

Mine ventilation characterisation through simulations

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PREFACE

This thesis was compiled and presented in **Article Format**. Accordingly, the four articles are appended showing the key results of the thesis. Each article was considered independently and was submitted to journals for publication. Each article was also presented with a logical flow to highlight the novel contributions made to the current field of knowledge. The significance of each article is unique, contributing towards one integrated research goal namely, mine ventilation characterisation through simulations. Permission was attained from all relevant parties for publication.

ABSTRACT

Title: Mine ventilation characterisation through simulations
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Keywords: Mine ventilation networks, Operational changes, Simulations, Optimisation, Sustainable cost saving, Life of mine, Primary access, Simulations, Integrated planning, Cost analysis, Economic quantification model, Energy efficiency, Non-energy benefits, Service delivery, Variable speed drives, Ventilation on demand, Greenhouse gas emissions.

The profitability of the mining industry is contingent on the industry's ability to improve upon the status quo of operational efficiency. If the archaic operating methods of mines are altered to embrace and incorporate simulation technologies, improvements can be made to, inter alia, characterisation, energy usage, planning, equipment utilisation, operational efficiency and profitability. Literature indicated a need for improved characterisation of complex mining systems. Mine ventilation is a complex mining system, which is crucial for safe and legal mining operations. Considering that this system may represent up to half of a mine's energy consumption, there is large scope for improved characterisation through simulations.

Literature indicated that there was a need for improved mine ventilation characterisation through simulations for operational changes. This study therefore focussed on developing a framework to characterise mine ventilation systems incorporating simulations. Through the use of the simulations, mine ventilation characterisation was improved for the quantification of energy efficiency projects, life-of-mine planning and the use of medium-voltage variable speed drives as part of ventilation-on-demand applications. As a result, four individual articles were compiled that contribute towards the framework. This framework lead to improved mine ventilation characterisation through simulations combining novel methods, models and variable speed drive technologies.

In Article I (Appendix A), a scalable, step-by-step method was developed to evaluate and optimise mine ventilation networks through simulations. This method was implemented on a case study mine ventilation network with the study validation resulting in an energy saving of 23% per annum. The most feasible operational change as indicated by the novel method has

been active for a period of 18 months. The total energy savings measured for this period amounted to 13.32 GWh, resulting in an energy cost saving of US\$0.7 million. In Article II (Appendix B), a novel economic quantification model was developed to quantify and monetise the true financial benefit of mine ventilation energy efficiency projects. The study validation showed that the feasibility of implementing energy efficiency projects on mine ventilation networks increases with the inclusion of non-energy benefits. The total financial benefit including non-energy benefits proved to be three times more and reduced payback periods by 33% on average when compared with traditional energy saving quantification models.

In Article III (Appendix C), a novel integrated simulation planning method was developed for primary access and ventilation network life-of-mine planning. This method was implemented successfully on a case study mining complex. The most feasible planning scenario, as indicated by the method, resulted in a cost avoidance of US\$28.8 million. This amounted to an average cost avoidance percentage of 27%.

In Article IV (Appendix D), characterisation and simulation were used to evaluate the use of medium-voltage variable speed drives as part of ventilation-on-demand applications. This was done on ten South African mine ventilation networks. The large-scale assessment was conducted for two ventilation-on-demand applications, namely, static and dynamic. The assessment results indicated that it was economically viable to implement both applications, which resulted in a combined estimated cost saving of US\$11.57 million with a payback period of nine months. This would result in an estimated energy saving of 53% on the ventilation network.

The final remarks of the thesis indicated that mine ventilation characterisation can be improved through simulations, thus contributing to the current field of knowledge.

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Thank you to the following whose contributions were critical to the success of this research.

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- Enermanage (Pty) Ltd for funding the research.

LIST OF ARTICLES

This thesis is based on the work described in the articles listed below, as such, an article format was selected. In the thesis, the four interconnected articles are referred to by Roman numerals. These articles are appended with permissions of the copyright holders.

- I. A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "A case study perspective: Evaluation of complex mine ventilation operational changes through simulations," *Journal of Energy in South Africa*, 2018.
- II. A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Economic quantification model for energy efficiency projects in the mining industry," *Energy*, 2018.
- III. A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Life-of-mine primary access and ventilation planning through simulations," *The Journal of the South African Institute of Mining and Metallurgy*, 2018.
- IV. A. J. H. Nel, D. C. Arndt, J. C. Vosloo, and M. J. Mathews, "Achieving energy efficiency with medium voltage variable speed drives for main ventilation fans in South African mines," *Sustainable Energy Technologies and Assessments*, 2018.

Conference proceedings:

- A. J. H. Nel, J. F. van Rensburg, and C. Cilliers, "Improving existing DSM initiatives on mine refrigeration systems for sustainable performance," *The 14th Industrial and Commercial Use of Energy Conference (ICUE)*, p 1–7, 2017.

Other planned publications, which are not included in this thesis:

- A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Lost blast analysis for the gold and platinum mining industry," *The Journal of the South African Institute of Mining and Metallurgy*, 2018.

The student, A. J. H. Nel, was responsible for the technical content of every article. The thesis was submitted with permission of the co-authors, namely, Dr J. C. Vosloo, Dr M. J. Mathews and Dr D. C. Arndt. The proof of permission of each article is shown by the co-author statement in Chapter 1.4.

TABLE OF CONTENTS

PREFACE	i
ABSTRACT.....	ii
ACKNOWLEDGEMENTS.....	iv
LIST OF ARTICLES	v
TABLE OF CONTENTS	vi
ABBREVIATIONS	viii
CHAPTER 1 INTRODUCTION	1
1.1 BACKGROUND	2
1.2 STUDY MOTIVATION	4
1.3 NOVEL CONTRIBUTIONS.....	5
1.4 CO-AUTHOR STATEMENT	10
1.5 THESIS OVERVIEW.....	11
CHAPTER 2 LITERATURE SURVEY	12
2.1 PREAMBLE	13
2.2 MINE VENTILATION OPERATIONAL CHANGES	13
2.3 ECONOMIC QUANTIFICATION MODEL.....	15
2.4 MINE VENTILATION LOM PLANNING	18
2.5 MINE VENTILATION VOD POTENTIAL.....	20
2.6 CONCLUSION.....	22
CHAPTER 3 PUBLICATIONS SUMMARY	23
3.1 PREAMBLE	24
3.2 ARTICLE I.....	24
3.3 ARTICLE II.....	25
3.4 ARTICLE III.....	26
3.5 ARTICLE IV	27
3.6 DISCUSSION	28
CHAPTER 4 CONCLUSION.....	34
4.1 PREAMBLE	35
4.2 CONCLUSION.....	35
4.3 FUTURE RESEARCH	37
CHAPTER 5 REFERENCE LIST	39

APPENDIX A: A CASE STUDY PERSPECTIVE: EVALUATION OF COMPLEX MINE VENTILATION OPERATIONAL CHANGES THROUGH SIMULATIONS.....	47
APP. A.1: ARTICLE I.....	48
APP. A.2: JESA GUIDELINES FOR AUTHORS.....	71
APPENDIX B: ECONOMIC QUANTIFICATION MODEL FOR ENERGY EFFICIENCY PROJECTS IN THE MINING INDUSTRY.....	78
APP. B.1: ARTICLE II.....	79
APP. B.2: ENERGY GUIDELINES FOR AUTHORS	103
APPENDIX C: LIFE-OF-MINE PRIMARY ACCESS AND VENTILATION PLANNING THROUGH SIMULATIONS	118
APP. C.1: ARTICLE III.....	119
APP. C.2: SAIMM GUIDELINES FOR AUTHORS.....	145
APPENDIX D: ACHIEVING ENERGY EFFICIENCY WITH MEDIUM VOLTAGE VARIABLE SPEED DRIVES FOR VOD IN SOUTH AFRICAN MINES	152
APP. D.1: ARTICLE IV	153
APP. D.2: SETA GUIDELINES FOR AUTHORS	179

ABBREVIATIONS

ACP	Air cooling power
CFD	Computational fluid dynamics
EE	Energy efficiency
GHG	Greenhouse gas
IGV	Inlet guide vane
IoT	Internet of things
LOM	Life-of-mine
MV	Medium voltage
NEB	Non-energy benefit
VOD	Ventilation on demand
VSD	Variable speed drive

CHAPTER 1 INTRODUCTION



1

“I find my greatest pleasure, and so my reward, in the work that precedes
what the world calls success.”

– Thomas A. Edison

¹ Harmony Gold, “Kusasaletu mine,” 2018. [Online]. Available:
<https://www.harmony.co.za/our-business/our-operations/kusasaletu> [Accessed 2 January 2018].

1.1 BACKGROUND

The global energy demand has steadily increased since the industrial revolution. The increase can mainly be attributed to the industrial and mining sector's rapid development to satisfy growing societal needs [1]. South Africa's economy is built on minerals extraction and processing, which is energy intensive by nature [1].

Historically, low coal and electricity prices contributed towards the country's energy intensive development and exacerbated the drive to improve upon the status quo of energy efficiency (EE) [2]. Energy conservation measures are seen as the most cost-effective approach to achieve sustainable economic development [3]. Considering the current global economic state and challenges faced with the profitability of mining in general, energy conservation measures could prove to be invaluable towards sustainable production [4]. Bleak economic outlooks are therefore forcing companies to investigate, plan, integrate and implement EE measures to improve operational efficiencies [4].

Considering that mine ventilation networks represent between 25% and 50% of the energy consumed in a mining operation, large potential exists to realise electrical cost savings through optimisation [5], [6]. Mine ventilation networks are used to ensure that underground environmental conditions are conducive to safe and productive mining [7]. This is done by supplying sufficient airflow to the working areas to govern heat stress imposed on workers, and to dilute and exhaust hazardous particulates to below statutory occupational exposure levels [8].

Typical backward curved airfoil centrifugal fans employed on deep-level mine as main fans have installed capacities ranging between 500 kW and 2.1 MW per fan [5], [9]. Mine ventilation networks consist of hundreds of interconnected sections and applications such as airways, raises, cross-cuts, main shafts, vent shafts, sub-shafts, raise boreholes, ventilation doors, travelling ways, fans and regulators [6]. In view of the complexity of the ventilation network and the progression of mine development, it is easy to comprehend that inefficiencies such as short circuits, insufficient airflow velocities, increasing temperatures and leakages occur in such a vast network [7]. The characterisation of such a critical complex system is therefore a very daunting, time-consuming task.

Due to the dynamic nature of deep-level mining, the engineering challenges faced to contend with higher virgin rock temperatures and more complex ventilation networks increase by virtue of increased depth [10]. The costs associated with providing acceptable working conditions

for reserves that are farther and deeper away from ventilation shafts become a critical determinant towards the feasibility of mining [8].

Operational efficiency is therefore the lifeline of increasing mine profitability as shown by the industry's drive to improve upon the status quo [5], [11]. In modern mining, there has been a recognition towards technological advances, to which the rapid development and increased production targets can be attributed [12]. Mines are therefore expanding operations vertically and horizontally in an effort to achieve these production targets in the most efficient manner possible. Research indicates that electricity, inter alia, possesses the largest potential to increase operational efficiency on mines [13].

Mine ventilation characterisation has a long and fascinating history as described by McPherson, with the basic principles established by Buddle and Atkinson in the late 1850s [14]. During the turn of the 19th century, measurements of airflow velocities, environmental temperatures and pressures to characterise ventilation networks, started to arise in a number of countries. Hinsley (1943) applied thermodynamic theory to mine ventilation networks to characterise the mechanisms involved with the behaviour of air in underground deep-level mines [14]. The incorporation of thermodynamic theory specifically contributed towards improved ventilation surveying techniques, particularly in mines with significant air density differences [15].

The turn of the digital age brought about mine ventilation simulation software as a characterisation tool to predict the airflow in underground working conditions [15]. The software dominated ventilation planning, which resulted in unprecedented levels of accuracy and flexibility [16]. Mine ventilation simulation software development continued to include thermodynamic relationships as opposed to only including the simpler laws of incompressible flow processing capabilities [14]. However, despite the availability and development of mine ventilation simulation software, several mines still use outdated methods to characterise mine ventilation networks [14], [15], [16].

It is only recently with technological advances that simulation packages became available to design, optimise and plan other critical systems such as primary access systems [17]. Life-of-mine (LOM) planning has been conducted in a segregated manner for mine ventilation networks, frequently omitting the interrelated effects of other systems [14]. Mine ventilation characterisation can be improved by incorporating an integrated approach towards planning to ensure acceptable underground working conditions.

Several EE initiatives have been implemented on mine ventilation networks, which yielded significant electrical cost savings [9]. In some cases, there are additional synergistic benefits, over and above the standard electricity cost savings, that arise from the implementation of EE projects [18]. These non-energy benefits (NEBs) have previously been incorporated as part of the motivation behind EE projects and technologies [19].

Nonetheless, in order for EE projects to appeal to the mining industry, the total financial benefit should be monetised to a single value [20]. This value should encompass all benefits in terms of energy, NEBs, as well as the effect on productivity and ultimately profitability [21]. It is therefore crucial to quantify the total financial benefit of implementing EE initiatives on mine ventilation networks as part of mine ventilation characterisation.

Positive economic development has been linked to increased energy and material usage [22], [23]. However, globally there is a growing concern of environmental and energy security, emphasising the need for intelligent novel energy solutions [24]. Fortunately, improving upon the status quo of operational efficiency has become the norm with archaic operations incorporating new innovative technologies [25].

A paradigm shift has occurred in the international mining arena towards using more efficient equipment that includes, inter alia, the installation of variable speed drives (VSDs) on refrigeration systems, pumps and fans [12], [26]. The viability of installing VSDs has been proven as a tool to achieve cost savings in various applications across complex industrial systems [27]. However, the use of medium-voltage (MV) VSDs as part of ventilation-on-demand (VOD) potential in South African mines has not yet been investigated. Therefore, it is extremely important to assess and establish the potential effects of incorporating MV VSDs as part of VOD potential in South African mines, especially for mine ventilation characterisation.

1.2 STUDY MOTIVATION

The aim of this thesis is to improve mine ventilation characterisation through simulations including novel methods, models and the use of MV VSDs. The aim is set to analyse, optimise and quantify mine ventilation characterisation to yield improved operational efficiencies and decision-making capabilities. Mine ventilation characterisation is addressed by considering four components. Firstly, the influence of various operational changes on mine ventilation networks. Secondly, the influence of quantifying the total financial benefit of EE initiatives applicable to mine ventilation networks. Thirdly, the influence of analysing and optimising the

primary access and ventilation LOM planning in an integrated manner. Lastly, the potential of incorporating new technologies such as MV VSDs as part of VOD potential on mine ventilation networks. The improved characterisation thereof has several advantages and include, but are not limited to:

- Improved evaluation of operational changes and LOM planning.
- Improved optimisation of operational changes and LOM planning.
- Reduced operational- and capital costs.
- Reduced greenhouse gas (GHG) emissions.
- Integration of mine ventilation network constraints and key performance indicators.
- Improved financial feasibility of EE initiatives on mine ventilation networks.
- Integration of primary access and ventilation LOM planning.
- Improved risk mitigation and feasibility analysis.
- Improved incorporation and utilisation of new technologies.

The holistic problem statement is summarised below as a guide through the thesis:

The characterisation of complex mine ventilation networks through simulations, methods, models and technology will result in improved evaluation, optimisation and planning capabilities for deep-level mines. This will increase the operational efficiency and therefore the profitability of these mines.

1.3 NOVEL CONTRIBUTIONS

The aim of this thesis is to satisfy the holistic problem statement to improve mine ventilation characterisation through simulations. This is satisfied by the developed framework, which can be defined as the primary novel contribution of this thesis. Nevertheless, this framework can be divided into sub-contributions. Each of the sub-contributions satisfy a specific section of the holistic problem statement and are listed below according to each article and subsequent research question. These contributions lead to improved mine ventilation characterisation through simulations.

Novel sub-contributions:

- I. A scalable, step-by-step method to evaluate and optimise operational changes in mine ventilation networks through simulations.

Current operations (How is it done?)

Mine ventilation operational changes are rarely optimised and evaluated in the mining industry. Many mines in the private sector implement operational changes and continue with mine development without considering ventilation. The mines that do optimise and evaluate operational changes in mine ventilation networks conduct these studies through manual calculations and continuous ventilation network testing, or rely on the experience of mine personnel for qualitative recommendations. These studies are extremely resource intensive and do not account for the varying level of detail required for optimisation and evaluation studies.

Limitations (Why are the current methods insufficient?)

Although simulations provide a more accurate, versatile and cost-effective solution for evaluation and optimisation studies for complex systems, these technologies are not incorporated in current mine procedures and standards. This can be attributed to a lack of information on exactly how to incorporate simulations as part of optimisation and evaluation studies. As a result, there is no step-by-step framework or method available in literature to incorporate simulations as part of optimisation and evaluation studies.

Requirement (What is needed?)

There is a need for a method incorporating simulations to evaluate and optimise operational changes in mine ventilation networks. Literature has shown that the operational efficiency of complex systems can be increased significantly with the use of simulations as part of these studies.

Contribution (How is it solved?)

In Article I, a scalable, step-by-step method was developed to evaluate and optimise operational changes in mine ventilation networks through simulations. The developed method specifically included a level of scalability to enable mine personnel to conduct varying degree of detail studies, lowering the required resource intensity for these studies.

- II. A novel, economic quantification model for EE projects in the mining industry. This model includes the quantification and monetisation of direct and indirect savings as a result of EE project implementation.

Current operations (How is it done?)

The feasibility of EE projects in the mining industry are currently evaluated according to the financial cost saving as a result of energy savings. However, in some projects, there are additional synergistic benefits over and above the traditional energy saving that arises from implementation. These NEBs have previously been incorporated as part of EE project motivation in industrial projects. However, in order for these projects to appeal to the struggling mining industry, the total financial benefit should be quantified and monetised to a single value, especially for mine ventilation EE projects.

Limitations (Why are the current methods insufficient?)

NEBs are frequently omitted in financial feasibility studies of mine ventilation EE projects. This is attributed to a lack of information on how to quantify and monetise NEBs in the mining industry, particularly, indirect NEBs that are extremely difficult to identify, quantify and monetise. Accordingly, there is no model available in literature to quantify and monetise the total benefit of EE projects in the mining industry.

Requirement (What is needed?)

There is a need to quantify and monetise NEBs of EE projects in the mining industry to increase the uptake and implementation of these projects. The total benefit should be comprehensive, encompassing all benefits related to these projects.

Contribution (How is it solved?)

In Article II, an economic quantification model was developed to quantify and monetise the total financial benefit of EE projects. The quantification and monetisation included direct and indirect NEBs. The developed model builds on work done nearly four decades ago.

- III. An integrated simulation planning method for primary access and ventilation LOM planning. This method includes the evaluation, optimisation and integrated planning of these two interrelated mining systems.

Current operations (How is it done?)

Traditional design and modelling methods used for LOM planning include manual calculations and manual interpretation of graphical information. LOM planning is predominantly used to determine the mineral reserves and spatial distribution of ore body grades. Simulations have previously been used as part of LOM planning for mineral reserves. However, the effects of

future planned production on other critical mining systems such as the primary access (hoisting) system and ventilation network have been neglected. LOM planning is therefore not integrated as it only considers a narrow bandwidth of production-related factors.

Limitations (Why are the current methods insufficient?)

Simulations have been incorporated as part of initial design and planning for complex mining systems. The primary access system and ventilation networks are such systems where extensive simulation developments have occurred. However, despite the availability of simulation packages for these systems, simulations have not been incorporated as part of LOM planning. In addition, the interrelated effects between the primary access system and ventilation network have been neglected in traditional LOM planning.

Requirement (What is needed?)

There is a need for an integrated method incorporating simulations as part of primary access and ventilation LOM planning. Literature indicated that simulations are the only viable method to thoroughly evaluate, optimise and plan complex systems. The method should provide the flexibility to determine and encapsulate the effects of future planned production rates on critical mining systems.

Contribution (How is it solved?)

In Article III, an integrated simulation planning method was developed to be used for primary access and ventilation LOM planning. The developed method provides a holistic approach towards LOM planning for critical mining systems through simulations. The integrated method was developed to take the interrelated effects of these two critical mining systems into account with the final cost analysis.

- IV. An assessment conducted on ten South African mine ventilation networks to determine the prospective utilisation of MV VSDs as part of VOD potential through mine simulation and characterisation. The large-scale study provides the method and calculations used to determine the energy savings, cost savings and GHG emission reductions for different VOD applications.

Current operations (How is it done?)

South African mine ventilation fans are currently controlled with inlet guide vanes (IGVs) to supply a constant airflow volume to the underground working areas. However, as a result of the cyclical nature of mining, the airflow demand profile is dynamic and the constant supply is therefore inefficient. VOD is an application in which the airflow volume supplied to the underground working areas is controlled according to the demand, thus improving operational efficiency. VSDs were proven to be the most efficient means of flow modulation and have been used for several applications in several industries. Nonetheless, there is no documented case study in which MV VSDs were installed on mine ventilation fans as part of VOD applications in South Africa. Additionally, there is no verified airflow demand profile available in literature to be used as part of VOD potential evaluations.

Limitations (Why are the current methods insufficient?)

The use of IGV for flow modulation was proven to be inefficient as a result of the pressure loss experienced across the vanes. Nonetheless, these technologies are still in use although new, more efficient technologies such as MV VSDs are available for flow modulation. This can be ascribed to a lack of information on the use of MV VSDs as part of VOD potential on mines. Therefore, no assessment is available in literature on the potential implementation of VOD applications.

Requirement (What is needed?)

There is a need for a novel assessment on the use of MV VSDs as part of VOD potential on South African mine ventilation fans. This would provide the potential use of MV VSDs to achieve energy savings, cost savings and reduce GHG emissions. In addition, a novel daily airflow volume demand profile is required to provide sufficient airflow volume to the underground working areas.

Contribution (How is it solved?)

In Article IV, an assessment was conducted on the use of MV VSDs as part of VOD potential. An established large-scale audit method was altered to provide a true indication towards the financial feasibility of installing MV VSDs as part of VOD potential. In the assessment, a unique method was developed to implement such applications without affecting service delivery. If the airflow leakage of typical mines is repaired, the airflow volume can be reduced through modulation resulting in the same service delivery conditions, with a higher airflow utilisation and lower energy consumption.

Scope of the thesis:

The scope of the thesis is mine ventilation characterisation through simulations. In particular, to improve the operational efficiency of mines by making more comprehensive decisions. This thesis endeavours to add new insights relating to operational changes, quantification of NEBs, LOM planning and the use of MV VSDs as part of VOD potential. In this regard, the novel contributions were successfully applied to case studies. Each novelty underlines the immense need for improved mine ventilation characterisation through simulations coupled with innovative methods, models and new technologies.

1.4 CO-AUTHOR STATEMENTS

I, J. C. Vosloo, hereby provide consent that the articles listed below (I to IV), may be used as part of A. J. H. Nel's PhD thesis.

Signature: Date:  2018

I, M. J. Mathews, hereby provide consent that the articles listed below (I to IV), may be used as part of A. J. H. Nel's PhD thesis.

Signature: Date:  2018

I, D. C. Arndt, hereby provide consent that the article listed below (IV), may be used as part of A. J. H. Nel's PhD thesis.

Signature: Date:  2018

Articles:

- I. A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "A case study perspective: Evaluation of complex mine ventilation operational changes through simulations," *Journal of Energy in South Africa*, 2018.

- II. A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Economic quantification model for energy efficiency projects in the mining industry," *Energy*, 2018.
- III. A. J. H. Nel, J. C. Vosloo, and M. J. Mathews, "Life-of-mine primary access and ventilation planning through simulations," *The Journal of the South African Institute of Mining and Metallurgy*, 2018.
- V. A. J. H. Nel, D. C. Arndt, J. C. Vosloo, and M. J. Mathews, "Achieving energy efficiency with medium voltage variable speed drives for main ventilation fans in South African mines," *Sustainable Energy Technologies and Assessments*, 2018.

1.5 THESIS OVERVIEW

The thesis overview is presented below to provide a structured approach to the appended research articles. The overview is intended to provide an introduction, summary and convey how each research article satisfies a research question.

Chapter 1: Introduction – A synopsis of the thesis is given and the thesis structure highlighted. This is done by providing the background and study motivation of the holistic thesis problem statement. The most important novel contributions of this thesis are underlined to provide a clear research objective.

Chapter 2: Literature survey – The literature relating to the formulation and need of each research question for the appended articles are presented. The research is structured to show the importance and relevance thereof towards the holistic thesis problem statement.

Chapter 3: Publications – A summary of each research article is presented with the novelty of each article highlighted and discussed.

Chapter 4: Conclusion – The concluding remarks of the thesis are presented with the final insights synthesised and future research proposed.

CHAPTER 2 LITERATURE SURVEY



2

“The noblest pleasure is the joy of understanding.”

– Leonardo da Vinci

² A. J. H. Nel, Personal photograph. "Mine surface ventilation fans," Gauteng, South Africa, 2015.

2.1 PREAMBLE

In this chapter, literature is provided on the limitations of current mine ventilation characterisation knowledge. An in-depth look at the current methods and techniques employed in industry are presented and analysed to highlight the need for this thesis. The literature survey is structured to emphasise the significance of each research question in the thesis. The chapter concludes with the formulation of each research question, which was satisfied by the novel contributions of the appended articles. The literature survey is presented in the same logical flow as the appended articles to underline the importance of each individual research question.

2.2 MINE VENTILATION OPERATIONAL CHANGES

Mine ventilation networks consist of hundreds of interconnected sections and applications [6]. This complex network has one main objective, namely, to provide sufficient quantity and quality of airflow to dilute and exhaust hazardous particulates to ensure safe working conditions for underground mineworkers [8], [15]. The exact definition of sufficient quantity and quality varies between countries and are dependent on the history of mining in each country [28]. However, the statutory ventilation requirements are specified for each country by law, underlining the importance of mine ventilation networks [14].

In South Africa, there are two important factors affecting the operations of mine ventilation, namely, wet-bulb temperature (T_{wb}) and air cooling power (ACP) [29]. Legislation stipulates that work should not proceed underground when the wet-bulb temperature exceeds 32.5°C or the dry-bulb temperature exceeds 37°C [10], [30]. Additionally, the ACP should be 300 W/m^2 as a minimum for acceptable working conditions [3], [10], [12]. The ACP takes both the wet-bulb temperatures and air velocities (v_a) per working area into account. The average typical volumetric flow range for South African mines is between $3\text{ m}^3/\text{s}$ and $6\text{ m}^3/\text{s}$ per kt of rock mined per month or $0.12\text{ m}^3/\text{s}$ per ton mined per day [31]. An average volumetric flow rate of $4\text{ m}^3/\text{s}$ per kt per month of fresh intake air is therefore sufficient for productive operations [32].

Literature indicates that complex systems, such as ventilation networks, can only be evaluated thoroughly with the use of computer-aided simulations [33], [34]. As such, mine ventilation simulation packages have begun to appear commercially during the late 1960s at the turn of the digital age [14]. These packages incorporated the simpler laws of incompressible flow for Newtonian fluids and provided, for the first time, an effective means of predicting airflows

underground [14], [31]. However, with the large variation in air density experienced underground, these packages became obsolete and development continued.

At the beginning of the 1970s, mine ventilation simulation packages evolved to include the thermodynamic relationships for Newtonian fluids [15]. As a result, mine ventilation simulation packages were more accurate, rapid and versatile than previous generations. This formed the basis of most modern ventilation simulation packages [6]. Modern ventilation simulation packages have evolved to such an extent that fluid dynamic properties, thermodynamic properties and network mass balances are included to provide a comprehensive solution [33].

Although several modern mine ventilation simulation packages are commercially available for initial mine design, these packages are not used to optimise and evaluate operational changes [16], [35]. Numerous mines in the private sector do not evaluate operational changes at all [36]. These mines, typically marginal mines, implement operational changes without regard to ventilation – until stopped by law or ventilation-related incidents or accidents [14]. Literature indicates that these mines implement only short-term measures to ensure continued mining [15]. These ad hoc measures are near-sighted and often lead to the premature termination of production or, in some cases, tragic consequences for the health and safety of underground mineworkers [15], [28].

This solicits the rhetorical question that, if simulations have been used to optimise and evaluate operational changes in these mine ventilation networks, would the outcome have been different for production or mineworkers? To answer this question, one has to understand how ventilation networks are currently optimised and evaluated, and how simulations are incorporated in these ventilation networks.

Several authors have developed techniques to model and optimise specific sections of mine ventilation networks through simulations [5]. Acuna and Lowndes conducted a review of such studies, which showed that there is still a knowledge deficit in addressing both cost and service delivery in ventilation optimisation techniques [16]. Additionally, their study indicates that industry practising professionals use tedious manual calculations and years of experience to evaluate operational changes [16]. Similarly, mine ventilation simulation packages proved to be labour-intensive and time-consuming [16], [31]. However, innovative methods may enable mines to evaluate operational changes accurately and cost-effectively using simulations.

Panigrahi and Mishra used computational fluid dynamic (CFD) simulations to optimise axial flow ventilation fan blade profiles [37]. Chatterjee and Xia developed a VOD optimisation

model that exploits the cyclical nature of mining to reduce ventilation fan operating costs [30]. Both these techniques show promise for further research. However, the optimisation of fan blade profiles is limited to component design, and the VOD optimisation model is limited to time-of-use electricity tariffs with no mention of operational changes [30], [37].

No literature provides a step-by-step method to evaluate and optimise operational changes in mine ventilation networks. Furthermore, there is no literature available for scalable techniques. All available optimisation techniques are localised with only single parameter evaluations typically limited to either cost or service delivery. There is therefore no comprehensive method in literature that evaluates multiple-criteria such as both cost and service delivery, which can be applied to simulations of varying degrees. This underlines the need for a method that is scalable and has multi-criteria evaluation capabilities to save on resource time and costs.

Therefore, a need exists for a scalable, step-by-step **method** to evaluate and optimise operational changes in mine ventilation networks through simulations. This need, as exemplified by literature, leads to the first research question as part of mine ventilation characterisation.

Research question 1:

Will a novel method prove to be successful to optimise and evaluate operational changes in complex mine ventilation networks through simulations?

2.3 ECONOMIC QUANTIFICATION MODEL

EE projects are seen as the most cost-effective approach to achieve sustainable economic development [3]. Considering the challenges faced with the profitability of the mining industry, EE projects could prove to be the answer towards sustainable production [4]. Mining companies are therefore forced to investigate, integrate and innovate their operations to improve upon the status quo of operational efficiency [4].

According to literature, there have been additional synergistic benefits as a result of EE project implementation [38]. These synergistic benefits are over and above the standard electrical cost saving and are classified as non-energy benefits [38], [39]. Several NEBs were previously incorporated as part of project feasibility and motivation [18], [38]. However, these NEBs were easily monetised and quantified to a single value [39]. Therefore, for EE projects to appeal to

the mining industry, the total financial benefit of each EE project should be monetised and quantified to illustrate the effect on mine profitability [40].

Mining companies typically only select a few projects from a large portfolio of projects for implementation [3]. These projects are analysed according to various financial indicators [41]. Nonetheless, the financial indicators misrepresent the true financial benefit by omitting NEBs [21]. This fact was emphasised by Pye and McKane who acknowledged the importance of quantifying and incorporating NEBs [42]. As a result of the vast array of NEBs applicable to EE projects across sectors, there is a variety of monetised and non-monetised NEBs available in literature [18]. However, previous studies provide limited data on the level of NEB quantification, with very little reference to the mining industry [41], [43].

Worrel et al. pioneered the inclusion of productivity benefits in the evaluation of EE projects for the United States iron and steel industry [40]. The results of the study revealed that the explicit inclusion of NEBs doubles the cost-benefit potential for EE projects, thereby improving project feasibility [38], [40]. Lung et al. later examined the NEBs by considering 81 industrial application case studies to determine a comprehensive cost of conserved energy [44]. Only 54 of the 81 case studies' NEBs could be quantified [44]. Together, the findings of these studies conclude that EE projects are understated by the omission of NEBs [38], [40], [44].

Worrel et al. and Lung et al. therefore demonstrated the influence of including NEBs in the financial feasibility of EE projects [44], [45]. This was underlined in their work with the focus on the value of NEBs in project feasibility, rather than the quantification and monetisation thereof. This movement continued, with Skumatz and Skumatz et al. analysing the effects of NEBs in the public, residential and non-residential sectors [43], [46]. The value of NEBs have been discussed frequently and are established in industry [42]. However, none of the authors have focussed on the quantification and monetisation of NEBs, especially in the mining industry [40], [43], [44], [46].

Historically, numerous NEBs were identified and discussed for the industrial sector [43]. The most important NEBs for the industrial sector were identified to be reduced operations and maintenance costs, reduced emissions and improved productivity [47]. In contrast, there is very limited information available in literature regarding NEBs applicable to the mining sector [48]. This leaves large potential for the quantification and monetisation of NEBs as a result of EE projects, specifically for the mining industry [20].

The author believes that research on NEBs in the mining industry has subsided due to the immense difficulty associated with quantifying and monetising difficult NEBs. In mining EE projects, there are direct NEBs that can be quantified and monetised as is the case in the industrial sector. However, indirect NEBs relating to worker productivity have been eluding quantification and monetisation for decades. It is extremely difficult to identify these NEBs and to establish or quantify any empirical relationship [21], [40]. Even though literature highlights that these difficult NEBs affect production, no attempts have been made to quantify and monetise these benefits over the past 36 years [20].

According to Pye and McKane, there are NEBs of industrial EE projects that can and should be included in financial feasibility calculations [42]. These NEBs have an established relationship with productivity or can typically be measured before and after EE project implementation [21], [42]. Nonetheless, there are difficult NEBs, which are challenging to identify and quantify, that may influence productivity [23]. The most important of the difficult NEBs relating to the mining industry is when working environmental conditions are improved [40].

