Reducing electrical costs for a mine ventilation system with the aid of simulation software

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ABSTRACT

Eskom, the South African state owned power utility, offers a demand side management (DSM) program that suggests different electrical energy tariffs during different times of the day for large consumers of electrical energy, such as the mining sector. Since ventilation systems are of the largest consumers of electrical energy on a mine, the focus of this paper is the application of simulation software to predict what potential savings can be achieved by applying configurational changes to a mine’s ventilation system, whilst maintaining a safe underground mining environment.

A combination of the VUMA3D-Network, VUMA3D-Live and VUMA3D-Transient mine planning and monitoring software packages are used to predict what the changes in a mine’s ventilation system will be before applying actual changes to the fan configurations. Different scenarios are simulated to ensure that the planned ventilation changes do not affect workers negatively or cause any health and safety issues. In this manner, the mine is assured that the ventilation performance remains within the specified limits as prescribed by the Mine Health and Safety Act of South Africa while saving on electrical energy costs.

Real-time data of specific events is obtained from a specific mine and compared to simulations done for the same events at the same mine. This is done to verify that the simulation software is accurate enough to be used as a prediction tool. Predictions are then made on an platinum mine in the Western region to determine what savings can be achieved under various ventilation scenarios.

Keywords: Demand side management, energy, energy saving, energy efficiency, Eskom, Gold mining, mining, time-of-use tariff, Ventilation on Demand, Ventilation Simulation, Vuma3D.

OPSOMMING

Eskom, die Suid-Afrikaanse staatsbeheerde kragvoorsiener, bied 'n aanvraagbestuursprogram wat beteken dat verskillende elektrisiteitstariewe gedurende verskillende tye van die dag vir groot verbruikers van elektriese energie, soos die mynbousektor omdat ventilasiestelsels van die grootste verbruikers van elektrisiteit op 'n myn is, is die hooffokus van hierdie verhandeling die toepassing van simulasiesagteware om die potensiële besparings te voorspel wanneer konfigurasieveranderinge aan die ventilasiestelsel van 'n myn aangebring word, terwyl daar terselfdetyd 'n veilige ondergrondse mynbou-omgewing gehandhaaf word.

'n Kombinasie van die VUMA3D-Netwerk, VUMA3D-Live en VUMA3D-Transient mynbeplanning en moniteringsagtewarepakkette word gebruik wat die veranderinge in 'n ventilasiestelsel se invloed sal te voorspel voordat daar enige werklike veranderinge aan die waaierkonfigurasies aangebring is. Verskillende scenarios is gesimuleer om te verseker dat die beplande ventilasieveranderinge nie 'n negatiewe invloed op werkers het of enige kwessies rakende gesondheid en veiligheid tot gevolg het nie. Dit verseker dat die ventilasieprestasie binne die gespesifiseerde perke bly soos voorgeskryf deur die Wet van Myngesondheid en – veiligheid van Suid-Afrika, terwyl daar besparings op die koste van elektriese energie bekom word.

Intydse data van spesifieke gebeure wat verkry word vanaf 'n spesifieke myn word vergelyk met simulasies vir eenderse gebeure op dieselfde myn. Dit word gedoen om te bevestig dat die simulasiesagteware akkuraat genoeg is om gebruik te word as 'n voorspellingsinstrument. Voorspellings word dan vir 'n platinummyn gemaak wat geleë is in die Westelike streek van die mynboubedryf in Suid-Afrika, om te bepaal watter finansiele kostes bespaar kan word onder verskillende ventilasiescenarios.

Sleutelwoorde - aanvraagbestuur, energie, energiebesparing, energierendement, Eskom, goudmyn, myn, tyd-van-gebruik-tarief, ventilasie op aanvraag, ventilasiesimulasie, VUMA3D.

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LIST OF ABBREVIATIONS

3D	3 Dimensional
AM	Ante Meridiem (before midday)
BAC	Bulk Air Cooler
BBE	Bluhm Burton Engineering
BP	British Petroleum
CFD	Computational Fluid Dynamics
CH_4	Methane
CO_2	Carbon Dioxide
CPP	Critical Peak Pricing
CSIR	Council for Scientific and Industrial Research
DB	Dry Bulb
DR	Demand Response
DSM	Demand Side Management
GDP	Gross Domestic Product
GHG	Green House Gases
IGV	Inlet Guide Vane
LES	Large Eddy Simulations
Mtoe	Million Tonnes of Oil Equivalent (1 Mtoe = 11630000000 kWh)
M&V	Measurement and Verification
MWh	Megawatt hours
NERSA	National Energy Regulator of South Africa
OECD	Organization for Economic Cooperation and Development
Pa	pascal
PM	Post Meridiem (after midday)
PV	Photo Voltaic
RTP	Real Time Pricing
SA	South Africa
SAPP	South African Power Pool
SQL	Structured Query Language
TOU	Time Of Use
UK	United Kingdom
USA	United States of America
VRT	Virgin Rock Temperature
VSD	Variable Speed Drive
W	Watt

LIST OF SYMBOLS

G	giga	10^9
K	kilo	10^3
M	Mega	10^6
P	power	W
Q	Flow	m^3s^{-1}

CHAPTER 1 – INTRODUCTION

1.1 Motive behind this study

Over the past decade, the South African state-owned power utility, Eskom, has increasingly been experiencing problems with the supply of electricity to South Africa. A load-shedding initiative was implemented by Eskom in January 2008 [1]. The reason for this being that South Africa encountered robust economic growth with which the supply of electricity could not keep up with. Since 2008 the supply of power has been unreliable. The load shedding situation is currently stable, but any unforeseen event might force Eskom to implement load shedding yet again. Load shedding had a significant impact on the economy, and ultimately the price of electricity. The reason for the impact on the economy includes loss of production, restart costs, equipment damage and raw material spoilage. Social impacts also have an impact on the economy with issues such as loss of leisure time, health and safety risks, and uncomfortable temperature [2]. Seeing that the mining industry in South Africa is a major consumer of electrical energy (approximately 15% of Eskom's annual output), it is an area where significant electrical energy savings can be achieved. A platinum mine's ventilation system generally accounts for approximately 7% of its electricity consumption [3].

Efficient underground ventilation forms a critical part of a sustainable platinum mining operation. Ventilation plays an important role in diluting gases, the removal of dust, as well as air temperature control [4] . A combination of smart planning and Eskom's time-of-use tariffs is the key to cheaper ventilation costs on any mine. There exists several energy saving strategies regarding mine ventilation. One strategy that is already widely implemented in platinum mines is Ventilation on Demand (VOD) [5]. It is the delivery of air to areas of the mine only when the air is needed which results in a decline in electrical energy usage by reducing fan operational hours. Another strategy makes use of inlet guide vanes (IGVs) installed on the main surface fans. The IGVs create a pre-swirl which reduces the load on the fan impeller [6]. Two other technologies that are used to reduce the load on main surface fans are Variable Speed Drives (VSDs) and fan outlet dampers. Pooe et al. [7] showed that energy savings of between 27% and 29% were achieved in three projects where main surface fan flow was reduced by 10% by means of IGVs. This was done in combination with one of Eskom's demand side management (DSM) techniques. It entails the reduction in the electrical energy load during the peak energy demand period which stretches from 18:00 to 20:00 during weekdays [8]**.**

It would be ideal to determine what mining conditions would be before physical changes are made. These changes could have significant consequences on the mining environment and the people that must work in it. Simulation software endows these kind of predictions [1]**.**

Simulation software exists that allows ventilation engineers to create 3D models of a mine [7]. The mine parameters are used as inputs and calculations are performed by the software to determine what underground mining conditions will be. Live versions of this software make use of underground environmental sensors to simulate the mine in real-time. This allows for minimum sensors to be installed at key locations across the mine. The main purpose of the software is to provide ventilation engineers with adequate information which they utilise to manage the underground ventilation system. This project makes use of the VUMA3D-Network, VUMA3D-Live and VUMA3D-Transient simulation software packages to determine if electrical energy savings can be predicted before any physical configuration changes are applied to the mine's ventilation system [9].

Thus, the motive behind this study is to make use of 3D-simulation software to create an accurate representation of a platinum mine's underground environment, focussing on the ventilation system. The accuracy of the simulations will be validated by actual underground data obtained from measurement instrumentation located on Mine A. Certain scenarios will be created to simulate what effect the changes might have on the underground temperatures. This will again be confirmed by the underground measurement instrumentation. This entire process will then be applied to a completely different mine, Mine B, with different parameters. The simulation will be used to determine underground temperatures after certain configuration changes to the ventilation system are applied. This will include scenarios where fans are slowed down or switched off during Eskom's peak hours. The main goal will be to maintain a safe underground working environment whilst saving on the operational costs of the mine's ventilation system.

1.2 Problem Statement

Ventilation systems are extremely hard to manage and control efficiently due to the continuous expansion of mines, as well as the difficulty in accurately measuring velocity (and thus flow). Live simulation monitoring software enables ventilation engineers to view a live model of a mine which helps them to identify problem areas within the ventilation system and also enables the engineers to predict the future behaviour of a ventilation system. Significant savings can be achieved in a mine's ventilation system when adequate planning is used in conjunction with Eskom's time-of-use pricing initiative. This initiative can be used together with simulation software to effectively determine where and when fan speeds can be reduced, switched off or even relocated. Future planning can be done without negatively affecting an underground mining environment. Assessments for this research have relied mostly on case studies conducted on Mine A to determine the efficiency of the simulation software. The software was then applied to Mine B to determine the possibility and quantity of savings that could be achieved by implementing the simulation and time-of-use technique.

1.3 Analysis Techniques

The research represented in this study is based on simulating the behaviour of a ventilation system in an underground platinum mine. The focus will be based on the relationship between the time-of-use tariffs and how and when a ventilation system is in operation.

1.4 Ventilation Simulation Software

A combination of various simulation software packages, which include VUMA3D-Network, VUMA3D-Transient and VUMA3D-Live, have been used to determine if Eskom's time-of-use tariff program could be used effectively to predict potential savings whilst maintaining a safe underground working environment. The VUMA3D software uses several parameters to determine the results of the simulation. These parameters include air density, temperature, quantity, pressure and obstructions within the mine tunnels.

1.5 Objectives

The objective of this study is to analyse the ventilation system of a platinum mine (Mine A) to determine the validity of the simulation software used. Three different software packages are used in aid of achieving this objective: VUMA3D-Network is used to build the mine model, VUMA3D-Live is used to monitor the mine during certain scenarios to obtain data, and VUMA3D-Transient is used to predict what the mining conditions will be at later instances.

The software is then used to determine the effects of configuration changes on another platinum mine's (Mine B) ventilation system to predict the potential electrical energy savings by means of Eskom's time-of-use tariff program. The minimum ventilation requirements as set out by the Mine Health and Safety Act of South Africa (MHSA) were considered to ensure that the predictions that are used to determine the energy savings are realistic.

Different ventilation parameters such as velocity, temperature and humidity have been determined and the ideal combination and speed of auxiliary fans were selected by using the simulation approach. The simulations from the two experimental mines have been compared to produce an efficient ventilation layout for the experimental mine known as Mine B.

CHAPTER 2 - ENERGY, MINING VENTILATION AND SIMULATIONS

2.1 Introduction

This chapter gives a brief overview of energy usage across the globe, Africa and South Africa and includes discussions based on underground mining ventilation and cooling systems as these are major consumers of electrical energy on a mine. The reasons why mines should be ventilated and where the underground heat source from will be discussed. It is important to understand that numerous energy and cost saving opportunities exist for fan and cooling systems**.** Different strategies to save energy, including Eskom's tariff initiatives are discussed.

The factors that have an influence on a fan ventilation system includes fan configuration, fan efficiencies, multiple fan system operation, inlet and outlet conditions and the application of fans to the requirements of a system [10]. This understanding is critical to enable the engineer to develop a new ventilation control strategy or to improve on existing strategies with the help of motor control, inlet guide vanes and 3D-simulation software. The main area of focus will be the reduction of electrical energy consumption whilst maintaining a safe underground mining environment. Hence, 3D-simulation software and how it is currently being used in aid of controlling and monitoring existing mining environments will also be investigated. A background on energy in South Africa and in the mining environment is discussed to give a clearer understanding as to why saving energy on mines can have a significant impact on a mine's operational costs as well as the South African electrical grid.

2.2 Energy in a Global Context

Energy is the entity that drives our planet. It comes in many different forms and is used in many different applications. The key drivers behind the growing demand for energy are population and income. The world's population is projected to increase by approximately 1.5 billion people to reach nearly 8.8 billion people by 2035. BP [11] expects the global Gross Domestic Product (GDP) to more than double over the same period. Africa accounts for almost half of the increase in the world's population, such that by 2035 it is projected to have 30% more people than China and 20% more than India. In contrast to this, Africa accounts for less than 10% of the increase in both global GDP and energy consumption over the period. It is also predicted that global energy usage will increase by 34% between 2014 and 2035 because of the world economic growth. A graph comparing population against productivity is depicted in Figure 2-1 below:

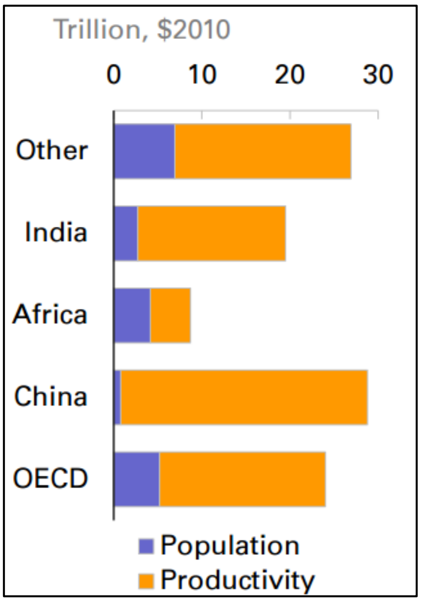


Figure 2-1: Contribution to GDP growth 2014-2035 [11].

In the regions as divided in Figure 2-1, where OECD (Organization for Economic Cooperation and Development) represents developed countries, Africa has the 3rd largest population, but is the least productive. This is in contrast with China which has the smallest population and the highest productivity. The difference between the energy usages of developing and developed countries can be linked to its productivity: higher productivity equals higher energy usage. Seeing that Africa has such an undesirable productivity rating in comparison with the rest of the world, energy demand is increasing faster than productivity due to the rapid increase in the population. This is causing energy supply, especially electricity, to become scarcer. The World Bank states that 32 of Africa's 48 nations are in energy crises [12]. This indirectly causes a lot of strain on the South African power grid seeing that it generates 21% of the continent's power as shown in Figure 2-2.

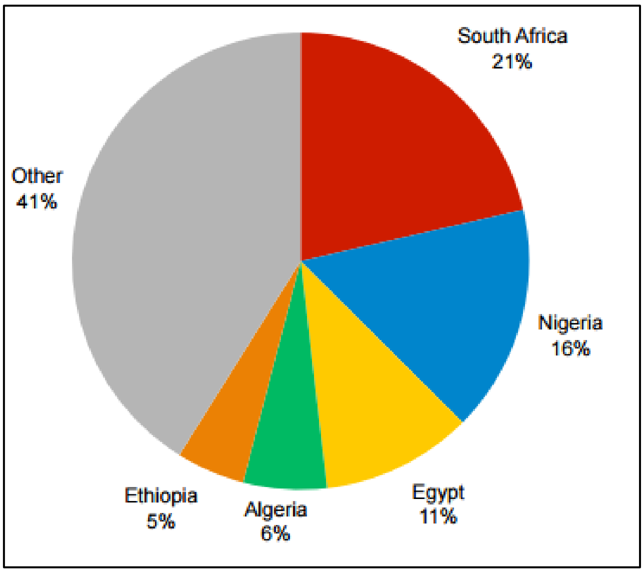
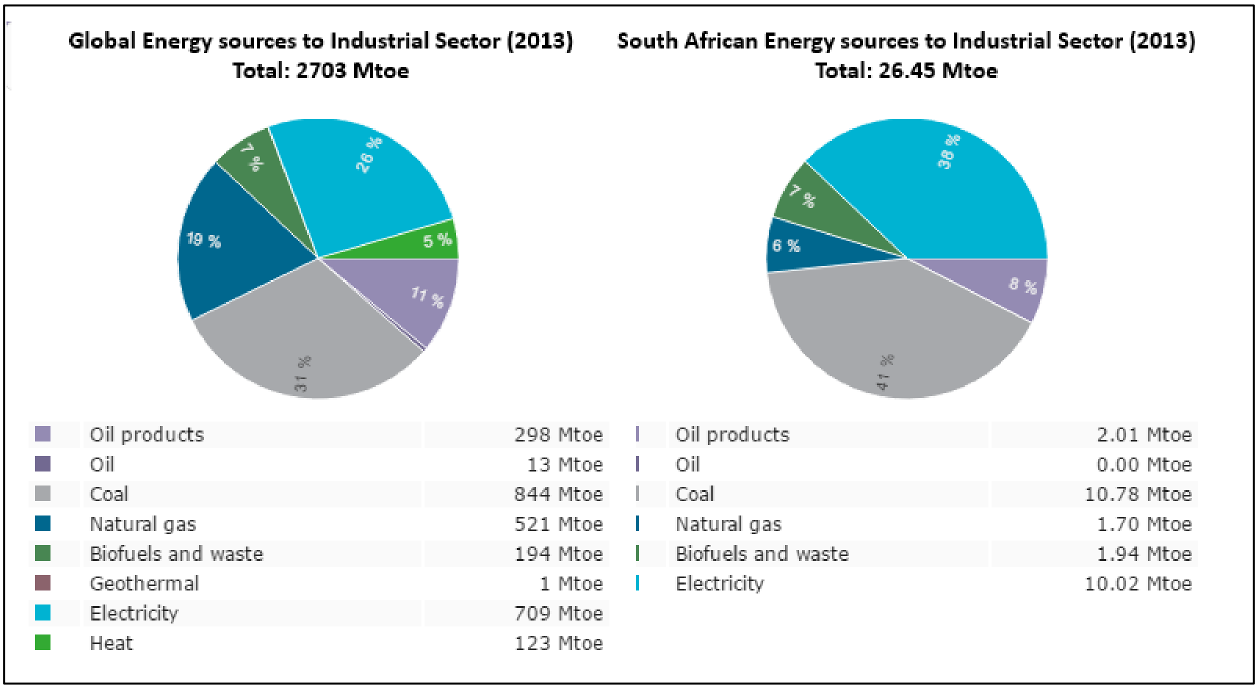


Figure 2-2: Energy Usage in Africa [13].

The South African industrial sector, which includes the mining sector, utilises more electrical energy when compared to the world average industrial usage. Approximately 38% of energy used in the South African industrial sector is electrical energy, whereas in a global context electrical energy only accounts for 26% of the total energy used in the same sector. This is illustrated by Figure 2-3. The unit of measurement used in this figure is million tonnes of oil equivalent (Mtoe). One toe equates to 11.63 MWh.



▨	Oil products	298 Mtoe
▨	Oil	13 Mtoe
▨	Coal	844 Mtoe
▨	Natural gas	521 Mtoe
▨	Biofuels and waste	194 Mtoe
▨	Geothermal	1 Mtoe
▨	Electricity	709 Mtoe
▨	Heat	123 Mtoe

I	Oil products	2.01 Mtoe
I	Oil	0.00 Mtoe
I	Coal	10.78 Mtoe
I	Natural gas	1.70 Mtoe
I	Biofuels and waste	1.94 Mtoe
I	Electricity	10.02 Mtoe

Figure 2-3: Energy Sources to Global & SA Industrial Sector [14].

Figure 2-3 shows that 38% of the energy used in the South African industrial sector is made up of electrical energy, whereas in a global context only 26% of the energy consists of electrical energy. This high electrical energy usage in the industrial sector provides several energy saving opportunities in the South African power grid.

Another major challenge is to supply clean energy in aid of the conservation of our planet. The trend at which South Africa is currently generating electrical energy is damaging the environment and is a major cause of climate change. The famous law of the conservation of energy by Gottfried Wilhelm Leibniz [15] which states that "energy cannot be created or destroyed, but only transformed from one form to another" is applicable in the generation of electrical energy. When energy obtained by, for instance, the burning of coal or gas, by-products such as carbon dioxide (CO_2) are produced and have a significant impact on the ecosystem. This means that when a mine reduces its energy usage, it indirectly helps to conserve our planet due to less electricity that has to be generated. Figure 2-4 shows the average greenhouse gas (GHG) emissions measured in tonnes CO_2 emitted per GWh of electrical energy generated by different energy sources which include coal, oil, lignite, natural gas, solar PV, biomass, nuclear, hydroelectric and wind.

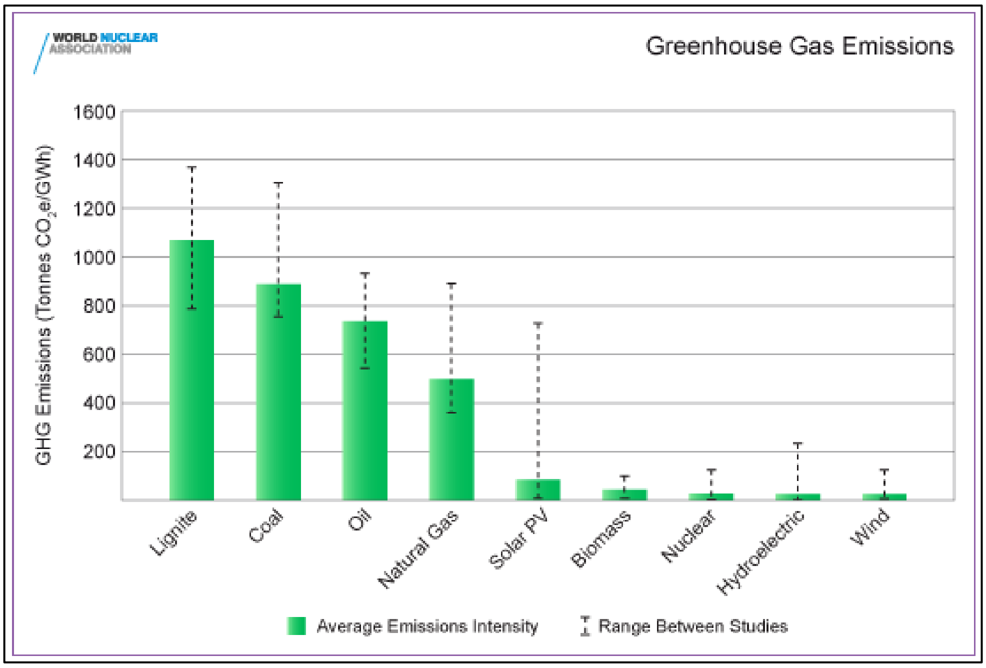


Figure 2-4: Greenhouse gas emissions from different energy sources [16].

South Africa's primary energy source is coal, which has one of the highest GHG emissions of all energy sources. As Africa's population and GDP are on the increase and with its intense usage of coal to generate electrical energy, it is important to take a good look at the major consumers. It is possible, especially in the mining sector, to apply small changes to a system to achieve significant energy savings.

2.3 History of Energy in South Africa

In the early years of South African electrical energy, power was generated by several private enterprises. After the establishment of Eskom in 1923, these enterprises were systematically incorporated into several 'undertakings', each with their own generating facilities. These undertakings or small power stations were powered by coal [17].

During the late 1950’s and early 1960’s these small power stations were interconnected to form a national grid [17]. In the early 1990’s when the new government came to power, in addition to supplying local municipalities and cities, Eskom then also started to supply the rural areas with electrical energy as well.

Due to an increase in electrical energy demand Eskom started to expand its operations. Larger power stations were being constructed in areas where coal was easily accessible. It was later realised that the growth in demand was slower than anticipated, which caused problems for the financing of expansion projects. A two-tier control system was implemented which consisted of a management board and a 15-member electrical energy council. The new council was instructed to slow down the build programme. Due to the excessive energy capacity that was available and the power supply to Mozambique that had been abandoned, the Southern African Power Pool (SAPP) was established to make better use of the available energy.

