MODELLING OF THE VENTILATION SYSTEM USING VENTSIM CONSIDERING THE FULL MINE MECHANIZATION DRIVE AT KONKOLA COPPER MINES

By

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Declaration

I, Dzwiti Kudakwashe, do declare that I am the author of this work. To the best of my knowledge and belief this dissertation contains no material previously published by any other person except where due acknowledgement has been made. This dissertation contains no material that has been previously submitted for the award of any other degree or diploma at this University or any other institution for academic purposes.

Signed:………………………………..   Date:………………………………..

Approval

This thesis of Kudakwashe Dzwiti is approved as a fulfillment of the degree of Masters of Mineral Science-Mining engineering of the University of Zambia

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Abstract

Konkola Copper Mines Plc (KCM) is undergoing full mechanization drive aimed at increasing levels of production from the current 2.4 million tonnes to 7.5 million tonnes per annum. The mechanization of the mines will provide a large potential for reduced costs and improved profits, while at the same time lead to increase in the demand of mine ventilation as more quantities of air has to be provided in order to meet levels of mechanization and to comply with government statutory requirements.

The continually rising energy costs and the fairly recent introduction of stricter legislation limiting exposure levels of miners to pollutants such as diesel particulate matter (DPM) have resulted in more complex mine ventilation networks, which cannot be solved by traditional methods currently being employed at KCM.

Therefore, this study was undertaken with the objective of modelling an effective and efficient 3D animated mine ventilation model for Konkola Copper Mines using a simulation program Ventsim Visual. The model has been developed with the intention of introducing a computer based computation and management of the ventilation system which is fast, easy and accurate over the traditional methods currently used at the mine. The study has highlighted how the developed model can be used for fault-finding of a problem area in the mine and options analysis for resolution of such problems.

Results of study indicate that it is possible to significantly reduce the mine ventilation operation costs under the current mechanization drive without compromising exposure levels. Using scenario 2 (20 years mine life), the study has established that 60 airways can be optimized to reduce cost with potential savings of about $1,715,158 and annual power saving of $355,659 respectively.

Acknowledgements

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Sincerely, I would like to thank the Chief Execute Officer, Steven Dean, management and staff of Konkola Copper Mines plc for their support and for permitting access to the underground operations and mining activity data for this research work.

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List of acronyms

Abbreviation	Description
CSV	Character Separated Variables
DXF	Drawing Exchange Format
DPM	Diesel Particulate Matter
WHO	World Health Organization
MSHA	Mine Safety and Health Administration
LHD	Load Haul Dump
VOD	Ventilation on Demand
STR	String format
KCM	Konkola Copper Mines
VFD	Variable Frequency Drive
bhp	brake horse power
cfm	cubic feet minute

CHAPTER 1 INTRODUCTION

1.1 Introduction

Ventilation plays a major role during the development and the operation of all underground workings. The ventilation system is designed based on the air contaminants generated, and location of the mining activities. The ventilation system of every mine should be designed to deliver large quantities of fresh air to all working areas and adjust to varying conditions. Generally, there are two different types of mine ventilation: natural and the artificial ventilation. Natural ventilation is controlled by nature while artificial ventilation is controlled by mechanical devices such as fans, regulators and seals to control the airflow through the underground network of airways. At Konkola mines, ventilation of the mines is usually done by artificial means more especially that mining is done at great depth.

Currently, Konkola Copper Mines Plc is undergoing full mechanization drive aimed at increasing levels of production from the current 2.4 million tonnes to 7.5 million tonnes per annum. While mechanization of underground hard rock mines provides a large potential for reduced costs and improved profits (Robbins, 2000), it however, leads to increase in the demand of mine ventilation as more quantities of air has to be provided in order to meet levels of mechanization and to comply with government statutory requirements. This results in operating costs of mine ventilation increasing in terms of energy consumption by primary and secondary fans. The current mechanization drive being undertaken at Konkola Copper Mines, means that it will require the use of software package in the design of effective and efficient ventilation systems to match the mechanization drive so as to come up with optimum solutions that will help in minimizing the operating costs of the ventilation system.

1.2 Problem statement

Konkola Copper Mines is expanding laterally and deeper as they extract deep ore reserves and this is increasing a load on the mine ventilation system. With the down fall trend of mineral prices, the mine needs to increase its production to keep the business profitable. With this in mind, the mine is fully mechanizing by employing high-powered machines which impose an increased burden on the ventilation system. Therefore, the ventilation system needs to be designed and operated efficiently to meet the underground demands.

Considering power demands alone, current mine ventilation practices lends ventilation to be the largest energy user in kWh per tonne of ore through the primary and secondary fans. (CEMI, 2009) This is because the ventilation system is designed upon peak air volume demands based upon diesel exhaust dilution or heat criteria and is operated at this maximum level regardless of true ventilation requirements. Despite the current full mechanization drive and mine expansion going on at the mine, ventilation personnel are still using the traditional manual methods, thereby handling large volume of datasets which are difficult to analyze and calculate.

In order to overcome the above challenges, there is need to use Ventsim Visual software which is capable of handling large volume of data and processing it with high accuracy. The software once employed will help in modelling and simulation of the effective and efficient ventilation system at the mines. It will also help in reducing the ventilation cost of the mines through optimizing of power consumed by the primary and secondary fans.

1.3 Research objectives

Main objective

To model the ventilation system using Ventsim Visual software at Konkola Copper Mines Plc considering the full mine mechanization drive.

Sub objectives

- To review current ventilation system at Konkola mines;
- To design an effective and efficient mine ventilation system using Ventsim;
- To optimize the primary and secondary ventilation system to provide adequate air quantity and quality air at the minimum possible cost to boost production; and
- To simulate the future mine ventilation networks so that future airways and fans required can be determined, constructed or acquired in time.

1.4 Research questions

In trying to achieve the above mentioned objectives, the following research questions need to be answered.

a) Can the lapses in the current ventilation system design be overcome without the use of Ventsim?
b) Can Ventsim be applied to model an efficient and effective ventilation system?
c) Can the operating cost of the mine ventilation system be minimized by application of Ventsim and to what extent?
d) If the mine is to be fully mechanized, will the ventilation system be able to meet the demand without violating the government statutory requirements?
e) Can Ventsim be used to simulate long term and short term mine ventilation networks?

1.5 Methodology

To achieve the above mentioned research objectives the following research design will be used. The research will be more of quantitative as a lot of numerical data will be gathered through underground operation surveys to acquire the parameters that will be used to come up with the model. The researcher will do an extensive review of the established literature to gain more knowledge about mine ventilation. Case studies of the application of Ventsim Visual will be evaluated to fully understand how to use it for the modelling and simulation of the ventilation system. Structured interviews will be carried out with the mine ventilation personnel. From the interviews, the researcher will identify gaps that will be addressed by the introduction of a computer aided software Ventsim.

Data that need to be used in designing the model will be obtained through ventilation survey. This will encompass doing underground ventilation surveys (pressure surveys and airflow surveys) to obtain data such as pressure differences, airflow velocity, airflow quantities, airway dimensions etc. To develop a ventilation model that does not result in cumbersome problems, the ventilation network will be developed using Surpac computer software and Surpac strings will be imported into Ventsim. Ventsim will be used to do the modelling of the mine, simulations to optimize the ventilation system and review of the long and short term mine plans.

1.6 Significance of the study

Konkola Copper Mines Plc is currently undertaking mechanization drive for the mines in order to boost its production. The mechanization drive once fully implemented will in turn increase the burden on the ventilation system requirements needed to maintain an acceptable working environment. Currently, the ventilation system consumes approximately 41.8% of the total mine energy, which shows that there is need to reduce this energy consumption for the mine by introducing efficient ventilation system to realize more profits.

The traditional manual methods currently employed at the mine for determining ventilation parameters has resulted in difficulties in processing large volumes of data thereby making it difficult to come up with proper ventilation system.

Therefore, there is need to introduce Ventsim software to handle large quantities of data and increase the speed and accuracy of data calculations, analysis of system in real-time, graphical display laneway in order to help the workers to understand the status of mine ventilation and allow for efficient and effective design and operation of the mine ventilation system.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter addresses an overview of the theoretical literature on planning and designing the ventilation system of the mine. It gives a general summary of how the ventilation parameters are calculated and used in the design of mine ventilation system. It establishes the basis and sets out the framework for developing an effective and efficient mine ventilation system.

2.2 Overview of Konkola Copper Mine ventilation system

Konkola mine uses an antitropal system whereby the airflow and transported ore move in opposite directions. The primary mine ventilation network utilizes an exhausting system. This type of a setup has a lot of advantages which includes easy installation, testing, access as well as maintenance and will also protect the fan in case of an emergency situation. The main fans are connected to the upcast shafts so that they suck out foul air out of the mine thereby creating a negative pressure in the mine which results in fresh air flowing through the downcast shafts. The mine is divided into six different sections, Bancroft Deep, Bancroft Central, Bancroft North, Bancroft Flats, Bancroft Extension and Bancroft East.

The mine has eight main surface fans, five of them being centrifugal fans and three being axial fans. Currently the mine is operating four main surface fans as a way of minimizing the energy consumption of the fans. Table 2.1 shows the upcast and the downcast shafts used at the mine.

Table 2.1 Upcast and downcast shafts

INTAKE/DOWNCAST	UPCAST
SHAFT 1	VS1A
SHAFT 3	VS1C
SHAFT 4	VS1E
VS1B	VS3A
VS1D	VS3C
VS3B	VS3E
PIPE SHAFT	
PORTAL	

Three axial fans are connected in series on Ventilation Shaft 3E (VS3E) and only two are in operation as one is on standby. The exhaust ventilation shaft is located at the central part of the mine in order to exhaust foul air from both the southern and northern section. Each fan at VS3E have the following specifications:

- Power rating = 2.6 MW
- Air quantity handled = 300m^3/s at 2.4 kPa

The rest of the exhaust shafts are mounted with centrifugal fans, each fan having a power rating of 2.4MW, handling air quantity 220m^3/s at 3.7kPa. Table 2.2 shows the type and number of fans mounted on each exhaust shaft and fans which are in operation.

Table 2.2 Surface exhaust fans mounted on the upcast shafts

EXHAUST SHAFT	TYPE OF FAN	NUMBER OF FANS	REMARKS
VS1A	Centrifugal	1	Switched off
VS1E	Centrifugal	1	Working
VS3A	Centrifugal	1	Switched off
VS3C	Centrifugal	2	One on standby
VS3E	Axial	3	One on standby

The total airflow quantity supplied to the mine is $1040m^3/s$ ($440m^3/s$ from two centrifugal fans and $600m^3/s$ from two axial fans).

Booster fans of capacity 75KW assist the through-flow of air in discrete areas of the mine and auxiliary fans are used to overcome the resistance of ducts in blind headings. They are installed to pressurize and direct air to the active workings. Regulators are used to reduce the flow rate in the less resistive airways and increase the availability of fresh air for other workings. The mine sunk shaft 4 referred to as Konkola Deep so as to access deep ore reserves. This will require proper ventilation design to supply adequate air to the new developed areas and to seal all the old workings to avoid short circuiting of air.

2.3 Review of general underground ventilation system

Underground ventilation system is needed to provide airflows in sufficient quantity and quality to dilute contaminants to safe concentrations in all parts of the facility where personnel are required to work or travel. (McPherson, 1993) The quantity and quality of air supplied is largely dependent on the efficiency of the ventilation system being employed at a particular mine. Therefore, every mine must ascertain that monitoring of ventilation conditions underground is undertaken regularly not only for the purpose of compliance with the statutory requirements but also to be proactive in contributing to the efficient running of the mine. An effective ventilation system will ensure that excessive heat, temperatures, dust and gases in the mine are taken care of.