Finman and Laitner conducted a study to determine the effects of NEBs by considering 54 industrial EE projects. The results demonstrated that the NEBs that were quantified and monetised proved to be at least equal to, or greater than the electrical cost saving [23]. This was not a unique finding but was well documented in literature as exemplified by a study conducted by Hall and Roth [49]. They found that the annual NEBs monetised were almost three times that of the electricity cost savings [49]. Hall and Roth successfully quantified and monetised almost 40% of the NEBs by establishing an empirical relationship through calibrated measurements [49]. Most of the NEBs that were quantified and monetised related to direct operational and maintenance cost savings [49]. However, the difficult NEBs relating to production were not quantified [49].

Literature has shown that the total financial benefit of EE projects are understated by the omission of NEBs [38]. Specifically, indirect benefits that are hard to identify, quantify and monetise should be included in feasibility studies [41]. Accordingly, NEBs are most often equal or greater than the direct electricity cost savings [23]. However, there are very limited literature available for NEBs in the mining industry in general [20]. Very few attempts have been made in history to quantify NEBs of EE projects in the mining industry, let alone the difficult NEBs associated with improving the environmental working conditions [20].

Therefore, a need exists for an **economic quantification model** to quantify the total financial benefit of EE projects in the mining industry. This model would therefore provide a model to quantify and monetise NEBs relating to mine ventilation EE projects. This leads to the second research question for this thesis, as part of mine ventilation characterisation.

Research question II:

Will a novel economic quantification model provide the true financial benefit of EE projects in the mining industry by including NEBs?

2.4 MINE VENTILATION LOM PLANNING

Primary access is defined as the method used to exploit underground mineral reserves [50], [51]. While there are a large variety of primary access options available, vertical shafts are the preferred method for underground access in deep-level gold mines [52], [53]. These vertical shafts and accompanying hoisting systems form the primary access route to the network of openings used to recover underground mineral reserves [52]. In addition, this system provides vertical transport of men and materials while providing an inherent escape way [53]. Mining operations are therefore dependent on the efficient flow of men and materials to extract ore from the underground working areas [53].

Literature indicates that there are several types of winder used as part of hoisting systems [54]. Rock winders are used to extract broken ore from underground mining operations to surface [55]. These winders are typically selected to satisfy the future planned production rate as part of the LOM plan [50], [51]. However, this infrastructure is directly coupled to the ventilation network as it provides intake and return capabilities for the mining complex [51]. The primary access or hoisting system therefore directly affects the ventilation network, especially in deep-level mines [55]. Intake capabilities are typically provided by the main hoisting shaft and sub-vertical hoisting shafts [17], [56]. Similarly, return capabilities are also provided through sub-vertical hoisting shafts depending on the underground ventilation network configuration [16], [55]. Mine ventilation networks are used to ensure that underground conditions are conducive to safe and productive mining [7]. The costs of providing acceptable working conditions for future mine development become a critical determinant towards the feasibility of mining and LOM planning development [8].

Traditionally, LOM planning and design includes manual calculations and interpretation of graphical information such as underground ore deposit forecasts [57]. These methods are,

firstly, very time-consuming and, secondly, very resource intensive [57], [58]. LOM planning is therefore used to determine the mineral reserves and spatial distribution of ore body grades, as well as the future planned production rate [59]. Geostatistical estimation methods have previously been used to model the distribution of grades within a reef ore mining block [59]. However, these models have not accounted for the in situ variability of ore grade deposits [59].

This problem was solved by developing computer-aided mine design and modelling methods, which resulted in faster, more accurate LOM planning results [57]. This development enabled mine planners to schedule, design and optimise multivariable models towards profitable mining [59]. As a result, several commercially available simulation packages were developed to determine the geology and spatial distribution of ore bodies [59]. These packages were incorporated as part of LOM planning and provided more accurate results cost-effectively [60]. However, these simulation packages focussed on mineral reserves and neglected the effect of future planned production on other critical mining systems such as the primary access and ventilation network [60].

Literature indicates that complex systems can only be thoroughly evaluated and planned using simulations [34]. The hoisting system is one such a system where extensive simulation developments have occurred [17]. Commercially available simulation packages are used to design and optimise these systems, incorporating safety features relating to emergency egress [61], [62]. Additionally, several case studies were published where the hoisting system was designed and optimised with the use of simulations [63]. However, these simulation packages have not been incorporated in LOM planning [31]. Subsequently, no method or framework exists that provides a means of incorporating simulation packages for hoisting systems to be included as part of LOM planning.

In contrast, the use of simulation packages has dominated mine ventilation planning since inception [14]. There are several case studies in which the ventilation network was designed and planned using simulations [64], [65], [66]. However, despite the availability of ventilation network simulation packages, some mines still use manual methods [14]. It is typical for new ventilation networks to be characterised according to simulations as part of design and requirement iterations to be included in LOM planning [67], [68]. Nonetheless, the planning was conducted only for the ventilation network; the integrated effect of other critical systems was disregarded. It is important to include the effects of related critical systems to provide a comprehensive LOM plan [69].

In conclusion, LOM planning is done in a segregated manner and only focusses on a narrow bandwidth of production-related factors and systems. Similarly, LOM planning is done using outdated, inefficient manual methods that often omit the inherent effects of different systems. Although simulation packages are available to optimise, evaluate and plan critical mining systems, they are not incorporated as part of LOM planning. LOM planning is therefore made with limited information, which increases the risk and likelihood of failure.

Therefore, a need exists for an **integrated simulation planning method** to be used for primary access and ventilation LOM planning. This method will ensure LOM planning is conducted in an integrated manner, thus ensuring that the effects of the primary access and ventilation network are optimised and evaluated, and that the best solution is selected to be included in the updated LOM plan. This leads to the third research question for this thesis, as part of mine ventilation characterisation, as stated below.

Research question III:

Will an integrated simulation planning method prove to be successful to optimise, evaluate and improve the primary access and ventilation network LOM planning?

2.5 MINE VENTILATION VOD POTENTIAL

A paradigm shift has occurred in the international mining arena towards using more efficient equipment that includes, inter alia, the installation of VSDs on refrigeration systems, pumps and fans [12], [26]. Consequently, several case studies were implemented, which resulted in significant cost savings [25], [26], [70]. The viability of installing VSDs was proven as a tool to achieve cost savings in various applications across complex industrial systems [26], [27]. The most successful case study results were obtained in systems of cyclical nature where part-load conditions were prevalent [70], [71]. Therefore, large potential should exist to realise cost savings with the installation and utilisation of MV VSDs as part of VOD potential on mine ventilation fans.

Various mine ventilation optimisation strategies have been developed and implemented [5], [8], [72]. Traditionally, the airflow volume of main ventilation fans in South African mines has been controlled through IGVs under constant speed applications [9]. However, while IGVs do provide some energy benefit, the use thereof results in increased frictional resistance, which causes a pressure drop [73]. Therefore, integrating modelling and simulation technologies [16] along with dynamic control strategies provide the platform for VOD solutions [30], [74]. State-

of-the-art technology for mine ventilation networks culminate to the principle of VOD by ensuring the dynamic facilitation of the true airflow requirements for the different underground mining operations [56], [75].

Literature indicates that it is currently common practice for South African mines to operate under constant airflow conditions to supply maximum volume regardless of varying production requirements [30], [73]. As such, the main ventilation fans are operated continuously [76], [77]. Furthermore, a study conducted on the in situ assessment of airflow leaks underground revealed that as much of 28% of airflow can be lost to return airways in South African mines [78]. Mine ventilation is therefore oversupplied and underutilised in the working areas [35]. This leaves opportunity for strategies to reduce the airflow leakages with modulation and to increase airflow utilisation through leak repair. Thus, VOD allows for variable airflow control by exploiting the cyclical nature of mining airflow requirements (dynamic) [30], [36] as well as allowing operations to adjust to reduced demand (static) [9], [32], [71].

Theoretically, the main ventilation fans could be controlled to supply sufficient airflow to satisfy the demand requirements underground [32], [74]. The airflow requirements may include dynamic and static control for ventilation fans over a daily profile [34]. As stated previously, airflow control in South Africa is currently done using IGVs [73]. However, the airflow control could be applied with much greater accuracy by adjusting the speed of the fan motors with VSDs [74], [79]. The effects of variable airflow on mines were investigated with pilot VSD implementation studies, which yielded positive results in Canada [32], [80]. However, it was found that these technologies have not been implemented in South African mine ventilation networks yet [9], [35], [81]. This may be due to a lack of knowledge regarding the use of MV VSDs as part of VOD applications on mine ventilation networks [77].

In conclusion, no literature was found that assesses VOD potential on a large scale in South African mine ventilation networks with the utilisation of MV VSDs. Furthermore, no literature was available to indicate the daily airflow requirements as used in VOD applications. As a result, no literature was available that provides an indication towards the financial feasibility of using MV VSDs as part of VOD applications on mine ventilation networks. This underlines the need for a novel assessment in order to establish the financial feasibility of installing MV VSDs as part of VOD applications.

Therefore, a need exists for a novel large-scale **assessment** on the use of MV VSDs as part of VOD potential in South African mine ventilation networks. This need leads to the final research question for the thesis as part of mine ventilation characterisation.

Research question IV:

Will a novel assessment on the use of MV VSDs as part of VOD potential on South African mine ventilation networks prove to be financially feasible?

2.6 CONCLUSION

Literature has emphasised the need for improved mine ventilation characterisation through simulations. This was exemplified by investigating the current methods and techniques employed by industry to illustrate the need for this thesis. The underlining aim was supported by the individual research questions relating to operational changes, quantification of NEBs, LOM planning and the use of MV VSDs as part of VOD potential.

The formulation of each research question was derived from a current knowledge deficit. Accordingly, there is a need for a scalable, step-by-step method to optimise and evaluate operational changes on mine ventilation networks through simulations. There is a need for an economic quantification model to quantify the total financial benefit of EE projects in the mining industry. Furthermore, there is a need for an integrated simulation planning method for primary access and ventilation network LOM planning. Lastly, there is a need to assess the use of MV VSDs as part of VOD potential on South African mine ventilation networks.

The formulation of the research questions concludes that there is a need for improved mine ventilation characterisation to improve upon the status quo of operational efficiency in the mining industry.

CHAPTER 3 PUBLICATIONS SUMMARY



3

“Simplicity is the ultimate sophistication.”

– Leonardo da Vinci

³ A. J. H. Nel, Personal photograph. "Mine surface ventilation fans," Gauteng, South Africa, 2016.

3.1 PREAMBLE

In this chapter, the most important results of the appended research articles and sub-contributions are critically analysed and summarised. The significance of the framework and sub-contributions are validated and proves the value of mine ventilation characterisation through simulations. The chapter is concluded with a detail discussion on the sub-contributions. The articles are presented in full in Appendix A to Appendix D.

3.2 ARTICLE I

A case study perspective: Evaluation of complex mine ventilation operational changes through simulations

In Article I (Appendix A), a novel scalable, step-by-step method was developed to optimise and evaluate complex mine ventilation networks. The innovative method was applied to nine operational change scenarios on a mining complex. Each of the nine operational change scenarios was optimised and evaluated according to the developed method. The most feasible option as indicated by the method was implemented, resulting in a measured 13.2 GWh energy saving over the course of 18 months. This amounted to a 23% energy saving per annum on the ventilation network with an increase in operational efficiency.

The significance of this method is that it enables mine personnel to make improved decisions, ensure legal compliance and improve underground working conditions for mineworkers. This method was implemented easily and was developed specifically to be scalable. The scalability of the method is extremely important for the successful implementation and utilisation thereof by industry practising professionals. The versatility of the method to conduct high-, medium- and low-level evaluation studies provides mine personnel with new insights on operational changes. The author has seen a newly instilled vigour in mine personnel where the method was applied as it was a new tool to be used for improving underground conditions and for increasing the profitability of deep-level mines.

This novel method was developed according to a continuous improvement process. This enables the method to be incorporated, while still being relevant in future developments such

as cases where Industry 4.0⁴ and the Internet of Things (IoT)⁵ technologies are applied to the mining industry. In conclusion, the novel method satisfies the research question as it contributes towards an improved characterisation of complex mine ventilation networks through simulations. The novel method was implemented on a mining complex where the method was adopted and incorporated to be the new mine ventilation standard.

3.3 ARTICLE II

Economic quantification model for energy efficiency projects in the mining industry

In Article II (Appendix B), a novel economic quantification model was developed for EE projects in the mining industry. This model was developed to determine the total financial benefit of EE projects – specifically to include NEBs as direct and indirect costs. The unique model was applied to an active mine ventilation EE project, which was implemented in June 2016 to show how the omission of these benefits influences the financial feasibility of EE projects.

The novel economic quantification model was implemented and analysed according to six progressive models. With each progressive model, a NEB was quantified, monetised and included in the financial feasibility calculations. The model included energy, maintenance, labour, water, service delivery and other NEBs such as carbon tax and 12L tax rebates. The unique economic quantification model was successful to quantify and monetise NEBs that are frequently omitted in the financial evaluation of EE projects in the mining industry.

The newly developed model was lacking in the service delivery quantification component, which was based on an assumption with limited data. However, this was addressed by recommendations for assumption improvement. Although the empirical relationship between the underground working environmental temperature and productivity of mineworkers was not validated, it was the first attempt since 1981, which is a step in the right direction for energy advocates.

⁴ Industry 4.0 is referred to as the fourth stage of industrialization, incorporating electronics and information technologies for a high level of automation for various applications [82].

⁵ Internet of Things are the information and communication technology infrastructure embedded in industry 4.0 to enable smart services [82].

The novel economic quantification model proved that there are several NEBs that have frequently been omitted in financial project feasibility calculations. The newly developed model therefore satisfies the research question by providing a model to quantify and monetise the total financial benefit of such projects. The significance of this model is justified only by the vast number of EE projects, which was deemed to be unfeasible. This unique model advances the boundaries of how EE projects are perceived in industry, not only in mining but in all industries where EE projects are implemented. In conclusion, this model improves on the status quo by including NEBs in financial feasibility calculations. Mine personnel and energy efficiency advocates alike will be able to make improved, more comprehensive project decisions based on the total financial benefit of EE projects. This contributes towards the characterisation of complex mine ventilation networks through simulations since the feasibility of such projects can now be quantified and monetised more accurately using the developed model.

3.4 ARTICLE III

Life-of-mine primary access and ventilation planning through simulations

In Article III (Appendix C), a novel integrated simulation planning method was developed for LOM primary access and ventilation planning. This method was applied to a case study project in which three simulation planning models were optimised, analysed and evaluated in terms of the primary access and ventilation network for the most financially feasible option. The most feasible simulation planning model, as indicated by the method, was selected to be included in the updated LOM plan. The updated LOM plan is currently being implemented, as a result of the novel simulation planning method, including the simulation planning model with the lowest capital and operating costs with the quickest implementation time.

This unique integrated simulation planning method provides a more rapid, versatile, accurate and comprehensive alternative to historical LOM planning. This method advances planning to take the effects of the primary access and ventilation network into account. This method also includes a unique feasibility indicator that enables mine personnel to implement a cost analysis quickly and easily. Since planned production rates and configuration changes occurs frequently in the mining industry, it is significant to have such a unique method available to make improved LOM planning decisions.

This method was adopted by the case study mining complex to be included as the preferred LOM planning method. The synergetic effects of the primary access and ventilation network enable mine personnel to optimise and evaluate these systems in an integrated manner which has traditionally not been possible. This comprehensive method has led to other advantages of improved interdepartmental collaboration and communication, improved operational efficiency, legal compliance and increased profitability. The author is convinced that this integrated simulation planning method will be used as the new industry norm.

In conclusion, the novel integrated simulation planning method satisfies the research question fully. This method enables mine personnel to make improved LOM planning decisions cost-effectively in a comprehensive manner. This contributes significantly towards the characterisation of complex mine ventilation networks through simulations as the LOM planning is conducted on a continual basis. The author recommends that a similar method be developed for other critical mining systems that have to be optimised and evaluated in an integrated manner.

3.5 ARTICLE IV

Achieving energy efficiency with medium voltage variable speed drives for VOD in South African mines

In Article IV (Appendix D), a novel assessment was conducted on the prospective utilisation of MV VSDs as part of VOD potential on ten South African mine ventilation networks. A detailed energy audit was applied to the selected ventilation networks while adhering to a large-scale audit method developed by Saidur et al. [70]. Feasibility indicators such as the cost savings, energy savings and GHG emission reductions under varying VOD conditions were calculated. Dynamic and static VOD applications were considered, and the potential thereof determined with the installation and utilisation of MV VSDs. The financial feasibility indicators revealed that it is economically viable to implement both VOD applications. A special case study was also considered where both applications were to be implemented simultaneously.

This unique assessment illustrates the large feasibility of applying VSD technologies coupled with industry leading methods to mine ventilation networks. As stated in Chapter 2.5, there are documented papers in which the energy savings were published for VOD applications. However, no airflow demand profile has been published in literature. The author therefore opted to develop an innovative daily airflow profile, which complies with the statutory

requirements for ventilation networks in South Africa. The significance of this article lies in the identification and quantification of the large potential that exists to improve the operational efficiency of mine ventilation networks using MV VSDs.

This assessment has definitively shown the feasible use of MV VSDs as part of VOD potential on South African mine ventilation networks. The author believes that the mining industry will be forced to include the installation of MV VSDs on the main mine ventilation fans to improve operational efficiency. If the use of MV VSDs were to be adopted, willingly and promptly, the profitability of the mining industry will be increased, which will contribute positively towards sustainable economic growth in South Africa. The author is convinced that the results of this study will lead to the adoption of such technologies and methods.

3.6 DISCUSSION

In this thesis, four individual research questions were derived that contribute towards a need for improved mine ventilation characterisation through simulations. The research questions were structured, inter alia, operational changes in mine ventilation networks, quantification and monetisation of EE projects relating to mine ventilation networks, primary access and ventilation LOM planning and, finally, the use of MV VSDs as part of VOD potential assessment on mine ventilation networks. The following discussion highlights the relevance of each novel contribution to the field of knowledge, and how the research questions, derived from literature, as stated in Chapter 2, are satisfied.

Previous literature has reported that complex systems can only be evaluated thoroughly with computer-aided simulations [34]. As a result, ventilation simulation packages were developed and advanced to include thermal-hydraulic solvers, which are currently in use [14], [31]. Although significant effort has been made to develop and advance such technologies globally, the literature review of Article I showed that most mines implement operational changes without regard to ventilation [14]. These mines, typically marginal, implement ad hoc measures that are near-sighted, which often leads to tragic consequences for workers and mine production [15]. This was a worrying discovery considering the statutory regulation of mine ventilation networks in South Africa.

Similarly, mines that do evaluate operational changes only consider single-criteria evaluations – often through tedious manual calculations, for example, service delivery such as volumetric airflow. These mines exclude multi-criteria evaluations such as service delivery and costs

attributed to the proposed operational changes [16]. These evaluations, which rarely include simulations, were also found to be time-consuming and labour-intensive [16].

The results of the literature review can be summarised that ventilation simulation packages were commercially available, but were rarely used to evaluate operational changes. The reason can be ascribed to a lack of information on scalable methods to evaluate operational changes accurately and cost-effectively. Hence, there is need for a step-by-step method to evaluate and optimise operational changes in mine ventilation networks through simulations.

The results of Article I indicates the large potential – specifically on the practicality of a scalable, step-by-step method. The proposed method was implemented successfully on a case study ventilation network in South Africa, resulting in a large sustainable electrical cost saving. To recognise the significance of this method, one has to consider the global implementation potential in the mining industry and not just the South African context. Authors such as Panigrahi and Mishra have exploited the use of CFD simulations on fan component level and considered the effects of varying blade profiles for an entire industry [37]. These authors have painstakingly determined their novelty in an international context. As such, the results of Article I acknowledged what previous authors have stressed regarding the subject of operational efficiency, mine ventilation simulations and evaluation studies [15], [31].

The most significant success factor of the developed method was adopting the method in the case study mine's standards as the new norm. The method was also developed to be relevant and capable of integration with the latest developments in technologies such as Industry 4.0 and the IoT [82]. The easy-to-use method satisfied research question I, as defined in Chapter 2.2, fully. Therefore, as a result of method implementation, mine personnel were enabled to make improved decisions for improved underground environmental working conditions and legal compliance.

EE projects are seen as the most cost-effective approach to achieve sustainable economic development [3]. According to previous literature, there have been additional synergistic benefits as a result of EE implementation, which are classified as NEBs [38], [39]. Previously, direct NEBs were incorporated as part of project feasibility and motivation since these benefits were easily quantified and monetised[18], [38]. However, there are indirect NEBs that are difficult to quantify and monetise to a single value. For EE projects to appeal to the mining industry, the total financial benefit of EE projects should be quantified and monetised. This statement was acknowledged and emphasised by Pye and McKane [42].

The results of the literature review for Article II indicated that the true financial benefit of EE projects was misrepresented due to the omission of NEBs [21]. Additionally, there was very limited data on the quantification of NEBs that specifically related to the mining industry [41], [43]. Worrel et al. and Lung et al. conducted studies in which only a few of the NEBs could be quantified and monetised for industrial applications [40], [44]. This finding was also achieved in other studies conducted by Finman and Laitner, Lilly and Pearson, and Hall and Roth [23], [47], [49]. These studies underline the need to quantify and monetise NEBs to be used as part of EE projects' financial feasibility. Hence, there was a need for a novel economic quantification model for EE projects in the mining industry.

The results of Article II correlate with published studies from previous literature, which indicate that the financial benefit of quantifying and monetising NEBs far outweighs the conventional electrical cost saving [43], [44]. A novel economic quantification model was therefore implemented successfully on a mine ventilation EE project. The model was successful to quantify and monetise NEBs that were frequently omitted as part of financial feasibility. However, the model was lacking in the service delivery quantification component, which was based on an assumption with limited data. This was addressed with recommendations for assumption improvement. Additionally, the questionnaires and interviews revealed that the omission of NEBs in financial feasibility evaluations was attributed to a lack of information on how to quantify and monetise these benefits. The selected industry experts acknowledged the existence of NEBs and the need for a quantification model. This strengthens the use of the novel economic quantification model developed for the mining industry. Research question II, as stated in Chapter 2.3, was fully satisfied with the developed model.

Primary access provides a method to exploit underground mineral reserves through the transportation of men and materials [50], [53]. It was found that extensive simulation package developments have occurred for the primary access system [17], [63]. However, these simulation packages were not incorporated in LOM planning [31]. Likewise, ventilation simulation packages are commercially available to be incorporated in LOM planning but some mines still use outdated manual methods [14]. Traditionally, LOM planning and design include manual calculations and interpretation of information such as underground ore deposit forecasts [57]. LOM planning is therefore used to determine the mineral reserves, spatial distribution of ore body grades and future planned production rate [59]. Although there is large scope for new technologies to be used, mine personnel opt for manual methods.

The primary access system directly affects the ventilation network as it provides intake and return capabilities [51]. However, these systems are planned in a segregated manner as

emphasised by Kocsis et al. [69]. It was found that omitting inherent effects between critical systems could have dire consequences for LOM planning. The results of the literature review for Article III indicated that LOM planning was conducted in a segregated manner with limited information, limited resources and without the use of simulation packages. This led to the development of research question III, as defined in Chapter 2.4.

The results of Article III proved that an integrated simulation planning method could be used for primary access and ventilation LOM planning. This enabled mine personnel to analyse, evaluate and refine LOM planning. A unique feasibility indicator was also developed specifically for this method, which enabled mine personnel to conduct a quick cost analysis of the proposed LOM plans. The scale of the novel method was exemplified by a cost avoidance of US\$28.8 million as part of case study validation. However, since LOM planning is conducted for the long term (± 10 years) and several configuration changes occur on the mine, constant LOM planning updates are required. The effect of this integrated planning method might not be tangible for the current year; however, it will prove to be invaluable for future developments. Mine personnel from the case study mining complex were therefore enabled to make improved, accurate and cost-effective LOM planning decisions regarding the primary access system and ventilation network.

The sustainability of most energy intensive economies are contingent on the industries' largest consumers to play a proactive role in the implementation of energy efficient solutions [83]. This is emphasised by reviewing past economic growth patterns in South Africa, which illustrate the deep-rooted effects of mining [84]. Nonetheless, there has been a paradigm shift towards improving operational efficiency with the installation of new more efficient technologies coupled with innovative methods, models and simulations [12], [26]. VSDs are example technologies, which have been proven to be the most efficient means to achieve electrical cost savings with modulation, especially in variable flow control applications [25], [26]. As a result, several case studies have been published as part of implementation validation, which yielded notable cost savings [25], [70]. However, no literature was available on the use of MV VSDs as part of VOD potential on mine ventilation networks.

Various ventilation optimisation strategies have been developed and implemented globally [8]. However, very few studies have been published on the forefront of the field, namely, VOD [36]. State-of-the-art technology for current ventilation knowledge culminates to the principle of VOD; that is to provide sufficient airflow to the underground working areas to satisfy the varying airflow requirements of the different mining operations [56], [75]. However, no airflow demand profile has been published in literature. Several manufacturers have claimed an

energy saving percentage as a result of VOD implementation. Nonetheless, no airflow demand profile has been published that reports the true airflow requirements for each operation. Additionally, literature indicated that as much as 28% of airflow can be lost through airflow leaks in South African mines [78]. This provides additional scope for using MV VSDs as part of VOD potential with the repair of leaks and improvement in airflow utilisation. The airflow supply experienced at the working areas can remain constant, while the speeds of the fan motors are reduced on a constant basis to achieve savings.

Since ventilation fans are operated continuously to provide the maximum supply airflow volume in South African mine ventilation networks, there was scope to apply the principle of dynamic VOD applications [35]. Thus, VOD allows for variable airflow control by exploiting the cyclical nature of mining airflow requirements (dynamic) [30], [36] as well as allowing operations to adjust to reduced demand (static) [9], [71]. The effects of variable airflow on mines were investigated with pilot VSD implementation studies, which yielded positive results in Canada [32], [80]. However, it was found that these technologies have not been implemented in South African mine ventilation networks [35], [81]. This underlines the need for a comprehensive assessment for the use of MV VSDs as part of VOD potential for both applications in South African mine ventilation networks.

The results of the literature review for Article IV reported that although the use of VSDs has been implemented across a large array of industries, this technology and the potential thereof have not been implemented or investigated on South African mine ventilation networks yet. Additionally, there is no similar study in literature in which the use of MV VSDs are assessed as part of VOD applications. This underlines research question IV, derived in Chapter 2.5.

The results of Article IV indicated that it was economically viable to implement MV VSDs as part of both VOD applications. The assessment indicated that the static VOD application was viable for all the considered airflow conditions. In contrast, the dynamic VOD application was only deemed viable with an airflow reduction of more than 12%. In a special discussion referring to both applications, it was found that there is potential to implement both applications to achieve a larger cost saving, energy saving and GHG emission reduction. However, the combination of both strategies should be analysed and considered logically and realistically.

It was shown that the best practice air leakage percentage for mines was 20%. One should therefore be conservative with airflow utilisation estimates through leak repair. The article assesses the use of MV VSDs as part of VOD potential on South African mine ventilation networks. The results have indicated the large potential for energy advocates and mine

personnel alike to improve upon the status quo of operational efficiency. The author believes that the publication of this knowledge will ensue a larger analysis and implementation of the proposed technologies.

To summarise:

In Article I, a novel scalable, step-by-step method was developed to optimise and evaluate complex mine ventilation networks through simulations. In Article II, a novel economic quantification model was developed for EE projects in the mining industry. In Article III, a novel integrated simulation planning method was developed for LOM primary access and ventilation planning. In Article IV, a novel large-scale assessment was conducted on the use of MV VSDs as part of VOD potential on South African mine ventilation networks. The newly developed methods, model and assessment were implemented successfully, satisfying four research questions, which thereby contribute towards the characterisation of mine ventilation networks.

The significance of each contribution was discussed and emphasised by adopting the newly developed methods by the case study mining complex. Mine ventilation characterisation is extremely important to gain a thorough understanding of the environment and operations. It is only when one understands and simplifies the problem, that one can start to make the necessary changes for improvement. In conclusion, four novel contributions were made to characterise mine ventilation networks through simulations. These contributions were implemented successfully to improve upon the status quo, inter alia, operational changes, quantification and monetisation, LOM planning and, finally, MV VSD technology utilisation as part of VOD.

CHAPTER 4 CONCLUSION



6

“However beautiful the strategy, you should occasionally look at the results.”

– Winston Churchill

⁶ A. J. H. Nel, Personal photograph. "Mine surface ventilation fans," North-West, South Africa, 2017.

4.1 PREAMBLE

In this chapter, the concluding remarks and insights of the framework and sub-contributions of each article are summarised. The final sub-contributions and conclusions that arose from the research questions are drawn. As a result, the author's viewpoints are expressed and brought to a final synthesis on the framework (primary contribution) and sub-contributions. The chapter further concludes with recommendations for future research relating to the developed framework and sub-contributions.

4.2 CONCLUSION

In this thesis, the role of thorough mine ventilation characterisation was studied in relation to operational changes, NEBs, LOM planning and the use of MV VSDs as part of VOD potential. Previous literature has indicated that there is a lack of research relating to ventilation characterisation in general. The study of mine ventilation characterisation is therefore insufficient considering the advancement and inclusion of new technologies, methods and models in other industries.

The mining industry is archaically inclined to continue operating as they have done the past 100 years. However, the current global economic state and marginal operations of mines are forcing this industry to improve upon the status quo of operational efficiency. The author first experienced this glimpse of a long-awaited paradigm shift towards sustainable development when mine personnel adopted the novel contributions as their own.

Article I showed that there was a need for a new method to optimise and evaluate operational changes in mine ventilation networks through simulations. Although mine ventilation simulation packages were developed and refined over time, no method was developed to illustrate how simulations could be used in evaluation studies. The author developed a novel method, which was implemented successfully for this purpose. This resulted in improved decision-making capabilities, which improved the operational efficiency and, subsequently, the profitability of the mining complex.

Article II aimed to show the effects of NEBs in EE projects in the mining industry. Literature indicated that NEBs have frequently been investigated in industrial EE projects. However, NEBs were omitted in investment calculations due to the lack of quantification and monetisation models. Additionally, very few attempts were made to research NEBs in the mining industry as a result of the immense difficulty associated with the quantification of some

NEBs. The last documented attempts were made almost four decades ago in the 1980s. Hence, the author developed a novel economic quantification method for NEBs in the mining industry. This model proved to be successful for the most part, especially for direct energy benefits. However, there were too many uncontrolled variables to validate the service delivery component of improving the underground working conditions. This model resulted in a working model that can be used by energy advocates to quantify the true financial benefit of EE projects in the mining industry.

Article III showed that there was a need for an integrated method to be used for primary access and ventilation network LOM planning. Literature indicated that although there were many simulation packages available for these critical systems, they were not incorporated in LOM planning. These critical mining systems were planned in a segregated manner without regard to the integrated effects between these systems. The author developed a novel integrated simulation planning method to evaluate, select and implement the most feasible LOM plan through simulations for the primary access and ventilation network. The developed method was implemented successfully, resulting in an average cost avoidance of 27% for the case study mining complex. Therefore, this method improved the long-term LOM planning with the use of simulations.

Article IV indicated that there was a need for a large-scale assessment on the use of MV VSDs as part of VOD potential on South African mine ventilation networks. Literature indicated that although several ventilation optimisation strategies have been implemented, the most efficient method to improve operational efficiency is to use MV VSDs as part of VOD potential. State-of-the-art technology for mine ventilation networks culminated to the principle of VOD, of which two applications were considered under varying airflow conditions. The author conducted the novel assessment and developed an innovative VOD airflow demand profile that complies with South African mine ventilation network statutory requirements. The results of the assessment indicated that it was economically viable to implement both applications, resulting in a payback period of only nine months. The use of MV VSDs as part of VOD applications was therefore proved to be feasible.

The studies included in this thesis emphasise the importance of an integrated solution incorporating the latest technologies such as simulations to improve mine ventilation characterisation. This thesis proves that improved decisions can be made by coupling simulations with innovative methods, models and MV VSD technologies. Therefore, it is the author's belief that operational efficiency and mine profitability can be improved if the novelty of this thesis are adopted by the mining industry.

4.3 FUTURE RESEARCH

Mine ventilation characterisation has a very large impact across a wide array of mining activities. It is important to consider the importance of future research, not only to advance the field of engineering, but also to ensure sustainable mining operations. Mine ventilation characterisation therefore has a very important role in increasing operational efficiency and subsequent profitability of mining.

It was shown that the developed methods, models and assessments were sensitive to the data incorporated in the simulations. As such, the author included verification steps as part of the methods, models and assessments. However, it is recommended that the accuracy of different measurement techniques be evaluated against the required resources. A balance can therefore be established between the required resources and attainable accuracy for each method to be able to incorporate the most efficient measurement technique for both surface and underground measurements. The developed methods, models and assessments could then be updated and refined to incorporate specific measurement techniques suited to specific applications.

It was shown in Article II that the quantification for improved underground working conditions could not be validated as a result of too many uncontrolled variables. It is recommended that a laboratory case study be conducted on a mine to limit the uncontrolled variables for improved empirical results. All variables related to improved underground working conditions and worker productivity should be measured and included in the investigation. Special attention must be given to the “human factor”, which plays a significant role in the quantification model. The results must be critically analysed as portrayed by the article findings which shows that empirical correlation does not necessarily imply causation. It is recommended that the developed quantification model be expanded and refined to other mining systems and other industries. The same methodology could be applied to other industries to provide more accurate quantification models.

