Development of an integrated project sustainability model using digital mining solutions

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ABSTRACT

Title: Development of an integrated project sustainability model using digital mining solutions

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Keywords: Project management, digital solutions, integrated simulation, digital reporting, deep-level mines, gold mining, compressed air system, dewatering system

Deep-level gold mining in South Africa faces various economic and social challenges. It is thus crucial to implement successful and sustainable projects. Project management models and digital solutions have shown to increase the success rate of projects in other industries. Simulations and reporting have also shown great potential.

Research has shown that projects tend to be implemented with a low degree of success. Project management models have shown to increase the success of projects. Various project management models exist in literature, but none can be directly applied to deep-level gold mining in South Africa. Due to the unique and complex nature of mining in South Africa a model is therefore required, that is tailored to this unique environment.

The objective of the study was to develop an integrated project management model from literature, integrated simulations, and failed past projects. Key success factors from literature were analysed and their application to deep-level gold mining examined. A project management model with four main phases was developed.

Failed projects on deep-level gold mines were investigated and it was found that projects in mining are not sustainable due to various reasons. One project was investigated in depth to understand why large capital projects tend to fail in mining. It was found that maintenance, resistance to change, and incorrect assumptions negatively influenced the project. These shortcomings were noted and incorporated into the model.

A sustainable project management model was developed that can be applied to mining using digital solutions. The core of the model is to ensure sustainable projects in deep-level gold mining. By taking the best information from literature and learning from the past, the model will address the current shortcomings in the industry.

The newly-developed model was applied to supply- and demand-side compressed air projects on an ultra-deep-level gold mine. The compressed air system of the mine was constantly over budget and was found to be inefficient. The system was investigated, and an integrated simulation constructed to scope projects.

Case study 1 focussed on limiting the wastage of a compressed air network on a mine. The new project was developed while incorporating the sustainable project management model. new, cost effective refuge chamber valves were designed and installed on 160 refuge chambers on the shaft. The new valve ensured compliance while reducing the compressed air demand.

Case study 2 was a re-evaluation and redesign of a failed project that had been implemented by the mine. The compressed air supply was controlled over a 24-hour period to match demand by means of control valves. Due to various reasons, the project was stopped. The control valve set-up was re-designed and implemented with great success and on time.

The mentioned projects were designed, implemented and managed successfully with the new model and a sustainable financial saving of more than R11.7 million per annum (p.a.) was achieved while also improving service delivery.

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All information portrayed in this thesis was done acknowledging sources and referencing published work.

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NOMENCLATURE

Unit	Name	Description
°C	Celsius	Temperature
kg/s	Kilogram per second	Volume flow rate
kPa	Kilopascal	Pressure
kW	Kilowatt	Power
L/s	Litre per second	Flow rate
m	Metre	Head, depth or length
m^3	Cubic metre	Volume
m^3/s	Cubic metre per second	Flow rate
mm	Millimetre	Length
MW	Megawatt	Power
MWh	Megawatt-hour	Energy
Pa	Pascal	Pressure

ABBREVIATIONS

BAC	Bulk Air Cooler
DSM	Demand-side Management
SCADA	Supervisory Control and Data Acquisition
VSD	Variable Speed Drive

CHAPTER 1: DEEP-LEVEL MINING, PROJECT MANAGEMENT AND INTEGRATED SIMULATIONS


[1]

"Gold Fields' Holland says what we all know: SA's gold mining is 'dead man walking'"
(16 August 2019, miningmX)

"Harmony will be operating in South Africa for a very long time"
(20 August 2019, Bloomberg)

[1] *FG. Jansen van Rensburg, personal photograph. "Wheels", Carletonville, 2017.*

1.1 PREAMBLE

The opening chapter presents a brief overview of deep-level mines, project management methods and general challenges faced in mining. The chapter will focus on what has been done in the field and highlight the need for this specific study. A basic background will be provided of engineering systems in deep-level gold mining.

An investigation into these challenges and how they can be addressed will conclude: deficiencies exist in the current methods. This chapter will demonstrate the value this thesis will add to the current fields of project management and mining.

1.2 OPERATION OF DEEP-LEVEL GOLD MINES

Gold mining in South Africa has become a marginal operation. The significant decrease in profitability is due to unstable commodity prices and labour issues [1, 2]. The weaker Rand, and consequently stronger gold prices, shielded South African mines in the past. Unfortunately, this means that mines are reluctant to fund capital expenditures due to the rise in mining costs [1, 2, 3].

Until 2009, South Africa was classified as the world's largest gold producer, but has since lost the position, despite still boasting 30 years' worth of ore deposits [4]. More recently, South Africa has lost its status as Africa's largest gold producer to Ghana[2].

South African mines are slowly losing their competitiveness due to socio-economic, technical and operational challenges. The most notable of these are [5, 6]

- the decline in the head grade of gold-containing ore,
- labour challenges,
- gold price instability,
- increased production costs,

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[2] F. Njini, "Mineweb," Bloomberg, 9 June 2017. [Online]. Available: https://www.moneyweb.co.za/mineweb/nation-built-on-gold-loses-its-african-crown-to-rival-ghana/. [Accessed 11 June 2019].

- depth of mines and accordingly dangerous working areas, and
- social and political uncertainty.

The South African gold mining industry contributes significantly towards employment and the gross domestic product [7, 8, 9]. South Africa boasts a third of the world's reserve[3] and is ranked eighth in production [9, 10, 11]. With the influence of these challenges, it is critical for mines to operate efficiently in terms of both production output and expenditure reduction [9]. Efficient project management is therefore crucial for sustainable mining. Projects are often neglected and, consequently, implemented and managed incorrectly, leading to wasted costs [12].

Mines can be categorised into two common types, namely surface or open-cast, and sub-surface. Surface mining includes, but is not limited to, strip mining and open pit processes. Worldwide, about 85% of all mining processes are surface mines [9]. Although opencast mining is used in some instances, the bulk of gold and platinum in South Africa is extracted via deep-level mining. Deep-level mines in South Africa are the deepest mines in the world and, as of 2015, mines have achieved depths of over 4 000 m [13, 14].

Most mines are divided into two working sections – engineering and production [15]. Engineering must ensure that all services are always available and are fully functioning. Services include compressed air, chilled water and ventilation. Production personnel must ensure that production and development targets are reached [16]. An example of the basic layout of a deep-level mine is shown in Figure 1.

3 F. Holmes, "U.S. Global Investors," U.S. Global Investors, 26 June 2019. [Online]. Available: http://www.usfunds.com/investor-library/frank-talk/top-10-gold-producing-countries/#.XXY_vW8zaUk. [Accessed 24 August 2019].

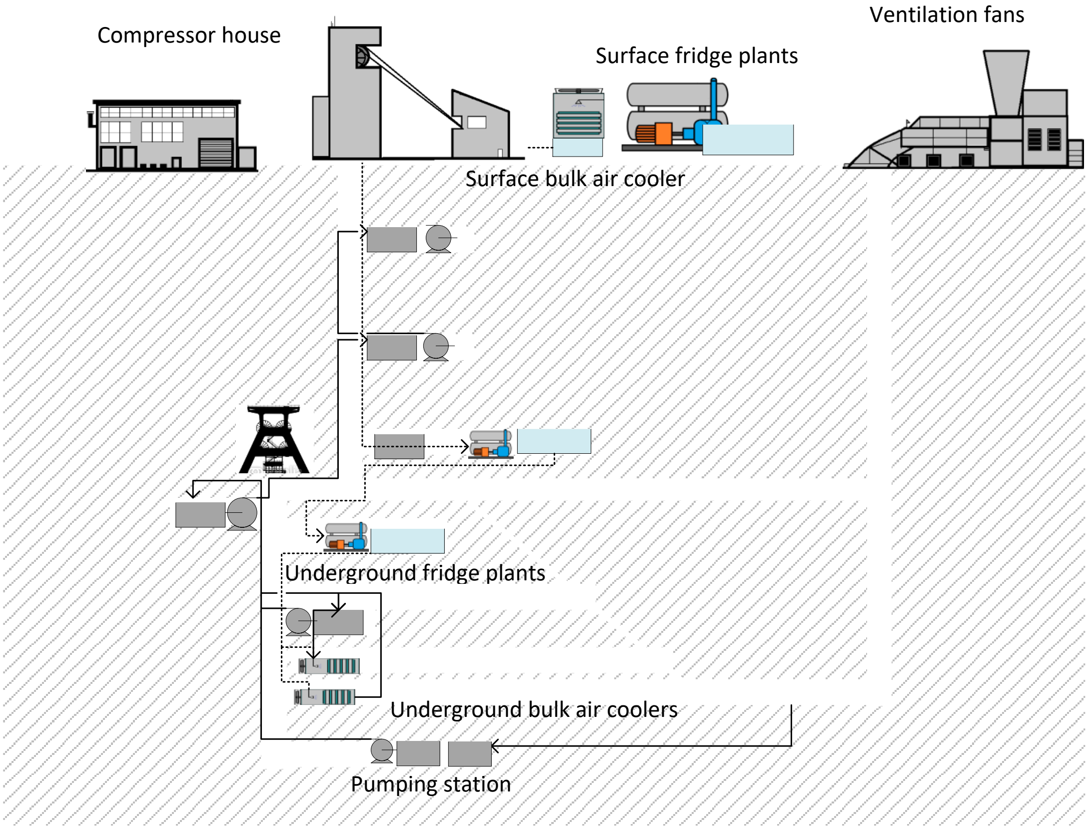

Figure 1: Deep-level mine supporting systems [13]

Extracting gold ore from a mine can only be done if an assortment of complex systems work in unison. Supporting systems are in place to guarantee that ore is extracted safely and efficiently [17].

Deep-level mines are equipped with large winders to transport workers, ore, equipment and materials to and from underground. In some instances, winders are located underground as well [18, 19, 20]. The other individual systems will be discussed in greater detail.

1.2.1 ENGINEERING SERVICES

Large engineering systems exist on mines to solve operational challenges. These systems are crucial for the operations of the mine to ensure safe environments and efficient production [21]. Greater detail of the systems will be discussed in in the sections below.

Cooling, Auxiliaries and Dewatering

Typical deep-level mines require large amounts of cold service water [22, 23]. This cold water is crucial for maintaining a safe underground working environment and therefore directly influences productivity [24, 25]. The refrigeration systems responsible for producing this cold water are highly energy intensive, however, and typically consume 25% of a deep-level mine's total electricity demand [23, 26].

Service water is used for cooling systems, drills, dust suppression and cleaning. The used water, along with fissure water (ground water seeping into the mine), is usually allowed to flow to designated dams underground via annex holes and pipes [27, 28]. The water accumulated in these dams must be pumped out of the mine to prevent flooding [29, 30, 31].

Environments where the wet-bulb and dry-bulb temperatures are greater than 32.5/37 °C are "abnormally hot conditions". Working in hot environments is not legalised by the Mine Health and Safety act [32, 33]. When a human is exposed to temperatures exceeding 36.9 °C (body temperature), it will cause undesired physical effects that affect labour efficiency [34]. The problem is mitigated by using chilled water to cool down air sent underground [29, 35].

Service water is chilled by surface- and underground fridge plants as shown in Figure 2. On the surface, cold water is used in the bulk air coolers which are used to chill the ambient air before it is sent down the shaft [36, 37]. As the ventilation air descends down the shaft, auto compression and other factors heat up the air [38, 39, 40] and thus additional cooling is required underground [35, 41].

The surplus chilled service water gravitates underground to a succession of sequential dams. [42, 43]. Due to rises in water temperatures as the water descends the shaft, underground cooling may be required. Underground, the air is chilled once again by bulk air coolers and spot coolers [44, 45, 46].

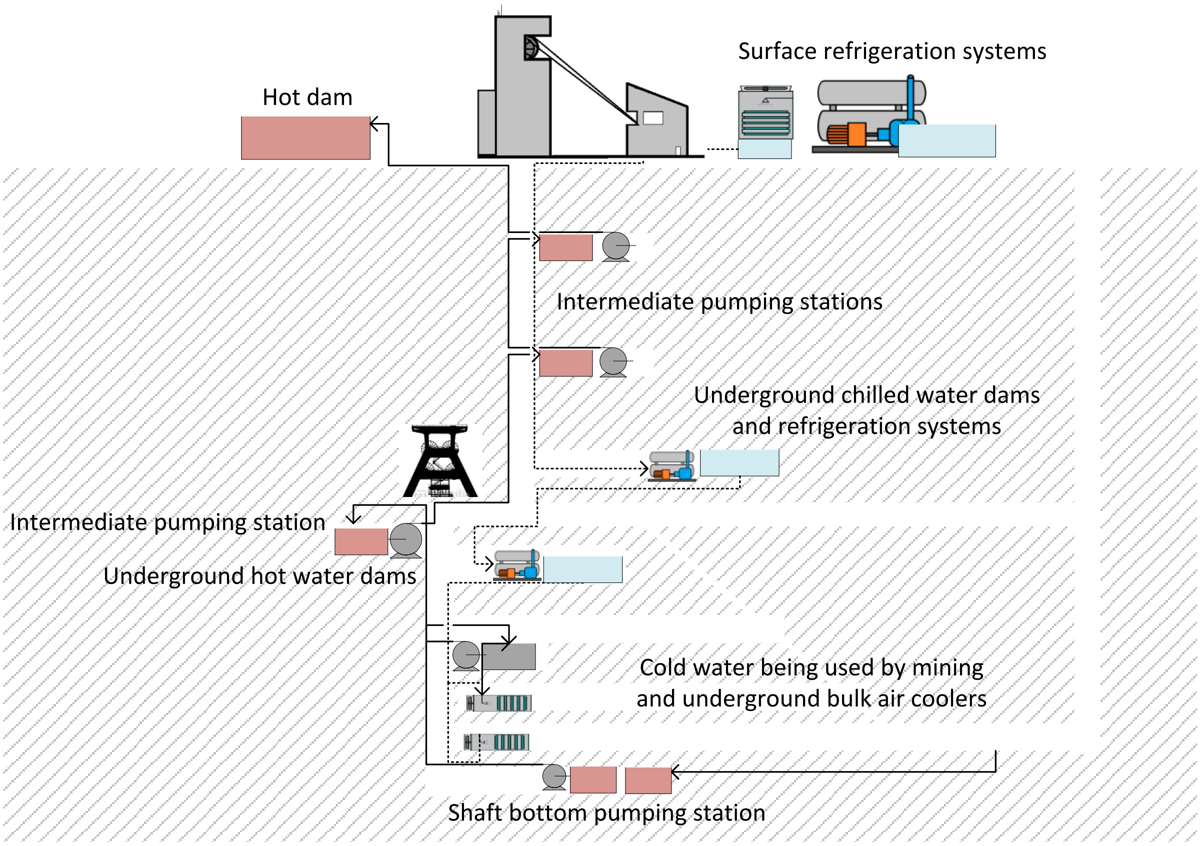

Figure 2: Dewatering and cooling of a typical mine

After the service water has been used for all the above-mentioned purposes, the water is pumped back up to the surface, by the dewatering pumps, where the cycle repeats itself as shown in Figure 2 [47]. Dewatering is an expensive and energy-intensive process [48, 49]. Hot water (typically 29°C) is pumped from underground to a hot water dam on the surface. From the hot dam, the water is pumped through pre-cooling towers, which use the ambient air to pre-cool the hot water before it is pumped to the pre-cool dam [50, 51, 52].

Water is then pumped from the pre-cool dams through the fridge plants to the chill dams by evaporator pumps. The fridge plants are supposed to cool the water to an average set point of 3.5 °C (depending on the operation). Although this set point is rarely reached, an average temperature reduction of 16 °C is obtained [50]. Water from the bulk air coolers is also returned to the pre-cool dam with the help of return pumps [36].

Ventilation

Ventilation is the most crucial service provided to mining. Fresh air is sent down the main shaft. The air sent down is commonly cooled by a surface bulk air cooler. The air is sucked through the mine instead of blown down it. The fresh air is directed throughout the mine to be used in working areas. The air heats up due to high auto compression, high virgin rock temperatures (VRTs), metabolic heat and mechanical heat that is generated underground [13, 30, 43] (refer to Figure 3).

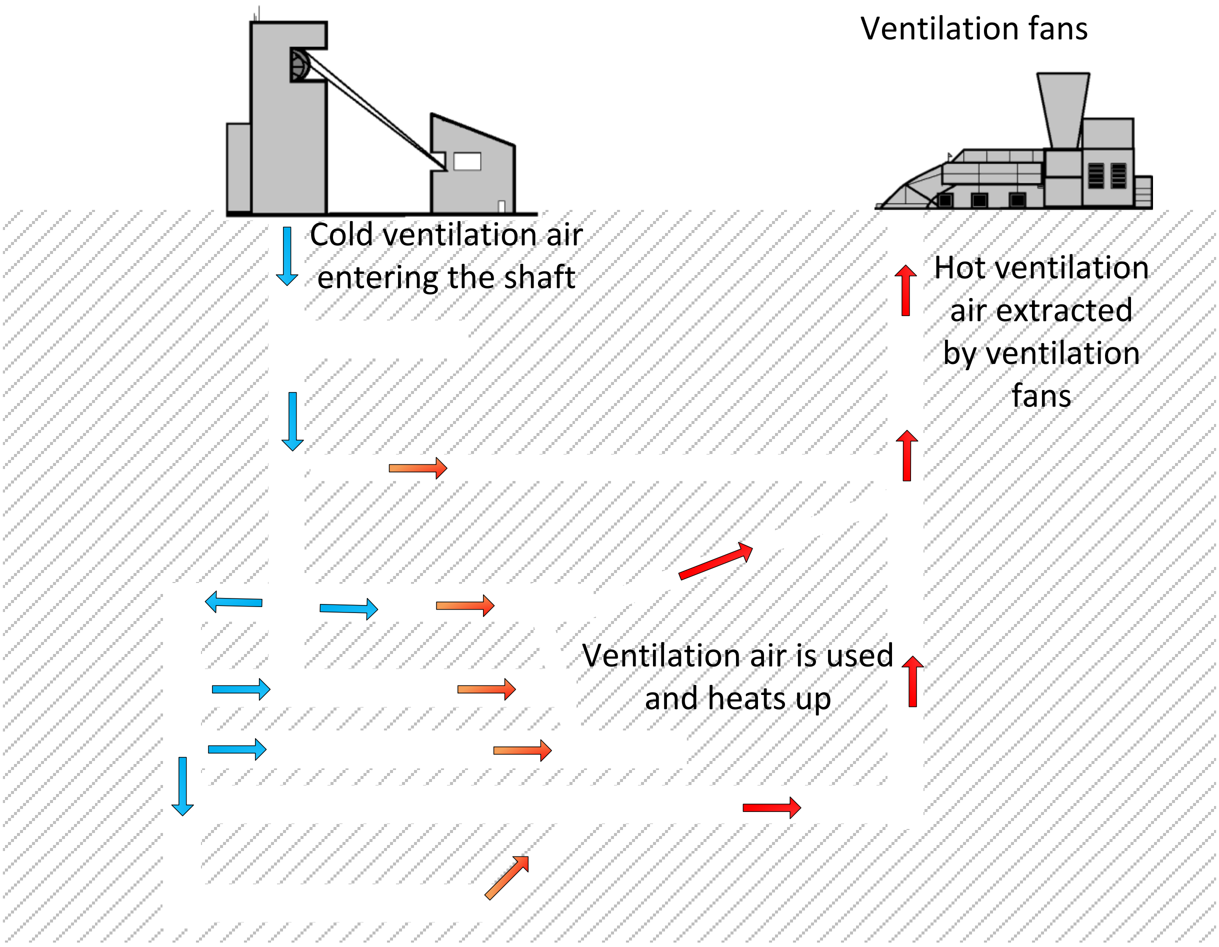

Figure 3: Ventilation layout of a typical mine

The mine is designed so that air can be safely extracted along with unwanted/harmful gasses such as methane and carbon monoxide. Usually an up-cast shaft is used where either two or more large fans extract the air from the mine [53, 54].

Compressed air system supply

Compressed air is generated in a surface compressor house by multi-stage centrifugal dynamic compressors, as preferred by the gold mining community [9, 21]. A typical compressor house on a -3 500 m / 600 kg gold/month shaft would use an average of 12 MW daily, resulting in a cost of R 400 000/day. Clearly, cost saving projects on compressor systems are crucial for the continued operation of these systems [55, 56, 57].

From the compressor house, the compressed air is sent underground to end-users via an intricate pipe network [58, 59]. As shown in Figure 4, compressed air is mainly used for drilling, agitation and refuge chambers, although leaks usually consume most of the compressed air [60]. In some cases, compressed air is also used by rocker shovel loaders, loading boxes and for ventilation purposes (although not standard policy) [9, 21, 61, 62].

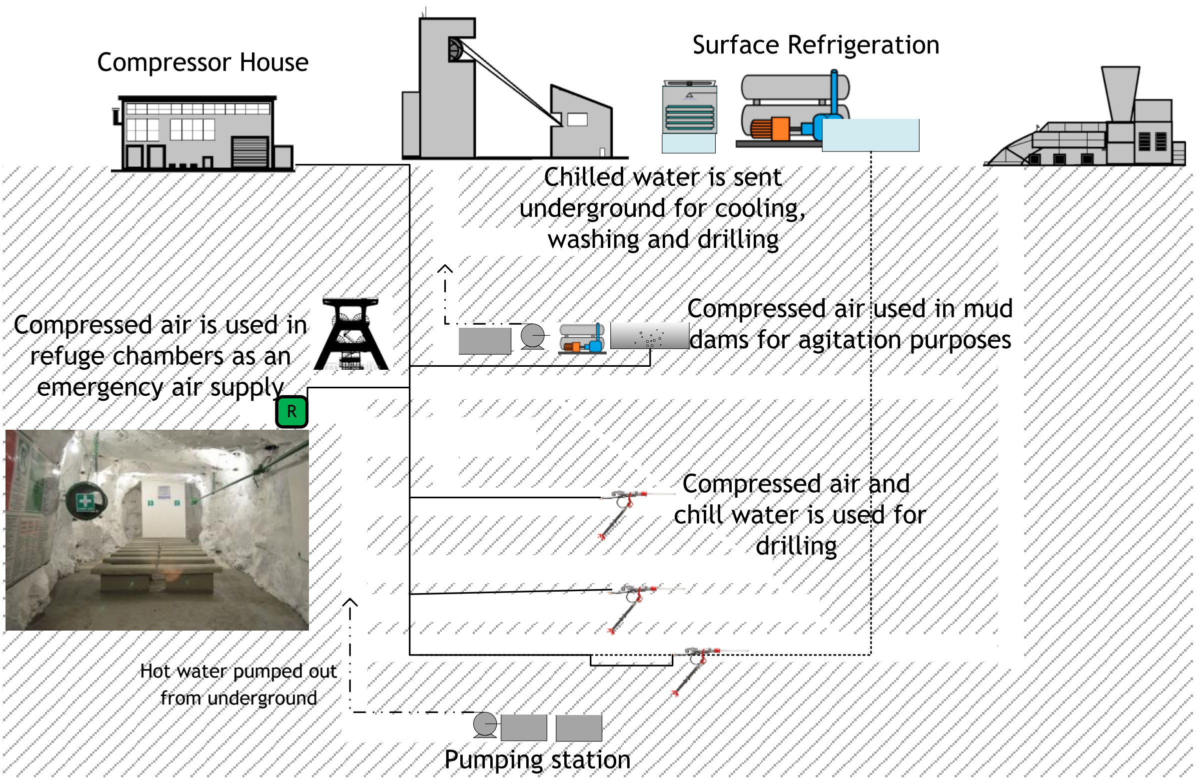

Figure 4: Compressed air systems of a typical mine

Compressed air is used in refuge chambers as emergency ventilation. According to the Mine Health and Safety Act 16.6(2), the refuge chambers need to be constructed in such a way as to prevent smoke and/or harmful gasses from entering the chamber [63, 64]. The mines accomplish this by pressurising the refuge chambers with compressed air.

Pressurisation of the chambers is done by a 2” (50 mm) ball valve installed inside the refuge chambers. These valves are supposed to be closed to between 75% and 90% [59]. This limits the rate at which air escapes the chamber. The exact percentage of opening depends on the discretion of the shift boss. Installed valves are usually manufactured out of mild steel. It has been found that the ball becomes stuck in the body of the valve due to the highly corrosive underground environment brought about by the humid conditions. Consequently, it is common to leave the valve open at 50%.

Compressed air is also used by pneumatic drills in most mines [9, 62]. The main reasons that pneumatic drills are still being used in mining today are their ease of use and reliability [65]. Some mines have started to use hydropower, although the use of compressed air as a medium will be prevalent for years to come [9, 21, 66].

Compressed air networks are crucial for production and safety reasons [9, 59, 64]. Implementing projects on crucial systems should be done sustainably [3]. This is not always the case though. A compressed air system of a deep-level mine is a critical part of all operations [67]. Due to the upgradability and alterability, ease of use and consistency of a compressed air system, it is still the preferred energy carrier in deep-level mines [68].

1.3 PROJECT MANAGEMENT PROCESSES

Projects are provisional tasks undertaken to achieve an end goal, service or product. Projects are temporary and have a definite beginning and end, the end being reached when the outlined outcomes have been achieved. Although temporary, project durations are not always short [3, 69, 70].

Project management, a temporary organisational form, is considered to be the application of knowledge and skills to achieve the project outcome(s) [69, 71, 72, 73]. Projects are intended to be on schedule, within budget and on scope, but it is often widely accepted when this is not the case and, consequently, projects fail [74, 75, 76, 77]. In mining, project management is no different.

Various literature is available about project management, but some of the most fundamental insights can be found in sources from the 1970s [78]. Morris and Hough [79] identified the three different measures of project success to be project functionality, project management and the contractor's commercial performance [79]. The mentioned measures translate to project success, project management success and financial outcomes [78]. Even though the success can be broken down to these three measures, it should be noted that there are many layers of this measurement of success or possible failure [78].

The termination process of a project is also notable and includes the reasons for termination and the process followed afterwards. If a project is cancelled prematurely, the process should be done efficiently to prevent further losses [79]. Morris and Hough explored the factors leading to the successes and failures of eight large implemented projects and identified the following key factors [79]:

- technical uncertainty and innovation;
- project objectives and their viability;
- politics;
- community involvement;
- schedule duration and urgency;
- financial, legal and contractual matters; and
- project implementation.

This list of factors is still relevant today [78].

Various project management models exist, but none are directly relatable to mining. Sustainability in project management has received a lot of attention in recent years [80, 81, 82]. Project management plays a critical role in realising sustainability [80, 83]. Project failures may occur based on how a project achieves its goals [84, 85]. It can also be argued that projects play a pivotal role in the sustainability of organisations [86].

With the integration of project management and sustainability, the role of an experienced project manager is crucial[4]. The project manager plays a pivotal role in the future sustainability

4 "Association for Project Management," APM, 2006. [Online]. Available: http://www.apm.org.uk/page.asp?categoryID=4. [Accessed 19 January 2019].

as well as success of the project. How these project managers consider sustainability is still to be established [87, 88, 89, 90, 91, 92].

Unfortunately, no project management model dedicated to mining-based projects exists [93, 94]. Project teams on shafts follow either the discretion of the unit manager or a generic project management model. Due to the unique nature of deep-level gold mining, a model is needed to suite the industry and its environment.

Mining houses spends large amounts of capital on new projects. Figure 5 shows the expenditure of Harmony Gold Mining Company Limited for the last five years.

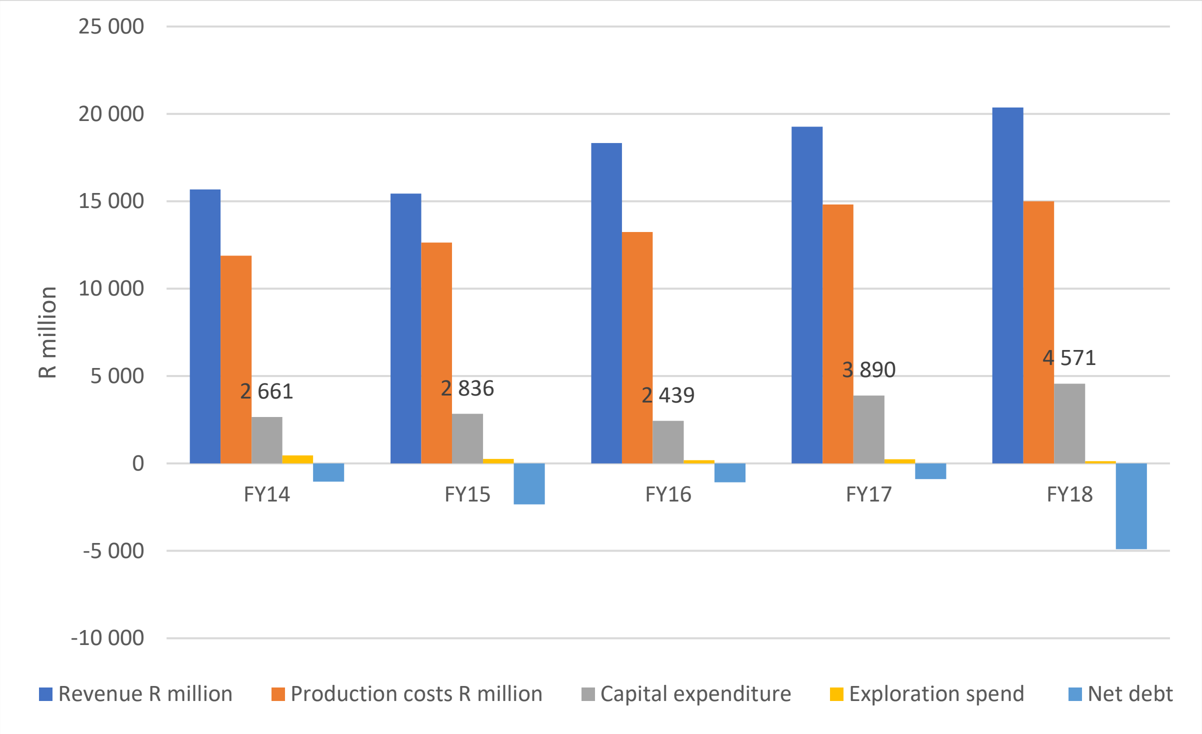

Figure 5: Expenditure of Harmony Gold Mining limited [95]

As shown, capital expenditure projects contribute vast amounts, and cost considerably more than exploration [95]. It is thus crucial to implement new projects efficiently, as it can be argued that the money spent on failed projects could have rather been spent towards nullifying the debt of the company and paying dividends.

1.4 CHALLENGES FACING GOLD MINING IN SOUTH AFRICA

Throughout the history of gold mining in South Africa, mines have operated in nearly the same way with stoping, blasting and cleaning at its core. However, mines have become deeper and viable ore bodies are located further from the shafts, increasing the distance and time workers need to travel to work in ever narrowing and steeper reefs [96]. Productivity, health, safety and production cost are severely negatively affected by the mentioned factors [97, 98].

The great majority (95%) of production stems from underground mines. Ore bodies in these deep mines are narrow and characterised by geological features. Mining methods in use are cyclic and rely on inefficient and equipment with limited capacity [45, 99].

South African mining companies have scaled down on technical personnel and use external contractors for highly technical expertise [100]. Mines are also hesitant to adopt new technologies and mechanisation [101]. The Chamber of Mines Research Organisation was considered a top research institute, but unfortunately has closed its doors. Mining is on the decline in South Africa with no end in sight [102].

Electrical costs typically constitute about 12% of the operational cost of a mining shaft [103, 104]. The increase in the cost of electricity has thus contributed to increased operating costs, which add more strain on the sector [105]. It has, however, been proved that demand-side management (DSM) initiatives are still a viable solution to reduce electrical cost and capital expenditure in the mining sector [55, 106, 107].

These systems offer large potential for optimisation in terms of load management [26, 108]. Load management measures have been proved to influence the service delivery of deep-level mine refrigeration systems [108]. In some cases, this is the result of poor maintenance practices along with ineffective control philosophies [13].

It is common practice in the mining environment that dedicated personnel focus on different sections [16]. The shortfall of this practice is that the personnel do not communicate with each other. This leads to a tug-of-war between departments. Illegal mining activities place a further strain on the system, leading to increased usage of services and security cost [109]. A holistic approach is essential for the future of the mining environment.

Unfortunately, the separate management of systems leads to the challenges faced when implementing projects on these systems. There are no truly independent systems or procedures on a mine. By following the sustainable project management model, most problems in the mining environment can be avoided. A valuable tool to help facilitate such a holistic approach is that of integrated simulation.

1.5 USE OF INTEGRATED SIMULATIONS IN MINING

Digital mining is a vital tool in the evaluation, mining and processing throughout the deep-level gold mining operations [100]. Digital mining included the use of various digital solutions for tracking, planning and simulations of the services in mining. The importance of simulations in mining projects has been discussed greatly and proven extensively [13, 110, 111, 112, 113, 114, 115, 116]. In recent years, project management simulations have been used as a tool, but only in the software industry [117, 118, 119]. The use of simulations in project management in the mining industry could make valuable contributions towards mining projects and possibly prevent failures [100].

The versatility of these simulations has been proved in the industry and a greater move towards integration of systems can be observed in literature [13, 14, 120]. This integration was highlighted in work preceding the current study [13]. As early as 2012, Vosloo *et al*. [14] integrated the water reticulation and refrigeration of a mine to minimise electrical cost and realised a 65% reduction in electrical cost by integrating the systems in simulations [121]. Various studies have also indicated that more integration is required [25, 120, 122, 123].

Numerous studies have been done on the control and maintenance of surface refrigeration, all with the assistance of simulations. A study done by Oberholzer [124] focussed on reconfiguring the cooling auxiliaries for optimal operation [124]. Oberholzer found that, by changing the sub-systems and doing maintenance on existing systems, an 11% electrical cost saving could be achieved while still delivering chilled water at 5 °C [124].

Furthermore, a study done by Peach [125] focussed on optimising refrigeration systems by changing the control philosophy and sequence of the system in order to optimise load management initiatives with minimal effect on the cold water dam temperatures [125]. Peach found that it was possible to realise cost savings through load management initiatives by using simulations to optimise the control philosophy [125].

Multiple load management initiatives on fridge plants and surface refrigeration have been successfully implemented and documented in South Africa in the past with the assistance of simulations [30, 47, 50, 66, 106, 107, 108, 126, 127]. Scope still exists, however, to integrate these simulations with the other systems [120].

A 2014 study done by Kriel *et al* [58] on compressed air systems indicated the importance of simulations in this network. Due to the isolated nature of the compressed air systems, it is challenging to integrate them with the other systems and tedious detailed audits are required [128]. For this study, the compressed air system will be integrated with the other services to have a holistic view of the entire system. A simulation model was built by Friden *et al.* [129] in Simulink (a math-based simulation package) to optimise the life cycle cost of compressed air systems [129]. The model could select and model the cheapest configuration in the system, once again proving the versatility of simulation in this environment [130].

In a study that was done by Nel *et al.* [131], they showed how a ventilation simulation can be successfully used to scope and implement a ventilation project [131]. According to a study done by Kocsis *et al.,* the advantages of using simulations are improved decision making, the option to explore possibilities, fault finding, and preparation for change [132, 133, 134]. A study by Swart [135] showed the benefits of integrating refrigeration and ventilation with considerable electrical cost savings [135].

Simulations or numerical methods have been used in rock burst experiments in geological studies of these deep-level gold mines for some time [136, 137, 138]. In a study done by Hagan *et al.* [139] in 2001, the great contribution of a simulation was highlighted. This supports the importance of applying simulations to the mining environment.

1.6 USE OF AUTOMATED REPORTING IN MINING

It has been found that regular reporting of key data increases the effectiveness and sustainability of operations. It has been shown that sending automated daily operational reports to key role players via email can improve the overall efficiency of operations and projects [140, 141].

A study done by Stols [142] emphasised the importance of daily reporting on condition monitoring of systems. These email notifications can be used as a formal notification of the machine's condition, but it can also be used for future planning. After the implementation of Stols' projects, a great decrease in incidents was observed over various shafts [142]. This is backed by a study done by Schools and Tod [143], although their study focussed on the implementation of such a system [143].