Planning and installation of an underground mine ventilation system is a complex and sometimes hardly manageable task. This initial design of the ventilation system encompasses balancing of many factors with health being of paramount importance. Once this system has been installed, it needs to be expanded and adapted during the whole lifetime of the mine. There are two different types of ventilation, the natural ventilation and the artificial ventilation. The natural ventilation is normally controlled by nature sometimes without any human influence, the artificial ventilation is generated by man-made installations like fans. The natural ventilation depends on the differences in the air density which cause a drop of pressure that increases with the temperature and the depth (Anna, 2013).

2.4 Basic principles of mine ventilation

Figure 2.1 shows how fresh air principally enters an underground mine through one or more downcast shafts, drifts (slopes, adits) or other connections to the surface. From the intake airways, it flows to working areas, where most of the pollutants are added to the air.

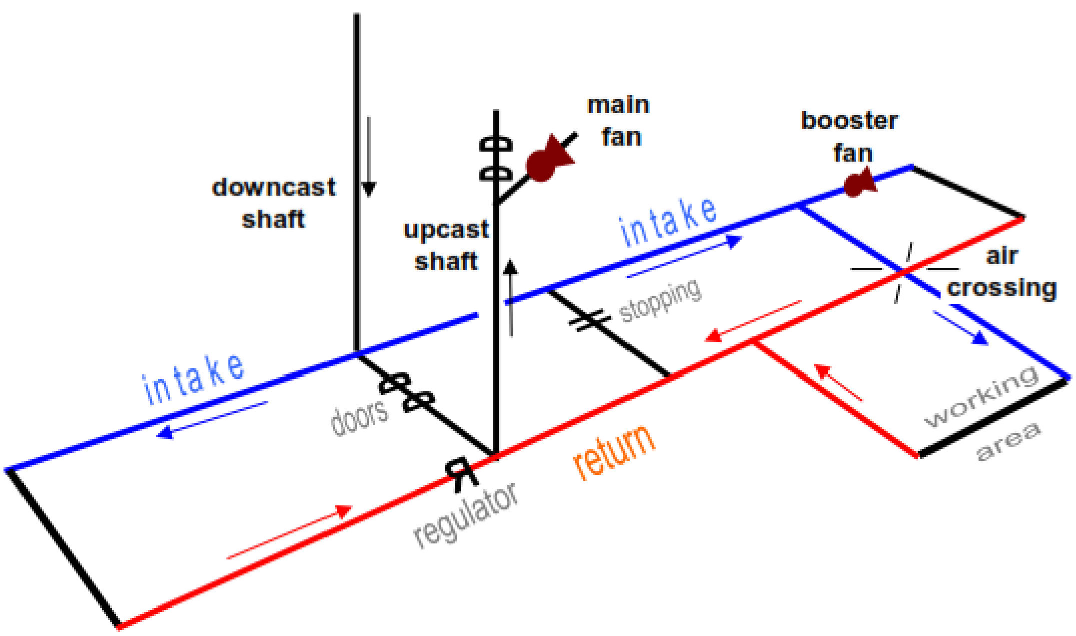


Figure 2.1 Typical elements of a main ventilation system (McPherson, 1993)

The foul air is then exhausted through the system along return airways and finally back to the surface through upcast shafts, or through inclined or level drifts. Contaminants that are added to the air on its way through the system include dust, toxic and explosive gases as well as heat, humidity and radiation. Usually the amount of toxic gases is limited to so called threshold limit values (TLV) which are adapted to the amount of gas a worker can be exposed to during his work time without endangering his health (McPherson, 1993).

Figure 2.1 also illustrates the installation of fans in order to supply fresh air to the system. Main fans, singly or in combination, either exhaust (pull) air or force (push) air into and through the system. So air that passes through the mine can be controlled by regulating the main fans. The location of main fans depends on several factors. Most of the mines in the world locate main fans on the surface. In coal mines, the location of the main fans can be legally obligated. Locating fans on surface facilitates installation, testing, access as well as maintenance and will also protect the fan in case of an emergency situation. Fans are normally installed underground when fan noise is to be avoided or shafts must be available for hoisting or free of airlocks. A problem associated with underground main fans arises from the additional doors, airlocks and leakage paths that then exist in the subsurface (McPherson, 1993).

In designing the mine ventilation infrastructure, a primary decision is whether to connect the main fans to the upcast shafts, that is, an exhausting system or, alternatively, to connect the main fans to the downcast shaft in order to provide a forcing or blowing system. These different choices can be illustrated as shown in the Figure 2.2:

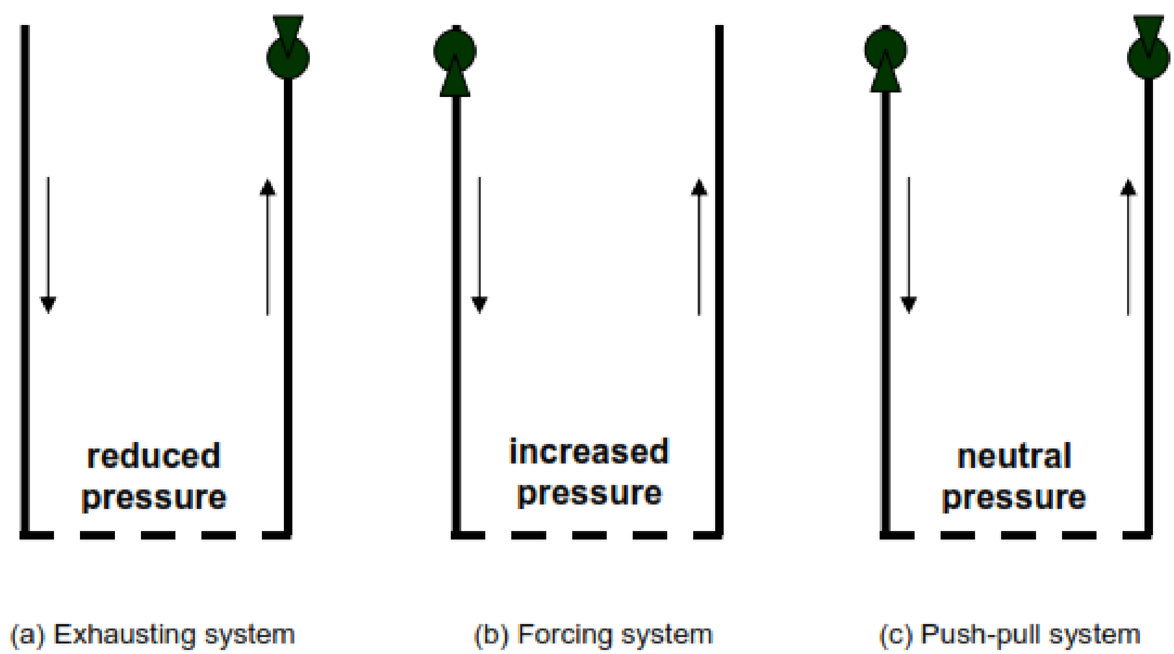


Figure 2.2 Possible locations of main fans *(McPherson, 1993)*

The decision of locating the main fans may be based on concerns like gas control, transportation, and fan maintenance and fan performance. As shown from the Figure 2.2, the subsurface air pressure is depressed by the operation of an exhausting main fan but is increased by a forcing fan. The choice of an exhausting or forcing system producing a few kilopascals will have little effect on the rate of gas production from the strata.

The pressure difference has a negligible influence on the rate of strata gas production but there is the danger of accumulation of gas in worked out areas, relaxed strata and voidage that are connected to the main ventilation system but not directly part of the system. These accumulated gases are at near equilibrium pressure with the adjacent airways. Therefore, any reduction in barometric pressure within the ventilation system will consequencely lead to the isothermal expansion of the accumulated gases and produce a transient emission of those gases into the ventilation system. This takes place naturally during periods of falling barometric pressure on the surface. Unusual heavy emissions of methane or deoxygenated air may be expected during these periods (McPherson, 1993).

The steady state operation of either exhausting or forcing fans will create no changes of air pressure in the subsurface. Nevertheless, the barometric pressure throughout the ventilation system will fall rapidly when the forcing fan stops. Accumulations of voidage gas will expand and flood into the working areas causing a peak concentration of gases. This is not the case when main exhausting fans stops, air pressure in the system increases, compressing accumulations of gas and no peak concentration of gas will occur in the airstream. When the main exhaust fan restarts, the sudden reduction in barometric pressure will then cause expansion and emission of accumulated gas. However, this occurs at a time of full ventilation and the peak of gas concentration will be much less compared to that one caused by stoppage of a forcing fan (McPherson, 1993).

The push-pull system shown in Figure 2.2 is a combination of main forcing and exhausting fans. A primary application of a main push-pull system is in metal mines employing caving techniques and where the zone of fragmented rock has penetrated through to the surface. The concept of maintaining a neutral pressure underground with respect to surface reduces the degree of air leakage between the workings and the surface. This is particularly important if the rubberized rock is subject to spontaneous combustion.

2.4.1 Air distribution and control

Air distribution is the supply of air in desired quantities to different working areas in an underground mine. It is successfully done by adopting a ventilation method and plan suitable for the mining method to be employed in exploiting the mineral deposit. Effective distribution of air ensures that both direction and quantity of airflow are controlled. Ventilation is said to be inefficient if the fresh air is not properly distributed to the active areas where it is required to maintain wet-bulb temperatures below the Threshold Limit Value (TLV) and dilute/remove contaminants.

The airflow delivered to the mine has to be carried through the underground network of airways to the destination where it is required. Successful air distribution can be achieved through optimal selection of the location of control devices and of fans. This results in several installations like stoppings, ventilation doors, seals and additional fans to handle air to the working places. During the development of a mine, there are connections made between intakes and returns which are later often not required anymore and should be blocked by stoppings in order to prevent short-circuiting of airflow. These stoppings are constructed from masonry, concrete blocks and fireproofed timber blocks or can also be employed as prefabricated steel stoppings. In weak strata or coal mines, it is important that stoppings are well keyed to the roof, floor and sides.

To prevent or minimize leakage, the high pressure face of the stopping can be coated with a sealant material and particular attention paid to the perimeter. If the strata is weak and chemically active, the coating should be extended to the rock surfaces for a few meters back from the stopping. There are several opportunities to avoid premature failing or cracking like for example sliding or deformable panels on prefabricated stoppings or so called "crush paid" at the top of the stopping. In all cases, stoppings are required to be fireproof and should not produce toxic fumes when heated (McPherson, 1993).

Abandoned mine areas are isolated by seals which are constructed at the entrances of the connecting airways. In case of coal mining, they have to be explosion-proof and therefore can consist of two or more stoppings, 5 to 10 meters apart, with the intervening space filled with sand, stone dust, compacted non-flammable rock waste, cement-based fill or other manufactured material. Steel girders between roof and floor can be used to add structural strength. In weak strata it may be necessary to grout the surrounding rock strata (McPherson, 1993).

2.4.2 Mine resistance

The concept of airways resistance is of major importance in subsurface ventilation engineering. The square law $\mathbf{p = RQ^2}$ shows the resistance, **R**, to be a constant of proportionality between frictional pressure drop, **p**, in a given airway and the square of the airflow, **Q**, passing through it at a specified value of air density. The parabolic form of the square law on a **p, Q** plot is known as the airway resistance curve.