One of the first issues that had to be addressed under the new government was the lack of electrical energy supply to black townships. In 1993 studies by the National Electrification Forum revealed that although many municipalities cross-subsidised services using electrical energy revenues, they failed to properly collect revenues and maintain infrastructure. The conclusion was that there were too many distributors and many were unable to afford the electrical energy supplied to them [18]. Hence, NERSA (National Electricity Regulator of South Africa) was established.

Eskom and the municipalities continued with the electrification process. In 1991 there were about 80 000 new connections, whereas at the peak of the electrification programme there were about 450 000 new connections a year. It is estimated that about 10 million homes are connected to the supply grid and only 3 million remain to be connected [19].

The increase in demand, the lack of maintenance and the poor management of generation and distribution have all been contributing factors to the energy crisis that South Africa recently faced [19]. Coal is currently being used to generate 77% of the country's energy where most of this energy is in the form of electrical energy [18]. In addition to coal as an energy resource, South Africa also makes use of biofuel, hydropower, solar power, wind power, hybrid systems, tradable renewables and nuclear power [20].

Figure 2-5 below shows the generation and consumption profile of South Africa over the last few years. A general increase in both the production and consumption can clearly be seen. Even though the average production is higher in 2014, the poor infrastructure caused major tension on the power grid and load shedding had to be implemented at certain stages. It is expected that electrical energy demand will double over the next 20 years [20].

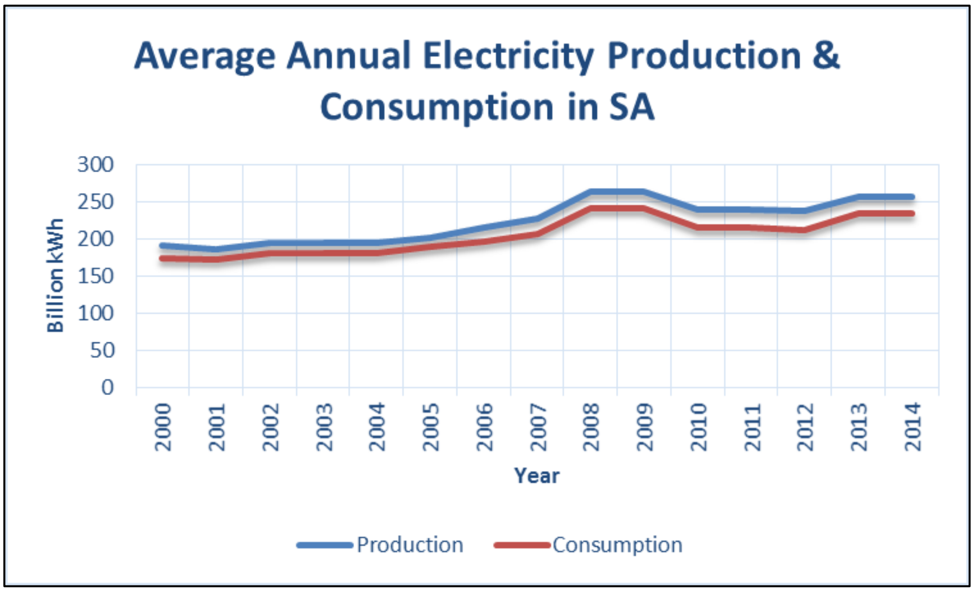


Figure 2-5: Electrical energy Production & Consumption in SA [21].

Major increases in electrical energy tariffs are also of great concern, especially to large consumers such as mines. Mines no longer have cheap electrical energy to use as they please, but are instead now forced to cut down on usage to achieve energy savings. Eskom was forced to increase tariffs more than was expected due to the power crisis that started in 2008 and to make up for losses during load shedding. Figure 2-6 indicates the increase in electrical energy prices in South Africa over the last 11 years. It is expected that prices will continue to increase even more.

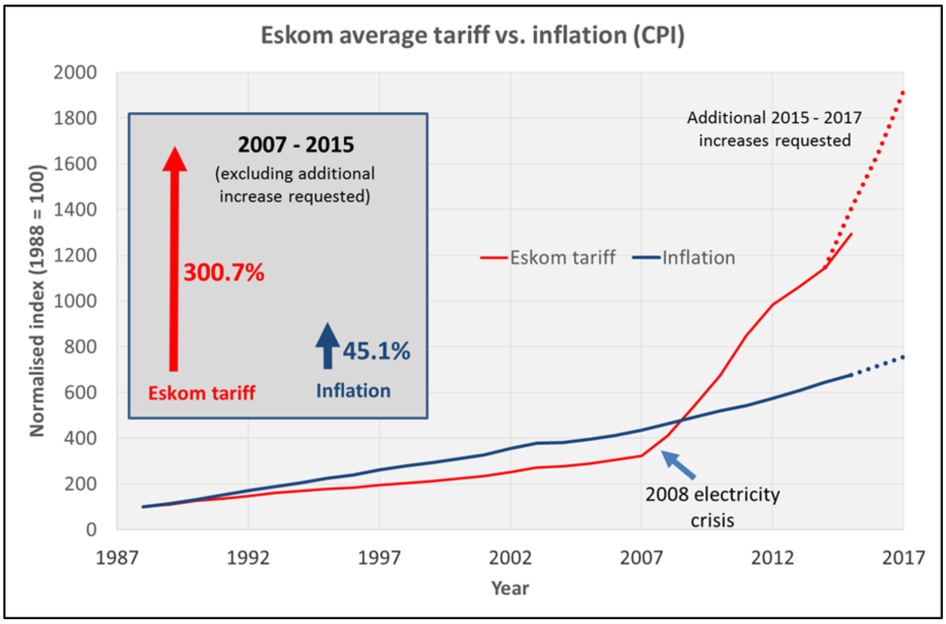


Figure 2-6: The annual tariff increase in South Africa [22].

This energy crisis opened a whole new section of energy saving opportunities in the mining industry, seeing that it is one of the largest energy consumers in the country. There are different ways of saving on energy usage, be it from the demand side or from the generation side.

2.4 Energy in the South African Mining Industry

The South African mining industry utilises about 15% of Eskom's annual electrical energy output, where 33% thereof is used by platinum mines. Surface and underground fans then consume about 7% and industrial cooling about 5% of the total electrical energy consumed on a platinum mine [3]. These statistics are depicted in Figure 2-7 below:

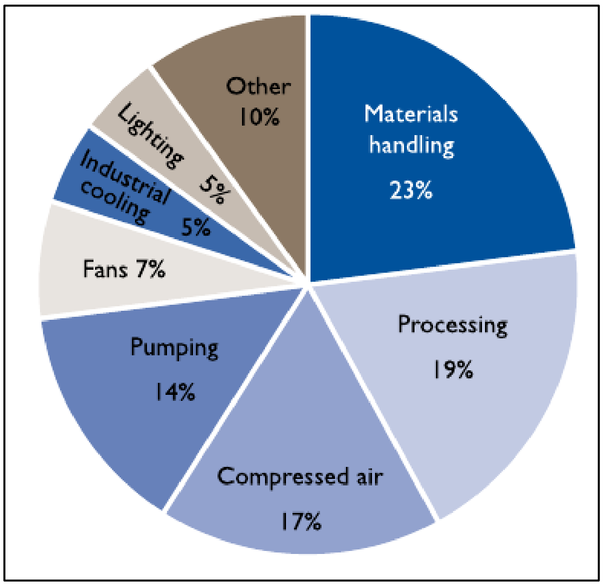


Figure 2-7: Areas of Electricity Consumption on a mine [3].

The areas of consumption as shown in Figure 2-7 are essential elements in the mining process. They are all needed for uninterrupted and sustainable production. Ventilation and cooling are needed in a platinum mine as virgin rock temperatures (VRT) can reach up to 70°C [23]. Underground workers can function optimally up until the temperature reaches 28°C wet-bulb. When temperatures increase passed this point the mine workers' concentration and ability to make accurate spatial perceptions decrease. Per a CSIR scientist, Schu Schutte, it is possible to continue working up until 32.5°C wet-bulb, though it is not desirable. Routine work should not be permitted when temperatures pass this point [24]. In 1976 it was established that the underground working environment was pleasant at 28°C and unbearable at 33°C [25].

If the fans and air-coolers (bulk air coolers and refrigeration) are properly managed and integrated into a fully functional and efficient system, significant savings can be achieved. In addition to electrical energy, water can also be saved. It is stated that for every kWh of electrical energy generated by Eskom, about 1.29 litres of water are consumed [26]. Thus, the mining industry indirectly accounts for 52 gigalitres of water being used annually.

As much as the ventilation and cooling systems are needed for a mine's survival, it is equally important for this system to be efficient and cost effective. With the rise in overall energy consumption and South Africa’s power utility struggling to keep up with energy demand, electrical energy tariffs are increasing. The increasing tariffs amplifies the importance for a mine’s ventilation and cooling systems to operate at higher efficiencies for the mine to be profitable.

Figure 2-8 below shows a simple diagram of where fans and coolers are commonly situated and how they help keep the mine temperatures within the specified limits.

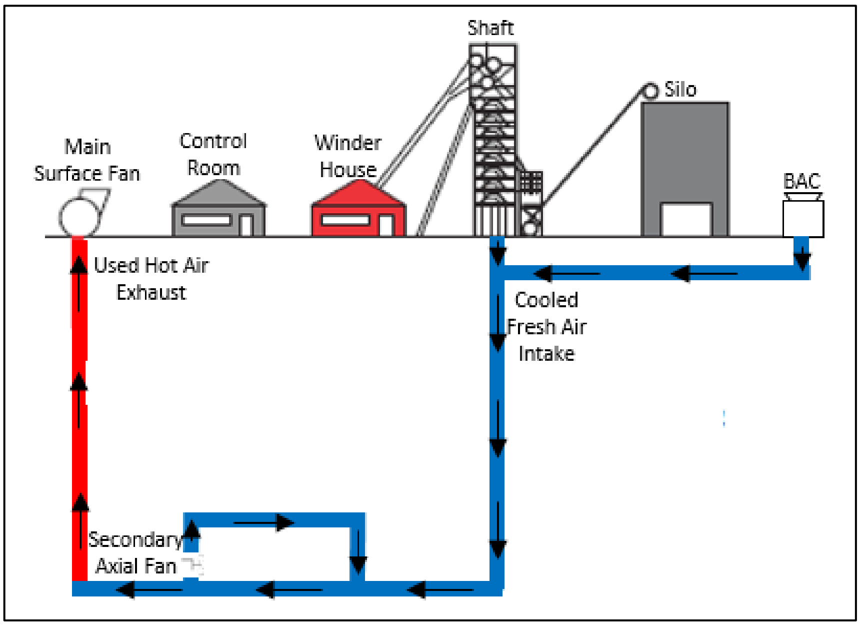


Figure 2-8: Basic Mine Ventilation and Cooling

Chilled water is used to cool down and dehumidify ambient air in the BAC located on surface. The cold dehumidified air, which is usually about 7°C wet-bulb, is forced into the intake ventilation shaft by an arrangement of ventilation fans [27]. The primary surface ventilation fans are responsible for the extraction of hot air, blasting fumes and dust particles. It is also responsible for the direction in which the air travels through the mine. Secondary ventilation fans are used to provide more air in areas of the mine where it is needed. The secondary ventilation fans can also be used to force a change in direction if the need arises. In some cases, in deeper mines additional underground coolers (BACs, cooling cars and sprays) may be added in areas where primary cooling alone may not be sufficient. This entire process is shown as a basic illustration in Figure 2-8. To fully understand the meaning of mine ventilation it is important to know where the heat in a mine originates from.

2.5 Sources of Heat in a Platinum Mine

Heat and a lack of fresh oxygen supply are the main reasons why a mine needs ventilation and cooling. The sources of heat can spring from various locations within the mine. Sources of heat in an underground mine can be classified as natural (heat from rock face) or artificial (machine heat or human body heat) [28].

2.5.1 Natural Heat Sources

There are two natural sources of heat in a mine. One involves the transfer of heat from the surrounding strata to the air inside the mine, either by convection by fissure water or by conduction through the strata. The second natural source results from the oxidation of the strata.

2.5.2 Artificial Heat Sources

There are various sources of artificial heat in an underground mine. They include machinery such as fans, hoists, lights, locomotives, motors, pumps, winches, diesel machinery, rock drills and explosives. It is estimated that up to 95% of the energy created in rock blasting will find its way into the ventilation system as heat [29]. These artificial sources are usually not continuous. This makes it very hard to calculate heat loads. Even rock temperatures vary with time and are sometimes wetted down during mine operations.

Although mechanised mines have less underground workers than conventional mines, some workers are still present. High temperatures in a mine can increase the risk of a miner suffering from heatstroke and decrease the worker's coordination, dexterity, alertness, reaction time and ultimately productivity [28].

To be able to remove this heat from a mine, sophisticated ventilation strategies are applied using different fan configurations as well as different types of fans. The different types of fans relevant to this project will be discussed in the following section.

2.6 Mine Ventilation Fans

In mine ventilation, various types of fans can be used depending on the application. The main fan types that are used include axial flow fans, centrifugal fans and centrifugal blower fans [30], a breakdown of these fans is depicted in Figure 2-9 below.

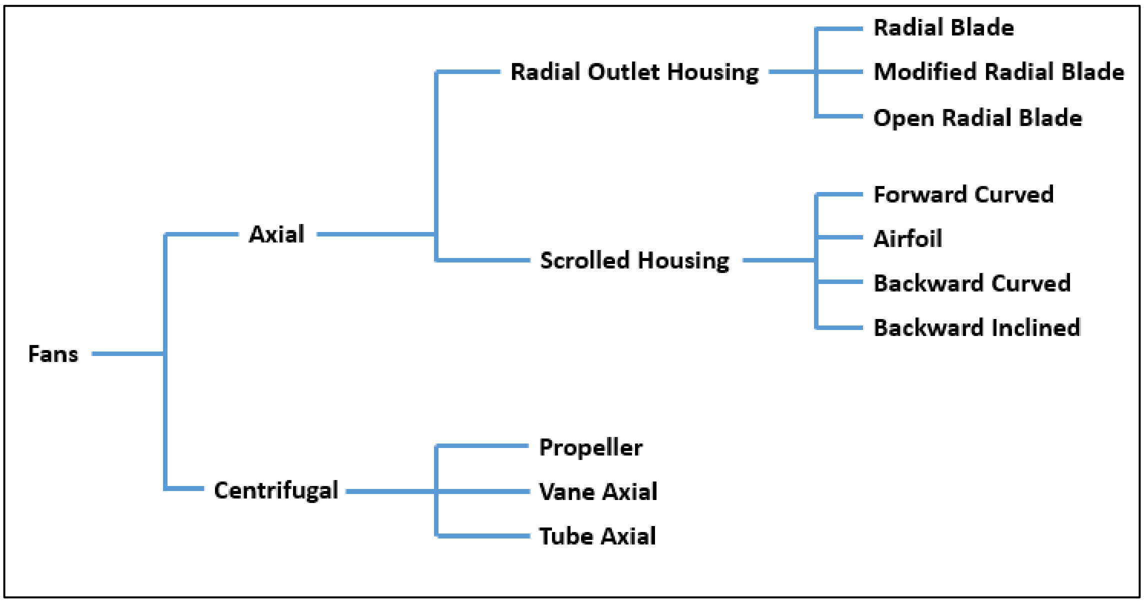


Figure 2-9: Breakdown of Fan Types [10].

Centrifugal blower fans are used in high pressure, low volume applications and are not adjustable except when it is fitted with a variable speed drive. Figure 2-10 below shows a typical centrifugal blower fan.

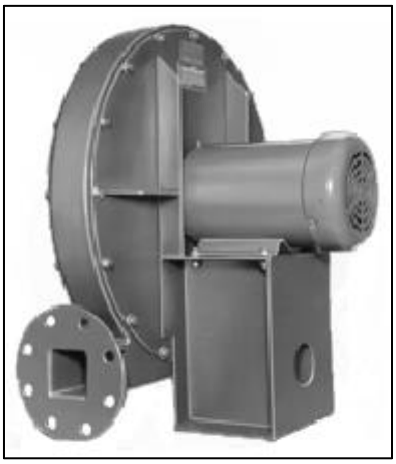


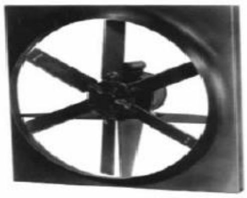
Figure 2-10: Centrifugal Blower Fan [30].

Centrifugal fans are used in high pressure applications (typically 2-8kPa). They are robust and have an efficient impeller design. The blades are curved backwards for a non-overloading fan curve. In the mining environment, this fan type is most commonly used on surface for being the main ventilation fan. Adjustable IGVs allow the phase-in of fan pressure over the life of a project. This is based on the theory that swirling the air in the same direction as the fan rotation reduces the pressure characteristics of the fan while maintaining the fan efficiency. Figure 2-11 shows a centrifugal fan impeller, the fan configuration as used by the mining community and on the right, the IGVs.

Figure 2-11: Centrifugal Fan Impeller (left), Fan Configuration (middle) and IGVs (right) [30].

In applications, such as main surface fans, centrifugal fans are mainly used. This is not necessary in cases where the mine is not that deep yet, this is not necessary. Axial fans are sufficient and are more cost effective than larger centrifugal fans. Axial flow fans are ideal for underground ventilation. They operate by moving an air stream along the axis of the fan. The three main types of axial flow fans are propellers, tube axial and vane axial fans and are summarised in Table 2-1 below.

Table 2-1: Axial Fan Type Breakdown

Fan Type	Image	Advantages	Disadvantages
Propeller		• High Volume, Low Pressure, • Not much ducting due to low pressure, • Inexpensive due to simple construction, • Achieve Maximum Efficiency, • Bidirectional Flow	• Relatively low energy efficiency, • Comparatively noisy

Tube Axial		• High Volume, Low Pressure, • Higher pressure and better efficiency than propeller fans, • Bidirectional, • Quick acceleration to rated speed, • Space efficient, • Sufficient pressure to overcome duct losses	• Relatively expensive, • Moderate noise, • Low efficiency (65%)
Vane Axial		• Medium to high Pressure, • Quick acceleration to rated speed, • Bidirectional, • Suited for direct connection to motor shafts.	• Comparatively expensive

Applications include booster fans, recirculation fans, BAC fans and in-line duct fans. Figure 2-12 shows how these fans are typically arranged when installed on surface.

Figure 2-12: Axial Surface Fans [30].

Axial fans are used in applications where a high volume of air is needed at a low pressure (<2kPa). A vane axial fan can be either driven by a direct drive or a belt drive [31]. Most axial fans used in the configuration and application, as on the platinum mines, are directly driven. Multistage units (co-rotating/contra-rotating) can be used in applications where higher pressure is needed. The difference between the single-stage and two-stage configuration is illustrated in Figure 2-13.

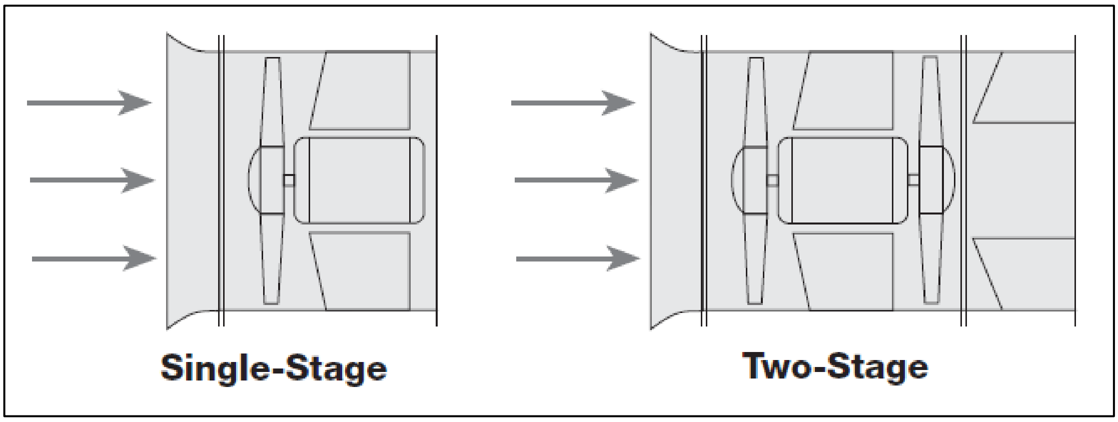


Figure 2-13: Single-stage vs. Two-stage vane axial fan [31].

High pressure axial flow fans use a large hub with relatively short blades as shown in Figure 2-14.

Figure 2-14: Higher Pressure Axial Fan Blades [30].

Adjustable pitch blades allow the phase-in of the pressure on the fan over the course of its life, an example of the pitch blades is shown in Figure 2-15.

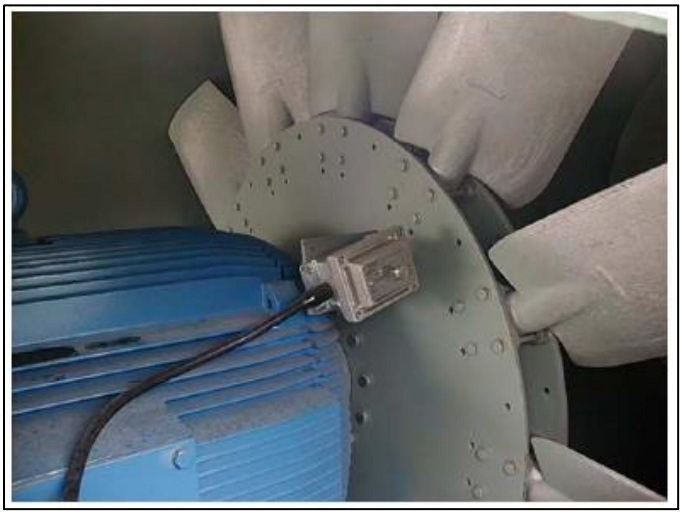


Figure 2-15: Axial Fan Pitch Blades [30].

The blades operate at high tip speeds; therefore, it is important to keep material strength in mind during material selection in the manufacturing of blades. X-ray tests are done on high stress impeller welds and on cast aluminium blades. The impeller blade tip clearance is usually smaller than 0.25% of the impeller diameter [32]. For their purpose on platinum mines the impeller is fitted directly onto the extension of the motor shaft. Axial fans are generally much noisier than centrifugal fans due to their operation at faster speeds. Silencers can be fitted in the inlet and the discharge to minimise noise levels. Further noise reduction can be achieved by fitting pods inside the silencers, but a side effect is some pressure loss [30]. Table 2-2 shows the areas of efficiency for the different axial fans.

Table 2-2: Axial Fan Efficiency Ranges [32].

Fan Type	Efficiency Range
Propeller	40-50%
Tube Axial	67-72%
Vane Axial	78-85%

Axial fan control is performed by altering speed (by means of VSDs), adjusting impeller blade pitch angle, and adjusting variable inlet vanes. Performance is also influenced by inlet cones, guide vanes, tail fairings and diffusers. The number of blades used can be adjusted depending on the application. Figure 2-16 shows different blade configurations, depending on what the need of the fan may be.

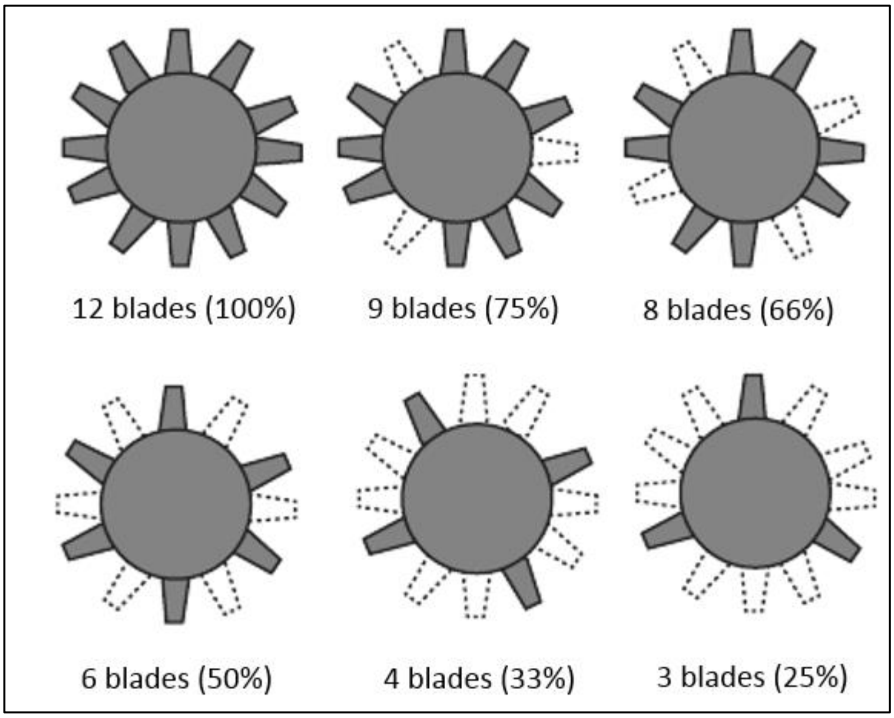


Figure 2-16: Axial Fan Blade Configuration [32].