In Article I, III and IV, the use of simulations was investigated as part of operational changes and LOM planning, and the use of MV VSDs was investigated as part of VOD potential. It is recommended that similar studies be conducted for other mining systems across the mining industry. This would result in improved decision-making capabilities, improved system control and improved operational efficiency. Similar studies should also be conducted for other

industries that are reliant on critical systems such as the manufacturing industry. Especially, the use of MV VSDs as part of VOD applications should be implemented and validated on a South African mine ventilation network. It is recommended that the potential and validation of MV VSDs as part of improved process control be validated on other industries. The sustainability of these initiatives should be documented and control methodologies developed for continuous improvement.

In summary, the author recommends future research be conducted on the following:

- Improvement of mine ventilation measurement techniques for surface and underground.
- Quantification of the interrelated effects of the sub-contributions through multiple case studies.
- Development of similar scalable, step-by-step simulation methodologies for other mining systems and systems in other industries.
- Quantification and monetisation of NEBs on other mining systems such as compressed air and refrigeration.
- Development of evaluation and optimisation methods for other mining systems incorporating simulations.
- Development of LOM simulation planning methods for other mining systems.
- Installation of MV VSDs as part of VOD in South African mine ventilation networks.

In conclusion:

The holistic research question of the thesis was satisfied, improving mine ventilation characterisation through simulations.

To quote Michael Shermer,

“Science is the best tool ever devised for understanding how the world works.”

CHAPTER 5 REFERENCE LIST



7

“Character is the only way to sustain success.”

– John C. Maxwell

⁷ Harmony Gold, “Rock drill operators,” 2018. [Online]. Available: <https://www.miningreview.com/wp-content/uploads/2016/01/Harmony-Gold-masimong-resized.jpg> [Accessed 2 January 2018].

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Appendix A:

A case study perspective: evaluation of complex mine ventilation operational changes through simulations

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A case study perspective: evaluation of complex mine ventilation operational changes through simulations

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Status confirmation:

A case study perspective: evaluation of complex mine ventilation operational changes through simulations

Andries Johannes Hendrik Nel, Jan C. Vosloo, Marc J. Mathews

Submission Review Copyediting Production

Round 1

Round 1 Status

A review is overdue.

Review Discussions

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No Items				

App. A.1: Article I

A case study perspective: evaluation of complex mine ventilation operational changes through simulations

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ABSTRACT

The profitability of the mining industry can be increased contingent on the industry's ability to improve upon the status quo of operational efficiency. Mine ventilation networks typically represent 25% to 50% of a mine's energy consumption and therefore exhibits scope for optimisation. Ventilation networks are comprised of an abundance of complex, integrated airways, branches and ventilation fans. The most prudent means to optimise and evaluate mine ventilation networks is through computer aided simulations. However, no framework exists to clarify exactly how operational changes in ventilation networks should be evaluated. In this paper, a scalable, step-by-step method was developed, implemented and analysed to satisfy the current knowledge deficit. The case study validation resulted in satisfying key performance indicators of both service delivery and operational energy costs, thereby increasing operational efficiency. The significance of the novel method lies in that it enables mine personnel to make improved operational decisions on mine ventilation networks. The value of the method was exemplified by the permanent adoption of the method by the case study mining personnel to form the new norm of their procedures and standards.

KEYWORDS

Mine ventilation networks, Simulations, Optimisation, Sustainable cost saving

HIGHLIGHTS

- Mine ventilation operational changes optimised and evaluated through simulations
- Scalable, step-by-step method
- Additional non-energy benefits

INTRODUCTION AND BACKGROUND

Mine ventilation networks are used to ensure that underground environmental conditions are conducive to safe and productive mining [1]. This is done by supplying sufficient airflow to the working areas to govern heat stress imposed on workers, and to dilute and exhaust hazardous particulates to below statutory occupational exposure levels [2]. However, due to the dynamic nature of deep-level mining, the engineering challenges faced to contend with higher virgin rock temperatures and more complex ventilation networks increase by virtue of increased depth [3]. The costs associated with providing acceptable working conditions for reserves that are farther and deeper away from ventilation shafts, becomes a critical determinant towards the feasibility of mining [2].

Operational efficiency is therefore the lifeline of increasing mine profitability as shown by the industry's drive to improve upon the status quo [4], [5]. In modern mining, there has been a recognition towards technological advances, to which the rapid development and increased production targets can be attributed [6]. Mines are therefore expanding operations vertically and horizontally in an effort to achieve these production targets in the most efficient manner possible. Research indicates that electricity, inter alia, possess the largest potential to increase operational efficiency on mines [7].

Considering mine ventilation systems represent between 25% to 50% of the energy consumed in a mining operation, large potential exist to realise electrical cost savings through optimisation [4], [8]. Typical backward curved airfoil centrifugal fans employed on deep-level mines, as main fans, have installed capacities ranging between 500 kW to 2.1 MW per fan [4], [9]. Mine ventilation systems consist of hundreds of interconnected sections and applications such as airways, raises, cross cuts, main shafts, vent shafts, sub-shafts, raise bore holes, ventilation doors, travelling ways, fans and regulators [8]. In view of the complexity of the system and the progression of mine development, it is easy to comprehend that inefficiencies such as short-circuits, insufficient air velocities, increasing temperatures and leakages occur in such a vast network [1].

Mine ventilation networks are required to comply with occupational health and safety standards and regulations as specified by the host country. In South Africa, there are two important factors affecting the operations of mine ventilation and subsequent working environments, namely, the wet-bulb temperature (T_{wb}) and air cooling power (ACP) [10]. Legislation stipulates that work should not proceed underground when the wet-bulb temperature exceeds, $T_{wb} \geq 32.5^{\circ}\text{C}$ or the dry-bulb temperature exceeds, $T_{db} \geq 37^{\circ}\text{C}$ [3], [10], [11]. Additionally, the ACP should be 300 W/m^2 as a minimum for acceptable working conditions [3], [10], [12].

As a result of constrained resources operational changes are not thoroughly evaluated on these complex systems in deep-level mines [9], [13]. Furthermore, decisions are often made with limited information which increases both risks and the likelihood of project failures. Consequently, deep-level mines require a reliable, scalable method to evaluate complex mine ventilation operational changes according to key performance indicators (KPI's) such as cost and service delivery [13].

Simulating and modelling of mine ventilation networks

Research indicates that complex systems can only be thoroughly evaluated with the use of simulations [13], [14], [15], [16]. Since the inception of the digital age, simulation technologies have subsequently been incorporated to solve large complex mine ventilation networks [4]. Nevertheless, these simulations require an abundance of dedicated resources to provide accurate results which is firstly, labour intensive and secondly, very time consuming [17]. However, recent technological advancements coupled with innovative methods may enable mines to evaluate operational changes accurately and cost-effectively.

Several authors have addressed techniques to model and optimise sections of mine ventilation networks [4], [16]. Acuna and Lowndes conducted a review of such studies which showed that there is still a knowledge deficit in addressing the effects of both cost and service delivery in ventilation optimisation techniques [16]. The techniques used in industry does not incorporate simulations but includes tedious manual calculations [16]. These techniques don't take the holistic effects of operational changes into account but is narrowed to only consider single service delivery parameter evaluations [13].

Panigrahi and Mishra used computational fluid dynamic simulations in an effort to optimise axial flow ventilation fan blade profiles [18]. This method shows promise for further research especially on airfoil and centrifugal ventilation fans, nonetheless, this method is limited to component design and cannot be applied to optimise the branches of complex ventilation networks. Chatterjee and Xia developed a ventilation on demand (VOD) optimisation model that exploits the cyclical nature of mining to reduce ventilation fan operating costs [19]. This model determines the optimal fan operating speeds during each hour of a day by considering the time-of-use (TOU) electricity tariffs [11]. Although the premise of the model is well founded, further research is required to develop VOD methods that includes network optimisation and inclusion of other techniques, to achieve an integrated solution.

Various mine ventilation simulation packages are available for initial mine planning and design [15], [16]. However, none of these packages are used for optimisation or evaluation studies [16], [20]. Many mines in the private sector does not optimise or evaluate operational

changes at all [11]. These mines typically implement operational changes to continue with mine development, without regard to ventilation, until stopped by law or ventilation related accidents [20]. This emphasises the need to optimise and evaluate operational changes through simulations.

95 In the 1960s, ventilation simulation packages incorporated the simple laws of incompressible flow for Newtonian fluids [20]. However, with the large variation in air density experienced in underground mines, these packages proved to be obsolete. In the 1970s, mine ventilation simulation packages developed to include the thermodynamic relationships for Newtonian fluids [21]. This forms the basis of most modern ventilation simulation packages. These
100 packages utilise the thermodynamic principles, fluid dynamic properties and network mass balances, typically of fluids such as air, to simulate actual ventilation networks [13], [20].

Modern simulation packages have varying degrees of complexity and accuracy [16]. One should therefore opt for a flexible, cost-effective simulation package based on the nature of work to be completed [13]. The novel scalable, step-by-step method satisfies this need by
105 providing a means to select and use a ventilation simulation package to optimise and evaluate operational changes. This innovative method will provide mine personnel with a means to make decisions to improve the operational efficiency and safety while ensuring legal compliance.

Mine ventilation optimisation

110 Typically, in hard rock mining, there are two critical mining shifts which need to be considered in ventilation optimisation [22]. The first being the drilling, charge-up and blasting shift and the second being the loading shift (when broken rock is removed from production faces) [17]. During these shifts, the complex ventilation network is used to ventilate the underground working areas. This is done in order to ensure compliance with health and safety standards
115 [3]. There is also a shaft clearance period between shifts, in which the hazardous particulates (toxic blasting gasses and dust) are diluted and exhausted by the ventilation network.

Conventionally, after the drilling shift, miners retreat from the production face to the main shaft haulage area where fresh air intakes are available until the clearance period has subsided or the miners have egressed from the mine [9], [17]. Even though mining is conducted by a
120 cyclical nature, maximum ventilation is typically supplied during all operating hours [9]. Only in recent studies have techniques such as ventilation on demand deemed to ask crucial questions regarding true ventilation requirements during each hour of a day, exploiting the cyclical nature to lower operational costs [9], [11].

In conclusion, it is clear from literature that simulations is a viable technique to optimise and evaluate complex mine ventilation networks [8], [13], [16]. However, most of the simulation packages are only used to evaluate either cost or service delivery during initial mine planning [9]. These KPIs are seldom considered simultaneously especially when operational changes are to be implemented on a mine ventilation network. Simulation packages are therefore not used to optimise or evaluate operational changes [20]. Other techniques were presented in literature to optimise mine ventilation networks. Conversely, none of the reviewed techniques provided a single framework or method which describes the process of optimising and evaluating operational changes through the use of simulations. Therefore, there is currently no method available for the use of simulations to optimise and evaluate operational changes in mine ventilation networks. This paper aims to satisfy this deficit by developing an innovative scalable, step-by-step method to describe how operational changes should be evaluated and optimised through simulations.

METHODOLOGY

As part of method development, various existing practices are combined to add new value. Existing practices are improved by considering an integrated and more comprehensive approach to method development. As such, several factors must be considered to produce repeatable, accurate and dependable method results [13], [19]. These factors can subsequently be categorised according to the type of data, as shown below by the high level data categories included in the novel method:

- Service delivery data
- Operational data
- Technical data

The user will identify a KPI or KPIs under each of these data categories to form part of the method. For example, wet-bulb temperatures and air mass flows can be included as KPIs for the service delivery category. The raise bore hole diameter can be included as a KPI for the operational category. Future production planning (tonnes) can be included as a KPI for the technical category. It is not necessary to select KPIs for each of the categories. However, most of the KPIs for complex ventilation networks can be divided into the listed data categories. The KPIs should therefore be clearly defined, since the simulation model and final evaluation are measured according to these indicators.

These high level data categories have lower boundaries and constraints that govern the state of the simulation [14], [23]. It is crucial to determine the level at which the simulation data is required in order to evaluate and optimise the ventilation network effectively. Such constraints, imposed by each data category, should be established and accounted for by the method,

The next step in the method is to benchmark the ventilation network (B) according to current operations. This can be done by using available mine data (B1 to B3) or by manual measurements (B4). The accuracy thereof is of extreme importance, especially when manual readings are collected with portable instruments[1]. Refer to (B5) in Figure. 1. for typical complex ventilation network data required to be able to construct a simulation model. The level at which the data is available provides an indication towards the degree of simulation accuracy that is achievable.

Due to the variations in magnitude of operational changes, the methodology specifically incorporates scalability. The methodology can therefore be implemented in order to evaluate and optimise various degrees of operational changes, ranging from high-level (Surface and KPI) to detailed low-level (Per mine stope) changes. As part of the methodology, it is vital to verify the collected data in an effort to ensure the simulation provides an accurate representation of the current operations (C).

Mines typically incorporate supervisory control and data acquisition (SCADA) systems to monitor, gather and store real-time data [24]. These systems' accuracies are dependent on the existing measuring equipment. The available SCADA data should be verified by the user with manual measurements, using calibrated measuring equipment, or calibration certificates. If limited SCADA data is available, data should be acquired through manual measurements as shown by the method. The verification step is the central focal point between two iterative processes including benchmarking and simulation calibration. The benchmarking process can therefore be iterated until the user is satisfied with the accuracy of the acquired data.

Subsequently, the KPIs of the proposed operational change should be determined (D). This is an extremely important step in the method since the simulation objectives and evaluation is based on these indicators. The KPIs typically relate to the drivers behind the operational changes and are most often, operational efficiency and underground environmental conditions. Indicators such as air mass flow, air velocity, underground wet-bulb temperature, energy consumption, suction pressure and intake flow rates are typically selected as a KPI, depending on the operational change and subsequent simulation objective. The KPIs will also be used to validate the impact of any operational changes made.

In the next step, the different simulation packages should be evaluated according to the simulation objectives and capabilities (E). As discussed previously, several simulation packages are commercially available, though, some provide different network capabilities. The correct package should consequently be selected to align with the level of data acquired [10]. For instance, if underground wet-bulb temperature is selected as a KPI for service delivery, then only simulation packages incorporating thermal-hydraulic solvers would have the

capability to evaluate and provide results relating to temperature. The simulation package should therefore be selected as a result of the selected KPIs. Simulation packages that typically incorporate thermal hydraulic solvers are Process Toolbox, Vuma3D and VentSim [8], [13].

Thereafter, the critical simulation boundaries (F) should be established and prepared to be incorporated in the simulation. These boundaries form part of the individual constraints of each of the KPI categories. In other words, service delivery as well as operational and technical boundaries are to be included such as minimum wet-bulb temperatures, planned production targets, shaft diameters, velocities and so forth.

The next step involves the construction and calibration of the ventilation network simulation (G). This is achieved by incorporating the verified data into the simulation and comparing the simulated results with the actual measurement. In this manner, the accuracy of the simulation can be determined by comparing, for example, KPI1 and KPI2 against the actual measured KPI1 and KPI2 of the verified data set. The simulation is then calibrated by manipulating the simulation parameters so that the results correspond to within 10% of the actual network values, thereby verifying the simulation. The calibration of the simulation should be conducted as required when changes in parameters occur.

After the simulation is calibrated, the proposed operational change can be simulated and the results analysed (H). As a result of the analysis, the simulation can be refined and any user input faults detected [10]. The simulation results are analysed according to the service delivery and the operating efficiency for each operational change scenario. Since not all changes can be quantified, the method includes a benefit and risk analysis included in step H. This provides a comprehensive approach to the method so that improved evaluations can be made.

The different operational change scenarios can then be evaluated according to the selected KPIs, comparing apples with apples (I). The typical KPIs that form part of the final evaluation are the wet-bulb face return temperatures, air mass flows and operating costs. The initial evaluation focuses on the comparison of the absolute performance improvement in operational KPI between scenarios. The secondary evaluation focuses on the relative cost and performance intensity improvement achievable between scenarios. These evaluations are then used to determine the most feasible operational change to implement, which would satisfy all service delivery requirements resulting in the highest operational efficiency.

METHOD VALIDATION

The success of the scalable, step-by-step method will be validated by applying the newly developed method to a case study. The simulated and actual measured results of the selected

KPIs will be compared to obtain an indication of the overall accuracy that was achieved. The success of the methodology will be measured according to the accuracy achieved in terms of the post-implementation KPI results. The scalable, step-by-step method for evaluating and optimising operational changes through simulations will be explained according to a case study in the following results section. The validity of the methodology will be confirmed by considering the long-term performance of the operational changes that were implemented based on the results of the methodology.

RESULTS

In this section, the newly developed method will be applied to a mining complex. The method will be applied in a step-by-step manner to show the significance of each step from A to I. The need of the method will be underlined by the background and case study problem statement.

The ventilation network of a deep-level South African mining complex was selected as a case study. The name of the mining complex is protected by confidentiality therefore, for this case study the complex will be referred to as DK. At DK, narrow-reef conventional mining is conducted at a depth of ± 1.9 km, focussing on the south reef ore body.

The operation has one production shaft which acts as the main downcast intake shaft (fresh air enters the ventilation network) and one up cast vent shaft (return air is exhausted after ventilating the working areas). DK also has a sub-vent shaft on the northern side and is interconnected with another mine, CK on two levels namely, 90L and 106L with twin airways. In between DK's main downcast intake shaft, is an up cast vent shaft, DK1A. This illustrates the complexity of mine ventilation systems.

DK vent shaft is installed with two 2.1 MW Fantecnic (Howden) WBF-390 main surface ventilation fans. Currently, both of these ventilation fans are operating to ensure that conditions are conducive to safe and legal mining. DK1A vent shaft is installed with three Artec Davidson main surface ventilation fans, two having an installed capacity of 1.01 MW and the last 1.3 MW. Currently, only one of the 1.01 MW rated ventilation fans is operational at DK1A vent shaft.

The case study mining complex started to experience temperature constraints on the main production levels, 192L, 197L and 202L which comprises the south reef section. The increasing temperatures were as a result of mine development. Mine personnel had to mitigate the increasing temperatures by implementing an operational change on the ventilation network. However, there were many operational changes available for implementation and mine personnel were challenged to determine the most feasible option. As a result, there was

a need to apply the novel method to solve their problem and determine the most feasible option.

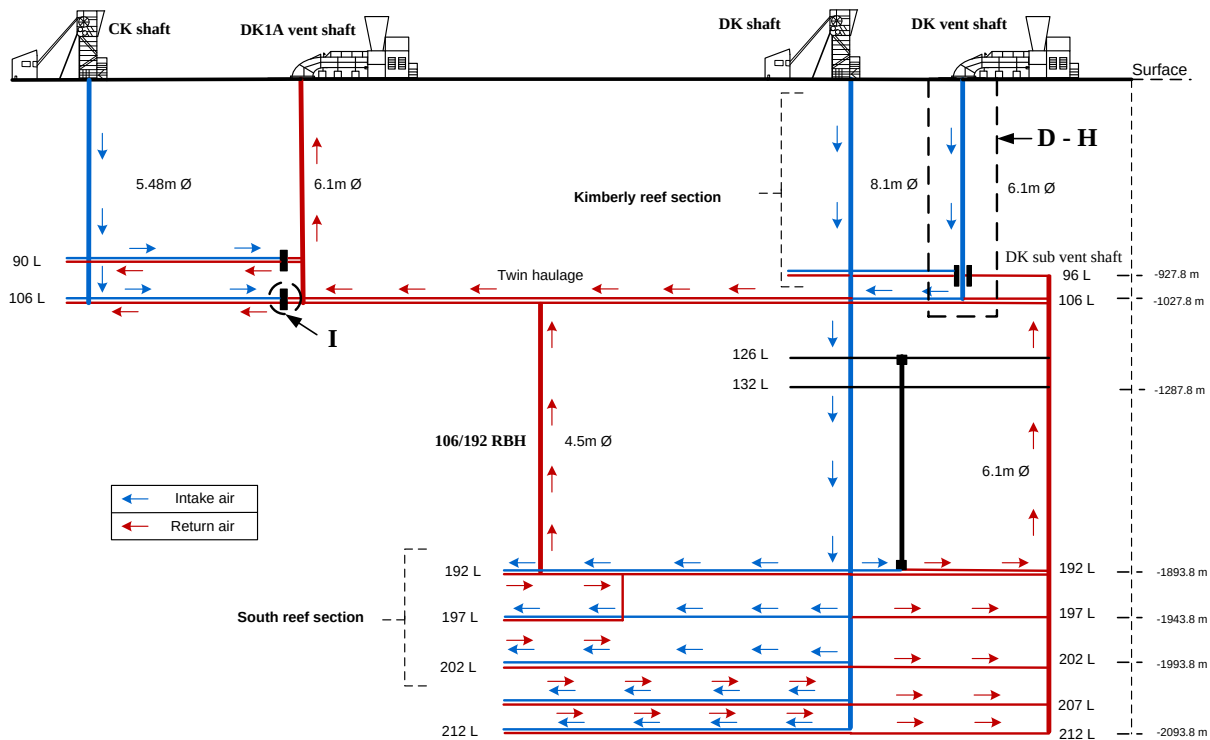
Operational changes (A)

As part of the novel method (A), nine operational change scenarios were identified to be optimised and evaluated. Each operational change will be simulated separately, however, the simulations bare similarities and were therefore grouped into three groups, namely group 1 (scenario A to C), group 2 (scenario D to H) and finally group 3 (scenario I). The different operational change scenario groups are displayed in Figure 2 on the next page. The operational changes are different between each scenario. These differences are highlighted in the discussion below.

Group 1 (scenario A to C), DK vent shaft was converted to a down cast shaft and the return from CK to DK1A closed off converting DK1A to the main up cast shaft. In scenario A, both the 1.01 MW ventilation fans and the larger 1.3 MW ventilation fans are operating at DK1A with no fans operating at DK vent shaft. In scenario B, the two 2.1 MW ventilation fans originally situated at DK vent shaft is moved to be operating at DK1A. In scenario C, the operating fan configuration is the same as in scenario B. However, the airway between DK and the 106/192 RBH is enlarged.

Group 2 (scenario D to H), DK vent shaft is kept as the main up cast shaft while only operating one of the 2.1 MW ventilation fans. This operational difference is indicated by the dotted rectangle in Figure 2. The fresh air intake for group 1, therefore changes to a return airway for group 2. Additionally, the returns from CK to DK1A will be closed and DK1A utilised as the second up cast shaft for DK operations. In scenario D to H, one 1.01 MW ventilation fan and the larger 1.3 MW ventilation fan will be operating at DK1A. In scenario E, the RBH diameter is enlarged from 4.1 m to 4.5 m. In scenario F, one of the twin airways between the RBH and DK1A is enlarged on 106L from 11.25 m² to 20 m². In scenario G, two 1.01 MW ventilation fans will be operating at DK1A. Also, for scenario G, one of the twin airways will be enlarged as discussed for scenario F. In scenario H, both 2.1 MW ventilation fans will be operating at DK vent shaft with only the 1.3 MW ventilation fan operating at DK1A.

Group 3 (scenario I) is shown in Figure 2.C, DK vent shaft is kept as the main up cast shaft, as in the case of group 2. However, a maximum return air mass flow of 150 kg/s should be maintained from CK to DK1A. The point where the air mass flow should be maintained are displayed in Figure 2, by the dotted circle.



RBH, denotes raise bore hole; Ø, diameter; L, level; D-H, group 2; I, group 3.

Figure 2. Operational change scenario A to I

310 Benchmark (B)

The unique methodology was implemented on a low level for the purpose of the study to illustrate the scalability and accuracy that is possible with the use of simulations. As part of the methodology (B), the ventilation network operations of the mining complex was benchmarked to include detailed data on a per stope basis. This included acquiring ventilation network data from the mine such as air mass flow, temperature, relative humidity, pressure, area and tons of reef mined on a per stope basis (B3, 5). Any missing data was manually measured with calibrated measuring equipment on a per stope basis as part of the methodology (B4).

Data verification (C)

The acquired data was verified (C) with manual measurements to ensure the accuracy of the data and subsequent simulation. Considering the latest life of mine plan, it was determined that the highest production rate planned for the specific mining complex was ± 120 kilotons (kt) per month. In South Africa's deep-level mines, the average typical volumetric flow range is between 3 to 6 m³/s per kt of rock mined per month or 0.12 m³/s per ton mined per day [17]. For this study, an average air mass flow of 4 kg/s was presumed to be sufficient in order to maintain production face wet-bulb temperatures of $\pm 29.5^{\circ}\text{C}$ for the south reef sections.

KPI selection (D)

The KPIs that were selected for the case study are shown below, categorised according to the data types (D):

- 330 • Service delivery KPIs – wet-bulb temperatures, air volumetric flow, air mass flow, air pressure.
- Operational KPIs – energy, maintenance.
- Technical KPI – air mass flow per kiloton production planned per month.

335 It is crucial to select applicable KPIs relating to the objective of the evaluation, as they form the basis on which the simulation and subsequent evaluation results are analysed. For this study, we want to improve the operational efficiency of the system, thereby reducing the energy costs while satisfying the service delivery requirements. Therefore, in terms of service delivery, the wet-bulb temperatures should be within acceptable limits and the energy costs must be kept as low as possible. The selected KPIs would indicate the success of the newly

340 developed methodology, by comparing the pre- and post-implementation effects of the KPIs.

Based off of this, the detailed simulation KPIs for the case study were determined and prioritised to be:

- Maintain production face return wet-bulb temperatures of $\pm 29.5^{\circ}\text{C}$ for the south reef sections
- 345 • Optimise each operational change scenario for increased operational efficiency - Energy
- Determine the suitability of existing infrastructures. Referring to existing main ventilation fans situated at DK vent shaft and DK1A vent shaft, minimum and maximum intake and return airway dimensions as well as the 106/192 RBH
- 350 dimensions.

Software selection (E)

Commercially available simulation packages were evaluated (E) and a package incorporating a thermal hydraulic solver was selected due to the detailed, per stope, simulation capabilities. Vuma 3D proved to be adequate and was already available on site. This simulation package

355 was specifically designed to model complex mine ventilation networks.

Simulation boundaries (F)

The next step in the methodology was to determine the ventilation network boundaries per KPI, as defined per data type category (F). Currently, the air handling capacity of DK is limited by the main down cast shaft for a maximum down cast volume of $600 \text{ m}^3/\text{s}$, at an air velocity

of 12 m/s. The collective up cast volume capacity of DK vent shaft and DK1A vent shaft is estimated at 1000 m³/s. Previous studies indicate that a minimum airflow volume of 470 m³/s is required to effectively ventilate the south reef sections. Furthermore, no mining is planned to be conducted at the Kimberly reef sections, above 106L, for the next ten years. The most critical simulation boundaries were established from the acquired data, as displayed by Table 2.

Table 2: Critical KPI simulation boundaries

Simulation boundaries	Parameters
Surface temperatures [°C WB/DB]	18/28
DK main shaft diameter [m]	8.1
Main intake and return airway [m ²]	11.55 (3.5 x 3.5)
Intake airway velocities [m/s]	6 - 8
Main return airway velocities [m/s]	10 - 12
Design air density [kg/m ³]	0.95
DK vent shaft diameter [m]	6.1

WB denotes, wet bulb; DB; dry bulb.

Simulation calibration (G)

As part of the innovative method (G), the simulation was constructed for the complex mine ventilation network by incorporating the acquired data per stope and simulation boundaries. The simulation was iteratively calibrated by comparing the actual verified data set with the simulation results on a per stope basis. Therefore, referring to Figure 1, the actual data for 192L's stope 5 west were compared with the simulated data for 192L's stope 5 west. The simulation was therefore constructed to include all nodes where actual verified data were available or measured. The actual and simulated data showed an overall resulting correlation of 8%. The identified operational change scenarios were then simulated individually, to be optimised and evaluated.

Simulating operational change analysis (H)

The different operational change scenarios were simulated and optimised. Conferring to the novel method (H), the results should be analysed according to the KPIs of each data type category. Each operational change scenario must therefore satisfy the service delivery and operational efficiency KPIs. Figure 1, illustrates the south reef section where the temperature constraints were experienced as a result of mine development, indicated by 192L, 197L and 202L. The air mass flows are therefore critical on these levels to mitigate the effects of the increasing temperature. The south reef air mass flow is the sum of the air mass flows on the

main production levels before the air is returned through the up cast sub shaft and 106/192 RBH. The simulation air mass flow results for each of the scenarios are shown by Table 3.

Table 3: Operational change scenario south reef air mass flow simulation results

Scenario	A	B	C	D	E	F	G	H	I
Mass flow [kg/s]	455.3	509.5	532.6	470.6	475.9	491.2	473.8	533.0	480.5
Air flow [kg/s per kiloton per month]	3.94	4.41	4.61	4.07	4.12	4.25	4.10	4.61	4.16

Table 3 indicates that all of the operational change scenarios would satisfy the air mass flow requirement. However, in order to evaluate and optimise the operational change scenarios, the service delivery constraints must be satisfied and adhered to by each for all the KPIs. Furthermore, it is critical that the ventilation network results in wet-bulb temperatures conducive to safe and legal mining operations as this is the most important KPI [3]. All the simulation scenarios were therefore analysed to satisfy and maintain production face return wet-bulb temperatures of $\pm 29.5^{\circ}\text{C}$.

The average production face wet-bulb return temperatures of the simulation scenarios are illustrated by Figure. 3. The average standard deviation between the nine simulation scenarios was calculated as, $\sigma = 0.13$. As a result of this small standard deviation, one can conclude that each scenario satisfies the most critical service delivery KPI.

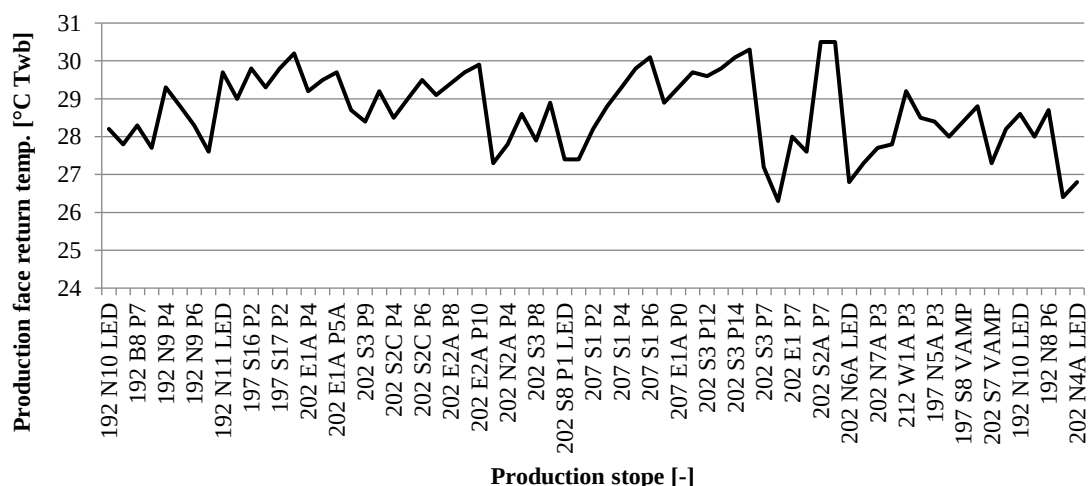


Figure. 3. Average production face return wet-bulb temperatures per stope

Evaluating operational changes (I)

Following the satisfaction of the wet-bulb temperature KPI, the evaluation of the individual operational change scenarios can commence in an effort to determine the most feasible solution (I). The evaluation is done according to the specified KPI categories. The individual operational change scenario, average face wet-bulb return temperatures, indicated by the bar chart, and air mass flows, indicated by the line chart, are illustrated by Figure. 4.

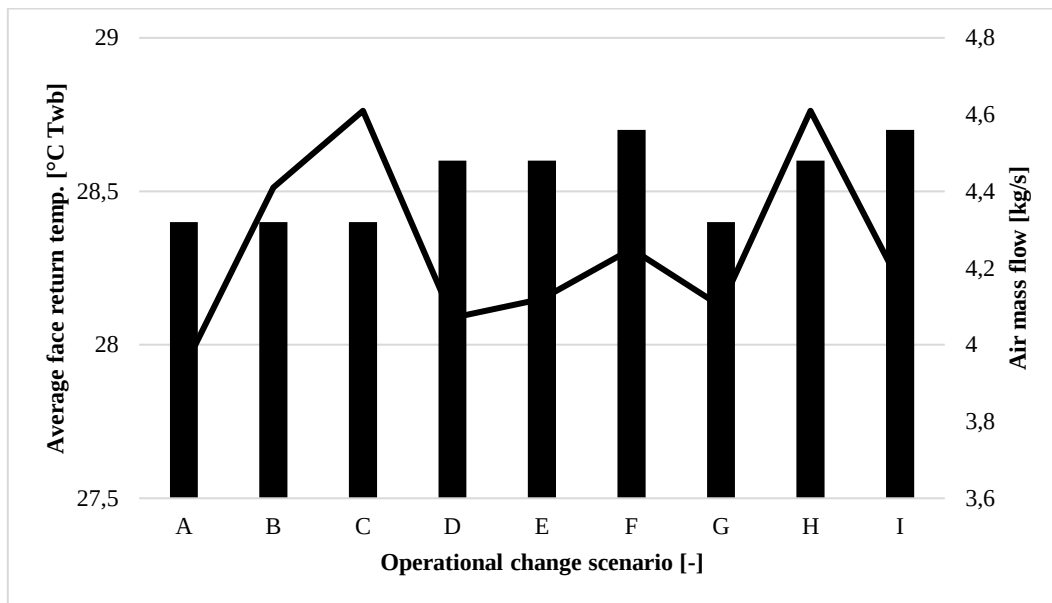


Figure. 4. Average production face wet-bulb return temperatures (bar) and average air mass flow rates (line) per operational change scenario

Upon first inspection, the results of the operational change scenarios illustrate that scenarios A, B, C and G has the lowest average face return temperatures displayed in the bar chart. Considering future mine development, the simulation results therefore indicate that these scenarios will be the most prudent operational changes to contend with the increasing rock face temperatures experienced on the south reef section. However, as part of the unique method, the other KPIs must also be satisfied and evaluated accordingly. Hence, considering the average simulation air mass flow design of 4 kg/s for a typical deep-level South African mine, scenario A, D, E and G have the closest correlation results. These scenarios will therefore ensure that sufficient air mass flow is provided to satisfy future production requirements.