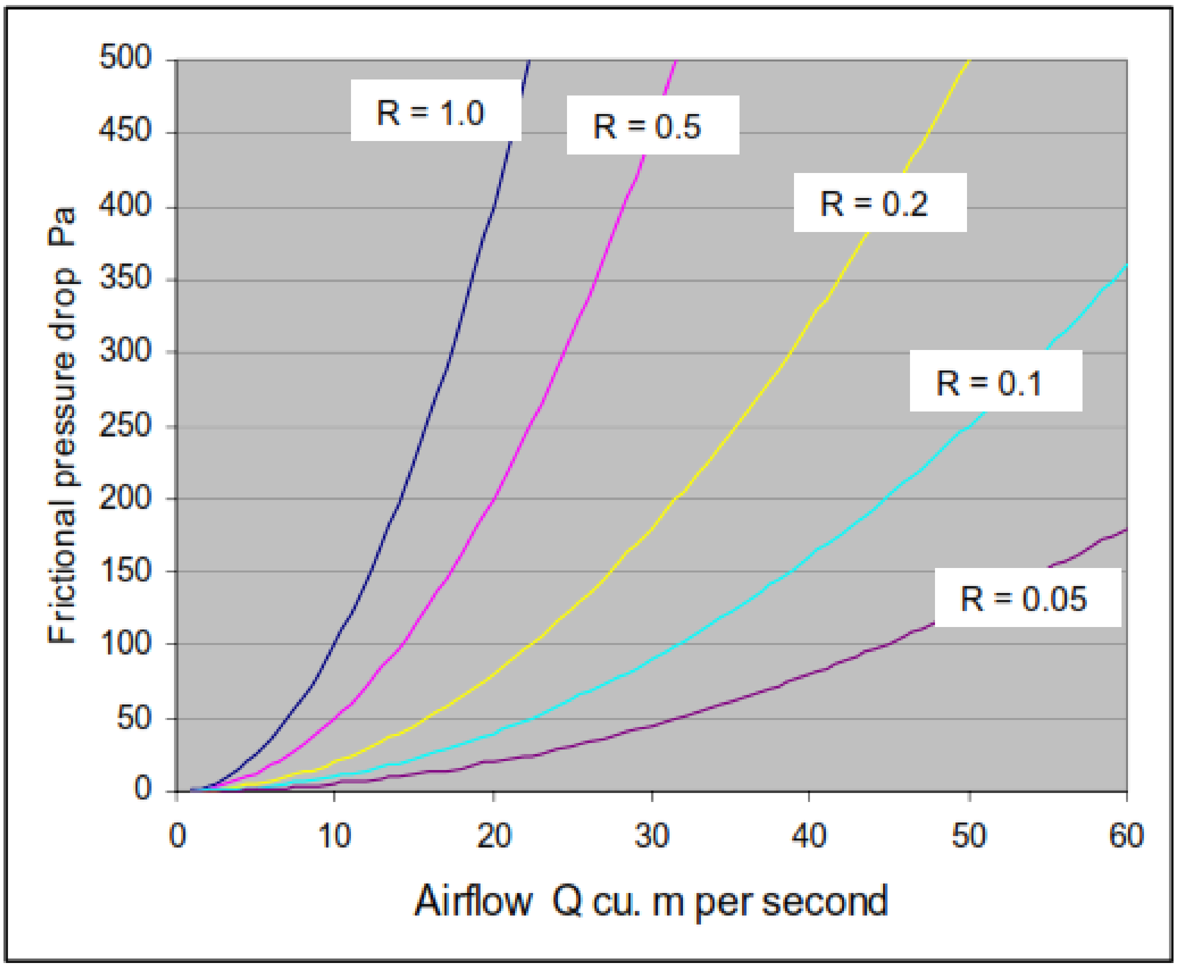


Figure 2.3 Airway resistance curves *(McPherson, 1993)*

Therefore, the total operating cost of a complete network is the sum of individual airway costs. The operational cost of ventilation is proportional to the resistance offered to the passage of air, for any given total airflow requirements. This resistance depends upon the size and number of the openings and the manner in which they are interconnected. Certain factors such as ground stability, air velocity and economics limit the sizes of airways. The resistance to airflow of these systems demands for efficient maximum utilization of air volumes necessary to maintain a safe and healthy underground atmosphere. This can be attained only by the proper distribution and control of adequate air volumes. Although there is no ideal or standard system of mine ventilation, the effectiveness and efficiency of the system will be determined by how well certain fundamentals are applied and maintained.

2.4.3 Recirculation and leakage of air

It is of great importance to design a subsurface ventilation system that minimizes leakage potential and to maintain the system in order to control that leakage. The intake and return airways or groups of airways should be separated geographically or by barrier pillars with a minimum of interconnections. This is done to avoid leakage of air between airways which results in a low volumetric efficiency of a mine. The volumetric efficiency (VE) of a mine is calculated using the following equation:

$$VE = \frac{Airflow\ usefully\ employed}{Total\ airflow\ through\ main\ fans}\ x\ 100 \qquad (1)$$

Where the ‘Airflow usefully employed’ is the total sum of the airflows reaching the working faces and those used to ventilate equipment such as workshops, electrical gear, pumps or battery charging stations. The volumetric efficiency of the mine varies from 75 percent down to less than 10 per cent.

A prerequisite in leakage control is that all doors, stoppings, seals and air crossings should be constructed and maintained to a good standard. If a stopping between a main intake and return airway is carelessly holed in order to insert a pipe or cable without necessary repairs, it may be a source of excessive leakage. It is the most common cause of inefficient distribution of air in underground mines. Leakage of air is more likely to occur at fan installations, in caved ground, in shafts between downcast and upcast compartments, at stoppings or doors in cross cuts between adjoining airways.

Recirculation of air is normally caused by leakage of return air, and results in an excessive load on the fan. The load on the fan can be minimized if precautions are taken to ensure an air-tight installation. It also happens when air is kept within a closed circuit and should not be confused with the situation when air is reused, as in series ventilation circuits. Recirculation provides challenges in the control of temperature-humidity of air in hot humid mines.

2.4.4 Adequate ventilation

One of the first steps in planning a mine ventilation system is the determination of the amount of fresh air which is required to be delivered to guarantee safe working conditions in the subsurface. During the calculations, the people working in the mine as well as the combustion engines operating underground need to be carefully weighed. The complexity of subsurface mine ventilation is not only caused by the mathematical and physical laws, which need to be considered, but also by the plenty geological influences on every specific mine

The quantity of air required to adequately ventilate active areas underground depends on factors such as the amount of explosives used, quantity of heat emitted into the ventilating air by various sources of heat, number of miners underground and various gases emitted by the rock. The Zambia Mine Regulations stipulate the conditions to be met for fresh air supplied to the working areas and travelling routes to be regarded as adequate.

Mining Regulations 902 (2) states that ventilation shall be deemed to be adequate if it:

a) Ensures that the amount of oxygen in the general body of air is not less than nineteen per centum by volume;
b) Ensures that the amounts of carbon dioxide, carbon monoxide, nitrous fumes, sulphur dioxide and hydrogen sulphide in the general body of the air do not exceed the quantities set out against each such gas in column 2 (Appendix A) in the Second Schedule to these Regulations;
c) Dilutes or removes any other toxic gas or fume so that the amount of such gas or fumes in the general body of the air conforms to the requirements prescribed, from time to time, by the Chief Inspector;
d) Dilutes or removes any harmful dust so that the amount of such dust in the general body of the air conforms to the requirements prescribed, from time to time, by the Chief Inspector;

e) Maintains working conditions free from dangerous temperatures at high relative humidities in the general body of the air; and
f) Provides any diesel unit with not less than 0.5 cubic meters of air per second per kilowatt for the purpose of diluting or removing any toxic gas or fume in the general body of the air at places where such diesel unit operates.

2.5 Ventilation planning

The planning of a mine ventilation addresses two major phases in the life of the mine. The initial stage is for a new mine when no actual structure is in place. The ventilation design at this stage will be based on the production rate, mine infrastructure (geometry) and consumers. The second stage occurs when the mine has been operational for a period of time and needs to be extended to access new ore zones, but must use the existing infrastructure. The design will be based on the same parameters as the initial stage.

In the second stage, the existing infrastructure will have a greater influence on the design of the new ventilation system. The new design will have to consider the existing infrastructure and the limitations imposed by existing fans and stoppings. Air leakages must also be part of this design. Each of the stages will trigger planning exercises that will need to satisfy criteria imposed by the quality and quantity of the air flowing in the mine (Cristian, 2010).

The underground mine environment is very dynamic and demands for ventilation planning exercises for any major change in the ventilation system. These major changes includes new production zones, old production zones that have become economical due to commodity appreciation on the market, or new ventilation structures (internal or external shafts, new or bigger fans, heaters, cooling systems). Most of these changes are integrated in the long term planning for production and based on the life of the mine scheduling.

The life of the mine schedule will show the time sequence of these changes and the parameters that are coupled to each infrastructure. It is very important to appreciate that in the planning department there must be two-way communication between the ventilation planning group and production scheduling group as each will have influence over the other. Based on this correlation, there will be multiple solutions and the critical path will be decided based on safety and economics (Cristian, 2010).

2.6 Ventilation system operations

All personnel must be able to conduct their work and travel within an environment that is safe and which provides reasonable comfort. The potential hazards during the development and operation of a mine arises from dust, gas emissions, heat and humidity, fires, explosions and radiation. (McPherson, 1993) The main method of controlling atmospheric conditions in the subsurface is by airflow. This is produced, primarily, by main fans that are normally, but not necessarily, located on surface. The main fans handles all of the air that circulates through the underground network of airways and underground booster fans serve specific districts only. To ventilate blind headings, auxiliary fans are used to pass air through ducts. The distribution of airflow in the mine is further controlled by ventilation doors, stoppings, air crossings and regulators.

The underground mine ventilation design and environmental control system is a complex process with many interacting features hence must not be treated in isolation during planning exercises. Most mine layout has been dictated by types, numbers and sizes of machines, the required rate of mineral production and questions of ground stability without initially taking the demands of ventilation into account (Ganguli & Bandopadhyay, 2004). This result in a ventilation system that may lack effectiveness and, at best, will be more expensive in both operating and capital costs than would otherwise have been the case. This has been noticed mostly on the size of shafts that are appropriate for hoisting duties but inadequate for the long term ventilation requirement of the mine. The consequences of inadequate ventilation planning and system design are premature cessation of production, high costs of reconstruction, poor environmental conditions and still too often, tragic consequences to the health and safety of the workforce. (Karoly-Charles Kocsis, 2009)

Underground ventilation system operated by electrical fans can account for a significant portion of a mine's energy consumption. Studies that were carried shows that the ventilation system in highly mechanized metal mines could be responsible for 40-60 % of the mines' energy consumption. Figure 2.3 shows typical contributions of different underground mining activities to total mine energy intensity and energy usage**.**

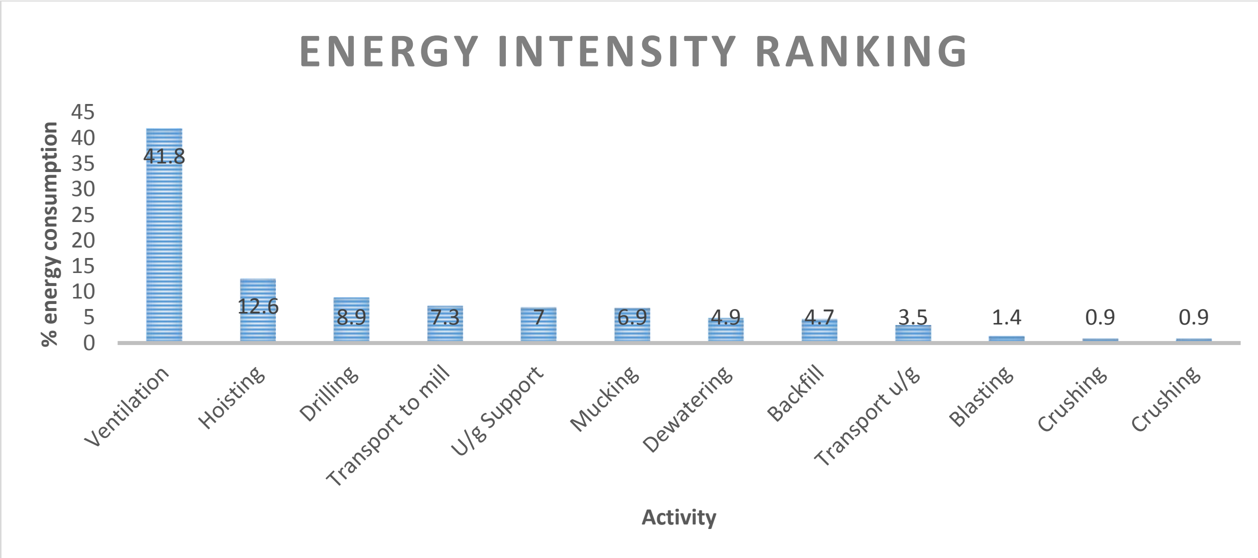


Figure 2.3 Contributions of different underground mining activities to total mine energy intensity and energy usage.