The fans installed at the mine where the VUMA3D-Live system is implemented are 75 kW vane axial fans. These specific fans have an efficiency of 85% per its specification sheets [33].

Air is a compressible gas; however, it is considered incompressible and of constant density for the sake of fan calculations. It must be considered where high or low temperature air streams are calculated [10].

2.7 Parallel Fan Operation and Fan Curves

Fans are mounted in series or parallel when a single fan within a system cannot deliver the required airflow to cool down the mine to the desired level [31], [34], [35]. This is usually done when high airflow is needed at lower pressure, and it has the advantage of not increasing the package size or fan diameter. Installing multiple smaller fans instead of a single large fan can also be more cost effective, especially when the cost of operation is critical [31].

In theory (when there is no back pressure to restrict airflow), two fans of equal size can provide double the airflow when they are operating in free air. Unfortunately, physical obstructions do not only provide a reverse pressure, which the fan must overcome, but can also mask components from the cooling air stream [35].

Certain losses also should be taken into consideration when fitting a fan which includes entry losses, exit losses, elbows, transitions, junctions, obstructions and fan connections. There are four ways of installing fans: types A, B, C and D [30].

- Type A - Free inlet, free outlet.
- Type B - Free inlet, ducted outlet.
- Type C - Ducted inlet, free outlet.
- Type D - Ducted inlet, ducted outlet.

The graph in Figure 2-17 shows a typical resistance curve of a mine.

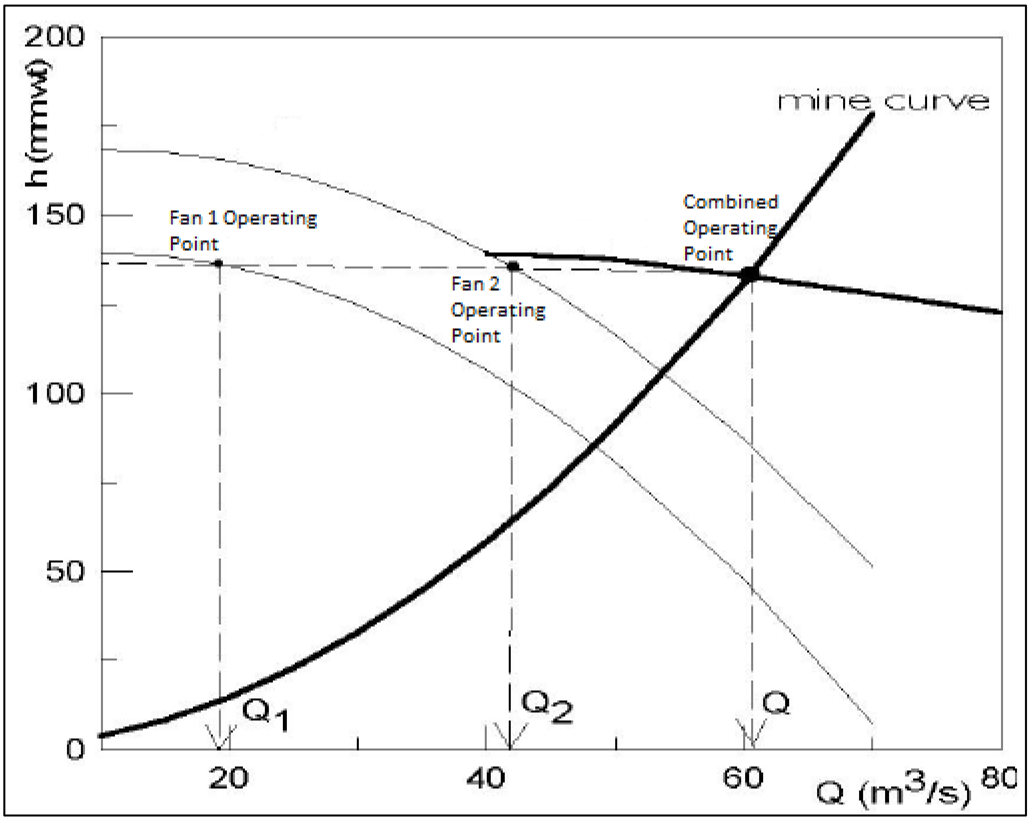


Figure 2-17: Typical Fan & System Resistance Curve [31].

Figure 2-17 indicates the curves for two fans operating in parallel, and the combined curve for these two fans. The operating point is the point where the combined fan curve intersects the mine resistance curve.

The fans installed on mine B are determined to be of type C installations.

2.8 The need for VOD in Underground Mines

Underground mine ventilation is one of the most important aspects of sustainable production in any mining operation. It is used to remove dust particles, various mine gases and minimise or eliminate radiation. It also provides underground mine workers with sufficient oxygen. In some cases, the ventilation can also control underground fires [8], [36]. In mechanised underground mines conditions are even worse due to emissions of machines used for mining [36]. The ventilation is dependent on factors such as the fan types, fan sizes, fan configuration and the density of the air inside and outside of the mine [37].

It is important to keep in mind that as the mining progress advances, at certain levels, the ventilation becomes unproductive due to short-circuit of airflow or leakages that may lead to inefficiency [37]. The conventional use of smoke tubes and anemometers are sometimes inaccurate and not suitable under certain conditions. In addition to this, leakages that occur may be difficult to quantify. Characteristics of an efficient ventilation system include a steady underground air flow, low resistance against ventilation, reasonable distribution, reliable facilities and a plan to address a disaster [38].

Mines tend to over-compensate for air in underground mines to prevent casualties. The ventilation is also important to remove hazardous gases from the mine [38]. The limiting flammable methane concentration level in the air in South African mines is 1.4% CH_4, while this level is even lower in other countries such as 1.25% in Australia, India and the United Kingdom (UK), and 1% in China, Germany and the United States of America (USA [39]. It is important that the air in a mine is sufficient to remove these gases.

The idea of ventilation on demand is to supply sufficient fresh air to mining areas that need it instead of ventilating a whole mine at full capacity. Applying a good VOD system requires a complex control system and sophisticated monitoring procedures and sensors [40]. Various models and simulation software packages have been researched and developed over the past couple of years in aid of developing and improving ventilation on demand strategies.

2.9 Ventilation Optimisation Methods

Over the years' various methods have been developed to improve the underground ventilation systems. A few of these methods are discussed below.

2.9.1 Gas Tracing

The gas tracing method is a method where gas is released into the ventilation network. The data that is obtained by the analysis of the dispersion characteristics is then used in a simulation to evaluate the diffusion coefficient that reflects the general dispersion characteristic of an entire mine. This data is then compared with studies done on other mines. This method is effective in finding leakages in a mine ventilation network [39]. By fixing these leakages, the ventilation network can be improved.

2.9.2 Ventilation Fan Improvements

Various methods are used to improve existing ventilation fans.

The Hermit Crab technique is a registered fan technology trademark of Fläkt Woods. This method is aimed at replacing existing fan impellers with impellers that are more suited for the ventilation needs of the specific mine [41]. The table below shows the performance of the Hermit Crab technique in a non-mining industry.

Table 2-3: Hermitt Crab Technique Data [41].

Area	**Previous Efficiency, %**	**Previous Power, kW**	**New Efficiency, %**	**Power After, kW**	**Return on Investment**
Cement, Philippines	70.7	1050	81	915	1 Year
Cement, Spain	63	688	74	513	< 1 Year
Steel, Korea	76.3	5780	88.6	5400	< 1 Year

It can be seen from Table 2-3 in the three cases shown that efficiencies improved, which resulted in a decrease in power usage.

The replacement of old conventional steel impellers with composite material impellers are also under discussion. This will reduce manufacturing and operating cost [41]. A few major problems are still preventing this from happening, one of them being debris damaging the impeller.

2.9.3 Variable Speed Drives (VSDs)

Variable Speed Drives are widely known in the industry. As the name suggest, it is used to control the speed at which motors operate. This helps reduce operating costs of motors and improves system efficiencies. One VSD manufacturer, ABB, estimates that its drives (in operation worldwide) saves approximately 115 million megawatt hours of electrical energy annually. This is equivalent to about 14 nuclear reactors [42]. The significant effect that an ABB VSD has on a fan’s energy usage compared to other control techniques can be seen in Figure 2-18.

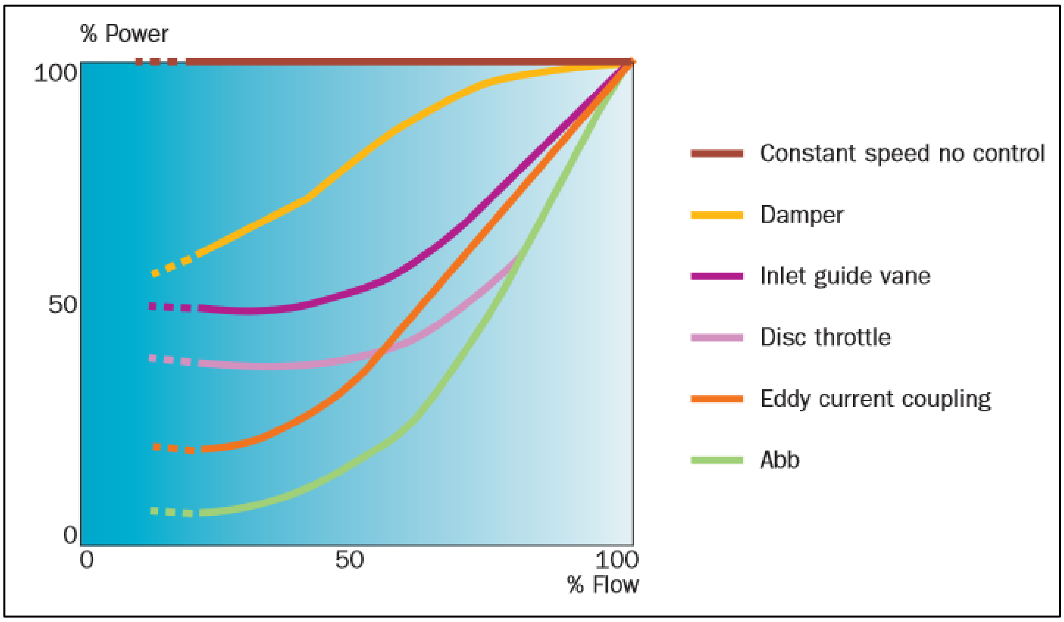


Figure 2-18: Power vs. Flow of Different Control Methods [42].

In a study done by G.E. du Plessis [27] on 20 different large mine cooling systems in South Africa it is stated that a total annual electrical energy saving of 144,721 MWh or 32.2% can be obtained by using VSDs on mine fans and pumps. This resulted in a possible cost saving of US$6 938 148 (approximately R 89 314 122) and CO_2 emissions reduction of 132 megatons.

These ventilation optimisation methods can be used in conjunction with energy saving strategies to create the most efficient mining environment possible. Next, the energy saving strategies that are applicable to mines will be discussed.

2.10 Energy Saving Strategies

Demand Side Management (DSM) is a strategy that users can implement to save on their electrical energy bill and it also minimises negative consequences of a power shortage on the South African economy [43]. DSM was developed in the USA in the early 1970s when oil prices skyrocketed, consequently causing energy prices to increase [44], [45]. In 1977 the USA implemented an amendment of clean air. This forced the state to implement a plan to reduce and control air pollution. These events helped to develop DSM in its early years. DSM has seen significant changes over the last couple of years and has been successfully implemented by developed countries such as Europe, the UK and Australia.

The way a mine utilize electrical energy is greatly influenced by DSM strategies. These strategies include load clipping, load shifting, valley filling and energy efficiency [44], [46], [47]. These strategies are also known as the modification of power curves [48]. It is possible to achieve significant savings in production with no real effect on productivity or product quality [47]. Demand

Response can be sub-categorised under DSM and is defined as the change in the consumption pattern of a mine in response to changes in electrical energy over time [49].

Eskom implemented different pricing initiatives which include real time pricing, nightsave, megaflex, miniflex and ruraflex. The tariff for a specific operation is classified under its energy capacity and requirements. The mining industry is a large consumer and makes use of the megaflex pricing initiative. The megaflex initiative includes two peak intervals during weekdays between 07:00 - 10:00 and 18:00 - 20:00. The load peaks during these times can be reduced by any load management strategy and can be applied on any energy using sector on a mine.

Apart from these two peak intervals, standard and off-peak alternative pricing ratios are also part of the megaflex initiative. Winter and summer profiles have recently changed as represented by Figure 2-19.

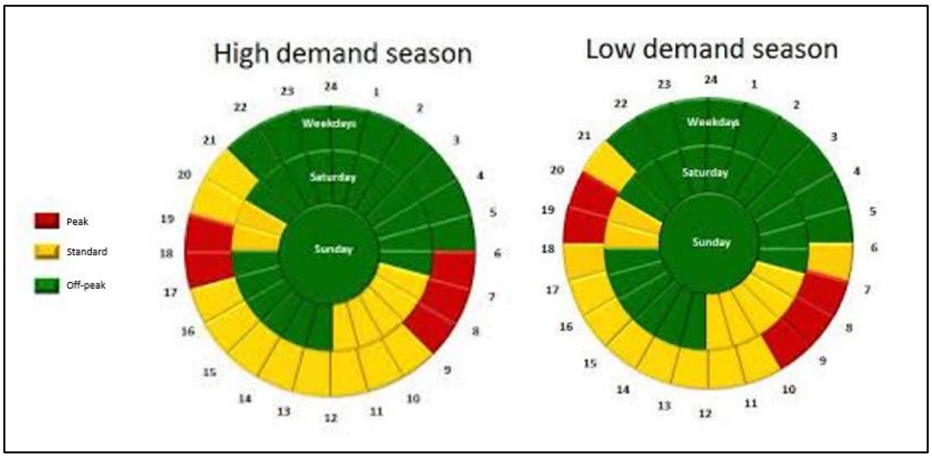


Figure 2-19: Eskom Time-of-Use Chart [50]

During weekdays, there are 5 peak hours, 11 standard hours and 8 off-peak hours. On Saturdays, there are no peak hours, 7 standard hours and 17 off-peak hours. Sundays are completely off-peak. The peak hours differ slightly for winter and summer months.

The different tariffs for the period 2015/16 are displayed in the graph below. The two lines indicate summer and winter. The tariffs include two peak times, a non-peak time and a standard time. The different prices with the times they are applicable are also given for every interval in Figure 2-20.

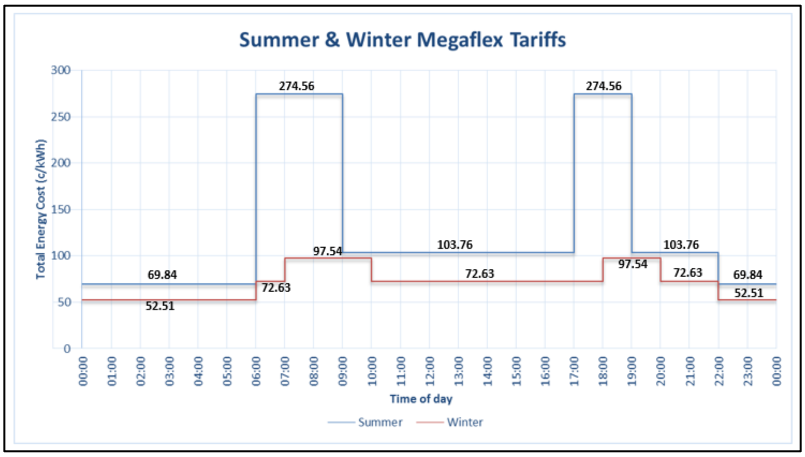


Figure 2-20: Eskom Time-of-Use Tariffs

Load clipping is the reduction of utility load primarily during peak demand periods [44], [51]. The load profile of the load clipping technique is given in Figure 2-21.

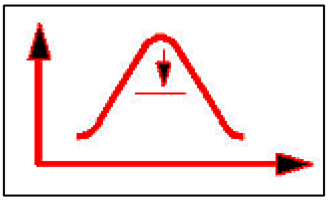


Figure 2-21: Peak Load Clipping Profile [51].

Peak clipping is achieved by either voltage control, which is directly controlled by the consumer, or by clipping of guide vanes. Both control methods can be used to reduce operating costs, reduce capacity requirements and dependence on critical fuel. Peak clipping is essential when the power utility does not have enough generating capabilities during peak hours.

This technique encourages consumers to use more energy at times when Eskom is most likely to have low cost energy available [48]. This can lower costs by spreading fixed capacity costs over a longer period of energy sales and then consequently lowers the average fuel cost. Valley filling may be desirable in the time of year where the long run incremental cost is less than the average price of electrical energy [52]. Figure 2-22 shows the typical load profile for the valley filling technique.

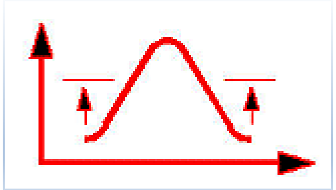


Figure 2-22: Valley Filling Load Profile [51].

Load shifting is when peak loads are moved to off peak time periods and the overall consumption is not necessarily changed [44]. This technique combines the benefits of peak load clipping and valley filling [48]. Figure 2-23 illustrates the profile for the load shifting technique.

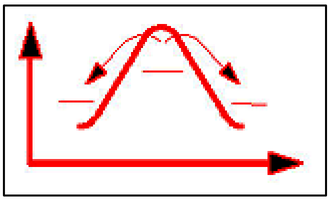


Figure 2-23: Load Shifting Load Profile [51].

This technique is ideal to use when the megaflex tariff structure is in use. The loads are moved from peak times as displayed in Figure 2-20 to times where tariffs are lower such as the off-peak times.

Strategic conservation is the improvement of the overall efficiency of the consumer. “Strategic” is intended to distinguish between naturally occurring and utility-stimulated [51]. Figure 2-24 shows the load profile for strategic conservation.

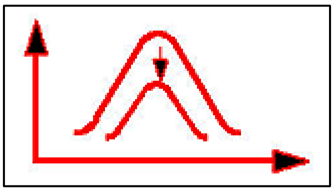


Figure 2-24: Load Reduction Load Profile [51].

This strategy is achieved by improving fan efficiencies by, for instance, the replacement of an existing impeller by a more efficient impeller.

Another energy saving strategy called Demand Response (DR) is linked to pricing. DR can be classified as either price based or incentive based [49], both of which are discussed below.

Price based DR can furthermore be classified as Real-Time Pricing (RTP), Time-of-Use (TOU) tariffs and Critical-Peak Pricing (CPP) [49]. These pricing strategies give customers time-varying rates that show the cost of electrical energy at different time periods. This strategy aids the customer in determining at what times prices will be high and allows them to manage their energy to save on consumption.

Incentive based demand response programs pay participating customers to reduce loads at times requested by the program sponsor (usually Eskom). These times are usually triggered by grid reliability problems or high electrical energy prices [49].

Guide vanes, also known as Inlet Guide Vanes or IGVs, create swirls in the direction in which the fan is turning. These swirls lessen the angle between incoming airflow and fan blades, thus reducing fan load, pressure and airflow [32]. This moves the fan operating point up the performance curve to a better efficiency [53]. By installing IGVs with main surface fans, significant energy savings can be achieved. It is predicted that by tilting the guide vanes to a 30° angle the load on the motor can be reduced by up to 20%, this is called clipping [54].

Ventilation on Demand (VOD), another form of energy saving in the ventilation section of mining, suggests the distribution of air to areas in need rather than ventilating the entire mine [37]. It involves reducing ventilation usage in times when and in locations where the air is not needed and at the same time providing sufficient air when it is needed [46]. In mechanised mining, equipment is moved to different areas of the mine on more rapid intervals than in conventional mining, causing VOD to be much more labour intensive when not automated. VOD that is automated with fan and louver control, responds quicker to data received from underground. This directs the required volume of air to the places in the mine where it is needed without a person having to do it manually [55].

VOD does come with some challenges, some having a greater influence than others. Some major challenges are listed below [56]:

- Difficulty to perform accurate and reliable measurements.
- Variables are interactive (when a variable change occurs elsewhere in the mine, that change influences all the other areas as well).
- The area to be ventilated is constantly changing.
- The system’s response is affected by multiple factors (drift obstructions, air density, auxiliary fan status etc.).

There are certain requirements that a mine must fulfil in order to be able to practice successful ventilation management, especially focussing on VOD. As new ore zones are brought into production, the ventilation requirements will continuously change and increase. To meet airflow demand from increasing production targets, the mine requires that the ventilation system be as flexible and efficient as possible [56]. Figure 2-25 shows the components for VOD on Mine B.

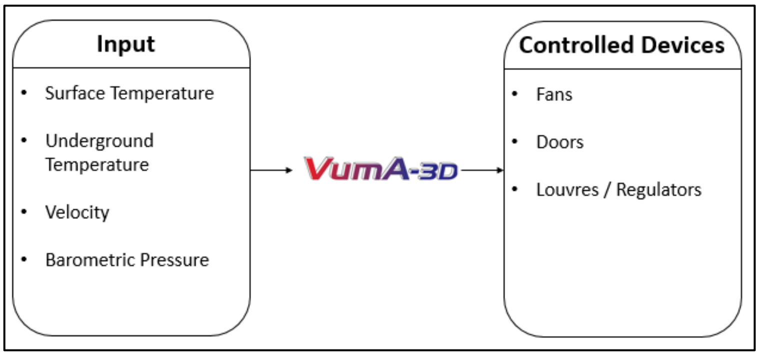


Figure 2-25: VOD Component Layout

Figure 2-25 describes the component layout for the VUMA3D-Live simulation package. It receives inputs such as temperatures, velocity and barometric pressure and then determines the areas where controlled devices such as fans, doors and regulators need to be adjusted to obtain efficient and adequate ventilation. It is important to have a good ‘on demand’ schedule. This means that all fans are modulated based on air demand in different work zones or based on minimum authorised air flow in accordance to the South African Mine Health and Safety Act [57].

The model in Figure 2-8 is very basic. More complex models can be built in simulation packages which have much more detail to use in aid of obtaining accurate results. Mine simulations or computational fluid dynamics (CFD) are increasingly being used to help in the managing of underground mine conditions. It allows for increased system efficiency and system cost effectiveness. Simulations are used to determine airflow and how it changes when certain system adjustments are made.

2.11 Examples of Energy Saving Strategies Applied in the Industry

The mines used as examples are situated in the Limpopo province in South Africa between the towns of Northam and Thabazimbi. These mines form part of the North-Western limb of the Bushveld Complex.

The savings in the following two scenarios were calculated for weekday evening peak hour clipping, and 24-hour weekend clipping. The permanent reduction in the baseline was not included in the calculations.

2.11.1 Example Mine X Main Surface Fans

Example mine X's main fan surface station consists of two 750 kW centrifugal fans with an approximate power factor of 0.84. Calculations predict that these fans each absorb a total of 630 kW. The 24-hour daily baseline signed off by a certified measurement and verification (M&V) team was calculated as 1328 kW. The difference in the baseline profile and the actual profile means that savings will be less than predicted by the M&V team. The project's aim was to save energy during evening peak hours between 18:00 and 20:00. Figure 2-26 shows the baseline and actual data for the fans at the example mine during March 2016. The fans were clipped before 17:30 and returned back to normal around 20:30 to ensure that consumption was lowered during peak periods to save electrical energy costs.

