessary for the project. Should they be needed, it must be determined what they will bring to the projects, such as tools, methodologies, experience or resources. A decision must be made as to whether the organisation has the capability of executing the process independently.

Management’s expectations of the project
Ultimately, the most critical constraints to consider are those set by management. Management expectations are the client requirements.

Experiment or benefit-driven
To understand the boundaries of which to work, one must define whether the management sees the project as an experiment or if they are looking for substantial gains. Although both options are result-oriented, the experiment has a hypothesised outcome where an outcome is expected if the focus is proven to be of value.

Financial budget
Management should state the financial freedom of the project and whether it has the capital for new projects. Finally, a timeline of implementation can be agreed upon. The timeline is set up by management, as well as the goals to be reached in this timeline.

Magnitude of change
The change the project will bring will have to conform to management’s expectations. In a large, intricate system, substantial changes can do more harm than good. It is essential to communicate the changes in the project to management and how to facilitate improvement.
At this stage, the exact changes are not yet necessary, but the scale of change planned should be discussed.

After all the constraints are considered, and the project seems feasible, the BPR process can be implemented. The next section will review each step.

**Rapid Process Re-engineering** [36]

Rapid Re BPR is adapted to the mining environment. It is essential to keep in mind who and with what one is working when implementing these steps. Additionally, it is vital to stay goal-orientated, and not make out-of-scope changes to a system. BPR steps according to Klein [36] are as follows:

1. Preparation
2. Identification
3. Vision
4. A-Techinical design, B-Social design
5. Transformation

**Preparation**

In the preparation step, the need for the re-engineering is identified. A team to execute the re-engineering is put together. Project set-up (previous section) forms part of the Preparation step. The goal is to organise and initiate the BPR process by assembling a team with the purpose of improving the system. The organisation must plan for change to facilitate the possible effects on performance with the new project.

**Identification**

To help identify the process of importance, the need for the end-user should first be defined. Secondly, the entities in the system should be defined. Processes should be defined starting from a top-level view of the system to a view of each of its processes.

Finally, the processes should be ranked by importance based on the need for improvement and role in the system. The identification step will help the company to identify the processes that need to be re-engineered. When confronted with a variety of processes to choose from, making a concise choice might be difficult. In this case, a weighted decision matrix can be used to facilitate easier decision-making. If the process to be redesigned is chosen, the
process must be fully understood before attempting to redesign it. The next step facilitates the complete definition of the process to be redesigned.

**Vision**
This step aims to understand the as-is process, choose a part to be redesigned and develop a process ideal for the redesigned part.

**Understand the as-is process**
The step starts by dissecting the process structure and process flow. It is vital to understand the complete process to redesign it properly. The role of each element in the process must be given in standard operating procedure. The deviation from the current standard operating procedure needs to be identified to highlight the current inefficiencies in the system. The redesign process must address these inefficiencies.

**Identify the most valuable activity**
If the process is understood and documented, the crucial part of the process must be identified. This so-called “value-adding activities” are the activities that add the value to the end-user. Value-adding activities are essential to the system; therefore, the redesign must revolve around these activities.

**Baseline performance**
The current baseline performance should be determined to assess the current system performance. If available, the performance could be compared to a benchmark for the process. If the current performance is accurately observed, the possible performance improvement could be estimated.

**Determine performance drivers**
The performance drivers of the process should be determined to use as a performance indicator. The performance drives are the attributes of interest based on what the goal of the redesign process is.
Develop ideal

Based on the performance indicator, an ideal is envisioned. The ideal is the desired operating procedure that mitigates all the current inefficiencies in the system. It also defines the preferred solution performance. The ideal is defined and given as goals for the solution step.

Possible benefit

The process ideal is used as a feasibility indicator for the project. Early financial evaluation can be done on the project. By calculating the theoretical benefit, the project can go through an early low-effort approval gate. The benefit is determined based on the baseline and ideal.

Solution

The solution step is divided into two paralleled steps, technical and social solution. The technical solution is the design of the technical part of the process including instruments, software and technology implementation. The social solution is the design with regards to the personnel in the process.

Technical solution

The technical solution considers all the non-human aspects of the project redesign. The following goals are suggested for the technical solution:

- Model entity relationships
- Re-examine process linkages
- Identify instruments needed
- Modularise
- Plan implementation

Social solution

In social design, the human factor of the process is considered. The new process should be modelled to indicate the interaction with the employees. The following goals are suggested for the social solution:

- Define new occupations
- Define skills and staffing needs
- Specify management structure
- Specify job changes
Design incentives
Design career paths

Combined solution
Finally, the two parts of the solutions are combined. The combined solution must meet the goals set out in the process ideal. The combined solution must be well defined and removed of any ambiguity. Given the solution, an implementation plan is to be devised.

Financial evaluation
In order to test the financial feasibility of the project, financial evaluation can be done, based on the planned cost of the project given the new solution. If the project seems beneficial, the next step in the BRP process can be taken.

Transformation
If the test implementation yields positive results, the full-scale implementation process can be initiated. It is vital that the staff receive the required training to understand the new system. The results can be analysed and reported upon once completion is reached.

Conclusion
The Rapid Re-engineering process is a simple, quick and comprehensive problem-solving approach. Traditionally, the BPR process attempts to redesign a part of the system for rapid change completely. The complete redesign ensures a new solution, rather than trying to improve the current process.