The underground ventilation systems are designed more towards the "worst-case-scenario" with respect to airflow demand, which usually occurs well into the future of a mine's operating life. (Karoly-Charles Kocsis, 2009) This results in the mine's intake air volume being well in excess of its "true" ventilation needs. These kinds of ventilation systems are inefficient and wasteful and this design approach needs to change if mines are to remain competitive by reducing the operating costs. (Karoly-Charles Kocsis, 2009)

2.7 Ventilation challenges in deep mines

The development of larger and more powerful machines for increasing higher production rates calls for increasing attention to mine ventilation planning. The changing of conditions in the mining industry such as higher production from fewer mines, low grade deposits, increasing depth of mines, extraction of thinner seams, and growing recognition of health and safety liability, have had a profound influence on mine ventilation planning and design of mines. Over the past twenty years, ventilation standards have risen steadily and stringent regulations have been enacted. It can also be seen that in the near future, ventilation requirements will become increasingly more demanding. The trend is a consequence of change in both mining conditions and equipment. (Ramani & Owili-Eger, 1990)

The extraction of minerals is growing deeper as shallow orebodies are depleting and as mines are looking forward to boost production to counter fluctuating mineral prices. The following trend can be observed:

- Mining operations are becoming increasingly mechanized,
- Mines are getting deeper, and
- Health and environment standards for the underground workers are becoming more stringent

2.7.1 The depth challenge

The depth of the mine can affect the ventilation economics in four different ways. Firstly, as the distance from surface to the production areas increases, the associated ventilation capital and operating costs will increase linearly. (Karoly-Charles Kocsis, 2009) This can be shown through a basic airflow relationship. For any given airway, this airflow relationship can be defined as:

$$P = RQ^2 \tag{2}$$

Where,

P = pressure differential (Pa)

R = resistance of the airway (Ns^2/m^8)

Q = quantity of airflow (m^3/s)

The frictional pressure drop (P) along an airway is a function of its length and this is because the resistance of the airway (R) is defined by:

$$R = k\frac{Lper}{A^3} \tag{3}$$

Where,

k = friction factor (kg/m^3)

L = airway length (m)

per = airway perimeter (m)

A = cross sectional area of an airway (m^3)

Moreover, the fan power required to overcome the frictional pressure losses along the airway can be defined as:

$$FP = PQ = RQ^3 \tag{4}$$

Where,

FP = fan power (W)

This shows that the fan power (FP) is linearly proportional to the resistance of the airway (R), hence the length of the airway (L). The fan power equation also elaborated that there is a cubic relationship between the fan power (FP) and the airflow current (Q).

Secondly, mine depth can affect the ventilation economics due to increased air leakage as the airways become older and more production levels are added to the mine's existing infrastructure. For example, as the production and development levels deepen, an addition of 10% to a mine's total intake air volume is required to compensate for leakage could increase the ventilation system's operating cost by 30-35%. (Karoly-Charles Kocsis, 2009)This calls for the need to manage and optimize the intake fresh air delivered underground.

Thirdly, as more intake air quantity is required to compensate for increased airflow leakage within the primary ventilation system, the pressure requirements from the primary fans and consequently the pressure differentials between the intake and exhaust airways would also increase. As a result, airflow leakage within the mines would further increase.

Fourthly, and mostly importantly, is that as the production workings deepen, the temperature of air in a mine will increase as a result of auto-compression of the air in the downcast airways and due to the heat transferred from the surrounding strata. This is normally unavoidable unless ameliorative measures are taken. To minimize this heat gain and to maintain the same cooling capacity of the air for the removal of machine heat, the intake air volume in the mine need to be increased with depth. This clearly shows that with increasing depth any increase in the mine's intake air volume can dramatically increase the ventilation system's energy consumption and consequently its operating costs.

2.7.2 The effect of increased mechanization

The productivity of mines can be greatly improved by the improvements in ventilation. Adequate supply of air to the mine workings has led to the introduction of high-powered machines to boost production. The required quality and quantity of air to be supplied to the mine workings is enshrined in the Mine Safety and Inspection Regulations. (Widzyk-Capehart & Watson, 2004)

Most of the mechanized mines consider the maximum number of diesel unit operating in each individual stope or development heading in assigning air quantities. The regulations states that the volume flow supplied must not be less than the sum of the volume requirement for the individual diesel units with the exception of light four wheel drive vehicles, drill jumbos and other diesel units of small engine capacity, operated intermittently. In highly mechanized metal mines the air quantity requirements are usually based upon diesel exhaust dilution criteria such as 0.04 – 0.06 m^3/s per kW of rated engine power (100 cfm/bhp). The airflow in any workplace in which a diesel unit is operated must be not less than 2.5 m^3/s.

When the diesel machinery was introduced in the mines, the mining equipment had diesel engines of less than 75kW (<100hp), and they were few in use. With time their numbers and engine sizes started to increase significantly. At first, the growth was in the primary haulage fleet, such as load-haul-dump (LHD) vehicles and haulage trucks. However, to ensure workforce mobility, the majority of underground workers now have access to a personnel carrier. For the haulage fleet, the capacity of the mining machinery and their diesel engines continued to increase. Large metal mines now are employing haulage trucks with 490kW (650hp) or more diesel engines (Karoly-Charles Kocsis, 2009)

Furthermore, the total required volume flow rate is specified with regard to the amount of exhaust gas emission in terms of the maximum rated engine output power. The increase in the number of machinery used underground increases the amount of diesel particulate matter (DPM) exhausted into the mine air. The World Health Organization (WHO) recognized the DPM as a carcinogen. The Mine Safety and Health Administration (MSHA) has recommended a number of control methods to help reduce DPM concentrations but a lot of mines are still struggling to remain complaint. A lot of recommendations by MSHA focuses on reducing the amount of DPM that is exhausted or created.

Some of the recommendations are:

(i) Purchasing low-emission engines
(ii) Improving engine maintenance
(iii) Using biofuels and,
(iv) Implementing after-treatments, such as passive regenerating ceramic filters

Other suggestions made focuses on reducing exposure through:

(i) Increased airflows
(ii) Improved barriers, for example, environmentally controlled equipment cabs, and,
(iii) Added administrative controls to limit a miner's exposure to DPM, e.g., reduced work hours in high-concentration areas or procedures to limit idling of equipment.

2.8 Heat sources in underground mines

Heat is emitted into the airways from various sources in the mine. Heat is normally the dominant environmental problem in deep metal mines and may necessitate the installation of large-scale refrigeration plant. In cold climates, the fresh air may require artificial heating in order to create conditions that are tolerable for both personnel and machinery. The four major heat sources in mines are the conversion of potential energy to thermal energy as air flows in the intake shafts or declines (auto compression), geothermal heat from the strata, machinery and production/development blasting (McPherson, 1993).

2.8.1 Auto compression

When air flows down in a shaft, some of its potential energy is converted to enthalpy producing increases in pressure, internal energy and hence, temperature. This is so because when air flows down the intake it is compressed hence rise in temperature. The increase in air temperature through a downcast shaft or other descentional airway is independent of any frictional effects. If there is no interchange in moisture content or heat into the airflow in the shaft, the compression occurs adiabatically, with the rise in temperature following the adiabatic law.

Accurate determination of the rise in temperature due to auto-compression can be challenging, mainly because of the non-adiabatic airflow that usually occurs in mine shafts and vertical excavations. This is so because air flowing in the shaft will concurrently pick up both strata heat and moisture along an intake shaft. Auto-compression can also be masked by the presence of other heating or cooling sources located in or close to the shaft such as air and water lines. (Karoly-Charles Kocsis, 2009)

2.8.2 Mining equipment

Machines operating throughout the mines, electrical transformers and fans are all devices that convert input power, via useful effects (i.e. work), into heat. Nearly all the energy consumed by a piece of mining equipment is transferred as heat to the airflow, since the power losses and most of the work done are converted directly or indirectly through friction into heat. The increase in mechanization and increase in the size of machinery used underground has resulted in such equipment being considered to be one of the major sources of heat. For electrical equipment, the total heat emitted is equivalent to the rate at which power is supplied.

The internal combustion engines of diesel machines have an overall efficiency of only one-third of that achieved by electrical units. This means diesel machines will produce nearly three times more heat than electrical equipment of the same mechanical work output. Nearly one-third of the heat generated by diesel machines appear as heat from the radiator and machine body, one-third as heat in the exhaust gases and the remainder as useful shaft power, which is also converted into heat through frictional processes. The major difference between diesel and electrical machines is that diesel machine produces part of their heat output in the form of latent heat.

2.8.3 Geothermal gradient (Strata)

When air is flowing through an airway, its temperature normally rises. This is caused by natural geothermal heat being transferred from the rock strata into the airway. The geothermal gradient varies according to the local rock strata's thermal conductivity and the depth of the excavation in the earth's crust (Gillies, et al., 2013). High percentage of heat transferred from the rock strata to the airway is realized in the working areas where rock surfaces are freshly exposed for example production blast, where the rock strata surfaces are often warmer than the air. As the airflow will be sweeping heat from the rock surfaces, the surfaces will cool down in time to reach an equilibrium point where the temperature of the rock surface will be a fraction of a degree centigrade higher than that of the air temperature.

The quantity of heat emitted to the air from the strata is also a function of depth. The rise in strata temperature with respect to depth is known as the geothermal gradient. In practical utilization, it is often inverted to give integer values and is referred to as the geothermal step. As the mine progresses deeper through a succession of geological formations, the geothermal step will vary according to the thermal conductivity and diffusivity of the local material. The geothermal gradient can be affected by the age of the rock, its thermal properties and its proximity to recent igneous activity (Karoly-Charles Kocsis, 2009).

2.8.4 Blasting operations

Over 75% of the explosive energy released during blasting is liberated in the form of heat. This makes blasting operations one of the significant source of heat in underground mines. Some of the heat liberated during blasting operations is stored within the blasting fumes, which can cause a peak heat load onto the ventilating air. The remaining heat is stored within the fragmented ore. The amount of heat stored within the fragmented ore depends upon the extraction method and the quality of ore fragmentation. Using electronic detonators and computer-controlled blasting, 40-50% of the heat produced by production and development blasts can be rapidly removed along with the blasting fumes (Karoly-Charles Kocsis, 2009).

2.9 Ventilation network analysis

The determination and distribution of the required air volumes to the production areas and throughout the mine is a very important component in the design of a new mine. It is very important to plan ahead during the operation of the mine so that new fans, intake and exhaust raises and other new infrastructures are available in a timely manner in order to efficiently provide the required airflow to the underground workings. The mine ventilation planning is a continuous process due to the dynamic nature of the underground operations with new orebodies and their production blocks under continuous development as older ones approach the end of their operating life (McPherson, 1993).