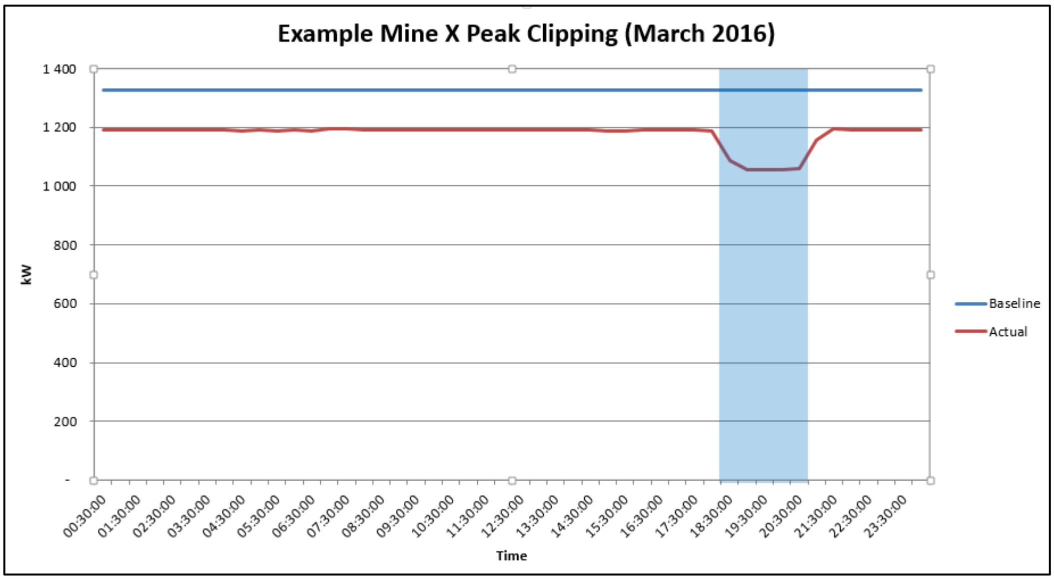


Figure 2-26: Mine X Main Surface Fan Peak Clipping Profile (March 2016)

The actual power of energy measurements is lower than what the M&V approved baseline is. This can be due to a change in ventilation operation schedule or the ventilation was reduced per what was needed, and at the time of measurement and verification, the ventilation was overcompensated for. The average at which the fans were running was 1190 kW, 138 kW less than predicted.

The reduction in power consumption during the evening peak interval was found to be 11% less than the normal actual operation of 1190 kW and 20% less than the M&V approved baseline of 1328 kW. This was achieved by tilting the guide vanes from a fully open position to a 30° angle to create a pre-swirl that reduces the load on the fan impeller and moves the fan operating point upwards on the performance curve to achieve a better efficiency. The annual kW, annual MWh, percentage savings and cost savings are shown in Table 2-4 below. Case 1 uses the M&V approved baseline of 1328 kW while Case 2 uses the average measured baseline of 1190 kW.

Table 2-4: Example Mine X March 2016 Savings

	Case 1	**Case 2**
Baseline (kW)	1328	1190
Clipping (kW)	1062	1062
kW Savings	266	128
% Savings	20%	11%
MWh Saving Annually	2190	1054
Cost Savings Annually	R 1 624 000	R 781 000

It is clearly shown that up to 20% of the initial consumed power can be saved which equates to an annual approximate saving of R 1 624 000. This is calculated with different tariffs for peak, off-peak and standard times, as well as winter and summer seasonal tariff differences.

2.11.2 Example Mine Y Main Surface Fans

Example Mine Y's main fan surface station also consists of two 750 kW centrifugal fans, each with an approximate power factor of 0.84. It is predicted by calculations that these fans each absorb a total of 630 kW. The 24-hour daily baseline signed off by a certified M&V team was calculated as 1282 kW. The reason why this baseline is lower than at Mine X can be attributed to a difference in motor power factors. The project's aim, like at Mine X, was to save energy during evening peak hours between 6 PM and 8 PM. Figure 2-27 shows the baseline and actual data for the fans at Mine Y during July 2015. The fans were clipped around 17:00 and returned to normal at about 20:30 to ensure that consumption was lowered during peak periods to save on electrical energy costs.

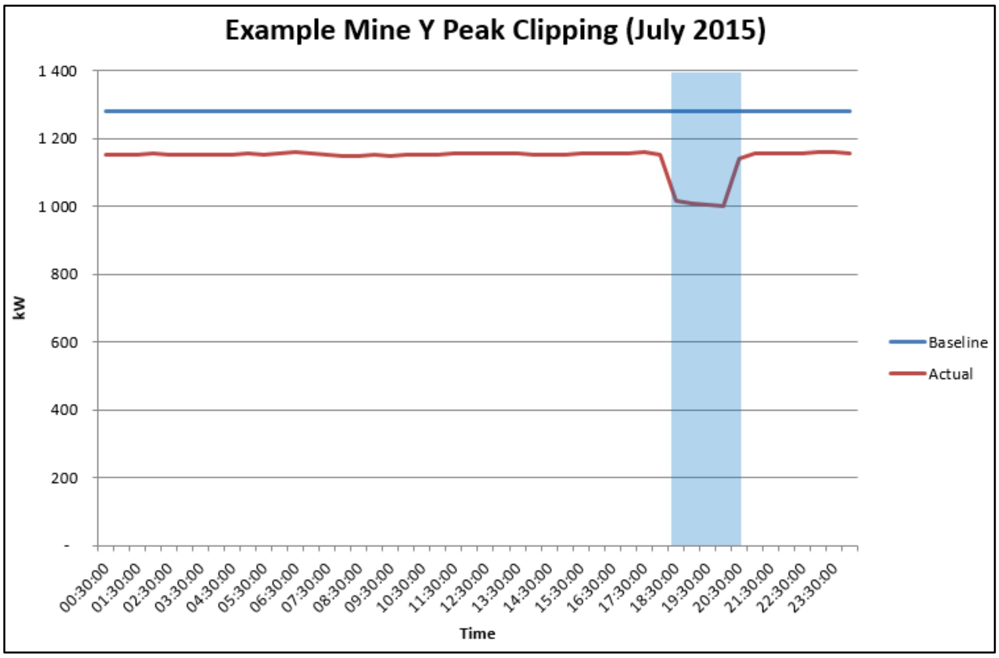


Figure 2-27: Mine Y Main Surface Fan Peak Clipping Profile (July 2015)

The actual kW measurements are also lower than what the M&V approved baseline is. The reason for this is the same as for the Mine X scenario. The baseline was calculated and not measured, and the fans were not running at the precise efficiency at which the M&V team initially thought it did. The average at which the fans were running was 1154 kW, 128 kW less than predicted.

The reduction in power consumption during the evening peak interval was found to be 13% less than the normal actual operation of 1154 kW and 21% less than the M&V approved baseline of 1282 kW. This was achieved by tilting the guide vanes from a fully open position to a 30° angle to create a pre-swirl that reduces the load on the fan impeller and moves the fan operating point up in the performance curve to achieve a better efficiency. The annual kW, annual MWh, percentage savings and cost savings are shown in Table 2-5 below. Case 1 uses the M&V approved baseline of 1282 kW while Case 2 uses the average measured baseline of 1154 kW.

The reason why there are two different values might be caused by ventilation configuration changes within the mining network. During the period when initial measurement and verification was done, the ventilation fans could have been running at a higher load. The inlet guide vanes could also easily have influenced the measurement, depending on the accuracy of the guide vane angle readings.

Table 2-5: Example Mine Y July 2015 Savings

	Case 1	Case 2
Baseline (kW)	1282	1154
Clipping (kW)	1007	1007
kW Savings	275	147
% Savings	21%	13%
MWh Saving Annually	2264	1210
Cost Savings Annually	R 1 679 000	R 897 000

This table also indicates that savings of up to 20% can easily be achieved. The number of savings will differ from mine to mine, but it is safe to say that power savings in the range of 20% can be achieved when clipping is applied. In this case an annual saving of approximately R 1 679 000 can be achieved.

It would be ideal to be able to predict these changes before they are applied to ensure sufficient ventilation. This can be done with the help of simulation software.

2.12 Application of Simulation Software in the Industry

Underground mining environments are ever-changing systems. Various points cannot be measured simultaneously, thus a margin of error is inevitable. Historically the acceptable error margin in measurements ranged from 5%-20%. Belle [58], in his paper on real-time velocity measuring in mines, found that the differences between ventilation surveys and real-time airflow monitoring was about 13.3% on the mine his research was based on.

A significant amount of studies has already been conducted over the last couple of years about underground mine ventilation modulation and software development. When ventilation systems were evaluated during the 1960's and 1970's only a few criteria were used to evaluate if a system can be ventilated easily, and included total air quantity to working faces and ventilation efficiency [59]. However, due to the increased complexity of mine networks, other factors had to be taken into consideration. Ventilation engineers now must consider more factors, in addition to VOD, which have an influence on the ventilation system.

In 2001 a study was conducted on a fire outbreak and evacuation simulation model called MFIRE [60]. The safety procedures provided information on setting up an emergency ventilation scheme, establishing and minimising damage in underground network systems. The study took place on a laboratory based fire simulation which did not deliver satisfying results due to the reduction of the physical scale. The study concluded that the simulation model could efficiently exhaust high temperature air and smoke out of underground facilities when a fire breaks out.

Subsequently in 2003 the National Institute for Occupational Safety and Health in the USA conducted a CFD (Computational Fluid Dynamic) study based on Large Eddy Simulations (LES). This was used to model floor level fires in a ventilated tunnel. The outcomes of this study were verified by comparing the simulated velocity profile against experimental measurements [61].

In 2005 the Jiangxi University of Science and Technology in China developed 3D simulation software for mine ventilation. This software included a combination of visual basic, SQL server and Solidworks. It was used to create 3D models of mines to help in managing the ventilation system [62].

In 2010 J. Toraño [63] presented a CFD model that studied the behaviour of airflow and dust in an auxiliary ventilation system, and could also locate the source of the dust. The accuracy of this model was verified by velocity and dust concentration measurements taken in six points within the related mine. The conclusion was that the CFD model could help to optimise the auxiliary ventilation whilst avoiding important deficiencies when calculating ventilation parameters with conventional methods.

In 2013 multiple studies were being done in the CFD field. In a study, very similar to the study done by L. Cheng et al. [60] in 2001, Jun Deng et al. [64] created and studied simulations on the critical velocity of a longitudinal ventilation tunnel fire. The critical velocity of a tunnel fire was simulated using a Fire Detection System (FDS) in 10 different fire strength scenarios. The effects that the critical velocity has on the rescue and evacuation process of the mine during a fire were analysed. Also in 2013, Ting Ren et al. [65] conducted a CFD study to help understand the behaviour of ventilation and dust flow in a mine. Modelling results indicated that respirable dust particles could be significantly diluted by increasing the ventilation volume from the intake. The CFD model was also used to investigate the flow behaviour of water mists when sprays were orientated at different directions. This CFD study helped in the development of new dust mitigation systems.

Later on, in 2013, Guang Xu et al. [66] used the combination of tracer gas and CFD to monitor the underground conditions of a mine in order to manage ventilation. The study was conducted in an underground mine with four different ventilation scenarios. The simulations were compared with field data to verify the models' accuracy. The aim was to demonstrate that tracer gas, in combination with CFD, can be used to detect any changes in a ventilation system.

In 2014, JP Hurtado [67] presented a study that estimated the operating points of newly installed ventilation fans in addition to the existing ones, and, to justify the parallel installation of the additional main fan. A CFD analysis was used to validate the operating point of the new fan system to guarantee stable operation of the fans.

Later in 2014, Zhou Lihong et al. [68] used CFD modelling to study airflow patterns and methane distribution at a continuous miner face. The simulations were validated with experimental data collected in a full-scale ventilation test facility. This helped to create a safer mining environment by minimising the concentration of methane in the underground ventilation system.

In another study done by Jianwei Cheng et al. [69] in 2014-2015, CFD modelling was used to optimise the ventilation system of a coal mine. The study concentrated mainly on using CFD to manage gas hazards and to reduce the risk of an underground fire. These findings can be applied to guide the mine design practices in improving safety.

In a paper about real-time air velocity monitoring, Bharath Belle [58] discussed the needs for real-time monitoring and its implementation benefit in mines. He also used this monitoring system to determine the range of acceptable measurement error. In the same paper, Belle discussed that real-time monitoring of underground mine ventilation has already been in use in most South African coal mines over the last three decades and it is becoming increasingly popular in other areas of mining. Real-time monitoring of velocity has several advantages which include:

- Continuous monitoring of the efficiency of the mine environment system and mine safety.
- Prevention of mine fires, spontaneous combustion and explosion events.
- Estimation of real-time carbon monoxide, methane and other noxious gas flow rates.
- Estimation of gas emissions from mechanised equipment.
- Estimation of gas emissions during panel development and longwall retreat.
- Improved confidence in Ventilation Air Methane (VAM) emission data.
- Accurate determination of heat loads and air cooling capacity for thermal hazard management.

All these studies suggest that CFD software is an effective way of easing the way ventilation systems are managed these days. The modelling allows innovation at very low cost. VUMA3D-Live creates a real-time 3D-model that can be viewed on screen and shows various parameters. VUMA-Transient can predict what the effect of certain changes at specified locations will be.

When using these two software packages in combination, one can predict what the ventilation network would look like after applying changes, and then monitor these changes on a real-time basis.

2.13 Available Software

There exists several CFD software packages and also other software that aids in efficient mine management. The three simulation packages developed by Bluhm Burton Engineering (BBE), the Mining Technology Division (MiningTek) and the Council for Scientific and Industrial Research (CSIR) are used in this paper. This includes VUMA3D-Network, VUMA3D-Live and VUMA3D-Transient.

2.13.1 VUMA3D – Network

The VUMA3D-Network simulation software package is an accurate mine network simulation tool. It is the ideal tool for ventilation engineers and mine planners to obtain an accurate representation of what mining conditions will be. VUMA3D-Network allows for steady-state simulation of mine ventilation airflow, air thermodynamic behaviour and dust and gas emissions. It is impossible to predict exactly what will happen when certain changes are made to a mine ventilation system, but the software offers an accurate model representing expected conditions. Accuracy of the results are dependent on the inputs of the model. The software allows for various inputs such as branch types. Different characteristics that influence the branch types are discussed below. Firstly, the input fields are discussed, which include aerodynamics, thermodynamics and contaminants. Accuracy is dependent on how much detail is presented in a simulation model's input.

Aerodynamics - Aerodynamics and other parameters influencing the flow of air are accounted for. The parameters include a tunnel's (branch) physical attributes and surface frictional resistance characteristics.

Thermodynamics - Thermodynamic properties in a mine include surrounding rock characteristics and equipment or activities within the mine. Surrounding rock characteristics are made up of rock density, conductivity and specific heat capacity. Other heat sources include age of excavation, rock surface covering, virgin rock temperature (VRT), vehicles, equipment, drains, ducts, pipes and electric equipment (transformers etc.).

Contaminants - This includes parameters that describe contaminant sources such as filters or scrubbers.

The branch types available for use in VUMA3D-Network include tunnels, production zones, development headings, shafts, fans, shaft stations and control managers. Tunnels are used to describe a normal part of a mine tunnel where not much input information other than physical dimensions are available. The production zone branch type allows for the input of conventional drill and blast type of mining or continuous mining. Development headings inputs also differ per type, which include drilling and blasting, road headers, continuous miners and tunnel boring machines. Shaft inputs are like tunnel inputs, shafts are just named differently for easier identification. Fan branches use the input of fan curves which are obtained from a pre-loaded fan database or from a custom fan curve. The software uses this curve to calculate the effects on airflow and temperature. Hence, the focus of this study will mainly be on the airflow and temperature comparisons. Shaft stations can be very complex due to several different factors contributing to environmental condition changes. The shaft input branch allows for a simplification of these sources (heat pump chambers etc.). Control managers allow for easier control of conditions within the simulation. If conditions of a certain parameter are known, it can simply be controlled by the control manager. Coolers (Fixed duty, fixed outlet condition etc.) and heaters (pumps, winders, transformers etc.) can be inserted. Other parameters that can be inserted with the control manager include leakage paths, flow regulators, bends, air crossings, abrupt contraction losses and abrupt enlargement losses. The last input parameter for the control manager, the contaminant parameter, involves the input of known gas and dust sources.

VUMA3D-Network solver makes use of all these inputs to simulate underground mining conditions and displays it as a three-dimensional model of the mine. Results can also be shown in a report view.

2.13.2 VUMA3D – Live

VUMA3D-Live offers a real-time, or quasi real-time simulation of underground mining conditions. The interval at which the simulation updates is given as an input. VUMA3D-Live needs some time to render and update the model with the new values, thus intervals such as 3 or 5 minutes are sufficient. This gives the software some time to update and prepare for the receipt of new values. The change in conditions can then be seen at any point in the mine. The values are then stored in a database for future reference.

2.13.3 VUMA3D – Transient

Transient, as defined by Oxford dictionaries online, is a momentary variation in current, voltage, or frequency. In this case the definition can be adjusted to the momentary variation in velocity or temperature. Due to the complexity of a mine and the incalculable variables, VUMA3D-Transient is best used when a single path within a mine is studied. A single path allows for more accurate results because of less influence of unknown variables. An example of how transient is applied on actual events is discussed next.

Transient Scenario - The ventilation engineer of a mine is certain that energy can be saved on the main ventilation fans. The engineer does not simply want to reduce the airflow without being certain that underground conditions will remain safe. VUMA3D-Transient can be used to accurately simulate what conditions will be when certain changes are made to the ventilation system. Different single-path areas can then be studied to conclude what effects might be. An illustration of what is meant by single path is given in Figure 2-28.

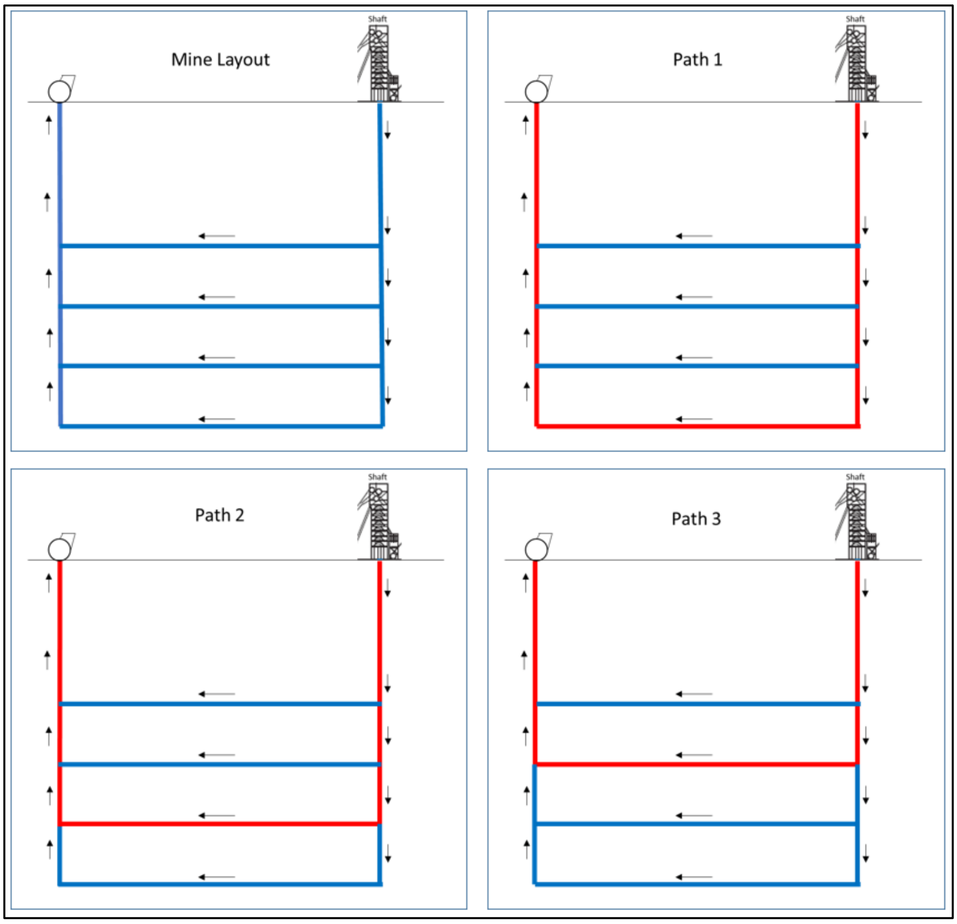


Figure 2-28: Example of Single Paths in a Mine for Transient Study

2.14 Conclusion

Electrical energy cost in South Africa is on the rise due to an increase in consumption and lack of maintenance and new generation infrastructure. This causes mine profits to decrease. Mining companies are all looking for new ways to save energy and seeing that ventilation systems contributes largely to a mines electrical energy bill, it is one of the first areas where a mine looks to save. Small configurational changes to a ventilation system can result in significant savings. Simulation software enables ventilation engineers to predict underground mining conditions before physical changing anything in the system. This allows for thorough preparation which also prevents money being spent on situations that may be catastrophic for the mine.

The focus of this study is on utilising 3D simulation software to determine what the environmental changes of a mine will be when making ventilation configurational changes, to save on ventilation costs. It can be concluded that software exists that allows the user to successfully determine future underground mining conditions, the prevent harm to the mining environment and the people working in it, and to ultimately save on electrical costs.

CHAPTER 3 – DATA COMPARISON METHODS AND RESULTS (MINE A)

3.1 Research Method

The main goal of this research was to determine if simulation software could be used successfully in aid of optimising a mine's ventilation network, and if so, to what level of accuracy it could do so. A research method was needed that allowed for the observation of performance problems in practice. Seeing that a high level of detail was needed, the case study research method was chosen. Case studies are widely used in research papers, with most researchers using only one case study. It is difficult to generalise the technique used in one case study seeing that no two mines are identical and results will most certainly differ in every case.

Due to the difficulty to obtain permission to adjust a mine's ventilation network for research purposes, only one site was available to be used for validation purposes. Mines operate 24 hours a day 7 days a week making it quite difficult to adjust the ventilation system to determine the effects of the changes. On this specific mine, only the observation of changes during specific events such as a power failure or a switch off of the fans for maintenance was allowed.

Two case studies were used to predict what changes could be made to the ventilation system to achieve certain savings without a significant negative impact on the underground environment. A comparison of the two sites used in the case studies is given in the Table 3-1 below:

Table 3-1: Comparison of Sites Used in Case Studies

	Case 1: Mine A	**Case 2: Mine B**
VUMA Model	Yes	Yes
Sensors Installed	Yes	Yes, but reinstall is needed
Sensors Calibrated	Yes	No
Type of mine	Conventional Platinum	Mechanised Platinum
Number of Fans Used	2	3
Fan Sizes	2250kW	75kW
Hottest WB point at Normal operation	29.6°C	26°C

Available for Monitoring	Yes	Yes
Available to adjust	No	No
Available for validation	Yes	No
Available for predictions	Yes	Yes

Based on these two case studies a method of comparing the available data was developed. Assumptions for the simulation models were also made per these sites. Both sites were perfectly suitable to use for data validation, but due to unforeseen technical problems on Mine B Only Mine A was used for validation purposes. The simulation software could be used for forecasting the energy savings on both sites once the simulation software was validated.

3.2 Selection of Case Studies

The ideal case study for a VUMA3D versus real-time comparison had to meet three major criteria. Firstly, the mine had to have an existing VUMA3D model, secondly the mine had to provide sufficient existing measurement infrastructure and communication, and finally the mine had to provide existing documentation that contained all the information regarding mine design and geometry, mine communication, and ventilation design parameters. The quality of the available documentation determines the quality of the VUMA3D model. Inconsistent documentation allows for errors in the model design which will increase the difficulty of calibrating the model with real-time data.

Mine A provided an accurate VUMA3D model, sufficient mine information documentation and measuring equipment with accurate results. The use of inaccurate measurement results would result in a VUMA3D model that might be inaccurate and prevent the forecasting of underground environmental changes when certain ventilation changes are applied.

Both sites used in the case study were available to use for the prediction of energy savings. Mine A was easier to use because of the physical distance from base and easy access to the data. Mine B is almost double the distance from base and the measuring equipment had some technical difficulties, this being the reason why the latter site was not used for validation purposes.