Maré [122] also indicated that reporting of the key parameters has a significant impact on the cooling performance of a shaft, as the daily reports were used as a tool by the personnel maintaining the systems. In the DSM sector, daily, monthly and quarterly reports have been used with varying degrees of success [144]. By learning from these authors, daily reporting of projects should be done during the planning phase and project management of a project.

1.7 PREVIOUS STUDIES

Various studies in the field of project management, project life cycle and mining have been done. The literature survey will summarise the work that has been done by others and highlight the shortcomings.

The literature review table will focus on questions highlighted from the research thus far. Each of the preceding sections clearly stated the current challenges and shortcomings. With the current political and economic challenges, the sustainable implementation of projects is crucial. The following questions and shortcomings can be inferred/deduced from the preluding research:

1. Why do projects fail generally, and more specifically in the deep-level gold mining environment?
2. How is success of a project measured?

3. Why does project management often fail, and more specifically in this specific environment? The current shortcomings in project management are exemplified in this unique and complex environment.
4. Is it sustainable to continue to implement new projects in deep-level gold mining despite numerous examples of projects failing?
5. It is possible to weed out potentially unsuccessful projects before they proceed to implementation?
6. Would it be possible to shorten implementation periods of projects or rather minimise delays?
7. What are the typical factors contributing to project delays?
8. Where does project management stop, and operations begin?
9. It has been shown that project manager experience is proportional to project success. Can this experience be substituted by a project management model?
10. Should projects in mining be implemented holistically? Would the holistic approach bridge the gap between engineering and mining sections?
11. To what extent have integrated simulations been used in mining, and more specifically project management?
12. Do systems of engineering affect one another and would the inclusion of systems in planning and simulations lead to sustainable projects?
13. It has been mentioned that the research and knowledge have been lost in the current mining environment. What is the effect of this loss on new projects?
14. How can the gap in operations between mining and engineering be addressed when it comes to new projects?
15. Are the mining systems, and specifically mining projects, adequately integrated presently?
16. Is daily reporting incorporated into project management from the start of the project?
17. How does a new project influence the operations and control philosophy of the system?

With all the raised questions, various shortcomings can be found in these processes. The following section will look to literature and try to find suitable solutions and then compare these solutions to the questions raised and objectives set out by this study. The above-mentioned questions are simplified into the research questions below.

[I] Has a generic project management model been developed from literature and practical experience that can be applied to deep-level gold mining?

It is clear from the sections above and questions posed that there are still shortcomings in the current models. Various models use theoretical analysis. Although it is insightful, practical examples and experience are required. The first focus of this question will be whether a model that focusses on both theory and practical experience exists. With this research question, other studies will be examined and scrutinised.

After models have been identified, the question will be raised whether these practices are suitable for the mining industry of South Africa. With the unique challenges faced in deep-level gold mining, any small shortcoming could lead to failure. The model needs to have the capacity to be used on all systems of engineering in deep-level gold mining.

[II] Is the project management model encompassing the long-term sustainability of the project from the first phase?

Various models focus only on project management and not necessarily on the implementation of long-term sustainable projects. Project management needs to incorporate strategies to mitigate possible failure in future projects. This research question will aim to investigate whether other models focus on sustainability during the project management phase.

This may include the addition of maintenance schedules during feasibility studies and planning with current and planned operations.

[III] Have integrated simulations been used in deep-level gold mining?

Various studies have used simulations as part of a project or operation change. The main question would be the degree to which systems were integrated in the simulation. It will be investigated what degree of integration is adequate.

[IV] Have integrated simulations been used to aid in project management?

As already indicated, only software engineering has adopted the use of simulations into project management, but various studies have used simulations to implement projects. The question remains: Does any model encompass the use of simulations in the project management cycle?

[V] Does the project management model examine various failed projects in mining?

Hindsight is 20/20 and various lessons can be learned from past mistakes. Most mistakes are avoidable, and this knowledge should be documented and incorporated into a project management model designed for the complex deep-level mining environment of South Africa.

[VI] Have engineering systems been integrated and has reporting been used during the project phase?

As stated, it is common for mines to view sections separately without considering the effect of the project on other areas of operation. This research question will examine the steps that have been taken to incorporate and holistically implement projects on a mine.

By adding reporting to the system on which the project is done, progress and performance can be monitored from the start. By starting early with reporting, various challenges may be resolved by the time the project is fully running. This will also ensure that, by the time that the project is up and running, all relevant personnel will be familiar with the expected performance and outcomes.

[VII] Has the study examined the effect of a new project on the current control philosophy and adapted the philosophy?

During the implementation period of a project, the current control philosophy needs to be evaluated and revised if necessary.

[VIII] Is the project management model derived from literature and practical experience using integrated simulations focussing on the long-term sustainability of the project specifically designed for the deep-level mining environment?

The final research question is based on the objective of this study. It will investigate whether any past studies have focussed on all the criteria set out by this question.

The table below contains an investigation into published studies with similar ideas. It indicates that not one study contains adequate models, methodologies or results to answer the questions to be answered by this thesis.

Study	[I] Generic project management model	[II] Project management includes sustainability	[III] Integrated simulation	[IV] Integrated simulation in project management	[V] Project management model learning from failures	[VI] Integration of systems and reporting during the project phase	[VII] New project on the current control philosophy	[VIII] Project management, sustainability for deep-level mining
[145][5]	Model examining the critical success							
[146]	Broad range knowledge							
[147]	Adopted by 29 countries							
[148]	Using experience				Experience was used, not past failures			
[149]	Examined critical factors leading to success and failure[6]	Client satisfaction leads to sustainable projects			Only notes factors, no mitigation	Project specific	Project specific	
[150]	Focus on management							
[151]	Individual contributions							
[152]	Standard does not attempt to define the issues involved							
[153]	Focus on quality management							
[154][7]	Project life cycle model	Project life cycle model to be used after project has been implemented				Use of IT systems encouraged		

[5] *Study will be discussed in detail.*

[6] *Study will be critically evaluated during model development.*

[7] *The study emphasised the need for sustainable projects by extending the model to beyond the completion of the project.*

Study	***[I]***	***[II] Project management incudes sustainability***	***[III] Integrated simulations used deep-level gold mining***	***[IV]***	***[V] Project management model learning from failures***	***[VI]***	***[VII] New project on the current control philosophy***	***[VIII]***
[70]	Exemplified the importance of project management				PM will only minimise failures			
[80]		Focus on environmental sustainability						
[155]		environmental sustainability						
[156][8]			Focus on compressed air					
[157]			Focus on Logistics					
[29]			Focus on cooling systems					
[158]			Focus on ventilation systems					
[13][9]		Sustainability encouraged	Focus on cooling				Crucial to adapt dynamically	
[159]			Focus on coal mining					
[46]			Focus on refrigeration					
[160][10]			Focus on refrigeration			Water and fridge plants integrated		

[8] *Simulation process is to be examined.*

[9] *Project is to be used as part of the model.*

[10] *Integration processes will be investigated.*

Study	*[I] Generic project management model*	*[II]*	*[III] Integrated simulations used deep-level gold mining*	*[IV] Integrated simulations used as aid in project management?*	*[V] Project management model learning from failures*	*[VI] Integration of systems and reporting during the project phase?*	*[VII] New project on the current control philosophy*	*[VIII] Project management model focusing on sustainability intended for the deep-level mining milieu?*
[123][11]			Focus on refrigeration			Water and fridge plants integrated		
[161][12]							Emphasises the importance of adaption in construction	
[162]				Risk simulations used, not operational simulations				
[163]	Training to students regarding project management			Used in the software development field	Aims to aid learner project managers			
[164]	Focus in construction			Cost estimation schedules	Based on probabilities			
[165]	Supply chain based					Based on information systems		
[166]	Focus on information systems				Manufacturing industry used	Integration of information systems		

[11] *Study proved the advantages of integrating water reticulation and refrigeration.*

[12] *Study emphasised the importance of adaptive control philosophies.*

Study	[I]	[II]	[III] Integrated simulations used deep-level gold mining	[IV] Integrated simulations used as aid in project management	[V] Project management model learning from failures	[VI] Integration of systems and reporting during the project phase	[VII] New project on the current control philosophy	[VIII] Project management model focusing on sustainability intended for the deep-level mining milieu
[122][13]			Focus on cooling performance			Reporting increased efficiency of the project		
[131][14]			Focus on ventilation	Simulation used to scope new projects in ventilation				
[125]			Refrigeration simulation used				Adapted control philosophy of existing project	
[167]			Only compressed air simulated			No integration		
[121]			Refrigeration systems integrated	Used in energy savings initiatives		Performance reports was sent out	No new project	
[168][15]						Focus on data and the development of daily reporting		
[169][16]						Project schedules daily reporting done		

[13] The daily reporting ensured that senior personnel are involved to optimise the efficiency of the initiatives.

[14] Study proves that a simulation can be used to scope new projects.

[15] Study stated that valuable reports can be used to produce faster feedback and problem resolution.

[16] Most studies focus on the daily reporting of the project schedules and tasks, not the system the project is done on.

As shown in the table above, no single study answers more than four of the questions and no project management models exist that focus on deep-level gold mining. In a study done by Fortune and White [145], 63 publications were analysed with various critical factors highlighted in the model.

For the first research question [I], a study done by Fortune and White (2006) will be used to determine whether a project management model that focusses on the criteria set out by study exists. In the study, a critical review was conducted of 68 projects and the critical success factors were noted. The critical review of this study is shown in Figure 6 and the full table with the references of the studies is shown in Appendix A.

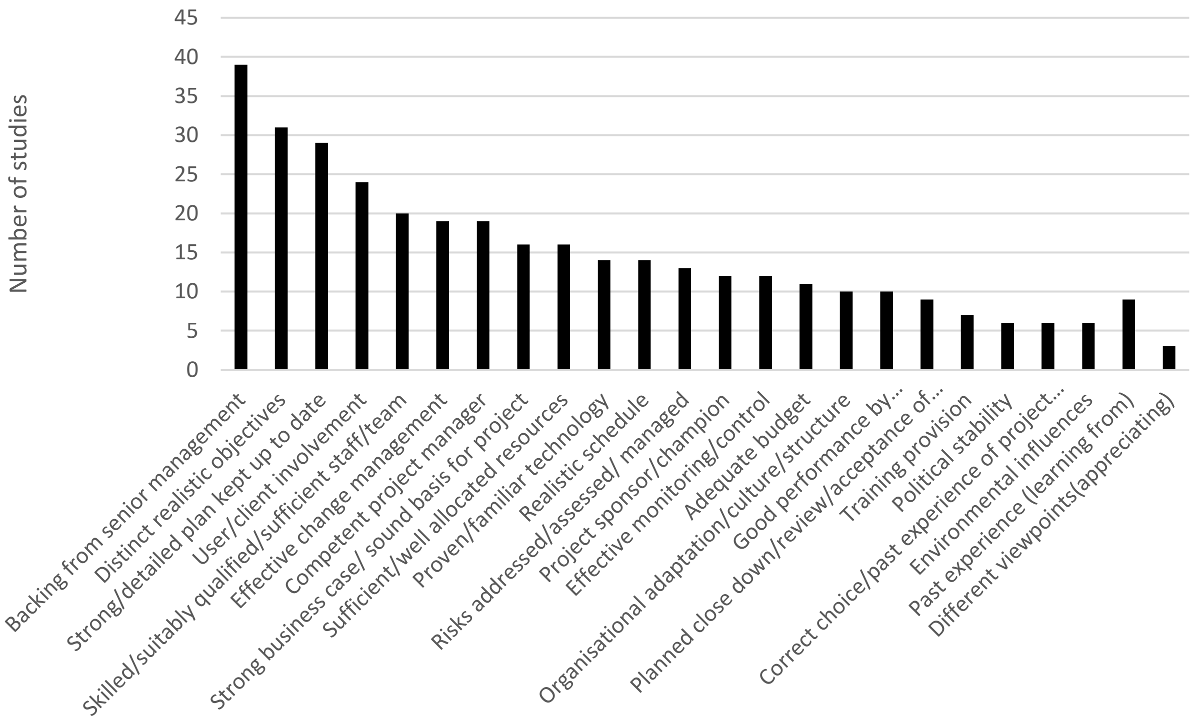

Figure 6: Critical review as reported by Fortune and White [145]

The research done by Fortune and White shows that not much work has been done to develop models that focus on past experiences. No reference was made to project sustainability and none of these models can be successfully applied to deep-level gold mining. A clear theme that was established by the study showed that deficiencies exist in the organisational structure of the systems [145]. With the already stated deficiencies in mining, the conclusion can be made that the organisational deficiencies will only be amplified in mining.

As shown in Figure 6, senior management support is beneficial to the success of a project. Daily system reporting to senior management is bound to minimise project failure. Only one study focussed on the adaptation of the control philosophy once a new project has been implemented, but there was no project management model, and only a small focus on sustainability [13].

The last question encompassing the essence of this study remained unanswered. Some of the studies have touched on some of the elements. It is clear from the literature that a need exists to implement projects in deep-level gold mines efficiently, and no clear solution exists.

1.8 NEED FOR STUDY AND RESEARCH OBJECTIVES

As stated in this study, deep-level gold mining in South Africa is under severe strain, but mines continue to produce in these difficult times. Operational costs have increased significantly over the past years, with labour and electrical cost showing the highest inflation rates. To continue mining using these old systems with old infrastructure, new projects will have to be implemented. These projects will have to be done in a cost-effective, sustainable manner.

Currently no project management models that can be directly applied to the unique deep-level mining environment exist. As indicated, good practice project management lead to various cost savings. By using a project management model an ineffable amount of manhours, materials and time could be saved.

The earlier a project can be completed; the earlier production can commence. It is clear that deep-level mining in South Africa is unique, and a unique solution is required. By examining various project management models and using the characteristics that are most applicable to mining, a model could be developed for mining.

While projects have been successfully implemented in the mining industry, the degree of success is relatively low, and projects tend to be unsustainable (as proven). Various reasons for the sustainability problems must be addressed. A model is required that learns from this unique environment by investigating past projects.

A model that is based on literature and practice, while still considering the current systems, is thus necessary. It has been shown that new projects lose traction by not fitting into the current system completely. It is crucial to adapt the old system as far as possible and integrate it with the new, post-project system.

With the current technology available in the Industry 4.0 era, it is possible to use digital mining solutions like simulations and digital reporting to better implement projects in mining. Simulations have long been used in the industry as discussed, but integration of systems is beneficial and can greatly assist with the management of new projects. Daily reporting will create awareness of the project and its outcomes and deadlines. Awareness tends to improve efficiency.

The research objectives of this study will be:

- The development of a project management model from literature and past failures and successes that can be applied to deep-level gold mining in South Africa.
- The development of a project management model that focuses on long-term sustainability of projects.
- The development of a project management model that uses industry 4.0 solutions (integrated simulations and digital reporting).
- The simulation model will integrate systems of engineering as far as necessary to be used in the project management model.
- By using integrated simulation and reporting, it would be possible to make better decisions and accurately scope new projects to either compliment the current project or achieve better outcomes for operations.
- It will be of the upmost importance to use the model stated to adapt the current control philosophy for optimal operation of the greater system.
- As stated, the probability of failure is highly dependent on the experience of the project manager. This model will aim to capture the experience element and enable relatively inexperienced project managers to achieve favourable outcomes.
- Using the integrated simulation model to predict the effect of minor changes to the system.
- To apply the model to a real-life case study to obtain measurable results.

To summarise, there is a great need to efficiently implement projects in deep-level gold mining, while minimising the cost and time spent implementing projects, and addressing the sustainability challenges.

1.9 ORIGINAL CONTRIBUTIONS OF THIS STUDY

The following section will indicate how this thesis aims to contribute to the current field of project management and deep-level gold mining.

1. **Development of a project management model derived from literature and past experiences that can be applied on deep-level gold mines in South Africa**

What needs to be done?

Projects need to be implemented successfully and on time. With mines becoming marginal, it is crucial that new projects be implemented sustainably and cost effectively. With the abundance of current project management models and failed projects, it is possible to develop a model to work for the deep-level gold mining milieu.

What is the situation currently?

Mines seldomly have dedicated project teams. New projects are either done by contractors or shaft personnel who are already over-worked. There is currently no project management model that can be directly applied to mining. Either other models are used, or projects are implemented solely on the experience and discretion of the manager in question. As stated, current models are inadequate and with the high turnover or lack of technical personnel in mining, this leads to projects failing or falling far behind schedule.

Why are the current methods insufficient?

As mentioned, mines are reluctant to spend capital on new projects due to the high failure rate of projects. However, for South African mines to continue to be competitive in the international market, progress is required.

How does this study solve the problem?

This study will develop a project management model that can be used in mining to efficiently implement new projects.

2. Development of a project management model focussing on the sustainability of projects to be applied on deep-level gold mines in South Africa

What needs to be done?

Projects tend to be unsustainable in the mining sector and overall. Questions have been raised in past studies, but only recently have the right questions been asked. A project management model is required that focusses on and addresses the long-term sustainably of projects in general, and more specifically in mining.

What is the situation currently?

Projects have definite starting points and endings, and usually once the project is in full operation, crucial elements of the project get lost in the transitions. In mining today, this is more prevalent. Projects are often seen as a “hand over and forget” process [151].

Mines operate on a stringent budget and commonly funds are not available for large-scale investment projects. Due to the mentioned phenomenon, it is tremendously important to ensure projects are implemented correctly. Presently, various quick and cheap solutions are implemented by mining personnel, thus the high failure rate of projects.

Why are the current methods insufficient?

The “change of ownership” of these projects leads to a decrease in efficiency or even failure. Due to communication problems, resistance to change and high rate of turnover of shaft personnel, projects often fall out of favour. In some instances, the projects implemented only focus on current operations and no future planning is considered.

How does this study solve the problem?

This study will focus on the hand over process required to ensure personnel who have to manage the operations after the project is complete will be competent to do so. If not, the project design needs to minimise the human factor by being as simple or automated as possible.

3. The development of a project management model that uses digital solutions (integrated simulations and digital reporting).

What needs to be done?

Most mines in the South African environment started operations over 30 years ago. Over time, various aspects of specific mines have changed (for example mine depth, mining locations and services requirements). Mine personnel are notorious for their resistance to change. By using this simulation model, predictions can be made to support new ideas and innovation to assist in persuading personnel. Reporting will create awareness and assist in the long-term substantiality of the project and minimise possible project delays.

How is it currently done?

Mines have different methods to make changes to current systems to improve efficiency. Usually these changes are made at the discretion of engineers or foremen. The major challenge is that most mines have a high turnover of the mentioned personnel. In various situations where changes had been made to the systems, current personnel do not know the reasons why this was done and continue to follow the "tradition".

Why is the process insufficient?

As stated, without proper communication and reports, some processes are done inefficiently because it has always been done that way. With the high turnover of personnel, knowledge of the system is lost in various cases.

How does this study solve the problem?

By using integrated simulation, smaller inefficiencies can be identified and rectified. The simulation will also be used to determine the long-term impact on the larger system. It has been found that a small change can have a quantifiable positive effect on the system. An example of such a change will be discussed in the case studies.

4. The development of a project management model that integrates the systems of engineering and simulations during the project phase.

What needs to be done?

Common practice in the mining environment is to have dedicated personnel focussing on different sections. The shortfall of this practice is that the personnel does not communicate with one another. This leads to a tug-of-war between departments. A holistic approach is essential for the future of the mining environment.

What is the situation currently?

Mines have foremen on each of the large systems, namely pumping, refrigeration, ventilation and compressors. Although pumping and refrigeration is integrated, the systems are viewed as different sections with separately allocated budgets and control philosophies. In most cases, the refrigeration and ventilation departments do not communicate and play the blame game on one another when a problem does occur.

For example, a smaller system such as a pre-cooling tower would be neglected. Focus would rather be placed on installing mobile cooling units and ventilation booster fans. If the maintenance on the pre-cooling tower was done correctly, colder air could have been sent underground making the use of these “quick solutions” obsolete, in turn saving man hours, cost and effort.

Why are the current methods insufficient?

As mentioned, the management of these systems are kept separate. Unfortunately, this leads to the challenges faced when implementing projects on these systems. There are no truly independent systems or procedures in a mining system.

How does this study solve the problem?

This study will focus on the prominence of holistically implementing engineering projects, maintenance and management on a mine.

5. The model will focus on addressing the need to update the current control philosophy of the system when a new project is implemented

What needs to be done?

A once-off simulation of a large system is not enough. The simulation will be continuously calibrated to ensure accuracy. This simulation will then be used for accurate decision making and scoping of projects. Achieving this high level of accuracy will require various audits and in-depth knowledge of mining. Achieving a good understanding of the systems can only be achieved through experience and dedication.

What is the current situation?

As mentioned, a simulation at this scale and depth has not been implemented on deep-level mining in South Africa. This study aims to be the first to achieve this milestone. The main area of focus will be to ensure the dynamic nature of the simulation.

Why are the current methods insufficient?

As mentioned, new projects tend to fall out of favour by operational personnel. A new project will affect the current operations of a system.

How does this study solve the problem?

By integrating systems in both the project management model and in the simulations, future challenges can be identified, and a new control philosophy can be developed where all parties benefit.

6. Using the integrated simulation as a feasibility tool to scope new projects and make changes during the project execution phase

What needs to be done?

By using this tool, the long-term effects of these solutions can be analysed and dismissed if necessary. The tool will shift the focus to doing efficiency improvements on current systems and the long-term effects thereof. Decisions on a mining system should not the taken without regarding the other systems, which is commonly the case.

How are projects currently scoped?

Mines have different methods to scope projects, including in-house calculations and consultant advice. In various situations, the work done by consultants is completely theoretical. The consultants use these theoretical values due to a lack of in-depth understanding of the specific site. Problems on most mines do not have plug-and-play solutions. By using the simulation, a site-specific problem can be solved in a cost effective and accurate way.

Why are the current methods insufficient?

As mentioned, plug-and-play solutions are not the answer to most questions on a mine. In various situations the problems can be solved by configuration or control philosophy changes.

How does this study solve the problem?

This study will use a calibrated site-specific simulation to address the inefficiencies found in the system, combined with hands-on audits done to ensure the simulation is accurate. By using this dynamically calibrated simulation, an informed decision can be made. This will, in turn, ensure the mine functions cost effectively, which might lead to a prolonged life of mine.

1.10 THESIS LAYOUT

Chapter 1 – The introductory chapter consists of several elements that needed to be discussed as a background to this study. The operations of deep-level gold mines are discussed, and individual systems explained with the current deficiencies. The section aims to provide the basic knowledge required to understand the systems and challenges faced.

Chapter 2 – The methodology chapter develops a new project management model that can be used in deep-level gold mining. The model will aim to address the deficiencies discussed. The model has been developed from literature and investigations into past failures and successes in mining projects, while using digital solutions.

The model will use an integrated simulation of the system to evaluate the effect of new projects on the current system to assist in project management. The developed model will aim to minimise project failure and ensure long-term sustainability.

Chapter 3 – The verification procedures that were conducted are explained in Chapter 3. The developed model and the simulation's accuracy are verified. The application of the model to a new project and a failed project done by the mine is discussed. The model, along with the integrated simulation, was used to scope and implement a project to solve a deficiency found in the system.

Chapter 4 – Chapter 4 concludes the study with findings and results. Recommendations are given to how the model can be enhanced for site-specific applications as well as for other industries. A set of questions was set out in Chapter 1, and if a question has not been answered by this study, it is discussed, and recommendations are given.

1.11 SUMMARY

Deep-level gold mining in South Africa is in trouble. The background provided indicated what project management is and how it is currently being implemented in the industry, as well as current research happening in the field. From here a trend emerged that a model is required for the mining industry. The current deficiencies in projects and project management are discussed.

An introduction to the challenges faced in deep-level gold mining is given. With various challenges faced, progression is still required to ensure the long-term prosperity of mines. Industry 4.0 solutions and applications to mining and their possible contribution to both mining and project management are discussed.

Research questions were developed from the challenges identified in the background study. Possible solutions were searched for in published studies. It was indicated that a deficiency to address the mentioned challenges in both project management and mining exists. A clear need for this study was stated and used as a clear framework to emphasise the novel contributions of this study.

Steps need to be taken to address the problems faced in mining, or the sector will not remain competitive enough to provide for another South African generation.

CHAPTER 2: DEVELOPMENT OF AN INTEGRATED PROJECT SUSTAINABILITY MODEL

[17]

[17] FG. Jansen van Rensburg, personal photograph. "Multi-stage", Carletonville, 2014.

2.1 PREAMBLE

There is a need to implement optimisation projects to increase the energy efficiency of systems. Previous implementations have shown that capital-intensive projects often fail due to incorrect processes followed during the project life cycle. An integrated project life cycle model was developed from literature, integrated simulations and past knowledge.

This chapter identifies the crucial factors contributing to success in project management. Each of the factors and whether it is applicable to the complex and unique mining environment will be discussed. In Chapter 1, various models have been examined and the most applicable factors have been chosen from the literature survey.

An investigation into projects that have been done on mines and reporting will follow. The key factors leading to the failures and successes will be analysed and added to the model where necessary. The model will provide possible mitigations to the challenges faced in gold mining to date.

Lastly, the use of digital solutions will be incorporated into the study. A simulation of a mineshaft has been completed and was used in this study. The building, calibration and processes of setting up such a simulation are only be briefly discussed. Reporting will play a key role in the long-term sustainability of projects, and basic recommendations are given on how this tool should be used during the projects.

2.2 PROJECT SUSTAINABILITY- AND MANAGEMENT CHALLENGES

Deep-level gold mining is facing various challenges and is under severe strain. Mining houses are hesitant to implement new capital expenditure (Capex) projects due to the unsustainable nature of such projects. A project management model suited to mining is therefore required.

There are generally two types of projects: delivery projects or innovative, transformational projects [154]. Delivery projects are changes to a current system or new installations, whereas innovative projects are majors shifts in the way the entity would operate [154]. The study focussed on delivery projects as the innovative projects are not applicable to mining. Delivery projects are projects that make minor changes to an existing facility and modify or replace equipment in a current system [154].

Presently, most top-level project life cycle models incorporate 4 stages, namely project start, project planning, project execution, and project close-out [154]. It has been proposed by Archibald *et al.* [154] to include two additional stages, namely incubation feasibility at the start, and project evaluation at the end of the project [154].

This process will be incorporated into the model. Project evaluation will include integrated simulations and reporting. The project feasibility should already incorporate the simulation. It is crucial to have all the available information on the table to ensure an accurate simulation of the system. A study by Morris [170] also emphasised that project management practices should be employed before the project starting phase [170].

To do a project evaluation at the end of the project is not enough, this step needs to be incorporated with other steps before the project is handed over. Project evaluation will thus not be a separate step or phase in the project management model. The shell of the model can be seen in Figure 7.

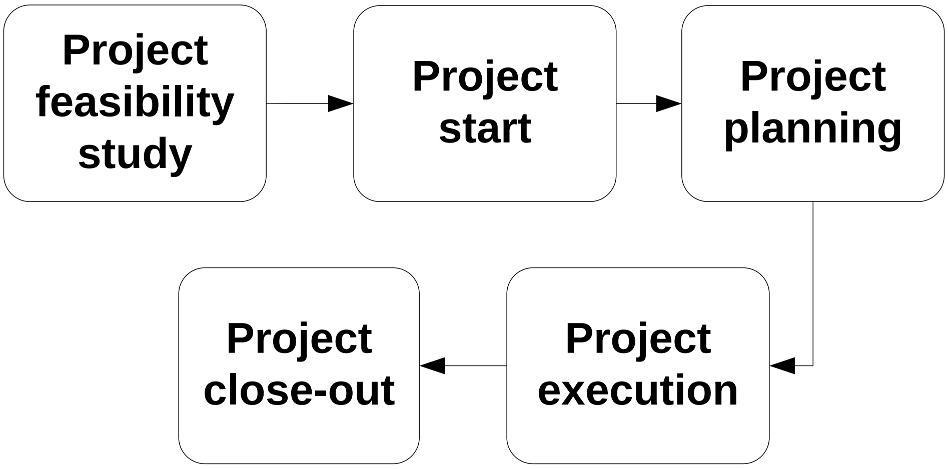

Figure 7: Project management model shell

With the shell of the model developed, the aspects within every phase of the project were developed next. Previous studies have noted which critical factors are leading to success and failure. A critical review was done by Belassi and Tukel [149]. The authors studied seven previous models and listed the critical factors that are unique to each of the studies. The results can be seen in Table 1.

Table 1: Lists of critical success factors for what? [149]

Martin (1976)	*Locke (1984)*	*Cleveland and King (1983)*	*Sayles and Chandler (1971)*	*Baker, Murphy and Fisher (1983)*	*Pinto and Slevin (1983)*	*Morris and Hough (1987)*
Define goals	Make project commitments known	Project summary	Project manager's competence	Clear goals	Top management support	Project objectives
Select project organisational philosophy	Project authority from the top	Operational concept	Scheduling	Goal commitment of project team	Client consultation	Technical uncertainty innovation
General management support	Appoint competent project manager	Top management support	Control systems and responsibilities	On-site project manager	Personnel recruitment	Politics
Organise and delegate authority	Set up communi-cations and procedures	Financial support Monitoring and feedback	Adequate funding to completion	Technical tasks	Community involvement	Financial contract legal problems
Select project team	Set up control mechanisms (schedules etc.)	Logistic requirements	Continuing involvement in the project	Adequate project team capability	Client acceptance	Implementa tion problems
Allocate sufficient resources	Progress meetings	Facility support		Accurate initial cost estimates	Monitoring and feedback	
Provide for control and information mechanisms		Market intelligence (who is the client)		Minimum start-up difficulties	Communication	
Require planning and review		Project schedule		Planning and control techniques	Trouble-shooting	
		Manpower and organisation		Absence of bureaucracy	Power and politics	
		Acquisition			Environment events	
		Information and communi-cation channels			Urgency	
		Project review				

The conclusion was made that four groups of factors can be derived from the research: factors relating to the project, factors relating to the project managers and teams, factors relating to the organisation, and factors relating to the external environment [149].

For this study, all factors relating to the organisation are generic, since the model focusses on mining. Thus, factors influencing success and models which suit mining best were chosen. The external environment was also set in place as the model will focus on deep-level gold mining in the South African milieu.

Factors related to the organisation can be reduced to the support of top management of the project, which is crucial in mining. The factors of the external environment can be reduced to the

- political environment,
- economic environment,
- social environment,
- technological environment, and
- sub-contractors.

Although the political environment of South Africa is unique, it is not at a stage where it influences the implementation of a project. South Africa is rated as a "mostly unfree" country by the Frazer Institute[18]. This is mostly due to the large size of the government, government integrity and the recent uncertainties in property rights. However, monetary and trade freedom still ranks high on a global scale.

As previously discussed, the mining industry is struggling to stay viable in the South African economy with an estimated GPD growth of 0.5 for 2019 [171]. With various mining companies scaling down and retrenching staff, it is crucial to implement cost-effective projects efficiently [13, 172]. This is one of the core aspects of the model.

As stated in Chapter 1, the social situation of mining is unique. The general workforce of a mine is being contracted in with only basic literacy and technical skills [96, 100]. Projects need

[18]*The Heritage Foundation, "2019 Index of Economic Freedom," The Heritage Foundation, 2019. [Online]. Available: https://www.heritage.org/index/country/southafrica. [Accessed 3 October 2019].*

to be understandable and as simple as possible. A simple, elegant solution will trump a technical, futuristic initiative in gold mining.

With Industry 4.0 already on our doorstep, it is crucial to take part in the revolution as far as necessary. There is a clear lack of Industry 4.0 technologies in South Africa and it is possible for South Africa to leap-frog global competitors [173]. Incorporating integrated simulations or "digital twinning" of shafts and digital reporting to project management it will be possible to efficiently and sustainably implement projects. The simulation should be integrated to incorporate any system that might affect the systems where the project will be done.
Steps of building, simulation and digital reporting will be discussed later in this chapter. As stated in Chapter 1, the use of simulations and reporting in project management is a shortcoming in literature and can be a major benefit to the field.

The use of sub-contractors in gold mining is a daily occurrence that needs to be used optimally in project management. Of all personnel employed in mining, about 10%[19] are contractors and this percentage is increasing yearly [174]. Sub-contracting in mining have various benefits and disadvantages [174]. The use of sub-contractors in projects is advised, as these contracts are performance-based and will lead to a "no performance no pay strategy", ensuring projects are completed in time. The knowledge of the impact of sub-contracting on project management in mining is based on the experience of the author and a full study thereof will be recommended for future work.

2.3 KEY SUCCESS FACTORS FROM LITERATURE

As discussed in Chapter 1 and shown in Figure 6, a critical review was done of 63 publications, and the most notable factors leading to success can be seen in the list below [145]. The factors were analysed to be applied to the mining processes.

- **Senior management backing:** This aspect is crucial, but in mining the aim would be to get backing from both engineering and mining management.

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[19] *Topco Media, "Top 500," ISSUU, 2019. [Online]. Available: https://top500.co.za/top500-companies/harmony-gold/. [Accessed 06 October 2019].*

- **Realistic objectives:** When projects are implemented, the outcome and effect on the day-to-day operations of the mine need to be taken into consideration. Drastically changing the schedule of an operator or miner is not realistic and will lead to resistance. The systems constraints and state of equipment need to be audited during the feasibility phase of the project before projects are proposed.

- **Project plan with realistic timelines:** The project needs to fit in with the current mining plan. No major installations can be done during the week. These are reserved for off-weekends (most mines have about 26 blasting days a month, this means there will be drilling and blasting on 2 weekends a month). If the project allows installation to be done during normal shifts, the schedule should be implemented strictly with the assistance of mining managers.

- **Qualified team:** This factor is unfortunately not always practical in mining. As previously stated, there is a lack of technical expertise in gold mining presently and most of the work will have to be done by contractors.

- **Effective change management:** Unfortunately, this is once again an area that will have to be addressed by the model to mitigate possible challenges. Good record keeping, bi-weekly meetings and communication with all the relevant personnel are of key importance. Digital reporting will mitigate some of the challenges faced.

- **Competent project manager:** As stated, this is a major shortcoming in mining today. The competence of the project manager is mostly based on his/her experience, and with the large number of experienced personnel leaving the industry, the problem will only get bigger. This model will aim to assist new project managers with projects in mining.

- **Strong business case:** As stated, mining is in trouble and mines are closing [172]. This means that new delivery projects should have a payback period of less than a year preferably. If a good case can be made for the project longer periods should be permitted.

- **Sufficient resources:** In deep-level gold mining this will be a challenge as mines are already understaffed, especially with regards to technical personnel [100]. The model will have to offer mitigations and recommendations.

- **Familiar technology:** This will be crucial, as major changes to current mining systems will lead to resistance and projects implemented in this way will fail.

- **Risks managed:** As stated in the previous sections, various risks make implementing projects challenging in mining. The model will have to address and mitigate various risks before they could become a problem.

- **Effective monitoring:** Digital reporting will be a great aid to ensure the project is sufficiency monitored during the project phases. Effective monitoring and reliable reporting are crucial, as bad information could lead to trust issues on the mining department side.

- **Adequate budget:** As budgets are being cut in these tough times, a good business case is crucial. Most of the financial aspects of the projects are handled by the financial department of the mine. Thus, a realistic budget needs to be applied for at the very start. A true representation of the maintenance cost once the project has been implemented is necessary as well.

- **Organisational adaption:** It is important for the new project to be fully adopted by the mine. The backing from both the engineering- and mining departments will assist in the successful adaption process. As stated, it is crucial that a new control philosophy should be adapted once a project is implemented.

- **Training provision:** This commonly falls short in the mining industry. Training of personnel involved in the project and in system thereafter is crucial.

- **Appreciating different viewpoints:** It is important to note the needs and daily schedule of mining. If the current systems are not respected and a new project forced into action, it will fail. Backing from both the mining- and engineering departments is crucial, and the milieu of South African mining will play a great role in the success of the project.

The mentioned success factors need to be incorporated into the project management model. By adding the discussed points, the model should be expanded. Some of the key factors play a pivotal role during certain phases of the project, while others play a part in most of the phases.

The study summed up the findings from literature, which were used as a base. The shortcomings in mining have already been discussed. The one truly critical factor that will come into play in mining is detailed audits of the current system. As mines are not correctly and accurately instrumented, it will be crucial to know the constraints of the current system and not work and plan on theoretical values and assumptions. The model can already be adapted to incorporate subsections of the project phases as seen in Figure 8.