Up till now, further analysis is required for the ventilation network to evaluate the operational change simulations in an integrated comprehensive manner. Subsequently, the next step in the method is to consider the KPI of operational efficiency, by evaluating the operational

change scenario energy costs indicated by the bar chart, and total air mass flow indicated by the line chart, as illustrated in Figure. 5. The energy cost for the case study was determined for each operational change scenario by multiplying the ventilation fans' energy consumption in kilowatt-hour for each scenario per month, with the South African national state owned power utility's 2015/2016 electricity tariff.

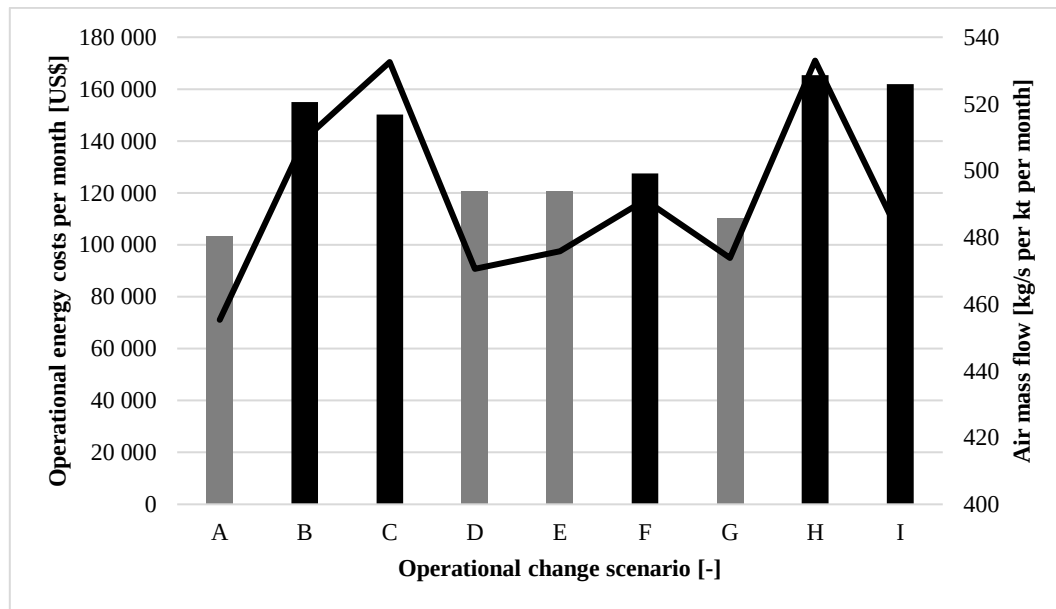


Figure. 5. Operational costs per month in US dollars (bar) and total air mass flow rates (line) per operational change scenario

Operational change scenarios A, D, E and G resulted in the lowest operational energy costs, as shown by Figure. 5. This correlates to the average air mass flow utilised by the south reef section, as the operating costs are directly proportional to the up cast ventilation fans' electricity usage. Only two operational change scenarios, A and G, would result in the lowest energy costs, thereby increasing the operational efficiency and satisfying the KPIs of the second data category.

The other operational change scenarios in contrast had shortcomings in at least one KPI. Therefore, only operational change scenarios A and G, satisfy the KPIs of all three data categories. However, in order to continue with the novel scalable, step-by-step methodology, the benefits and risks should be analysed. The inclusion of the benefits and risks of each operational change scenario was incorporated in the method to make provision for a comprehensive, thorough evaluation. The author has found that although most benefits or risks cannot be quantified to a monetary value, they should definitely still form part of the final evaluation.

Benefits

450 Scenario A will have the lowest operating costs by only operating the DK1A ventilation fans only. Scenario A will also provide a means to convert DK vent shaft to a second escape route for shaft egress. Scenario B will provide flexibility to the network in the form of different ventilation fan operating configurations, flexibility in the up cast airflow capacities and a means to ventilate the old Kimberly reef section if required in future.

455 Risks

Scenario A has no flexibility or redundancy in the ventilation fans. If any of the DK1A ventilation fans experience a breakdown, work in the south reef must be halted according to legal standards. In scenario A, DK1A vent shaft limits the total up cast airflow capacity. There is also no flexibility to ventilate the old Kimberly reef section in future. In scenario G, DK vent shafts limits the down cast airflow capacity.

As mentioned previously, the only operational change scenarios which satisfied the KPIs of the three categories are A and G. Although scenario A has the lowest operational energy cost, the risks involved could have dire consequences for the mining complex and underground miners. Not all benefits and risks can be quantified to a monetary value, but should be included in the final evaluation of operational changes. Therefore, following the evaluation and simulation analysis, operational change scenario G will be implemented to achieve the desired results (I). The final simulation results for **scenario G** were as follows:

The novel scalable, step-by-step methodology was used to optimise the operational energy costs on the mine by satisfying KPIs of the three data categories. The most critical service delivery KPIs were satisfied by scenario G. The operational energy saving would therefore be realised by operating a 1.01 MW ventilation fan at DK1A vent shaft, instead of the 2.1 MW ventilation fan at DK vent shaft. This will result in a cumulative energy efficiency saving of **±9.64 GWh per annum**. This energy efficiency saving per annum was determined by multiplying the average energy saving per hour in kWh with 24 hours over a 1 year period.

475 VALIDATION

The operational change scenario G was implemented on the mining complex and monitored for 12 months. During this period, the cumulative energy efficiency saving measured through calibrated Schneider-Electric Powerlogic ION7330 power meters amounted to **8.50 GWh**. This resulted in an energy saving of 23% on the ventilation network through the implementation of the most appropriate operational change as identified by the scalable step-by-step method. However, the total energy saving achieved was less than the simulation results indicated. The

difference is attributed to the sealing of the return from CK shaft to DK shaft which failed as a result of a temporary wooden seal. This was solved by a permanent seal, constructed from vermiculite bricks and cement packing.

As part of the unique method's final KPI validation, the simulated and actual results must be compared. This will provide an indication towards the accuracy and success of the newly developed method. For that reason, the most important KPIs of the main production levels on the south reef section are analysed in Table 4. The average daily simulation KPI results are compared to the actual average daily KPI values, measured over the 12 month period. This indicates the accuracy of the calibrated simulation to forecast the effects of implementing an operational change. The average standard deviation of the daily wet-bulb temperatures were calculated to be, $\sigma = 1.5$.

Table 4: Post-implementation average daily KPI validation for main production levels

Level	Simulated Temp.	Actual Temp	Temp Error	Simulated Airflow	Actual Airflow	Airflow Error
	T _{wb} [°C]	T _{wb} [°C]	Absolute [%]	Mass flow [kg/s]	Mass flow [kg/s]	Absolute [%]
192	29.5	29.2	1	47.5	51	7
197	28.5	26.5	8	9.5	11.4	17
202	25.5	23.4	9	114	104.5	9

wb denotes, wet bulb.

The most important objective of implementing the operational change is to ensure acceptable working conditions conducive to safe and productive mining at the highest operational efficiency, thereby lowest operational energy costs. From Table 4, the actual and simulated average daily wet-bulb temperatures correlate to within 9%. Moreover, the average daily airflow to each production level was found to be sufficient to ensure acceptable working conditions, and in some cases, to supply supplementary airflow capacity. The service delivery KPIs are therefore satisfied for the main production levels.

Additionally, to thoroughly compare the results, other average daily KPIs for the integrated complex ventilation network were considered, as shown by Table 5. The average daily simulation air mass flows are compared to the actual average daily air mass flows, measured over the 12 month period. The absolute error of the average daily air mass flows are presented to indicate the level of simulation accuracy.

Table 5: Post-implementation average daily KPI validation for the integrated, complex mine ventilation network

Section	Simulated mass flow [kg/s]	Actual mass flow [kg/s]	Absolute error [%]
South Reef	473.8	478	1
192/106 Raise bore hole	185	165	12
DK Vent Surface fans	298.6	340	12
DK1A vent surface fans	299.9	313	4

510 Considering the average daily air mass flow results comparison, displayed in Table 5, the difference in air mass flow for each of the service delivery KPIs can be ascribed to variations in the data used to construct the simulations, as well as external factors such as air leaks and underground configuration changes having an influence on the network. Due to the complexity of the ventilation network, these small differences between the simulated and actual results, 515 are negligible and the novel method is validated in terms of service delivery.

Another factor to consider, as part of the KPI validation, is operational efficiency. It is extremely important to illustrate the energy cost benefit realised as a result of implementation. Moreover, the implementation costs should also be included in the analysis. Therefore, the costs to install and close the return from CK shaft to DK shaft amounted to US\$3 312, ZAR to US\$ exchange 520 as on 13 Nov. 2017. The costs to reduce the RBH and seal the old Kimberly reef sections amounted to US\$3 450. The cost to increase one of the return airways on 106L amounted to US\$2 070. The total cost of implementing operational change scenario G, amounted to **US\$8 832**. The implementation time used to complete the operational change was **1.5 months**. The implementation time would have been much shorter, had it not been for 525 extended lead times for vermiculite bricks and cement packing used to construct the underground seals.

DISCUSSION

The operational change was implemented and had been active for a period of 18 months during the time this study was compiled. The total energy savings, measured by the calibrated 530 meters for this period amounted to **13.32 GWh** which, if converted to costs according to the tariffs as mentioned earlier, resulted in an energy cost saving of **±US\$0.7-million**.

The significance of this novel method lies in that it enables mine personnel to make improved decisions regarding operational changes on mine ventilation networks through simulations. The importance of this method is emphasised by the validation, in which scenario A, B, C and G satisfied one KPI. However, if scenario B or C was implemented, the operational costs would have been much higher when compared to scenario G. Likewise, the resulting air mass flow of scenario B and C would have proved to be unnecessary for this project. Furthermore, if scenario A had been implemented, the mine would have had a much larger risk of losing production or experiencing an underground working fatality as a result.

This method was easily implemented and was specifically developed to be scalable. The scalability of the method is extremely important towards the successful implementation and utilisation thereof by industry practising professionals. The versatility of the method to conduct high, medium and low level evaluation studies provides mine personnel with new insights on operational changes. The author has seen a newly instilled vigour in mine personnel where the method was applied as it was a new tool to be used for improving underground conditions and for increasing the profitability of deep-level mines. The importance of this method was stressed by the adoption of this method by industry practising professionals to form the norm of their mining standards on operational changes.

This novel method was developed according to a continuous improvement process. This enables the method to be incorporated and still be relevant in future developments such as cases where industry 4.0 and the Internet of Things (IoT) technologies are applied to the mining industry [13]. This will enable mine personnel to develop a digital simulation twin of the entire ventilation network to be evaluated on a continuous basis incorporating these new technologies.

CONCLUSION

In this paper, a novel scalable, step-by-step method was developed to optimise and evaluate mine ventilation networks through simulations. Nine operational change scenarios were optimised and evaluated on a deep-level mining complex. The method was used to determine the most feasible option. The most feasible option was implemented successfully, resulting in a 23% energy saving.

Mine personnel was challenged with a decision of which operational change to implement, selecting from a vast array of operational changes. The method provided a means for mine personnel to select the best decision based on a comprehensive evaluation. The true value of the method lies in that it enables mine personnel to make improved decisions regarding

565 operational changes. As exemplified by the mine personnel, adopting the method as part of
their own standards and procedures after successful validation.

The method promotes improved safety, underground working conditions, legal compliance
and mine productivity as a result of the thorough evaluation which was not previously available
for mine personnel. This method's versatility and scalability truly makes it applicable to all
570 ventilation networks, including future developments such as industry 4.0 or IoT technologies.

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DECLARATION OF INTEREST

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App. A.2: JESA GUIDELINES FOR AUTHORS

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Manwell, J. F., McGowan, J. and Rogers, A. 2002. *Wind power explained: Theory, design and application*, second edition. Chichester, UK: Wiley.

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Appendix B:

Economic quantification model for energy efficiency projects in the mining industry

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Status of article: Reviewed, under final revision for publication

Economic quantification model for energy efficiency projects in the mining industry

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App. B.1: Article II

Economic quantification model for energy efficiency projects in the mining industry

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ABSTRACT

The impact of industrial EE projects have previously been understated by the omission of non-energy benefits (NEBs). As a result, several fruitful projects have not been implemented which could have dire consequences for energy intensive industries, such as the mining industry.

5 Typically, project feasibility is determined through financial evaluation techniques such as payback period, internal rate of return and return on investment. These techniques are limited to the monetisation of benefits, NEBs therefore, has to be quantified, monetised and included in these techniques. However, not all NEBs have direct costs, there are NEBs which affects productivity but the relationship cannot be empirically calculated. Therefore, this paper aims
10 to develop a comprehensive economic quantification model that can be used by energy advocates to quantify and monetise NEBs for EE projects in the mining industry.

KEYWORDS

Mining, Economic quantification model, Energy efficiency, Non-energy benefits

HIGHLIGHTS

- 15 • Economic quantification model for EE projects in the mining industry
- Non-energy benefits (NEBs) quantified and monetised
- Improved financial feasibility of energy efficiency (EE) projects

INTRODUCTION AND BACKGROUND

The global energy demand has steadily increased since the industrial revolution. The increase
20 can mainly be attributed to the industrial and mining sector's rapid development to satisfy growing societal needs [1]. South Africa's economy is built on minerals extraction and processing, which is energy intensive by nature [1]. Historically, low coal and electricity prices

contributed towards the country's energy intensive development and exacerbated the drive to improve upon the *status quo* of energy efficiency (EE) [2]. Energy conservation measures are seen as the most-cost effective approach to achieve sustainable economic development [3]. Considering the current global economic state and challenges faced with the profitability of mining in general, energy conservation measures could prove to be invaluable towards sustainable production [4].

Bleak economic outlooks are forcing companies to investigate, integrate and implement EE measures to improve operational efficiency [4]. In some cases, there are additional synergistic benefits arising from the implementation of EE projects, over and above the standard energy cost savings [3]. These non-energy benefits (NEBs) have previously been incorporated as part of the motivation behind EE projects and technologies [5]. However, in order for EE projects to appeal to the mining industry, the total financial benefit should be monetised [6]. This value should encompass all benefits in terms of energy, NEBs as well as the effect on productivity and ultimately profitability [7]. There is thus a need to quantify NEBs in the mining industry to increase the uptake of EE projects.

Pye and Mckane acknowledge the importance of quantifying NEBs and have described the incorporation of these benefits as "making business sense of energy efficiency" [8]. Additionally, mining companies are typically only able to select a handful of projects for implementation from a portfolio of potential projects [3]. The projects in the portfolio are analysed and selected according to various financial indicators but exclude NEBs [3], [5].

Worrel et. al. pioneered the inclusion of productivity benefits in the evaluation of EE projects [7]. The results of the study, conducted on the United States (US) iron and steel industry, revealed that the explicit inclusion of such benefits in the modelling parameters would double the cost-benefit potential for EE projects [5], [7]. Lung et. al. later examined ancillary savings and production benefits by considering 81 industrial application case studies to determine a comprehensive cost of conserved energy [9]. However, only 54 of the 81 case studies' ancillary and production benefits could be quantified, emphasising the need for a comprehensive economic quantification model [5], [9]. Together, these studies conclude that the total financial benefit of industrial EE projects are often understated by the omission of NEBs [5], [7], [9], [10].

Non-energy benefits categorisation

Non-energy benefits is a comprehensive phrase that covers a wide array of benefits as a result of EE projects [10]. NEBs are most commonly categorised according to the level at which they are perceived as well as the type of benefit produced [10], [11]. In literature, there is no clear

distinction between the qualification criteria for benefits to be classified as NEBs [10]. However, there has been several categorisations such as productivity benefits [7], [12], ancillary benefits [9], indirect benefits [13] and co-benefits [14] which can be encapsulated by NEBs [7], [8], [12].

Considering the magnitude and classification range of NEBs, there is a variety of monetised and non-monetised NEBs in literature [10]. Nonetheless, previous studies conducted on the NEBs associated with industrial EE projects have limited detail on the level of quantification [13], [15]. Similarly, only one previous study was found relating to NEBs in the mining industry, emphasising the need and importance of this study [16].

Worrel et al. and Lung et al. investigated NEBs in industrial EE projects in an effort to determine the influence on the financial feasibility of such projects [7], [9]. Although the authors had shown that NEBs are important in determining financial feasibility, none of the NEBs for the case studies were quantified [15]. The focus was rather to illustrate the importance of including NEBs in the financial indicators. Likewise, there have been documented studies of NEBs in the Swedish residential sector, however, none of the NEBs were quantified [15], [17].

Historically, several NEBs were identified for the industrial sector [15], [18]. In contrast, there has only been one documented case study for the mining industry, conducted by Krige et al. [16]. The study was conducted and published in 1981 [16]. The study aimed to establish empirical relationships between mine productivity and the main drivers thereof. However, the study was not verified nor validated. The authors failed to discuss any particulars of the study relating to measuring equipment used, measurement calibration, data acquisition methods and data validity. The authors acknowledged that the results of their study should be considered with a low confidence level based on the limited data used. Although no validated relationship was established, the study revealed that the average underground environmental wet-bulb temperature is the most significant measure for environmental quality in mines. The authors emphasised the need for continued research and analysis in South African mines due to the sharp production decline and recommended qualitative analysis are included in future studies relating to mining NEBs. Considering the crucial state of the global mining economy, the decline in production warrants such studies [4].

The most important NEBs relating to the industrial sector were identified as the operations and maintenance cost saving, reduced emissions and improved productivity [7], [15], [19]. Industrial NEBs were classified according to six categories, until recently when Cooremans introduced a wider perspective, pertaining to cost, value and risk [7], [12], [13]. This emphasises the diversity of benefits and underlines the comprehensive perspective that is required to model the total benefit of EE projects [15].

Quantification of non-energy benefits

Considering the dynamic nature of mining, there are supposed to be NEBs as a result of EE project implementation [7]. Most of the NEBs should be easily quantified and monetised, as the case with industrial EE projects for example. However, there may be NEBs related to productivity which are difficult to identify, quantify and monetise [16].

Productivity is defined as the relationship between the services or goods produced and the resources required to produce said goods or services [7], [11]. In terms of deep-level gold mining this equates to the ratio of tonnes of gold produced (outputs) versus the resources required to produce the tonnes of gold [16]. NEBs relating to worker productivity have eluded quantification and monetisation for decades. This comes as a result of the many uncontrolled variables which makes the quantification thereof extremely difficult.

Typical energy efficiency projects in mining include waste heat recovery, energy generation from by-products and energy management [20]. There has been numerous energy management strategies implemented on mine utility systems including the refrigeration, water reticulation, compressed air and ventilation systems [21], [22]. Many of the strategies rely on increased utilisation and equipment scheduling to achieve an optimally controlled load profile [23]. In contrast, other strategies rely on the replacement of old, inefficient equipment with new more efficient equipment to achieve the efficiency increase [24]. However, the true effect of these projects, specifically related to mine production have not been established. Additionally, there may be many NEBs arising from the implementation of these projects which are omitted in financial evaluation techniques, although quantifiable.

Industrial compressed air systems have been investigated to establish the full extent of energy usage, energy savings and additional NEBs [25]. These systems are controlled according to a pre-determined pressure or flow requirement [26]. The relationship between the pressure and flow have previously been linked to production for industrial applications in factories [25]. In mining, compressed air systems are used to supply compressed air to pneumatic rock drills which directly affects the rock penetration rate and subsequent mine production [27]. A laboratory investigation have shown the effects of varying compressed air pressure supply on rock penetration rates of varying rock samples [28]. However, the relationship between pressure, flow and rock penetration rate has not been established with production nor other NEBs.

According to Pye and McKane, there are NEBs of industrial EE projects which can be included in financial evaluations [8]. Hence, the relationship between these NEBs and productivity are empirically based and therefore easily quantified and monetised [7], [8]. However, there are

NEBs which may influence productivity in the mining industry which are difficult to quantify and monetise [8], [11], [12]. The most important of these NEBs are when the underground working environmental conditions are improved, through improved temperatures [7], [16]. A systematic literature review conducted by Rasmussen illustrates the very limited research within the empirical context for energy efficiency projects in general which is also the case for mining [29].

Research indicates that it is essential for the feasibility of EE projects that NEBs be included in the evaluation [7], [8], [12]. The results of Finman and Laitner's study demonstrated that of the 54 case studies considered, the NEBs that were quantified and monetised proved to be at least equal to or greater than the energy cost saving [11], [12]. This result is not by odd occasion, but well documented in literature, as described by Hall and Roth which found that the annual NEBs monetised, were almost three times the energy cost savings [10], [30].

NEBs that can easily be quantified and monetised in the mining industry should therefore be included in feasibility calculations. In Hall and Roth's study, almost 40% of the NEBs were successfully quantified and monetised [30]. These benefits were quantified based on empirical finding, such as measurements conducted before and after EE project implementation[30]. Most of the NEBs were related to operations and maintenance cost savings [30]. Furthermore, several studies stressed the importance of quantifying and monetising all NEBs [7], [8], [13]. Little effort has been made to quantify the total benefits of EE projects in the mining industry, which leaves large potential for a comprehensive economic quantification model [5], [11].

Literature indicates that the total financial benefit of industrial EE projects are often understated by the omission of NEBs [5], [7], [9], [10]. Studies have shown that NEBs are most often, equal or greater than the direct energy cost savings [11], [12]. However, there are limited literature available that provides quantification and monetisation models for NEBs, specifically relating to the mining industry [5], [11]. Accordingly, only one documented attempt have been made to quantify NEBs associated with mine EE projects [7], [16].

Therefore, this paper aims to satisfy the knowledge deficit by developing a comprehensive economic quantification model for EE projects in the mining industry. This model would be used to quantify and monetise NEBs associated with EE projects in the mining industry to provide the true financial benefit.

DATA COLLECTION

The following data were required as part of the study i.e. energy data, potable water data, labour data, maintenance data, ventilation data and finally production data. It is important for reproducibility to note that all data used in the study, were obtained from calibrated meters

and systems, irrespective of the type of meter. However, due to the variation in data and meters used to measure the data, only the most critical measuring equipment are highlighted. The energy data used in the study were measurements obtained from Schneider Electric ION Powerlogic ION7330 power meters. These meters were calibrated regularly by the mine or third-party metering companies. However, as an extra measure, the energy data provided were verified with manual measurements using calibrated datalogger power smartloggers.

Due to the large variation in data types, different meters were used to provide and verify each of the required data. The potable water consumption would be measured with an electromagnetic flow meter and typically verified with an ultra-sonic flow meter. However, there was no water savings component for the case study EE project. The labour and maintenance data were obtained from the financial maintenance system and calibrated biometric fingerprint clocking system. The dry-bulb and wet-bulb temperatures as part of the ventilation data, were obtained from resistance temperature detection (RTD) sensors and verified with handheld thermocouple sensors. These sensors also included pressure and relative humidity sensors which was verified by the mine and third-party consulting engineering firm. The production data, namely tonnes of ore mined, were obtained from level specific weigh-bridges, installed with load cells and scale sensors. The data was verified from an independent third-party company specialising in mine production data measurements and management.

To determine the effects of the proposed EE initiatives and NEBs, a three-year average data baseline period was selected for pre-implementation, to be compared with post-implementation. The data for the baselines were available on the mine's supervisory control and data acquisition (SCADA) system [31]. This system included actual measurements in five second intervals for all utility systems. The SCADA also included the average labour cost as determined by a fixed tariff as a product of time for the mine technician and the average maintenance costs for each mining utility system. The time required for maintenance was also logged on the technician's time sheets, over the last three years and daily hours verified with biometric fingerprint readers. Qualitative data collection methods were also used in the study, such as interviews and questionnaires from industry experts, but are discussed further in model development.

MODEL DEVELOPMENT

The first step in developing a novel quantification model for EE projects in the mining industry is to start with the existing industry employed model, that is, to only consider energy cost savings [32]. According to the International Performance Measurement and Verification Protocol (IPMVP), energy savings is defined as the difference between the current year's energy usage and previous baseline year's energy usage with adjustments taken into

195 account [33]. The adjustments are made to ensure the system is considered under the same set of conditions for both years, to provide a conservative indication as to what would have happened without the intervention [33], [34].

The existing economic quantification model for EE projects is illustrated by Equation. (1).

$$T_{Bi} = \sum_{j=1}^n T_{Ej} \quad (1)$$

200 where T_B is the total benefit for model $i = 1, 2, \dots, m$ and T_E is the energy cost savings for $j = 1, 2, \dots, n$ affected systems. Although Lilly et al. developed a more comprehensive model for industrial EE programs, it is still not widely implemented or recognised by industry [10], [19].

Following the successfully proven energy savings model, we want to use similar thinking to factor in the additional benefits and costs to progress on the *status quo*. We therefore opted
205 to classify the benefits from EE projects as *inter alia*, direct and indirect costs [6]. The classification is done according to the level of quantifiability of each of the benefits. Direct costs are highly quantifiable NEBs, with the direct effect of the EE project measured pre and post implementation. Direct costs are typically monetised as part of business as usual processes. Indirect costs are NEBs which are difficult to quantify and monetise. Due to the
210 wavering effects of such NEBs and in some cases, the reliance on specific governmental policies, the quantification and monetisation is hardly ever obvious. Only when both the direct and indirect costs are included in the model, will the true benefit of EE projects be quantified and monetised.

Direct costs

215 Building on the industry's convention to only consider energy costs, Equation (1) is updated with direct NEBs to provide Equation (2). The economic quantification model's development is shown by Equation. (2).

$$T_{Bi} = \sum_{j=1}^n T_{Ej} + T_{Mj} + T_{Lj} + T_{Wj} \quad (2)$$

220 This model builds on the existing economic quantification model by including the direct quantifiable NEBs namely, maintenance, labour and water cost savings for $j = 1, 2, \dots, n$ affected systems as denoted by T_M , T_L and T_W respectively. These factors were included as direct costs since it was reported that most NEBs were experienced on these systems in previous industrial EE projects [10]. The direct costs are easily quantified through the use of M&V principles with regards to calibrated measurements and verified data [32], [34]. However,

225 in order to widen the perspective to attain the full value of EE projects, all NEBs must be considered as emphasis by Finman and Laitner, Worrel et al. and DeCanio et al. [7], [12], [13].

Indirect costs

Continuing with the economic quantification model development, the indirect NEBs are included into

230 Equation (2) to give Equation (3).

$$T_{Bi} = \sum_{j=1}^n T_{Ej} + T_{Mj} + T_{Lj} + T_{Wj} + \text{abs}((x_{ij})T_{SDj}) + T_{Oj} \quad (3)$$

where T_{SD} is the service delivery cost savings and T_O is the other additional cost savings for $j = 1, 2, \dots, n$ affected systems. Furthermore, x_{ij} denotes the confidence level at which the service delivery cost saving is applied in the model. Starting with the level of quantification, 235 the other cost savings can be demarcated as tax incentive rebates or losses provided by government and similar institutions for the implementation of EE projects [35]. Furthermore, T_{Oj} 's NEBs are typically well controlled and measured to ensure compliance with governmental policies [33], [34]. The process to verify and validate the specific tax rebates or additional tax are documented according to the IPMVP [35]. There are mainly two applicable 240 tax policies in South Africa, the 12L tax rebate incentive and additional carbon emissions tax [34]. The guidelines on how these taxes and rebates are regulated, implemented and enforced vary from country to country and are stipulated by government [36], [37].

In contrast, service delivery (T_{SDj}) NEBs which affect production, such as improved working environmental conditions, are extremely difficult to quantify and monetise. Several studies 245 have acknowledged and emphasised the importance of quantifying such NEBs, nevertheless, no progress have been made due to the immense difficulty associated with these kind of studies as a result of the many uncontrolled variables [5], [7], [10], [12], [38], [39].

Service delivery

Several authors have acknowledged that the underground working environmental conditions 250 has an effect on worker productivity [5], [40]. Additionally, underground working environmental conditions have been identified as one of the most important NEBs relating to EE project evaluation [32]. However, according to literature, there have only been two attempts to quantify and monetise the effects thereof, across all industries [16], [40].

Historically, wet-bulb (WB) temperatures are used as the primary indicators towards 255 environmental quality and working environment [16], [41]. Krige et al. lead a study in which 27 deep-level gold mines were empirically evaluated to determine the effects of productivity

drivers such as wet-bulb temperatures on mine productivity [16]. By means of regression analysis, the results showed that for a wet-bulb temperature decrease of 1°C, a 3% to 4% production increase can be expected. Conversely, the results were based on a wet-bulb temperature bandwidth of only 3.2°C, between 27.9°C and 31.1°C [16]. The results indicated a zero slope at a wet-bulb temperature of 28°C, which was supported by findings of the research laboratories of the chamber of mines in South Africa [16]. Therefore, the highest production rate was achieved during an average wet-bulb environmental temperature of 28°C.

Wyon et al. investigated the effects of air temperature on factory workers. The tests were founded on empirical results by applying a specific test methodology and measuring key physiological aspects of each worker [40]. The results had shown that a general performance peak was experienced at 32°C for conditions at low humidity [40]. Unfortunately, the author failed to specify the exact relative humidity reading and in doing so, didn't specify the wet-bulb temperature which is critical for deep-level mining. It was assumed that peak worker productivity was experienced at a wet-bulb temperature of 28°C, that was the same for mining.

Based on the empirical study from Wyon et al. and supporting work from Krige et al., the authors assumed that the peak physiological productivity of underground mine workers, correlate to those experienced by factory workers of the same ethnic group, location and country. Therefore, we assumed that the underground mine workers are 100% productive at a wet-bulb temperature of 28°C, with a linear decline in work performance to 88% at a wet-bulb temperature of 38°C WB. This assumption for the service delivery component is illustrated by Figure 1.

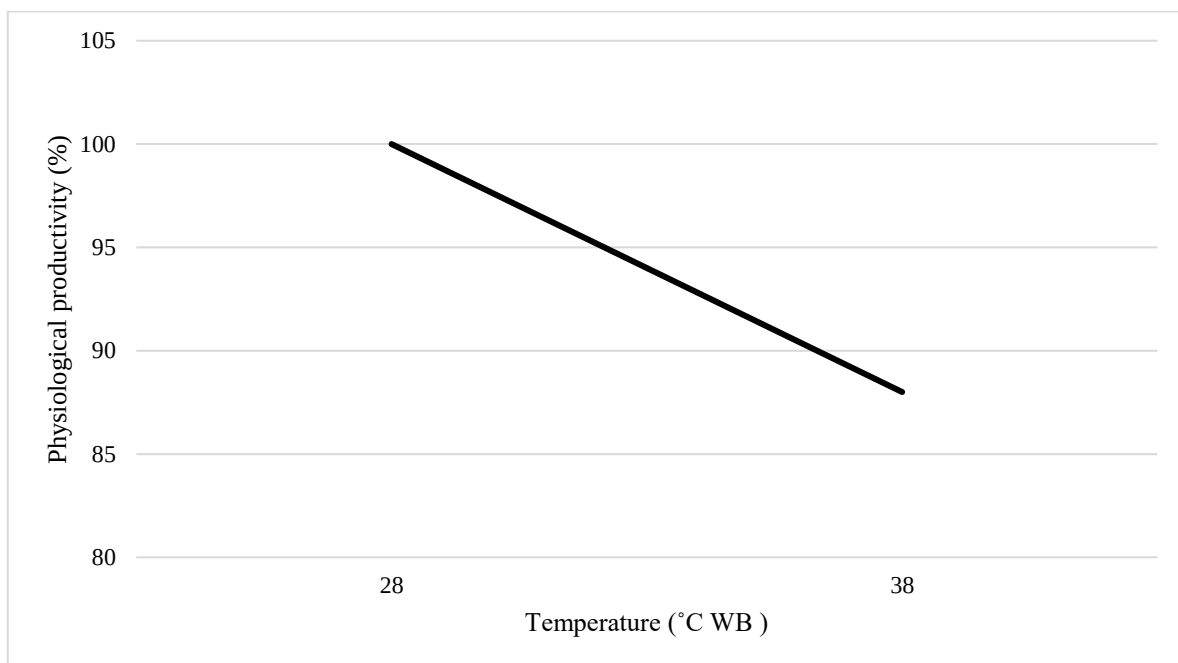


Figure 1. Effect of environmental temperature on physiological productivity (%)

280 The assumption, as illustrated by Figure. 1, is expressed by Equation. (4). below.

$$T_{SDj} = 0.012 \times T_{Rj} \times T_{TDj} \quad (4)$$

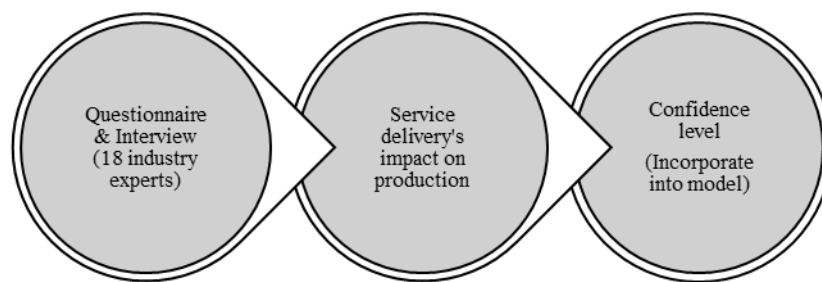
285 where T_R is the production related revenue and T_{TD} is the wet-bulb underground working environmental temperature reduction in degrees Celsius ($^{\circ}\text{C}$), for $j = 1, 2, \dots, n$ affected working areas. The service delivery cost saving was therefore quantified as a function of the wet-bulb underground working environmental temperature between the ranges of 28°C WB and 38°C WB.