3.3 Early Comparison

Early comparisons were made just to demonstrate why certain measurement data did not differ much when compared, while other measurement data differed quite significantly. The graph in

Figure 3-1 shows the actual velocity measurements versus the simulated velocity at the same points within the mine on the 28th of April 2016. This point was specifically chosen due to the sensor that was already situated at this location to obtain the most accurate results as possible.

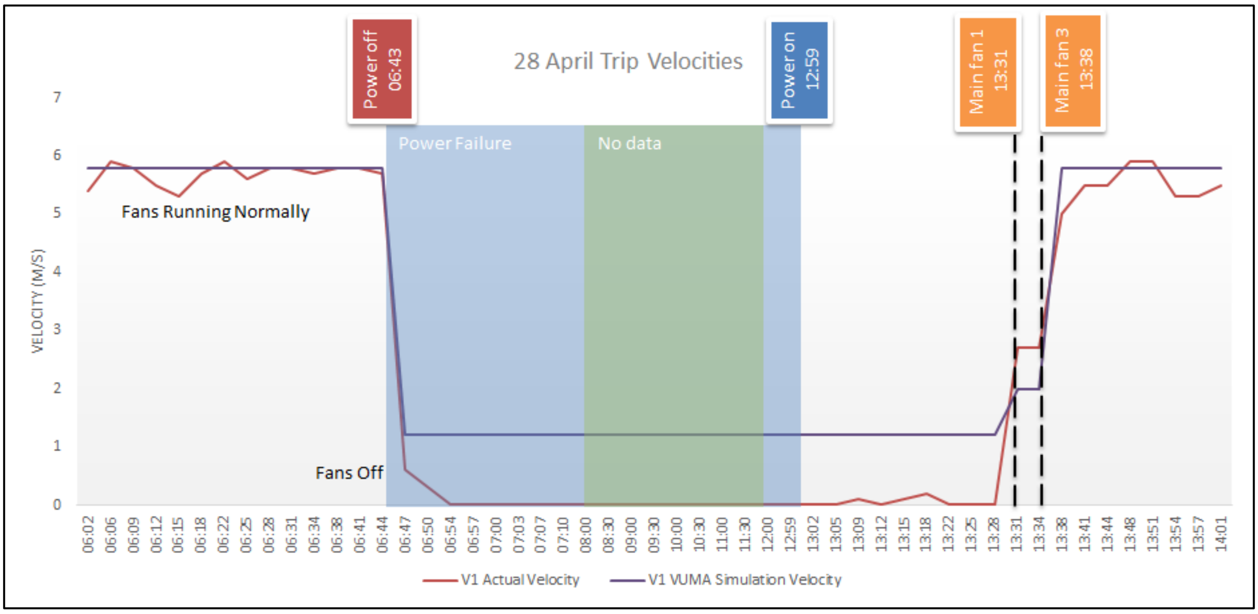


Figure 3-1: Early Velocity Comparisons between Actual and Simulated Velocity Measurements.

From the graph, the fan operated normally at a relatively constant velocity. At about 06:43 the velocity suddenly dropped which was due to a power failure experienced by the mine. The power failure lasted for about six hours up until 12:59. During which a few minutes' worth of data went missing. This was ignored seeing that the data before and after the missing gap do not differ much. The graph also shows the two main fans being switched on at different times. The effect of the fans on the underground environmental readings can clearly be seen in both sets of data.

Assumption 1:

The VUMA3D model cannot capture all the dynamic effects of the actual airflow, which include turbulent airflow. An illustration of turbulent airflow is given in Figure 3-2 below:

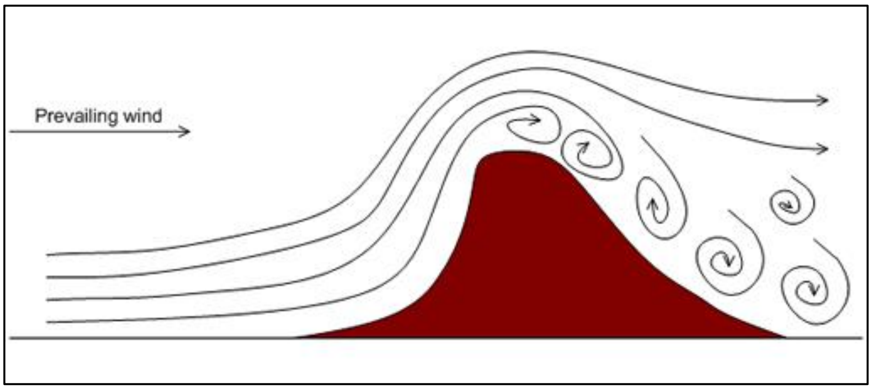


Figure 3-2: Turbulent Airflow [70].

Turbulent airflow is caused by obstructions in the path where the air flows. The air is mixed and irregular air patterns occur. If the airflow sensor is situated in the turbulent area of flow, the actual flow characteristics are not measured and this causes a deviation from the simulated data.

Assumption 2:

Velocity measurements are spot measurements and do not directly correlate with the average airflow over the area where the sensors are situated.

Figure 3-3 illustrates how velocity is measured to help give a better understanding. The red dot marked with a V indicates the typical installation location of a velocity sensor. The blue line and arrows indicate how velocity is manually measured with a device called a traverse, which is indicated in the illustration as a yellow circle with a T.

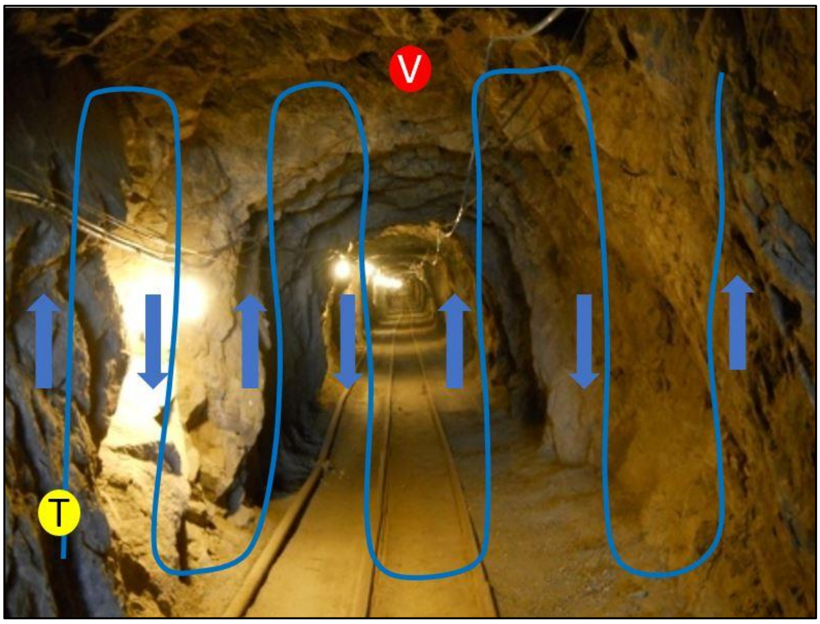


Figure 3-3: Illustration of how Velocity is Measured.

Comparing the two techniques of measurement it can be assumed that a result that best represents the velocity will be obtained from the traverse technique simply because it considers a much bigger area than the sensor, which measures at a stationary single location.

Assumption 3:

The VUMA3D model cannot capture the effects of every single obstruction within the tunnels of the entire mine. The mine can be seen as a living organism, objects and equipment are being moved around continuously. Locomotives, underground vehicles and people are always on the move which can influence the sensor readings at any time.

All three of these assumptions can be seen in some form in Figure 3-4. The steel beam to the left of the sensor can be seen as a turbulence causing obstruction, this is an example of assumption one.

Figure 3-4: Velocity Sensor Placement in the Mine

The sensor is placed in the middle of the tunnel to capture the most accurate reading that could represent the whole area of that point in the mine. The overhead piping and cabling on the wall may have an influence on the flow, but this is the best placement of the sensor in this scenario. This is an example of assumption two.

The overhead piping, steel beams and cabling that can be seen in this image are not accounted for in the simulation which may cause some differences between simulated data and actual sensor measurements which illustrates assumption three.

To minimise the controllable errors, all the sensors had to be calibrated accurately as described in the following section.

3.4 Data Comparison Method

Certain steps were identified to compare actual measured data with simulation data. Based on the flow of data, step one involves the preparation of the collection of data. Step two involves the matching and comparison of all available data at selected points within the mine while step three deals with the evaluation of the findings of the data comparison of step two. These steps will be thoroughly discussed. Figure 3-5 gives a detailed picture of what is included in each step and also shows the flow of data.

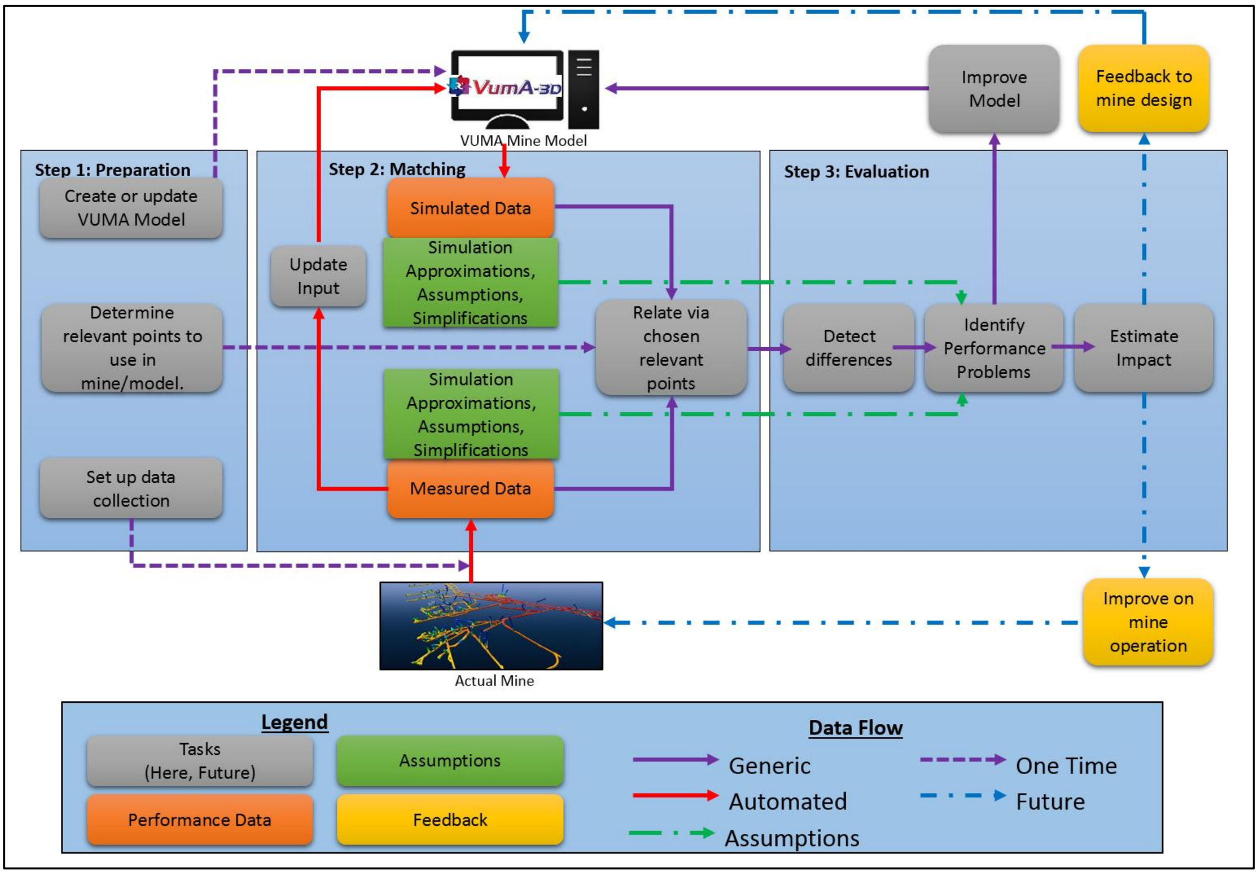


Figure 3-5: Data Comparison Steps

The first step, the preparation step, is usually a once-off step in the kick-off phase of a project. It includes the creation and/or development of the VUMA3D model, as well as the setup of data collection sensors. The decision is then made where the sensors will be placed within the mine to measure the data to the best of the sensors' capabilities. It is important that this is done correctly because if a velocity sensor is not directly in line with the direction of flow, the edges of the sensor may disturb the airflow and cause turbulence. The points where the sensors are placed in the mine will later be used in the simulation to ensure that the datasets that are used correlate with one another.

Part of the preparation is to ensure that the sensors that are installed are calibrated. This means that the values that are seen on the SCADA system on surface must correspond with values measured underground. This is done by means of a hand-held kestrel anemometer. One engineer measures the relevant parameters where the different sensors are located. The readings obtained at each sensor is communicated back to surface where another engineer compares it to the SCADA reading. Settings are then adjusted on the SCADA system to ensure that the values that are shown represent the most accurate readings. A small diagram showing this is illustrated in Figure 3-6.

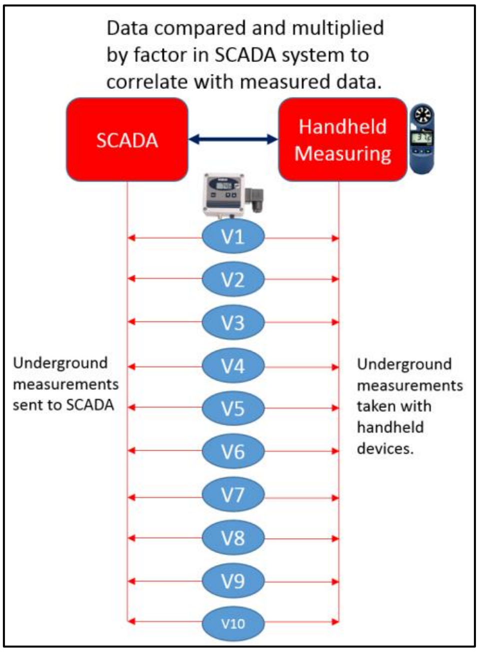


Figure 3-6: Underground Kestrel Data compared with Surface SCADA readings

Figure 3-6 shows the ten sensors that are installed underground. The diagram shows that each of these sensors send their data to the SCADA. It also shows that each sensor is measured with the hand-held kestrel anemometer. The two data sets are then compared on a real-time basis via a 2-way radio system and the necessary adjustment are made on the SCADA. Once this process is complete and the data sets correlate with one another, the sensors are classified as calibrated.

The second step, the matching step, is the part in the process where actual and simulated data are collected and compared. The measured data is obtained from ten sensors that are installed in key locations underground. Most of these sensors give a humidity, temperature and velocity reading from which other parameters can be calculated. This process can be discussed with the help of a diagram as shown in Figure 3-7. The diagram shows that the data from the V1 sensor (actual data) is used for comparison against simulation data at V1.

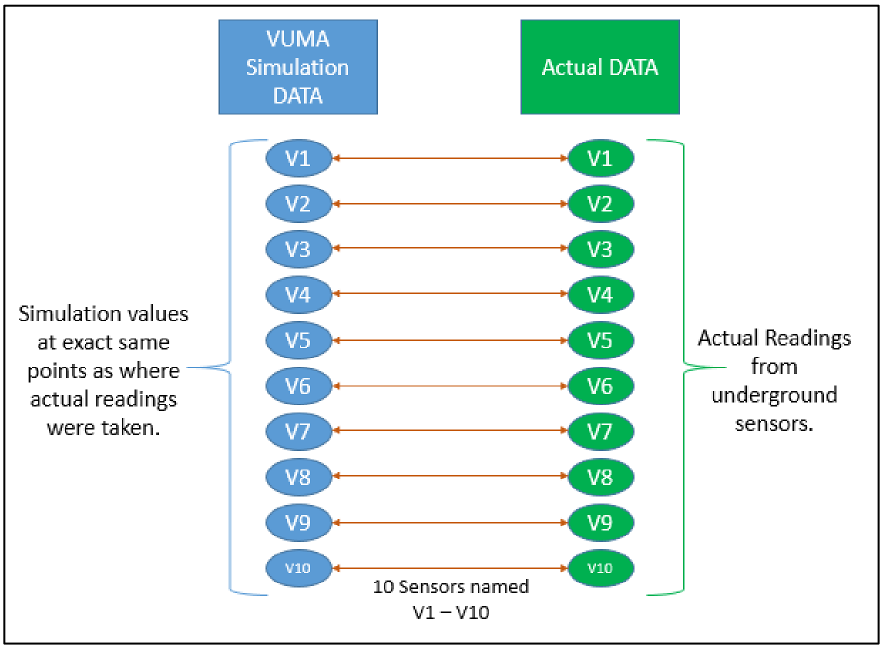


Figure 3-7: Comparison Process between Actual and Simulated data at Corresponding Locations.

V1 is placed in a certain location in the mine and provides measurements for velocity, humidity and dry-bulb temperature for that specific area. The area of the location is known from a manual measurement during the kick-off phase. From these measurements, parameters such as mass flow, volume flow and wet-bulb temperature can be calculated. The sensors are connected to the mine's SCADA system. The computer that is equipped with VUMA3D has access to this data which is fed to VUMA3D-Live to give a real-time (updated every 3 minutes) simulation of the mine. The data is then stored in a database for future reference.

To simulate a specific event in VUMA3D and VUMA3D-Transient, the base model values first must be adjusted to correlate with the mines actual conditions during the time of the event. This is done to minimise differences in simulation and measured data. An example of data comparison is a comparison between the measured velocity at V1 and the simulated velocity at V1.

The process is the same for each of the sensors (V1 - V10). Assumptions are made for actual and simulated data before any comparisons are made to minimise differences.

The last step is the evaluation of the results. Figure 3-8 visually illustrates how this process works. It typically starts with the sensor that delivers data for temperature and velocity. For both the temperature and velocity there is data for when the mine ventilation fans were operated under normal conditions and under a power failure condition. This is indicated as fan on and fan off in Figure 3-8. From there the real-time data is averaged to obtain a value that best represents the data set. The relative error between the actual data and averaged data is important to consider due to the importance of accuracy. The relative error can be explained by using the V1 dataset as an example. Table 3-2 shows V1's actual, averaged and simulated velocities at three minute intervals between 06:02 AM and 06:44 AM. The table also shows the difference and percentage difference between the actual and averaged values. The average percentage for V1 while the fans were running was found to be 2.44%.

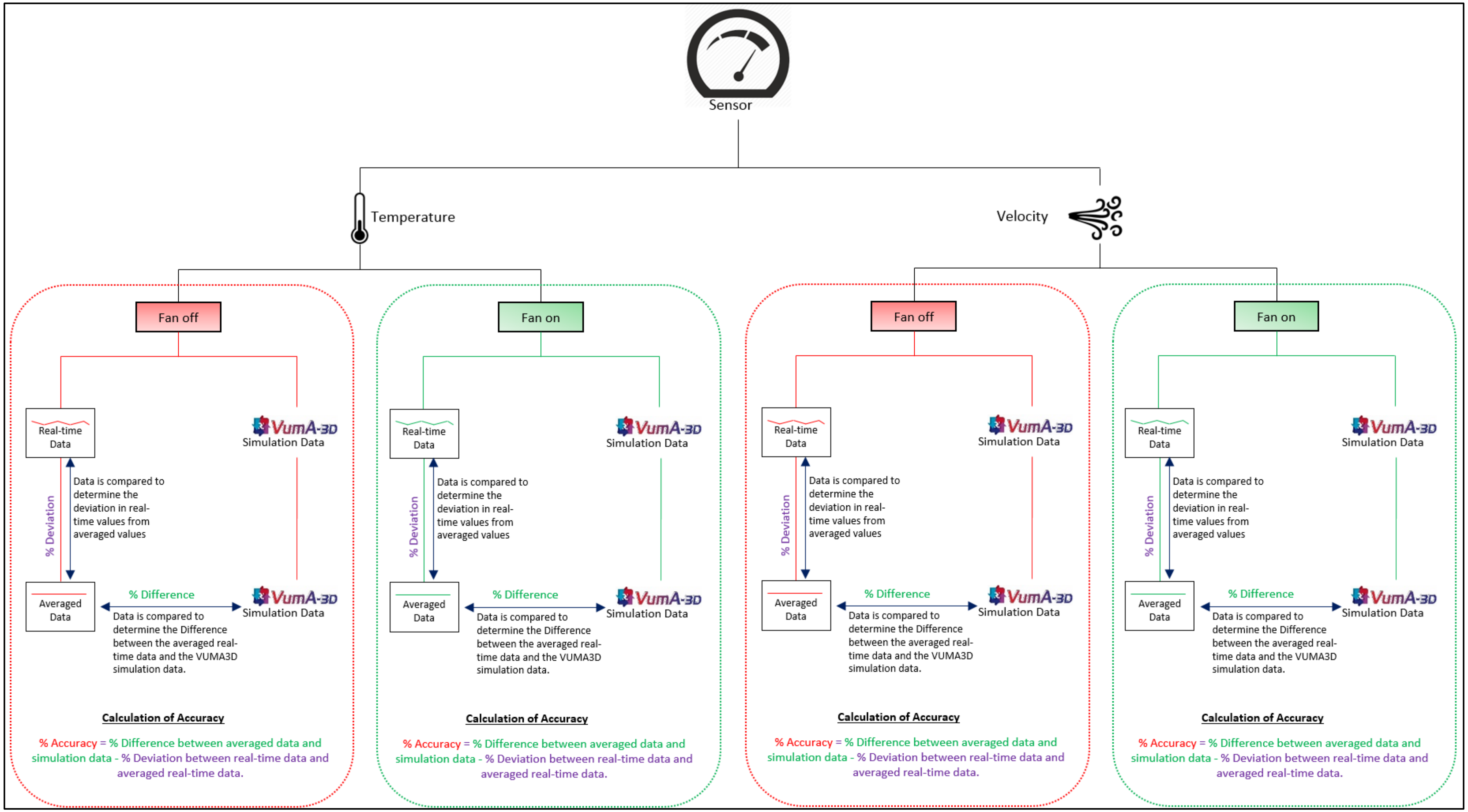
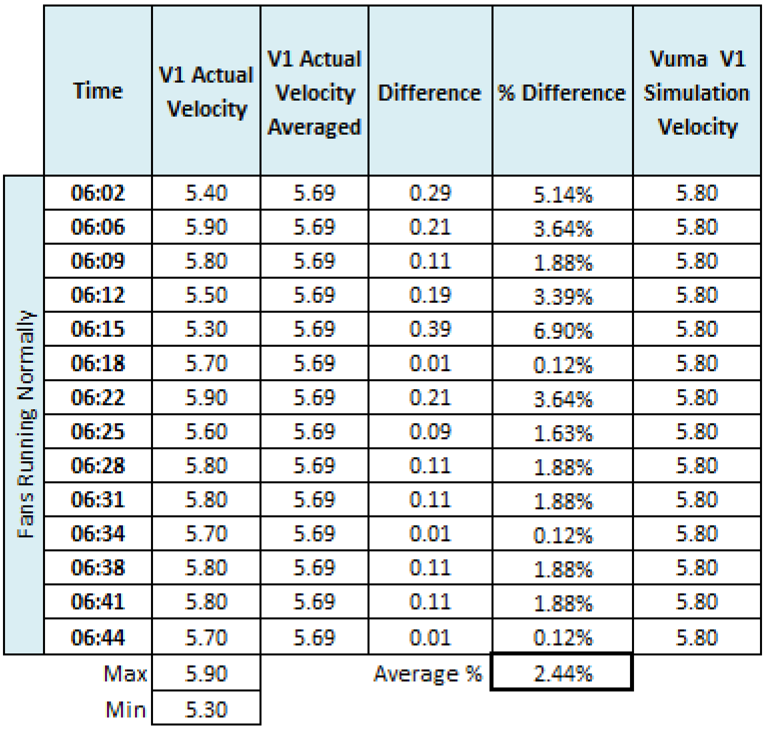


Figure 3-8: The Process of Comparison between Simulated and Actual Results

Also shown are the minimum and maximum actual readings. If the simulated data falls within these limits, it is assumed that the simulation is on par. It is also assumed that simulated conditions are much the same as actual conditions in that area, allowing measured data to be as expected.