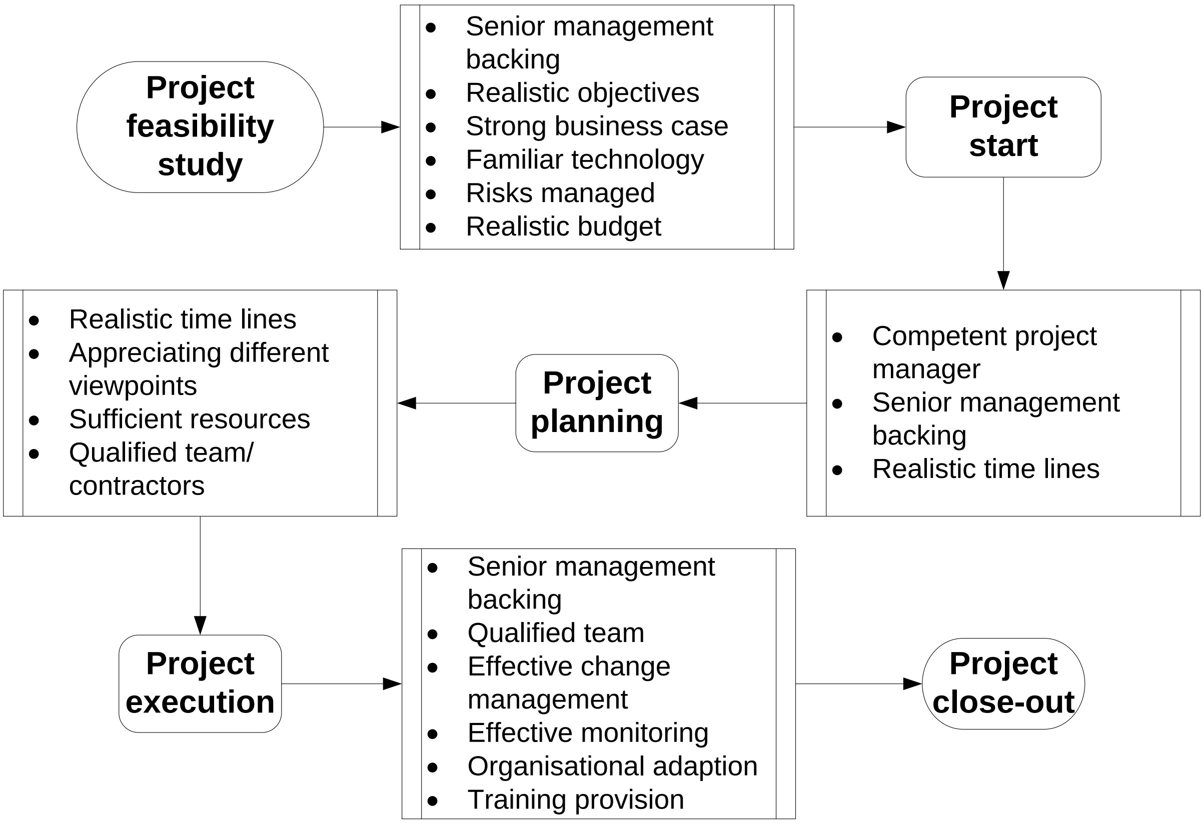

Figure 8: Project management model integrating critical success factors from literature

It is important to notice that some factors are repeated in various phases. This is crucial and should be done throughout the project phases. It has been found that, if a change in some aspect in the general operations of mining will occur while the project is implemented, senior management should be consulted before continuing with the implementation of the project.

It should be noted that the financial planning is not discussed in this model. In the mining industry it is common to have a budget approved by a committee, where after the budget is allocated to the project team. Project teams are managed to stay within this rigid budget, which is why a realistic costing of the project needs to be done during the project feasibility study.

2.4 KEY FAILURE FACTORS FROM LITERATURE

Knowing which factors lead to success is a good start to the model, but factors leading to failure are also notable. Most literature on why projects fail can be found in the Information Technology (IT) sector. A study done in 2002 by Robbins-Gioia [20] found that 51% of enterprise resource planning projects were implemented unsuccessfully. The cost of failed IT projects reached an estimate of £ 75 billion in 1998 [175]. The United States and United Kingdom are the leaders in project management, but their failure rates of projects were 83% and 70%, respectively, in the 1990s [176].

What defines a failed project has been classified in literature [177]. A study done by Lyytinen and Hirschheim [178] stated that projects fail due to four categories [178]:

- correspondence failure
- process failure,
- expectation failure, and
- management failure

A study done by Flowers [179] stated that projects are failures when the project does not operate as expected or when the project costs are greater than the benefits. It is thus crucial

[20] *Robbins-Gioia. (2002). ERP survey results point to need for higher implementation success Available: http://www.robbinsgioia.com/news_events/0128 02_erp.aspx.*

to do an in-depth feasibility study to ensure the benefits outweigh the cost, especially in mining. Keeping the project on time will also ensure the costs stay low.

In a study done by Salamah and Alnaji [180], reasons why projects have failed in industry were noted as follows (in order of relevance):

1. change of project scope;
2. conflict between project and departmental tasks;
3. resource contention;
4. lack of resource use tracking system;
5. shortage of resources;
6. lack of a defined project management methodology;
7. lack of a defined software project management methodology framework;
8. unclear or conflicting project prioritisation;
9. ad hoc projects and tasks assigned to resources;
10. poor software quality; and
11. unrealistic project expectations and optimistic planning.

Each of these factors can be applied to mining in some way or another, most notably a change in project scope. A change of project scope has been observed by the author in various projects. Sometimes the scope change is not a big change, but just enough to have the project deadline postponed to a state of no return.

Conflict between project and departmental tasks is also a great area of concern. As previously stated, technical personnel in gold mining are becoming a scarce commodity, and any time when an operational problem affecting mining occurs, the problem needs to be solved first. This can easily lead to projects going far beyond set deadlines. The same can be said for artisans and engineers on mines; production always receives preference [181].

Resource contention will always be a problem in mining, as the compressed air and/or water is needed daily for production. As stated, most projects requiring the shut-off of any of these services will have to wait for off-weekends when it is safe to do so. It is crucial to add this to the project planning and timelines.

The shortage of resources is also prevalent in mining. As already stated, mines have scaled down on technical personnel [100]. It is common for mines to have one person dedicated to

Supervisory Control and Data Acquisition (SCADA) systems development and maintenance. If a project needs to be commissioned on the SCADA, timelines will have to be adjusted to accommodate for this shortcoming. The same can be said for artisans. This also applies to point 8 - ad hoc projects and tasks assigned to resources.

A lack of a defined project management methodology is a clear shortcoming in mining and, as already stated, no sufficient models exist for the mining environment. Projects are commonly implemented at the discretion of the project manager. This study will rectify the deficiency.

Unclear or conflicting project prioritisation will also be addressed and incorporated into the model. Proper communication and reporting can mitigate the challenge. For this reason, management backing, as well as organisational adaptation, is crucial. This point correlates well with unrealistic expectations and planning. All parties need to be fully aware of the implications of the project. Getting the approval from both the mining- and engineering departments is thus crucial.

Poor quality software can be interpreted as poor-quality equipment in terms of mining. The correct use of equipment and materials is crucial. The harsh conditions found in mining require good quality hard products. For example, a valve and actuator need to be able to withstand the harsh underground conditions as well continuous daily opening and closing of the valve. If a sub-par combination is used, problems will occur.

The model will now be updated to incorporate decision making and more detailed processes will be added to the model. The model is shown in Figure 9. As indicated, the project feasibility is the most important step in the process with the most critical decisions to be made.

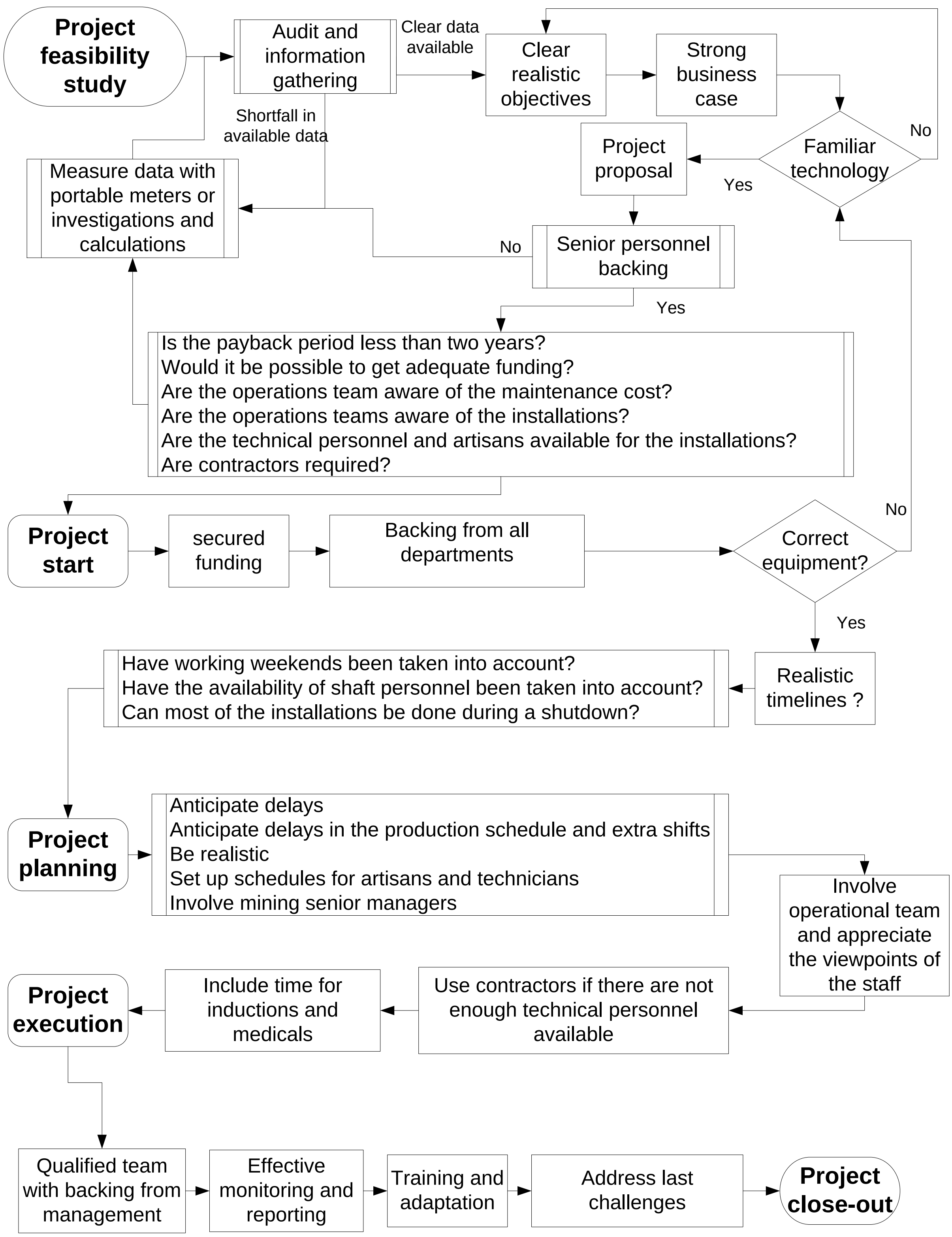

Figure 9: Updated project management model incorporating critical factors of failure

From the model (Figure 9) above, an improved model can now be developed that focusses on deep-level gold mining in South Africa.

2.5 KEY FACTORS FROM FAILED MINING PROJECTS

Common practice in the mining environment involves dedicated personnel focussing on different sections [16]. The shortfall of this practice is that the personnel do not communicate with each other. This leads to a tug-of-war between departments. A holistic approach is essential for the future of the mining environment.

Unfortunately, the separate management of systems leads to the challenges faced when implementing projects on these systems. There are no truly independent systems or procedures in a mining system. By following the stated model, most problems in the mining environment can be avoided.

A good example of an unsuccessful project on a compressed air network was studied by Bredenkamp, Schutte and van Rensburg [181]. This Demand Side Management (DSM) project, which had been implemented on the mine (and failed), is presented as the case study reported in this study. It was stated that the reasons for failure of the project were [181]

- practical challenges,
- delays,
- control limitations, and
- maintenance.

From literature and past experiences, projects in the gold mining sector are not implemented sustainably [181], further emphasising the need for this study.

2.5.1 Failed projects

A list of projects that have been implemented and failed on deep-level gold mines throughout South Africa is reported in Table 2, along with the project life-times and reasons for failure. Only projects in which the author was directly or indirectly involved are included. The projects span over various shafts and mining houses. It is important to analyse the mistakes made in the past to prevent them from happening again.

By studying the mistakes made in the past, it is possible to derive a model to mitigate the possible failure of future projects in deep-level gold mines. Table 2 focusses on the reasons for failure.

Table 2: Past failed mining projects, along with corresponding lifetimes and reasons for failure

Projects	***Initial success***	***Failure***	***Lifetime***	***Reason for failure***
Pumping load shift	Yes	Pump became inefficient and dams filled up with mud. The problem could have been averted if the settlers had been maintained and dams cleaned yearly.	Several months	Maintenance
Closed-loop bulk air cooler	No	Various issues, the project will be discussed in detail	Never completed fully	Management
Head gear compressor installation	Yes	Due to a lack of any maintenance, the compressor broke down and the repair cost was deemed too high	2 years	Maintenance
Compressor surface set-point control	Yes	Due to a major increase in demand, the set-point had to be readjusted. It was found that the increase was mainly due to wastegate. Various leaks were reported to management, but most were not fixed after audits (6 months later)	2+ years	Maintenance
Optimisation of air networks	Yes	Pneumatic actuators were used, and the size of the by-pass pipelines was specified incorrectly. This project is re-evaluated in the case studies.	3 months	Equipment
Fridge plant evaporator VSDs	Yes	Low quality variable speed drives were purchased and not maintained. The VSDs were also always used at either 100% or 0%, making the functionality of the VSDs null and void.	6 months	Control philosophy
Refrigeration and BAC load shift	Yes	Project fell out of favour by new services engineer.	3 months	Management
115L flocculation change over	No	The water usage of the mine became more than the original design of the settlers. Is was decided to use a faster coagulant. The equipment adding the coagulant to the water was not enough. This led to a failed project, dams filled up with mud and the pumps were damaged.	Never completed	Equipment
Ventilation fan peak clipping	No	As part of a DSM project, a peak clip was done on the main ventilation fans. Low quality guide vanes and control caused the fans to vibrate excessively. The control boxes were cut off the fans by the mine.	0 months	Equipment
Stand-alone compressors	No	Due to bad management the project fell behind schedule and was never completed.	Never completed	Management
Pre-cool dam actuator	Yes	Project fell out of favour by new services engineer and control staff neglected the control and would disable the automatic function of the valve. The engineer did not care about the project.	6 months	Control philosophy
BAC control philosophy change	Yes	Project fell out of favour by new services engineer. The inexperience of the project manager led to mistakes being made during tests, which stopped the project completely.	3 months	Management
Surface refrigeration control philosophy shift	Yes	Project fell out of favour by new services engineer. The inexperience of the project manager led to mistakes being made during tests, which stopped the project completely.	6 months	Management
Stope isolation valves	No	The project was designed incorrectly and in principal a failure. Too many assumptions were made, and operational personnel were never trained nor consulted.	Never completed	Equipment
Underground turbines	Yes	The maintenance cost was never estimated by management. After various budget cuts, the maintenance of the turbines was never budgeted for and due to various failures, the project stopped working. Repairs to the system are made sporadically, which leads to the project working off and on again.	Continuous but ineffective	Management
Stand-alone compressors	No	Stand-alone compressors were implemented by the plant to reduce the reliance on the shaft. Due to various failures, it was decided by management to rather go back to the old way of running off the shaft compressors. This led to a project on the shaft being stopped as the plant requires a set pressure over 24 hours.	3 months	Equipment

It can be seen from Table 2 that mining projects fail due to four commonly occurring reasons:

- Equipment – Incorrect equipment is used during the installation and design phase, commonly due to budget constraints or uninformed decisions made by mining personnel.
- Management – Due to the constant turnover of engineers and technical personnel on shafts, some projects fall out of favour by the newer personnel and often become neglected.
- Maintenance – Due to the harsh economic circumstances, maintenance budgets are cut on "less important" projects not related to production.
- Control philosophy – Due to the dynamic nature of gold mining, it is crucial that the control philosophy be updated periodically to accommodate process changes [13].

It is important to note that there is a clear difference between project failure and project management failure, as stated. Current project management methods are insufficient for the deep-level gold mining milieu, as some tend to fail during implementation. As shown in Table 2, most projects get implemented successfully, but the projects do not remain sustainable very long after implementation.

As discussed in Chapter 1, implementation of a sustainable project is lacking in literature. From Table 2, the deficiency in literature carries over to the practical application in mining, stressing the need for a model focussing on sustainability Table 2 shows why projects tend to fail after implementation. These deficiencies will be addressed in the following section.

2.5.2 Critical review of sample project

The sample project focussed on is the closed-loop project noted in Table 2. The initial capital expenditure of the project was R 180 million, but the exact amount spent before the project was abandoned is difficult to estimate. The aim of the project was to replace spot coolers with BAC on every production level.

As the mine already had fridge plants underground, it was decided to design the system as a closed-loop system, allowing the water to return to the fridge plant level via gravity. New refrigeration units were also being commissioned on the mentioned level. This would add the required water to run the BAC and supply water to mining.

The layout of the current system is very similar to the example used in Chapter 1 for refrigeration and reticulation. A proposed design can be seen in Figure 10. Service water is reused underground with only make-up water coming from the surface fridge plants. The water used by mining was to be used in both the surface and underground fridge plants.

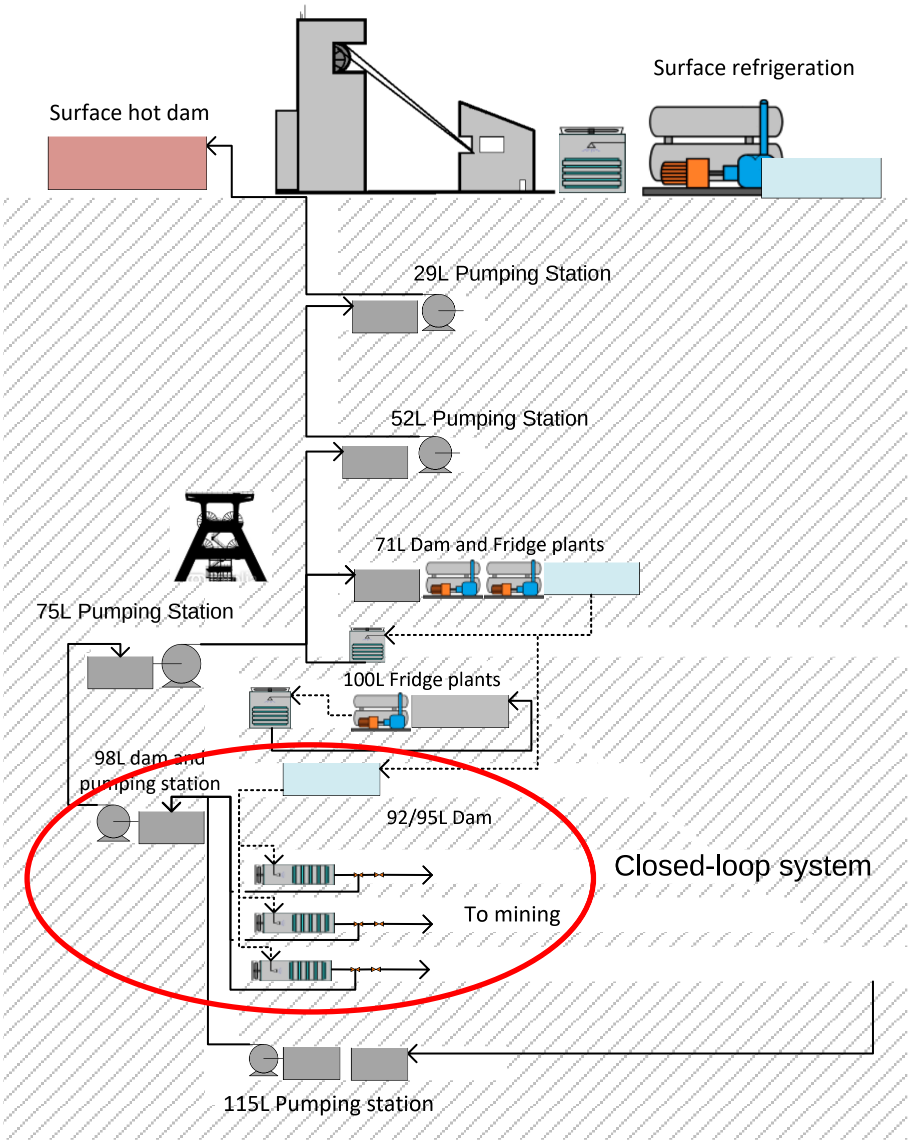

Figure 10: Closed-loop project proposal

Before the installation, the mining levels required 550 l/s of service water for drills, cleaning and spot coolers. Ventilation air was primarily cooled on surface by BACs. The air was then once again cooled by the 75 level (75L) and 100 level (100L) BACs. The working areas on this shaft are located around 5 km from the station. Air was cooled once again by spot coolers close to the working areas.

The 100L BACs are in a closed loop with the 100L fridge plants. There are three fridge plants running in series located on 100L. These fridge plants do not supplement water going to mining. The 75L BACs are fed by three of the nine fridge plants on 71L in a closed loop. The remainder of the 71L fridge plants feed mining. Around 250 l/s of service water is supplemented by the surface fridge plants, as shown in Figure 10.

It was proposed to install four 1 MW BACs on each of the production levels. This would allow the mine to remove the current spot coolers. Literature have shown that spot coolers are inefficient and seldomly well maintained [45]. The spot coolers on this shaft also just dumped the water onto the footwall, leading to wet conditions in the working areas and a large amount of water ending up in the settlers, which ultimately led to more water that needed to be pumped.

The level BACs would be gravity fed from the 92/95L dam, and due to the high pressure, it would have been possible to push the water through the level BACs and back up to the 98L dams, reducing the pumping required from 115L after the water had been used by mining. The water would then be pumped from 98L to 75L, from where it would be pumped up to the 71L fridge plant to be cooled again.

Pneumatic valves and pressure reduction stations were to be installed after the level BACs to have half of the water sent to the level be used by mining and the other half returned to 98L. The original design was to have sent 120 l/s to each of the BACs and have 60 l/s return to 98L, while 60L/s would have been used by mining.

The water would heat up through the BACs before it is used by mining, but the increase was deemed small enough to not have an influence on operations This project was meant to revolutionise mining on this shaft and ensure profitability. The project had a pay-back period of two years. The savings would have come from

- reduced pumping costs,
- reduced refrigeration costs,
- removal of maintenance-intensive spot coolers,
- saving on chemicals used in settlers, and
- maintenance costs of pumps.

The project would also lower working temperatures as a benefit, leading to an increase in production. The project was a no-brainer and had to be done, and the original project proposal was completed in 2011, but installations only started in 2014. From here, many things went wrong. The project was only partially successful with costs, equipment and man-hours wasted.

The project kicked off in 2014 but is currently not working completely. Various delays and design challenges caused the installation of the infrastructure to go far beyond the initial deadline. To date, the BACs have been installed and all the pipes and valves work, but no water has returned to the 98L dams. Only a few tests have been conducted, but none have been successful.

Although the level bulk air coolers have a positive influence on the underground temperatures, the closed-loop aspect of the systems was, and still is, a failure. The process that lead to the partial failure of the system is as follows:

- Insufficient feasibility study processes.
- Usage of levels was theoretically determined instead of measured. As mentioned, it was assumed that 60 l/s would be used by mining, but when the project was implemented 110 l/s was used by mining.
- Outdated data was used. The cooling capacities of the fridge plants were also assumed and not measured. More service water had to be sent from surface since the underground plants could not meet the demand. An increase in water being sent from the surface meant more water had to be pumped from underground.
- Incorrect assumptions were made on the required head of the systems, which meant that some of the levels could not return water to the 98L dams.
- Critical equipment was neglected. Maintenance schedules were set to be established once the level BACs was up and running, but this never happened and while the other pipe work was completed, the level BACs became clogged. The pressure reduction through the clogged level BACs lead to a deficiency in pressure and water could not be returned to the 98L dam.
- Ineffective project management. The project was managed by four different project engineers, each with their own set of ideas. This led to some aspects of the design being neglected.
- Since the design was old, none of the current employees had been involved in the design process.

- An external consulting firm was contracted. The data used by the contractor was incorrect. Some critical features of the project were also left out. For example, flange covers were never in the original design. This led to a major oversight as this system would be operating at around 80 MPa. A flange leak would have various safety hazards and could potentially cause deaths at the mentioned pressures.
- Incorrect equipment was specified and installed.
- Pneumatic actuators were used on all the control valves. The compressed air supply on the mine is wet and dirty. This caused frequent malfunctions during control. In the end the valves were switched to manual control and left open.

Most of the reasons why the systems have never returned water to the 98L dam are listed above, but they are not limited to this list. As a result of the project, 21 cooling cars were removed, resulting in a 68 l/s noticeable saving, but 22 remained. A project will be launched to amend some of the issues. The final results will unfortunately not be available to be used in this study. The reasons for failure of this project tie in with the reasons set out earlier in this section, namely

- equipment,
- management,
- maintenance, and
- control philosophy.

Various countermeasures could have made this project successful. By learning from the mistakes made in mining, a model could be developed that will be integrated into the current model. It is important to note that an integrated simulation of the system would have solved various of the issues discussed.

2.5.3 Model from key factors learned from mining

Figure 11 presents a model that was derived from the mistakes made by the reviewed and failed projects. This model will be incorporated into the model derived from literature. When the two models are completely combined, it would form a sustainable solution for the project management problems experienced in mining today.

As shown in Figure 11, when starting off with a project it is crucial to ensure that the project is feasible from all angles before the project is even considered.

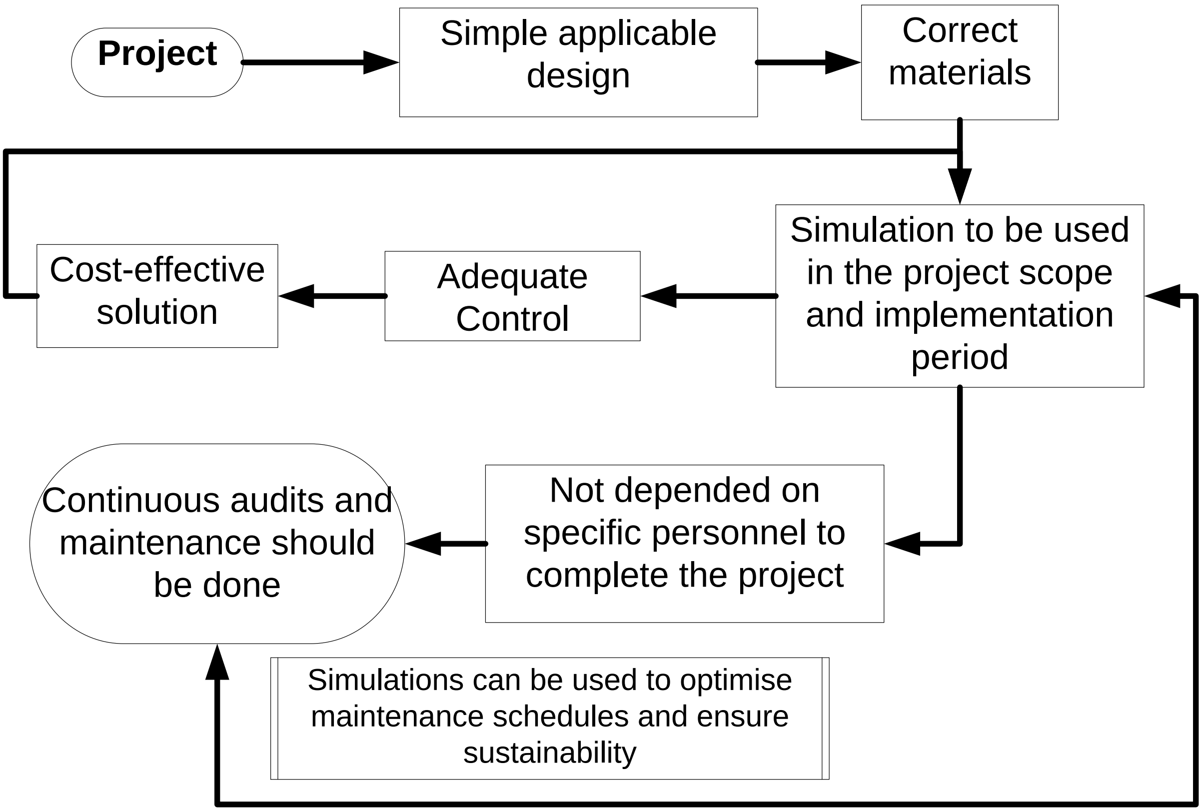

Figure 11: Model derived from a critical review of failed projects

It is crucial that the project be feasible before the project management starts. The following guide will ensure that as many as possible common mistakes are avoided. To ensure that a project would be successful, it is important that the design of the project is a simple solution to the problem at hand. An example of this will be provided in the first case study. As stated previously, the project should be simple enough to be understandable to non-technical personnel. If the design is too technical or difficult to understand, it is recommended to go back to the drawing board.

After a design has been chosen, it is critical that the correct materials are used in the production of the solution. As stated, the conditions underground are humid and contain oxidising gasses. It is recommended to use corrosive-resistant and hardened equipment. On surface the problem is not as prevalent, depending on the location of the system. If the installation is close to the ventilation fans, cooling towers or condenser towers, corrosive-resistant materials are recommended. The same can be said for any equipment on a gold processing plant, as various chemicals are employed in the process.

Due to the dynamic nature of a mine, a calibrated simulation should be used throughout the design, approval and implementation periods. From here an integrated simulation becomes a tool and good addition to the model. A baseline-integrated simulation should be correctly calibrated to ensure good results. The simulation is to be used to test the feasibility of the project and payback period. It is crucial to measure all values that will be used in the simulation. This simulation is to be used in various stages of the feasibility study as well as implementation of the project. This will ensure swift reaction if a parameter on the greater system changes.

The control of the system should be automated as far as possible and should be fail-safe. The next step is to establish the way in which the process will be controlled, as most projects will require dynamic control interventions. Automating the control of the system is recommended as it prevents human error. Although this is not always possible, it will ensure long-term sustainability of the project.

The equipment chosen for the control is also important. In the past, pneumatic actuators were used due to their reliability compared to older electric actuators. If the water traps and filters are not well maintained, this advantage is lost, which is commonly the case in mining. Valve types is an important aspect of the design. Where possible, only reliable over-specified valves should be used.

In recent years, electrical actuators have become much cheaper and lighter than pneumatic actuators, as well as more reliable. Electrical actuators are the way forward and should be used in most applications. The type of valves used in different applications should be specified correctly. For instance, using a butterfly valve to control compressed air is not sufficient and should be avoided and a ball valve would be better suited. The correct equipment will contribute greatly to the sustainability of the project.

To ensure project proposals are accepted and budgets awarded, a cost-effective solution is required. As emphasised in Chapter 1, mining is currently under strain and projects with a payback period of less than a year are preferred, depending on the advantages of the project.

It should be noted that the procurement stage of projects in mining is at least three to six months. Thus, the influence of inflation should be added in the budget.

With the correct equipment, control equipment and other considerations, it is crucial to re-run the simulation to reaffirm the feasibility of the project. Most projects can be done in stages and this sequence should be established by running various scenarios in the simulation. This will shorten the payback period significantly.

The project or the operation thereof should never be dependent on specific persons with specific skill sets. As already stated, the use of contractors is encouraged. However, if this is not possible due to budget constraints, it is crucial that the project is not dependent on one person to complete. There should be back-up personnel who can continue with the work if someone is not available. Far too many projects have been delayed due to being dependent on one personnel member on a shaft. The project or solution should always be generic in nature.

By design a project should need as little maintenance as possible, but nothing is truly maintenance free. Maintenance schedules should be added to the project management plan. The maintenance cost of the project should be calculated during the project feasibility phase, and an audit schedule set up. This will influence the costing of the project and might make it unfeasible, but it is better to stop a project before money has been spent than after installation. Where possible, solutions should be chosen that are less maintenance intensive and do not require any specialty personnel.

The already set up simulation can now be used as a guide to ensure the project is done correctly during each phase of the installation. This will be demonstrated during the case studies. The simulation should be integrated as already stated, as this will point out if other systems that might have been missed during the initial phases will be affected by the project. This will improve decision making [129, 132, 133, 134].

2.6 INTEGRATED SIMULATIONS

As stated, the simulation should be integrated enough to encompass the adjacent systems that might be affected by the project installation. Digital twinning would be the best form of such a simulation. No true digital twin for mining exists in literature. This is due to the fact that all gold mines in South Africa are older than two decades. Various simulation packages exist on the market today, but the one chosen for this study was readily available to the author and was powerful enough to encompass all the systems.

Due to the old infrastructure and the lack of technical personnel in mining, various measurement equipment underground is not calibrated routinely [160]. By just using the uncalibrated values, an untrue picture of the underground operations is painted. It is crucial to audit and verify most readings [128].

The different systems should be integrated. Any pumping project will have an effect of refrigeration, and these systems should be integrated. Refrigeration will also influence ventilation; thus, it is recommended to include it. Building a fully calibrated ventilation simulation is a challenge and possibly a project on its own. Instead, clear boundaries and limitations can be placed on the simulated control of the system. Incorporating compressed air into the system is recommended, except if the project focusses solely on a compressed air system. For this study, a fully integrated simulation of pumping, refrigeration and compressed air, is used.

Although the study does not focus on building such a simulation or the set-up of the reporting, recommendations will be given on the integration of the different services. This study will use these digital solutions as a tool. To correctly build an integrated simulation, it is recommended that the following list be followed [129, 131, 135, 160]:

1. Build the shell of the simulation by using Digital Exchange Format (DXF) files and satellite images. The DXF files of the levels can be obtained from the mine drawings office. Google Earth can be used for surface operations.
2. The mine's SCADA can be used as a base to start adding daily values to the system.
3. Complete audits to establish the validity of the DXF files will be required. During these audits, the general pipe layouts, design specifications and verification of meters can be done.

4. Calibrations of the simulation is required to ensure accuracy. Pumps become less efficient over time and this should be accounted for. By using the SCADA data, a general flowrate can be established and used in the simulation.
5. After the calibration (comparing a real day with the simulation with the same inputs) an accuracy of at least 90% is required for this application.
6. The calibrated simulation is then used as the baseline simulation. From here the proposed changes of the system can be simulated. This will also establish the estimated payback period.

With the completed baseline simulation and project simulation, the influence of each of the individual changes to the system can be simulated beforehand to identify any safety risks and risks to other systems.

2.7 DIGITAL REPORTING

During the project implementation phase, reporting is to be used as a vital tool to the success of the project [168]. Reporting should be automated as far as possible. The report should serve as a guide and a means to identify shortcomings during installation.

For example, during the commissioning of the discussed closed-loop project, the decline in efficiency of the levels' BAC could have been a good indication that there would be a large pressure loss though the BAC. This would reduce the system's capability to overcome the required head to return to the 98L dam.

The set-up of the project reporting is a study on its own, but some recommendations are given:

- All critical equipment's flow and energy usage should be reported on.
- All critical flowrates and pressures in the system should be reported on.
- All critical cooling duties of electrical usage should be reported on
- The use of targets is recommended, but just using the design spec of the system is not recommended. A realistic target should be clearly indicated in the reports to ensure the system operates close to what is expected.

These reports are to be sent out daily from the first installation to critical role players. These reports can also be used to track installations as a clear change in operation will be observed in the reports.

The digital solutions will be added to the model to improve the efficiency of project management as well as the long-term sustainability of the project.

2.8 DEVELOPMENT OF AN INTEGRATED PROJECT SUSTAINABILITY MODEL

As indicated in the sections above, a model is developed encompassing project management models from literature, critical success factors, failure factors and lessons learned from mining projects. All the mentioned models will be incorporated into one model that will ensure successful project management practices in deep-level gold mining.