Literature has indicated that of all the difficult NEBs affecting production, wet-bulb temperature has the largest effect [41]. Wet-bulb temperature was therefore proven to have the largest impact of all the different variables, on the productivity of deep-level mines [7], [16], [41].

290 **Confidence level verification**

As part of the model to quantify and monetise difficult NEBs, a confidence factor was incorporated to account for uncertainty. According to M&V guidelines, there will always be some degree of uncertainty applicable to any EE project [34]. Nevertheless, the uncertainty can be managed to produce a balanced solution with acceptable boundaries [33].

295 A confidence factor was incorporated into the quantification model to lower the uncertainty. The authors opted to conduct both interviews and questionnaires with 18 industry experts. The method used to gather the empirical data in order to determine the total service delivery benefit is illustrated by Figure 2



300 Figure 2. Data collection method applied in the research process

All of the industry experts that formed part of the sample were multidisciplinary engineering graduates, actively working and contributing in the mining field. Of the sample, 88% had post-graduate degrees in engineering with a focus on a mining related topic. The discipline

distribution of the sample was as follows: mechanical 61%, electrical 22% and chemical 17%.

The age of the industry experts ranged between 25 and 65 with a combined experience in excess of 100 years in the mining field.

The findings of the interviews and questionnaires highlighted the importance of quantifying NEBs in industry. Most of the experts revealed that although they had previous knowledge of NEBs relating to EE projects, no economic quantification model was available for the quantification and monetisation of these benefits. The most significant information acquired through the questionnaires were the expert's opinions on what percentage underground wet-bulb temperatures affect the productivity of miners. Interestingly, all of the expert acknowledged that there is a definitive relationship between the wet-bulb temperature and mine production. However, none of the experts could provide a tangible percentage value from empirical data and the results were therefore only qualitative. The analysis of the questionnaires and interviews revealed that the experts are of the opinion that the underground wet-bulb temperature affects miner productivity by 80%. Therefore, an average confidence factor of 0.8 for the service delivery NEBs were incorporated into the newly developed economic quantification model. The confidence factor was supported with a standard deviation of 0.2 for the study. In other words, the industry experts are of the same opinion that underground wet-bulb temperatures greatly affect the miners' productivity. The confidence factor will be used to bias the service delivery component (T_{SDj}) in Equation (3), to provide a more conservative model.

Model development conclusion

In conclusion, the economic quantification model for EE projects in the mining industry is demonstrated by Equation (5).

$$T_{Bi} = \sum_{j=1}^n T_{Ej} + T_{Mj} + T_{Lj} + T_{Wj} + abs(0.8 \times T_{SDj}) + T_{Oj} \quad (5)$$

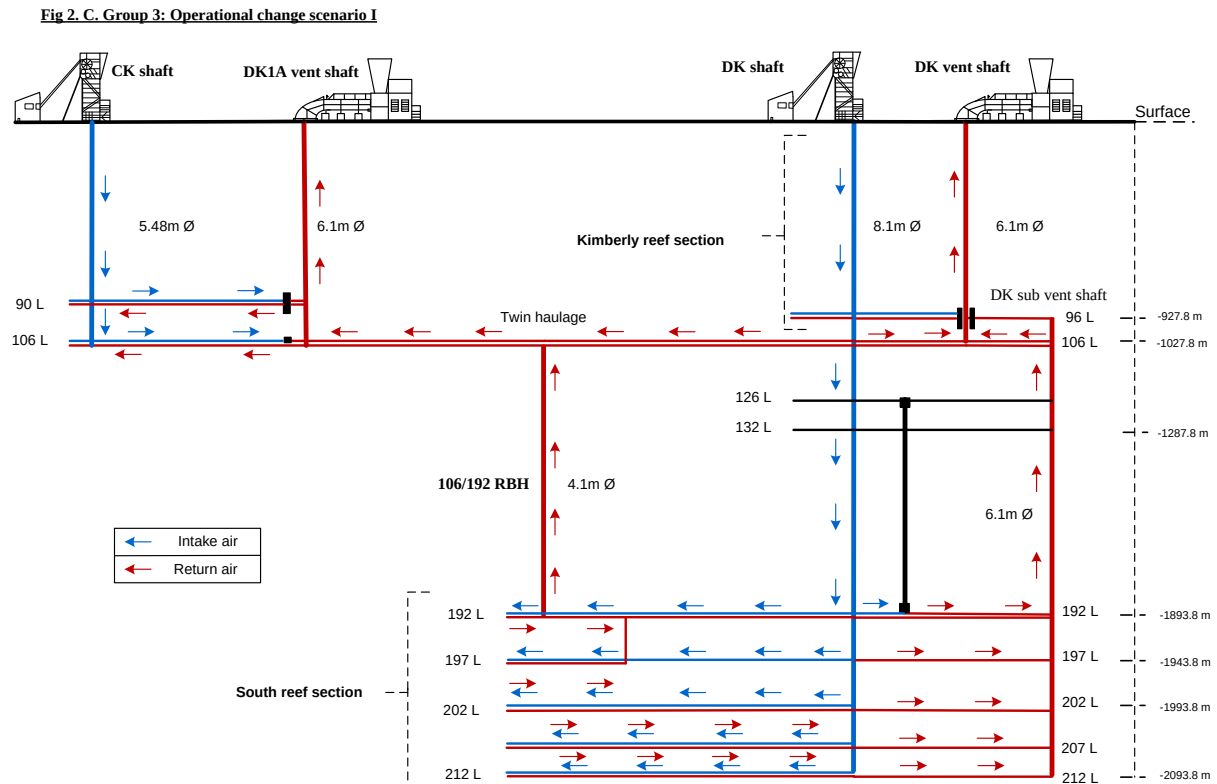
with, $T_{SDj} = 0.02 \times T_{Rj} \times T_{TDj}$, in lieu of wet-bulb underground working environmental temperature improvements (delta T) for $j = 1, 2, \dots, n$ affected working areas and model $i = 1, 2, \dots, m$. The user can quantify and monetise direct and indirect costs relating to EE projects to provide a comprehensive financial feasibility analysis. The economic quantification model was developed to include a broad perspective of benefits relating to the mining industry. However, for specific projects which do not have a labour component for instance, can be omitted in the final calculation. As part of model validation, the economic quantification model was implemented on a case study mine ventilation EE project.

STUDY SITE

The findings for a ventilation fan EE optimisation project implemented on a deep-level South African mining complex was selected as a case study. The name of the mining complex is protected by confidentiality, however, for this case study the complex will be referred to as DK. Narrow-reef conventional mining is conducted at a depth of ± 1.9 km, focussing on the south reef ore body. The mining complex has an estimated 18 years life-of-mine remaining with an average gold ore grade of 4.97 gram per tonne.

DK vent shaft is installed with two 2.1 MW Fantecnic (Howden) WBF-390 main surface ventilation fans. In addition, DK1A vent shaft is installed with three Artec Davidson main surface ventilation fans, two having an installed capacity of 1.01 MW and the last 1.3 MW. Before the implementation of the EE project, both 2.1 MW ventilation fans were operating at DK shaft with only one of the 1.01 MW ventilation fans operating at DK1A vent shaft.

After the completion of a raise bore hole (RBH) between 106L and 192L in June 2016, the ventilation system was optimised as part of an EE project, to achieve improved production face temperatures at a lower operating cost, as illustrated by Figure 4.



RBH, denotes raise bore hole; Ø, diameter; L, level.

Figure 4. DK ventilation fan EE optimisation project

The ventilation circuit was optimised through the installation of strategic underground seals on 90L, 96L and 106L to convert DK1A shaft to a second up cast shaft for DK shaft. Temporary and permanent seals were used to seal off the Kimberly sections and the return from CK shaft to DK1A shaft. Vermiculite bricks were incorporated to construct the permanent seal on CK shaft's 90L due to the high pressure experienced in this region, temporary seals proved insufficient. The incorporation of these seals lead to the increased utilisation of the airflow supplied to the underground working areas to achieve lower production face temperatures.

The new optimised ventilation fan configuration was implemented from July 2016 with DK shaft only operating one 2.1 MW surface fan, providing flexibility to the system in the form of a backup 2.1 MW surface fan. As a result of the new airflow branches and fresh air intake to 192L (main production level), lower production face temperatures were experienced and several booster fans were switched off as part of the project. The underground working environmental conditions were measured after 18 months. These values were used to determine the service delivery improvement, by comparing the wet-bulb environmental conditions before and after project implementation, as shown in Table 1.

Table 1. NEBs service delivery improvement

Level	Pre- implementation Temp.	Post- implementation Temp.	Service delivery improvement (Difference)
	T _{wb} [°C]	T _{wb} [°C]	T _{wb} [°C]
192	31.6	29.2	2.4
197	29.0	27.5	1.5
202	28.5	28.0	0.5

wb denotes, wet bulb.

A cumulative energy saving of **22.3 GWh** was achieved for the EE project, after the 18 month period. The majority of the energy saving (14.39 GWh) was attributed to the ventilation fan configuration change in which a 1.01 MW ventilation fan was operated instead of the 2.1 MW ventilation fan. The minority of energy savings (7.91 GWh) was attributed to the 11 underground booster fans that was rendered obsolete as a result of the optimisation.

QUANTIFICATION MODEL IMPLEMENTATION

In order to analyse the quantification model, it is important to illustrate the effects of each of the NEBs that is typically not considered in mine EE projects, as part of the financial evaluations. For that reason, the quantification model was segregated into small increments and subsequent models to provide a more comprehensive perspective of the total benefit

resulting from EE projects and the effects thereof. Table 2 illustrates the incremental models that was constructed through the segregation of the economic quantification model, from model A to F.

385

Table 2. Quantification model analysis

Model	A	B	C	D	E	F
Energy T_{Ej}	X	X	X	X	X	X
Maintenance T_{Mj}		X	X	X	X	X
Labour T_{Lj}			X	X	X	X
Water T_{Wj}				X	X	X
Service delivery $abs(0.8 \times T_{SDj})$					X	X
Other benefits (12L, Carbon tax)						X

$T_{Ej}, T_{Mj}, T_{Lj}, T_{Wj}, T_{SDj}, T_{Oj}$ as described in Equation (1) to (5).

Considering Table 2, model A illustrates the typical model used in industry to evaluate the financial feasibility of EE projects. In contrast, model F illustrates the comprehensive economic quantification model developed for the mining industry, including NEBs. Since the analysis was done after an 18 month period, the actual project costs were obtained from the mine, as shown in Table 3. However, to abide by convention, the implementation costs were categorised and incorporated in the energy costs. Additionally, since the ventilation fan EE project didn't incorporate any water component, the incremental water saving cost model had no effect on the total benefit.

395

Table 3. DK EE project actual costs

Model	Pre-implementation (US\$)	Post-implementation (US\$)	Netto (US\$)
Energy T_{Ej}	3 122 653	2 185 858	936 795
Maintenance T_{Mj}	5 756	2 518	3 238

Labour T_{Lj}	15 534	5 814	9 720
Water T_{Wj}	-	-	-
Service delivery $abs(0.8 \times T_{SDj})$	-	1 511 437	1 511 437
Other benefits (12L, Carbon tax)	-	563 252	563 252

$T_{Ej}, T_{Mj}, T_{Lj}, T_{Wj}, T_{SDj}, T_{Oj}$ as described in Equation (1) to (5).

As a result of the EE project, additional NEBs was experienced as illustrated by Table 3. The NEBs were quantified and monetised to realise a total financial benefit for each model as illustrated by Table 4.

400

Table 4. Total financial benefit for the incremental models

Model	A	B	C/D	E	F
Total benefit (US\$)	936 795	940 033	949 753	2 461 190	3 024 442

Service delivery quantification

405

After analysing the actual production data, the effects of improving the underground working environmental conditions were not empirically seen as a production increase. The production stayed relatively constant when comparing the pre and post implementation production data. Realistically then, the economic quantification model's service delivery component requires additional research to be able to model the effects accurately.

410

In order to critically analyse the service delivery component, the authors identified reasons that may have attributed towards the absent correlation. Firstly, it is possible that the assumption made of a linear relationship is wrong. Secondly, it is possible that there are too many other varying factors which influence production for it to be dependent only on environmental conditions. Thirdly, it is possible that the mine workers were indeed more productive but the daily production targets were not increased by the mine. Finally, it is possible that the human factor was not managed properly by the mine during the implementation period or that the miners were already operating at 100% productivity. Nevertheless, it is extremely important to include this finding as part of the model to ensure continued advancement and refinement.

415

RESULTS

It is important to identify which of the typical evaluation techniques. are currently being used in industry as part of EE project feasibility, before the results are analysed. Nehler and Rasmussen conducted a study on 13 participating firms which showed that of all the different evaluation techniques utilised by these firms, the payback period (PBP) has the most important contribution towards project evaluation and subsequently implementation [32]. Respondents of these studies indicated that their firms required PBPs from one to three years and in some cases, less than one year before projects were considered feasible [32].

Another study conducted on 100 Australian firms, by Harris et al. established that a long PBP and low internal rate of return (IRR) are the main obstacles for implementing EE projects [42]. This once again lay emphasis on the need for a novel economic quantification model to determine the total benefit of EE projects. Literature had shown that the feasibility of EE projects increase dramatically with the inclusion of NEBs [12]. The results of this study will be analysed according to the PBP and IRR, conforming to the most important financial evaluation techniques used in industry. However, other financial evaluation techniques are also shown for a comprehensive in-depth understanding of the total financial benefit.

Fleiter et al. determined the specific ranges attributed to IRR and PBP to yield positive financial evaluations for EE projects [43]. Positive IRR percentages are deemed at above 30%, similarly, positive PBP are deemed at less than two years [32], [43]. These measures were applied to the incremental model financial evaluation results, as illustrated by Table 5.

Table 5. Incremental model financial evaluation results (per annum)

Model	PBP (days)	ROI (%)	NPV (US\$)	IRR (%)
A	5.2	69.7	557 454	6 971
B	5.1	69.9	559 406	6 995
C/D	5.1	70.7	565 265	7 069
E	2.0	184.8	1 476 326	18 477
F	1.6	227.3	1 815 831	22 729

NPV, denotes, net present value at a discount rate of 10.6%; ROI, return on investment.

Considering the PBP of the incremental models and case study EE project as a whole, this project was deemed feasible. Moreover, this is illustrated by the IRR value being above 30%. Although the PBP and IRR are most commonly used in industry, the authors prefer to use return on investment (ROI) as the true financial indicator towards the feasibility of a project.

Table 5 illustrates that the incorporation of NEBs, increase the financial feasibility with a PBP of 5.2 days being reduced to 1.6 days. Although the results for the specific EE project showed the immense financial benefit of EE projects, similar projects are often neglected in industry. Although the specific case study EE project had an impressive PBP, model development can be applied to other projects and systems which won't have the same feasibility. In this manner, the economic quantification model could be refined for each system and each project. This refined model can then be used to predict the feasibility and true benefit of various EE projects.

DISCUSSION

The relevance of the economic quantification model is emphasised by the current global economic state [39]. Research indicated that it is essential for the feasibility of the mining industry to improve upon the *status quo* of EE [7]. However, the only way to enable a paradigm shift is with increased EE project feasibility and subsequent implementation. Although authors such as Finman, Laitner, Hall and Roth have shown the importance of NEBs in industrial EE projects, there has only been one study conducted in the mining industry [12], [16], [30]. This study was conducted by Krige et al. in 1981 and stressed the importance of continued research [16]. It was proven for industrial EE projects that the omission of NEBs in financial evaluations exacerbates the negative economic trend, which is also the case for the struggling mining industry [32].

The contribution of this study builds on the work of Rasmussen, Nehler, Wyon et al. and Krige et al. by providing a means to quantify and monetise the true financial benefit of EE projects in the mining industry by including NEBs [11], [16], [29], [40]. The most significant advantage of this study is that the same model development can be followed and applied to other mining systems to develop similar baseline economic quantification models. Cilliers conducted an energy benchmarking study on deep-level mines which showed that there are other mining systems which may also have NEBs relating to production, such as the compressed air system [44]. The same methodology used to develop the economic quantification model could be applied to determine the NEBs for those mining systems. The economic quantification model for each system could then provide an indication towards the positive or negative effects of EE projects and NEBs.

The baseline economic quantification models for each system could then be used to predict the effects of similar projects. Once future EE projects are implemented and the actual NEBs measured, a comparison can be drawn between the predicted and actual values. In this way, the baseline economic quantification model can be refined for increased prediction accuracy, tailored for each individual mining system and also for each type of EE project. Several baseline models can then be developed for the different projects on the different mining systems, providing for the first time, a practical means to calculate the total financial benefit.

Although the model development was done by considering a historic ventilation optimisation project for this study, the effects are everlasting on the way we consider EE projects' feasibility worldwide. This specifically has far reaching effects on the energy intensive mining industry of South Africa.

As a practical example, if we consider a similar EE ventilation optimisation project with a calculated energy saving of 2 MW, then the economic quantification model could be used to predict the NEBs and subsequent total benefit. The predictive nature of the model is established by a ratio applicable to each NEB, acquired through the model development process. Therefore, the ratios for the case study EE project are displayed in Equation (6) and (7):

$$T_{Bi} = \sum_{j=1}^n \left(\frac{T_{Ej}}{T_{Ej}} \right) \times T_{Ej+1} + \left(\frac{T_{Mj}}{T_{Ej}} \right) \times T_{Ej+1} + \left(\frac{T_{Lj}}{T_{Ej}} \right) \times T_{Ej+1} + \left(\frac{T_{Wj}}{T_{Ej}} \right) \times T_{Ej+1} + \left(\frac{T_{SDj}}{T_{Ej}} \right) \times T_{Ej+1} + \left(\frac{T_{Oj}}{T_{Ej}} \right) \times T_{Ej+1} \quad (6)$$

$$\therefore T_{B2} = \sum_{j=1}^n (1) \times T_{E2} + (1) \times T_{E2} + (1) \times T_{E2} + (0) \times T_{E2} + (2.6) \times T_{E2} + (3.2) \times T_{E2} \quad (7)$$

The factors were determined from the baseline economic quantification model development of the case study project and can be applied to the proposed future EE project. Using Equation (7), the total benefit of the future ventilation EE project was determined. The results of the predicted model are displayed, segregated into the incremental models in Table 6.

Table 6. Total financial benefit for the incremental models of a future mine ventilation EE project

Model	A	B	C/D	E	F
Total benefit (US\$-million)	1.24	1.25	1.26	3.28	4.03

This model is extremely important for future energy policy planning. If this model is included in the national energy policy, it would provide a means to evaluate and consider projects more accurately and efficiently, promoting EE in an energy intensive country. There are several

advantages to include this model in energy policy planning, to name a few, improved decision-making capabilities, improved energy efficiency awareness, reduced greenhouse gas (GHG) emissions, reduced waste and resources and finally improved EE project implementation.

In South Africa, the government has already included tax rebate incentives to promote the implementation of EE projects, namely 12L as discussed in the indirect costs section, this is seen as the carrot method. In contrast, new policy planning has lead to the application of carbon tax specifically to GHG emissions. This is seen as the stick method for industry to lower GHG emissions. The novel economic quantification model, will provide government and industry with the means to calculate and predict the total benefit of each EE project. In doing so would strengthen the economy.

The linear relationship between production and improved underground wet-bulb temperatures were not validated. However, considering this was the first attempt to quantify this difficult NEB in 37 years, it is an extremely important finding for literature [16]. The importance of this finding demonstrates that although there might be a linear relationship between temperature and productivity, it does not relate to improved production for the mining industry [40]. Therefore, other requirements have to be included to ensure the improved conditions result in improved production. Yet, it could be possible that such a linear relationship could be proven by increasing the daily production targets for the miners; to record and measure production affecting factors such as thrust applied to the pneumatic rock drill by the rock drill operators; to develop a real-world test facility (what if analysis) in which each factor can be controlled individually. These solutions were outside the scope of this study, but the authors predict that the recommendations would prove valuable for future studies.

CONCLUSION

The importance of NEBs in EE projects have previously been emphasised in literature. Several studies have shown that EE projects are understated by the omission of numerous NEBs. This paper developed an innovative, comprehensive economic quantification model which can be used to quantify and monetise the total benefit of EE projects in the mining environment. The model included the first quantification attempts for improved underground working conditions in nearly four decades.

The economic quantification model was largely successful to quantify and monetise the true financial benefit of EE projects. The model included several NEBs that are typically omitted in financial evaluations. The model worked particularly well for NEBs that could be measured as

535 direct costs. However, the model was lacking in the service delivery component but recommendations were added for future studies.

The case study proved that the typical financial evaluation techniques used in industry, were satisfied and increased with the inclusion of NEBs, as supported by literature. As a result, the PBP of the case study project was reduced from 5.2 days to 1.6 days. The economic
540 quantification model can be used in predictive studies to model the total benefit of similar EE projects as well as other mining systems. Future research should include baseline economic quantification model development for EE projects on other mining systems. Continuous model refinement should be done to improve on the model's accuracy and reproducibility. Similarly,
545 the model should be advanced to include difficult to quantify NEBs of other mining systems related to production such as improved compressed air pressure supplied to pneumatic rock drills underground.

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550 DECLARATION OF INTEREST

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TABLE OF CONTENTS

• Description	p.1
• Audience	p.1
• Impact Factor	p.1
• Abstracting and Indexing	p.2
• Editorial Board	p.3
• Guide for Authors	p.5



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Life-of-mine primary access and ventilation planning through simulations

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Life-of-mine primary access and ventilation planning through simulations

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App. C.1: Article III

Life-of-mine primary access and ventilation planning through simulations

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ABSTRACT

The feasibility and profitability of the mining industry hangs in the balance as a result of the current economic climate. Sustainable mine development and efficient life of mine (LOM) planning are keywords in a global effort to improve upon the status quo of mining operations.

5 Traditional LOM planning methods are outdated, resource intensive, unreliable and uneconomical. However, with the turn of the digital age, a paradigm shift was made towards LOM planning through simulations. Simulations provided a more rapid, versatile and accurate means to evaluate, optimise and plan complex mining systems. Nevertheless, existing LOM planning simulation packages are limited to production related factors only, such as mineral
10 reserves. The effect of future production is therefore neglected on other critical mining systems such as the hoisting system (primary access) and ventilation network. Although simulation packages have been used for planning of hoisting systems and ventilation networks, it has been done in a segregated manner and has not been included in the LOM plan. Therefore, LOM planning is not integrated, only considering a narrow bandwidth of production related
15 factors. Additionally, literature indicates that no frameworks or methods exist which describe the process of incorporating an integrated planning approach through the use of simulations, as part of LOM planning. In this paper, an integrated simulation planning method was developed to be used for primary access and ventilation LOM planning. The integrated simulation planning method was applied to a case study in which the simulation models were
20 evaluated, optimised and analysed for the most feasible model to be included in the updated LOM plan. The updated LOM plan therefore included the model with the lowest capital and operating costs and quickest construction time as a result of the integrated simulation planning method.

25 KEYWORDS

Life of mine, Primary access, Ventilation networks, Simulations, Integrated planning, Cost analysis

HIGHLIGHTS

- LOM primary access and ventilation planning through simulations
- 30 • Integrated simulation planning method
- Energy optimisation

INTRODUCTION AND BACKGROUND

Primary access is defined as the method used to exploit underground mineral reserves [1], [2].

35 Wilson et al. conducted a study in which the optimum primary access method, for any particular orebody could be determined [2]. While there are a large variety of access options available that would provide a suitable conduit, this study is limited to vertical shafts. In deep-level gold mines, vertical shafts are the preferred primary access method and seen as the “lifeline” of underground mining operations [2], [3], [4]. The vertical shaft and hoisting system

40 provide access to the network of logistical openings used to recover the underground mineral reserves [3]. Additionally, the hoisting system provides vertical transport of mine workers and materials and serves as an escape way in case of emergency egress [4]. The underground mine workers are therefore dependent on the primary access or hoisting system for safe, uninterrupted and efficient flow of materials to serve the workings of the mining complex [4].

45 A typical hoisting system consists of several components, contributing to the winding process [4]. The primary energy consuming components are the winder induction motors [5]. For the purpose of the study, it is important to understand the most basic components of the hoisting system. Therefore, a winder is defined as a drum wound by the winder cable that lowers or raises the conveyance (mine cage) or skip (bucket containing ore and rock) between the

50 underground mining levels and surface [6]. The headgear is installed at the top of the vertical shaft to support the sheave wheel over which the hoisting rope passes [6]. Fundamentally, the broken rock is loaded into the skips and subsequently hoisted to surface by the rock winder [5]. There are numerous types of rock winder configurations available commercially, of which size, speed, cycle time and skip capacity differs [1]. Literature indicates that rock winders are

55 typically selected according to the future planned production rate as part of the life-of-mine (LOM) plan [1], [2], [4].

Primary access infrastructure is directly coupled to the ventilation network, as it provides down and up cast capabilities for the mining complex [2]. The hoisting system therefore directly

affects the ventilation network, especially in deep-level mining [2], [5]. Mine ventilation networks are used to ensure that underground environmental conditions are conducive to safe and productive mining [7]. This is done by supplying sufficient airflow to the working areas to govern heat stress imposed on workers, and to dilute and exhaust hazardous particulates to below statutory occupational exposure levels [8]. However, due to the dynamic nature of deep-level mining, the engineering challenges faced to contend with higher virgin rock temperatures and more complex ventilation networks, increase by virtue of increased depth [9]. The costs associated with providing acceptable working conditions for reserves that are farther and deeper away from ventilation shafts, becomes a critical determinant towards the feasibility of mining and future LOM development planning [8].

Mine ventilation networks consist of hundreds of interconnected sections and applications such as airways, raises, cross cuts, main shafts, vent shafts, sub-shafts, raise bore holes, ventilation doors, travelling ways, fans and regulators [10]. In view of the complexity of the system and the progression of mine development, it is easy to comprehend that inefficiencies such as short-circuits, insufficient air velocities, increasing temperatures and leakages occur in such a vast network [7]. Mine ventilation networks are required to comply with occupational health and safety standards and regulations as specified by the host country. In South Africa, there are two important factors affecting the operations of mine ventilation and subsequent working environments, namely, the wet-bulb temperature (T_{wb}) and air cooling power (ACP) [11].

Research has shown that work should not proceed underground when the environmental conditions wet-bulb temperature exceeds 32.5°C or the dry-bulb temperature exceeds 37°C [9], [11], [12]. Legislation stipulates that formal controls be put in place in the form of a heat stress management program (HSM) when wet-bulb temperatures exceed $T_{wb} > 27.5^{\circ}\text{C}$ [9], [12]. The ACP takes both the wet-bulb temperatures and air velocities (v_a) per working area into account. In ventilation design, a minimum ACP level of 300 W/m^2 is acceptable for underground working conditions [9], [11], [13]. The T_{wb} and v_a are therefore very important constraints that should be considered when LOM planning is conducted.

As a result of constrained mine resources, LOM planning for these crucial systems is still done by hand, utilising old, outdated and unreliable methods [14], [15]. The LOM planning is conducted in a segregated manner, often omitting the inherent effects between the different systems [16], [17]. LOM planning is therefore made with limited information which increases both risks and the likelihood of failure. With recent technological advancements, an integrated simulation planning method, to be used for primary access and ventilation network LOM planning, may prove to be a suitable solution.

NEED FOR STUDY

95 CONVENTIONAL LOM PLANNING

Traditional design and modelling methods used for LOM planning include manual calculations and manual interpretation of graphical information [18]. These methods are extremely time and resource intensive, which prolongs a very critical process [14], [17], [18]. LOM planning is mainly used to determine the mineral reserves and spacial distribution of ore body grades [19].

100 Historically, geostatistical estimation methods have been used to model the distribution of grades within a reef ore body mining block [19]. The main disadvantage of these models are that the in situ variability of ore grade deposits are not taken into account [19].

This fact was addressed with the advancement of computer aided mine design and modelling methods [18]. The inclusion of technology has resulted in faster, improved LOM planning
105 results [18]. Modern methods enable mine planners to optimise mine designs and production schedules for multiple models [18], [19]. Subsequently, there are several commercially available simulation packages to be used as part of LOM planning to determine the geology and spacial distribution of the ore body more accurately and cost effectively [16], [18], [20]. However, these simulation packages are focussed on the mineral reserves and neglects the
110 effects of future planned production, on other mining systems such as the hoisting system or ventilation network [20].

Modern day conventional LOM planning therefore requires an integrated simulation method to analyse the effects on other mining systems, to be included in the LOM planning. An integrated simulation planning method would ensure LOM planning be conducted accurately,
115 cost effectively and holistically. In this manner, the LOM plan would be optimised for increased feasibility and future mine sustainability.

SIMULATION PLANNING FOR PRIMARY ACCESS AND VENTILATION NETWORKS

Research indicates that complex systems can only be thoroughly evaluated and planned with the use of simulations [20], [21], [22], [23], [24]. Since the inception of the digital age,
120 simulation technologies have subsequently been incorporated to solve large complex mining systems [20], [25]. The hoisting system, is one such system where extensive simulation developments have occurred [5], [6], [26]. There are commercially available packages to design and optimise hoisting systems, taking emergency egress routes into consideration [27], [28]. Nevertheless, no frameworks or methods exist explaining how these
125 simulation packages could be incorporated in LOM planning.

In literature, several case studies have been published where the hoisting system was optimised and designed through simulations [5], [6], [16]. However, up till now, simulations for the hoisting system have not been incorporated in LOM planning [29]. There is therefore a need for an integrated simulation planning method, to incorporate the optimised simulation results of the different models, as part of the LOM plan.

According to McPherson, in organisations worldwide ventilation simulation packages have dominated ventilation planning since inception [14]. These packages proved to be more versatile, accurate and cost effective than traditional methods [14], [30]. However, despite the availability of ventilation network simulation packages and the development thereof over the past 30 years, some mines still utilise traditional, unreliable methods in planning- incorporating assumptions, outdated values and inaccurate measurements [14]. Literature indicates that some mines disregard ventilation planning completely in LOM planning, in which mining continues until stopped by law or ventilation related incidents [14].

In modern mining, the only viable method to evaluate and plan complex ventilation networks is through the use of simulations[30]. As such, there have been several case studies in which the ventilation network was evaluated, optimised and planned [31], [32], [33]. Modern simulation packages were developed to include thermal hydraulic solvers to simulate the effects as a result of heat transfer [30]. LOM planning had been implemented for new ventilation networks in order to characterise the ventilation network design and requirements [34], [35], [36]. However, this was done by only considering the ventilation network as an individual system. The integrated effects of other designs such as the hoisting system, were neglected. Additionally, the case studies were implemented on newly designed ventilation networks, which lacks the effect of LOM planning on existing mine operations.

Therefore, a need exists for an integrated simulation planning method that can be used for ventilation networks to be included in the LOM plan. This integrated simulation planning method should provide the flexibility to determine and encapsulate the cumulative effects of future production rates on the ventilation system and subsequent mining operations.

CONCLUSION

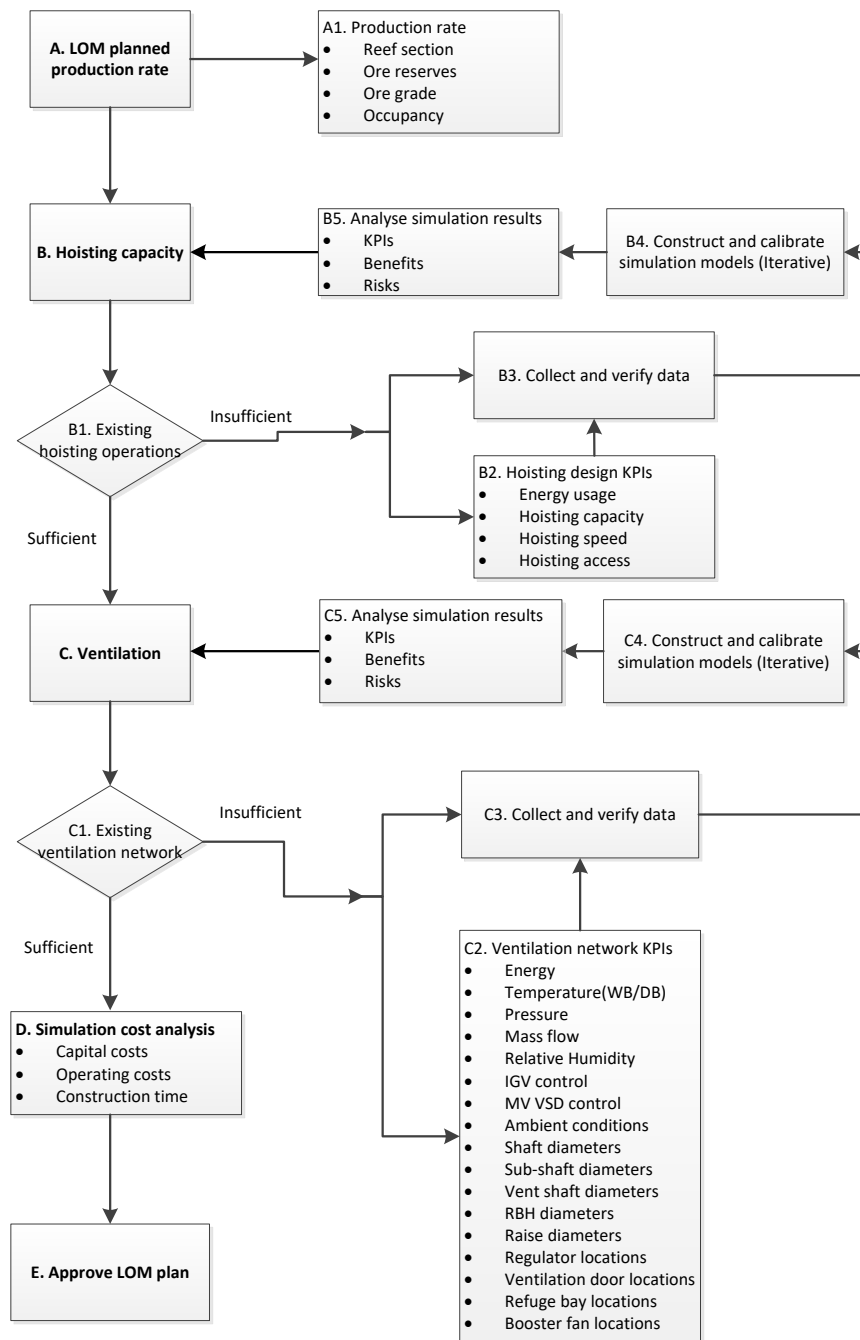
Traditional modelling and LOM planning methods make use of manual calculations which is extremely time-consuming, resource intensive and uneconomical [18]. However, with the inception of the digital age, simulation packages were developed for mine planning which provided more rapid and accurate results, more cost-effectively [30]. It is clear from literature that simulations are the only viable method to thoroughly evaluate, optimise and plan complex systems [20], [21], [22], [23], [24].