Table 3-2: V1 Data Table



	Time	V1 Actual Velocity	V1 Actual Velocity Averaged	Difference	% Difference	Vuma V1 Simulation Velocity
Fans Running Normally	**06:02**	5.40	5.69	0.29	5.14%	5.80
	06:06	5.90	5.69	0.21	3.64%	5.80
	06:09	5.80	5.69	0.11	1.88%	5.80
	06:12	5.50	5.69	0.19	3.39%	5.80
	06:15	5.30	5.69	0.39	6.90%	5.80
	06:18	5.70	5.69	0.01	0.12%	5.80
	06:22	5.90	5.69	0.21	3.64%	5.80
	06:25	5.60	5.69	0.09	1.63%	5.80
	06:28	5.80	5.69	0.11	1.88%	5.80
	06:31	5.80	5.69	0.11	1.88%	5.80
	06:34	5.70	5.69	0.01	0.12%	5.80
	06:38	5.80	5.69	0.11	1.88%	5.80
	06:41	5.80	5.69	0.11	1.88%	5.80
	06:44	5.70	5.69	0.01	0.12%	5.80
	Max	5.90		Average %	2.44%	
	Min	5.30				

The data from Table 3-2 is represented in a line graph in Figure 3-9. The two red lines indicate where the minimum and maximum borders are. The purple line is the average of the actual measurements and the green line represents the simulated data. It can clearly be seen that the simulated data falls within the limits of measured data. The simulated data is a bit higher than the average data, but seeing that it falls within the limits it is assumed negligible for this study. This is not true for all cases. Scenarios where simulated data falls outside the limits do occur and a deviation is calculated. Such a scenario is shown in the graph in Figure 3-9.

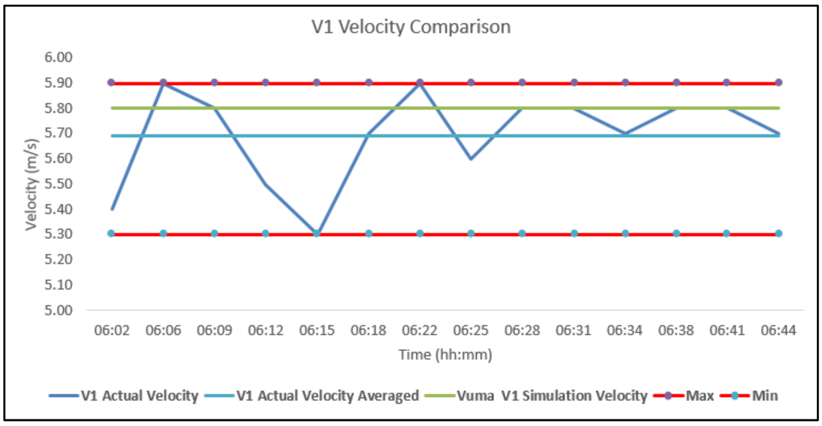


Figure 3-9: V1 Velocity Data Graph

The simulated data from V2 falls outside the minimum and maximum boundaries as seen in Figure 3-10. The difference between the simulated data and the nearest boundary is then calculated and represented as a percentage deviation. The assumptions discussed earlier can then be applied to justify why such a deviation exists.

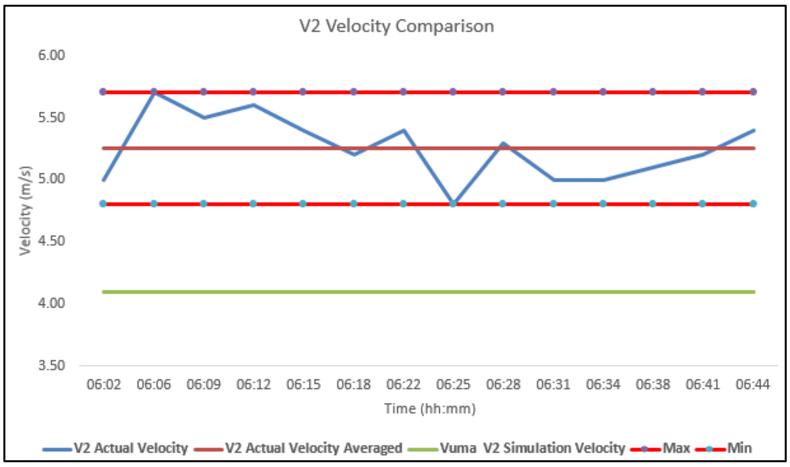


Figure 3-10: V2 Velocity Data Graph

Velocity is a very difficult parameter to measure due to its continual change, however, temperature is much easier to measure seeing that it does not have rapid changes. The graph below shows the temperature comparison for V1.

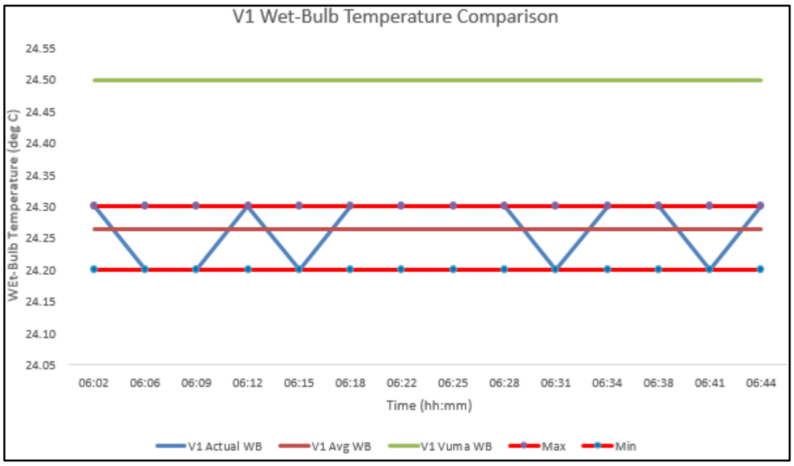


Figure 3-11: V1 Temperature Data Graph

This figure shows that the simulated temperature data for V1 falls outside the limits of the actual data. The deviation is relatively small. The difference can be calculated as in the V2 velocity scenario. In this case the maximum limit is the nearest border. The difference between this line and the simulated data is calculated and a percentage deviation is obtained. In this case, it equates to 0.19% which is virtually negligible.

It is easiest to use equations to summarise how results are obtained. Firstly, the average of measurements is calculated.

$$X_{avg} = \frac{1}{n}(x_1 + x_2 + x_3 + \ldots + x_n) \tag{3.1}$$

where n is the number of measurements.

The standard deviation (s) is calculated with:

$$s_x = \sqrt{\frac{1}{1-n}[(x_1 - x_{avg})^2 + (x_2 - x_{avg})^2 + \ldots + (x_n - x_{avg})^2]} \tag{3.2}$$

These steps are followed for every on and off scenario for every sensor location to obtain an average accuracy of the model.

3.5 Comparison Results and Errors

The results for all the comparisons done between actual and simulated data are given in three sections within this chapter. The comparisons were made for velocity, temperature and humidity. The actual and simulated data sets are compared and a deviation between the two sets are calculated for each sensor location for the three measured entities. The ten measurement locations were each equipped with a velocity, temperature and humidity sensor except for stations V8, V9 and V10 which were equipped only with a velocity sensor.

3.5.1 Velocity

Figure 3-12 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V1. The broken line in the graph represents the actual data, the gap in the line is due to a power failure. The results don't differ a lot when the fans are in normal operation. During the power failure, the actual velocity drops to almost zero while the simulated results shows a velocity of about 1m/s. This difference can be attributed to the assumptions that were made regarding differences between actual and simulated results.

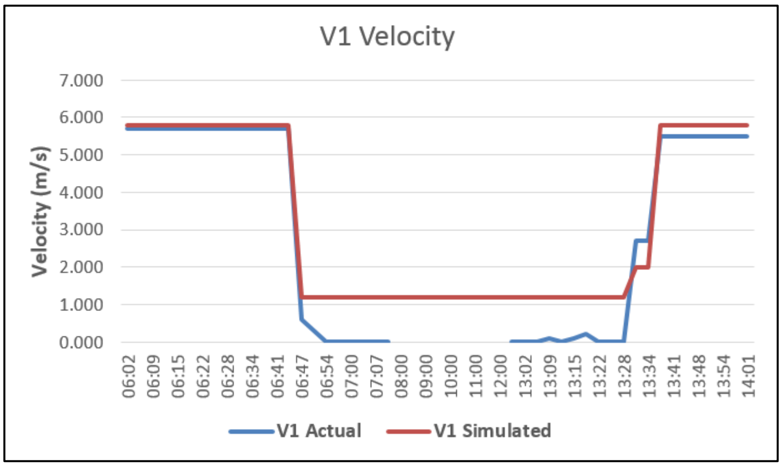


Figure 3-12: V1 Velocity Comparison Results

Figure 3-13 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V2. The higher result in the actual reading is caused by obstructions in the area where the sensor is installed which causes an increase in velocity in that specific area.

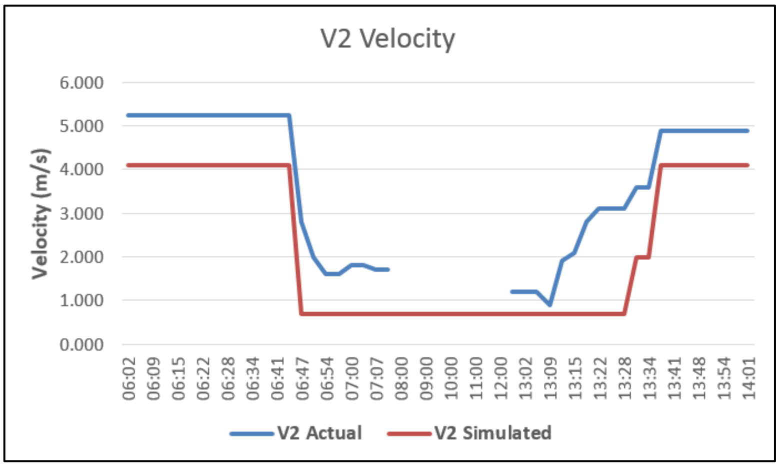


Figure 3-13: V2 Velocity Comparison Results

Figure 3-14 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V3. The lower result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

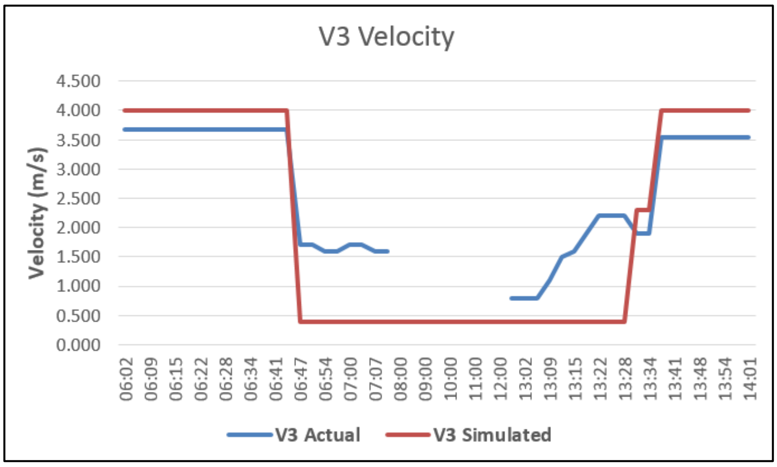


Figure 3-14: V3 Velocity Comparison Results

Figure 3-15 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V4. The lower result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

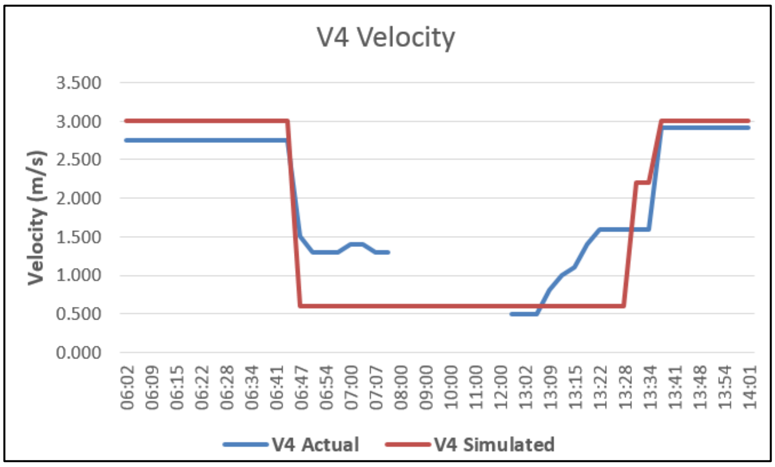


Figure 3-15: V4 Velocity Comparison Results

Figure 3-16 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V5. The lower result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

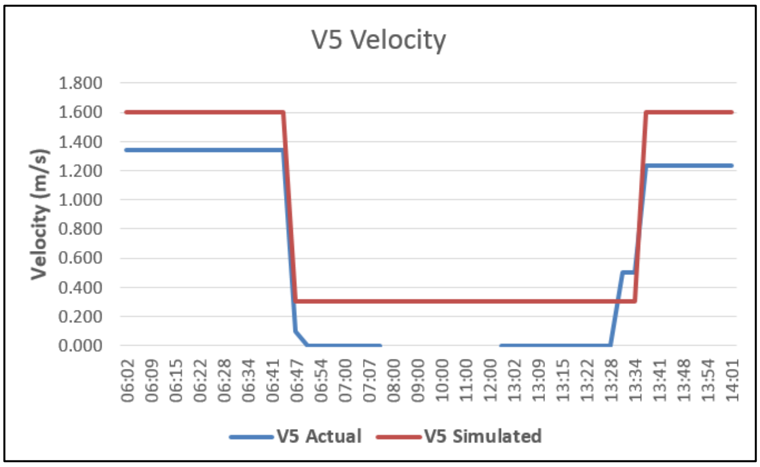


Figure 3-16: V5 Velocity Comparison Results

Figure 3-17 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V6. The lower result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

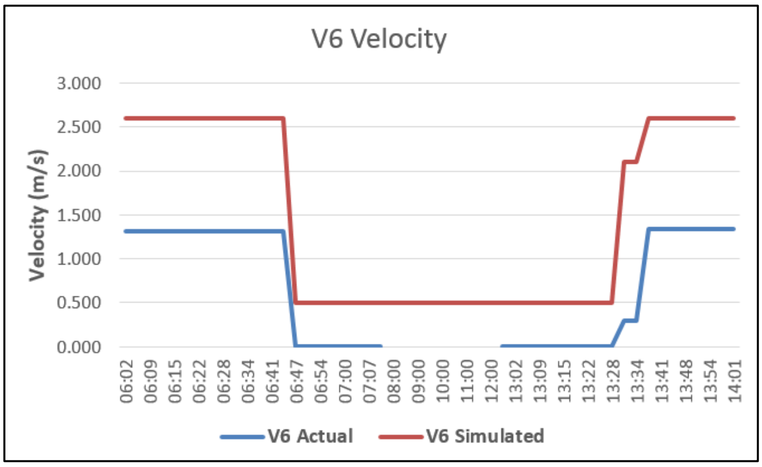


Figure 3-17: V6 Velocity Comparison Results

Figure 3-18 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V7. The actual and simulated results for V7 are relatively similar.

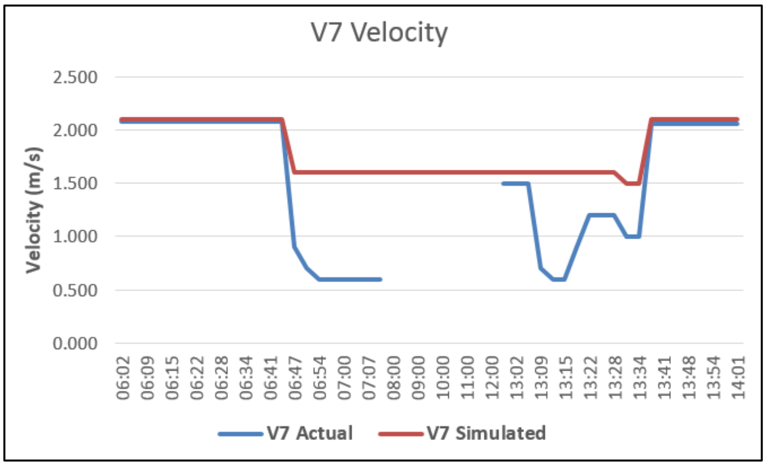


Figure 3-18: V7 Velocity Comparison Results

Figure 3-19 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V8. The higher result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

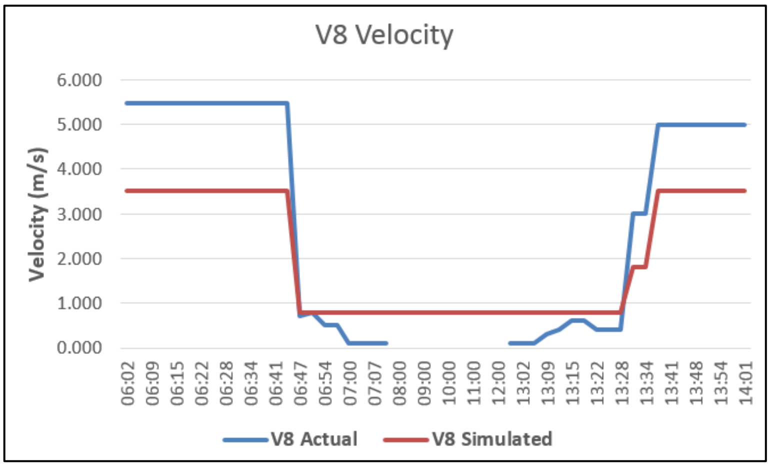


Figure 3-19: V8 Velocity Comparison Results

Figure 3-20 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V9. The higher result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

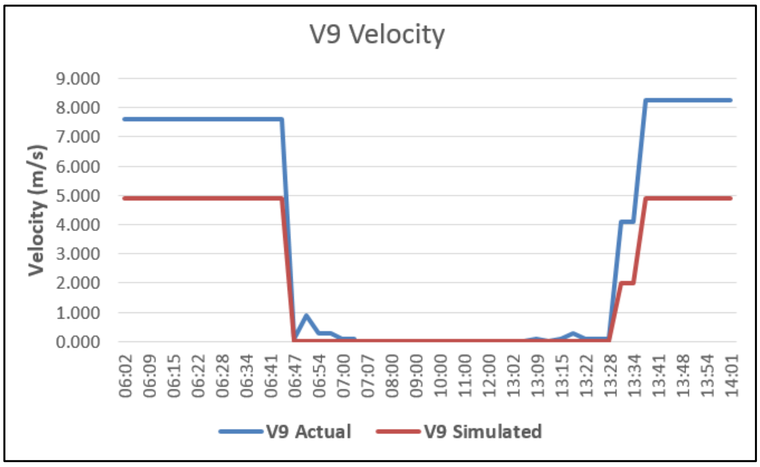


Figure 3-20: V9 Velocity Comparison Results

Figure 3-21 shows the results for the comparison between the simulated and actual data for the velocity of the sensor located at V10. The higher result in the actual reading may be caused by a combination of assumptions as discussed earlier in Chapter 3.

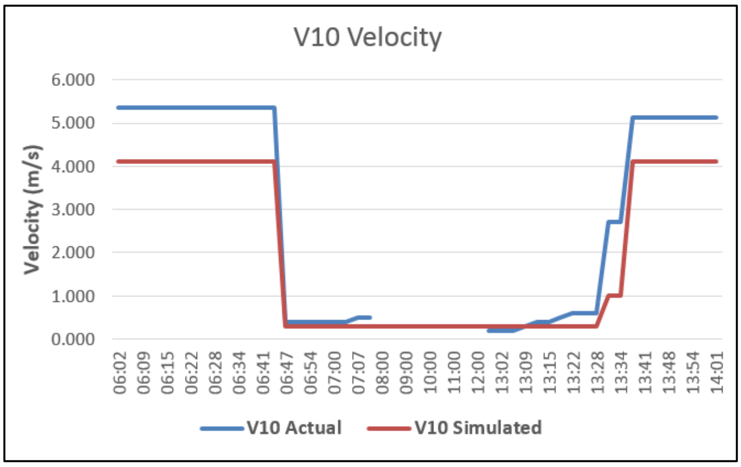


Figure 3-21: V10 Velocity Comparison Results

The results for all the sensors are given in Table 3-3, Table 3-4 and Table 3-5. In the worst case the difference between the measured and simulated velocity was 2.7 m/s. This difference can be explained by the assumptions that were made in the previous chapter.

3.5.2 Temperature

Figure 3-22 shows the simulation and actual comparison results for the temperature of all ten sensors. The broken lines in the graphs represent the actual data, the gap in the lines are due to the power failure. It can clearly be seen that the results differ in each scenario.

Only the results for V1 to V7 are shown as there were no temperature sensors installed at V8, V9 and V10.

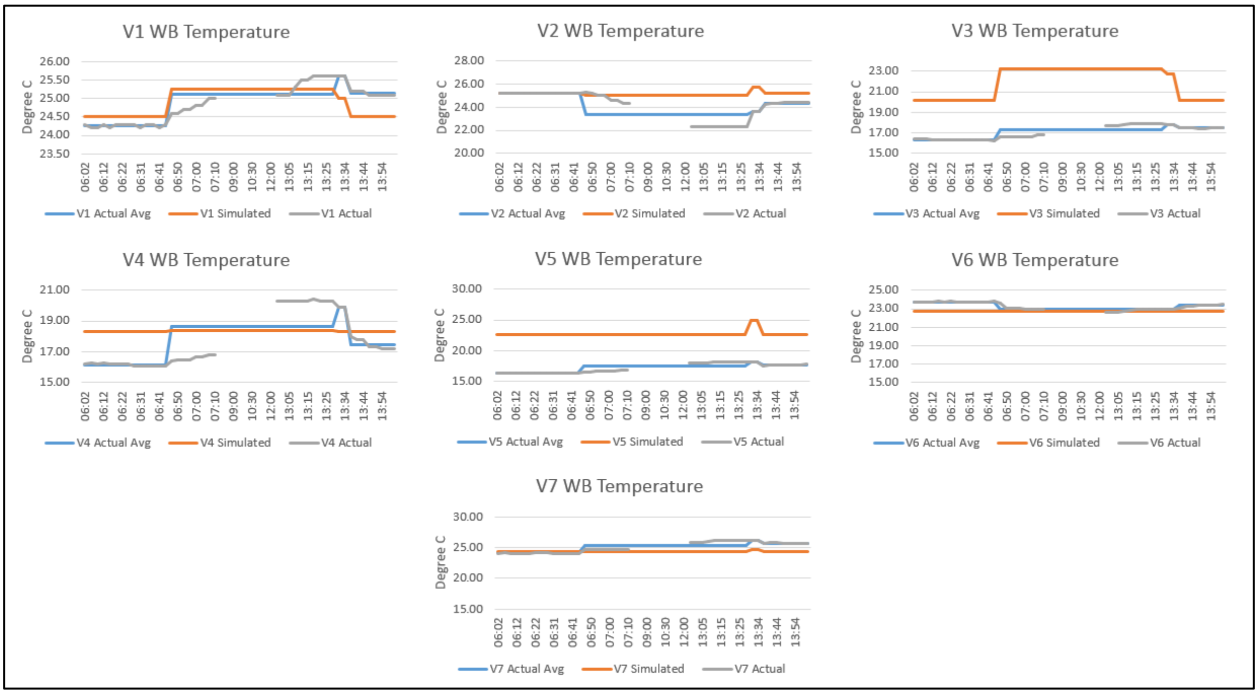


Figure 3-22: Temperature Comparison Results

For V1, the actual WB temperature was measured at 25° C with the fans in full operation and during the power failure. The simulated temperatures were 24.26° C with the fans in operation and 25.12° C during the power failure. This shows a good correlation between the actual and measured results. The rest of the temperature results are summarised in Table 3-3, Table 3-4 and Table 3-5.

In the worst case the difference between the measured and simulated temperature with the fans in operation was at V5 with a difference of 6.3° C. The worst-case difference during the power failure was at V3 where the difference was at 9° C. This can also be caused by the assumptions discussed in the previous chapter.