The design of a new ventilation system or optimization of the existing ventilation systems with the objective of minimizing ventilation redundancy within the production areas and throughout the mine requires the following questions to be asked (Hardcastle, et al., 2005)

- How many production areas in the mine are truly active? Are there any potential production workings, which due to planning or other operational reasons became temporarily inactive?
- In a production stope with multiple draw-points, can the auxiliary airflow be managed such that fresh air is delivered only to the draw point(s) where the fragmented ore is loaded and removed by LHDs?

- Does the mine need to deliver the same amount of airflow to these production areas? Can the air volume within the temporarily inactive areas be reduced such that only minimum airflow velocities are maintained along the main levels?
- For how long does the entire mine be active? Is there a uniform pattern during which the entire mine becomes inactive, during which both the primary and auxiliary ventilation delivery can be scaled down? In some cases, airflow delivery would be required continuously, such as to control blast fume clearance. Nevertheless, is this airflow requirement as demanding as for diesel usage?
- What will be the impact of stopping airflow delivery for a few hours or over a longer period of time such as weekends considering that strata is an infinite source of heat. Of course this will result in heat up in the mining areas, but how long would it take for the mining area to return to adequate climatic conditions once the airflow delivery is resumed?
- Most of the highly mechanized mines employ large auxiliary fans, will they cause a significant increase to the air temperature within the ducting system downstream.

If answers are provided to these questions and taken into account, then significant savings in the mines' intake air volumes can be achieved. Moreover, considering the cubic relationship between the mines' delivered air power and the airflow (P α Q^3), then any small decrease in the mines' intake air volume can generate significant savings in underground energy consumption and operating costs.

The allocation of ventilation typically occurs after a production schedule has been developed. The fact that ventilation systems are very expensive and require a significant amount of fixed infrastructure, it is sometimes challenging to meet the ventilation requirements of a production schedule without investing additional capital. The current focus of the mining industry is on designing systems in which ventilation can be adjusted based on immediate need. This concept is referred to as Ventilation on Demand (VOD) which minimizes ventilation costs by only using air where and when it is needed. For the auxiliary fans variable frequency drives (VFD) can be used which makes it possible to adjust the speed of the fan blades to produce the required airflow (Brickey, 2015).

Ventilation network analysis is a generic term for a family of techniques that enable quantitative determination of the distribution of airflow and the operating duties of the fans in a ventilation network where the resistances of all airways are known. For a given network, there are theoretically an infinite number of combinations of airway resistances, pressure generators and regulators that will give a desired airflow distribution. The techniques of ventilation network analysis that are applicable and useful for industrial applications must be flexible and converge to a solution in a short period of time in order to allow multiple alternative solutions to be evaluated (McPherson, 1993).

2.9.1 Methods of solving mine ventilation networks

There are basically two methods of solving fluid networks:

a) Analytical methods, which involves the formulation of the governing laws into sets of equations that can be solved analytically in order to obtain a solution, and
b) Numerical methods, which become very popular with the availability of personal computers, which were then used to solve the equations through iterative procedures.

2.9.1.1 Analytical methods

The most elementary method of solving and balancing a ventilation system is the use of equivalent resistances. If two or more airways are in series or parallel then each of those sets of airway resistances can be combined into a single "equivalent" resistance. It is more useful when combining two or more airways that are connected in parallel. This technique allows simplification of the network schematic by reducing thousands of branches that may exist in a mine to hundreds which therefore reduces the amount of data required to be processed and consequently, minimizing the time of solving and balancing a ventilation system (McPherson, 1993).

Kirchhoff's first law states that the mass flow entering a junction must be equal to the mass flow leaving the junction:

$$\sum_{j} M = 0 \; or \; \sum_{j} Q\rho \qquad (5)$$

Where;

M = mass flow (kg/s) positive and negative entering junction "j"

Q = air volume (m^3/s)

P = air density (kg/m^3)

The variation in air density around any single junction can be considered negligible, therefore:

$$\sum_{j} Q = 0 \tag{6}$$

Kirchhoff's second law applied to ventilation networks is that the algebraic sum of all pressure drops around a closed mesh in the network must be zero:

$$\sum (P - P_f) - NVP = 0 \tag{7}$$

Where;

P = frictional pressure drop (Pa)

P_f = rise in total pressure across the fan (Pa)

NVP = natural ventilation pressure (Pa)

Kirchhoff's law makes it possible to do calculations at each independent junction of the network and each independent mesh. The direct applications of these laws to a mine ventilation network could result in several hundred equations that are needed to be concurrently solved (McPherson, 1993).

2.9.1.2 Numerical methods

Atkinson suggested a method of successive approximation in which the airflows were initially approximated, then adjusted towards their true value through a series of corrections. The numerical method widely used in computer programs for ventilation network analysis is the one devised by Hardy Cross in 1936.

2.10 Computer application in mine ventilation studies

Ventilation has a considerable impact on the health and safety of the workers in the short term, but over time it has a significant impact relative to chronic respiratory diseases. This presents challenges to the overall improvement in underground ventilation systems, and minimization of the cost of implementing and operating these systems. The primary forces for changes in mine ventilation management is the major advancements in the computer technology with respect to reduction in size and increased computation speed, accompanied by development of efficient computer algorithm, new sensor technologies, advanced monitoring and control systems, newer communication technologies societal demands for safe working place and quality of life (Ganguli & Bandopadhyay, 2004).

Before mid-1950s, there was no practicable means of conducting detailed and quantitative ventilation networks analysis for complete mine systems. Mine ventilation planning was carried out using hydraulic gradient diagrams formulated from assumed airflows or simply, based on the ventilation engineer experience and intuition. Scott et al. (1953) produced the first viable electrical analogue computers to simulate ventilation networks and then later in the United States by McElroy, 1954. These analogues enabled Ohm's law for electrical conductors to emulate the square law of ventilation networks. Later in the 1960s, ventilation simulation programs for mainframe digital computers started to appear. These proved to be versatile, rapid and accurate and their role dominated ventilation planning and system design. In the 1980s, the enhanced power and relatively reduced cost of personal computers led to the development of mine ventilation programs, which also incorporated the use of graphics (McPherson, 1993).

Application of computers has played a tremendous role in the evaluation of ventilation parameters and processes. The use of the digital computer has expanded in an unprecedented manner from purely commercial applications to the problems involving the design, maintenance and control of technical systems. In mine ventilation, the major development of computer applications has been in the field of ventilation planning. When an enormous amount of data has been acquired, a computer can be used advantageously to relieve the ventilation engineer from the tedium of routine repetitive calculations.

Furthermore, digital data processing has both short and long term significance. Long range data processing involves such observations which are routine and are being continually recorded. An accumulation of such data could be tested for statistically significant trends and can then be used in planning the ventilation of new sections or adjacent mining operations. Short term data processing involves spot testing and checking of such parameters as fan performance, optimum airway sizes, air power losses, and statistical examination of information surveys.

The introduction of computerized network analysis in the planning and installation of an underground mine ventilation system has made it easier to perform these tasks (Anna, 2013). Before the use of computers, the planning and modelling of ventilation was largely based on experience, guesswork and extensive calculations (Chasm Consulting, 2012).

As the mines will be progressing deeper for extraction of deep ore reserves which are usually high grades, the ventilation system becomes complex and difficult to manage. The problems encountered at these levels can be mitigated by the practical use of three-dimensional simulation software Ventsim. (Feng, et al., 2011). The simulation and analysis performed by the software depends on the accuracy and reliability of input data. Any small error in the input data will result in a serious mistake in simulating the network especially when the network consists of thousands of airway branches.

2.11 Ventsim Visual modelling software

A simulation programme is a mathematical model written to conform to one of the computer languages. The main role of a simulation programme is the production of numerical results as an approximation to those given by the real system. The accuracy of a simulation programme is governed by the following considerations:

- The adequacy to which each individual process is represented by its corresponding equation (for example the Square Law).
- The precision of the input data which characterizes the real system (e.g. resistance values)
- The accuracy of the numerical procedure (e.g. the cut-off criterion to terminate cyclic iterations) (McPherson, 1993).

Several interacting features including both physical systems and organizational procedures are represented by simulation programmes. The design elements and parameters that are required to develop the ventilation model of an underground operation are:

- Numerical data used to define each airway (branch) of the ventilation network
- A schematic representation of the ventilation network, which consists of junctions and delineating branches in a closed circuit. Each branch can represent a single airway, leakage path, or a group of airways combined into an equivalent branch.
- Data required to define the locations and characteristics of the mechanical ventilation devices (i.e. fans, doors, regulators, bulkheads).

The software Ventsim was designed as a ventilation tool, which can be operated independently of other mine planning packages, but maintains a level of compatibility which ensures that data from mine planning packages and other ventilation software can be passed to the program. The software allows a full toolbox of tightly integrated utilities to analyze ventilation flows, heat, contaminants and financial aspects of mine ventilation. Ventsim Visual intents to make the process of ventilation network analysis feasible even for those without substantial ventilation experience.

The system can model true three-dimensional ventilation system and achieve a great success from the original two-dimensional display to the present three-dimensional display, which fill the gaps in this field of the mine's history. The Ventsim software is not only used in the ventilation network calculation and merry-demand simulation and dynamic of airflow, but is also used to assist in the short-term and long-term planning for ventilation system. This makes it able to simulate planned new developments or paths and is able to simulate concentrations of smoke or dust, for emergency situations or simply for reasons of planning (Jing & Cheng, 2016) .

The 3D model developed can be viewed from multiple angles making it easier to resolve some confusing and difficult problems associated with two-dimensional graphics. Taking for example, a mine layer overlap in the two-dimensional graph cannot display an airway in the real coordinates, and the connection relationship between layers cannot be displayed. But now, these problems were easily resolved by the ability to develop a 3D model. The three-dimensional ventilation system offers a rich layer management tool to help hide network data which is not important in the complexity ventilation network and concisely display the emphasis data.

The 3D model allows the user to easily set up and get the three-dimensional coordinate of any node and adjust any airway section size, the three-dimensional view area will reflect all the adjustments taken in real time. The software utilizes a visual approach to manage ventilation data and the 3D model corresponds to the actual mine, and parameters are directly displayed on the airway. The software can display all these data in 3D view, and customize it in the data table and output, and set the data range with different color legend through the color legend manager. (Feng, et al., 2011)

The 3D model developed by Ventsim looks very natural and easy to understand, even for people who are not familiar with mine ventilation. The system is able to detect after every 5 seconds whether the 3D model or parameters has changed, if "yes", then the model will re-simulate ventilation and the corresponding data are displayed on the airways. Each airway has dynamic triangles which move all the time indicating the airflow direction. The software utilizes both a color manager and a data manager control form to assist in rapid analyzing and changing of on screen data, which help ventilation management quickly master the mine current situation.

The ventilation models uses a fan database built within the software. This fan database contains all the fans used at the mine and fans that will be used on short, medium and long term production scheduling. Each fan curve in the database is built based on the fan curve obtained from the fan manufacturer. The database can have more than one curve for the same fan type based on the blade setting that is intended to be used (Cristian, 2010). Figure 2.4 shows an example of Joy series 2000 axivane fan performance curves displayed in Ventsim.