160 Modern day LOM planning packages are limited, focussing only on the mineral reserves, and
neglects the effects of future planned production on other mining systems, such as the hoisting
system(primary access) and ventilation network [20]. LOM planning is therefore not integrated,
only considering a narrow bandwidth of production related factors. Furthermore, there are
165 numerous commercially available simulation packages, specifically designed for mining
systems such as the hoisting system and ventilation network [5], [14], [16]. In ventilation, these
simulation packages have been used for ventilation planning over the course of the last 30
years [14]. However, these systems are evaluated, optimised and planned in a segregated
manner, not being utilised or included as part of LOM planning. Additionally, no framework or
method was developed which describe the process of incorporating an integrated planning
170 approach with the use of simulations.

Therefore, a need exists for an integrated simulation planning method to be used for primary
access and ventilation LOM planning. This method would provide a holistic approach to LOM
planning, incorporating the latest simulation technologies in order to evaluate and optimise
future production planning.

175 **METHOD DEVELOPMENT**

In order to develop an integrated simulation planning method to be used for primary access
and ventilation network LOM planning, several factors must be considered to produce
accurate, dependable and cost-effective results [19]. The most important of these factors
include the LOM planned production rate. The integrated simulation planning methodology is
180 based on the LOM planned production rate. The emphasis is therefore placed on ensuring
that the production rate is determined accurately before the method is implemented. The
integrated simulation planning method for primary access and ventilation LOM planning is
illustrated by Figure 1.



185 Figure 1. Simulation planning method for primary access and ventilation network LOM planning

As shown by Figure 1, the first step in the simulation planning method is to establish the planned production rate (A). This is typically a result of mine development, benchmarking and geological surveys [20]. It is important to establish production factors (A1) for example, the reef section where the production will commence; the ore reserves and ore grade available at the selected reef section; the required occupancy to satisfy the future production rate. Production factor data are frequently available and updated on mines, often verified with manual measurements by mine personnel. The accuracy of these factors are of extreme importance since the simulation method is founded upon the planned production rate.

190

The next step in the method is to address the primary access planning (**B**). The existing hoisting operations are compared to the LOM planned production rate. If the existing system is able to satisfy the future production rate, the method continues to the next step. In contrast, if the existing system is determined to be insufficient, the following steps would commence: The key performance indicators (KPIs) of the hoisting system would be selected (**B2**) while concurrently collecting and verifying the existing system's data (**B3**). Data are frequently available through the mine's Supervisory Control and Data Acquisition (SCADA) system. The meters transmitting the operational data to the SCADA often have calibration certificates available. However, in cases where certificates are not available, manual measurement should be conducted with calibrated instrumentation.

The next step is to construct and calibrate a simulation model with the verified data set for the current operations (**B4**). The simulation model can be refined and calibrated iteratively, until the user is satisfied with the accuracy of the model. The author recommends an error lower than 10%, to be sufficient for the mining industry. Thereafter, upon recommendation from mine management, different simulation planning models should be constructed. These simulation planning models should then be thoroughly analysed according to the KPIs selected in step B2. The benefits and risks thereof should also be established and stated. Once the simulation planning model satisfies the LOM production rate, the feedback loop discontinues and the next planning phase is entered, ventilation (**C**).

The existing ventilation network duty is compared to the LOM production rate requirements (**C1**). Similarly, as in the case with the hoisting system, if the ventilation network satisfies the production rate requirements the simulation network continues to the next planning phase. In contrast, if the ventilation network is insufficient, a feedback loop is entered to re-evaluate and plan the network. The first step of the feedback loop is to concurrently establish the ventilation network KPIs (**C2**) and to collect and verify ventilation network data (**C3**). In ventilation networks, data is typically available considering the effect on the environmental underground working conditions and subsequent impact on the health and safety of mine workers.

Ventilation network data can be attained and calibrated with the same procedure described for the hoisting system (B2, B3). Thereafter, a simulation model of the existing ventilation network would be constructed, incorporating the verified data set (**C4**). The simulation would be calibrated and refined iteratively, until the user is satisfied with the accuracy of the calibration. The simulation planning models, as identified by mine management, would be simulated and the effects thoroughly analysed (**C5**) according to the KPIs selected in step C2. Once the simulation planning model satisfies the LOM production rate, the feedback loop discontinues to the simulation cost analysis (**D**).

In this step, the simulation planning scenarios are thoroughly analysed according to their capital and operating expenditures. The construction time is also taken into consideration to provide a holistic indication towards the feasibility of each simulation planning model. Once the simulation planning model with the highest feasibility is determined, the planning thereof is included and approved in the updated LOM plan (E).

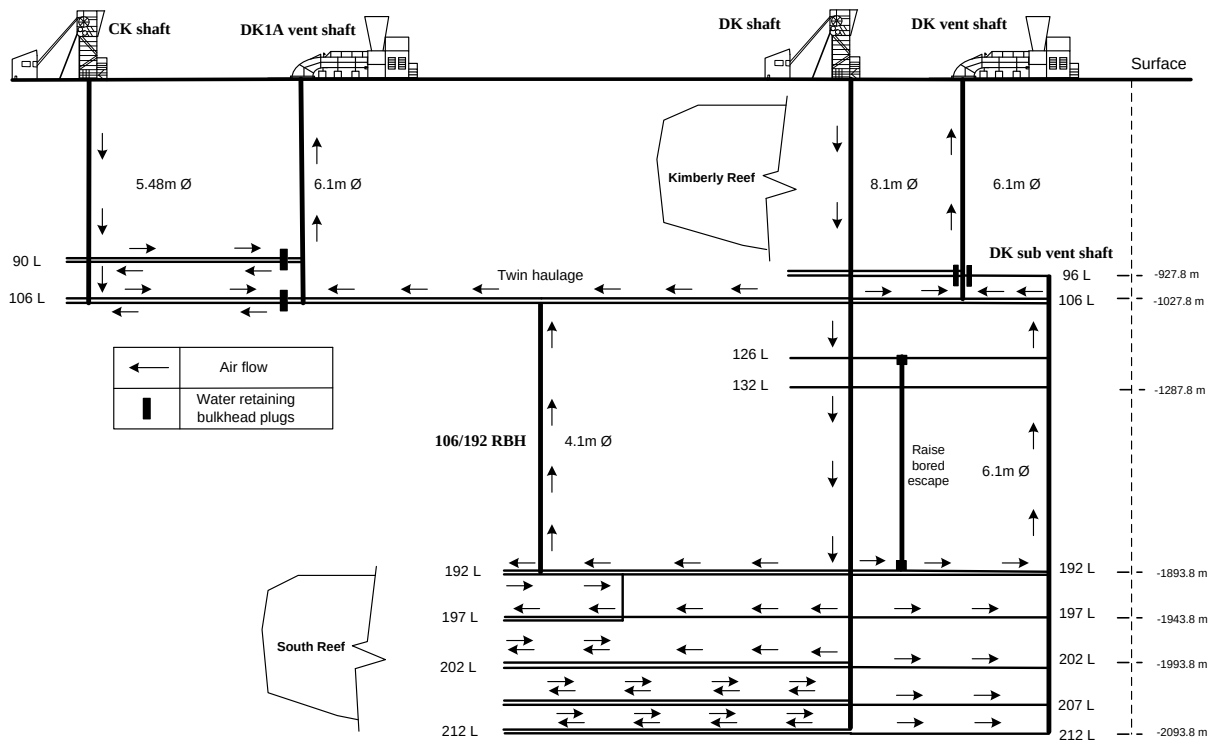
CASE STUDY BACKGROUND

The LOM plan of a deep-level South African mining complex was selected as a case study. The name of the mining complex is protected by confidentiality, therefore for the purpose of this case study the complex will be referred to as DK. At DK, narrow-reef conventional mining is conducted at a depth of ± 1.9 km, focussing on the Kimberly and South reef ore bodies.

DK has one production shaft which acts as the main downcast shaft (fresh air enters the ventilation network) and one up cast vent shaft (return air is exhausted after ventilating the working areas). DK is installed with a 6.0 MW English electric rock winder, 3.4 MW Toshiba dual purpose (DP) winder and a 3.4 MW Toshiba man winder. The rock winder is responsible for two 15.5 ton material skips, tipping into the upper conveyer belt leading to the gold plant. The DP winder is responsible for two 11 ton skip cages, whilst the man winder is responsible for two 3 tier man cages capable of leading 40 miners per tier. DK has a sub vent shaft on the northern side which is fitted with a 100 kW Toshiba rock winder on 96L.

DK is interconnected with another mine, CK on two levels, namely 90L and 106L with twin haulages. CK has one production shaft acting as the main downcast shaft for the mine. However, the shaft is owned by a third party and is mainly used for pumping purposes. Due to the poor state of the shaft and questionable infrastructure which may lead to DK flooding, DK and CK have been adequately separated through the installation of bulkhead water retaining plugs. Additionally, in between DK's main downcast shaft and CK's main downcast shaft is an up cast vent shaft, DK1A. The general mining complex layout is shown by Figure 2.

DK vent shaft is installed with two 2.1 MW Fantecnic (Howden) WBF-390 main surface ventilation fans. In addition, DK1A vent shaft is installed with three Artec Davidson main surface ventilation fans, two having an installed capacity of 1.01 MW and the last 1.3 MW. Both of the 2.1 MW ventilation fans were operating at DK vent shaft, with only one 1.01 MW fan operating at DK1A



RBH, denotes raise bore hole; Ø, diameter; L, level.

Figure 2. Existing mining complex layout

DK's ventilation department anticipated the need for a second independent outlet for the south reef section, to contend with the increasing temperature constraints experienced on the main production levels. The main production levels of DK are 192L, 197L and 202L, and comprise the south reef section of the mining complex. A raise bore hole (RBH) of 6.1 diameter was drilled between 192L and 106L in an effort to reduce production face temperatures to within acceptable limits on these levels. The consequence of the RBH being completed is that 106L is now a major return airway for the south reef sections.

In view of the rapid mine expansion and operational changes, there is a need to re-examine the LOM plan for DK shaft to ensure sustainable production. The hoisting system and ventilation network would therefore need to be sufficient to enable the future planned production. Simulations have proven to be the only viable solution to predict future operations accurately and cost-effectively [20], [21]. Therefore, for the purpose of this study, the primary access and ventilation systems will be analysed and optimised to accommodate future mining production requirements.

METHOD IMPLEMENTATION

As part of the integrated simulation planning method, the hoisting and ventilation systems were investigated to satisfy future production rates. The first step in the integrated simulation planning method was to establish the future planned production rate (A). DK has an existing

total hoisting capacity of 113 kt/month and an estimated LOM of 18 years. DK has mineral reserves in excess of 4.6 million tons, with an average ore grade of 4.96 g/t. The estimated gold reserves are therefore 23 tons or an equivalent 735 000 oz. Future production is planned to take place at both the Kimberly and South reef ore bodies. However, the bulk of the production will be mined from the South reef situated at the lower levels. A total hoisting capacity of 200 kt/month, is required to satisfy future production targets, of which 160 kt/month will be supplied from the South reef and 40 kt/month from the Kimberly reef (A1). It is planned that DK will host 3 600 employees as part of the increased planned future production effort.

PRIMARY ACCESS

The existing ore hoisting capacity of DK was therefore insufficient for the required 200 kt/month LOM planned production rate (B1). Therefore, the hoisting system must be optimised to satisfy future production requirements (B2). Taking the existing ore hoisting capacity into account, DK requires an additional ore hoisting capacity of at least 90 kt/month. Additionally, DK's gold plant has a maximum milling capacity of 220 kt/month which needs to be considered before the hoisting design is optimised.

As part of the integrated simulation planning method, the most important KPIs of the hoisting system should be identified and thoroughly considered (B3). Hence, for the purpose of this case study, the following KPIs were identified and selected:

- Hoisting capacity: 200 kt/month
- Gold plant milling capacity: 220 kt/month
- Second means of egress during shaft sinking.

Since two water retaining bulkhead plugs were installed in each of the twin haulages at 90L and 106L, the second means of egress, through CK shaft, was unavailable. This poses a large operational risk for existing operations and needs to be addressed as part of the KPIs. The health and safety of mine workers have the top priority in the effort towards sustainable mining.

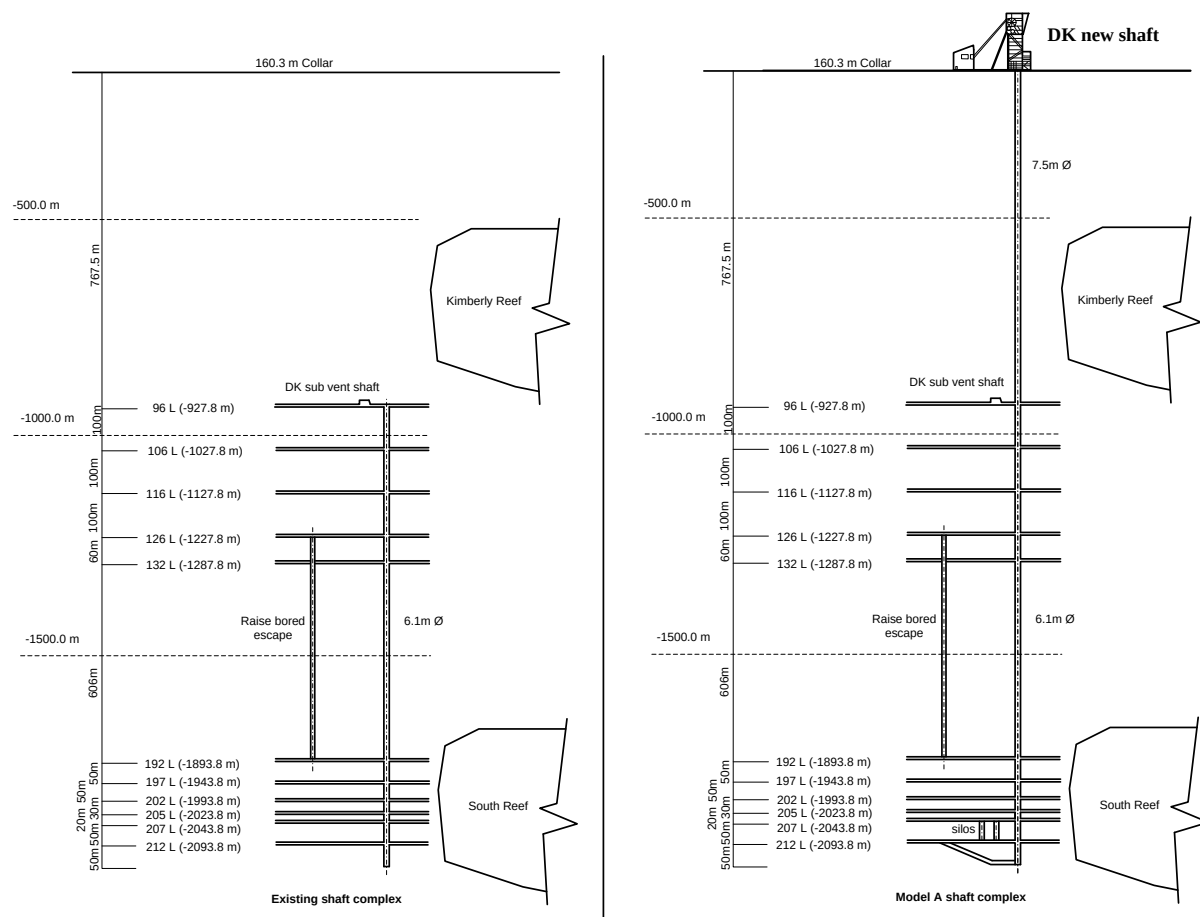
Three simulation planning models were developed to satisfy future production rates, whilst incorporating a safety factor for additional target increases. The three models were based on a rock winder production capacity of 80 kt/month of reef and 16 kt/month of waste. The man and material hoisting conveyance were determined to have a load capacity of 10 tons with a speed of 9.5 trips per hour. The proposed simulation planning would therefore satisfy the additionally required 90 kt/month of ore hoisting capacity. The cumulative ore hoisting capacity of the existing and proposed rock winders would amount to 182 kt/month. The rock winder capacity coupled with the DP winder capacity of 80 kt/month would therefore surpass the 200 kt/month production requirement.

Each of the three simulation models therefore satisfies the hoisting and gold plant milling capacity KPI. However, to gain an in depth understanding, each simulation model is discussed further to be analysed according to the KPIs, benefits and risks.

SIMULATION PLANNING MODELS

320 MODEL A

In Model A, the existing sub vent shaft would be extended to surface to establish a new production shaft. The new top section would be conventionally sunk to 96L to interface with the existing shaft. This model arrangement would accommodate for the sinking of the new top section and equipping down to shaft bottom, 50m below 212L. This model would require additional rock silos to be excavated between 207L and 212L, as well as the loading pocket below 212L as displayed in Figure 3. A ramp from 212L to shaft bottom would also be required for access to clear spillage and the shaft bottom pumping station. This model incorporated a rock hoist of 4.5 MW and a service hoist of 2.4 MW for men and material transport.



330 RBH, denotes raise bore hole; Ø, diameter; L, level.

Figure 3: Simulation planning longitudinal section for Model A

Second means of egress

The existing means of egress was along the 106L haulage to CK shaft, with the sub vent shaft providing access to the deeper portion of the mine. However, since this is no longer available, egress will be via the existing raise bored escape between 192L and 126L. This escape would need to be equipped with a ladderway to ensure safe egress. The existing traveling ways between the lower levels (212L to 192L) and upper levels (126L and 90L) proved to be sufficient in case of emergency and would therefore still be utilised.

Benefits

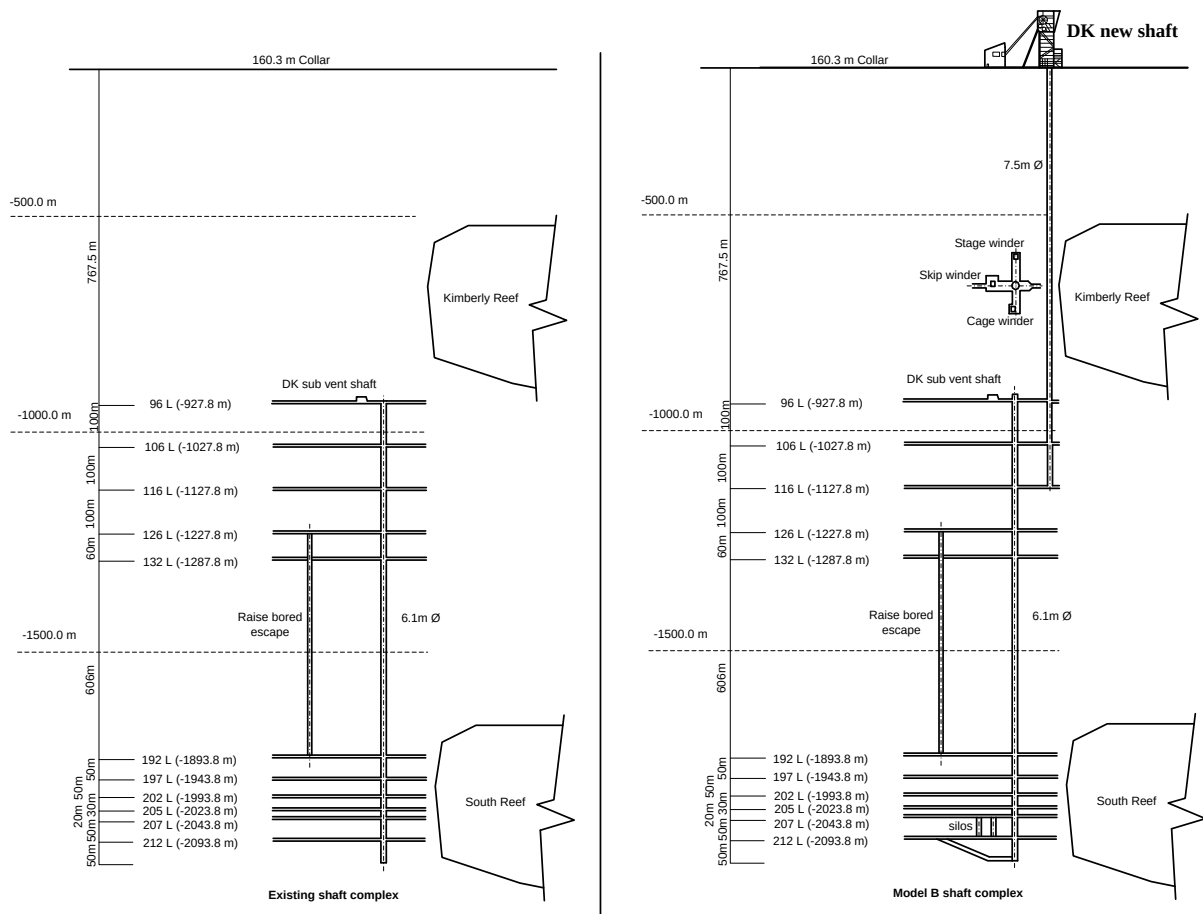
The sub vent shaft was already smooth concrete lined, reducing shaft sinking costs. The only equipment that would need to be designed is a Bunton chair plate arrangement to be bolted to the concrete lining. The vertical alignment of the Bunton and guide steelwork between the existing sub vent shaft and sink portion would provide flexibility to provide sufficient lateral adjustments, if required. However, there would be a concomitant cost and time delay, if misaligned.

Risks

The most significant risk to consider for Model A is a possible misalignment of the new top section with the existing sub vent shaft. This model therefore requires accurate survey measurements and geological core drilling to ameliorate the risk as far as possible.

MODEL B

In Model B, a new stand-alone conventionally sunk shaft would be incorporated from surface to 106L. The shaft would be concrete lined to a finishing of 6.1m diameter. The existing sub vent shaft headgear would have to be stripped out and the space equipped with Bunton chairs, guides and a shaft bottom loading station arrangement. A new hoist chamber and rope raise would be excavated on 96L. The sub vent shaft headgear and rock transfer interface with the new vertical shaft would be excavated on 96L and 106L. This model would require additional rock silos to be excavated between 207L and 212L, as in the case with Model A. Similarly, the loading pocket would be excavated below 212L and an access ramp installed to shaft bottom as illustrated by Figure 4. The new vertical shaft rock hoist would be 2.65 MW with a service hoist of 2.4 MW. Additionally, the new sub vent shaft rock hoist would be 3.25 MW.



RBH, denotes raise bore hole; Ø, diameter; L, level.

Figure 4. Simulation planning longitudinal section for Model B

365 Second means of egress

As the case with Model A, there would need to be an emergency access during the period the sub vent shaft is decommissioned for work. The same solution would be applied for Model B, to egress via the existing raise bored escape between 192L and 126L, once fitted with a ladder. The existing traveling ways between the lower levels (212L to 192L) and upper levels (126L and 90L) proved to be sufficient in case of emergency and would therefore still be utilised.

Benefits

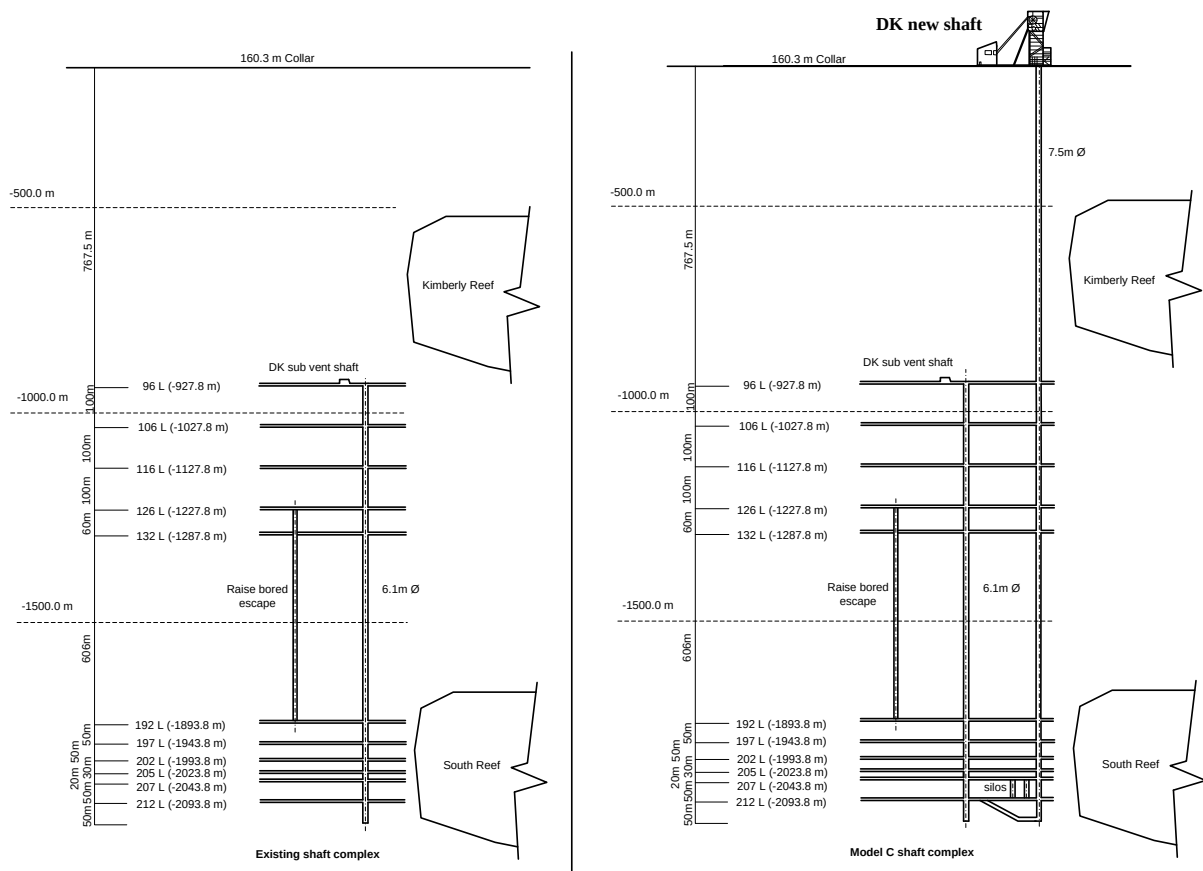
As previously stated, the existing sub vent shaft was concrete lined which is a large cost benefit. Concurrent activities would be conducted for Model B, saving an estimated 28 months on the construction time. The new shaft section would be conventionally sunk while the decommissioning and re-equipping of the sub vent shaft occurs concurrently.

Risks

- 380 The most significant risk of Model B would be the additional usage of an already constrained main shaft. Any concurrent work that would require access via the main shaft, would impede normal production activities.

MODEL C

- 385 In Model C, a new stand-alone conventionally sunk shaft is incorporated from surface to 50m below 212L, as illustrated by Figure 5. The new shaft would be concrete lined and finished to a 7.5m diameter. Additional rock silos would need to be excavated between 207L and 212L, as was the case of both Model A and B. However, the silos would be situated next to the new independent shaft. This model would require that a loading pocket be excavated below 212L and an access ramp be installed. The ramp would provide access to the shaft bottom pump station and provide a means to clear spillage using mechanised machinery. The new vertical shaft would incorporate a rock hoist of 4.5 MW, and a service hoist of 2.4 MW. The sub vent shaft's headgear would not have to be decommissioned and may be utilised for additional hoisting capacity.
- 390



- 395 RBH, denotes raise bore hole; Ø, diameter; L, level.

Figure 5. Simulation planning longitudinal section for Model C

Benefits

As previously stated, the existing sub vent shaft was concrete lined which is a large cost benefit. Model C's construction would occur completely independent of the existing production operations, not impeding production. Additionally, there would be no risk of misalignment with an existing sub vent shaft, as the stand-alone shaft would be vertically sunk on its own. The existing sub vent shaft head gear would not have to be decommissioned and may provide additional hoisting capacity.

Risks

There is a risk of misalignment between the new vertical shaft and the existing levels. Since ten stations would be linked between the vertical shaft and the existing shaft configuration, extra caution should be taken to establish accurate survey measurement and sufficient geological samples.

HOISTING SIMULATION PLANNING CONCLUSION

All three of the simulation planning models satisfied the KPIs of hoisting capacity, gold plant milling capacity and egress during construction. The models would therefore satisfy future production requirements in terms of ore, material and man conveyance. As part of the integrated simulation planning method, the effects on the ventilation network should also be established and optimised.

VENTILATION

As part of the integrated simulation planning method, an investigation was launched into the effects of the ventilation network as a result of the hoisting capacity increase and future planned production rates (C). The existing hoisting capacity of 113 kt/month would be increased to 200 kt/month as part of the LOM plan. DK has two existing up cast shafts namely, DK vent shaft and DK1A shaft as, discussed previously. The combined up cast volumetric flow rate of these shafts is in excess of 1 000 m³/s. However, DK only has a single downcast shaft, namely DK main shaft, which is limited to a down cast volumetric flow rate of 600 m³/s as a result of the shaft dimensions.

In South African deep level mines, the typical average volumetric flow range is between 3 to 6 m³/s per kt/month [29]. For the purpose of this study, an average design volumetric flow of 4.25 m³/s per kt/month would be sufficient. Considering the planned production of 200 kt/month, the ventilation fans would need to be able to accommodate a volumetric flow rate of 850 m³/s. However, the required airflow to ventilate future production areas is limited by the

current down cast capacity of DK main shaft. Additional down cast capacity was required for the ventilation network to satisfy future production requirements (C1).

The two 2.1 MW existing Fantecnic ventilation fans installed at DK vent shaft have a combined suction pressure of 4.86 kPa and a volumetric flow rate of 505 m³/s. The 1.01 MW existing Artec Davidson ventilation fan at DK1A has a suction pressure of 1.95 kPa, and a volumetric flow rate of 272 m³/s. The existing ventilation fans have the capacity to provide the necessary volumetric flow rate of 850 m³/s through the mine for future production rates. However, the fans are limited by the single down cast shaft. For that reason, there is a need to optimise the ventilation network in order to satisfy the future planned production rate included in the LOM plan (C2).

As part of the integrated simulation planning method, the latest ventilation network measurements were acquired and verified (C4). Concurrently, it was established that the KPIs for the ventilation network were selected to be the following (C3):

- Production face wet bulb return temperatures: $\pm 28^{\circ}\text{C}$
- Design volumetric air flow rate: 4.25 m³/s per kt/month

The verified data were used to determine the existing constraints of the ventilation network, as displayed in Table 1.

Table 1. Simulation constraints

Simulation constraints	Parameters
Surface temperatures [$^{\circ}\text{C}$ WB/DB]	18/28
DK shaft diameter [m]	8.1
DK vent shaft diameter [m]	6.1
DK1A vent shaft diameter [m]	6.1
Main intake and return airway [m ²]	11.55 (3.5 x 3.5)
Intake airway velocities [m/s]	6 - 8
Main return airway velocities [m/s]	10 - 12
Design air density [kg/m ³]	0.95

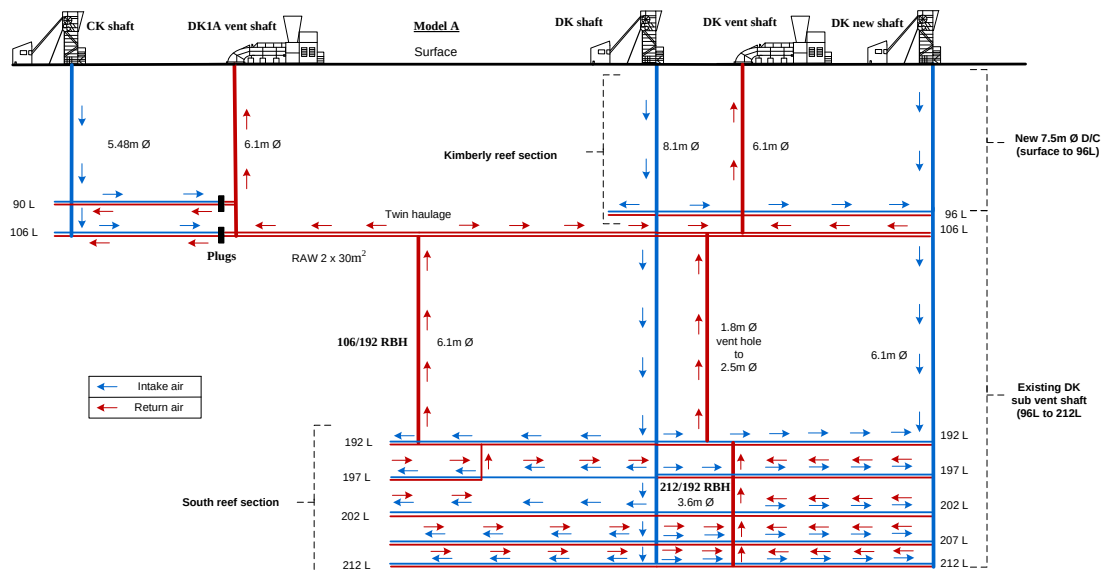
WB denotes, wet bulb; DB; dry bulb.