3.5.3 Humidity

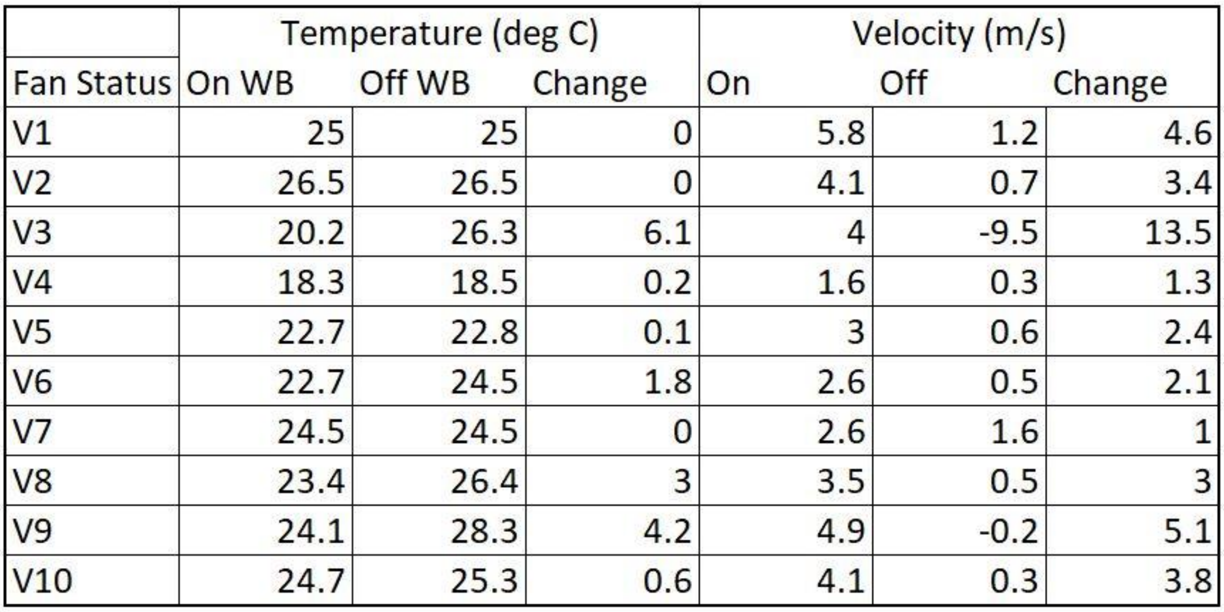
There were no humidity sensors installed at V8, V9 and V10. From all the graphs in Figure 3-23 an increase in relative humidity is observed from the actual data, while the simulation software shows a constant humidity. The change in humidity cannot be seen in such a short period as in the case with velocity. Better data can be obtained by studying the change in underground conditions in a controlled area over a longer period. Unfortunately, the actual data for this study is only for a short period. It is expected that the humidity change in the simulation will be seen when a longer period will be used.

Figure 3-23: Humidity Comparison Results

3.5.4 Comparison Error Margin

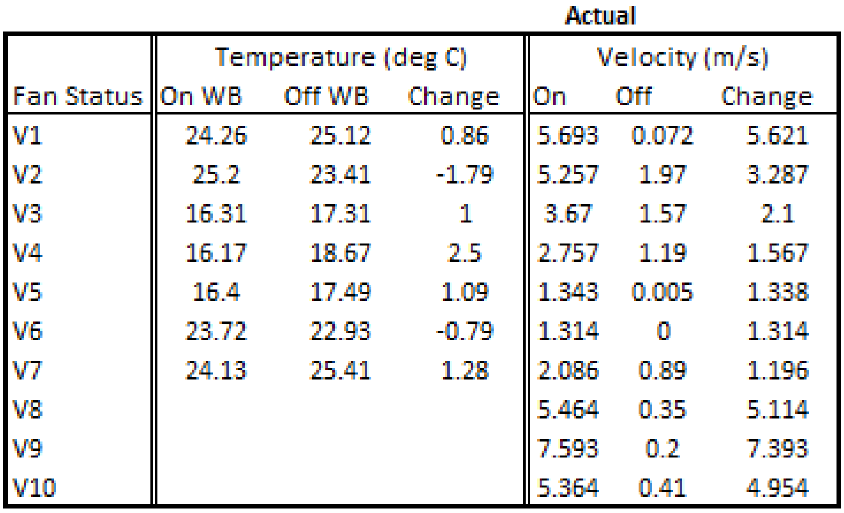
The results of all the sensors are summarised below. Table 3-3 shows the simulated results, Table 3-4 shows the actual results and Table 3-5 summarises the difference between the simulated and actual results.

Table 3-3: Simulated Results and Compared Difference



	Temperature (deg C)			Velocity (m/s)		
Fan Status	On WB	Off WB	Change	On	Off	Change
V1	25	25	0	5.8	1.2	4.6
V2	26.5	26.5	0	4.1	0.7	3.4
V3	20.2	26.3	6.1	4	-9.5	13.5
V4	18.3	18.5	0.2	1.6	0.3	1.3
V5	22.7	22.8	0.1	3	0.6	2.4
V6	22.7	24.5	1.8	2.6	0.5	2.1
V7	24.5	24.5	0	2.6	1.6	1
V8	23.4	26.4	3	3.5	0.5	3
V9	24.1	28.3	4.2	4.9	-0.2	5.1
V10	24.7	25.3	0.6	4.1	0.3	3.8

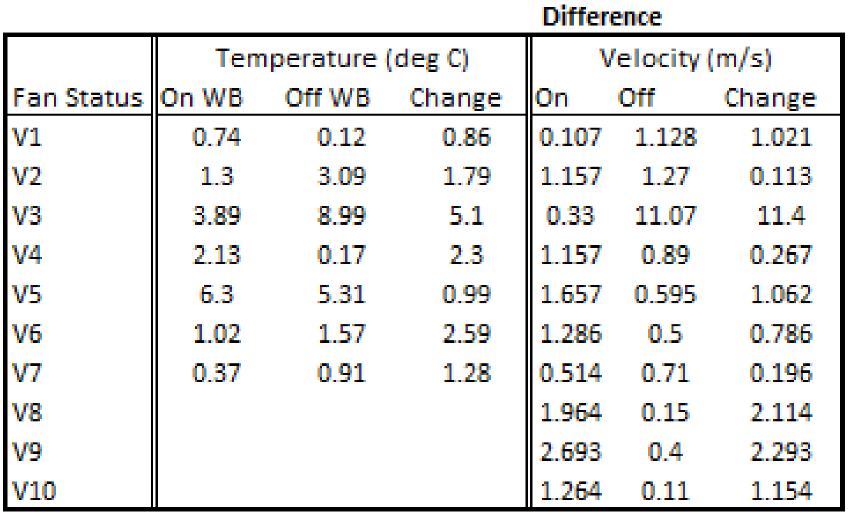
Table 3-4: Actual Results and Compared Difference



Actual

Fan Status	Temperature (deg C)			Velocity (m/s)		
	On WB	Off WB	Change	On	Off	Change
V1	24.26	25.12	0.86	5.693	0.072	5.621
V2	25.2	23.41	-1.79	5.257	1.97	3.287
V3	16.31	17.31	1	3.67	1.57	2.1
V4	16.17	18.67	2.5	2.757	1.19	1.567
V5	16.4	17.49	1.09	1.343	0.005	1.338
V6	23.72	22.93	-0.79	1.314	0	1.314
V7	24.13	25.41	1.28	2.086	0.89	1.196
V8				5.464	0.35	5.114
V9				7.593	0.2	7.393
V10				5.364	0.41	4.954

Table 3-5: Results and Compared Difference



Difference

Fan Status	Temperature (deg C)			Velocity (m/s)		
	On WB	Off WB	Change	On	Off	Change
V1	0.74	0.12	0.86	0.107	1.128	1.021
V2	1.3	3.09	1.79	1.157	1.27	0.113
V3	3.89	8.99	5.1	0.33	11.07	11.4
V4	2.13	0.17	2.3	1.157	0.89	0.267
V5	6.3	5.31	0.99	1.657	0.595	1.062
V6	1.02	1.57	2.59	1.286	0.5	0.786
V7	0.37	0.91	1.28	0.514	0.71	0.196
V8				1.964	0.15	2.114
V9				2.693	0.4	2.293
V10				1.264	0.11	1.154

Six steps were followed to calculate the average accuracy of the simulation software, without considering the initial assumptions that may have a significant influence on results.

Some constants are defined first:

- a = raw actual data
- b = raw simulated data

Step 1

Considering the whole raw set of actual data, the absolute difference between the actual data and the difference between the actual and simulated data. This can be better represented by the following formula.

$$c = |a| - |a - b| \tag{3.3}$$

where c = absolute raw difference.

Step 2

This step divides c (actual raw difference) with every individual measurement value to obtain an accurate difference.

$$e = \frac{c}{b} \tag{3.4}$$

Step 3

Some more constants include:

- f = averaged actual data
- g = averaged simulation data

$$h = |f - g| \tag{3.5}$$

where h = difference between the averaged actual data and averaged simulation data.

Step 4

$$i = \frac{h}{f} \tag{3.6}$$

Step 5

$$j = |i - e| \tag{3.7}$$

This is done for the velocity, temperature and humidity of all ten measurement stations.

Step 6

The last step is to take an average of all the measuring stations to obtain a single margin of accuracy.

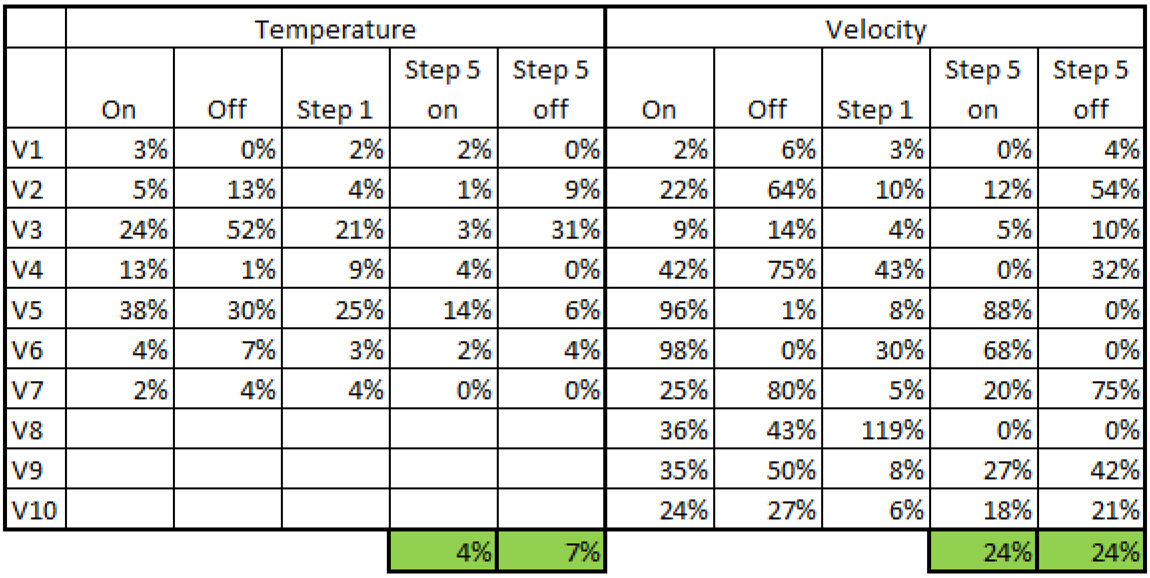
With these steps the results for the velocity with the fans in operation and during the power failure were calculated to have an error margin of 24%.

The WB temperature calculations were calculated to have an error margin of 2% with the fans running and 5% during the power failure.

The results for the WB temperature were more accurate than that of the velocity. The higher error margin in the velocity results can be attributed to the fluctuations in the velocity measurements. The error margin in the WB temperature measurements is much smaller due to constant temperature readings.

The final error margin results are summarised in Table 3-6. The calculations were performed for a scenario where the fans were operating normally, as well as a scenario where the fans were off due to power failure.

Table 3-6: Error Margin Calculation



	Temperature					Velocity				
	On	Off	Step 1	Step 5 on	Step 5 off	On	Off	Step 1	Step 5 on	Step 5 off
V1	3%	0%	2%	2%	0%	2%	6%	3%	0%	4%
V2	5%	13%	4%	1%	9%	22%	64%	10%	12%	54%
V3	24%	52%	21%	3%	31%	9%	14%	4%	5%	10%
V4	13%	1%	9%	4%	0%	42%	75%	43%	0%	32%
V5	38%	30%	25%	14%	6%	96%	1%	8%	88%	0%
V6	4%	7%	3%	2%	4%	98%	0%	30%	68%	0%
V7	2%	4%	4%	0%	0%	25%	80%	5%	20%	75%
V8						36%	43%	119%	0%	0%
V9						35%	50%	8%	27%	42%
V10						24%	27%	6%	18%	21%
				4%	7%				24%	24%

3.6 Conclusion

The ideal case study for a VUMA3D versus real-time comparison had to meet three major criteria. The case study used in this study met the three major criteria. Three parameters were measured and simulated to determine an error margin which will be used in the calculations of Mine-B.

An error margin of 24% was calculated for the velocity in the case where fans were running and in the case where the fans were off.

An error margin of 4% was calculated for the temperature in the scenario where the fans were on and 7% in the case where the fans were off.

Humidity is difficult to measure accurately over a short period of time; thus, no valid conclusions could be made for the humidity measurements. This measurement can be study in future research projects over a longer period.

CHAPTER 4 - UNDERGROUND ENVIRONMENTAL CHANGE AND COST SAVING ANALYSIS (MINE B)

4.1 Introduction

VUMA3D-Network and VUMA3D-Transient were used to predict what the changes in the underground mining conditions would be when certain configuration changes were applied. Two platinum mines were used to simulate these changes. Mine A, which is situated in Rustenburg, was simulated and monitored with a combination of underground instrumentation and VUMA software. This was done to determine whether the simulation software could be used as a valid tool in the prediction of underground environmental changes and ultimately to determine energy savings. Mine B, situated on the eastern limb near the small town of Burgersfort, was used to simulate different ventilation configurations to predict what the most energy efficient layout of the ventilation system will be.

It is important to save energy costs, but it is equally important to maintain a safe mining environment. The simulations serve as a check to prove that savings can be achieved by maintaining a safe mining environment in accordance with the mine health and safety act of South Africa.

Mines are very complex and can be seen as ever-changing living organisms. Due to its complexity, a mine in its entirety cannot be seen in transient view in VUMA3D. Only one path can be selected and viewed at a time. Both sites had their own uniquely selected paths and areas that were analysed. Each of them will be discussed in detail to explain the effect of that specific area on the mine as a whole.

4.2 Mine B Underground Environmental Change Prediction

For this mine, the prediction for underground environmental changes were made, as well as the possible cost saving analysis. Mine B is a relatively new and small platinum mine. There are currently, among others that do not have an influence on this analysis, three 75 kW axial fans that are extracting air out of the mine. These fans are concentrated mainly on ventilating the material decline and incline conveyor areas as shown in Figure 4-1 thus the study focussed only on this area. This forms a perfect path from surface to almost where the mine is at its deepest, and then back up to the surface again. This is an ideal path to be simulated in VUMA3D-Transient. Figure 4-1 shows the full VUMA3D model for this mine.

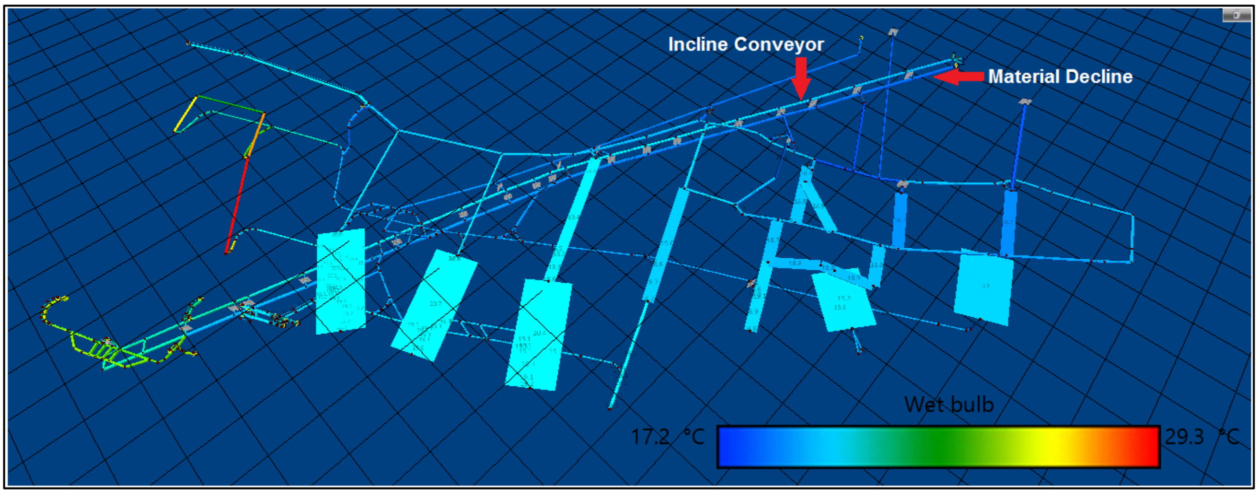


Figure 4-1: Mine B VUMA3D Model

The four scenarios that were studied include:

Scenario 1 - One fan was switched off permanently and two fans were running permanently.

Scenario 2 - One fan was switched off during peak times on weekdays, while the remaining two fans ran permanently.

Scenario 3 - One fan was switched off over weekends.

Scenario 4 - Two fans were switched off over weekends.

Simulations were done for the different combinations of fans to determine what underground conditions will be.

The simplified model is shown in Figure 4-2. The path is clearly shown and the tunnel is starting at the surface, continues down to the bottom of the mine, and comes back up again. The labels showing node 3, 9, 24, 49 and 55 within this path indicates the locations of the areas with the highest temperatures.

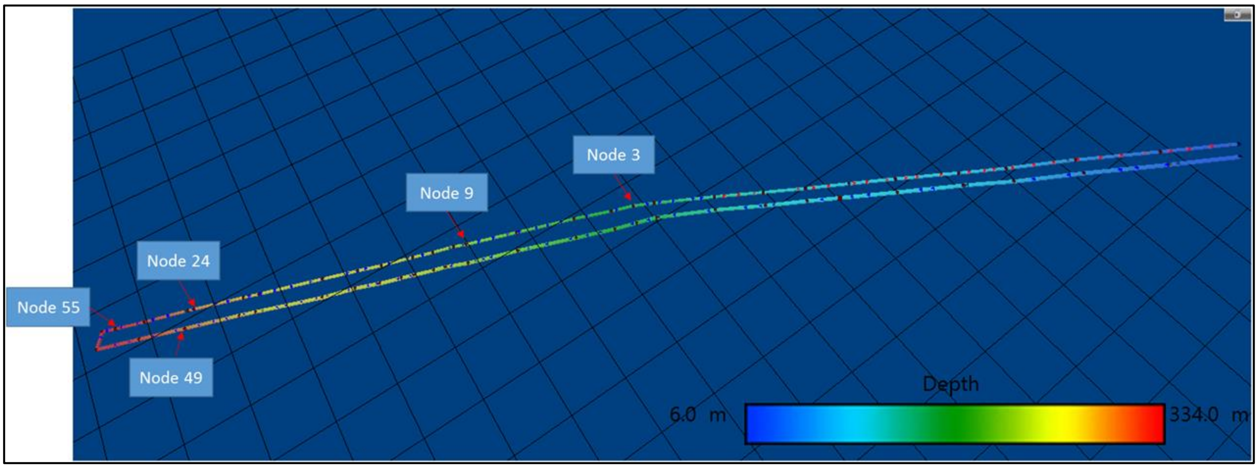


Figure 4-2: Mine B Simplified VUMA3D Model

The transient simulation was done for three scenarios. Firstly, with all three fans running for a period of 60 minutes, then with two fans running for a period of 30 minutes and then with 1 fan running for another period of 30 minutes. The changes in velocity, wet-bulb temperature and humidity were analysed.

Node 3, shown in Figure 4-3 is used as an example for explaining how each node calculation was approached. The temperature increase could be seen every time a fan was switched off. Notice how the maximum temperature (shown on each picture in Figure 4-3) increased every time a fan was switched off.

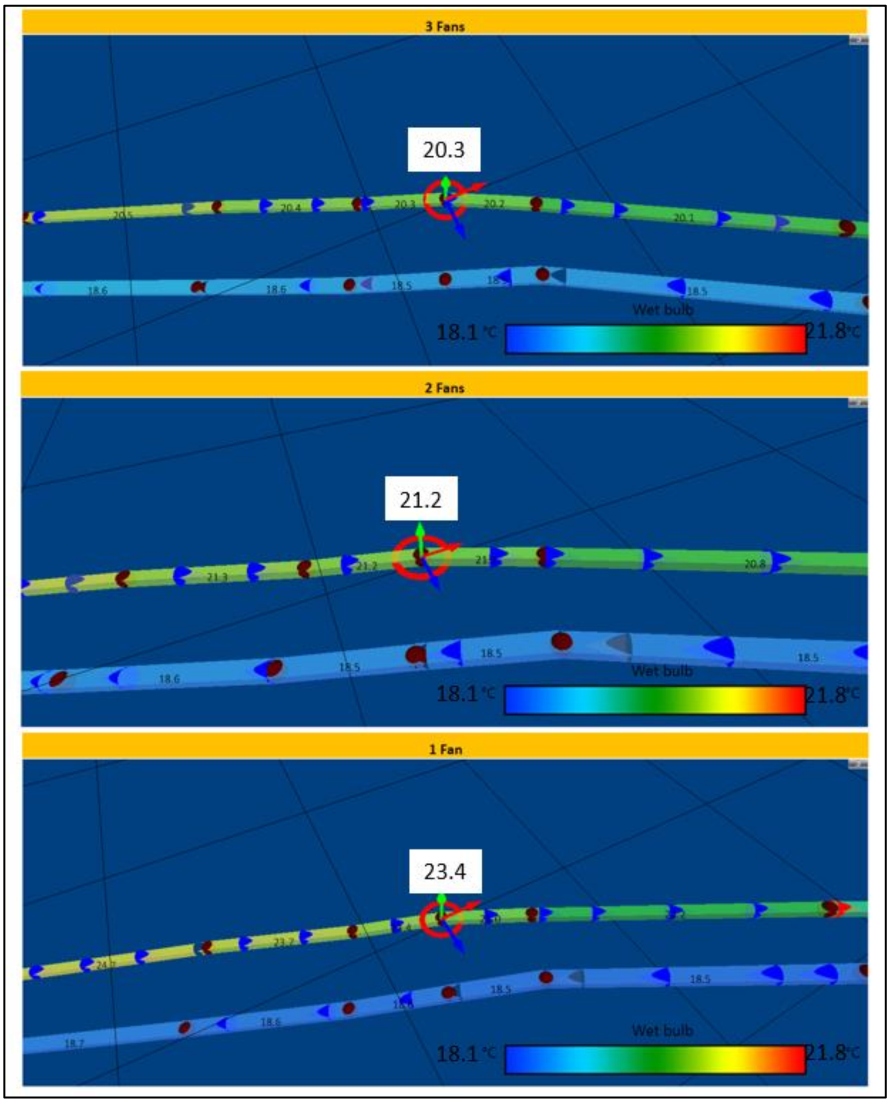


Figure 4-3: Node 3 shown with 3 fans, 2 fans and 1 fan running

The results of the simulations done for node 3 in this scenario is shown in the graphs in Figures Figure 4-4 and Figure 4-5. In Figure 4-4 it can be seen how the wet-bulb temperature increased when the velocity (and in turn the flow) was decreased. The initial network maximum temperature was at 21.8°C when all three fans were running and increased to a network maximum 26.5°C when only one fan was running.