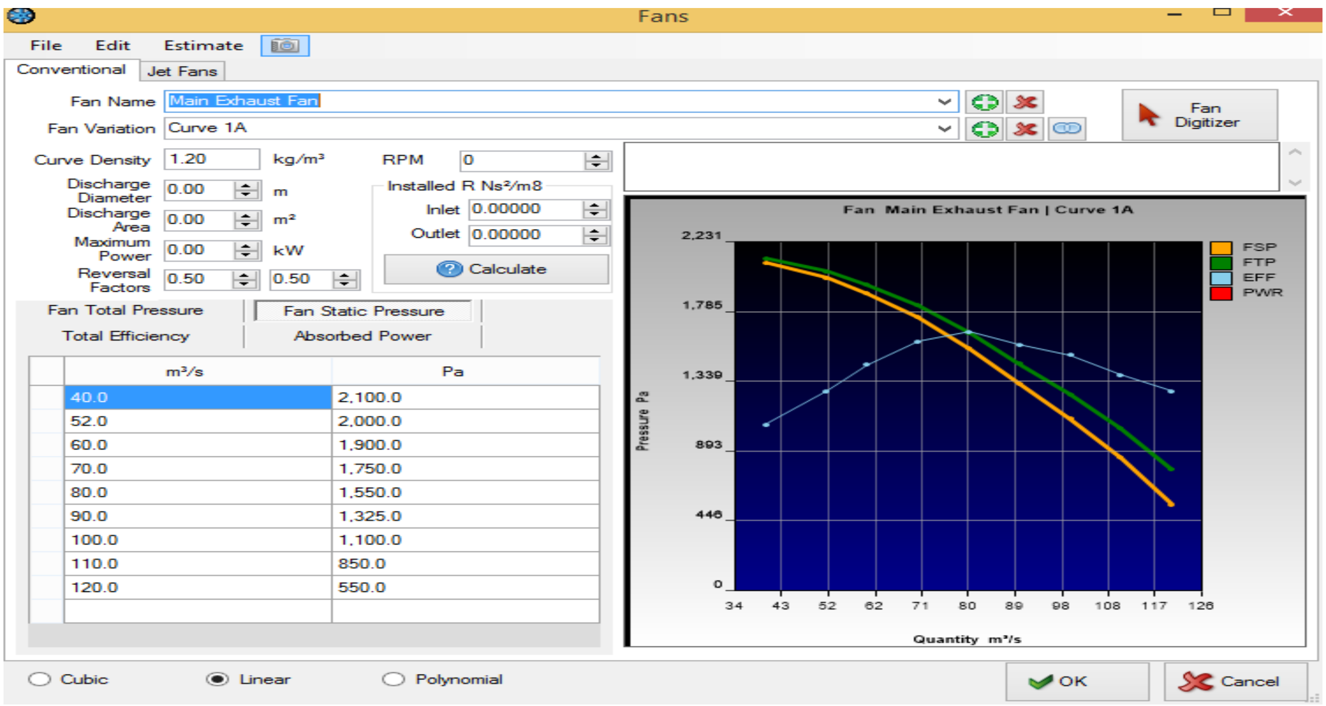


Figure 2.4 Joy series 2000 axivane fan performance curve - Ventsim representation

Ventsim software performs simulations to determine the optimum ventilation network that can best service the expands of the mining areas with regards to the existing ventilation infrastructure, system and fan performance, ease of installation, power distribution, future extension/production upgrades and capital and operating expenditures. The evaluation of airflow is based on the Hardy Cross method, which is an iteration estimation method used to adjust the airflow until the estimation errors lie within acceptable limits.

There are other nonlinear programming methods used by engineers and academics to evaluate mine ventilation networks, in addition to the Hardy Cross method. One of the simplest nonlinear programming techniques, Steepest Descent, is used by Sarac and Sensogut in conjunction with the

Hardy Cross method, resulting in improved solution time. The Hardy Cross method typically starts by setting all branch air quantities to zero, nevertheless, it has been shown that by using Steepest Descent method for the first few iterations, it is possible to obtain air quantities that are nearly optimal. If the initial values determined with Steepest Descent are used, the Hardy Cross algorithm can be used to converge to the optimal solution in approximately half the time relative to the Hardy Cross method (Brickey, 2015).

Ventsim software provides the following capabilities to the user:

- Simulations and providing a record of flows in an existing underground mine
- Performing "what if" simulations for new planned mine development
- Assisting in selection of types of circuit fans for mine ventilation, development fans and ventilation bags
- Helping in Short and Long term planning of ventilation requirements
- Assisting in financial analysis of ventilation options
- Simulating paths and concentrations of smoke, dust or gas for planning or emergency situations (Widzyk-Capehart & Watson, 2004).

It is important to realize that a mine is a very complex environment and activity is not confined to development and stopes. Some other important consumers are: electrical substations, electrical and mechanical shops, sumps, charging stations and waiting places. A ventilation model must ensure that enough airflow for each of these consumers is delivered to the levels required by legislation (Cristian, 2010).

The results obtained from primary ventilation survey, performed every three months or less depending on the mine are used to compare the airflows of the mine against the simulation and regulations. This process is used to verify the validity of the ventilation model developed and to update the model with current information. If the values from the real ventilation circuit and the simulation do not agree yet the simulation is deemed to be acceptable by engineers, then the discrepancy indicates major leakages and short-circuits occurring somewhere in the mine, which warrants the need for a detailed analysis of the ventilation network (Widzyk-Capehart & Fawcett, 2002).

2.11.1 Types of models

A ventilation model must have a framework of connected airways or branches. Each airway must have a connecting airway at the entry and exit for the airflow to successfully travel along an airway. All airways that are not connected at either end will not carry airflow unless connected to the surface. A ventilation model can be developed as either a closed or open model

2.11.1.1 Closed model

This type of a model does not have any airways connected to the surface. This is normally used for diagnostic purposes since it is unusual to have a real mine with this kind of a set up. It continually circulates air around the modelled airways. To build up this kind of a model, all the airways are connected and looped so that they form a continuous path and all airway ends are connected to at least one another. Pressure and energies placed within the model to distribute flows are entirely consumed by the airways in the model since the system is entirely self-contained. There is no ventilation energy that is lost to outside sources.

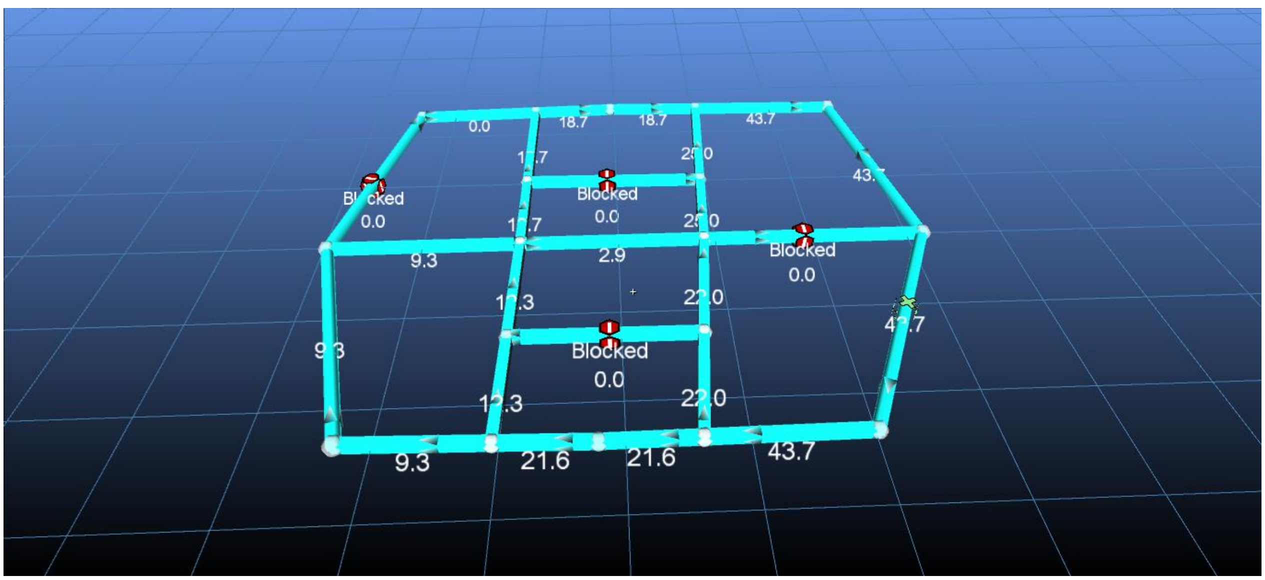


Figure 2.5 Example of a closed loop

2.11.1.2 Open model

This type of model has at least two airways which are connected to the surface, at least one is an intake airway, and another one is an upcast (exhaust) airway. This model gives a true picture of the real mine. Airflow that exits an exhaust airway influences the pressure (or temperature) of the airflow entering an intake airway. The airflow velocity pressures and energies lost from an exhaust airway are assumed lost to the model.

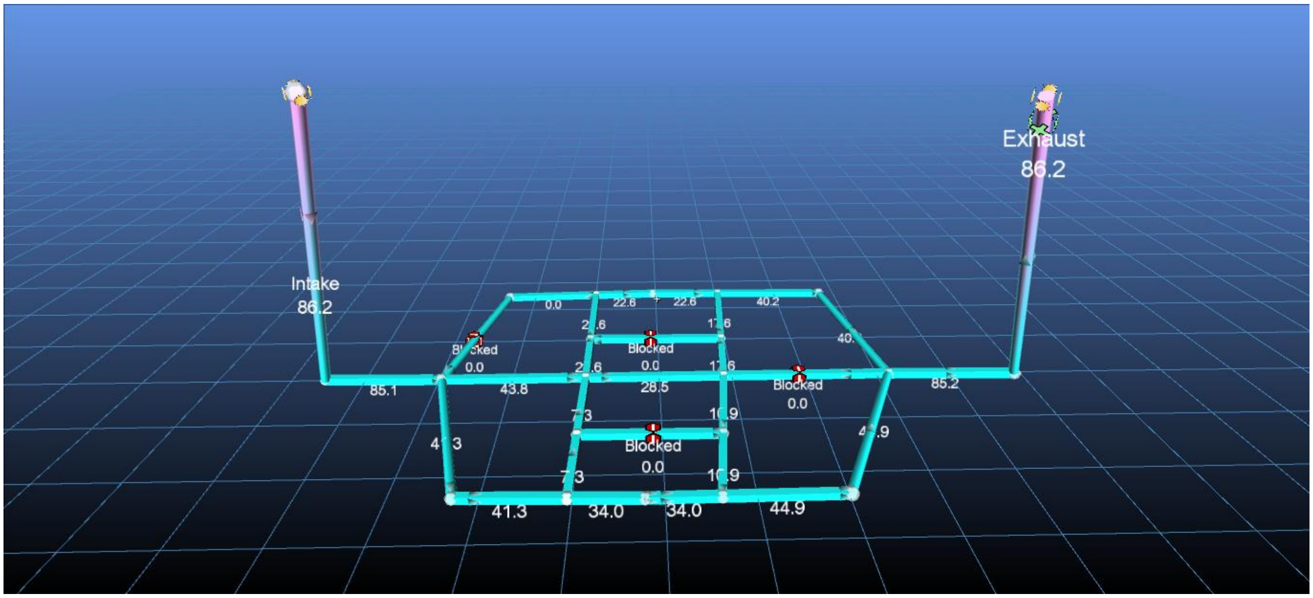


Figure 2.6 Example of an open loop

2.11.2 Process simulation

Process simulation is the imitation of a real-world process or system over a period of time. Simulation involves the generation of an artificial history of the system (i.e. model development), which when extensively analyzed generates inferences concerning the operating characteristics of the real system. Today, simulation has become an essential problem solving methodology for the solution of many "real-world" problems.

Simulation and animation can be used to describe and analyze the behavior of a system, ask "what-if" questions about the real system and simulate scenarios generated by these questions in order to support the design of real systems. Either the existing or conceptual systems can be simulated by means of computer modelling techniques. Ventsim Visual provides tools to make full thermodynamic analysis of heat, humidity and refrigeration in underground mines or to check for recirculation in mines (Karoly-Charles Kocsis, 2009).