The constraints displayed in Table 1 were determined through the verified data set. These constraints will be incorporated in each of the simulation planning models, as discussed in the next section.

VENTILATION SIMULATION PLANNING

MODEL A

In Model A, the once up cast sub vent shaft would be extended to surface and converted to the second down cast shaft for the DK mining complex. The existing 1.8m diameter vent hole between 106 and 192 would be enlarged to 2.5m diameter. The twin return airways (RAWs) on 106L, between the 106/192 RBH and DK1A vent shaft, would be slyped to 30 m² as illustrated by Figure 6.

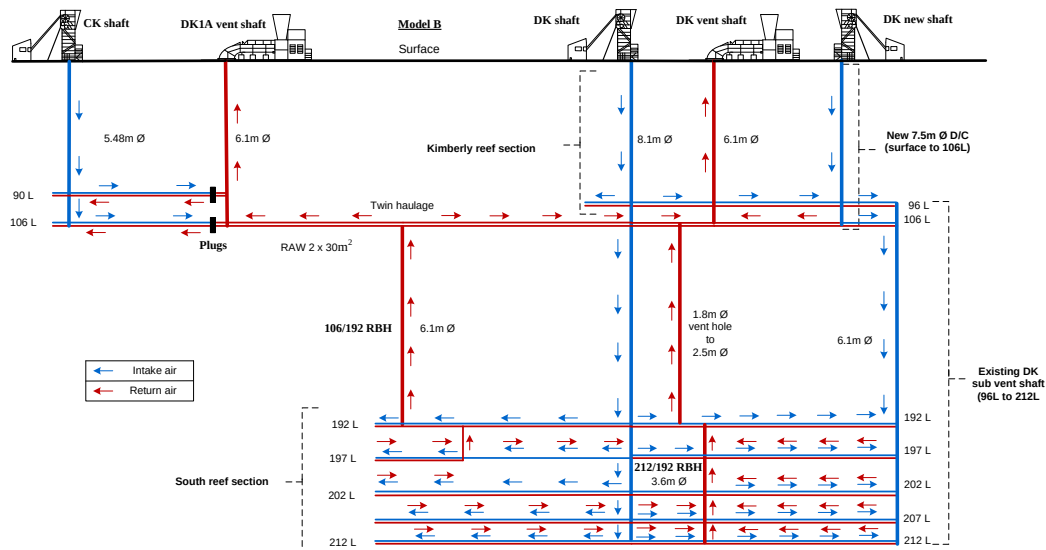


RBH, denotes raise bore hole; D/C, downcast; Ø, diameter; L, level.

Figure 6. Ventilation simulation planning for Model A

MODEL B

In Model B, the existing sub vent shaft is converted to a downcast shaft with the addition of a new downcast top section as displayed in Figure 7. The existing 1.8m diameter vent hole would be enlarged to 2.5m diameter, as in the case with Model A. Similarly, the RAWs would also be slyped to 30 m². The remainder of the twin airways leading to DK vent shaft would be cleaned of the broken rock currently stored there. However, in Model B, additional hoists are required on 96L which would introduce additional heat loads in the mine. Any cooling medium such as water or ice would also have a more convoluted route when compared to Model A.

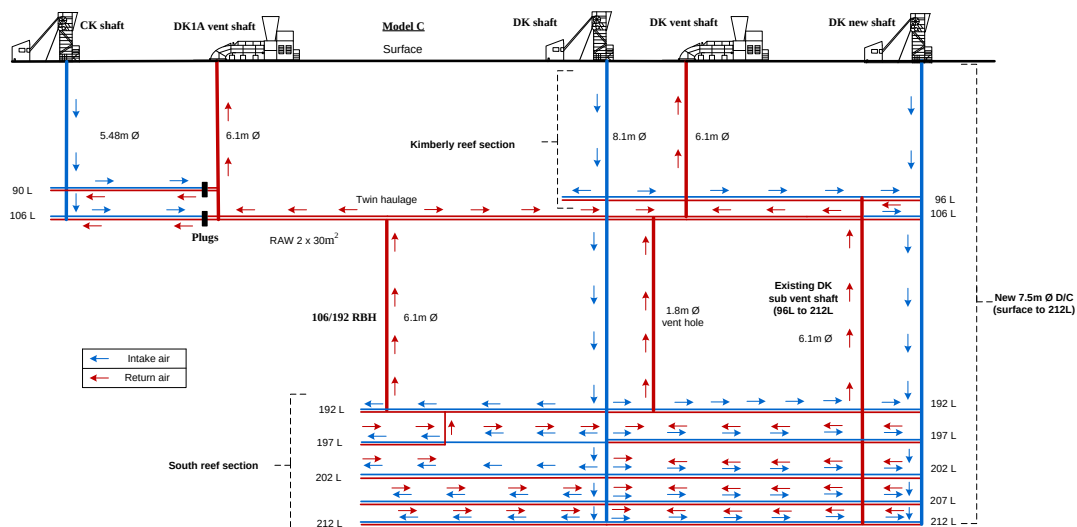


RBH, denotes raise bore hole; D/C, downcast; Ø, diameter; L, level.

Figure 7. Ventilation simulation planning for Model B

475 MODEL C

In Model C, a complete new vertical shaft would be sunk adjacent to the sub vent shaft. The new shaft would act as a second down cast shaft for DK operations. The sub vent shaft would therefore remain an up cast vent shaft, as utilised in the existing operations. The RAWs on 106 would be slyped to 30 m², similar to Model A and B. The 1.8m diameter vent hole will remain, as the existing DK vent shaft would be used for shaft egress in case of emergency.



RBH, denotes raise bore hole; D/C, downcast; Ø, diameter; L, level.

Figure 8. Ventilation simulation planning for Model C

The next step in the integrated simulation planning method (C5) was to construct a detailed simulation of the different models. A thermal-hydraulic simulation package was selected and the simulation planning models constructed and calibrated. The constraints listed in Table 1

were incorporated in each model. The models were simulated for worst case summer scenarios, where the maximum heat loads were applied to the mining complex. The complex ventilation network simulation diagram is displayed in Figure 9.

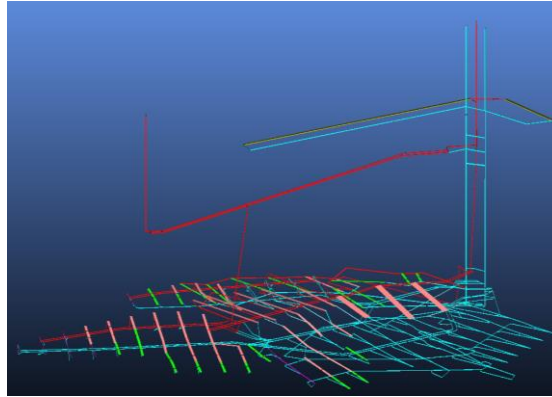


Figure 9. Complex ventilation network simulation diagram

The simulation planning model results are displayed in Table 2. In view of the simulation results, all three simulation planning models would satisfy the future planned production rate in terms of the selected KPIs. The simulation results show that the average production face wet bulb return temperatures remained within the design of $\pm 28^{\circ}\text{C}$, and that the design volumetric flow rate of $850 \text{ m}^3/\text{s}$ was satisfied. In terms of the ventilation network, all three models proved to be suitable for future implementation as part of the LOM plan (C6).

Table 2. Simulation results

Simulation results	Mass flow [kg/s]
DK D/C shaft	415
New D/C shaft	385
DK U/C vent shaft	385
DK1A U/C vent shaft	415
192/106 RBH U/C serves DK1A vent shaft	364
192/126 Raise hole U/C serves DK vent shaft	256
Kimberly reef section	180
South reef section	620

D/C, denotes downcast; U/C, upcast; RBH, raise bore hole.

Benefits

All three simulation planning models would retain the existing up cast shafts and subsequent ventilation fans, reducing the LOM planning costs. Additionally, each model incorporated an additional downcast shaft which would add flexibility to the existing operations. The flexibility in airflow capacity, could be used to moderately increase the tons at concentrated mining

505 areas without the need for additional fans. For example, if mining was planned to occur at the south reef sections only, the upper Kimberly reef sections would be sealed and the airflow utilised to the lower levels.

Risks

510 Model B could have a higher system resistance when compared to the other models depending on the size and configurations of the excavations mined to link the DK sub vent shaft and the new shaft section. Additionally, Model B would introduce additional heat loads as a result of the sub vertical hoists which would need to be dissipated by the ventilation network.

RESULTS

515 The final step in the integrated simulation planning method (D1) was to conduct a simulation cost analysis, in terms of capital costs and annual operating costs of each of the simulation models, as well as to also consider the estimated construction time of each of the simulation planning models. The simulation cost analysis would then provide the final indicator towards the most feasible model for implementation, to be included in the LOM planning. A unique
520 feasibility indicator was specifically developed to provide a more comprehensive cost analysis than commercially available, as demonstrated by Equation (1) and (2).

$$f_{LOM} = T_{CO} \times \frac{Y_C}{Y_{LOM}} \quad (1)$$

$$\therefore f_{LOMi} = \left(\frac{T_{oi} + T_{ci}}{1\,000\,000} \right) \times \frac{Y_{Ci}}{Y_{LOMi}} \quad (2)$$

525 where f_{LOM} is the feasibility indicator and T_{CO} the summation of the total operating costs and the total capital costs for each model (i). Additionally, Y_C is the total construction time required for each model expressed in years and Y_{LOM} the mining complex's LOM, expressed in years.

The capital and annual operating costs, including the estimated construction time of each model, are displayed in Table 3.

Table 3. Simulation method results

Model	A	B	C	Average
Capital cost (US\$)	58 722 667	75 535 349	87 554 300	73 937 439
Operating cost p.a.	3 426 946	5 127 448	3 422 813	3 992 402

Construction time	37	41	70	49
(Months)				
f_{LOMi}	11	15	29	18

f_{LOM} was determined for model A, B and C with a LOM estimation of 18 years.

The comparison between the different models in terms of capital costs, favours Model A. However, if the operating cost of each model is to be considered per annum, Model C is favoured. The primary access and ventilation network KPIs are satisfied by each of the three simulation planning models. Nonetheless, the result of the higher system resistance and additional heat load experienced in Model B can be seen by the highest operating cost per annum. If the primary access capital costs were considered independently of the ventilation network and subsequent operating costs, a substantial error would have occurred

Model A would therefore be included in the updated LOM plan, ensuring future planned production requirements could be met by the hoisting system and ventilation network. The novel integrated simulation planning method provided a means for mine personnel to accurately and cost-effectively establish and update the LOM plan for primary access and ventilation, through the use of simulations. The case study validation is currently ongoing, as the water retaining bulkhead plugs have already been installed and the survey and geological samples are under way.

CONCLUSION

Traditional LOM planning methods are outdated, resource intensive, unreliable and uneconomical. In contrast, simulations provide a more rapid, versatile and accurate means to evaluate, optimise and plan complex mining systems. However, although the paradigm shift was made towards LOM planning through simulations, these simulations are limited to only consider production factors such as mineral reserves, ore grade and spacial distribution. Therefore, LOM planning neglects the effects of future production rates on other mining systems, such as the hoisting system (primary access) and ventilation network. Although planning has been done for these systems through simulation, it has been done in a segregated manner, not being included in the LOM plan.

Therefore, LOM planning is not integrated with the hoisting system and ventilation network. Additionally, literature indicates that no frameworks or methods exist which describe the process of incorporating an integrated planning approach through the use of simulations for these systems as part of LOM planning

In this paper, an integrated simulation planning method was developed to be used for primary access and ventilation LOM planning. The methodology were implemented on a case study in which three simulation planning models were evaluated and optimised to satisfy future production requirements. The simulation planning model which proved to have the highest feasibility was included in the LOM plan. The case study validation is currently ongoing, as the water retaining bulkhead plugs have already been installed and the survey and geological samples are under way.

Future studies should commence to include similar simulation planning methods for other critical mining systems, such as the compressed air system, to be included in the LOM plan. Additionally, a method should be developed to evaluate and optimise operational changes for all applicable mining systems through simulations.

ACKNOWLEDGEMENTS

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DECLARATION OF INTEREST

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App. C.2: SAIMM GUIDELINES FOR AUTHORS

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Papers should be uploaded through the SAIMM website or e-mailed as an attachment to the journal@saimm.co.za for the attention of Ms K. Matthee.

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Authors are encouraged to develop arguments that lead in a sequence from one stage to another and finally to a conclusion. Each paragraph should address a topic and contain an idea where each sentence in the paragraph logically develops that idea. Be objective. Do not include irrelevant or extraneous matter. Sentences should be punctuated correctly to make for easy reading. Use the present tense to describe actions, conditions, and findings with ongoing applicability in the present. Use the past tense to describe actions, conditions, and results that occurred at a specific time in the past.

Quotation marks should be the 'single' type for quotations and "double" for quoted matter within quotations.

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Mathematical and chemical equations should be numbered consecutively in square brackets on the right-hand side of the page:

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$$\text{Fe}_2\text{O}_3 + 6\text{H}(\text{C}_5\text{H}_7\text{O}_2) \rightarrow 2\text{Fe}(\text{C}_5\text{H}_7\text{O}_2)_3 + 3\text{H}_2\text{O} \quad [1]$$

Units and symbols are laid down in the SI guide from the US National Institute of Science and Technology <http://physics.nist.gov/cuu/pdf/sp811.pdf> Where acronyms (e.g. UNO) are used for the first time the full words must be given with the abbreviation in brackets thereafter. A full stop after an abbreviation is used only when the last letter of the abbreviation is not the last letter of the word. If a large number of symbols are used, they may be listed in a separate Nomenclature section at the end of the paper, immediately preceding the list of references.

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The body of the paper will typically consist of an Introduction; Background; Literature Survey; Theory; Experimental; Results; Discussion; Conclusions; Acknowledgements; References.

A literature survey is essential for every research project, because it provides the author or authors with guidelines for the project, while at the same time it makes a positive contribution to the

solution of the problem and it lends credibility to a project.
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Article in a journal

Bezuidenhout, G.A., Eksteen, J.J., and Bradshaw, S.M. 2009. Computational fluid dynamic modeling of an electric arc furnace used in the smelting of PGM containing concentrates. *Minerals Engineering*, vol. 22, no. 11. pp. 995–1006.

Do not abbreviate journal titles.

Paper published in a conference proceedings

Nell, J. 2004. Melting of platinum group metals concentrates in South Africa. *Proceedings of the VII International Conference on Molten Slags, Fluxes and Salts*, Cape Town, South Africa, 25–28 January 2004. Southern African Institute of Mining and Metallurgy, Johannesburg. pp. 165–170.

Urquhart, R.C., Rennie, M.S., and Rabey, C.C. 1976. The smelting of copper-nickel concentrates in an electric furnace. *Proceedings of Extractive Metallurgy of Copper: Vol. 1. Pyrometallurgy and Electrolytic Refining*. Yannopoulos, J.C. and Agarwal, J.C. (eds). The Metallurgical Society of AIME, Warrendale, Pennsylvania. pp. 275–295.

The date may be repeated if it forms part of the Proceedings title or subtitle.

If Proceedings were edited, give editor(s) name(s) and initials as for a book.

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States in the USA may be abbreviated either the traditional way *e.g.* Mass. for Massachusetts or the two-letter postal code MA.

Book

Wills B.A. and Napier-Munn, T. 2006. Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery. 7th edn. Elsevier/Butterworth-Heinemann, Amsterdam.

Chapter in an edited book

Mills, K.C. 1986. Estimation of physicochemical properties of coal slags. *Mineral Matter and Ash in Coal*. Vorres, K.S. (ed.). ACS Symposium Series 301. American Chemical Society. Washington DC. pp. 195–214.

Report

Tarrant, G. 2001. Assessment of support requirements associated longwall reorientation. Report no. MET2431. Strata Control Technology. Wollongong, NSW, Australia. 30 pp.

Serbousek, M.O. and Signer, S.P. 1987. Linear load-transfer mechanics of fully grouted roof bolts. *Report of Investigations* 9135. US Bureau of Mines, Pittsburgh, PA.

If no authors are identified, the organization issuing the report is regarded as the author.

Thesis

Forsbacka, L. 2007. Experimental study and modelling of viscosity of chromium containing slags. PhD thesis, Helsinki University of Technology, Finland.

Patent

Arvidson, B. and Zhu, D. 2007. OutotecOyj. Methods of separating feed materials using a magnetic roll separator. US patent 7296687.

State name of inventor followed by the assignee if different from author. The issuing country may be abbreviated according to the ISO 3166 standard to be found at https://en.wikipedia.org/wiki/ISO_3166-1_alpha-3

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Paul, S. 2012. Rio Tinto's Australian trains go driverless. *Star Business Report*, 21 February p. 22.

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Acts of parliament and other government documents

South Africa. 2008. Mineral and Petroleum Resources Royalty Act of 2008. *Government Gazette*, vol. 351, no. 31636, 24 Nov. 2008, as amended. Mineral and Petroleum Resources Royalty (Administration) Act 29 of 2008, *Government Gazette*, vol. 521, no. 31624, 26 Nov. 2008, as amended.

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As for the various types of publication above, with the URL and date of access appended, e.g., Anglia Ruskin University. 2011. Guide to the Harvard style of referencing. <http://libweb.anglia.ac.uk/referencing/harvard.htm> [accessed 23 February 2012]
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Webber-Youngman, R.C.W. 2011. School of Mining, University of Pretoria. Personal communication.

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Achieving energy efficiency with medium voltage variable speed drives for VOD in South African mines

Journal submitted: Sustainable Energy Technologies and Assessments (SETA)

Status of article: Under review

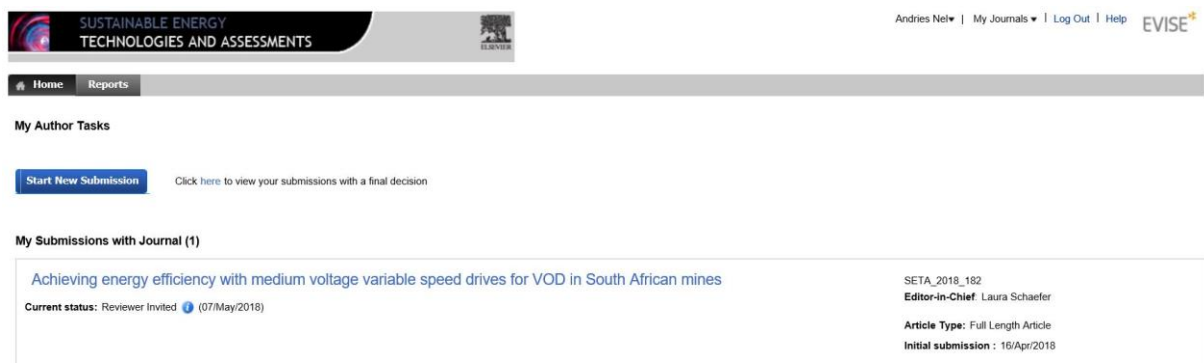
Achieving energy efficiency with medium voltage variable speed drives for VOD in South African mines

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ABSTRACT

The profitability of the mining industry can be increased contingent on the industry's ability to improve operational efficiency. The advancement of energy efficient technologies coupled with modern strategies have resulted in large industrial energy efficiency improvements. Mine ventilation fans in South Africa were identified as large energy consumers with potential for efficiency improvements, with the installation of new medium voltage (MV) variable speed drive (VSD) technologies. An extensive energy audit was conducted on ten mine ventilation networks. Feasibility indicators such as the cost savings, energy savings and greenhouse gas emission reductions were calculated and assessed under varying ventilation on demand (VOD) airflow conditions. Two VOD applications were considered namely, constant speed reduction- and dynamic applications. The financial indicators revealed it is economically viable for the implementation of VSDs as part of both VOD applications. On the ten mines investigated, a maximum annual electrical energy saving of 179 421 MWh could be achieved with the implementation of both VSD applications. The resulting cost saving is estimated at US\$11.57-million with an average payback period of 9 months. Accordingly, the average GHG emissions will be reduced with 53% per annum. The feasibility of installing VSDs on South African mine ventilation fans as part of VOD potential was proven. The results underlines the importance of incorporating new technologies to increase operational efficiency and positively contribute towards sustainable profitable mining.

20 KEYWORDS

Variable speed drive, Ventilation on demand, Energy savings, Cost savings, GHG emissions

HIGHLIGHTS

- Ventilation on demand potential assessed on 10 South African mine ventilation networks.
- 25 • Savings calculated for medium voltage variable speed drive implementation of mine fans.

INTRODUCTION AND BACKGROUND

Positive economic development has been linked to increased energy and material consumptions [1], [2]. It is estimated that the worldwide industrial energy consumption will increase with 1.4% per year [3]. However, globally there is a growing concern of environmental and energy security, emphasising the need for intelligent energy solutions [4], [5]. Fortunately, improving operational efficiency has become the norm in the 21st Century [6]. Therefore, the sustainability of the economy is contingent on the industries' largest consumers to play a proactive role in implementing energy efficient solutions [7].

35 The South African economy was built on the exploitation and processing of naturally occurring mineral resources [1]. Reviewing past economic growth patterns illustrate the deep-rooted effects of mines in South Africa [8]. Nonetheless, research indicate that there is scope for operational efficiency improvements in this sector, as a result of the archaic operating models still in use today [9], [10].

40 A paradigm shift has occurred in the international mining arena towards the use of more efficient equipment inter alia the installation of variable speed drives (VSDs) on refrigeration systems, pumps and fans [9], [10]. Consequently, several case studies have been implemented which resulted in significant cost savings [6], [9], [11]. The viability of installing VSDs has been proven as a tool to achieve cost savings in various applications across complex industrial systems [9], [12]. The most successful case study results were obtained in systems of a cyclical nature where part load conditions were prevalent [11], [13].

45 Considering mine ventilation networks represent between 25% to 50% of the energy consumed in mining, large potential exist to realise cost savings with the installation of VSDs on these systems [14]. Mine ventilation networks are used to ensure that underground environmental conditions are conducive to safe and productive mining [15]. This is done by supplying sufficient airflow to the underground working areas to govern heat stress imposed

on workers, and to dilute and exhaust hazardous particulates to below statutory occupational exposure levels [16].

Various mine ventilation optimisation strategies have been developed and implemented [16], [17], [18]. Traditionally, in South African mines main ventilation fans' airflow volume has been controlled through inlet guide vanes (IGV), under constant speed applications [19]. However, while IGV does provide some energy benefit the use thereof results in increased frictional resistance and a pressure drop as a result [20]. Therefore, integrating modelling and simulation technologies [21] along with dynamic control strategies provide the platform for Ventilation on Demand (VOD) solutions [22], [23]. The state of art for mine ventilation networks culminate to the principle of VOD by ensuring the dynamic facilitation of the true airflow requirements for the different underground mining operations [24], [25].

Literature indicate that it is current common practice for South African mines to operate under constant airflow conditions supplying maximum volume regardless of varying production requirements [23], [20]. As such, the main ventilation fans are operated continuously [26], [27]. Furthermore, a study conducted on the in situ assessment of airflow leaks underground, revealed that as much of 28% of airflow can be lost to return airways in South African mines [28]. Mine ventilation is therefore oversupplied and underutilised in the working areas [29]. This leaves opportunity for strategies to reduce the airflow leakages with modulation and to increase airflow utilisation through leak reparation. Thus, VOD allows for variable airflow control by exploiting the cyclical nature of mining airflow requirements (dynamic) [4], [23] as well as allowing operations to adjust to reduced demand (static) [19], [13], [30].

Theoretically, the main ventilation fans could be controlled to supply sufficient airflow to satisfy the demand requirements underground [30], [22]. The airflow requirements may include dynamic and static control for ventilation fans over a daily profile [31]. Airflow control is currently done using IGVs in South Africa [20]. However, the airflow control could be applied with much greater accuracy by adjusting the speed of the fan motors with VSDs [22], [32].

The effects of variable airflow on mines have been investigated with pilot VSD implementation studies which yielded positive results in Canada [33], [30]. However, it has been found that these technologies have not been implemented in South African mine ventilation networks [19], [29], [34]. This may be due to a lack of knowledge for the scope of VOD potential on mine ventilation networks [27].

Chatterjee et al have used a theoretical model to show that VOD is predominantly effective when energy efficiency and load management control are implemented simultaneously [23].

As such, the ventilation fan motor speeds are controlled according to the airflow requirements taking the time-of-use (TOU) electricity tariffs into account, resulting in a dynamic fan power profile [23]. This type of control aims to provide a load shift saving during peak electricity periods and an energy efficiency saving during all other periods. The optimiser was specifically developed to maximise the achievable cost savings according to the TOU electricity tariffs [1], [4]. Therefore, if the electricity tariff is not dependent on the TOU, energy efficiency strategies would be the most effective means to achieve the maximum cost savings.

Nonetheless, there have been case studies of static applications in the building services industry where energy efficiency savings were achieved by installing and controlling VSDs on a continuous speed or static basis [13], [35]. In some cases, the saving proved to be considerably more when compared to the savings achieved during variable conditions [32]. The cost saving opportunities of both static and dynamic applications should therefore be investigated to make informed decisions.

The novelty of this paper lies in assessing VOD potential on mines, more specifically South African mines with the installation of VSDs. The energy consumption of main ventilation fans are evaluated and the potential effects on greenhouse gas (GHG) emissions, energy and cost savings are calculated. The financial feasibility of the potential VOD implementation is also calculated through the payback period.

FUNDAMENTAL THEORY

FAN PERFORMANCE CHARACTERISTICS

In order to comprehend the effects of variable speed on ventilation fans as used in VOD, it is best to begin with an arbitrary fan performance curve of a fixed blade angle centrifugal fan under constant speeds [33]. Centrifugal fans are most often used as main mine ventilation fans [21], [36]. Any main ventilation fan's performance can be characterised by its performance curve, which is often supplied by the original equipment manufacturer (OEM) with purchase [14], [23]. The performance curve indicates the static pressure required by the ventilation fan to supply a certain airflow volume [33], [37]. Fan performance curves vary considerably in industry but may include the efficiency, absorbed power, system resistance and performance effects at different inlet guide vane angles or speeds [38].

Figure 1 illustrates an example of fan performance curves incorporating the absorbed power, distinguished by different colours, according to varying speeds. In addition to the static pressure, airflow volume and absorbed power, Figure 1 indicates a high- and low system resistance. The system resistance of a ventilation network is based on the state of the system,

that is, the underground ventilation circuit [17]. The resistance is therefore dependant and can be altered with different techniques such as slyping, strategic seal installations, ventilation doors and airflow regulators [39], [40].

A fan's performance at a given speed is characterised by the corresponding fan curve, therefore by adjusting the speed, a new fan curve is established [33]. This is demonstrated by the different colour curves in Figure 1, for example the absorbed power of the black dotted curve is much higher when compared to the red dotted curve. In essence, if the fan speed is reduced under a given system resistance it will result in a lower pressure requirement to supply the same airflow volume, consuming less power [41]. This underlying principle is best described when the relationship between the static pressure and airflow volume is considered in the fan efficiency calculations.

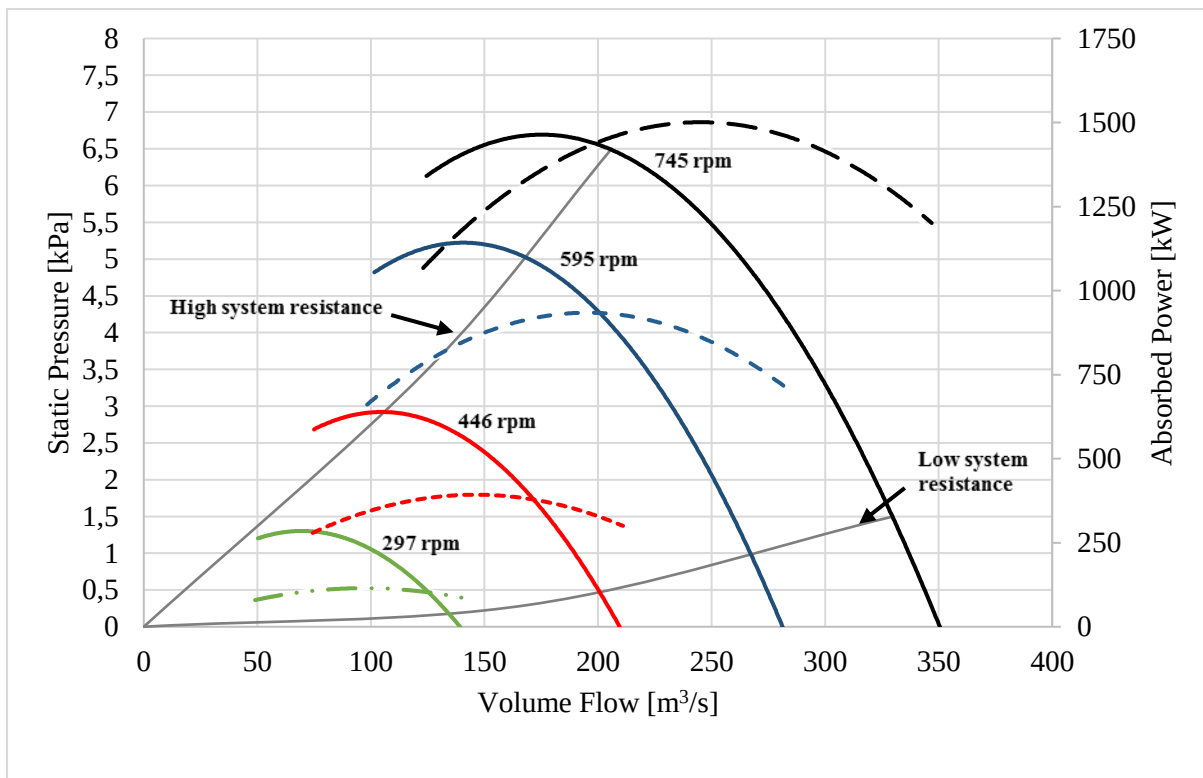


Figure 1: Ventilation fan performance curve under varying speeds

Main ventilation fans are further characterised according to their static efficiency, as illustrated by Equation 1. The static efficiency is the ratio of the static air power to the absorbed shaft power [23]. The static air power is defined as the product between the static pressure and airflow volume for the fan at a given speed [14], [21]. The equation provides the relationship between the pressure and airflow volume. However, in VOD, the fan is controlled to supply sufficient airflow volume to satisfy the demand requirements [22], [23]. The relationship between airflow volume and power therefore needs to be established to characterise the

effects of VOD. The static efficiency for main ventilation fans are mathematically defined as follows:

$$\eta_s = \frac{\dot{W}_s}{\dot{W}_{sh}} = \frac{\dot{m}(P_i - P_o)}{\rho \dot{W}_{sh}} = \frac{\dot{Q}(P_i - P_o)}{\dot{W}_{sh}} \quad (1)$$

where η_s is the static efficiency (%); $\dot{W}_s$ is the air power (kW); $\dot{W}_{sh}$ is the shaft power (kW); $\dot{m}$ is the airflow mass flow rate (kg/s); $(P_i - P_o)$ is the pressure difference from initial conditions (*i*) to the output conditions (*o*) in (kPa); ρ is the air density in (kg/m³); $\dot{Q}$ is the airflow volume in (m³/s).

The relationship between the airflow volume and power is defined according to the fan affinity laws [33]. The fan affinity laws is a set of mathematical equations which governs the relationship of the fan speed, the shaft power and the fan pressure. The affinity laws are expressed in Equations 2 to 4 below:

$$\frac{P_{wri}}{P_{wro}} = \left(\frac{N_i}{N_o} \right)^3 \quad (2)$$

$$\frac{P_i}{P_o} = \left(\frac{N_i}{N_o} \right)^2 \quad (3)$$

$$\frac{\dot{Q}_i}{\dot{Q}_o} = \frac{N_i}{N_o} \quad (4)$$

where (*i*) denotes the initial conditions and (*o*) denotes the output conditions; P_{wr} is the shaft power in (kW); N is the fan speed (rpm); P is the pressure (kPa); $\dot{Q}$ is the airflow volume in (m³/s). Equation 4 illustrates that the airflow volume ratio is directly proportional to the fan speed ratio. This proportionality is used to establish the cubic power-airflow relationship [23]. It is this relationship, which enables a large power reduction with a small fan speed reduction [9].

In summary, because the use of a VSD allow for the control of fan speed, the airflow volume can subsequently be controlled [22]. This in turn has an effect on the power consumption, as defined by the cubic power-airflow relationship [9], [11]. Thereby, providing a means to calculate the new shaft power for a given fan, after the fan speed has been controlled to produce a pre-determined airflow volume.

VSD CHARACTERISTICS

A variable speed drive is a component which incorporates pulse width modulation (PWM) to create variable current, voltage and frequency outputs to an electric motor. By regulating these outputs, the motor torque, speed and power can be varied and controlled [12], [42]. This allows for variable duty points to be modulated, which was proven to be the most efficient method for

variable load control [6], [43], [44]. The frictional increase and pressure drop experienced as a result of typical IGV control is nullified with VSDs, by opening the IGVs to 100% and modulating the flow with the VSDs[45]. VSDs experience load losses from 2% to 3% as a result of motor current, resulting in VSD efficiencies of between 97% to 98% [33]. Literature indicates that systems will experience a significant life-cycle cost saving and additional GHG emission reduction with the use of VSDs [9].