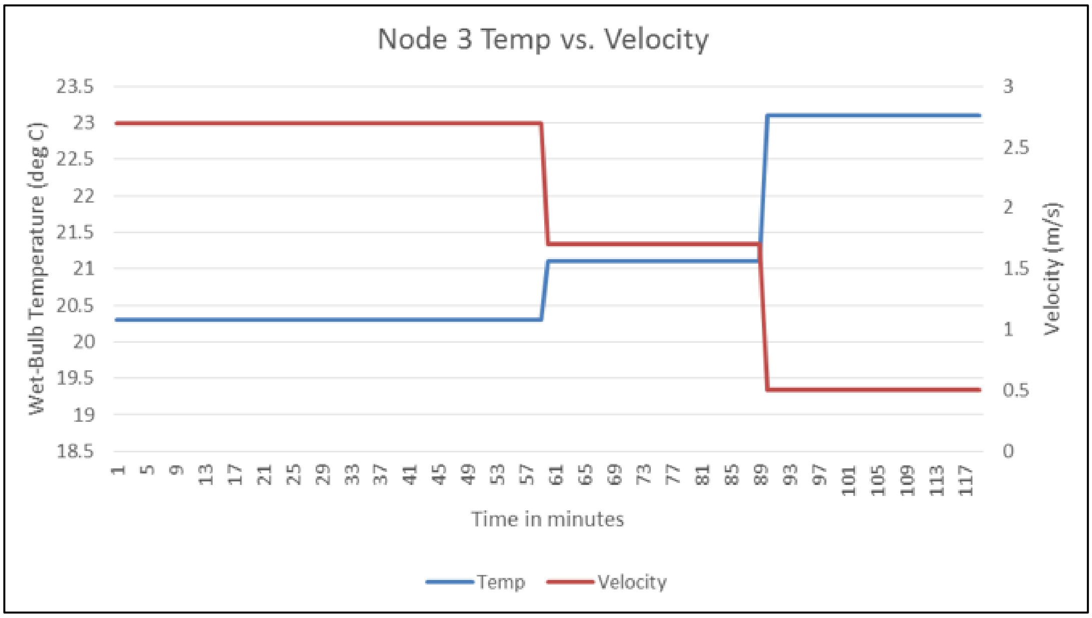


Figure 4-4: Node 3 Temperature and Velocity over time

Figure 4-5 shows the increase in humidity at node 3 when the two fans were switched off. After the first fan was switched off, the humidity had risen with 1% to a total of 95%. When the second fan was switched off, the humidity remained at 95%.

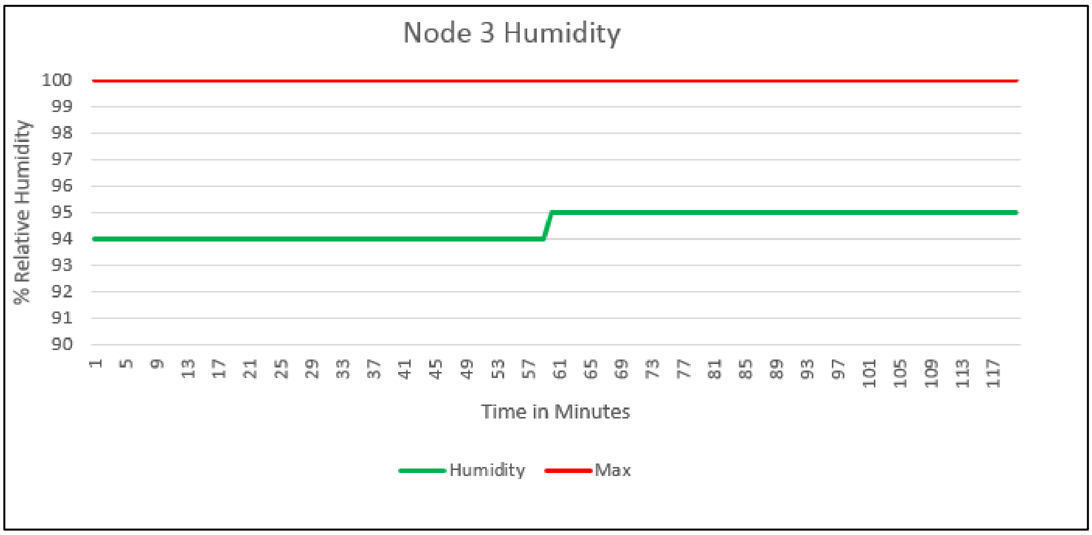
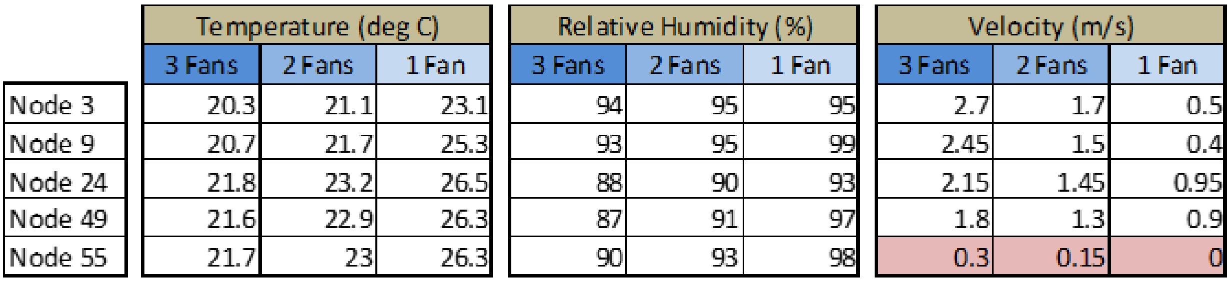


Figure 4-5: Node 3 Humidity over time

The changes to the system would not have such a rapid effect, but the simulation software assumes that these changes are instantaneous. The results for all the areas that were focussed on are shown in Table 4-1 below.

Table 4-1: Mine B VUMA Simulation Results Summary



	Temperature (deg C)			Relative Humidity (%)			Velocity (m/s)		
	3 Fans	2 Fans	1 Fan	3 Fans	2 Fans	1 Fan	3 Fans	2 Fans	1 Fan
Node 3	20.3	21.1	23.1	94	95	95	2.7	1.7	0.5
Node 9	20.7	21.7	25.3	93	95	99	2.45	1.5	0.4
Node 24	21.8	23.2	26.5	88	90	93	2.15	1.45	0.95
Node 49	21.6	22.9	26.3	87	91	97	1.8	1.3	0.9
Node 55	21.7	23	26.3	90	93	98	0.3	0.15	0

The area with the highest maximum temperature with 1 fan running was located at node 24. This temperature, 26.5°C wet-bulb, was within the specified limit (32.5°C). The relative humidity at the same time and location was at 93% which is high, but only 5% higher than what it was before any alterations were made to the ventilation system.

When considering only wet-bulb temperature, the maximums fell within the legal limit of operation. Looking at humidity, some of the values were too high. The simulation of two fans running resulted in a maximum humidity measurement of 95% which is not much higher than the results of the simulation before alterations to the ventilation system were applied. These are acceptable values. Also, the velocity was very low at some of the locations when only one fan was in operation. Thus, the conclusion was made that it will be acceptable to run only two fans under normal conditions, but it is important to notice that environmental conditions might change during blasting hours. The environmental conditions might change due to heat generate by the blasts. Various factors contribute to this such as friction between rocks, dust being created by the blast and also the humidity can be influenced by dust and heat. The results of Table 4-1 can be represented by graphs for better understanding.

The graph in Figure 4-6 shows the increase in wet-bulb temperature of each node. With two fans running, temperatures were still relatively close to what it initially was. Temperatures showed quite a substantial increase when only one fan was running.

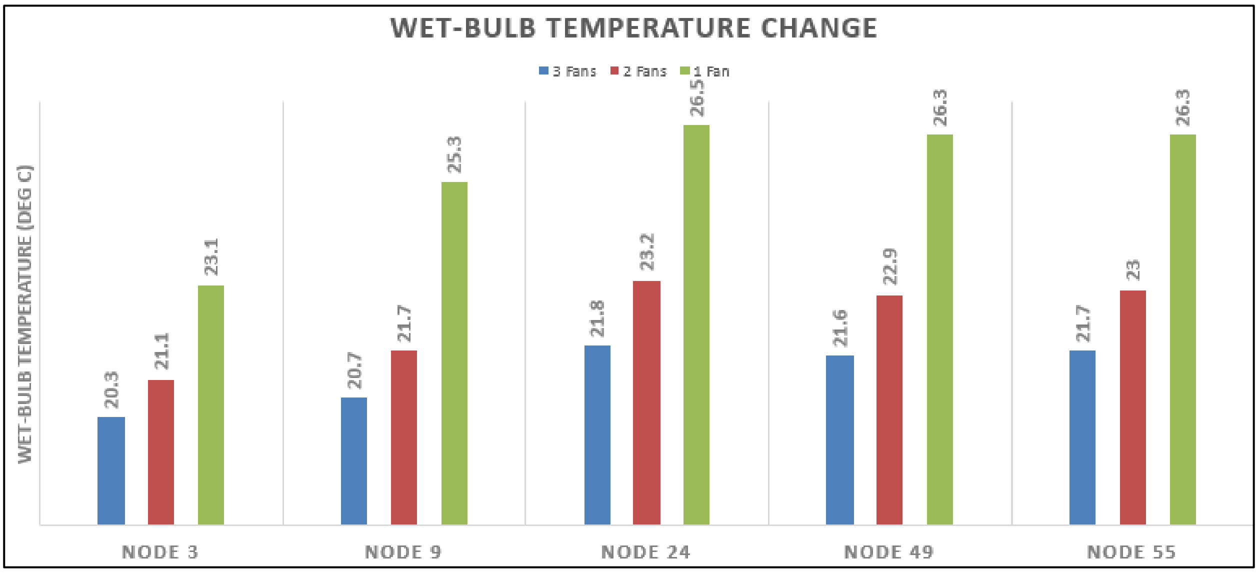


Figure 4-6: Mine B Temperature Change with 1 Fan Off

The bar graph in Figure 4-7 shows the humidity of the five different nodes. An increase in humidity can clearly be seen. As with the temperature, the increase in humidity when only one fan was switched off was not as big as when an additional fan was switched off. When only one fan was in operation, three of the five locations had relative humidity reaching almost up to a 100%.

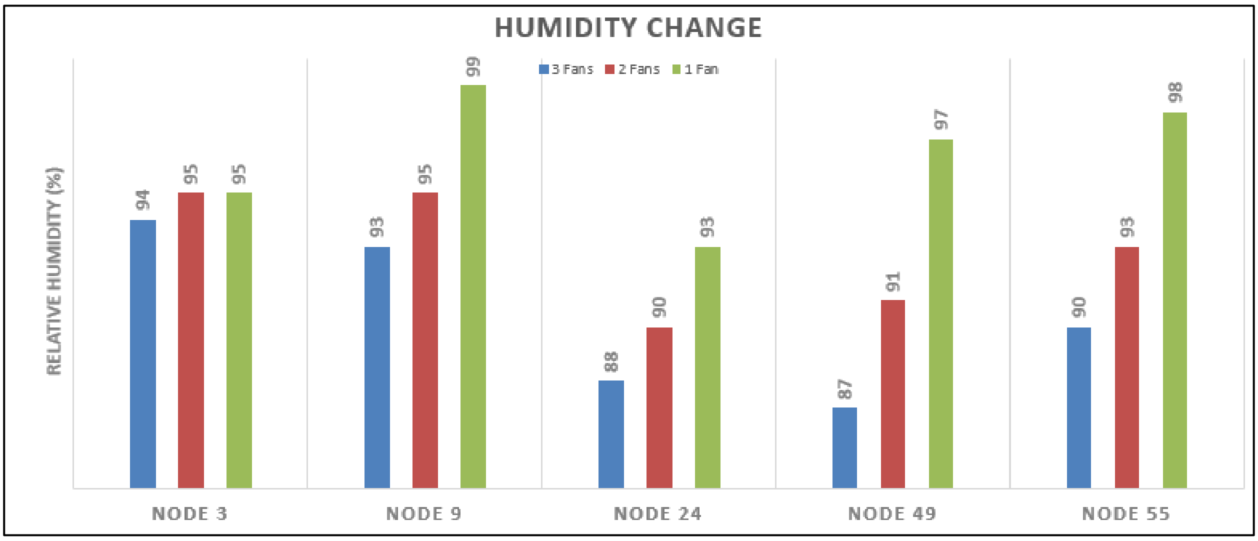


Figure 4-7: Mine B Humidity Change with 1 Fan Off

The bar graph in Figure 4-8 shows the velocity of the five different nodes. A decrease in velocity can clearly be seen. A significant decrease in velocity was especially noticed when only one fan was in operation.

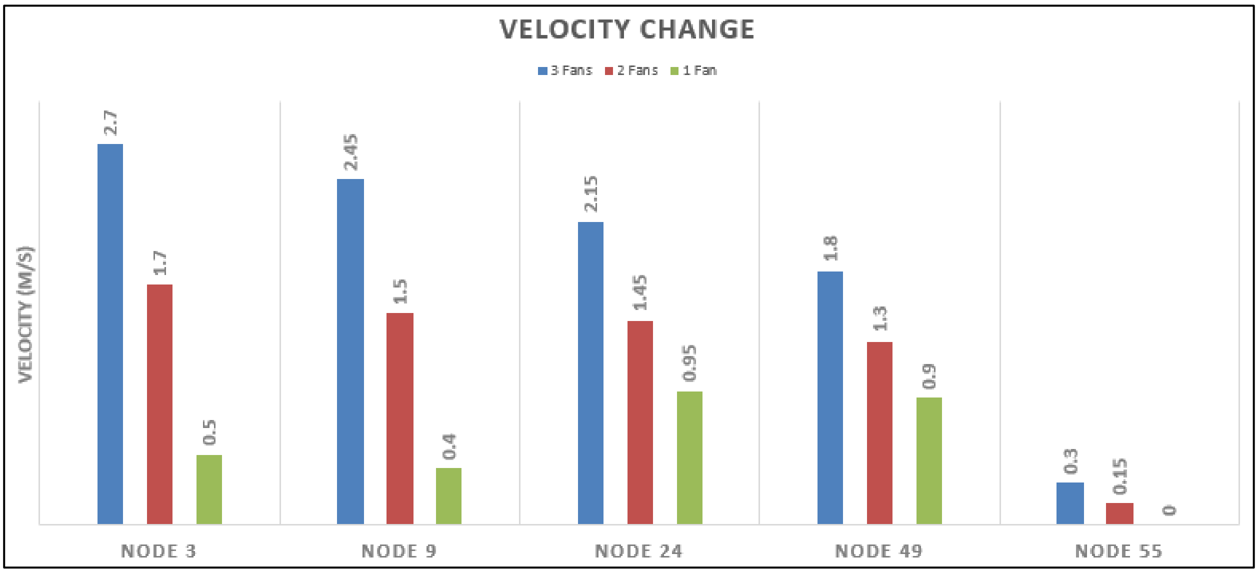


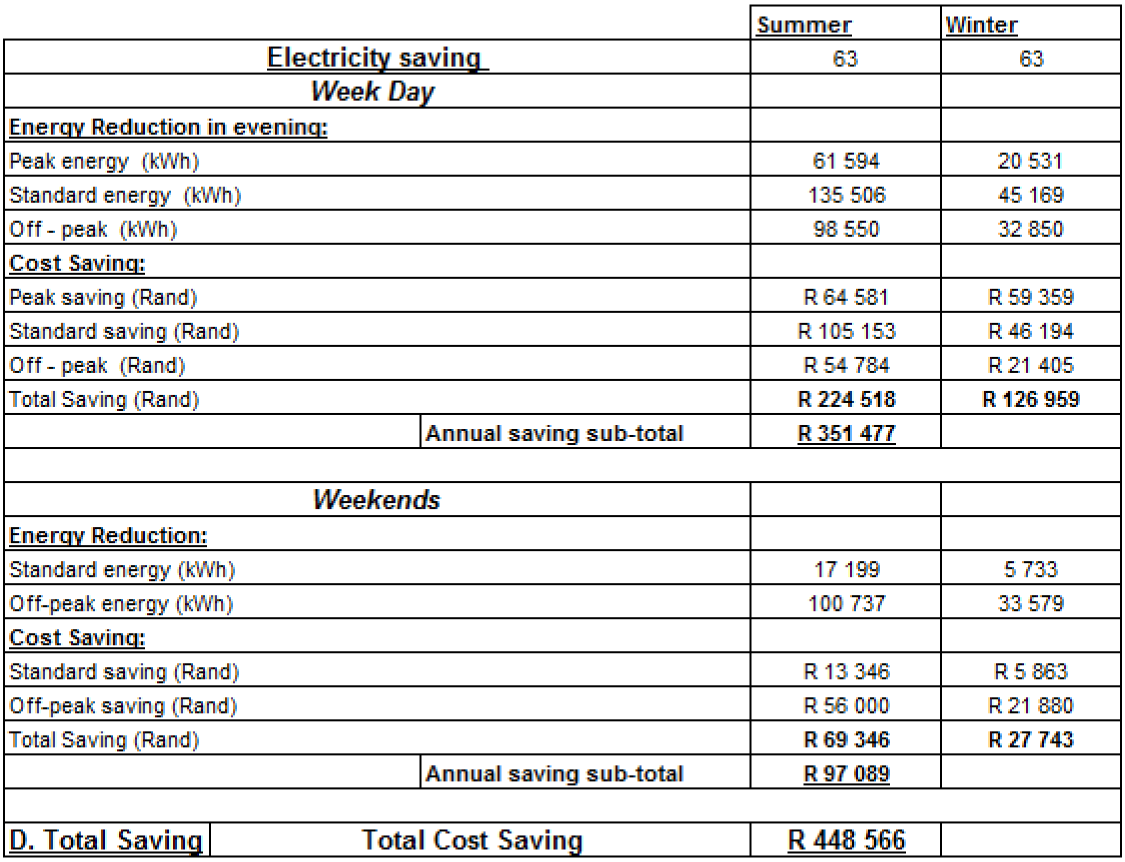
Figure 4-8: Mine B Velocity Change with 1 Fan Off

4.3 Mine B Energy and Cost Saving Analysis

Costs were analysed for part of the scenario where the underground environmental conditions were acceptable. Doing this allowed the successful prediction of what potential cost savings could realistically be achieved.

Permanently switching off one fan would result in a power reduction of 63 kW (fan absorbed power) which amounts to a total of 551 448 kWh of electrical energy per annum. When the Eskom megaflex pricing structure is considered, the savings that can potentially be achieved amounts to R 449 000 per year. This calculation is shown in the table below:

Table 4-2: Saving Calculations for Mine B Scenario 1



		Summer	Winter
Electricity saving		63	63
Week Day			
Energy Reduction in evening:			
Peak energy (kWh)		61 594	20 531
Standard energy (kWh)		135 506	45 169
Off - peak (kWh)		98 550	32 850
Cost Saving:			
Peak saving (Rand)		R 64 581	R 59 359
Standard saving (Rand)		R 105 153	R 46 194
Off - peak (Rand)		R 54 784	R 21 405
Total Saving (Rand)		**R 224 518**	**R 126 959**
	Annual saving sub-total	**R 351 477**	
Weekends			
Energy Reduction:			
Standard energy (kWh)		17 199	5 733
Off-peak energy (kWh)		100 737	33 579
Cost Saving:			
Standard saving (Rand)		R 13 346	R 5 863
Off-peak saving (Rand)		R 56 000	R 21 880
Total Saving (Rand)		**R 69 346**	**R 27 743**
	Annual saving sub-total	**R 97 089**	
D. Total Saving	**Total Cost Saving**	**R 448 566**	

It is estimated that the annual cost of running three fans simultaneously would be approximately R 1 182 14. A saving of R 449 000 means that the operating costs of the fans are almost halved.

From the same table, it is calculated that R 97 000 (157 248 kWh) can be saved annually by switching off one fan only during weekends.

There are 5 peak hours every weekday. This includes three hours from 06:00 to 09:00 and again for two hours from 18:00 to 20:00 during summer months. During the three winter months, the time intervals shift to an hour later in the morning, which is then 07:00 to 10:00 and an hour earlier in the evenings, which is then 19:00 to 21:00. Switching off one fan during these hours will save 157 000 kWh of electrical energy and R 221 000 in energy costs.

Scenario 2 involves switching off one fan during weekday peak hours whilst the remaining two fans run permanently. This configuration will result in an electrical power saving of approximately 63 kW for 5 hours daily (excluding weekends). Annually, this amounts to 157 000 kWh of energy. When the Eskom megaflex pricing structure is considered, the savings that can potentially be achieved amounts to R 221 000 per year. This calculation is done exactly as in Table 4-2, except for the total number of hours being different. This equates to an approximate saving of 18.7%.

4.4 Conclusion

VUMA3D-Transient was used to simulate a certain path in Mine-B in order to determine what the effect of certain changes to the ventilation system might have on the mine's underground environmental conditions as well as the total ventilation energy usage.

It was determined that, with the current configuration of this mine, switching one or two fans will not create any risks regarding ventilation safety. The main surface fans provide most of the ventilation needs of the mine. The extra axial fans (which the study is based on) are only used to give the extra bit of ventilation needed. Running only one fan would be suffice for this purpose, this is one of the reasons why the study was suggested to be on this mine. If further research is conducted it might be proven safe to permanently switch off these fans without creating safety issues and ultimately save on ventilation electrical energy consumption costs.

CHAPTER 5 - CONCLUSION

5.1 Conclusion

It has been proven that the effects of ventilation configuration changes can be predicted accurately with the aid of simulation software. This enables ventilation engineers to make use of this software to determine what future underground conditions will be by simulating different scenarios before any actual changes are applied. Using this in conjunction with Eskom's DSM initiative the engineer can develop different strategies such as reducing fan consumption during peak hours. Specifically looking at axial fans, fan consumption can be reduced by means of VSDs, utilising IGVs or by completely switching off a fan during peak hours.

The software accuracy was tested on Mine A. Ten sensor locations provided environmental data which was used in the simulation software. Two scenarios were monitored and compared to confirm that the accuracy of the software is the same, or relatively close, in all circumstances. After confirming that the software was valid to use in the prediction of future underground environmental conditions, the software was used to make predictions on Mine B to fulfil the primary objective, which is saving electrical energy.

The accuracy of the software was determined by comparing actual underground environmental measurement data to simulated data. The margin of error for the velocity concluded to be at 24%. The reason for the high margin error can be attributed to the difficulty in measuring velocity to a constant value. Another reason why the margin is high is that not all obstructions in the ventilation system are accounted for in the simulation, these obstructions have an influence on the velocity and may cause turbulent airflow around the sensor.

The margin of error for the WB temperature was much lower than that of the velocity. Temperature measurements are more stable in the sense that it does not fluctuate as much as velocity measurements. With the fans in operation, the margin of error was calculated to be 4%, while the margin of error was 7% with the fans off.

Cost saving predictions were based on simulations that allowed for energy savings, but also provided safe working conditions. The simulations used for this research were based on a specific section of Mine B. The five locations that had the highest temperatures in Mine B were focussed on. The conclusion was made that when one of the three 75 kW fans was switched off during peak hours (or even permanently) cost savings of up to R 449 000 (552 000 kWh) can be achieved annually whilst operating within the specified mining environmental condition limits. R 97 000 or 157 000 kWh can be saved by switching off one fan every weekend. When switching off one fan only during peak hours, savings of R 221 000 can be obtained.

Sufficient ventilation is available from the main surface fans to maintain safe mining conditions when the axial fans (which the study is based on) is switched off completely for a short period, for instance during peak demand hours. Further study may suggest that these fans can be permanently switched off to maintain the predicted savings. The savings will also grow annually with the projected Eskom price increase.

5.2 Recommendations and Future Work

Due to some technical difficulties that were experienced on Mine B, VUMA3D-Live could not have been successfully integrated within the mine. It is proposed that this task has to be completed in order to obtain live data from underground which will ultimately be used to compare with transient data. In this manner, the most accurate results will be obtained.

Comparisons can then also be made between the results for the live data, as well as the transient data for both mines. More data to compare will ultimately result in more accurate prediction with the help of VUMA3D-Transient.

Furthermore, in depth analysis of the ventilation system configuration and layout can be conducted to determine the most energy efficient result. Tools such as VSDs, Eskom DSM initiatives and IGVs need to be taken in consideration, as well as other similar means of reducing electrical operational costs. Various simulations with different ventilation configurations can be compiled to create a better understanding of the options that are available.

Further research can also be done on Mine B to prove that the fans on which the study is based be switched off permanently. This may depend on current and future mining plans. The mine is currently under care and maintenance for an indefinite period. If a study is conducted soon, significant amounts of energy can be saved.

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