The basis of the model includes five main phases into which a project will be divided. Of the five, the first stage is the most crucial. By removing any uncertainties or factors for failure it can be ensured that no project is proposed that may become unsustainable or uncompleted. The first phase is shown in Figure 12.

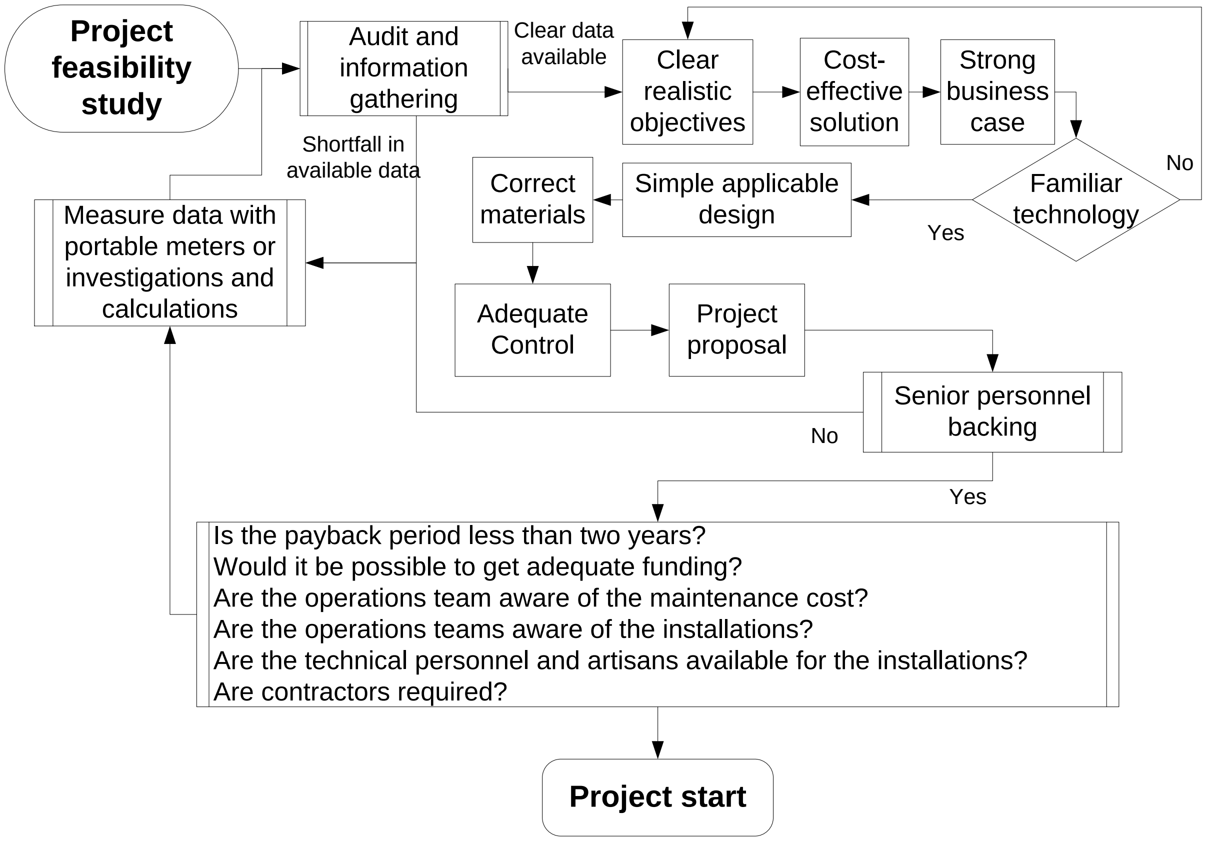

Figure 12: First phase of the sustainability project management model

As shown, the very first step is to understand and simulate the systems in which the project will be proposed. As stated, a high degree of accuracy is necessary for the integrated simulation. If all the data is processed and already being used for measuring performances, it is recommended to verify at least 80% of the measurements. If the data available is inadequate, a full investigation, audits and measurements are required. This is crucial, as an integrated simulation with bad data will only create an integrated simulation with bad results.

The next step would be to ensure that the objectives of the project are realistic. The planned project should fit in with the current mining milieu as discussed. The solution should be cost effective and payback periods should be kept to a minimum. With various uncertainties in mining, it is crucial to implement simple and high paying projects. Mines are hesitant to implement large-scale projects with long payback periods.

When the project is proposed, it is crucial to obtain the backing from senior management and personnel on the shaft. By meeting the key role players, the project and objectives have to be discussed. From these sessions, valuable input can be gathered. It is recommended to have one-on-one sessions with foremen and lower ranking personnel as they tend to be more open when senior management is not involved in the meetings. If management or senior personnel do not back the project, another solution needs to be proposed or the business case needs to be stronger.

The technology used in the project should be familiar to the mine or easily understandable. It is crucial that any proposal involving new technologies take into consideration the life-of-mine. It has been found that new technologies are not easily adopted by mining. Thus, if this is the case, a strong business case is required.

When the design specifications of the project are being proposed, it is recommended to go with the easiest project to implement. The equipment selection and construction materials are important. As stated by the model, corrosion resistant material should be used in the construction of the equipment. Along with this, the correct control measures should be used as stipulated in Figure 12 and discussed.

The second to last block in the process is a basic checklist to reaffirm the preluding factors in the model. After the investigation is finished and a project proposal is drafted, backing needs to be sourced once more from senior personnel. The projects need to have backing from the general manager of the mine and a senior engineering manager. The project should only be discussed with either of the managers once the full proposal is complete.

After a complete feasibility of the study has been completed, the project start can commence. The very first process would be to secure funding for the project. If the senior managers have approved the proposed project, the funding will only be a process to follow. Most of the work on this is done by the mine's financial department.

In this process only supporting documentation will be required from the project manager. This process may take up to six months, depending on the capital cost of the project. That is why it is crucial to ensure inflation and payback period delays are accounted for in the final costing. The project start phase is shown in Figure 13.

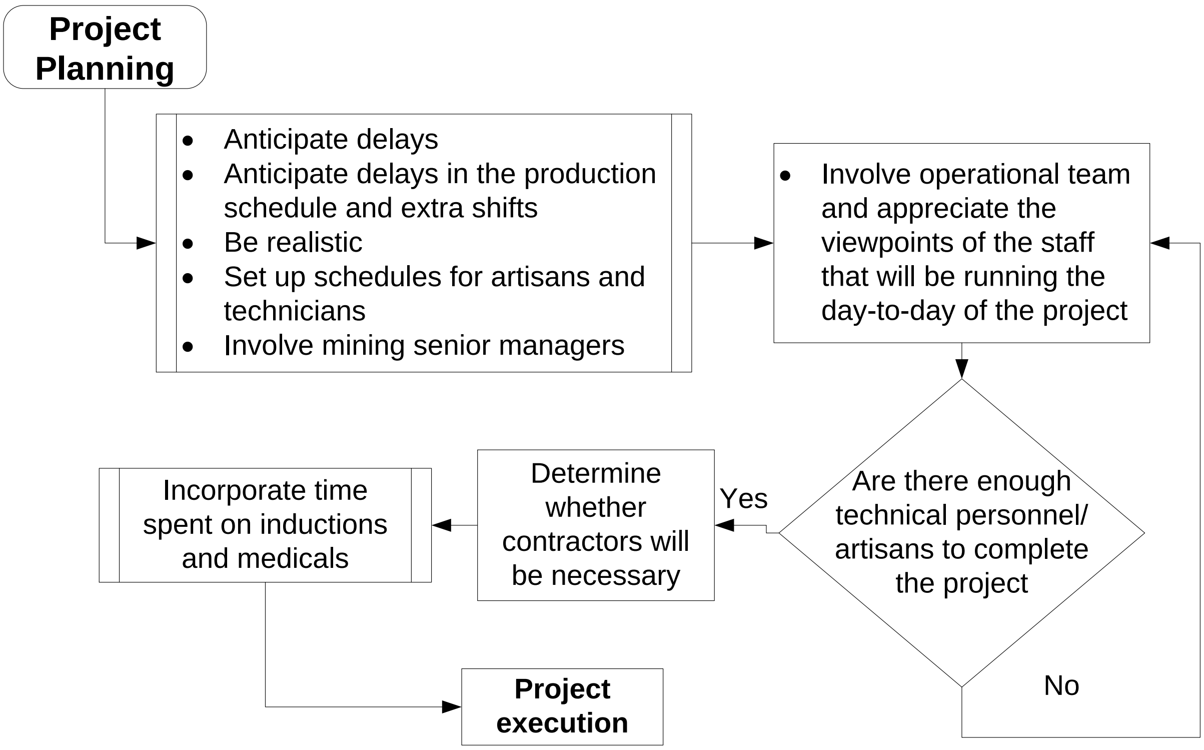

Figure 13: Second phase of the sustainability project management model

During this phase of the project, all processes leading up to installations should be addressed. Ensuring that the correct equipment is purchased by the mine's procurement department is crucial. After a project is proposed and the equipment needs to be sourced, a "buyer" (staff member in the procurement department) will place orders for the required equipment.

Unfortunately, the “buyer” usually does not have any technical background and he/she may need support to ensure that the correct equipment is purchased.

The timelines should be discussed and approved by the senior mining personnel, taking an availability of staff as resources into account. If the budget allows it, contractors should be used. As previously mentioned, the installation of equipment and set-up of systems should never be reliant on a specific person.

The next phase is the planning phase. This phase will ensure that all the required boxes are checked, and resources are available. The most crucial part of this project is to be realistic. The third phase is shown in Figure 14. If contractors that are not on site continuously will be used, it is important to allow for time in the project planning for these contractors to finish screening, medicals and induction.

The final phases will be the actual execution of the project and project handover and close-out as shown in Figure 14. These phases should not be seen separate and the execution of the project should flow into the project hand-over. If these phases are kept separate, the project will not be sustainable.

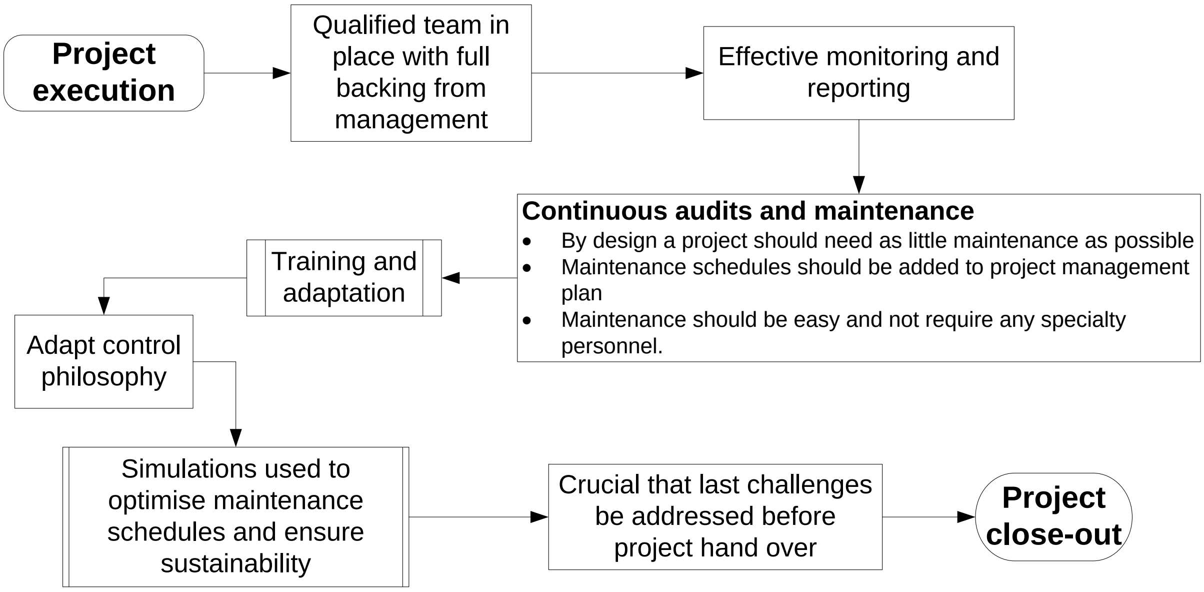

Figure 14: Final phases of the sustainability project management model

During the execution phase of the project, a qualified team should already be employed. The project should also be implemented in phases, if possible. The simulation will be of great assistance to ensure that the most important installations are done first. Maintenance schedules and auditing schedules should be confirmed at this time.

Digital reporting should be set up at the start of installations to ensure the installations happen on time and to monitor complete installations. As stated in Chapter 1, the control philosophy of the system needs to be updated when a new project is implemented. This may also serve as a warning system if something fails. The complete model can be seen in Figure 15.

By using the model, efficient, sustainable implementation of projects will be possible. This model should also be used by inexperienced project managers in the mining industry. Literature has shown that the experience of a project manager is relatable to the success of a project. This model will assist inexperienced project managers to substitute or supplement their knowledge.

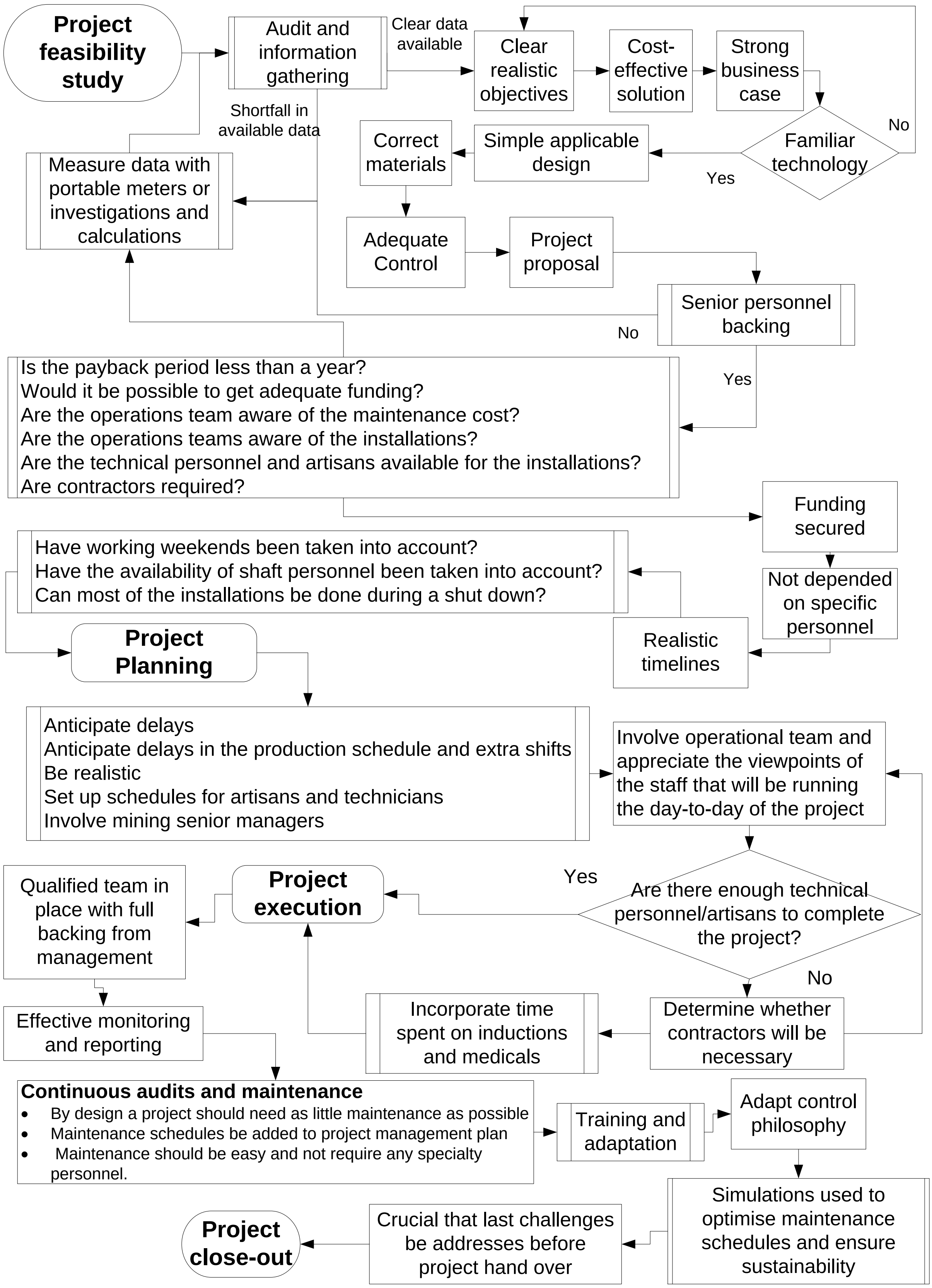

Figure 15: Integrated sustainability project management model for deep-level gold mining

2.9 VERIFICATION OF METHOD

The model and methods shown in the previous section have been derived from

- Project management models found in literature [69, 70, 71, 72, 73, 74].
- Critical success factors of project management found in literature [76, 79, 85, 145].
- Critical factors leading to failure of projects from literature [75, 77, 78, 79, 81, 82, 83].
- Critical factors leading to failure from a mining project from literature [181].
- The value of an experienced project manager is emphasised in literature. This model aims to assist and/or replace the required experience [145].
- Integrated simulations and reporting have shown to improve decision making and implementation of projects [131, 132, 133, 134].

Various project management models were analysed, and a five-phase project management plan was chosen. Four- and six-phase project management plans have had various successes in the industry and are well documented [79, 149, 154].

This model was therefore derived from already working models, verifying the legitimacy of such a model. The failed projects in mining that have been studied correlated well with the study done by Bredenkamp *et al.* [181], once again proving the legitimacy of the model.

The model can therefore be verified from literature, as various publications have shown the benefits and deficiencies addressed in the model. The focus of this model is deep-level gold mining, where the unsuccessful nature of projects have been proven. By learning from literature and past mistakes, a model was derived. The model will be validated by three case studies.

The model was applied theoretically to the closed-loop project on which the critical review was done and a matrix was created to establish whether the measure set out by the model would have possibly mitigated the problem as shown in Table 3 and Table 4. The green boxes indicate that the model would have mitigated these challenges.

Table 3: Critical project review feasibility matrix

	Factors leading to failure								
Sustainable project management model steps	*Insufficient feasibility study*	*Theoretical values used*	*Capabilities of equipment not measured*	*Assumptions made*	*Critical equipment neglected*	*Ineffective project management*	*No personnel involvement*	*Incorrect equipment was installed*	*Pneumatic actuator*
Project feasibility study									
Audit and information gathering [21]									
Set clear realistic objectives									
Cost-effective solution									
Strong business case									
Familiar technology									
Simple, applicable design									
Correct materials									
Adequate control									
Senior personnel backing									
Secure funding									
Not dependent on specific personnel									
Realistic timelines									
Checklist [22]									

[21] *Most uncertainties would have been cleared up with the audit and simulation*

[22] *The checklist is designed as a last step check to ensure all the parameters set out by the model was met in the project feasibility phase.*

Table 4: Critical project review execution matrix

	Factors leading to failure								
Sustainable project management model steps	*Insufficient feasibility study*	*Theoretical values used*	*Capabilities of equipment not measured*	*Assumptions made*	*Critical equipment neglected*	*Ineffective project management*	*No personnel involvement*	*Incorrect equipment was installed*	*Pneumatic actuator*
Project planning									
Involve operational teams									
Checklist									
Project execution									
Qualified team with management backing[23]									
Effective monitoring and reporting[24]									
Continuous audits and maintenance									
Training and adaptation									
Adapt control philosophy									
Simulation									
Address last challenges[25]									
Project close									

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[23] A clear project management model would have mitigated the delays

[24] An attempt was made to incorporate monitoring to the system, but this was done after the return portion of the project was abandoned. Once the reporting was up and running, it indicated that the system is in dire need of maintenance which is too late.

[25] Unfortunately, the project never reached this stage

Table 3 focusses on the feasibility phase of the project management model. From the matrix is it evident that all the stated challenges have been addressed. Most critically, a full audit and integrated simulation were lacking. An integrated simulation would have indicated that the control parameters set were not realistic.

Table 4 focusses on the remainder of the project phases, and as expected, it directly addresses challenges related to the execution of the project, the most critical being the shortcoming in project management. As stated, a project management model will already lead to more efficient implementation of projects as well as project success.

This study set out to develop a project management model focussing on suitability and incorporating digital solutions. With the information presented in this section, it is clear that the validity of the model is confirmed from literature and practice.

2.10 SUMMARY

Chapter 2 showed the development process of the integrated sustainability project management model. A model was derived by firstly investigating what a good project management model offers, secondly identifying the critical factors leading to success and failures, and lastly by applying all the mentioned parameters to mining.

The first section examined project management models found in literature. It was decided to use a five-phase management model. Literature showed the significance of a project management model. The shell of the model was derived from this section. It was found that external factors affecting the success of a project are the political environment, economic environment, social environment, technological environment and sub-contractors. Each of these factors and their application to the deep-level gold mining environment were discussed. A more detailed look at the influence of sub-contractors on projects is recommended for future studies.

The key success and failure factors mentioned in literature were investigated and incorporated into the model. It was found, from various resources, that the biggest factors contributing to success are senior management backing, realistic objectives, a project plan with realistic timelines, a qualified team, and a competent project manager. Various other factors and their application to deep-level gold mining were discussed as well. Each of the factors were then incorporated into the model. It is also important to learn from past mistakes and therefore the factors leading to failures were also analysed and measures were put in place to mitigate potential failures.

After the second stage of the model development was completed, the reasons for past project failure in mining were investigated. It was found that the major contributing factors are equipment, management, maintenance, and the lack of control philosophy adjustments. Numerous failed projects were analysed, and it was also found that many projects in mining were not sustainable. It was also proven that digital solutions will have a positive effect on the model, and it was incorporated. All the mentioned factors were then incorporated into a project management model focussing on implementing successful, long-term sustainable projects in the deep-level gold mining environment. The use of digital solutions was incorporated into the model. The model was verified from literature and practice.

CHAPTER 3: RESULTS AND VALIDATION THROUGH CASE STUDIES


[26]

"Knowing is not enough; we must apply. Willing is not enough; we must do."
Johann Wolfgang von Goethe

[26] FG. Jansen van Rensburg, personal photograph. "Pre-cooling", Carletonville, 2017.

3.1 PREAMBLE

When capital expenditure projects are implemented on compressed air systems, it should be done efficiently and sustainably. The model was applied to two projects on a deep-level gold mine in the Carletonville area. The first project (Case Study 1) was a completely new design, and the second project (Case Study 2) was a re-evaluation and re-installation of an old, unsuccessful project.

The integrated baseline simulation was used to simulate different solutions and accurately estimate the potential savings. The results of Case Studies 1 and 2 will be discussed together due to the fact that the installation of the projects overlapped. A brief discussion on how the model can be applied to other projects will follow. The model will be validated through the results of the case studies and a conclusion will follow.

3.2 BACKGROUND OF CASE STUDY SHAFT

Gold mining operations in the western Witwatersrand Basin frequently exceed 3 000 m in depth, and large geothermal gradients ensue [103, 123]. The virgin rock temperature at the abovementioned depth approaches 70 °C [31, 182, 183, 184]. Mineshaft A is a deep-level gold mine where mining takes place at depths between 2 982 m and 3 462 m. Furthermore, the work areas are located two - six km from the shaft stations, making cooling and ventilation crucial for maintaining safe working conditions at this mine [23, 123].

Surface refrigeration operations were found to be highly inefficient at Mineshaft A, thus jeopardising the safety and productivity of personnel because of hot working areas underground. The deficiencies in ventilation lead to the abuse of compressed air. It is recommended that the impact of lower temperatures in the working areas on compressed air usage should be investigated and quantified.

In the current cooling and ventilation system, hot water (29°C) is pumped from underground to the hot water dam on the surface as shown in Figure 16. From the hot dam, the water is pumped through two pre-cooling towers, which use the ambient air to pre-cool the hot water before it is sent to the pre-cool dam [37, 39]. Water is then pumped from the pre-cooling dam through the fridge plants to the chill dam by the evaporator pumps. The fridge plants are supposed to cool the water to a set-point of 3.5 °C. Although this set point is rarely reached, an average temperature change of 16 °C is generally obtained over the fridge plants [37].

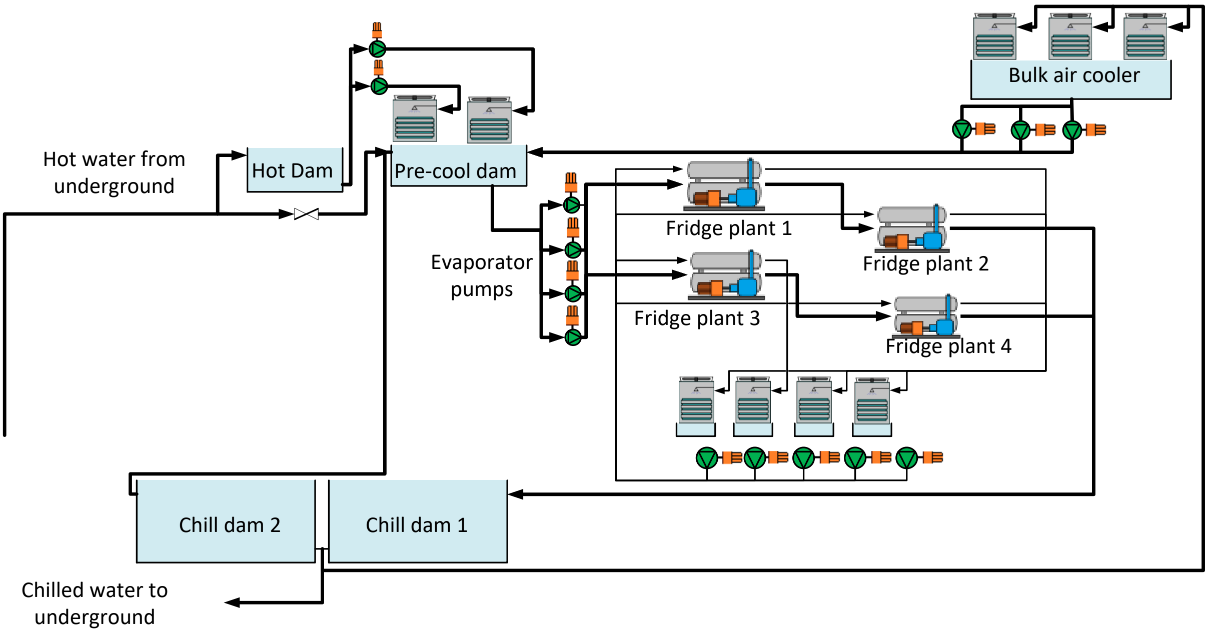

Figure 16: Refrigeration cycle of Mineshaft A

From the chill dam, water is sent to the surface bulk air coolers to cool the air heading down the shaft and the excess cold water is sent underground for mining purposes. Water from the bulk air coolers is returned to the pre-cool dam with the help of return pumps [22]. Additional bulk air coolers are located on two separate levels underground, along with fridge plants.

The shaft has five compressors located on surface. Four of the compressors are 4.2 MW units and the last a 2.5 MW trimming compressor. Compressed air is sent by a 600 mm pipeline underground to the production levels. From the stations, 400 mm pipes are employed up to the crosscuts and 100 mm pipes are used from there up to the reef horizons.

Compressed air is used by pneumatic drills (stoping and development), bushman loaders, refuge chambers and agitation. The shaft's compressed air network was found to be inefficient, with various leaks and open ends. The shaft was over its energy budget for the compressors, so it was decided to launch energy saving interventions.

An integrated simulation was built of the entire network of the mine. Due to the size and complex nature of the simulation, it will only be used as a supporting tool. The steps set out by Chapter 2 were followed. Mineshaft A is complex, and the steps should be meticulously followed to ensure the integrated simulation is an accurate representation of the operations. The DXF (Drawing eXchange Format) files of all the levels on the mine were obtained from the drawing office.

Over a two-month period, all the levels were meticulously audited to search for possible projects and inefficiencies. The piping layout of every level was mapped, and an example of the notes can be seen in Appendix C. An example of a completed level audit can be seen in Figure 17. The piping layouts obtained from the drawings as well as from end-users were used in the building of the simulation.

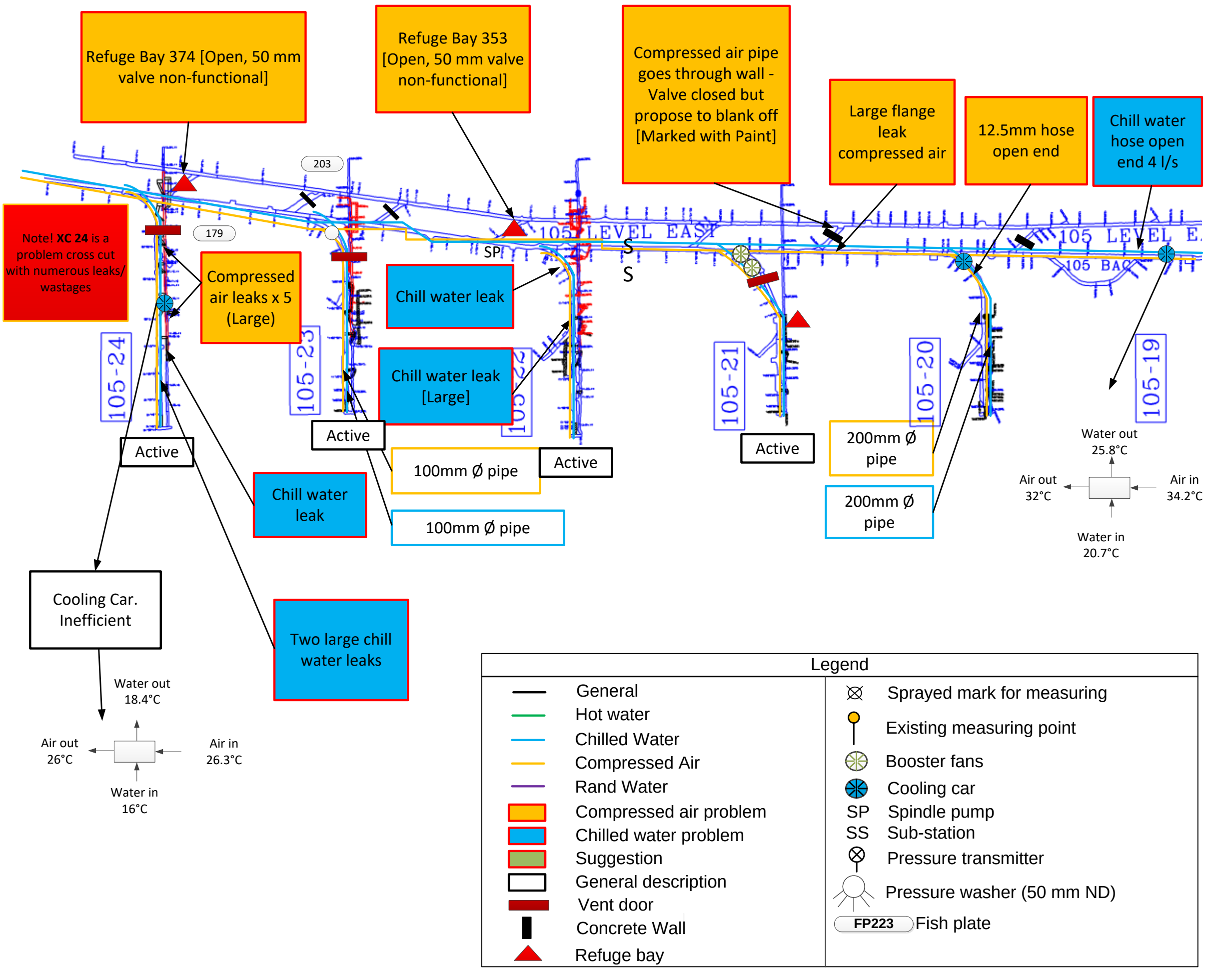

Figure 17: Example of the audit drawings and findings

The mine SCADA values were used as preliminary data. All the water- and compressed air flows and pressures were measured with portable flow meters and pressure loggers. Most of the flow and pressure transmitters were found to be accurate enough to model the system from the data found on the SCADA and SCADA historian.

It was found that the surface flow meter reading was inaccurate, and, after further investigation, it was found that the meter has not been calibrated in the last decade. A portable flowmeter was installed for a period of two months to get accurate daily profiles. After the simulation was complete and ready to be calibrated, the portable flow meter was installed once again.

It was decided to integrate refrigeration, dewatering, ventilation and compressed air in the simulation. Other systems like ventilation of the mine were found to be inefficient as well, and it was decided to integrate the mentioned systems to allow for the scoping of projects for the other systems as well. The integrated simulation was built and calibrated and found to be 98% accurate. The integrated simulation is shown in Figure 18. Due to the scale of the operations, Figure 18 only serves to showcase the complexity of the model and is not intended to provide detail.

Figure 18 illustrates that the integrated simulation was built in a three-dimensional (3D) environment. This was made possible by the coordinate system the DXF files are based on. The original equipment manufacturers were contacted to obtain information that was not available from mining personnel.

This calibrated integrated simulation was used in all the case studies of this section. It is now possible to test different scenarios, determine the impact of projects and to make an informed decision on which project would be most beneficial.

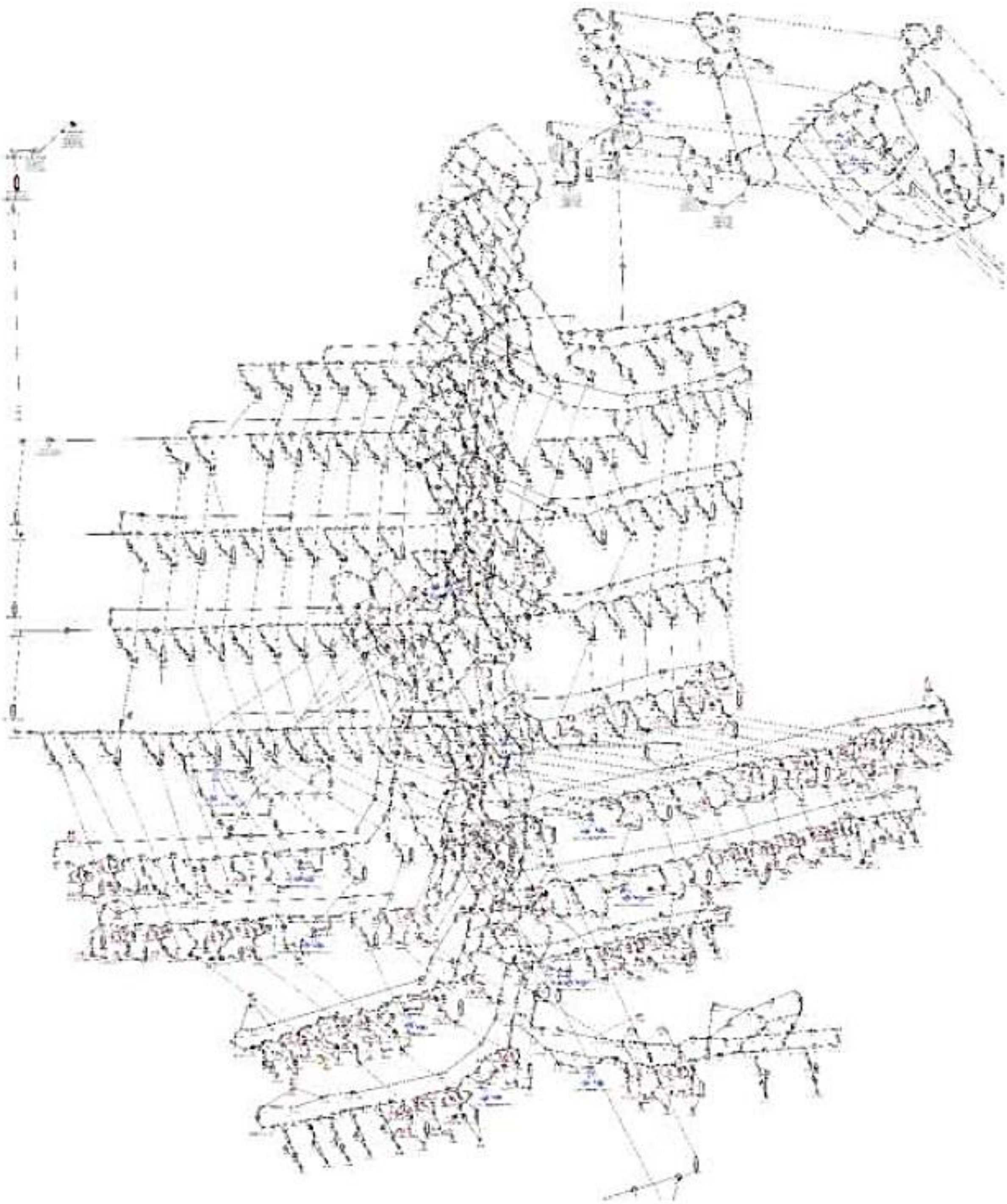

Figure 18: Integrated simulation showcasing the complexity of modelling

The model was applied to supply- and demand side compressed air projects on an ultra-deep-level gold mine. The mentioned projects were designed, implemented and managed successfully with the new model and a sustainable financial impact of more than R 11.7 million p.a. was achieved while also improving service delivery.