2.11.2.1 Contaminant simulation

Ventsim Visual can perform steady or dynamic contaminant simulation based on the position of contaminant source placed in the network. These are used to assist in making emergency rescue measures. During the simulation process, the 3D model will display the polluted airways in different color, and dynamically display the concentration of polluted airways and its changes over time.

A sourcing simulation can be performed using the software and this is similar to a reversed contaminant simulation. (Chasm Consulting, 2012) This type of simulation tracks airflow back from a placed contaminant source, and indicates the percentage of airflow which contributes to the airflow through the contaminant marker. This tool was designed to assist in quickly identifying the possible locations of a fire or contaminant source (such as dust or production fumes) underground.

2.11.2.2 Fan selection and anti-wind simulation

The software contains the most commonly used fan databases, which can add a new fan data and automatically generate the fan curve. Since the three-dimensional model's airway length, cross-section shape, friction coefficient and other parameters correspond with the actual underground airway, the simulation performed by the software will produce real results of the prevailing underground ventilation conditions. With the model providing the realistic underground situation, the type of fans can be chosen, which can not only meet the airflow requirements, but also make the fan operate at stable conditions with minimum power consumption. The fan blade angle can be adjusted to evaluate how it affects the entire ventilation system and to view the fan operating point.

2.11.2.3 Recirculation of air

Uncontrollable recirculation can be dangerous to the mine as it leads to accumulation of heat and toxic gases at the working areas resulting in uncomfortable working conditions to the workers. It is advisable for the ventilation management to not only understand the existence of circulating air throughout the mine, but also to know the amount of circulating air. (Chasm Consulting, 2012) The software uses a custom algorithm to track the paths and recirculated portion of every airflow throughout the mine, and report where airflow may recirculate. To avoid repeated reporting of recirculating air, a default tolerance of 1 m^3/s or 1% recirculation is used.

2.11.2.4 Maintenance of the 3D model

The mine ventilation officers can go through a short training course and can maintain the 3D model by themselves. This will not only help to reduce the cost of maintenance greatly, but also timely response to the conditions of the mine underground. It will allow them to do some simulations on the software to evaluate how the model is going to behave. If the results are positive for the optimization of the mine ventilation system, they can now go underground to do the adjustment to achieve the same results shown on the model.

CHAPTER 3 METHODOLOGY

3.1 Introduction

To achieve the mentioned research objectives the following research design was used. The research was more of quantitative as a lot of numerical data was gathered through underground operation surveys to acquire the parameters that was used to build the model.

3.2 Research design

The research was done based on the methodological framework shown in Figure 3.1. This framework illustrates the modelling of the Konkola Copper Mine ventilation system using data obtained from ventilation surveys and gathered from other linked departments. It also shows how the model developed will be used for establishing a more efficient and effective ventilation system by performing different simulations in trying to optimize the system.

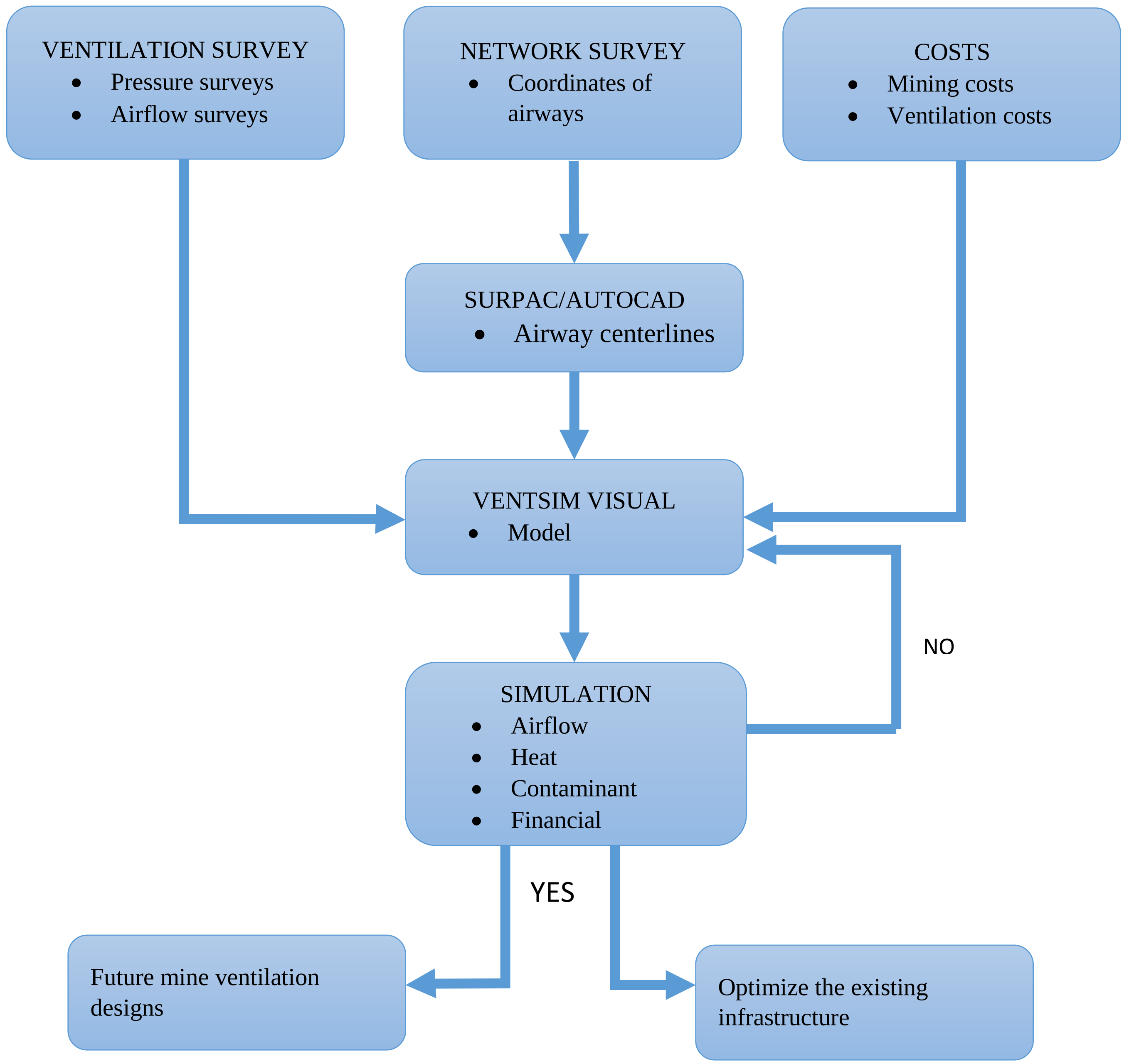


Figure 3.1 Overview of the methodological framework

3.3 Literature review

An extensive bibliographical review of literature to gain more knowledge about mine ventilation was done. The subjects of interest was underground mine ventilation, planning design, production scheduling and underground mine ventilation operations management. The application of Ventsim Visual was evaluated to fully understand how to use it in modelling and simulation of the ventilation system. The comprehensive literature review involved the usage of:

- Journals
- Internet
- Textbooks and,
- Structured interviews

3.4 Field work

This involved underground site visits to measure all the required parameters and to check the prevailing ventilation conditions. The survey involved measurement of cross sectional areas, air quantities, velocities, pressures, virgin rock temperatures, wet and dry bulb temperatures in different locations of the mine in the airways. The compilation and processing of data provided by Konkola Mine was also done and the data includes:

- Ventilation directives
- Planning and scheduling outputs
- Mining plans
- Regulatory licenses

3.4.1 Ventilation survey

A very important step in mine ventilation modelling is to determine the minimum airflow requirements for different areas in the mine. Few principles will establish the critical path and the final result must meet quality and quantity criteria for airflows required by the Mining Acts and Regulations (Cristian, 2010).

Data that need to be used in designing the model was obtained through ventilation survey. The major objective of ventilation surveys was to obtain the frictional pressure drop, p, and corresponding airflow, Q, for each of the main branches of the ventilation network. From these data, the following parameters were computed for the purpose of both designing and planning:

- Distribution of airflows, pressure drops and leakage
- Airpower (p x Q) losses and hence, distribution of ventilation operating costs throughout the network
- Branch resistances ($R = p/Q^2$)
- Natural ventilating effects
- Volumetric efficiency of the system
- Friction factors

The observations of airflow and pressure differentials concerned with the distribution and magnitudes of air volume flow, and other measurements were taken as an integral part of a pressure/volume survey in order to indicate the quality of the air. These measurements includes wet and dry bulb temperatures, barometric pressures, dust levels and concentrations of gaseous pollutants. The survey measurements across all the airways was used for calibrating the model.

3.4.1.1 Air quantity surveys

The quantity of air, Q, passing any fixed point in an airway or duct every second was determined as the product of the mean velocity of the air, u, and the cross sectional area of the airway or duct, A

$$Q = u \; x \; A \tag{8}$$

Where;

Q = quantity of air in m^3/s

u = velocity of air in m/s

A = airway cross sectional areas in m^2

3.4.1.1.1 Measurement of air velocity in airways

The rotating vane anemometer was used to measure the airflow speed in conjunction with a stopwatch. This is an instrument that when held in a moving airstream, the air passing through the instrument exerts a force on the angled vanes, causing them to rotate with an angular velocity that is closely proportional to the airspeed. A gearing mechanism and clutch arrangement mounted in the instrument couple the vanes to a digital counter. To obtain a reliable measure of the mean air velocity of all the underground airways the following procedure was carried out:

Moving traverses

Traverses in the airways to measure the mean air velocity were done. Since the airways at the mine are high, the anemometer was attached to a rod of greater than 1.5m. The attachment mechanism was done to permit the options of allowing the anemometer to hang vertically or to be fixed at a constant angle with respect to the rod. For the airways that are inclined greater than 30^{o}, the anemometer was clamped in a fixed position relative to the rod and manipulated by turning the rod during the traverse such that the instrument remains aligned with the longitudinal axis of the airway.

The observer was supposed to face the airflow holding the anemometer rod in front of him/her so that the dial was visible and at least 1.5m upstream from his/her body. The traverse commenced from a lower corner of the airway, with the counter reset to zero until the vanes had accelerated to a constant velocity. The path followed during the traverse across the airway is shown in Figure 3.2.

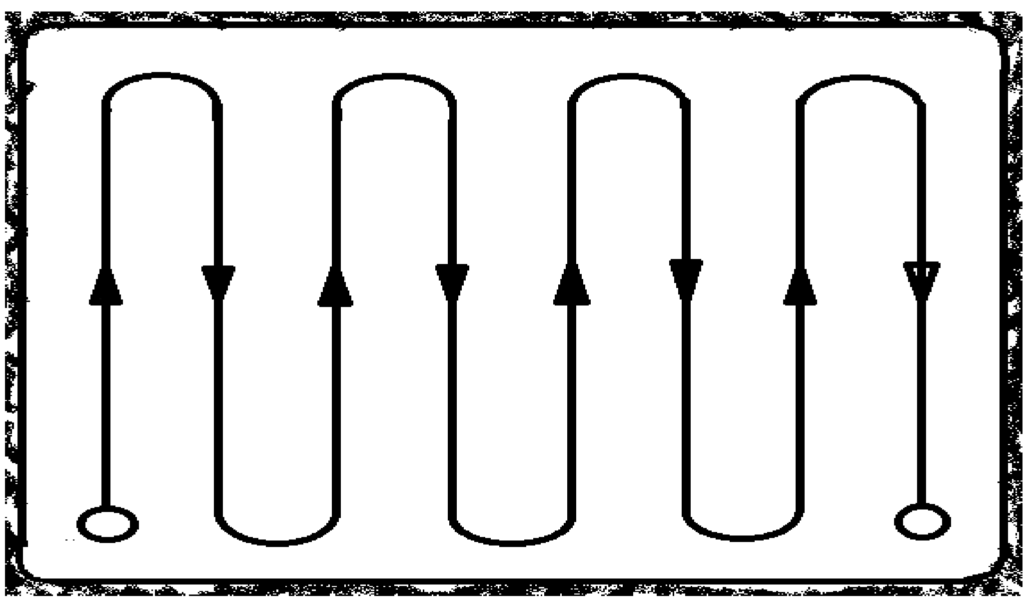


Figure 3.2 Path of a moving anemometer traverse

The anemometer was traversed at a constant rate not greater than 15 per cent of the airspeed. To cover the equal fractions of the airway cross sectional area in equal times, the stopwatch observer called out the elapsed time at ten second intervals. The complete traverse took not less than 60 seconds and was considerably more for large or low velocity airways. The length indicated by the anemometer was red and booked and the instrument reset to zero.