The use of VSDs as a means to realise energy cost savings have become a more widespread solution in various sectors [6]. Several successful case studies have been published on boilers [46], conveyor systems [47], [48], refrigeration systems [9] and pumping systems [49]. Figure 2 illustrates the relationship between the motor power and rated speed as a percentage [11].

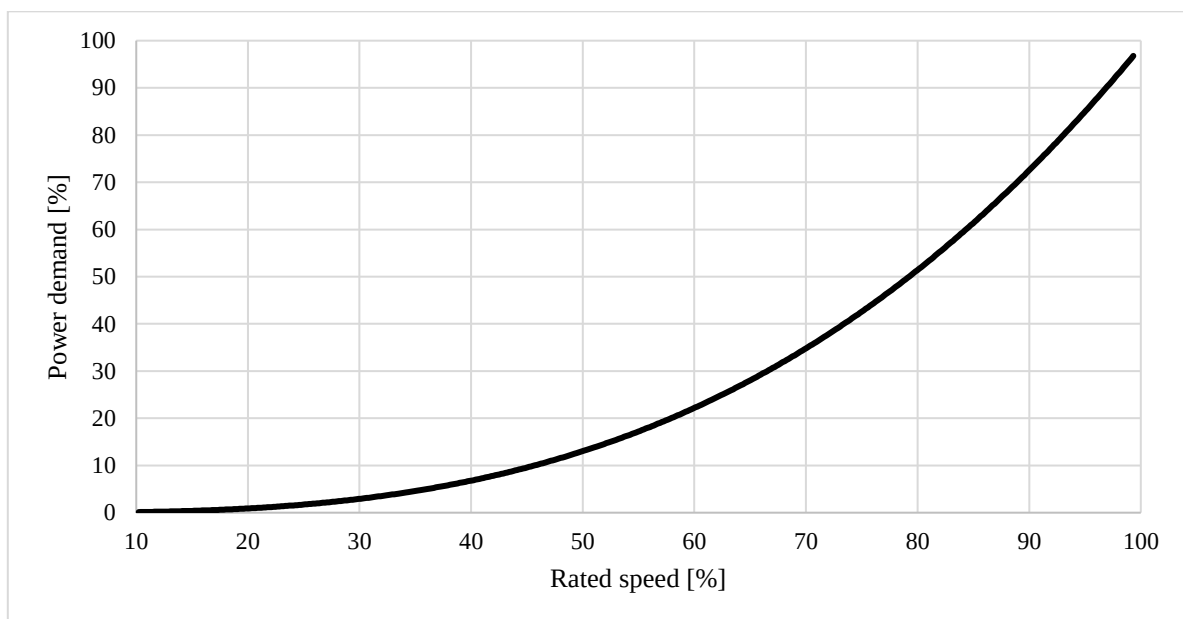


Figure 2: Relationship between motor power and rated speed

Figure 2 illustrates that a small electric motor speed reduction result in a large power reduction [11]. Additional benefits of using VSDs to modulate flow include extended equipment life as a result of inherent soft start-up and shutdown capabilities [50]. Improved process control [9], improved reliability and system performance [11], improved power factor correction [51] as well as reduced maintenance [52].

FINANCIAL FEASIBILITY

The financial feasibility of installing VSDs as part of energy saving measures should be evaluated thoroughly before implementation [6]. Typically, companies evaluate energy projects through financial indicators such as the payback period (PBP) and return on investment (ROI) [53]. In this paper, the PBP was selected as the main financial indicator

towards feasibility. The PBP indicates the cost-effectiveness of a project as calculated by Equation 5 [11].

$$PBP = \frac{C_{TE}}{C_{TS}} \quad (5)$$

where PBP is the payback period per annum (-) C_{TE} is the total project expenditure including capital costs, installation and commissioning costs per annum (US\$); C_{TS} is the total cost saving for the project per annum (US\$). In South Africa, the total cost saving is a product of the energy savings and its unit price or electricity tariff [9]. This is as a result of the TOU electricity tariffs [1], [54].

Literature indicate that energy projects are deemed viable with PBPs of less than one third of the electric motor's life expectancy [52]. The average typical life expectancy of electrical motors fitted to main mine ventilation fans are 25 years [55]. As a result, energy projects on main ventilation fan motors having a PBP of less than 8 years will be deemed as financially feasible. However, international case studies have reported PBPs of less than two years to be the norm for VSD utilisation projects [46]. This coincides with the feasibility criteria applicable to the South African Mining industry [56].

The advancement of technology coupled with the increase in VSD utilisation has led to a significant cost reduction in the last five years [11]. Especially low voltage (LV) VSD applications have thrived in industry [6]. Although it has been proven that the cost intensity (US\$/kW) for medium voltage (MV) VSDs have reduced, the implementation thereof have been limited [46]. Table 1 indicate the costs of MV VSDs applicable to main mine ventilation fans in South Africa.

Table 1: Typical 6.6 kV MV VSD costs (US\$) in South Africa

Motor capacity:	800 kW	1000 kW	1200 kW	1500 kW	1900 kW
Supplier 1	82 516	97 268	112 652	134 136	170 359
Supplier 2	92 903	105 774	120 823	144 454	174 012
Supplier 3	87 487	103 736	118 453	131 556	172 449
Average MV VSD	87 635	102 260	117 309	136 715	172 273
Installation	13 796	14 204	14 459	15 020	16 603
Commissioning	7 718	7 718	7 718	7 718	7 718
MV VSD intensity (US\$/kW)	110	102	98	91	91
Installation intensity (US\$/kW)	17	14	12	10	9
Commissioning intensity (US\$/kW)	10	8	6	5	4
Total MV VSD intensity (US\$/kW)	136	124	116	106	103
Additional optional costs::					
5 year warranty	11 669	11 669	11 669	11 669	11 669
5 year maintenance	25 490	25 490	25 490	25 490	25 490

Critical spares	24 633	26 160	30 515	34 083	39 632
Warranty intensity (US\$/kW)	15	12	10	8	6
Maintenance intensity (US\$/kW)	32	25	21	17	13
Critical spares intensity (US\$/kW)	31	26	25	23	21
Total cost intensity (US\$/kW)	214	188	173	154	144

Exchange rate 1US\$ = 11.63 ZAR. *Note the costs were extracted from quotes obtained from reputable MV VSD manufacturers' such as ABB, ZEST WEC, and Rockwell Automation.

215 Table 1 indicate that the cost intensity decreases with an increase in motor capacity. Thus, the feasibility of implementing VSD projects on large capacity motors are therefore enhanced. Even so, the costs of MV VSDs are still higher in South Africa when compared to prices abroad, as a result of the low demand [9]. This underlines the importance of assessing the potential of VOD in the South African mining industry. Modern manufacturers of MV VSDs
220 have addressed the once critical technical factors prohibiting VSD installations [11]. Technical concerns are unjustified if the MV VSD drive is correctly installed and commissioned [9]. Additionally, manufacturers provide extended maintenance plans and warranties to ensure normal MV VSD operations for at least five years [9], [57]. The surveyed manufacturers provide training and immediate support to mine personnel during this five year period at no
225 additional cost.

VOD POTENTIAL

South African mine ventilation networks were investigated as part of VOD potential assessment. The service delivery and energy consumption of 10 mine ventilation networks were evaluated. The scale of the ventilation networks varied considerably to provide a
230 comprehensive assessment of VSD utilisation in a national context, as opposed to mine specific modulation strategies. The investigation included seven deep-level gold mines and three platinum mines of varying complexities and production rates.

MINE VENTILATION NETWORKS

In hard rock mining, there are typically two critical mining shifts which need to be considered
235 for ventilation operations [39]. Although airflow is required during both these shifts, the function of the airflow are different [23], [40]. The first being the drilling, charge-up and blasting shift and the second being the loading shift (when broken rock is removed from production faces) [29]. During these shifts the main ventilation fans coupled with underground booster fans are used to ventilate the underground working areas. This is done to ensure statutory compliance
240 of health and safety standards in terms of temperature and particulate matter [58]. There is also a shaft clearance period between shifts, in which the hazardous particulates (toxic blasting gasses and dust) are diluted and exhausted by the ventilation network [22].

Conventionally, after the drilling shift, miners retreat from the production face to the main shaft haulage area where fresh air intakes are available until the clearance period has subsided or the miners have egressed from the mine [19]. Even though mining is conducted by a cyclical nature, maximum ventilation is typically supplied during all operating hours in South African mines [19]. Only in recent studies have techniques such as VOD deemed to ask crucial questions regarding true ventilation requirements during each hour of a day [23].

Improving the operational efficiency of mine ventilation networks have been investigated by various authors[21]. Du Plessis et al. implemented IGV control according to TOU tariffs to achieve cost savings on South African mines [19]. Chatterjee et al. developed a theoretical VOD optimiser according to the TOU electricity tariffs to incorporate the true airflow requirements during the different mining shifts [23]. However, the potential of implementing VSDs as part of VOD strategies have not been investigated on South African mines [19]. Furthermore, several authors have emphasised the need for such a study, to assess the savings potential of installing VSDs on mine ventilation fans[19], [26], [33].

MINE VENTILATION ENERGY AUDIT

The first step in evaluating energy projects is through a systematic process called an energy audit [59]. An energy audit is a comprehensive technique used to evaluate and analyse systems for energy saving opportunities [60]. In this paper, ten mine ventilation networks were audited to evaluate the energy consumption and service delivery of each.

Historical system data of the ventilation networks were provided by mine personnel in periods, ranging from three months to three years. This was used in conjunction with fan performance curves and other system specifications to analyse and characterise the current operations [13], [57]. The ventilation fan loading and energy consumption should provide an indication towards flow modulation [13]. The energy consumption of a main ventilation fan can be calculated with Equation 6 below [61].

$$E_{Fan} = (T_o)(L_F)(\dot{W}_F) \quad (6)$$

where E_{Fan} is the electrical energy consumption of the fan motor (kWh); T_o is the operating hours (h); L_F the power load factor (%); $\dot{W}_F$ the maximum fan motor rated capacity (kW). The load factor is therefore the ratio of the measured capacity to maximum motor rated capacity [60]. The average load factors for the ten selected mines were calculated using Equation 6. The most important results of the load factors are displayed in Table 2. As part of the evaluation, ten mine ventilation networks were considered with 33 main ventilation fans. The fan motors varied in capacity, ranging from 1.0 MW to 4.1 MW with static ventilation fan

efficiencies of 15% to 78%. The average power load factor of the evaluated fans were 77%, with the fans accounting for 12% of the total mines' energy consumption per annum.

Centrifugal, backward inclined ventilation fans were installed as main fans on all the selected mines with a standard supply voltage of 6.6 kV. All of the ventilation fans were fitted with IGV control. However, some of the IGVs were in a very poor state with several vanes fixed in a constant position. The IGV control mechanism of these vanes were broken as a result of excessive vibrations. None of these main ventilation fans were installed with VSDs, although the most technologically advanced mines were selected in South Africa. Therefore, it is reasonable to conclude that the potential of VOD by installing VSDs have not been investigated nor implemented in the country.

Table 2: Electrical characterisation of selected South African mine ventilation networks

Mines	Power load factor	Installed fan Qty.	Operating fan Qty.	Individual fan rated power	Total fan rated power	Total average power demand	Total energy consumption
	[%]	[-]	[-]	[kW]	[kW]	[kW]	[MWh/year]
1 _P	62	2	1	1 900	3 800	1 170	10 277
2 _P	76	6	6	1 200	7 200	5 446	47 837
3 _P	73	5	5	1 200	6 000	4 356	38 263
4 _G	91	3	2	4 100	12 300	7 492	65 809
5 _G	78	3	2	1 000	3 000	1 551	13 623
6 _G	79	3	2	2 100	6 300	3 300	28 987
7 _G	81	3	3	2 250	6 750	5 481	48 145
8 _G	82	3	2	2 200	6 600	3 610	31 622
9 _G	61	3	2	1 450	4 350	1 774	15 582
10 _G	82	2	2	2 540	5 080	4 150	36 453
Total	77	33	27	19 940	61 380	38 330	336 598

G, denotes gold mine; P, platinum mine.

The absence of VSD implementation as part of VOD can be attributed to the lack of awareness and potential assessment of these initiatives [13]. Historically, electricity tariffs were low in South Africa to the effect that energy efficiency were not prioritised by mine personnel [1]. As a result, energy saving measures were neglected which still appears to be the case among mine personnel today [19]. However, most of the personnel were willing to consider installing VSDs as part of VOD strategies, if the potential of these initiatives were provided. Thus, there is significant scope to assess the VOD potential in South African mines by utilising new efficient technologies such as VSDs.

Considering the power load factors in Table 2, inefficient operations exist which can be mitigated with effective airflow modulation through VSDs. Only four of the ten mines that form part of the assessment have power load factors above 80%. The other six mines' ventilation fans were controlled with IGVs resulting in inefficient control and low power load factors. The low factors indicate significant scope for variable airflow control as a means to improve the operational efficiency. For that reason, there is significant scope for the installation of VSDs. However, the feasibility of installing VSDs must be proved with saving calculations.

SAVING CALCULATIONS

Savings estimates should be made as accurately and conservatively as possible to make intelligent business decisions [62]. Several methods have been developed to estimate the potential savings of installing VSDs on pump and fan motors [60]. For the purpose of this study, a simplified method developed by Saidur et al. was followed and adapted to calculate the energy savings [63]. This method is well suited for extensive evaluation studies of complex systems, such as mine main ventilation fans [63]. The energy savings of installing VSDs on mine ventilation fans can be calculated using Equation 7 for various speed reductions [50].

$$ES_{Fan} = (T_o)(SP_F)(\dot{W}_F) \quad (7)$$

where ES_{fan} is the electrical energy saving (kWh); T_o is the operating hours (h); SP_F is the energy saving percentage (%), as calculated using Equation 2 at an assumed airflow reduction; $\dot{W}_F$ the maximum fan motor rated capacity (kW).

Additional benefits of reducing energy consumption is a reduction in greenhouse gas (GHG) emissions associated with coal-fired electricity generation [64]. In South Africa more than 85% of the electricity is generated through coal-fired power stations [65], [66]. Considering South Africa's GHG emissions increased 20% from 2000 to 2009, the reduction in emissions as a result of energy savings may contribute towards the required paradigm shift in industry towards sustainable development [65]. Therefore, the GHG emission reductions as a result of energy savings can be calculated using Equation 8 [6].

$$ER_{GHG} = ES_{Fan} \sum (F_{\%} \times E_f) \quad (8)$$

where ER_{GHG} is the GHG emission reductions per annum for CO₂, SO₂ and NO_x (kg); ES_{Fan} is the electrical energy saving (kWh); $F_{\%}$ the percentage of fuel for electricity generation (%); E_f is the emission factors based on coal-fired electricity generation (kg_{GHG}/kWh). The emission factors for each of the GHGs considered are, 0.990, 0.00825 and 0.00411 (kg/kWh) for CO₂, SO₂ and NO_x respectively [67]. The emission reductions should be included in the assessment of VOD potential in South African mines.

RESULTS

The potential of VOD in South African mines by the installation of VSDs are assessed in the following section, incorporating all the collected data during the investigation. The energy savings, cost savings and GHG emission reductions are calculated which can be realised as a result of VSD implementation. As part of the assessment, Equations (6) to (8) were used to determine the effects associated with different airflow conditions. Finally, the financial indicators were calculated for each of the airflow scenarios to indicate the feasibility and potential of this strategy.

VOD POTENTIAL IN SOUTH AFRICAN MINES

VOD potential can be assessed, according to dynamic and static control applications as stated previously [9], [46]. The principle of VOD is based on satisfying the varying airflow requirements of the different mining operations for a typical mining day, thereby forming part of the dynamic applications [23]. The result of VOD is a dynamic daily airflow profile and subsequent dynamic fan speed- and energy profile. However, there are applications where airflow is oversupplied to underground working areas or poor underground airflow utilisation occurs which pose scope for constant speed reductions [21], [28]. The low airflow utilisation can typically be attributed to poor underground seals, worn out ducting, improper circuit design and unforeseen mining changes [21], [24].

Previous studies in South African mines indicate that 28% of the airflow supplied by ventilation fans are leaked to the return airways without being utilised underground [28]. This means that the airflow utilisation can be increased with the installation of proper ventilation seals to direct the airflow to the designated underground working areas. Subsequently, almost 28% of the supplied airflow can be reduced in South African mines to provide the same level of service delivery [15], [19], [28]. Therefore, to assess the potential of VOD in South African mines, these constant speed applications need to be considered first.

Table 3 illustrates the total energy consumption of the operating fans for each of the ten mines under evaluation. The estimated energy consumption of the fans were calculated under different airflow conditions. As stated earlier, the reduction in airflow can be attributed to the reduction in airflow to mitigate the oversupply or the reduction as a result of installing ventilation seals underground increasing the airflow utilisation (28% leakages). It was assumed that the proposed airflow reductions will be achieved by the installation of strategic underground seals at the respective mines. An airflow reduction range of 10% to 28% were selected for this study to calculate the maximum potential savings associated with the effective

sealing and reparation of underground airflow leakages [28]. Table 3 incorporates the load losses and therefore the efficiency of each MV VSD to be utilised.

Table 3: Site specific energy consumption and VSD installation costs.

Mines	Energy consumption with VSDs under constant percentage airflow reduction (E_{VSD})					C_{TE}
	Without MV VSDs (E_{NO_VSD})	10% Airflow	15% Airflow	20% Airflow	28% Airflow	All costs included
	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	[MWh/year]	US\$-million
1 _P	10 277	8 016	6 783	5 755	4 008	0.36
2 _P	47 837	35 708	30 425	25 716	19 292	1.52
3 _P	38 263	26 987	23 020	19 485	14 662	1.27
4 _G	65 809	51 332	43 434	36 853	25 666	1.35
5 _G	13 623	10 627	8 992	7 629	5 353	0.52
6 _G	28 987	22 610	19 132	16 233	11 305	0.82
7 _G	48 145	37 553	31 776	26 961	18 777	0.83
8 _G	31 622	24 734	20 929	17 758	12 367	0.83
9 _G	15 582	12 155	10 285	8 726	6 077	0.66
10 _G	36 453	28 434	24 059	20 414	14 217	0.92
Total	336 598	258 156	218 835	185 530	131 724	9.09
$ES_{Fan}\%$	-	23	35	45	61	-

G, denotes gold mine; P, platinum mine, TE, total expenditure; Exchange rate 1US\$ = 11.63 ZAR; E_{Fan} as the electrical energy consumption of the fan, C_{TE} as the total expenditure costs for the projects; $ES_{Fan}\%$ as the energy saving percentage.

The total costs for the MV VSDs, as displayed in Table 3, includes costs such as the installation, commissioning, bypass panels, five year maintenance and warranty, MV VSD costs as well as the construction of new substations to house the MV VSDs. The total costs are limited to the current operating fans on the ten mines. The standby fans were therefore not included, to be installed and controlled with MV VSDs as they serve as redundancy to the ventilation network. The construction and installation costs for the underground airflow seals were also excluded. The costs for MV VSDs have reduced significantly with the advancement of technology [68]. In some countries, such as the European Union (EU) minimum energy performance standards have come into effect, promoting the installation of MV VSDs [68]. However, the implementation of MV VSDs in South Africa will ultimately depend on the financial feasibility of the projects [9], [69].

In the event of a MV VSD breakdown or scheduled maintenance, there is redundancy and flexibility built in the solution. Most of the considered mines have standby fans installed as part

of redundancy which could be started in the event of VSD breakdowns. Additionally, most main ventilation fans' electrical motors are started with direct on line (DOL) starters or with the use of liquid resistance starters [52]. These starters are not removed with the installation of MV VSDs, but are rather connected to bypass panels to serve as a viable backup to the VSDs. The bypass panels provide a convenient means to switch between the different starting methods [11]. MV VSD have soft starting and stopping capabilities, providing sufficient torque and cooling to be the primary choice for operation [9].

The savings and payback periods were determined when installing MV VSDs on all of the main ventilation fans of the ten mines, under various airflow conditions. The combined results of installing MV VSDs and reducing the supply airflow are shown in Table 4. An energy saving of 204 874 MWh/year is possible with a 28% reduction in airflow for the combined sites. As a result, an estimated carbon dioxide emission reduction of 202 Mt will be achieved per annum. This equates to an estimated average energy saving of 22 236 MWh/year for each mine resulting in an average estimated carbon dioxide emission reduction of 20 Mt per annum.

Similarly, the sulphur dioxide and nitrogen oxide emissions for the combined sites will be reduced with 1 690 ton/year and 842 ton/year respectively. The maximum estimated annual cost savings for constant speed applications on the 10 sites amounts to US\$13.21-million with a positive payback period of only 8 months. The average payback period for each of the airflow reduction scenarios proved to be viable, having payback periods of less than the benchmarked 24 months. The results indicate there is substantial scope to install MV VSDs on main ventilation fan motors as part of constant speed applications in South African mines.

Table 4: Assessment results of VOD potential on constant speed applications

Feasibility indicators:	Airflow reduction with VSDs (Static application)				
	Unit	10%	15%	20%	28%
E_{fan} (E_{NO_VSD})	[MWh/year]	336 598	336 598	336 598	336 598
E_{VSD}	[MWh/year]	258 156	218 835	185 530	131 724
ES_{fan}	[MWh/year]	78 442	117 763	151 068	204 874
$ES_{fan}\%$	[%]	23	35	45	61
ER_{GHG} :					
ER_{CO_2}	[kg/year]	77 657 580	116 585 370	149 557 320	202 825 260
ER_{SO_2}	[kg/year]	647 147	971 545	1 246 311	1 690 211
ER_{NO_x}	[kg/year]	322 397	484 006	620 889	842 032

C_{TE}	[US\$-million]	9.09	9.09	9.09	9.09
C_{TS}	[US\$-million]	5.06	7.59	9.74	13.21
PBP	[Months]	22	14	11	8

Exchange rate 1US\$ = 11.63 ZAR.; C_{TS} , calculated with average TOU tariff of 0.06US\$/kWh; E_{fan} (ENO_VSD) as electrical energy consumption of the fan motor; EVSD as electrical energy consumption of the fan motor with VSD installed; ES_{fan} as the electrical energy saving; $ES_{fan}\%$ as the electrical energy saving percentage; ER_{CO_2} as the carbon dioxide emission reduction; ER_{SO_2} as the sulphur dioxide emission reduction; ER_{NOx} as the nitric oxide emission reduction; C_{TE} as the total expenditure; C_{TE} as the total cost savings.

Table 4 indicate that the savings and financial feasibility of installing MV VSDs improve with the reduction in airflow and subsequent ventilation fan motor speed. Although this study only considered a maximum airflow reduction of 28%, literature indicates that the underground airflow utilisation can be increased by 50% in some mines [22], [70]. A study conducted by Kocsis on Canadian mines revealed a best practice air leakage percentage of 20% as a realistic value, which underlines the potential not only in South Africa, but also abroad [71]. Furthermore, additional savings will be realised by opening the IGVs to 100% open, eliminating the pressure drop experienced when controlling with IGVs. However, these savings are difficult to quantify and were excluded from the paper's calculations [72].

In order to assess the VOD potential in South African mines, dynamic applications should also be considered. These applications necessitate a dynamic airflow profile to satisfy the requirements during different times in mining operations underground [23], [73]. In South Africa's deep-level mines, the average typical volumetric airflow range is between 3 to 6 m³/s per kt of rock mined per month or 0.12 m³/s per ton mined per day [40]. Nonetheless, the requirements for the different mining operations varies from mine to mine and between shifts. This is a result of differences across the mines pertaining to geography, size and depth of operations, type of mining and complexity [30]. Nonetheless, the airflow requirements should be established as part of the dynamic VOD application to show the viability thereof [26].

Ideally, each mine would be considered individually, but for the purpose of this large scale evaluation it was assumed that the VOD airflow requirements shown in Figure 3, satisfies the required air cooling power, heat load rejection capabilities and dilution factors for safe and productive mining [26], [40]. For the purpose of this study, an average volumetric airflow of 5.25 m³/s per kt/month would be sufficient.

Figure 3 illustrate the average airflow requirement and average airflow delivered on a daily basis to the ten mines. The typical airflow requirement for each of the mining operations were assumed and adapted from Acuna et. al. considering an average 200 kt/month production rate [73]. The different mining operations are indicated in Figure 3, with the blasting and clearance shift requiring the highest airflow volume. This requirement stems from the hazardous

435 particulates and toxic blasting gasses that need to be diluted during this shift to enable legally compliant mining [74].

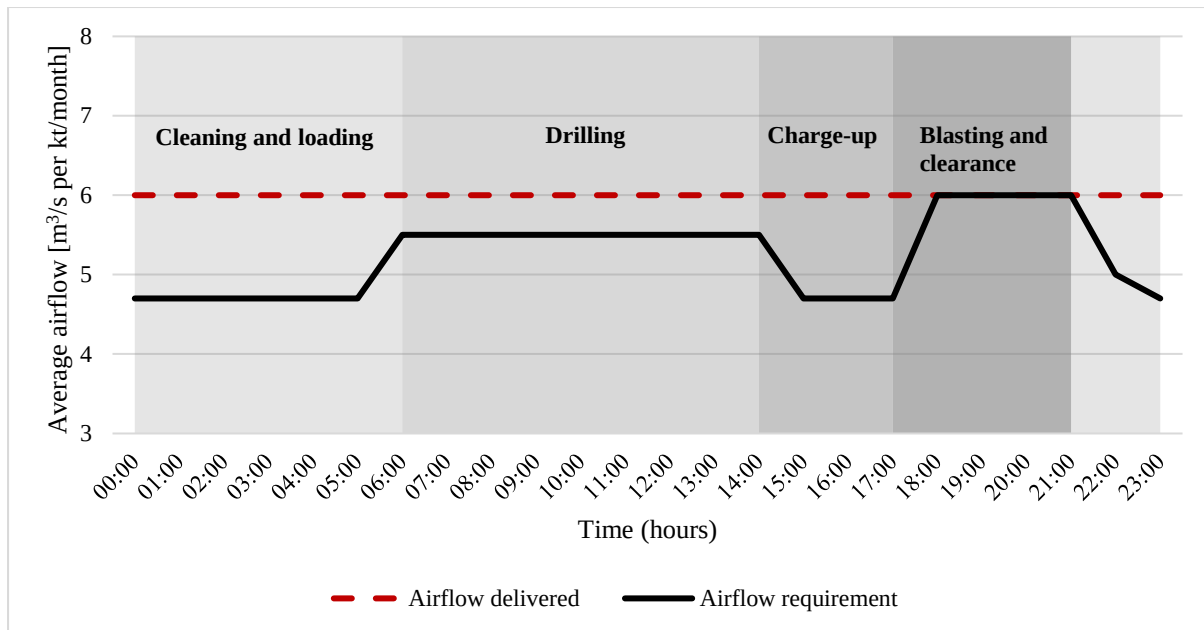


Figure 3: Average VOD airflow for dynamic applications

440 If the airflow requirement for the dynamic VOD application is followed, it will result in an additional maximum energy saving potential of 30% over and above the achievable energy saving for the constant speed applications (Table 5). Nonetheless, the two application results were analysed separately to illustrate the potential and effects of each. The estimated savings scope of the proposed profile is in line with what international manufacturers claim [75]. Manufacturers have claimed to achieve energy savings in excess of 40% for dynamic VOD applications [75]. However, this potential is affected by various factors such as fan characteristics, ventilation network system resistance and network complexity which differs from mine to mine [32], [35].

450 Table 5 indicates the potential saving estimates by applying VOD as a dynamic application to main mine ventilation fans. This excludes the energy savings achievable through the constant speed applications as stated earlier. The average airflow reduction potential is far less when compared to the constant speed applications because the airflow reduction is far less. These airflow reduction values for main mine ventilation fans are from the assumptions made in Figure 3.

Table 5: Assessment results of VOD potential on dynamic applications

Feasibility indicators:	Airflow reduction with VSDs (Dynamic applications)
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	Unit	3%	6%	9%	12%
E_{fan} (ENO_VSD)	[MWh/year]	336 598	336 598	336 598	336 598
E_{VSD}	[MWh/year]	326 500	302 938	269 278	235 619
ES_{fan}	[MWh/year]	10 098	33 660	67 320	100 979
$ES_{fan}\%$	[%]	3	10	20	30
ER_{GHG} :					
ER_{CO_2}	[kg/year]	9 996 961	33 323 202	66 646 404	99 969 606
ER_{SO_2}	[kg/year]	83 308	277 693	555 387	833 080
ER_{NO_x}	[kg/year]	41 503	138 342	276 684	415 025
C_{TE}	[US\$-million]	9.09	9.09	9.09	9.09
C_{TS}	[US\$-million]	0.65	2.17	4.34	6.51
PBP	[Months]	168	50	25	17

455 Exchange rate 1US\$ = 11.63 ZAR.; C_{TS} , calculated with average TOU tariff of 0.06US\$/kWh; E_{fan} (ENO_VSD) as electrical energy consumption of the fan motor; E_{VSD} as electrical energy consumption of the fan motor with VSD installed; ES_{fan} as the electrical energy saving; $ES_{fan}\%$ as the electrical energy saving percentage; ER_{CO_2} as the carbon dioxide emission reduction; ER_{SO_2} as the sulphur dioxide emission reduction; ER_{NO_x} as the nitric oxide emission reduction; C_{TE} as the total expenditure; C_{TE} as the total cost savings.

460 The combined results indicate that an energy saving of 100 979 MWh/year could be possible on the 10 mines with a 12% reduction in airflow, by applying the dynamic VOD application. As a result, an estimated carbon dioxide emission reduction of 99 Mt will be achieved per annum. This equates to an estimated average energy saving of 10 098 MWh/year for each mine resulting in an average estimated carbon dioxide emission reduction of 9.9 Mt per annum
 465 across all 10 sites. The maximum estimated annual savings when applying the dynamic VOD application amounts to US\$6.5-million with a payback period of 17 months.

In contrast to the constant speed applications, the dynamic VOD applications were shown to be unfeasible when airflow reductions of less than 12% were considered. The payback periods of these applications proved to be more than the benchmarked 24 months. Although these
 470 projects are unfeasible at the moment, with the reduction in MV VSD costs and advancement in technology, these projects might prove to be feasible in the near future [9]. Nonetheless, dynamic VOD applications are feasible when considering airflow reductions of more than 12% or in combination with static VOD applications. This emphasises the immense scope for dynamic VOD applications with the installation of MV VSDs in South African mine ventilation
 475 networks.

VOD POTENTIAL DISCUSSION

In theory, both the constant speed and dynamic VOD applications can be applied to a mining ventilation network. However, this must be approached and applied in a scientific and realistic manner to illustrate the true implementation capabilities, accounting for all constraints.

Therefore, for the purpose of this study, one conservative combination of these applications were considered resulting in an overall 22% airflow reduction.

Literature indicate that the best practice airflow leakage percentage is 20% for Canadian mines [71]. In contrast, the best practice airflow leakage percentage for South African mines have not yet been determined. However, it was documented that South African mines experience airflow leakages of up to 28% [28]. It is therefore reasonable to conclude that 10% of airflow can be reduced with the reparation of airflow leakages underground. Additionally, since the dynamic VOD application with an airflow reduction of 12% proved to be the most conservative financially feasible option, it was selected to form part of the combined analysis.

If the constant speed application were applied to a mine reducing the airflow with 10%, after airflow leakages were repaired with seals underground; and the dynamic VOD application were applied to the same mine reducing the airflow with an additional average 12%. An estimated energy saving of 53% could be achieved. For the combined sites, this would amount to an energy saving of 179 421 MWh/year with an estimated carbon dioxide emission reduction of 177 Mt/year. Similarly, the combined sulphur dioxide and nitrogen oxide emission reductions will amount to 833 ton/year and 737 ton/year respectively. The estimated annual savings when applying both the specified constant speed- and dynamic applications amounts to US\$11.57-million with an average payback period of 9 months. Therefore, there is considerable potential to install VSDs as part of VOD potential in South African mines.

CONCLUSION

There is a global paradigm shift towards sustainable economic development. Large energy consuming industries, such as the mining industry are contingent on the implementation of energy efficient technologies to improve upon the status quo of energy and GHG emissions. As a result, the widespread use of VSD technologies have been implemented in various applications across industries. Mine ventilation fans were identified to have significant potential for efficiency improvements with the introduction of MV VSDs as part of VOD strategies.

A large-scale energy audit, conducted on ten mine ventilation networks revealed significant potential for both the static and dynamic applications on main mine ventilation fans. The financial indicators were positive with payback periods of less than two years for both

510 applications. Furthermore, the study revealed that the most prudent results will be obtained
with the systematic implementation of both applications. The combined estimates indicate that
an annual electrical energy saving of 179 421 MWh could be achieved with the installation of
MV VSDs on the ten mine main ventilation fan motors. Subsequently, the total cost saving
estimate amounts to US\$11.57-million with a payback period of 9 months. Accordingly, the
515 GHG emissions will be reduced with 53% on average.

Therefore, it can be concluded that there is a definite VOD potential in South African mines
with the installation of VSDs on main ventilation fans. It is recommended that such initiatives
are duly considered by energy advocates to improve operational efficiency. This would
positively contribute towards global efficiency, economy and sustainability.

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DECLARATION OF INTEREST

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App. D.2: SETA GUIDELINES FOR AUTHORS



SUSTAINABLE ENERGY TECHNOLOGIES AND ASSESSMENTS

An International Journal

AUTHOR INFORMATION PACK

TABLE OF CONTENTS

• Description	p.1
• Audience	p.1
• Editorial Board	p.1
• Guide for Authors	p.3



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DESCRIPTION

The world must move toward a more sustainable energy future, and the development of technologies that facilitate this for transport, heating, and power systems is crucial. This journal encourages papers on any aspect and scale of technologies for energy generation and/or utilization that decrease the impact of that production and use, from the laboratory to commercial applications.

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