3.3 CASE STUDY 1

A main factor leading to over expenditure of the energy usage of the compressors was found to be wastage. It was found that refuge chambers were a large contributor to the wastage. Due to the size of the operations and mining regulations, there are 160 refuge chambers on the shaft, as there needs to be a refuge chamber within 750 m of any working area [32].

Model project feasibility phase

Of the 160 underground refuge chambers, 90% of the refuge chamber valves were either completely open or stuck on 50%. The mine used 50 mm butterfly valves as shown in Figure 19. Due to the characteristics of butterfly valves, the flow through the valve is greater than 90% when the valve is half-way open, leading to major losses [62]. Butterfly valves are also prone to internal and external leakages [185].

As shown in Figure 19, the butterfly valves in use are corroded on the outside and not in a good general condition. The top left valve is used to supply compressed air to the refuge chamber while the bottom valve supplies air to the emergency whistle. The refuge chamber supply valve in this instance was found to be broken in an open position.

Figure 19: Example of a refuge chamber valve[27]

[27] FG. Jansen van Rensburg, personal photograph. Carletonville, 2019.

This resulted in major inefficiencies and placed unnecessary strain on the compressed air network. In this configuration, the compressor systems operating costs were constantly over budget, and supply pressures on the corresponding levels were insufficient. A large savings and service delivery improvement potential was identified on the shaft. The feasibility phase steps are discussed in Chapter 2. By following the project sustainability model, it became evident that a full redesign of the valve was necessary.

The model was applied to solve the problem at hand. As seen in the model (Appendix C) and in the summary above, the first step was to gather all the relevant information. In the sections above it is evident that the process was completed thoroughly. The clear realistic object of this project is to reduce the compressed air wastage on the shaft. During the audits it was found that the refuge chambers of the shaft are not up to standard.

After comprehensive research into alternative refuge chambers and refuge chamber pressurisation techniques, it was decided to design and install a valve with a hole in the ball to ensure continuous air flow into the refuge chamber. Three options were considered. The first was a drilled ball valve, the second a three-way valve with a dead-man handle (a spring-loaded handle that returns to the closed position when not locked in place or held open) and the last was a sophisticated automated control system with gas monitors and pressure sensors.

The three-way valve and drilled ball valve would have similar effects on the system, but the drilled option was cheaper to source. The automated control system would have been the best option but it was too expensive. But these units are 100 times more expensive than the ball valves. Since the shaft has 160 of these chambers, the automated control units would not be feasible. As stated by the model, a simple solution would trump a sophisticated solution in the mining environment.

By following the model, choosing the drilled ball valves would be a cost-effective solution for the problem. The project was proposed to senior personnel, mentioning the added benefit of improving the refuge chamber conditions. Due to the win-win nature of the project, full backing was obtained from engineering, mining and the occupational hygienist.

The valve design calculations were done to establish the diameter of the hole to be drilled in the valve. A ball valve containing an opening through the ball is commonly called a crack valve in mining. Figure 20 shows the flow through the hole drilled in the ball valve. A 3 mm hole will give enough flow to pressurise the refuge chamber, but for this project a 4 mm hole was chosen to ensure adequate flow and ease of manufacture, reducing costs.

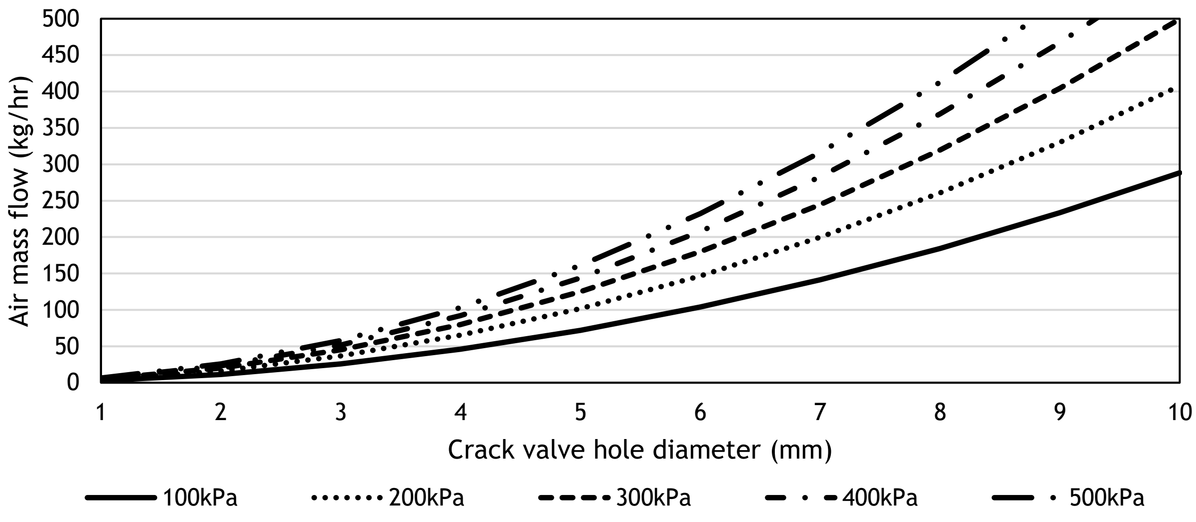

Figure 20: Compressed air mass flow rates through valve

An off-the-shelf 50 mm ball valve was chosen to be modified. Figure 21 shows the design drawing of the valve. This drawing was sent to various manufacturers for costing. It was found that the hole would have to be drilled before assembly to make sure the integrity of the seals is not compromised. Due to this, the delivery period from suppliers would be extended, but it was found to still be shorter than the other alternatives.

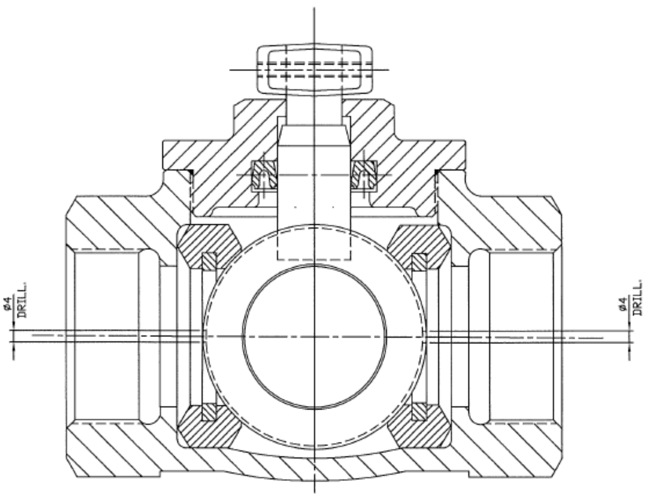

Figure 21: Refuge chamber drilled valve design

A simulation was done to test what effect the closing off all the refuge bays has on the system's energy- and air usage. Based on test results, refuge bay leaks were added to the mine's compressed air simulation model. The difference between the baseline and the optimised simulations were compared to determine the system impact and the total savings obtainable.

Table 5: Simulated results of replacing all the refuge chamber valves

Simulation scenario	*Simulated power saving*	*Compressed air reduction*	*Drilling shift pressure increase*	*Cost saving p.a.*
Closing refuge bays on all levels to a safe limit	840 kW	6 158 m³/h	15 kPa	R 5.1 million

As stated by the model (correct materials), a full stainless-steel construction valve was recommended with either a flange or threaded connector to ease installation. The ball valve design drawing was sent to various manufacturers and the best candidate was chosen based on cost and delivery time. Due to the simple nature of the solution, a regular 50 mm stainless steel ball valve could be modified and supplied. Figure 22 is a summary of how the model was applied during the project feasibility phase.

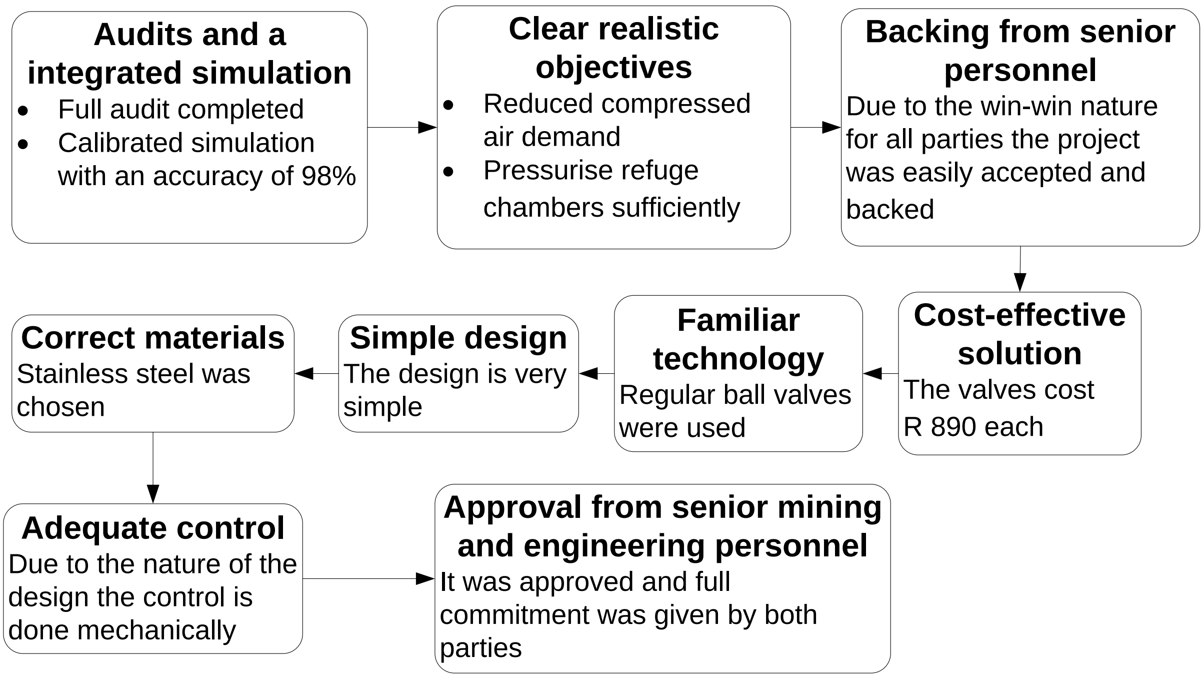

Figure 22: Summary of Case study 1 project feasibility phase

Project start and planning phase

Due to the simple nature of the project, installation could proceed without isolating any lines or hindering work elsewhere. Also, the change of a 50 mm ball valve does not require specialised artisans. The work was done and completed by fitter assistants. After each installation was completed on a refuge chamber, the valve was audited by the section shift boss as part of their daily audit, as required by law [63].

The compressors were unable to reach their set-points during drilling shifts. The simulation indicated that, by reducing the airflow to all refuge bays, the service delivery can be increased. The refuge chamber project was fully implemented at nearly the same time as a bypass valve configuration project. The proposed solution was economical and beneficial for both mining- and engineering personnel, which ensured full support from both departments. The summary of how the model was used in these phases is shown in Figure 23.

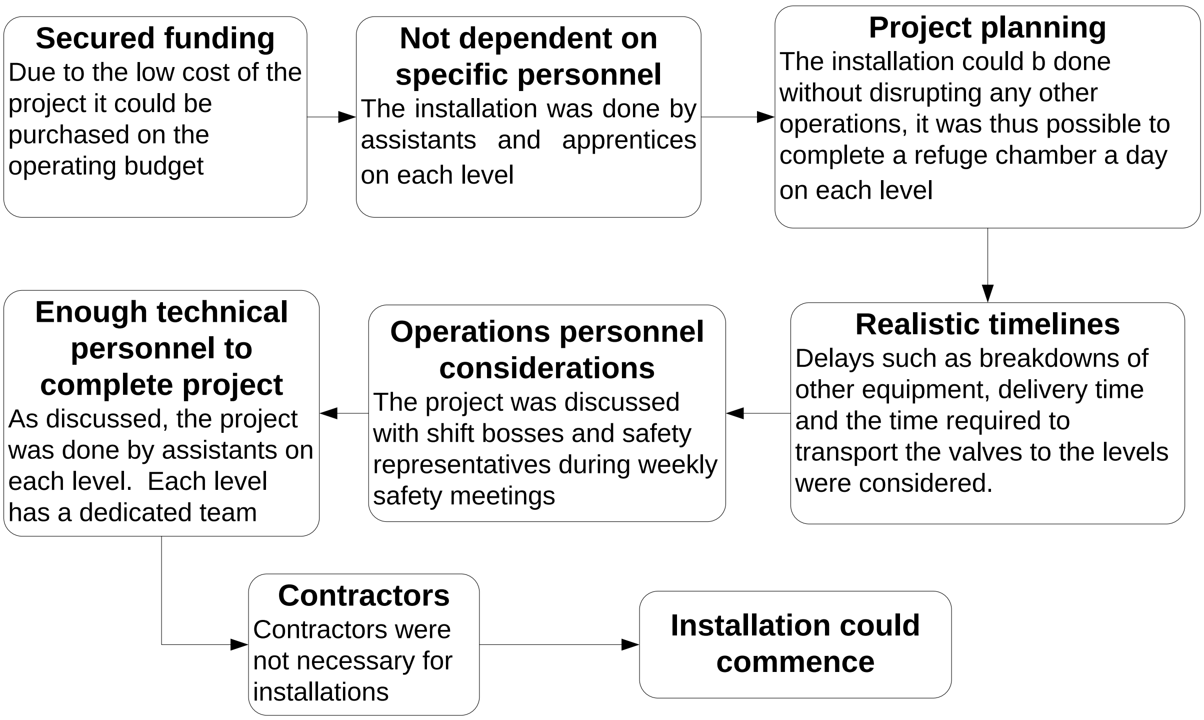

Figure 23: Summary of Case study 1 project start and planning phase

Project execution phase

When an entire level was completed it was audited by a specialised team. Pressure readings and photos were taken of each of the refuge chambers and handed to management at the mine. This meant that every refuge chamber was audited three times to confirm installation: once by the fitter assistant, once by the specialised team, and daily by the section shift boss.

The continuous nature of the audits, along with the simple design, will ensure long-term functionality and sustainable cost saving. Due to the low price of these valves, it was also possible to acquire spares and store them on the levels. This ensures that, when a valve fails, it can be replaced within the time frame of a single shift. The summary of how the model was used in these phases is shown in Figure 24.

The daily audits are captured in a report that is sent out to various senior managers. An extract from the report can be seen in Appendix D. Due to confidentiality, the detail of the shafts and names have been hidden. The report was already used on site and, by changing the valve criteria, the newly installed valves are now also checked daily. Daily reports of the consumption and pressures are also sent out to key personnel. This will be discussed in greater detail in the second case study.

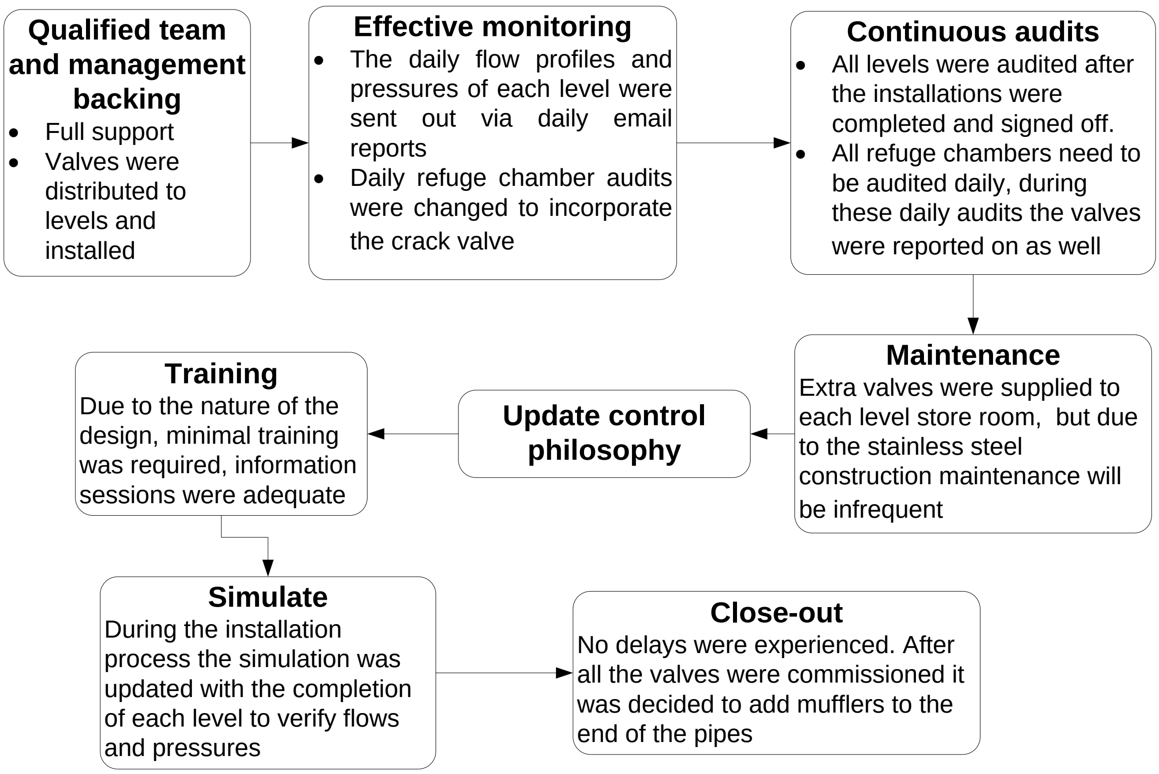

Figure 24: Summary of Case study 1 project execution phase

Project close-out phase

From inception until full installation, the project took 6 months, with the budget approval accounting for most of the allotted time. Most of the installation was completed within a month. The full cost benefit is discussed later. The model was followed clearly throughout the investigation, simulation and project management phases of this project. A photo of the installed valves can be seen in Figure 25.

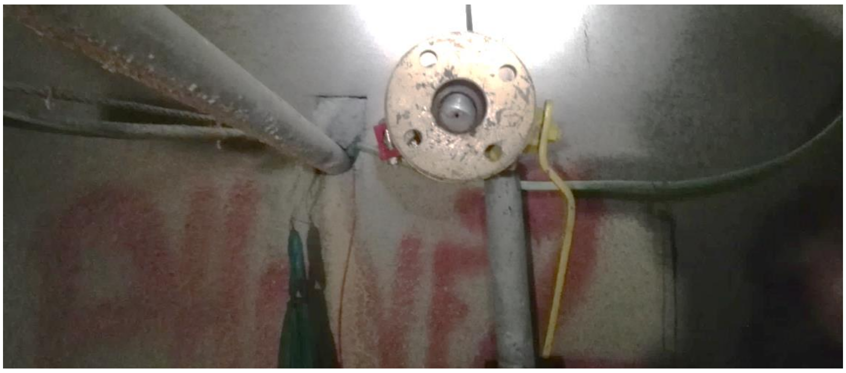

Figure 25: Installed new refuge chamber valve[28]

3.4 CASE STUDY 2

The mine has three shifts, namely drilling, and blasting on dayshift, and cleaning on nightshift. A compressed air pressure of at least 450 kPa is required during the drilling shift to operate the pneumatic rock drills. Since drilling and the bulk of operations only takes place during the drilling shift (06h00 to 14h00), it is possible to reduce the pressures on the levels during the other shifts, because of a lower air pressure required, accept when pneumatic loaders are used on nightshift for the cleaning of development ends.. During the cleaning shift (22h00 to 06h00), at least 250 kPa is required to operate the pneumatic loaders and pneumatic cylinders to open and close the loading boxes. During the blasting shift (14h00 to 22h00), the drilled blast-holes are primed and charged with explosives and ignite, after the shaft is cleared, usually around 18h00, no one is permitted underground during that period between blasting and clearing the period (18h00).

It is thus possible to control the underground pressures to deliver the required pressures as stated and shown in Figure 26. This is done by installing control valves on surface and underground to control the downstream pressures. The compressors are equipped with guide vane control to cut back when less pressure is required. This cut-back on the guide vanes leads to energy savings.

[28] FG. Jansen van Rensburg, personal photograph. Carletonville, 2019

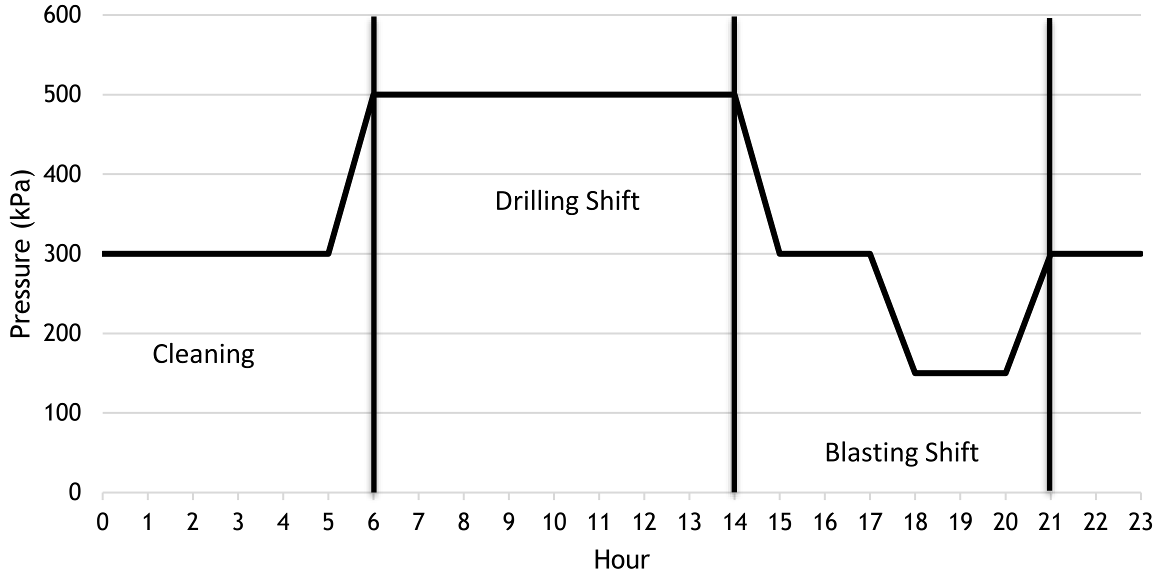

Figure 26: Shaft pressure requirements

A similar project was done previously on the mine, but the project soon deteriorated. The model developed was used to blow new life into the project and restore the initial project goal. Automated valves are installed on the main compressed air pipelines of all the production levels (levels 98 – 113) at the mine. The valves are installed in a bypass configuration with a smaller bypass pipeline over an automated shut-off valve in the main line.

The bypass configuration is commonly used to reduce the cost of the installation as the price of control valves increase exponentially as the size increases. It also has an added advantage that the pressure can be lowered even when the bypass valve is not controlling and left in an open position.

Model project feasibility phase

The initial project entailed controlling the valves during the Eskom evening peak periods (18:00-20:00), when electricity is more expensive, to reduce the pressure downstream of the valves to a certain pressure set-point. This was achieved by closing the mainline valve and controlling the downstream pressure with the bypass control valve. The configuration of the bypass valve setup and the mentioned control philosophy is illustrated in Figure 8.

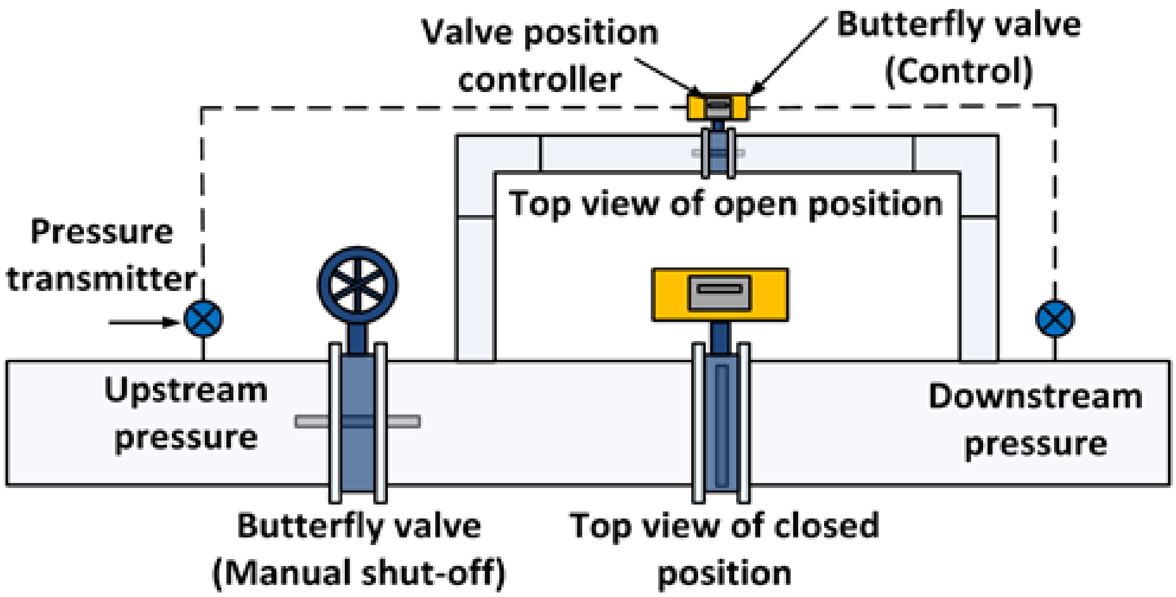

Figure 27: Illustration of bypass valve setup

The valves were installed as part of an old DSM project. Since the implementation of the project, the valve control has been disabled. This was mainly due to the large pressure drop caused by the 50 mm bypass pipelines when the mainline shut-off valves are closed, as well as the unreliability of the actuators. If the valves are unable to open an entire drilling shift may be lost and the mining personnel opted to rather leave the valves open.

Investigations into the previous configuration of the compressed air control valves on the production levels of the mine were done. The pressure control with the valve configurations is limited due to inadequately sized bypass pipelines. This results in a large pressure drop when the control is enabled on the valves. A photo of the initial valves that were used to control the pressures is shown in Figure 28.

As shown in Figure 28, the initial control valves used a 50 mm bypass pipeline with four bends in total, two butterfly valves and the control valve. The pressure drop over this installation was tremendous. When the mainline valve was closed, the downstream pressure dropped below 170 kPa. This pressure was not enough to pressurise the refuge chambers.

Figure 28: Initial control valves[29]

The control is only enabled between 18:00 and 20:00 as this period aligns with the blasting shift. During the other periods of the day, the valves cannot be controlled due to the higher pressure demand on the production levels.

The aim of the project was to develop and simulate a new bypass configuration that will enable valve control over a 24-hour profile, while accommodating the required demand flow. The new configuration must satisfy the compressed air demand on the production levels, while increasing the upstream system pressures, which in turn will lead to energy savings on the compressors. Most of the valves and infrastructure also require minor refurbishment to enable the recommissioning of the control over the valves.

Prior to the recommissioning of the control of the valves, it is recommended that larger bypass pipes and valves be installed. This will allow sustainable valve control over a 24-hour profile, increasing the energy savings potential on the mine's compressors. A simulation model was constructed to predict the pressure loss over various butterfly valve sizes based on their respective flow coefficients (C_v). The C_v values are based on manufacturer specifications of a certain butterfly valve.

[29] FG. Jansen van Rensburg, personal photograph. Carletonville, 2019

The pressure and flow demand of 105 level were used to develop a baseline simulation. This level was used because it has the highest pressure and flow demand of all the production levels at the mine. The assumption was therefore made that the simulated pipe and valve sizes for this level would be sufficient for all other levels and would ensure adequate control for future expansion. A standard size of valve control configuration will be beneficial to the mine.

The simulation model used was shown previously in Figure 18. It should be noted that six different sets of inputs were used to obtain the correct bypass configuration. The simulation was also used to quantify the electricity cost savings when such a bypass valve configuration is installed.

The assumption was made that the mainline pipe dimensions and valve flow coefficient (C_v) remain constant for all six models. The bypass pipe and valve sizes were, however changed from 50 mm up to 350 mm in 50 mm increments. Note that there are three butterfly valves on the bypass sections: one manual valve at each end of the bypass pipeline and a control valve in the centre for maintenance purposes.

Figure 29 illustrates the proposed pressure set-point for the control of the compressed air pressure on the various levels. The proposed set-points are based on the existing compressed air requirements and mine schedules. It was found that the pressure can also be reduced during shift changes, leading to additional cost savings.

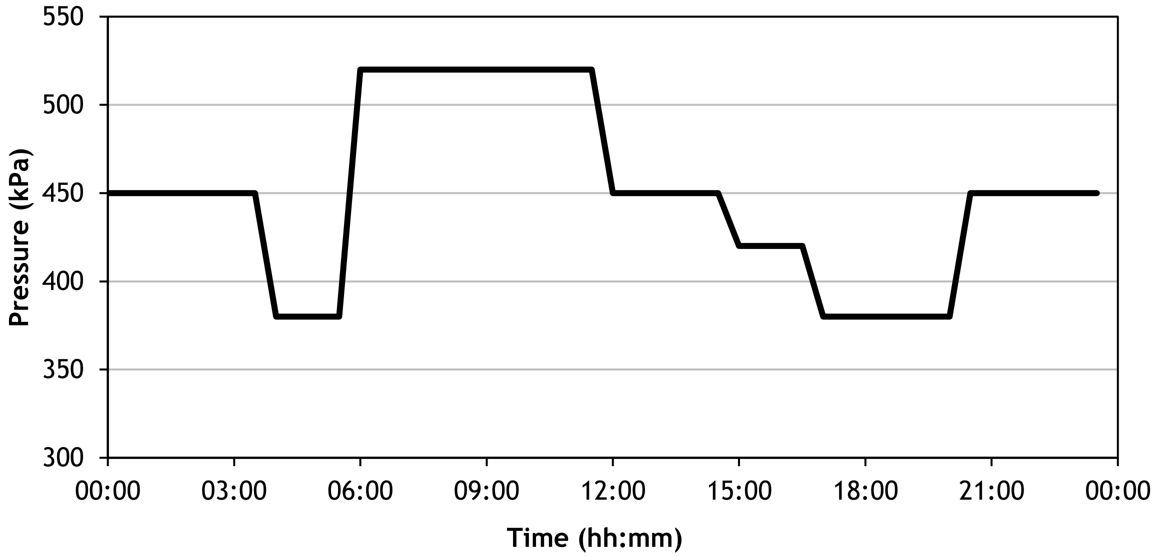

Figure 29: Proposed pressure control set-point for various levels

The proposed pressure set-points and the required compressed air demand profile were used to simulate the impact of the different valve sizes on the pressures downstream of the valves on the production levels. Table 6 gives the simulated station pressure and airflow after the bypass valve configuration for different bypass pipe and valve sizes. With the available supply pressure and required demand pressure, the available pressure and flow through the bypass valves are reported in Table 6.

Table 6: Available pressure and flow after the bypass valve configurations

BYPASS SIZE	*AVERAGE AVAILABLE PRESSURE (KPA)*	*AVERAGE AVAILABLE AIR FLOW (KG/S)*	*VALVE FLOW COEFFICIENTS (CV)*
50 MM (PRESENT CONFIGURATION)	238.4	5.7	105
125 MM	442.6	9.5	930
200 MM	456.3	10.6	2, 854
350 MM	459.1	10.6	11, 917

From Table 6, it is evident that only 5.7 kg/s of compressed air at a pressure of 238 kPa is available if the present configuration is implemented throughout a normal mining weekday. This shows that the installed 50 mm bypass valve configuration restricts the flow and results in a large pressure drop when the control is enabled.

Figure 30 illustrates the average daily downstream pressure profiles for the bypass valve sizes that were simulated. The valves were controlled according to the pressure set-points depicted in Figure 30.

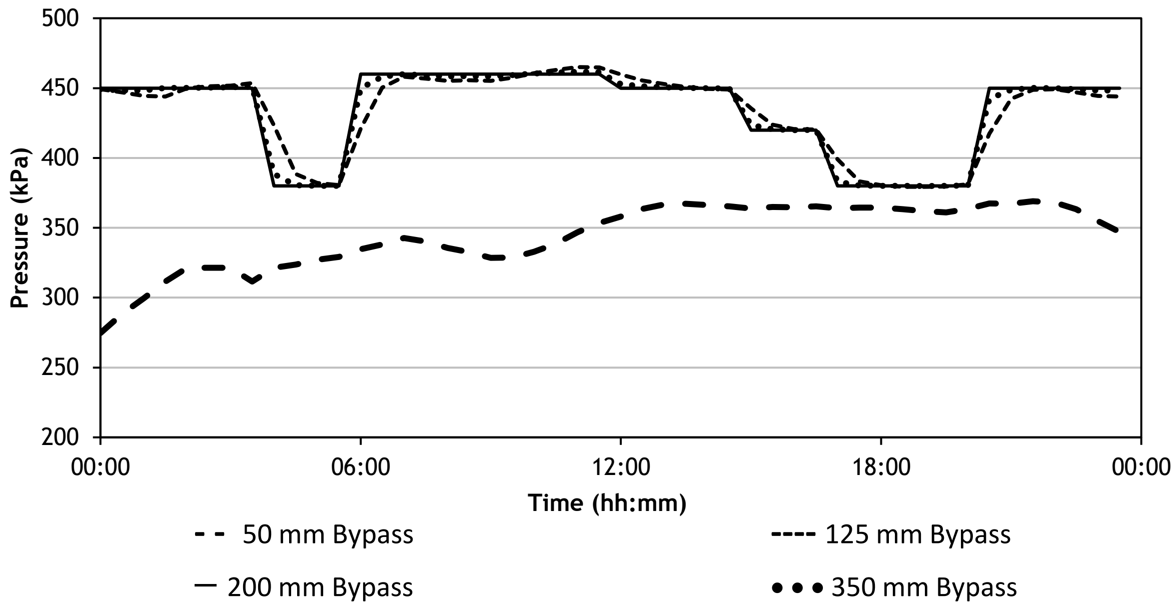

Figure 30: Controlled pressure for various bypass valve configurations

From Figure 30 it is evident that the 50 mm bypass valve configurations are not sufficient to maintain the pressure set-point with the present compressed air demand on 105 level. However, the 125 mm, 200 mm and 350 mm valve configurations are sufficient. It is important to consider that the 125 mm configurations do not have much more capacity for effective control when the compressed air demand at the mine increases.

Bearing this in mind, it is advised to install a 200 mm bypass pipe valve configuration. The project was proposed and approved as the 200 mm pipeline will also ensure that the project remains feasible even with an increase in production and/or compressed air usage. The summary of how the model was followed in the feasibility phase of the project is shown in Figure 31.

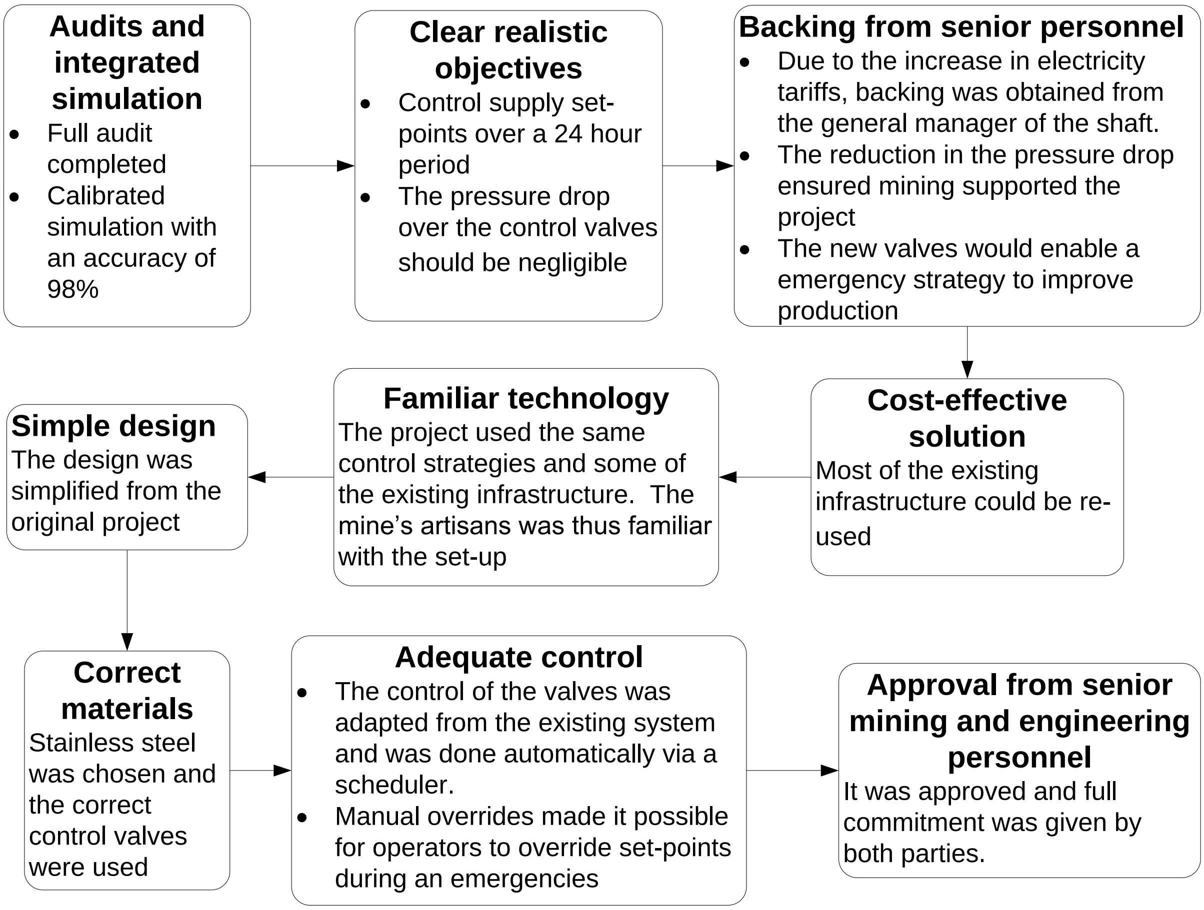

Figure 31: Summary of Case study 2 project feasibility phase

To get backing from mining personnel, the pressure set-point and schedules were discussed and signed off. The valves also added an extra benefit for emergencies. If one or two compressors trip, fewer essential production levels could be closed to 150 kPa to increase pressures in high grade mining areas to continue production. This will lessen the problem until the compressors can be brought back online. This was a crucial selling point for the mining personnel, as a full production shift would not be lost during such an event.

Project start and planning phase

With the clear financial benefit, funding was secured from the mine's projects budget. The mainline valve, which is the most expensive piece of equipment, could be refurbished and used for this project. All the control equipment and instrumentation were used as is. Considering this, the cost of the project was relatively low with great benefits.

A payback period of 2 months was calculated from the integrated simulation. A summary of how the model was applied is shown in Figure 32.

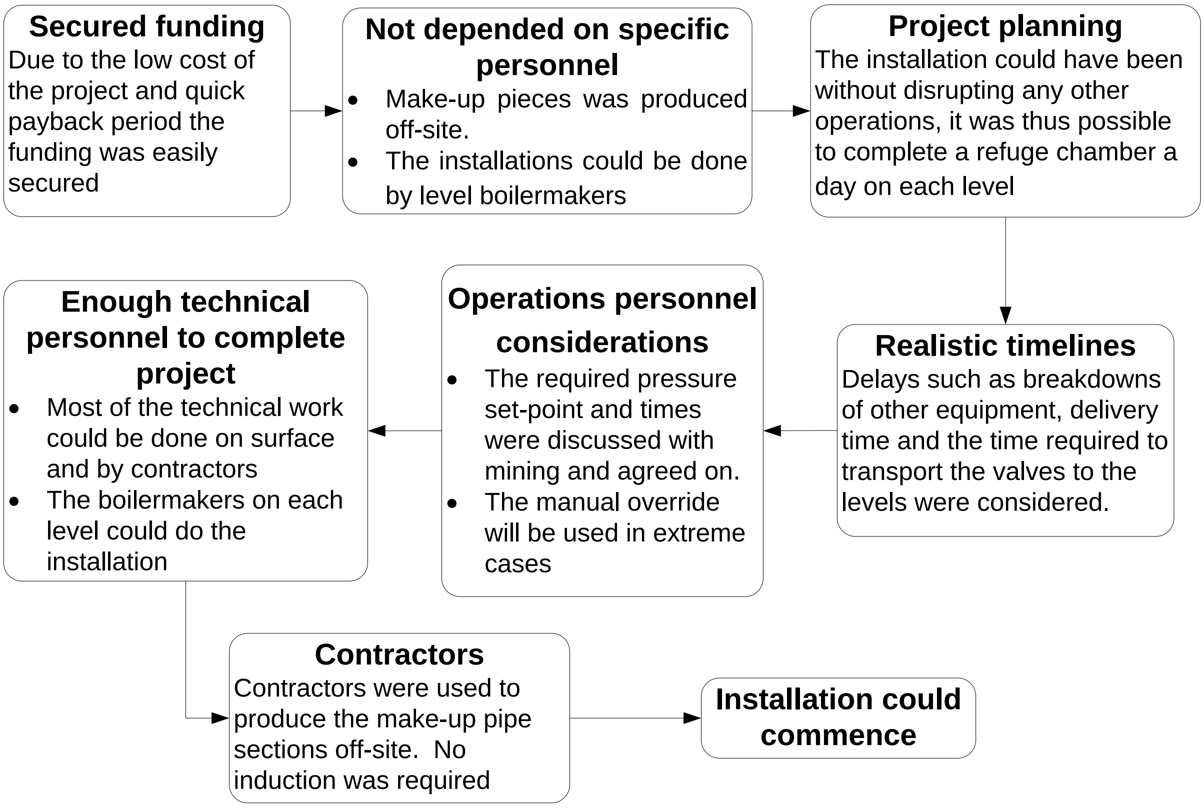

Figure 32: Summary of Case study 2 project start and planning phase

Installation of the valves was scheduled during a weekend when no mining occurred. With support from both engineering- and mining personnel, the installations happened swiftly. As most of the control of these valves would be outside of mining periods, the impact on mining personnel would be minimal.

Installations were done one level per off-weekend and enough technical personnel and artisans were available to complete the project. To mitigate possible construction and installation challenges, the bypass configurations were made up off-site by an external contractor and married with valve setups before going underground for installation. This ensured that the bypass set-up was on site and working before the delivery date.

Project execution phase

With the assistance of the simulation, it was decided to start the installation on levels with a higher consumption to maximise the financial gain. As the first installations were completed, the control philosophy was tested and implemented. This meant that, by the time the second bypass set-up was installed, the control philosophy was already tested and implemented, resulting in a “copy and paste” process for the rest of the valves. A summary of how the model was followed is shown in Figure 33.

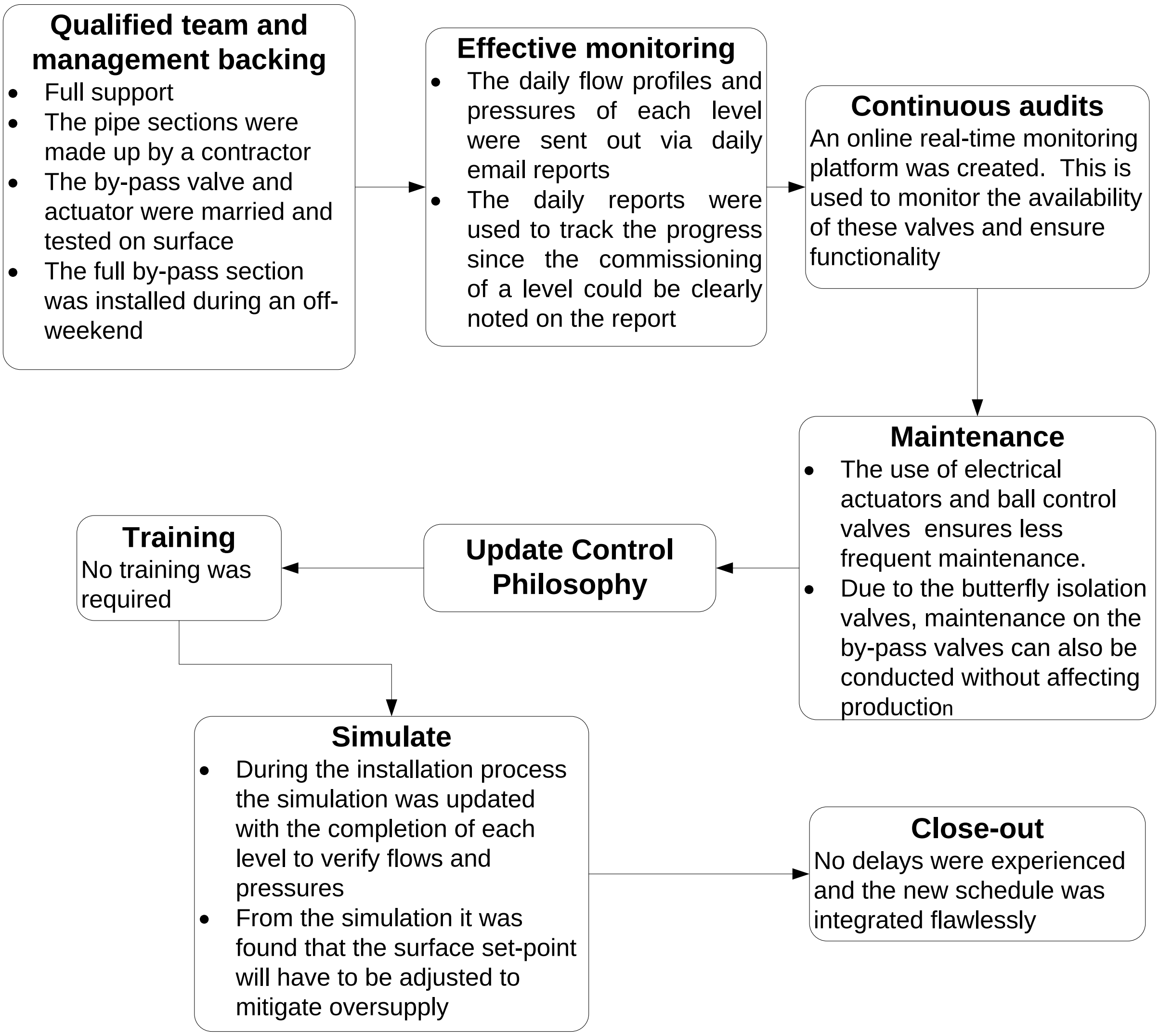

Figure 33: Summary of Case study 2 project execution phase

During installation, a daily report was created and sent out to key personnel. This report was also used to track the installation. Figure 34 is an example of how it can be seen that one control valve combination has started working and the other not. The schedule was updated daily until the savings could be maximised without affecting mining.

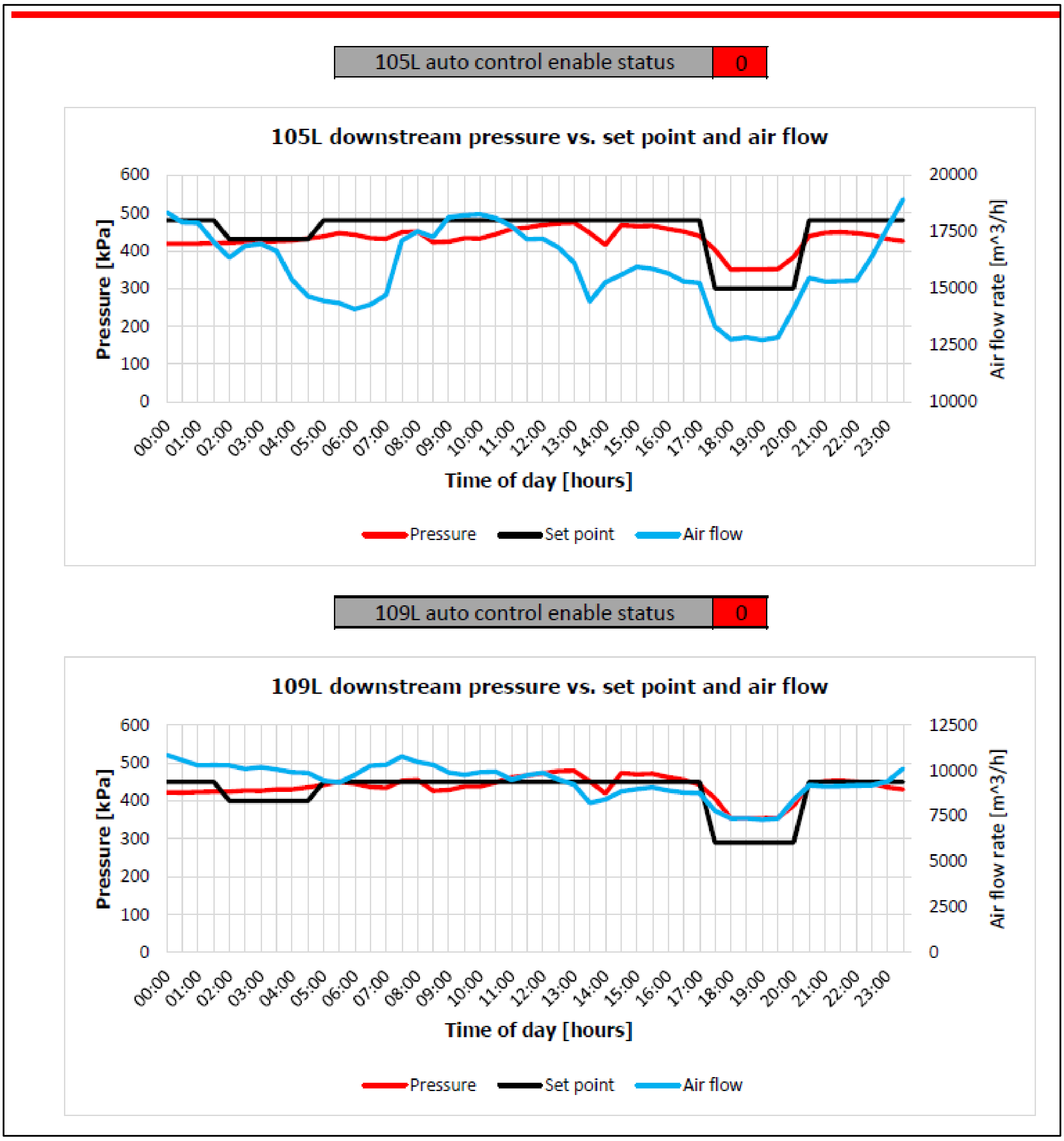

Figure 34: Extract from daily report illustrating the difference between a working control valve combination and a non-working combination

To increase awareness of the project and to make it easier to ensure all the valves are working constantly, a web-based platform was created to monitor the system in "real-time" (30-minute delay). This was used as a tool to audit the system continually to ensure sustainability of the project and quick reaction time to possible failures. A screenshot of the platform can be seen in Figure 35.

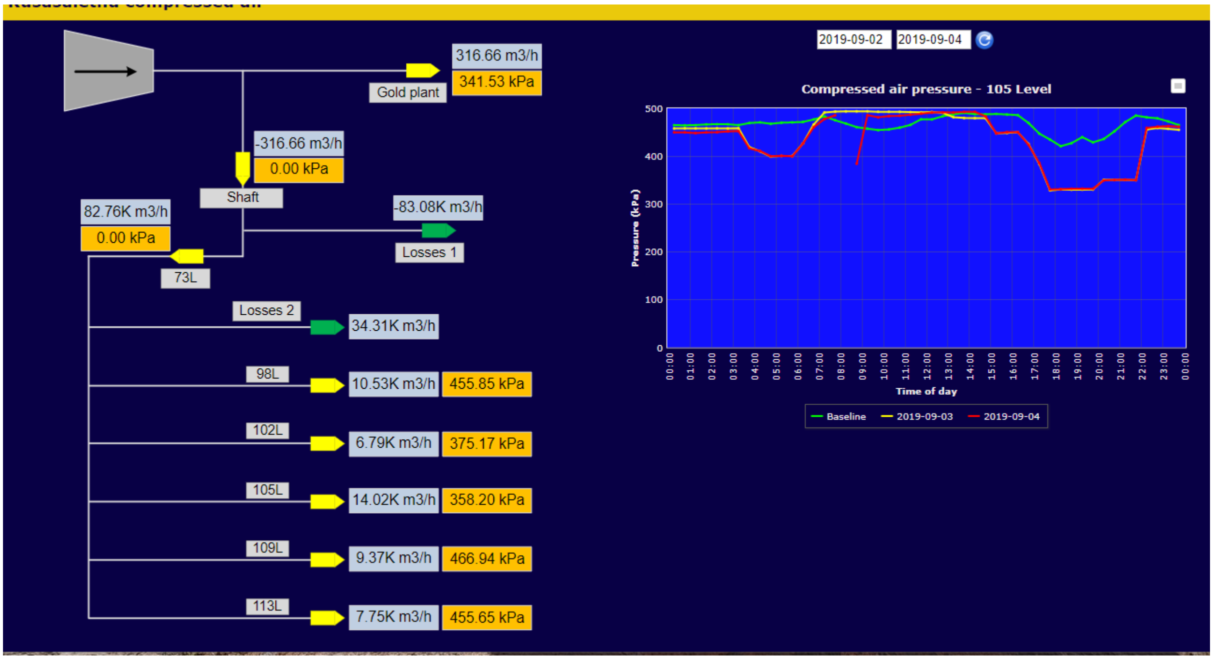

Figure 35: Screenshot of web-based monitoring tool

The platform updates every 30 minutes and the last two days of the selected level's pressure profiles can be seen on the graph. As shown, the platform also indicates the current flow and pressures of each level, the surface and the 73L. With this platform, the consumption of the system can be monitored. This information can be used to detect sudden changes in the system.

During the project planning phase, it was decided to only do installation during off-weekends. This ensured that the installations were completed on schedule. As the installations were very similar to the old set-up, no training was required. While the simulation was used during the installation phase, it was found that the surface set-point of the compressors can be adjusted to maximise savings, as stated, but the control philosophy needs to be updated with the implementation of a new project. This will be discussed in the results.

Project close-out phase

From inception until full installation the project took 6 months, with the budget approval accounting for most of the time. The full cost benefit is discussed later. The model was followed clearly throughout the investigation, simulation and project management phases of this project. A photo of the installed valves can be seen in Figure 36.

Figure 36: New control valve set-up

3.5 RESULTS

The results of the projects will be discussed together since the projects were implemented during the same financial year and overlapped during installation and control optimisation. The project sustainability model put forth in Chapter 2 was followed throughout the duration of the projects. The projects also increased air pressures on production levels, which theoretically would increase production. After the projects were implemented, an increase in production was seen, but this could be attributed to other factors as well, although the compressed air pressure increases likely had an influence.

During the installation of the refuge chamber valves, it was noticed that, due to the decreased consumption, the surface compressed air set-point can be lowered to prevent over-supply. It was also found that, when the new control valves were installed, it was possible to further reduce the surface set-point during off-peak mining hours due to the higher pressure in the system.

As stated, the shaft is deep, and auto-compression can increase the pressure on 105L by 158 kPa. It is thus possible to lower the surface set-point to 400 kPa during the blasting shift, increasing cost savings and reducing the strain on the compressors. This proves that the control philosophy of a system should be re-evaluated and adjusted after a project has been implemented.

The implementation period of the projects overlapped. The installation of the refuge chamber crack valves (Case study 1) started in February 2018 and continued until May 2018, while the new bypass valve configuration (Case study 2) started in May 2018 and was completed in July 2018. Case study 2 was implemented in stages and the first levels were online and working during June 2018. Due to the parallel implementation period, separating the results would be challenging.

The energy consumption of the compressor house is used to measure the success of the project. This is done since the compressed air flow meters on the shaft were found to be very unreliable. The compressor house energy measurements are reconciled monthly with the Eskom invoice, making the values traceable.

Figure 37 shows the total monthly energy consumption of 2017, 2018 and 2019. The previous years' actual data is also used for the budget for the next year. As shown, the usage differs from month to month due to maintenance and production cycles. These cycles are consistent every year (for example Easter break, yearly winter maintenance and Christmas break), which is why the previous year's usage is used for budgeting. It is evident from the graph that energy consumption reduced greatly after both projects and even during the project implementation.

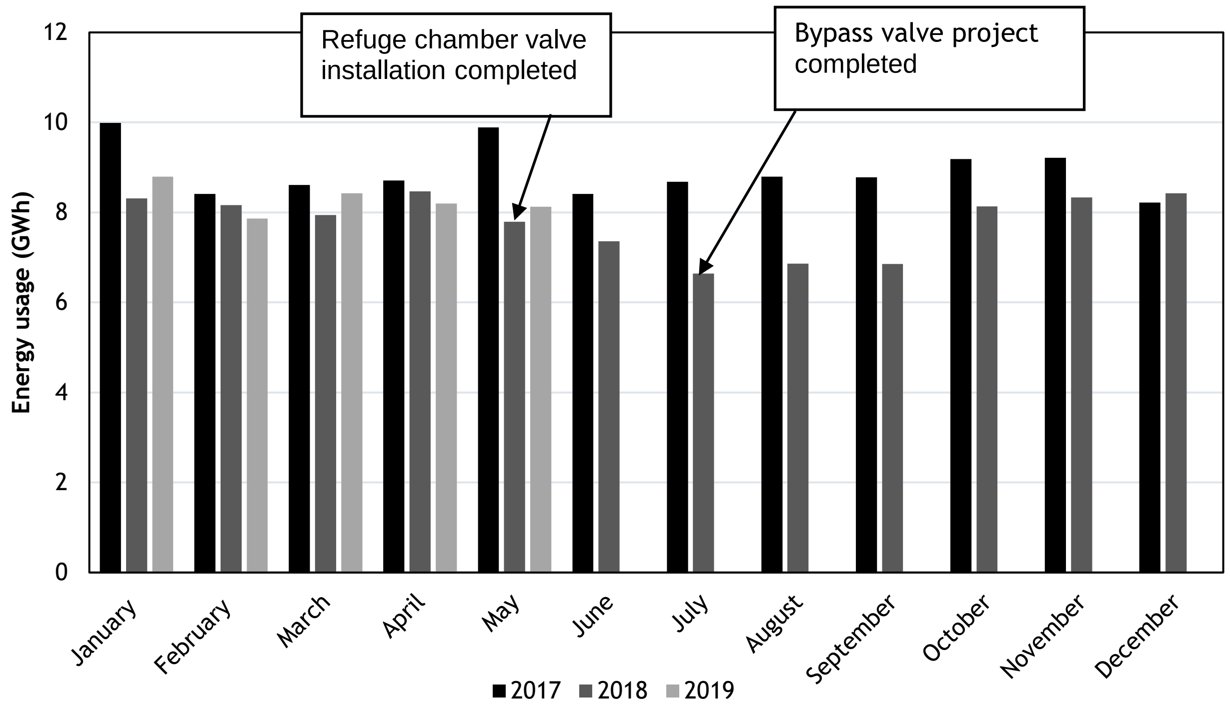

Figure 37: Case study 1 and 2 results depicting reduction in energy usage

In May 2018, a large decrease in the energy consuption can already be noticed, but it is important to note that a strike occurred. Thus, the real savings of the project could be calculated from June 2018, when conditions were back to business as usual. However, it is evident that both the projects led to substantial savings.

It is notable that the power consumption increased from October 2018. This is due to 10 additional mining crews that were appointed on the mine. The new crews had not been budgeted for and were as a result of the increase in the gold price and lower Rand-Dollar exhange rate. Follow-up audits of the refuge chamber valves were completed and handed to management during January 2019. It was found that some of the crack valves were being used in the same way as the old normal 50 mm butterfly valves. The valves were closed and their use discussed in safety meetings. From February 2019 it can be seen that the usage stabilised to relatable values.

This decline in energy usage can be directly attributed to the projects implemented during this period. If taken from the final installation date, the payback period of the combined project was 2 weeks, fulfilling the criteria the model stated. From inception to completion of both projects, the electrical cost savings that have been realised amount to R 11.7 million (May 2018 – May 2019). Continuous savings are being realised, proving the sustainability of the model.

3.6 VALIDATION OF MODEL

Due to the success of the refuge chamber valve project on Mineshaft A, the project will be rolled out to various other shafts and mining companies. The same project management model will be followed to ensure success. This project proves that simple solutions are better in the mining environment. These case studies prove the validity of the model as both projects were implemented on time, successfully and are producing long term savings.

Each of the suitability project management model steps were followed meticulously and it led to a positive impact on the mine. The project also had various other positive effects on the shaft that are not quantified by this study. This model was also rolled out to the closed-loop project discussed in Chapter 2. The project is still in installation phase but is showing great potential. Some results can be seen in the screenshot of the daily report in Figure 38. As shown, 113L has started to return water to the 100L dams during blasting. This was the original design of the project as discussed in Chapter 2.

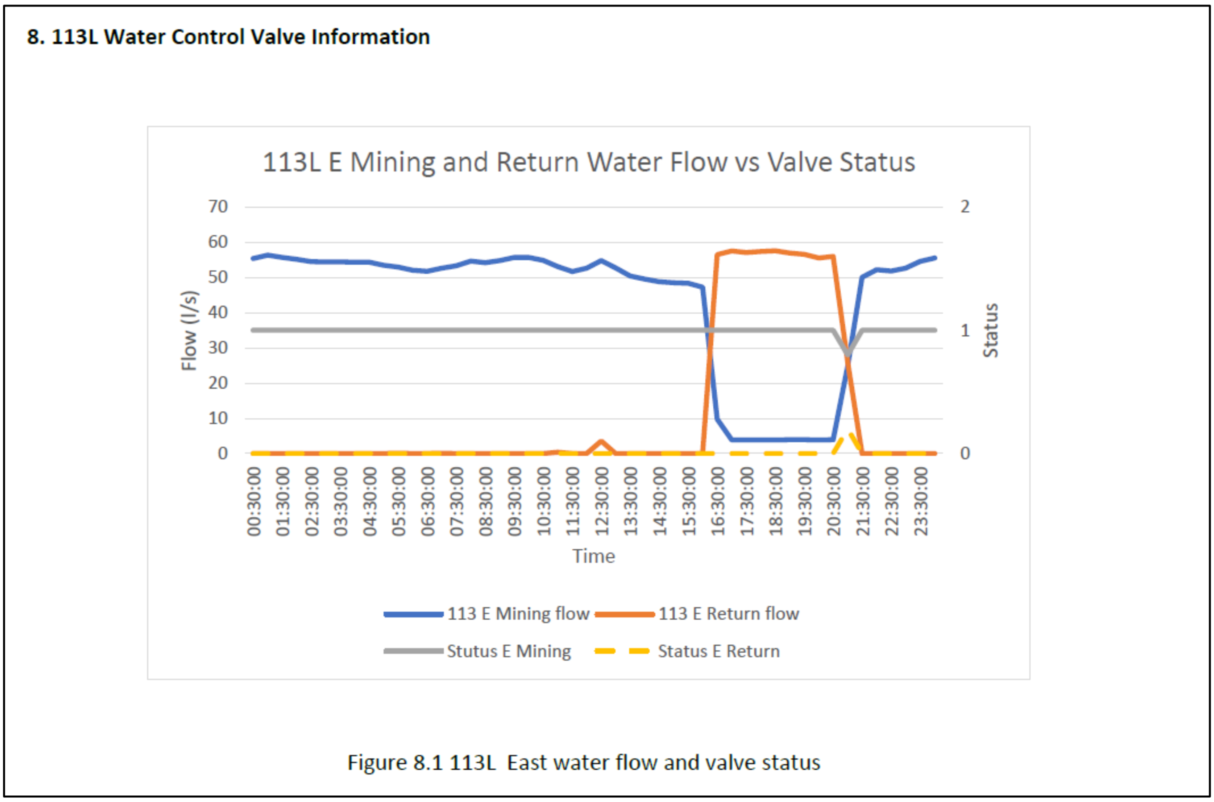

Figure 38: Extract of closed-loop daily report

This project will, however, not be discussed as a case study since no long-term data are available to prove the sustainability of the model. However, it shows that the model can easily be applied to other systems than that of compressed air. This sustainability project management model developed for deep-level gold mining in the South African environment has the potential to yield similar results in other mining industries in South Africa and developing countries.

In Chapter 1, eight research objectives were stated. They are reiterated and discussed here:

1. **The development of a project management model from literature and past failures and successes that can be applied to deep-level gold mining in South Africa.**

The project management model was developed from literature and past experience and each of the factors' application to mining was discussed. By learning from past mistakes in mining and indicating the need for substantiality, factors such as the correct equipment, materials and digital reporting of the system from the start of the project were added to the model to improve sustainability.

2. **The development of a project management model that focusses on long-term sustainability of projects.**

The project feasibility phase placed an emphasis on making the correct decisions to ensure long term sustainability. Failed projects were studied and the factors leading the unsustainable projects were addressed. It is evident from the case studies that the model solves these challenges

3. **The development of a project management model that uses Industry 4.0 solutions (integrated simulations and digital reporting).**

Question 3 incorporates the use of digital solutions. As discussed in Chapter 2 and shown in Chapter 3, the model proved that digital solutions have a positive short- and long-term effect on the projects implemented. Integrated simulations ensure projects are possible before any money is spent.

4. **The project management model model will integrate systems of engineering as far as necessary to be used in the project management model.**

As discussed, integration of systems is crucial in mining. There are no truly independent systems and for the case studies the systems were integrated. This integration indicated that schedule adjustments were necessary on the surface compressors as well. When used in dewatering, the effects on refrigeration will be notable as well.

5. **By using the integrated simulation and reporting it would be possible to make better decisions and accurately scope new projects to either compliment the current project or achieve better outcomes for operations.**

Literature has shown the effectiveness of simulating systems before implementing projects. As shown in both case studies, the integrated simulation was used as a tool to determine possible cost savings and to optimise the implementation plan. From literature it was proven that reports create awareness and increase the efficiency of projects. This was again proven in both case studies.

6. **It will be of the upmost importance to use the model stated to adapt the current control philosophy for optimal operation of the greater system.**

As indicated in the model and proven in the case studies, it is necessary to change the control philosophy of a system once a new project has been implemented, even if it is not directly. The case studies proved that changes in the control underground influenced surface operations and the control philosophy had to be updated to maximise savings.

7. **As stated, the probability of failure is highly dependent on the experience of the project manager. This model will aim to capture the experience element and enable relatively inexperienced project managers to achieve favourable outcomes.**

The importance of an experienced project manager has been discussed in Chapter 1. This model can be used as supplementary knowledge to enable an inexperienced project manager to still successfully implement a project in the deep-level gold mining industry. This model captures the essential knowledge of projects in mining. This is necessary due to the high turnover of technical personnel in mining. As mining and the country as a whole loses experienced personnel, it is crucial to document and retain the knowledge.

8. **Using the integrated simulation model to predict the effect of minor changes to the system.**

The simulation was used in various stages of project management and has the ability to recognise when changes to other systems will be necessary to maximise savings, as was proven in both case studies. If the surface pressures were not adjusted, the compressors would have oversupplied air to underground, leading to unnecessary waste and strain on the pipe network.

9. Was the model applied to a real-life case study with measurable results?

As indicated by the case studies, the sustainable project management plan was successfully used in the implementation of two projects on a deep-level gold mine. The results are measurable and sustainable.

It is clear that each of the research objectives was achieved by the model and proven by the case studies.

3.7 SUMMARY

The model was applied to two projects implemented on a deep-level gold mine. A new refuge chamber valve was designed to solve a problem involving legal compliance and wastage. Due to the simple nature of the project, it was highly successful. The model was also applied on a failed project. After reconfiguration, the project was brought back from the grave. The results of both projects prove the success of the model.

The saving to date amounts to R 11.7 million and will remain sustainable if the project is maintained. Even with the addition of 10 mining crews, the projects maintain a lower compressor energy usage as that set out by the project objectives. Project management in mining is crucial in the current economic climate. With the project sustainability model developed in this study, projects in mining will be implemented with a higher success rate. The model can be applied to other mining systems as those shown, but unfortunately data are not available yet to show the sustainability of the model when applied to refrigeration and dewatering systems.

The model was validated by the results and it was proven that all the research objectives have been achieved by the model.

CHAPTER 4: CONCLUSION AND RECOMMENDATIONS FOR FURTHER STUDY

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[30] [30] FG. Jansen van Rensburg, personal photograph. "Concrete head gear", Carletonville, 2016.

4.1 CONCLUSION

The South African gold mining industry is under strain due to numerous challenges. Due to this economic stress, mines cannot embark on large-scale capital expenditures. Maximising of profits through increased revenue and cost savings, therefore, need to be realised with very little capital available for infrastructure upgrades.

In deep-level gold mines, it is also crucial to provide adequate cooling to underground working areas to ensure safety and increase the productivity of mine employees. Energy-intensive refrigeration systems are used for this purpose. Compressed air is used for drilling, cleaning, and emergency air. The pressure must be kept above 150 kPa in all the refuge chambers to pressurise the refuge chambers, to prevent toxic gasses from entering the chambers.

The current project management processes found in mining are inadequate. Various models exist in literature and in the industry. A model that is tailor-made for the mining environment is, therefore, necessary. Various factors affect the success in project management, the most notable being

- technical uncertainty and innovation;
- project objectives and their viability;
- politics;
- community involvement;
- schedule duration and urgency;
- financial, legal and contractual matters; and
- project implementation.

These factors have a varying degree of influence on the South African mining environment. It has been found that the experience of the project manager is a key factor for success. With the shortage of skills and experience in mining, this factor is a contributor to the uncertainty of projects in mining.

Deep-level gold mines face many challenges today, and the end is not in sight. The most notable challenges are the skills shortage, deep ore reserves, and economic uncertainty. It is thus crucial that, when projects are implemented in this industry, it be done sustainably. Adding to the current strain is the recent increase in electrical costs. As the mine's supporting systems use vast amounts of energy, these increases could have a detrimental effect on gold mining as we know it. More efficient mining methods are required.

Industry 4.0 principles have revolutionised the manufacturing industry and the same principles can be applied to mining. Past studies have noted the benefits of incorporating integrated simulations and digital reporting into the mining processes. The degree of integration is lacking in the industry as well as in project management.

These digital solutions could greatly benefit the project management sector as well. Integrated simulations can be used for smarter decision making and fault finding. The degree of integration is crucial, as there are no independent systems in mining. A project on one system could easily affect another system. Automated reporting was shown to increase awareness while saving costs. Automated reporting has various benefits for project management of sustainable projects.

It was found that a project management model that focusses on substantiality, is suited to the deep-level gold mining environment and uses digital solutions is required. The following research questions were raised:

- Was a generic project management model that can be applied to deep-level gold mining developed from literature and practical experience?
- Is the project management model encompassing the long-term substantiality of the project from the first phase?
- Were integrated simulations used in deep-level gold mining?
- Were integrated simulations used to aid in project management?
- Does the project management model examine various failed projects in mining?
- Has the study integrated other engineering systems and reporting during the project phase?
- Has the study examined the effect of a new project on the current control philosophy and adapted the philosophy?
- Is the project management model derived from literature and practical experience using integrated simulations and focussing on the long-term sustainability of the project specifically designed for the deep-level mining environment?

Various studies were examined to establish if such a system exists in industry and literature. It was found that a need for this study exists. No study addressed all the questions, and due to the unique complex environment of mining, no such model exists. Currently, no project management models exists that can be directly applied to the unique deep-level mining environment. As shown, good-practice project management leads to various cost savings.

The research objectives of this study were as follows:

- The development of a project management model from literature and past failures and successes that can be applied to deep-level gold mining in South Africa.
- The development of a project management model that focuses on long term sustainability of projects.
- The development of a project management model that uses Industry 4.0 solutions (integrated simulations and digital reporting).
- The model will integrate systems of engineering as far as necessary to be used in the project management model.
- By using integrated simulation and reporting, it would be possible to make better decisions and accurately scope new projects to either compliment the current project or achieve better outcomes for operations.
- It will be of the upmost importance to use the model to adapt the current control philosophy for optimal operation of the greater system.
- As stated, the probability of failure is highly dependent on the experience of the project manager. This model will aim to capture the experience element and enable relatively inexperienced project managers to achieve favourable outcomes.
- Using the integrated simulation model to predict the effect of minor changes to the system.

There is a great need to efficiently implement projects in deep-level gold mining, while minimising cost and time spent implementing projects, and addressing the sustainability challenges. Each of these questions was addressed and discussed in Chapter 3. It is clear that the model incorporates all the mentioned questions.

The novel contribution of this is set out as:

1. **Development of a project management model derived from literature and past experiences that can be applied on deep-level gold mines in South Africa.**

The model was developed as explained in Chapter 2 and validated through case studies as discussed in Chapter 3. The model was firstly developed from literature (Section 2.2, 2.3 and

2.47) and practical experience (Section 2.5). The model has specifically been developed for deep-level gold mining. The model was then applied to two case studies, and proven successful, which validated the model.

2. Development of a project management model focussing on the sustainability of projects to be applied on deep-level gold mines in South Africa

In Section 2.5, the long-term sustainability of projects in mining and ways to mitigate these challenges were discussed. In Section 2.5.3, the challenges were addressed and incorporated into the model to ensure long-term suitability of projects in mining. In both case studies, the suitability of the projects was proved by the results.

3. The development of a project management model that uses digital solutions (integrated simulations and digital reporting).

The benefits of integrated simulations was discussed in Chapter 1 and Chapter 2. Steps to successfully integrate and build simulations were discussed in Chapter 2, section 2.6. In Section 2.9, the importance of the integrated simulation is once again reaffirmed. Integrated simulations and digital reporting are critical factors for success in the model. In the case studies, integrated simulation and reporting were used to great effect.

4. The development of a project management model that integrates the systems of engineering and simulations during the project phase.

As stated in Chapter 1, integration of systems is crucial, as no mining system is truly independent. It is emphasised by the model that an integrated system should be built in the first stage of the project feasibility phase (Section 2.6). Simulations are used as a tool throughout the model up until the project execution phase. With the assistance of the integrated simulations, the effects on the surface operations were shown and mitigated.

5. The model will focus on addressing the need to update the current control philosophy of the system when a new project is implemented.

As discussed in Chapter 2, new projects will influence the current operation, and the influence might lead to the project failing. By adapting the current control philosophy to the new system, sustainability will be ensured. In the case studies, the control philosophy of the surface operations have been adjusted to prevent oversupply.

6. Using the integrated simulation as a feasibility tool to scope new projects and make changes during the project execution phase

Integrated simulation is used during the execution phase of the project in the model as described in Chapter 2. In Chapter 3, this was applied to the case studies. In Case Study 1 and Case Study 2, the simulation was used to determine the most cost-effective manner to implement the projects. In Case study 2, specifically, the simulation was used to determine where installation should start to maximise the cost benefit of the project. The simulation could correctly predict the effect of the first installations on the rest of the system as discussed in Section 3.4.

A clear need for this study was stated and used as a clear framework to emphasise the novel contributions of this study. A model was therefore derived from firstly investigating what a good project management model offers, secondly identifying the critical factors leading to success and failures, and lastly all the mentioned parameters were applied to mining.

The first step of the development process was to examine project management models found in literature. A five-phase management model was chosen as its best suits mining. Literature showed the significance of a project management model. It was found that external factors affect the success of a project, and these factors where addressed.

The key success and failure factors found in literature were identified and incorporated into the model. It is also important to learn from past mistakes. Therefore, the factors leading to failures were also analysed and measures were put in place to mitigate potential failures. The reasons for past project failure in mining were investigated. It was found that the major contributing factors are

- equipment,
- management,
- maintenance, and
- the lack of control philosophy adjustments.

Many failed projects were studied, and it was found that projects in mining are not sustainable. Although various projects are implemented successfully, the projects become redundant within a year. It was also proven that digital solutions will have a positive effect on the model, and it was incorporated.

All the mentioned factors were then incorporated into a project management model focussing on implementing successful, long-term sustainable projects in the deep-level gold mining environment. The key factors of the model are shown in a simplified version in Figure 39.

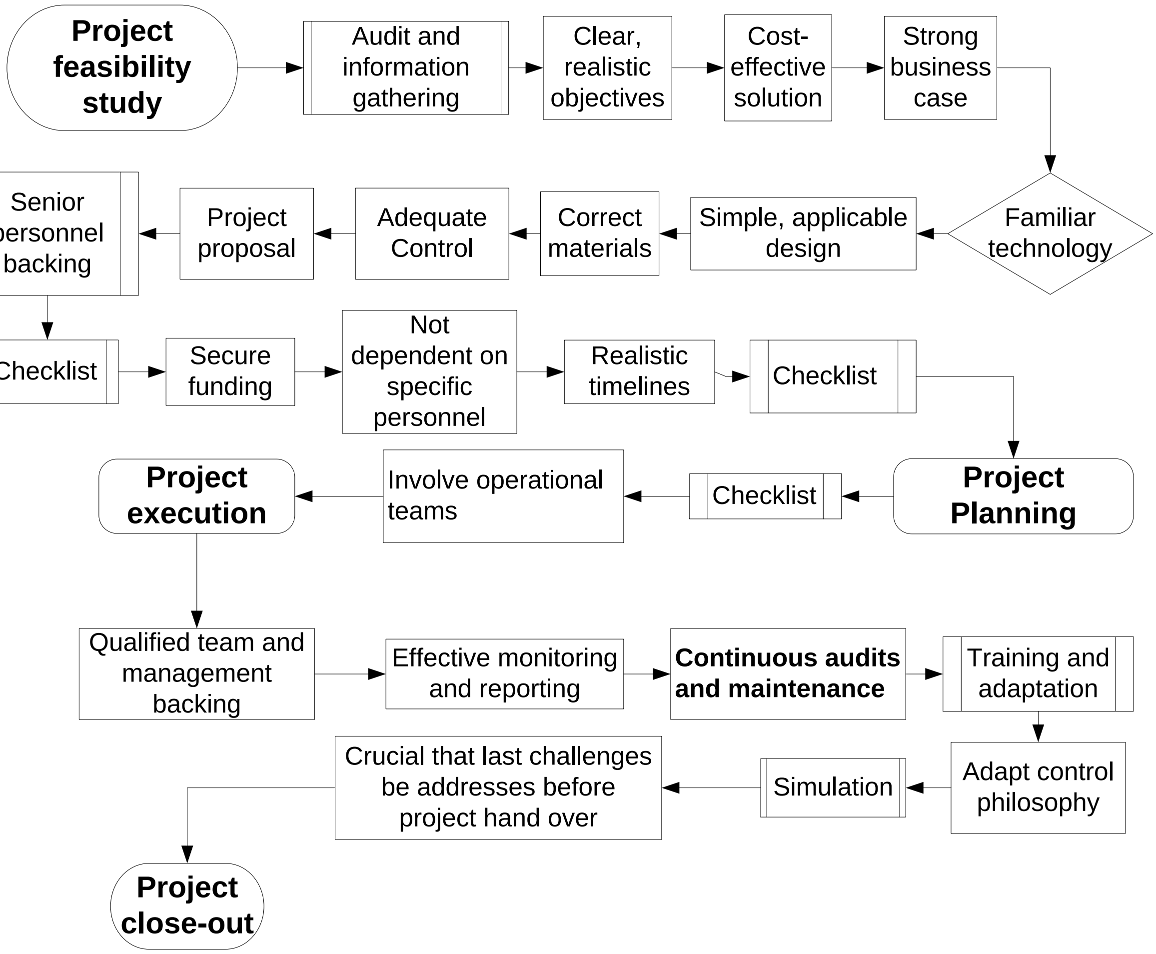

Figure 39: Simplified sustainable project management model for mining

The model was verified from literature, as the model builds on what is already stated in literature by incorporating challenges faced in mining. Digital solutions have shown to improve the efficiency of projects and scope exists to incorporate these solutions to project management. The IT industry has shown the success of using simulations in project management.

The model was successfully applied to two projects on the same compressed air system of a deep-level shaft. The first project was a completely new design to address the overconsumption of the shaft's compressed air. The project also ensured that all the refuge chambers in the shaft are compliant to the Mine Health and Safety Act.

The shaft used to have 50 mm butterfly valves in the refuge chambers to pressurise the inside of the chambers. A 50 mm stainless steel ball valve was designed with a 4 mm hole drilled through the ball of the valve. This was a cost-effective solution to the problem. Due to the simple nature of the project, it was possible to re-install all the valves within a month. Reporting and continuous audits ensured the project stayed sustainable for the period in which the results were measured.

The second project was the revival of an old DSM project. The downstream pressures of production levels were control over 24 hours to optimise the supply to these levels. Due to a strict budget, a cost-effective solution was required. The model was applied, and an efficient solution was created that accommodated for future expansion. One of the main reasons the original project failed was due to the short-sighted nature of the initial installation.

The majority of the old equipment could be re-used for the project, keeping the installation cost low. The installation process was also optimised by having the pipework done by contractors. The pipe sections and bypass valves could be married on surface to reduce the installation time.

Both projects used integrated simulations and digital reporting extensively. The refuge chamber project incorporated daily audits and reporting. A web-based platform was designed for the bypass valve project to monitor the progress and ultimately the daily performance. The digital solution proved integral to the success of both projects.

The combined cost benefit of both projects resulted in an R11 million saving over a year. Even with 10 new crews being appointed, the projects remained sustainable. The model can be applied to any project in mining. By mitigating the minor challenges found in mining, the model ensures efficient project management and long-term sustainable project performance.

4.2 RECOMMENDATIONS FOR FURTHER WORK

The investigation of the influence of sub-contractors on projects is recommended for future studies. It was found that sub-contractors have a positive influence on the implementation times of projects. However, the overall impact of contractors on site needs to be fully established as studies have noted negative impacts on mining.

It recommended that the model be implemented on ventilation systems to prove the efficiency of the model. Ventilation of a mine has an impact on the compressed air consumption, but the exact impact is not known. Figure 40 shows how compressed air is being incorrectly used for cooling. The hose shown is connected to a compressed air outlet and openings have been made in the pipe.

Figure 40: Compressed air being abused for cooling

If ventilation is improved on shafts and the model is used to implement the project, it will have a positive effect on the compressed air systems.

4.3 CLOSING REMARKS

Mines are hesitant to implement large Capex projects, and the unsuccessful nature of project management in mining contributes to the lack in confidence in large-scale Capex projects. Sustainable project management has been discussed in resent years, but not for the deep-level gold mining industry of South Africa. A model was developed with the help of simulations and investigations into past failed projects. The model focussed on the practical challenges faced in the past and offered mitigation.

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BIBLIOGRAPHY

[1] Price, Waterhouse and Coopers, "Highlighting trends in the South African mining industry," vol. 5, 2013.

[2] Price, Waterhouse Coopers, "Highlighting trends in the South African mining industry," *SA Mine,* vol. 7, 2015.

[3] J. I. G. Bredenkamp, A. J. Schutte and J. F. van Rensburg, "Challenges faced during implementation of a compressed air energy savings project on a gold mine," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2015.

[4] P. N. Tholana and T. Neingo, "Trends in productivity in the South African gold mining industry," *The Journal of the Southern African Institute of Mining and Metallurgy,* vol. 116, no. 3, pp. 283-290, 2016.

[5] J. A. Deysel, M. Kleingeld and C. J. Kriel, "DSM strategies to reduce electricity costs on platinum mines.," in *International Conference on the Industrial and Commercial Use of Energy (ICUE) (pp. 89-96).*, Cape Town, 2015.

[6] L. Mogotsi, "Challenges facing the South African gold mining industry," *Alchemist,* vol. 38, no. 1, pp. 15-17, 2005.

[7] G. Geldenhuys, E. R. Rohwer, Y. Naudé and P. B. Forbes, "Monitoring of atmospheric gaseous and particulate polycyclic aromatic hydrocarbons in South African platinum mines utilising portable denuder sampling with analysis by thermal desorption–comprehensive gas chromatography–mass spectrometry," *Journal of Chromatography,* vol. A, no. 1380, p. 17–28, 2015.

[8] R. Spalding-Fecher and D. K. Matibe, "Electricity and externalities in South Africa," *Energy Policy,* vol. 31, no. 8, p. 721–734, 2003.

[9] C. Cilliers, "Benchmarking electricity use of deep-level mines," Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2016.

[10] L. Van der Walt, S. S. Cilliers, K. Kellner, D. Tongway and L. Van Rensburg, "Landscape functionality of plant communities in the Impala Platinum mining area, Rustenburg," *Journal of Environmental Management,* vol. 113, p. 103–116, 2012.

[11] P. F. Peach, “Modelling of different long-term electrical forecasts and its practical applications of transmission network flow studies,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2005.

[12] H. J. Groenewald, M. Kleingeld and J. C. Vosloo, “A performance-centred maintenance strategy for industrial DSM projects.,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2015.

[13] F. G. Jansen van Rensburg, J. I. Bredenkamp and J. F. van Rensburg, “Optimising load management on a deep-level Mine's refrigeration systems through maintenance and operational improvements,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2017.

[14] J. Vosloo, L. Liebenberg and D. Velleman, “Case study: Energy savings for a deep-mine water reticulation system.,” *Applied Energy,* vol. 92, pp. 328-335, 2012.

[15] T. D. Moodie, “ The Formal and Informal Social Structure of a South African Gold Mine,” *Human Relations,* vol. 33, no. 8, pp. 555-574, 1980.

[16] A. C. Lawrence, “The importance of human factors in mining productivity.,” *Journal of the Southern African Institute of Mining and Metallurgy ,* vol. 74, no. 12, pp. 399-404, July 1974.

[17] A. Schutte, “An integrated energy-efficiency strategy for deep-mine ventilation and refrigeration,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2013.

[18] M. Buthelezi, “Load shift through optimal control of complex underground rock winders,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2009.

[19] S. Kaczmarczyk and W. Ostachowicz, “Transient vibration phenomena in deep mine hoisting cables. Part 1: Mathematical model,” *Journal of Sound and Vibration,* vol. 262, p. 219–244, 2003.

[20] J. Vosloo, “Control of an underground rock winder system to reduce electricity costs on RSA gold mines,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2006.

[21] J. I. G. Bredenkamp, L. F. van der Zee and J. F. van Rensburg, “Reconfiguring mining compressed air networks for cost savings,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2014.

[22] D. H. Diering, “Ultra-deep level mining-future requirements,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 96, no. 6, pp. 249-255, 1997.

[23] D. Stephenson, “Distribution of water in deep gold mines in South Africa,” *International Journal of Mine Water,* vol. 2, p. 21–30, 1983.

[24] J. Buys, “Optimising the refrigeration and cooling system of a platinum mine,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2014.

[25] W. Bornman, “Improved mine cooling system performance through the control of auxiliary systems,” M.Eng. Dissertation, Dept. Mech. Eng., North-West University, Potchefstroom, 2012.

[26] H. G. Brand, J. C. Vosloo and E. H. Mathews, “Automated energy efficiency project identification in the gold mining industry,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2015.

[27] P. Oberholzer, “Best practices for automation and control of mine dewatering systems,” Master's Dissertation, Department of Mechanical Engineering, North-West University, Potchefstroom, 2014.

[28] N. Oosthuizen, “Optimum water distribution between pumping stations of multiple mine shafts,” M.Eng. Dissertation, Dept. Elec. Eng., North-West University, Potchefstroom, 2012.

[29] W. Bornman, J. Dirker, D. Arndt and J. Meyer, “Integrated energy simulation of a deep level mine cooling system through a combination of forward and first-principle models applied to system-side parameters,” *Applied Thermal Engineering,* vol. 123, pp. 1166-1180, 2017.

[30] W. Booysen and J. F. Van Rensburg, “Load management on closed loop underground fridge plants and the effects on working conditions,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2013.

[31] J. M. Calm , “Refrigerants for Deep Mine Refrigeration,” in *ICR2011*, Prague, 2011.

[32] Department of Mineral Resources, “Guideline for a Mandatory Code of Practice for an Occupational Health Programme (Occupational Hygiene and Medical Surveillance) On Thermal Stress,” Mine Health and Safety Inspectorate, 2016.

[33] R. M. Franz, W. M. Marx, R. C. W. Webber and P. C. Schutte, “A review of local and international heat stress indices, standards and limits with reference to ultra-deep

mining," *The Journal of The South African Institute of Mining and Metallurgy,* pp. 313-324, June 2003.

[34] V. F. N. Torres and R. N. Singh, "Thermal State and Human Comfort in Underground Mining," in *Developments in Heat Transfer*, M. A. Dos Santos Bernardes, Ed., InTech, 2011.

[35] R. C. Burton, W. Plenderleith, J. M. Stewart, B. C. B. Pretorius and W. Holding, "Recirculation of air in the ventilation and cooling of deep gold mines," in *Proceedings Third International Mine Ventilation Congress*, Harrogate, England, 1984.

[36] S. Van Jaarsveld, J. N. du Plessis and R. Pelzer, "A control system for the efficient operation of Bulk Air Coolers on a mine," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2015.

[37] S. Van Jaarsveld, "A control system for the efficient operation of bulk air coolers on a mine," Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2014.

[38] A. M. Donoghue, "Donoghue, A. M. "Occupational health hazards in mining: an overview.," *Occupational Medicine,* vol. 54, no. 4, pp. 283-289, 2004.

[39] H. Wagner, "The management of heat flow in deep mines (part 2)," *Geomechanics and Tunnelling,* vol. 4, no. 2, pp. 157-163, 2011.

[40] D. J. Stanton, "Development and testing of an underground remote refrigeration plant," in *International Platinum Conference*, Rustenburg, 2004.

[41] P. Maré, "Improved implementation strategies to sustain energy saving measures on mine cooling systems," Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2014.

[42] H. Wagner, "The challenge of deep-level mining in South Africa.," *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 86, no. 9, pp. 377-392, 1986.

[43] J. L. Buys, M. K. Kleingeld and C. Cilliers, "Refrigeration and Cooling System of a Platinum Mine," in *Industrial and Commercial Use of Energy Conference (ICUE)*, Cape Town, 2015.

[44] H. L. Hartman, J. M. Mutmansky, R. V. Ramani and J. L. Wang, Mine ventilation and air conditioning, 3rd ed., Hoboken: John Wiley & Sons., 2012.

[45] H. J. van Staden, "Optimal use of mobile cooling units in a deep-level gold mine," Master's Dissertation, Department of Mechanical Engineering, North-West University, Potchefstroom, 2018.

[46] G. E. Du Plessis, D. C. Arndt and E. H. Mathews, " The development and integrated simulation of a variable water flow energy saving strategy for deep-mine cooling systems," *Sustainable Energy Technologies and Assessments,* vol. 10, pp. 71-78, 2015.

[47] A. Van Niekerk, D. C. Uys and J. F. Van Rensburg, "Implementing DSM interventions on water reticulation systems of marginal deep level mines.," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2014.

[48] W. Schoeman, R. Pelzer and J. C. Vosloo, "Valve solutions for mine dewatering systems.," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2012.

[49] C. Cilliers, "Cost savings on mine dewatering pumps by reducing preparation- and comeback loads," M.Eng. Dissertation, Dept. Mech. Eng., North-West University, Potchefstroom, 2014.

[50] J. Van der Bijl, "Sustainable DSM on deep mine refrigeration systems: A novel approach," Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2007.

[51] D. G. Kröger, Air-cooled heat exchangers and cooling towers, vol. 1, PennWell Book, 2004.

[52] A. J. Schutte, R. Pelzer and E. H. Mathews, "Improving cooling system efficiency with pre-cooling," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Stellenbosch, South Africa, 2012.

[53] X. Nie, X. Wei, X. Lu and C. Lu, "Heat treatment and ventilation optimization in a deep mine," *Advances in Civil Engineering,* vol. 2018, p. 12, 2018.

[54] W. C. Kukard, "Research on reducing costs of underground ventilation networks in South African mines," Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2006.

[55] J. Bredenkamp, "An integrated energy management strategy for the deep-level gold mining industry," Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2016.

[56] A. De Coning, "Sustained energy performance on compressed air systems for expanding gold mines," Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2013.

[57] R. Joubert, “Cost and time effective DSM on mine compressed air systems,” M.Eng. Dissertation, Dept. Mech. Eng., North-West University, Potchefstroom, 2010.

[58] C. J. Kriel, J. H. Marais and M. Kleingeld, “Modernising underground compressed air DSM projects to reduce operating costs.,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2014.

[59] J. H. Marais, “An integrated approach to optimise energy consumption of mine compressed air systems,” Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2012.

[60] K. Van Tonder, “Sustaining compressed air DSM project savings using an air leakage management system,” Master's Dissertation, Department of Mechanical Engineering, North-West University, Potchefstroom, 2010.

[61] G. Heyns, “Challenges faced during implementation of a compressed air energy,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2014.

[62] J. Bredenkamp, “Reconfiguring mining compressed air networks for cost savings,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2013.

[63] Department of Mineral Resources, “Mine Health and Safety Act, 1996 (Act no 29 of 1996),” *Government Gazette,* vol. 906, pp. 4-6, 21 November 2014.

[64] A. J. Kielblock, J. P. Van Rensburg, A. Van der Linde, A. J. Van Rensburg, H. M. Rust and C. Haven, “The functional performance of formal gold mine and colliery refuge bays with special reference to air supply failure,” *Journal of the Mine Ventilation Society of South Africa,* vol. 5, no. 10, pp. 58-69, 1998.

[65] F. Fraser, “The energy and water required to drill a hole,” in *4th International Platinum Conference: Platinum in transition 'Boom or Bust'*, Sun City, 2010.

[66] R. Els, “Energy evaluations and load shift feasibility in South African mines.,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2002.

[67] S. J. Cloete, D. J. Le Roux and R. T. Buhrman, “Reducing compressed air wastage by installing new technology in underground mines,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2013.

[68] R. Saidur, N. Rahim and M. Hasanuzzaman, "A review on compressed-air energy use and energy savings," *Renewable and Sustainable Energy Reviews,* vol. 14, no. 4, p. 1135–1153, 2010.

[69] K. H. Rose, "A guide to the Project Management (PMBOK guide)," *Project management journal,* vol. 44, no. 3, 2013.

[70] A. K. Munns and B. F. Bjeirmi, "The role of project management in achieving project success," *International Journal of Project Management,* vol. 14, no. 2, pp. 81-87, 1996.

[71] R. M. Bakker, "Taking Stock of Temporary Organizational Forms: A Systematic Review and Research Agenda," *International Journal of Management Reviews,* vol. 4, no. 12, pp. 466-486, 2010.

[72] R. Buttrick, The project workout. The ultimate handbook of project and programme management, 4th ed., Harlow: Pearson UK, 2009.

[73] R. P. Oisen, "Can project management be defined," Project Management Institute, 1971.

[74] A. A. Altshuler and D. Luberoff, Mega-projects. The changing politics of urban public investment., Washington, D.C: Brookings Institution Press, 2003.

[75] B. Flyvbjerg and A. Budzier, "Why your IT project may be riskier than you think.," *Harvard Buniness Review,* vol. 89, no. 11, pp. 22-22, September 2011.

[76] H. Priemus, B. Flyvbjerg and B. van Wee, "Decision-making on mega-projects. Cost-benefit analysis, planning and innovation.," Edward Elgar, Cheltenham, UK, Northampton, 2008.

[77] D. N. Wagner, "Breakin' the Project Wave: Understanding and avoiding failure in project management," *PM World,* vol. 5, no. I, 2016.

[78] D. Dalcher, "The nature of project management," *International Journal of Managing Projects in Business,* vol. 5, no. 4, pp. 643-660, 2012.

[79] P. W. G. Morris and G. H. Hough , The Anatomy of Major Projects: A Study of the Reality of Project Management, Chichester: Wiley, 1987.

[80] G. A. Silvius, M. Kampinga, S. Paniagua and H. Mooi, "Considering sustainability in project management decision making; An investigation using Q-methodology," *International Journal of Project Management,* vol. 35, no. 6, pp. 1133-1150, 2017.

[81] J. R. Otegi-Olaso, M. E. Aguilar-Fernández, C. Cruz-Villazón and B. Fuentes-Ardeo, "Towards sustainable project management. A literature review," in *19th International Congress on Project Management and Engineering*, Granada., 2015.

[82] A. J. Silvius, R. Schipper, J. Planko, J. van den Brink and A. Köhler, “Sustainability in Project Management.,” Gower Publishing, Farnham, 2012.

[83] S. Marcelino-Sádaba, A. Pérez-Ezcurdia and L. F. González-Jaen, “Using project management as a way to sustainability. From a comprehensive review to a framework definition,” *Journal of cleaner production,* vol. 9, pp. 1-16, 2015.

[84] P. Lehtonen and M. Martinsuo, “Three ways to fail in project management and the role of project management methodology,” *Project Perspectives* , vol. 28, no. 1, pp. 6-11, 2006.

[85] j. Kivilä, M. Martinsuo and J. Vuorinen, “Sustainable project management through project control in infrastructure projects,” *International Journal of Project Management,* vol. 35, pp. 1167-1183, 2017.

[86] N. Zainul-Abidin and C. L. Pasquire, “Revolutionize value management: a mode towards sustainability,” *International Journal of Project Management,* vol. 25, no. 2, pp. 275-282, 2007.

[87] B. G. Hwang and W. J. Ng, “Project management knowledge and skills for green construction: Overcoming challenges.,” *International Journal of Project Management,* vol. 31, no. 2, pp. 272-284, 2013.

[88] R. &. S. D. Maltzman, Green project management., CRC Press, 2010.

[89] D. Goedknegt, “Responsibility for adhering to sustainability in project management,” in *7th Nordic Conference on Construction Economics and Organization*, Trondheim, 2013.

[90] G. Silvius, “Integrating sustainability into project risk management.,” *Global Business Expansion: Concepts, Methodologies, Tools, and Applications,* pp. 330-352, 2018.

[91] A. J. Silvius and R. P. Schipper, “Sustainability in project management: A literature review and impact analysis.,” *Social Business,* vol. 4, no. 1, pp. 63-96, 2014.

[92] D. K. Anderson and T. Merna, “Project management strategy—project management represented as a process based set of management domains and the consequences for project management strategy,” *International Journal of Project Management,* vol. 21, no. 6, pp. 387-393, 2003.

[93] U. Chinbat and S. Takakuwa, “Using simulation analysis for mining project risk management.,” in *Winter Simulation Conference*, Austin, 2009.

[94] Y. Li, Y. Lu, Q. Cui and Y. Han, “Organizational Behaviour in Megaprojects: Integrative Review and Directions for Future Research,” *Journal of Management in Engineering,* vol. 35, no. 4, p. 04019009, 2019.

[95] Harmony Gold Mining Company Limited, “Financial Report 2018,” Harmony Gold Mining Company Limited, Randfontein, 2018.

[96] Institute for Future Research, “NEDLAC Futures of work in South Africa,” NEDLAC Reseach Group, Stellenbosch, March 2019.

[97] R. Baxter, “25 years of evolution: a view from the Minerals Council,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 119, no. 125 Year Anniversary Edition, pp. 14-16, 2019.

[98] G. Khan and G. Krige, “Evaluation of the structural integrity of aging mine shafts,” *Engineering Structures,* vol. 24, no. 7, p. 901–907, 2004.

[99] P. N. Neingo and T. Tholana, “Trends in productivity in the South African gold mining industry,” *The Journal of the Southern African Institute of Mining and Metallurgy,* vol. 116, no. 3, pp. 283-290, 2016.

[100] D. Ross-Watt, “Mining engineering. Some perspectives on managing risk,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 119, no. 125 Year Anniversary Edition, pp. 24-26, 2019.

[101] R. Dixon, “About a rights-based health and safety dispensation to developing the SAMREC code and more,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 119, no. 125 Year Anniversary Edition, pp. 28-30, 2019.

[102] N. van der Merwe, “There was a time,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 119, no. 125 Year Anniversary Edition , pp. 46-47, 2019.

[103] L. F. Van der Zee, Modelling of electricity cost risks and opportunities in the gold mining industry, Doctoral Thesis, Department of Mechanical Engineering: North-West University, Potchefstroom, 2014.

[104] J. Bredenkamp, “Reconfiguring mining compressed air networks for cost savings,” Master's Dissertation, Department of Mechanical Engineering, North-West University, Potchefstroom, 2013.

[105] E. H. Mathews, M. K. Kleingeld, J. Van Der Bijl and N. Jordaan, “Real-time Energy Management in the Cement Industry,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2007.

[106] R. Pelzer , E. H. Mathews , D. F. le Roux and M. Kleingeld , “A new approach to ensure successful implementation of sustainable demand side management (DSM) in South African mines,” *Energy,* vol. 33, no. 8, pp. 1254-1263, 2008.

[107] A. Hughes, M. I. Howells, A. Trikam, A. R. Kenny and D. van ES, “A Study of Demand Side Management Potential in South African Industries,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2006.

[108] R. Gouws, “Measurement and verification of load shifting interventions for a fridge plant system in South Africa,” *Journal of Energy in Southern Africa,* vol. 24, no. 1, pp. 9-14, 2013.

[109] N. C. Steenkamp and V. Clark-Mostert, “Impact of illegal mining at historic gold mine locations, Giyani Greenstone Belt area, South Africa,” in *9th International Mining History Congress*, Johannesburg, 2012.

[110] L. Liebenberg, D. Velleman and W. Booysen, “A simple demand-side management solution for a typical compressed-air system at a South African gold mine,” *Journal of Energy in Southern Africa,* vol. 23, no. 2, pp. 20-29, May 2012.

[111] A. J. Basu and E. Y. Baafi, “Discrete event simulation of mining systems: current practice in Australia,” *International Journal of Surface Mining,* vol. 13, no. 2, pp. 79-84, 1999.

[112] J. C. Vosloo, “Control of an underground rock winder system to reduce electricity costs on RSA gold mines,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2006.

[113] G. Whittle, W. Stange and N. Hanson, “Optimising project value and robustness,” in *Project Evaluation Conference*, Melbourne, 2007.

[114] M. M. Fioroni, L. C. A. dos Santos, L. A. G. Franzese, I. R. Santana, G. D. Telles, J. C. Seixas, B. Penna and S. de Alkmim, “Logistic evaluation of an underground mine using simulation.,” in *Winter Simulation Conference*, Austin, 2014.

[115] W. Conradie, M. Kleingeld and F. G. Jansen van Rensburg, “Development of A Model to Predict Cost Savings of Reconfigured Mine Water Reticulation Systems,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, South Africa, 2018.

[116] R. Turner, “Simulation in the mining industry of South Africa,” *International Journal of Surface Mining,* vol. 13, no. 2, pp. 47-56, 2007.

[117] D. E. Post and R. P. Kendall, “Software Project management and quality engineering practices for complex, coupled multiphysics, massively parallel computational simulation: Lessons learned from ASCI,” *The International Journal of High Performance Computing Applications,* vol. 18, no. 4, pp. 399-416, 2004.

[118] D. Pfahl, O. Laitenberger, J. Dorsch and G. Ruhe, “An Externally Replicated Experiment for Evaluating the Learning Effectiveness of Using Simulations in Software Project Management Education,” *Information and software technology,* vol. 46, no. 2, pp. 367-395, 2003.

[119] P. J, “The changing paradigms of project management,” *International Journal of Project Management,* vol. 25, no. 3, pp. 266-274, 2007.

[120] W. Bornman, J. Dirker, D. C. Arndt and J. P. Meyer, “Integrated energy simulation of a deep level mine cooling system through a combination of forward and first-principle models applied to system-side parameters.,” *Applied Thermal Engineering,* vol. 123, pp. 1166-1180, 2017.

[121] J. Vosloo, L. Liebenberg and D. Velleman, “Case study: Energy savings for a deep-mine water reticulation system,” *Applied Energy,* vol. 92, p. 328–335, 2012.

[122] P. Mare, H. J. Groenewald and J. C. Vosloo, “Digital twinning: The future of mine cooling?,” in *29th Annual Conference of SAIIE*, Stellenbosch, 2018.

[123] P. Marè, C. J. R. Kriel and J. H. Marais, “Energy efficiency improvements through the integration of underground mine water retiulation and cooling systems,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2017.

[124] K. J. Oberholzer, Reconfiguring mine cooling auxiliaries for optimal operation, Master's Dissertation, Department of Mechanical Engineering : North-West University, Potchefstroom, 2016.

[125] P. F. H. Peach, “Optimising deep-level mine refrigeration control for sustainable cost savings,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2017.

[126] J. Calitz, “Research and implementation of a load reduction system for a mine refrigeration system,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2006.

[127] I. G. Boake, “A strategy for electrical load management in the South African mining industry,” Doctoral dissertation, Rand Afrikaans University, Johannesburg, 2003.

[128] D. Seslija, S. Milenkovic, Dudic S and J. Sulc, “Improving energy efficiency in compressed air systems–practical experiences,” *Thermal Science 20,* p. 2016, 2 June 2016.

[129] H. Fridén, L. Bergfors and A. Björk, “Energy and LCC Optimised Design of Compressed Air Systems A mixed integer optimisation approach with general applicability,” in *UKSim*

14th International Conference on Computer Modelling and Simulation, Cambridge, 2012.

[130] W. Shaw, M. Mathews and J. Marais, “Using specific energy as a metric to characterise compressor system performance.,” *Sustainable Energy Technologies and Assessments,* vol. 31, pp. 329-338, 2019.

[131] A. J. Nel, D. C. Arndt, J. C. Vosloo and M. J. Mathews, “Achieving energy efficiency with medium voltage variable speed drives for ventilation-on-demand in South African mines.,” *Journal of Cleaner Production,* vol. 232, pp. 379-390, 2019.

[132] C. K. Kocsis, R. Hall and S. G. Hardcastle, “The integration of mine simulation and ventilation simulation to develop a ‘Life Cycle’ mine ventilation system.,” *South African Institute of Mining and Metallurgy,* vol. Application of Computers and Operations Research in the Minerals Industries, pp. 223-230, 2003.

[133] J. Banks, S. Carson, B. L. Nelson and D. Nicol, Discrete-Event System Simulation, Upper Saddle River, NJ: Pearson, 2010.

[134] A. M. Law and W. D. Kelton, Simulation modelling and analysis (Vol. 3), New York: McGraw-Hill, 2000.

[135] C. Swart, “Optimising the operation of underground mine refrigeration plants and ventilation fans for minimum electricity cost,” Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2003.

[136] D. F. Malan, “Time-dependent behaviour of deep level tabular excavations in hard rock.,” *Rock Mechanics and Rock Engineering ,* vol. 32, no. 2, pp. 123-155, 1999.

[137] D. F. Malan, U. V. Vogler and K. Drescher, “Time-dependent behaviour of hard rock in deep level gold mines.,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 97, no. 3, pp. 135-147, 1997.

[138] e. Sellers, A. Vervoort and J. Van Cleynenbreugel, “Three-dimensional visualization of fractures in rock test samples, simulating deep level mining excavations, using X-ray computed tomography.,” *Geological Society, London, Special Publications,,* vol. 215, no. 1, pp. 69-80, 2003.

[139] T. O. Hagan , A. M. Milev , S. M. Spottiswoode , M. W. Hildyard , M. Grodner , A. Rorke and D. M. Grave, “Simulated rockburst experiment-an overview.,” *Journal of the Southern African Institute of Mining and Metallurgy,* vol. 101, no. 5, pp. 217-222, 2001.

[140] W. A. Pelser, J. C. Vosloo and M. J. Mathews, “Results and prospects of applying an ISO 50001 based reporting system on a cement plant,” *Journal of Cleaner Production,* vol. 198, pp. 642-653, 2018.

[141] A. Holman, “Benefits of improved performance monitoring of mine cooling systems,” Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2013.

[142] A. Stols, C. Cilliers and J. F. van Rensburg, “Implementing a remote condition monitoring system for South African gold mines,” in *29th Annual Conference of SAIIE*, Stellenbosch, 2018.

[143] Schools and Todd, “Condition monitoring of critical mining conveyors: conveyor systems, integral to operations, require conditioning monitoring to ensure uptime,” *Engineering & Mining Journal,* vol. 216, no. 3, p. 50, 2015.

[144] J. Van Der Bijl, “Sustainable DSM on deep mine refrigeration systems: A novel approach,” Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2007.

[145] J. Fortune and D. White, “Framing of project critical success factors by a systems model,” *International Journal of Project Management,* vol. 24, pp. 53-65, 2006.

[146] G. Aouad, J. Hinks, R. Cooper, D. Sheat, M. Kagioglou and M. Sexton, “Map for a generic design and construction process protocol,” *Journal of Construction Procurement,* 1998.

[147] G. Caupin, “International Project Management Association Competence Baseline,” Eigenverlag, Bremen, 1999.

[148] G. Themistocleous and S. H. Wearne, “Project management topic coverage in journals,” *International Journal of Project Management,* vol. 18, no. 1, pp. 7-11, 2000.

[149] W. Belassi and O. I. Tukel, “ A new framework for determining critical success/failure factors in projects.,” *International journal of project management,* vol. 14, no. 3, pp. 141-151, 1996.

[150] P. W. G. Morris, “The management of projects,” Thomas Telford Services Ltd, London, UK, 1995.

[151] R. D. Archibald, “Organizing the project team: duties of project,” in *Project management*, K. W. Cleland DI, Ed., New York, USA, John Wiley & Sons, 1983.

[152] British Standards Institution (BSI), “Guide to project management,” British Standards Institution, London, UK, 1996.

[153] British Standards Institution (BSI), "Quality management—guidelines to quality in project management," British Standards Institution, London, UK, 1997.

[154] R. D. Archibald, I. Di Filippo and D. Di Filippo, "The six-phase comprehensive project life cycle model including the project incubation/feasibility phase and the post-project evaluation phase.," *PM World Journal,* vol. 1, no. 5, pp. 1-40, 2012.

[155] J. W. Brook and F. Pagnanelli, "Integrating sustainability into innovation project portfolio management–A strategic perspective.," *Journal of Engineering and Technology Management,* vol. 34, pp. 46-62, 2014.

[156] P. Mare, J. I. G. Bredenkamp and J. H. Marais, "Evaluating compressed air operational improvements on a deep-level mine through simulations," in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2017.

[157] M. Fioroni, A. dos Santos, L. A. G. Franzese, R. Santana, D. Telles, C. Seixas, B. Penna and M. de Alkmim, "Logistic evaluation of an underground mine using simulation," in *Proceedings of the Winter Simulation Conference 2014 Simulation Conference*, Savanah, GA, USA, 2014.

[158] N. J. Smit, "Reducing electrical costs for a mine ventilation system with the aid of simulation software," Master's Dissertation, Department of Mechanical Engineering , North-West University, Potchefstroom, 2017.

[159] R. J. Turner, "Simulation in the mining industry of South Africa.," *International Journal of Surface Mining, Reclamation and Environment,* vol. 13, no. 2, pp. 47-59, 1999.

[160] J. C. Vosloo, "A new minimum cost model for water reticulation systems on deep mines," Doctoral Thesis, Department of Mechanical Engineering, North-West University, Potchefstroom, 2008.

[161] L. Koskela, "Application of the new production philosophy to construction. (Vol. 72)," Stanford University, Stanford, CA, 1992.

[162] D. A. Wood , "Risk simulation techniques to aid project cost-time planning and management.," *Risk Management,* vol. 4, no. 1, pp. 41-60, 2002.

[163] D. Pfahl, M. Klemm and G. Ruhe, "A CBT module with integrated simulation component for software project management education and training.," *Journal of Systems and Software,* vol. 59, no. 3, pp. 283-298, 2001.

[164] L. J. Isidore and W. E. Back, "Multiple simulation analysis for probabilistic cost and schedule integration.," *Journal of Construction Engineering and Management,* vol. 128, no. 3, pp. 211-219, 2002.

[165] M. Braglia and M. Frosolini, “An integrated approach to implement project management information systems within the extended enterprise,” *International Journal of Project Management,* vol. 32, no. 1, pp. 18-29, 2014.

[166] A. M. Aladwani, “An integrated performance model information systems projects,” *Journal of Management Information Systems,* vol. 19, no. 1, pp. 185-210, 2002.

[167] C. J. Kriel, J. H. Marais and M. Kleingeld, “Modernising underground compressed air DSM projects to reduce operating costs.,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2014.

[168] A. D. Russell, “Computerized daily site reporting,” *Journal of Construction Engineering and Management,* vol. 119, no. 2, pp. 385-402, 1993.

[169] Y. C. Yang, C. J. Park, J. H. Kim and J. J. Kim, “Management of daily progress in a construction project of multiple apartment buildings,” *Journal of Construction Engineering and Management,* vol. 133, no. 3, pp. 242-253, 2007.

[170] P. W. Morris, “Managing the Front-End: how project managers shape business strategy and manage project definition,” in *Project Management Institute Global Congress Proceedings*, Edinburgh, Scotland, 2005.

[171] National Treasury of South Africa, “Budget Review 2019,” 20 February 2019. [Online]. Available: http://www.treasury.gov.za/documents/national%20budget/2019/review/FullBR.pdf. [Accessed 2019 October 2019].

[172] Statistics South Africa, “The South Africa I know, the home I understand,” Fieldworker, 2019 February 2019. [Online]. Available: http://www.statssa.gov.za/?p=11921. [Accessed 2019 October 06].

[173] G. J. Maasz and H. Darwish, “Towards an Initiative-Based Industry 4.0 Maturity Improvement Process: Master Drilling as a Case Study,” *South African Journal of Industrial Engineering,* vol. 29, no. 3, pp. 92-107, 2018.

[174] J. Crush, T. Ulicki, T. Tseane and E. Van Veuren, “Undermining Labour: The Rise of Sub-Contracting in South African Gold Mines.,” *Journal of Southern African Studies,* vol. 27, no. 1, pp. 5-31, 2001.

[175] D. V. Chulkov and M. S. Desai, “Information technology project failure: applying,” *Information Management & Computer Security,* vol. 13, no. 2, pp. 135-143, 2005.

[176] T. Kippenberger, “Management’s role in project failure,” *The Antidote,* vol. 5, no. 4, pp. 30-33, 2000.

[177] K. T. Yeo, “Critical failure factors in information system projects,” *International Journal of Project Management,* vol. 20, no. 3, pp. 241-246, 2002.

[178] K. Lyytinen and R. Hirschheim, “Information failures - a survey and classification of the empirical literature,” in *Surveys in Information Technology*, Oxford, Oxford University Press, Inc, 1987, pp. 257-309.

[179] S. Flowers, “Information systems failure: identifying the critical failure factors,” *Failure and Lessons Learned in Information Technology Management ,* vol. 1, no. 1, pp. 19-29, 1997.

[180] H. Salamah and L. Alnaji, “Challenges leading to projects struggle in IT project management office,” *WSEAS Transactions and Business Economics,* vol. 11, pp. 262-271, 2014.

[181] J. I. G. Bredenkamp, A. J. Schutte and J. F. van Rensburg, “Challenges faced during implementation of a compressed air energy savings project on a gold mine,” in *Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2015.

[182] D. del Castillo, “Air Cycle Refrigeration System for Cooling Deep Mines,” *International Journal of Refrigeration ,* vol. 11, no. 2, pp. 87-91, 1988.

[183] A. J. Schutte, M. Kleingeld and H. J. Groenewald, “A holistic energy-cost evaluation of ice vs chilled water in mining,” in *International Conference on the Industrial and Commercial Use of Energy (ICUE)*, Cape Town, 2016.

[184] Mackay, L, S. Bluhm and J. F. Van Rensburg, “Refrigeration and cooling concepts for ultra-deep platinum mining,” in *The 4th International Platinum Conference, Platinum in transition*, Sun City, 2010.

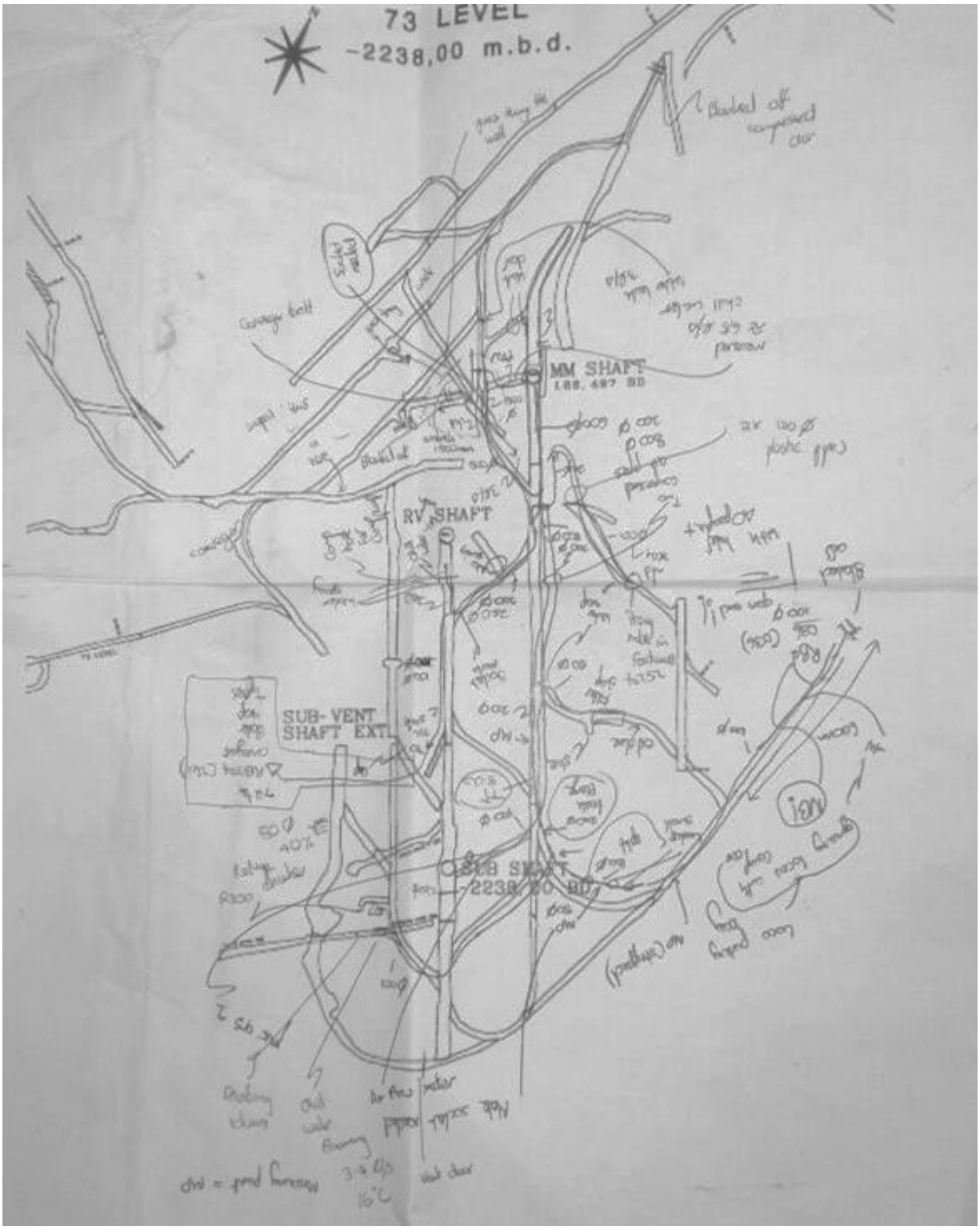
[185] H. S. Phull, “New developments in triple-offset butterfly valves,” *World Pumps,* vol. 456, pp. 40-44, 2004.

Appendix A – Fortune and White critical analysis

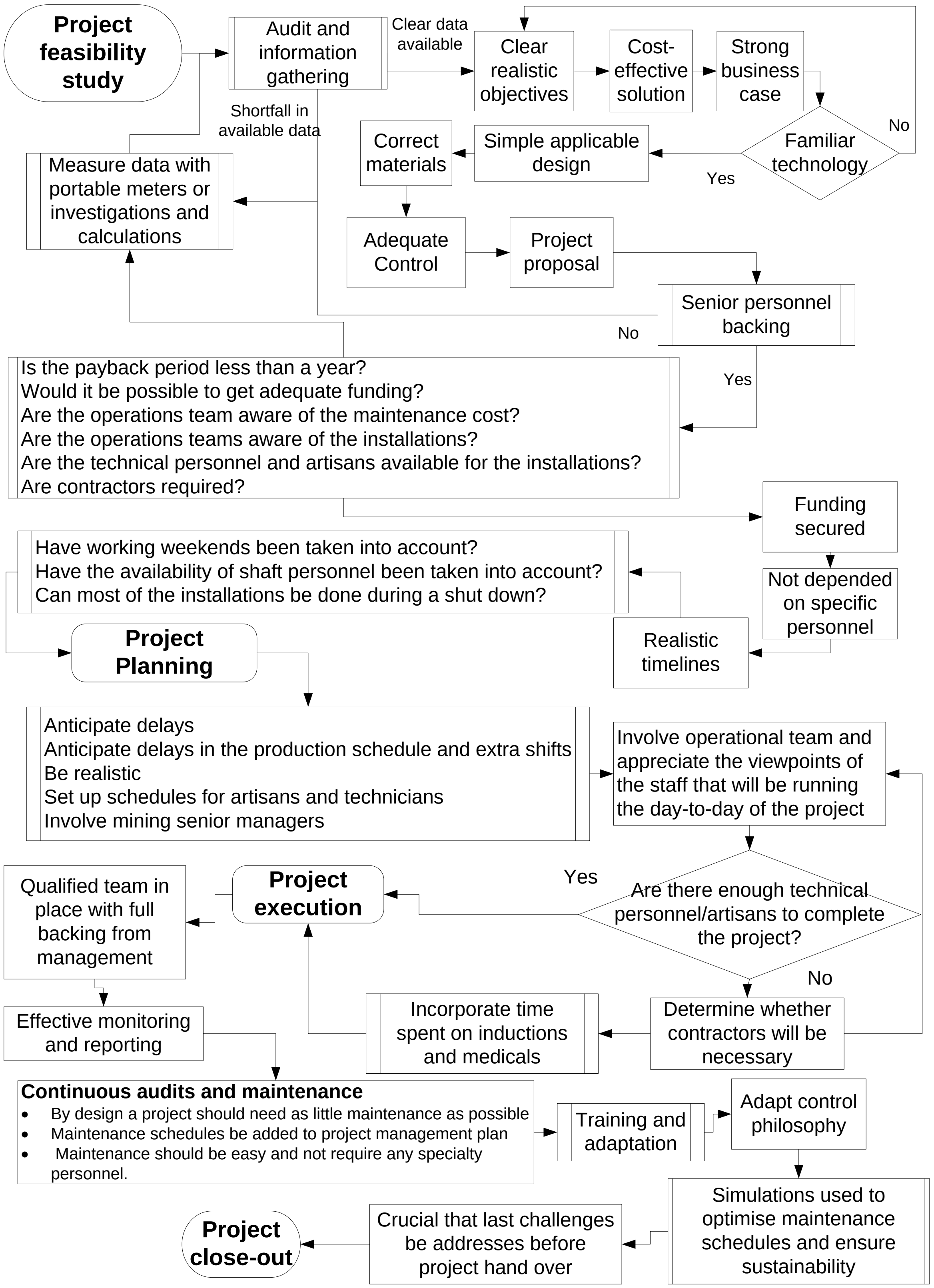
Criteria	Literature	Citations
Support from senior management	Avots [5] , Cleland and King [6] ; Morris [7] ; Pinto and Slevin [8] ; Morris and Hough [9] ; Stoddart-Stones [10] ; Magal et al. [11] ; Pinto and Mantel [12] ; McComb and Smith [13] ; Cashand Fox [14] ; Yap et al. [15] ; Pollalis and Frieze [16] ; Tennant [4] ; Selin and Selin [17] ;Martinez [18] ; The Standish Group [19] ; Couillard [20] ; Wastell and Newman [21] ; Tan [22] ;Munns and Bjeirmi [23] ; Belassi and Tukel [24] ; KPMG [25] ; McCormack [3] ; McGolpin and Ward [26] ; Dvir et al. [27] ; Kasser and Williams [28] ; Jang and Lee [29] ; Whittaker [30] ; Turner [31] ; Weir [32] ; Taylor [33] ; Thite [34] ; Poon and Wagner [35] ; Cooke-Davies [36] ; Andersen et al. [37] ; Caldeira and Ward [38] ; Yeo [39] ; Westerveld [40] ; Turner [41],	39
Clear, realistic objectives	Baker et al. [42] ; Morris [7] ; Hughes [43] ; Pinto and Slevin [8] ; Pinto and Mantel [12] ;Tennant [4] ; Selin and Selin [17] ; Harding [44] ; Couillard [20] ; Yeo [45] ; Wateridge [46] ; The Standish Group [19] ; Beare [47] ; Tan [22] ; Munns and Bjeirmi [23] ; Spinelli [48] ; Cicmil [49] ; Dvir et al. [27] ; Glass [50] ; Kasser and Williams [28] ; Jang and Lee [29] ; Clarke [51] ; Weir [32] ; Taylor [33] ; Thite [34] ; Poon and Wagner [35] ; Anderson et al. [37] ; Caldeira and Ward [38] ; Yeo [39] ; Westerveld [40] ; Turner [41],	31
Strong/detailed plan kept up to date	Avots [5] ; Baker et al. [42] ; Cleland and King [6] ; Morris [7] ; Morris and Hough [9] ; Pinto and Mantel [12] ; Pollalis and Frieze [16] ; Martinez [18] ; The Standish Group [19] ; Wateridge [46] ; Couillard [20] ; Smart [52] ; Williams [53] ; Belassi and Tukel [24] ; KPMG [25] ; Spinelli [48] ; McCormack [3] ; McGolpin and Ward [26] ; Dvir et al. [27] ; Kasser and Williams [28] ; Glass [50] ; Whittaker [30] ; Clarke [51] ; Turner [31] ; Taylor [33] ; Andersen et al. [37] ; Yeo [39] ; Westerveld [40] ; Turner [41]	29
User/client involvement	Morris [7] ; Pinto and Slevin [8] ; Curtis et al. [54] ; Magal et al. [11] ; Pinto and Mantel [12] ; McComb and Smith [13] ; Yap et al. [15] ; Pollalis and Frieze [16] ; Wateridge [46] ; Smart [52] ; Beare [47] ; Wastell and Newman [21] ; Belassi and Tukel [24] ; Munns and Bjeirmi [23] ; Cicmil [49] ; Spinelli [48] ; McCormack [3] ; Dvir et al. [27] ; Jang and Lee [29] ; Turner [31] ; Caldeira and Ward [38] ; Yeo [39] ; Westerveld [40] ; Turner [41],	24
Skilled/suitably qualified/sufficient staff/team	Baker et al. [42] ; Morris [7] ; Pinto and Slevin [8] ; Curtis et al. [54] ; Magal et al. [11] ; Pinto and Mantel [12] ; McComb and Smith [13] ; Cash and Fox [14] ; Pollalis and Frieze [16] ; Tennant [4] ; Martinez [18] ; Willcocks and Griffiths [57] ; The Standish Group [19] ; Dvir et al. [27] ; Glass [50] ; Jang and Lee [29] ; Weir [32] ; Poon and Wagner [35] ; Caldeira and Ward [38] ; Westerveld [40]	20
Effective change management	Avots [5] ; Pinto and Mantel [12] ; McComb and Smith [13] ; Cash and Fox [14] ; Pollalis and Frieze [16] ; Martinez [18] ; Willcocks and Griffiths [57] ; Smart [52] ; The Standish Group [19] ; Hougham [58] ; Cicmil [49] ; McGolpin and Ward [26] ; Dvir et al. [27] ; Weir [32] ; Taylor [33] ; Thite [34] ; Poon and Wagner [35] ; Cooke-Davies [36] ; Yeo [39]	19
Competent project manager	Avots [5] ; Baker et al. [42] ; Morris [7] ; Pinto and Slevin [8] ; Pollalis and Frieze [16] ; Martinez [18] ; Cannon [59] ; Couillard [20] ; Pinto and Kharbanda [60] ; Belassi and Tukel [24] ; Munns and Bjeirmi [23] ; Spinelli [48] ; Dvir et al. [27] ; Glass [50] ; Weir [32] ; Taylor [33] ; Andersen et al. [37] ; Westerveld [40] ; Turner [41]	19
Strong business case/ sound basis for project	Avots [5] ; Pollalis and Frieze [16] ; Smart [52] ; Pinto and Kharbanda [60] ; Munns and Bjeirmi [23] ; KPMG [25] ; McGolpin and Ward [26] ; Dvir et al. [27] ; Whittaker [30] ; Poon and Wagner [35] ; Cooke-Davies [36] ; Andersen et al. [37] ; Caldeira and Ward [38] ; Yeo [39] ; Westerveld [40] ; Turner [41]	16
Sufficient/well allocated resources	Morris [7] ; Pinto and Slevin [8] ; Morris and Hough [9] ; Yap et al. [15] ; Pollalis and Frieze [16] ; Tennant [4] ; McCormack [3] ; The Standish Group [19] ; Belassi and Tukel [24] ; Gowan and Mathieu [55] ; Dvir et al. [27] ; Kasser and Williams [28] ; Turner [31] ; Caldeira and Ward [38] ; Westerveld [40] ; Turner [41]	15

Proven/familiar technology	Morris [7] ; Pinto and Mantel [12] ; McComb and Smith [13] ; Pollalis and Frieze [16] ; Cannon [59] ; Williams [53] ; Yeo [45] ; Tan [22] ; KPMG [25] ; Dvir et al. [27] ; Glass [50] ; Poon and Wagner [35] ; Caldeira and Ward [38] ; Yeo [39]	14
Realistic schedule	Cleland and King [6] ; Morris [7] ; Morris and Hough [9] ; Pinto and Mantel [12] ; McComb and Smith [13] ; Tennant [4] ; Selin and Selin [17] ; Dvir et al. [27] ; Glass [50] ; Kasser and Williams [28] ; Weir [32] ; Yeo [39] ; Westerveld [40] ; Turner [41]	14
Risks addressed/ assessed/ managed	Morris and Hough [9] ; Selin and Selin [17] ; Smart [52] ; Beare [47] ; Williams [53] ; KPMG [25] ; Baldry [61] ; Dvir et al. [27] ; Whittaker [30] ; Weir [32] ; Cooke-Davies [36] ; Yeo [39] ; Westerveld [40]	13
Project sponsor/champion	Morris [7] ; Morris and Hough [9] ; Cash and Fox [14] ; Yap et al. [15] ; Martinez [18] ; McGolpin and Ward [26] ; Jang and Lee [29] ; Baldry [61] ; Thite [34] ; Poon and Wagner [35] ; Caldeira and Ward [38] ; Yeo [39]	12
Effective monitoring/control	McComb and Smith [13] ; Cash and Fox [14] ; Pollalis and Frieze [16] ; Selin and Selin [17] ; Cicmil [49] ; Dvir et al. [27] ; Weir [32] ; Thite [34] ; Poon and Wagner [35] ; Cooke-Davies [36] ; Westerveld [40] ; Turner [41]	12
Adequate budget	Baker et al. [42] ; Cleland and King [6] ; Morris and Hough [9] ; Dvir et al. [27] ; McComb and Smith [13] ; Pollalis and Frieze [16] ; Tennant [4] ; Glass [50] ; Caldeira and Ward, [38] ; Westerveld [40] ; Turner [41]	11
Organisational adaptation/culture/ structure	Pollalis and Frieze [16] ; Cannon [59] ; Willcocks and Griffiths [57] ; Martinez [18] ; Couillard [20] ; Hougham [58] ; Gowan and Mathieu [55] ; Taylor [33] ; Thite [34] ; Cooke-Davies [36]	10
Good performance by suppliers/ contractors/ consultants	Morris and Hough [9]; Pollalis and Frieze [16] ; McCormack [3] ; KPMG [25] ; Glass [50] ; Jang and Lee [29] ; Caldeira and Ward [38] ; Yeo [39] ; Westerveld [40] ; Turner [41	10
Planned close-down/review/ acceptance of possible failure	Avots [5] ; Cleland and King [6] ; Sauer [62] ; Beare [47] ; Pinto and Kharbanda [60] ; Munns and Bjeirmi [23] ; McCormack [3] McGolpin and Ward [26] ; Dvir et al. [27]	9
Training provision	Magal et al. [11] ; Yap et al. [15] ; Pinto and Kharbanda [63] ; Pinto and Kharbanda [60] ; McCormack [3] ; Dvir et al. [27] ; Caldeira and Ward [38]	7
Political stability	Morris and Hough [9] ; Pollalis and Frieze [16] ; Tennant [4] ; Sauer [62] ; Yeo [45] ; Pinto and Kharbanda [60]	6
Correct choice/past experience of project management/ methodology/tools	Hughes [43] ; Munns and Bjeirmi [23] ; Dvir et al. [27] ; Glass [50] ; Jang and Lee [29] ; Turner [41]	6
Environmental influences	Morris [7] ; Cleland and King [6] ; Archibald [65] ; Pinto and Kharbanda [60] ; Caldeira and Ward [38] ; Westerveld [40]	6
Past experience (learning from)	Yap et al. [15] ; Dvir et al. [27] ; Jordan et al. [64] ; Sauer [62] ; Cooke-Davies [36], 5, Project size (large)/level ofcomplexity (high)/number of people involved (too many)/ duration (over 3 years), Hughes [43] ; Selin and Selin [17] ; Cannon [59] ; Cooke-Davies [36	4
Different viewpoints (appreciating)	Curtis et al. [54] ; Pinto and Kharbanda [63] ; Turner [41]	3

Appendix B – Audit Notes



Appendix C – Model



Appendix D – Case study 1 daily report

DATE: 2019/10/23 DAILY REFUGE CHAMBER CHECKS

DAILY/ WEEKLY	REFUGE BAY	SECTION	RESPONSINBLE HOD	PERSON REPORTING	PHONE NUMBER	PHONE INORDER?	COMPRESSED AIR WORKING?	WATER AVAILABLE?	FRONT/REAR WALL IN ORDER?	OTHER DEVIATIONS ?
DAILY	2-5 level Station	02P	D. LINGWOOD		1407	Yes	Yes	Yes	Yes	No
DAILY	17 Level Station	02P	D. LINGWOOD		1703	Yes	Yes	Yes	Yes	No
DAILY	18 Level Station	Engineering	D. LINGWOOD		1418	Yes	Yes	Yes	Yes	No
DAILY	19 Level Station	Engineering	D. LINGWOOD		1419	Yes	Yes	Yes	Yes	No
DAILY	20 Level Station	Enginnering	D. LINGWOOD		1510	Yes	Yes	Yes	Yes	No
DAILY	21 Level Station	Engineering	D. LINGWOOD		1375	Yes	Yes	Yes	Yes	No
DAILY	22 Level Station	Engineering	D. LINGWOOD		1351	Yes	Yes	Yes	Yes	No
DAILY	22/43	022A	E. Zimila		1780	Yes	Yes	Yes	Yes	No
DAILY	22/43	022A	J. Du Plooy		1627	Yes	Yes	Yes	Yes	No
DAILY	23 Level Station	Engineering	D. LINGWOOD	Thabo	1427	Yes	Yes	Yes	Yes	No
DAILY	23 43 (8#)	022A	S Dlamini		1777	Yes	Yes	Yes	Yes	No
DAILY	23 43	022E	S Dlamini		1629	Yes	Yes	Yes	Yes	No
DAILY	23 44	022A	E.Zimila		1524	Yes	Yes	Yes	Yes	No
WEEKLY	23 Tram Hlge 3#	TRAMMING 4#	D. LINGWOOD		3632	Yes	Yes	Yes	Yes	No
WEEKLY	23 HLGE 4#	TRAMMING 4#	D. LINGWOOD		1785	Yes	Yes	Yes	Yes	No
WEEKLY	23 HLGE 7#	TRAMMING 4#	D. LINGWOOD			Yes	Yes	Yes	Yes	No
DAILY	23 60 (Minus)	02P	D. LINGWOOD	Timbane	1493	Yes	Yes	Yes	Yes	No
DAILY	24 Level Belt 1	Engineering	D. LINGWOOD		1492	Yes	Yes	Yes	Yes	No
DAILY	24 Level Belt 2	Engineering	D. LINGWOOD		1553	Yes	Yes	Yes	Yes	No
DAILY	24 Level Station	22A	E. Zimila		1257	Yes	Yes	Yes	Yes	No
DAILY	25 65 XC	024A	F. Borissza		1749	Yes	Yes	Yes	Yes	No
	25 Level Station	022A/ 022C	E. Zimila/G. van Wyngaart		1776	Yes	Yes	Yes	Yes	No
	25/47	NO WORK				Yes	Yes	Yes	Yes	No
DAILY	25/42 X/C	22D	J. Du Plooy		1625	Yes	Yes	Yes	Yes	No
DAILY	25/49 X/C	22A	E Zimila		1391	Yes	Yes	Yes	Yes	No
DAILY	VCR 25/50	ROSOND	W. DIPHOKO		1438	Yes	Yes	Yes	Yes	No
DAILY	25/53 X/C	024A	F. Borissza		1353	Yes	Yes	Yes	Yes	No
DAILY	MB 25/54 FWD	22B	G.VAN WYNGAARDT		1462	Yes	Yes	Yes	Yes	No
DAILY	MB 25/54 HWD	24A	F. Borissza		1260	Yes	Yes	Yes	Yes	No
DAILY	MB 25/55	02TT	H Blom	Francisco	1386	Yes	Yes	Yes	Yes	No
DAILY	MB 25/55	02TT	H Blom		1387	Yes	Yes	Yes	Yes	No
DAILY	MB 25/61	022B	F. Borissza		1465	Yes	Yes	Yes	Yes	No
DAILY	MB 25 61	022B	G.VAN WYNGAARDT		1258	Yes	Yes	Yes	Yes	No
DAILY	MB 25 61	022B	G.VAN WYNGAARDT		1560	Yes	Yes	Yes	Yes	No
DAILY	26 LEVEL STATION	Engineering	D. LINGWOOD		1428	Yes	Yes	Yes	Yes	No
	26 45 XC E	NO WORK			1288	Yes	Yes	Yes	Yes	No
DAILY	26 42 XC E	022D	J. DU PLOOY	Mafueka	1225	Yes	Yes	Yes	Yes	No
	26/47	NO WORK			1390	Yes	Yes	Yes	Yes	No
DAILY	27 Level Station	Engineering	D. LINGWOOD	Dean	1747	Yes	Yes	Yes	Yes	No
DAILY	VCR 27/42	022D	J. DU PLOOY	Matiwane	1280	Yes	Yes	Yes	Yes	No
DAILY	VCR 27 45	022D	J. DU PLOOY	Mnakane	1305	Yes	Yes	Yes	Yes	No
DAILY	MB 27 43	02TT	H Blom	Phakathi	1763	Yes	Yes	Yes	Yes	No
DAILY	MB 27/50	022A	E. Zimila		1227	Yes	Yes	Yes	Yes	No
DAILY	MB 27/53	24A	F. Borissza		1559	Yes	Yes	Yes	Yes	No
DAILY	MB 27 55	22E	S.Dlamini	Sandile	1470	Yes	Yes	Yes	Yes	No
DAILY	MB 27/58	22A	E. Zimila	Albert	1652	Yes	Yes	Yes	Yes	No
DAILY	MB 27/64	024A	F. Borissza		1704	Yes	Yes	Yes	Yes	No
DAILY	MB 27/65	022E	S.Dlamini		1410	Yes	Yes	Yes	Yes	No
DAILY	MB 28 45	022E	S.Dlamini		1251	Yes	Yes	Yes	Yes	No
DAILY	MB 28 55	022E	S.Dlamini		1363	Yes	Yes	Yes	Yes	No
DAILY	MB28 60	24A	F Borizza		1231	Yes	Yes	Yes	Yes	No
DAILY	28 Level Station	Engineering	D. LINGWOOD	Joseph	1301	Yes	Yes	Yes	Yes	No
DAILY	KLF 28/32	022E	S.Dlamini	Monwabisi	1248	Yes	Yes	Yes	Yes	No
DAILY	VCR 28/45	022D	J. DU PLOOY		1495	Yes	Yes	Yes	Yes	No
DAILY	VCR 28/55	022D	J. Du Plooy		1345	Yes	Yes	Yes	Yes	No
DAILY	KLF 28/34	022D	J. DU PLOOY		1503	Yes	Yes	Yes	Yes	No
DAILY	KLF 28/40	02TT	H Blom	Stimela	1373	Yes	Yes	Yes	Yes	No
DAILY	MB 28/43	02TT	H Blom	Majoe	1309	Yes	Yes	Yes	Yes	No
DAILY	VCR 28/44	022D	J. DU PLOOY		1251	Yes	Yes	Yes	Yes	No
DAILY	MB28/53	022E	S.Dlamini		1467	Yes	Yes	Yes	Yes	No
DAILY	VCR 28/49	022C	G.VAN WYNGAARDT		1504	Yes	Yes	Yes	Yes	No
DAILY	VCR 28/49	022DE	J. DU PLOOY	Charlie	1468	Yes	Yes	Yes	Yes	No
DAILY	29 Level Station	Engineering	D. LINGWOOD	Nelson	1509	Yes	Yes	Yes	Yes	No
	KLF 29/39	NO WORK				Yes	Yes	Yes	Yes	No
DAILY	VCR 29 43	022D	J. DU PLOOY		1774	Yes	Yes	Yes	Yes	No
DAILY	MB 29/43	02TT	H Blom	Mhlanga	1748	Yes	Yes	Yes	Yes	No
DAILY	MB 29/53	022E	S.Dlamini	Joana	1757	Yes	Yes	Yes	Yes	No
DAILY	MB 29/63	022E	S.Dlamini	Tshidi	1246	Yes	Yes	Yes	Yes	No
DAILY	MB 29/58	02TT	H Blom	Kgotso	1282	Yes	Yes	Yes	Yes	No
DAILY	MB 29/60A/61	24A	F. Borissza/E. Zimila		1284	Yes	Yes	Yes	Yes	No
DAILY	29/63	22A	E Zimila		1241	Yes	Yes	Yes	Yes	No
DAILY	30 Lev Stn 1 Sub	Engineering	D. LINGWOOD		1240	Yes	Yes	Yes	Yes	No
DAILY	VCR 30/43	022C	G.VAN WYNGAARDT		1255	Yes	Yes	Yes	Yes	No
DAILY	MB 30/43	02TT	H Blom		1238	Yes	Yes	Yes	Yes	No
DAILY	MB30/57	24A	F Borizza		1235	Yes	Yes	Yes	Yes	No
DAILY	MB 30/55	24A	F. Borissza	Anderson	1247	Yes	Yes	Yes	Yes	No
DAILY	VCR 30/43	022C	G.VAN WYNGAARDT	Thobela	1565	Yes	Yes	Yes	Yes	No
DAILY	31 Level Station	Engineering	D. LINGWOOD		1478	Yes	Yes	Yes	Yes	No
DAILY	MB 31/43	02TT	H Blom		1242	Yes	Yes	Yes	Yes	No
DAILY	MB 31/43	02TT	H Blom		1479	Yes	Yes	Yes	Yes	No
DAILY	MB 31/43	022C	G.VAN WYNGAARDT	Mthimkhulu	1335	Yes	Yes	Yes	Yes	No
DAILY	MB 31/56	24A	F. Borissza	Ncamile	1333	Yes	Yes	Yes	Yes	No
DAILY	32 43 X/C (1)	22A	E. Zimila		1713	Yes	Yes	Yes	Yes	Yes
DAILY	32 43 X/C (2)	22A	E. Zimila		1713	Yes	Yes	Yes	Yes	No