The same procedure was repeated, but now traversing in the opposite direction across the airway. This was repeated until three readings were obtained that agree to within +/- 5 per cent. To avoid discrepancy of measurements, any ventilation doors close to the measuring stations were closed during the period of measurement. The mean of the station velocities, ignoring any values outside the +/-5 per cent tolerance, was considered the observed mean velocity. This observed mean velocity was then corrected according to the calibration chart or curve for the instrument to give the actual mean velocity, u.

Powder Method

In airways that comprises of low velocity to be detected by vanes, powder method or smoke tubes was used to determine air velocity. One of the team was holding the smoke tube and the other one was standing at a fixed distance with a spot-beam cap lamp. The length of airway chosen was significant such that at least one minute elapsed during the progression of the smoke between the two fixed points.

A pulse of air forced by a rubber bulb through a glass phial containing a granulated and porous medium soaked in titanium tetrachloride or anhydrous tin produced a dense white smoke. This was released upstream of the two fixed points in the airway. The time taken for the cloud of smoke to travel the length of airway between the marks was considered as an indication of the center-line velocity of the air. This was adjusted by a center-line correction factor, 0.8, to give the mean velocity.

3.4.1.1.2 Cross sectional area measurement of an airway

The airways at Konkola Copper Mine have different shapes implying that their cross sectional areas were computed according to the shape. For all rectangular and square airways, the cross sectional area was obtained from the product of the width and height. The two dimensions were measured using a distance meter. The cross sectional area for all arched airways as shown in Figure 3.3 were computed by employing the following formula;

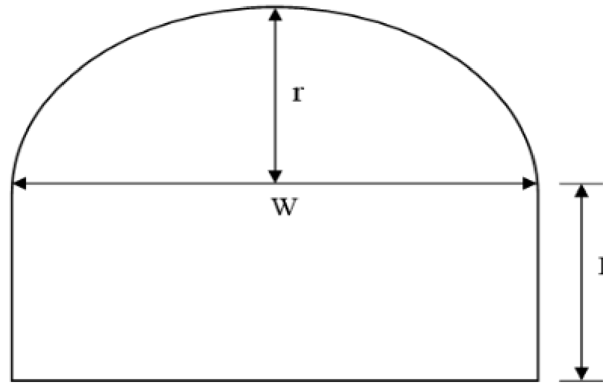


Figure 3.3 A cross sectional area of an arched airway

$$A = (W \ x \ H) + \ \pi r^2/2 \tag{9}$$

Where;

A = area of the arched airway

W = width of the airway

H = height of the tunnel

r = radius of the arch

3.4.1.2 Temperature measurements

The surface and underground wet-bulb and dry-bulb temperatures of air were determined using the whirling hygrometer.

Whirling Hygrometer

A wet and dry bulb hygrometer is a pair of balanced thermometers, one of which has its bulb shrouded in a water-saturated muslin jacket. Air passing over the two bulbs will cause the dry bulb thermometer to register the ambient temperature of the air. Nevertheless, the cooling effect of evaporation will result in the wet bulb registering a lower temperature. The whirling or sling hygrometer has its thermometers and water reservoir mounted on a frame which may be rotated manually about its handle. Having the knowledge of the wet and dry bulb temperatures, together with the barometric pressure, allow all other psychrometric parameters to be calculated.

Measuring procedure

The whirling hygrometer was first exposed to the surrounding environment so that it attained the temperature of the ambient air. The instrument was held at arm's length whilst facing the air current. It was then whirled at a rate of approximately two hundred revolutions per minute for at least thirty seconds to give an air velocity of about 3 m/s over the bulbs. In airways where the velocity of the air was more than 3m/s, whirling of the instrument was not necessary, the instrument was just held normal to the flow of the air current. This is normally applied when measuring the velocity of air discharged from the ventilation duct. After thirty seconds of rotation, the whirling was terminated (but not by clamping one's hands around the bulbs), the instrument was held such that the observer was not breathing on it, and the wet bulb was red immediately. The process of whirling was repeated until the reading became constant. The instrument was kept away from any near-by source of heat such as lamps.

3.4.1.3 Measurement of virgin rock temperature

The virgin rock temperature (VRT) is defined as the temperature of the insitu rock which has not been affected by heating or cooling from any artificial source. It is the linear increase in depth for each unit increase in temperature. The virgin rock temperatures (VRT) are employed in determining the geothermal gradient of the mine. The geothermal gradient varies according to the local rock strata's thermal conductivity and the depth of the excavation from the surface. To determine the strata heat flow in subsurface environments it is vital that the geothermal gradient is determined. For determining these temperatures, the Laser beam thermometer was used to measure the temperature of the insitu rock.

Measuring procedure

Data on the natural rock temperature at a known elevation is required to measure virgin rock temperature. A 6m long, 40mm diameter hole was drilled by a rock drilling jumbo. The borehole was drilled into the fresh air course close to the working face. A Laser thermometer was pointed into a borehole drilled and then a scan button on the thermometer was pressed. The temperature recorded on the thermometer was noted and the scan button released. The same procedure was repeated at least five times and then the average temperature was calculated. The average temperature was then used as the virgin rock temperature (VRT) of that location.

3.5 Developing mine ventilation line diagrams/ circuits using Surpac and Autocad

Konkola Copper Mine consist of a sophisticated and complex ventilation network. This circuit can be developed directly in Ventsim Visual but it will cause problems due to its complexity. Therefore to develop a ventilation model that does not result in cumbersome problems, the ventilation network was developed using Surpac computer software. The coordinates data (eastings, northings and elevations) of the airways were obtained from the survey department and these were used to develop strings in Surpac.

3.6 Modelling the mine

There are many different methods of building a computer ventilation model. Ventsim Visual software utilizes a visual approach in creating models and the fundamental structure of this model was developed using imported centerlines from Surpac software. A true to scale 3D model was developed to allow Ventsim to automatically use parameters such as size, length and depth for simulation. Since the model comprises of compressible airflow, this resulted in automatic density adjustment and natural ventilation pressure application, resulting in more accurate and realistic results. Furthermore, rock temperature and auto compression can be automatically calculated for heat simulation.

3.6.1 DXF/ DWG graphics import

To produce a more accurate model, the actual mine designs from Surpac software were imported into Ventsim to use as a template to construct a true to scale model. The import function was activated from the file import menu. The data imported were center lines of surveyed mine floors. The following criteria was used to avoid excessive post import editing:

- Only minimum data required was imported. A skeleton ventilation model consisting of interconnected lines within Surpac package was developed before importing into Ventsim Visual.
- Making sure that lines join to each other, so that Ventsim Visual knows they are junctions through which air can flow.

The imported data, center lines were converted to airways using the “convert to airways” option in Ventsim Visual.

3.6.2 Modifying and validating import data

Once imported into Ventsim Visual, the program assigned default airways sizes and shapes to all the imported airways. These defaults settings would have been set in the settings menu during software calibration. This was done to avoid re-editing of all the airway sizes and shapes.

3.6.3 Correcting errors

To quickly sort and validate the imported airways, an airflow simulation was done. At this stage the model did not simulate correctly and this was done to check the duplicates and unconnected airway ends as a way of speeding up the process of establishing a working model.

3.6.3.1 Filtering tools

A number of tools are provided in the "tools >filter menu" to help tidy up the model and correct initial errors by binding disconnected airways and removing duplicates airways.

3.6.4 Creating pressure for flow

For air to flow in the model, pressure must be applied. The following methods were used to produce pressure within the model to motivate airflow:

- Fans: it utilizes a fan curve to establish accurate working flows and pressure in a ventilation model
- Fixed pressures: it uses a consistent pressure to induce an airflow in a ventilation model. The airflow produced varies on the resistance encountered by the pressure.
- Fixed airflows: it uses a consistent airflow to induce flow through a model. The pressure necessary will be adjusted to whatever is required to produce the airflow.

Without at least one of the above methods to produce model pressures, airflow will remain stagnant.

3.6.5 Perform Ventsim simulation to optimize the ventilation system

After the model was developed, Ventsim Visual was used to simulate airflows, heat, contaminants, recirculation and financial costs.

3.6.6 Review of the long and short term mine plans

The developed model was simulated to evaluate if it was giving the real values experienced in the mine. The model showed that the airflow are tallying with the underground prevailing conditions and it was them used to develop new mining districts according to the mining plans.

CHAPTER 4 DATA COLLECTION AND MODELLING

4.1 Introduction

The ventilation model for Konkola Copper Mine was created based on the data acquired during ventilation surveys, airway coordinates and ventilation devices' specifications. The methodological framework mentioned in Chapter 3 was used to gather data and build the model.

4.2 Preparation steps

The required measurements were carried out during the course of attachment at Konkola Copper Mines. An airflow quantity survey and pressure differentials across stoppings were measured. In order to determine quantity of air passing in an airway, entering and exiting the mine, the cross sectional areas of the airways were measured using the disto-meter. The dimensions and profile of the measured shafts are shown in Table 4.1.

Table 4.1 Shafts details

Shaft Name	Shaft profile	Dimension (m)	Collar elevation (m)	Bottom elevation(m)	Purpose
1	Rectangular	7.1 x 4.267	1331.366	260.341	Man/other
3	Circular	6.1 diameter	1299.277	619.658	Man/other
4	Ellipsoid	9.4 x 7.0	1332.750	Mining in progress	Man/other
VS1A	Circular	3.7 diameter	1325.907	531.366	Upcast
VS1B	Circular	3.7 diameter	1325.907	346.366	Downcast
VS1C	Circular	3.7 diameter	1317.160	726.366	Upcast
VS1D	Circular	3.7 diameter	1317.266	726.366	Downcast
VS1E	Circular	3.7 diameter	1328.812	531.366	Upcast
VS1F(Pipe shaft)	Circular	4.9 diameter	1326.686	332.686	Downcast
VS3A	Circular	3.7 diameter	1297.448	1058.918	Upcast
VS3B	Circular	7.4 diameter	1300.805	707.050	Downcast
VS3C	Circular	3.7 diameter	1301.400	989.970	Upcast
VS3E	Circular	7.2 diameter	1308.400	Mining in progress	Downcast

The horizontal airways (haulage, drainage, extraction drive and drawing points) assume an arch profile and their dimensions were measured and found to be 5m x 5m. The design dimensions for these excavation was 4.7m x 4.7m but the actual mine was 5m x5m due to over break. The return raises that were mined close to the stoping area to channel foul air from the working faces into the drainage drive were 2m x 2m.

4.2.1 Main fan performance

To find the true values of air handled by the main fans, main fan performance calculations were conducted. The main fans were connected directly to the electrical motors (direct drive) which delivered power to the drive shaft of a fan impeller. Losses occurring in both motor and transmission were calculated in determining the fan efficiency and overall efficiency. If the electrical motor and transmission are properly maintained, 95 per cent of the input electrical power may be expected to appear as mechanical energy in the impeller drive shaft. The fan impeller converts most of that energy into useful airpower to produce both movement of the air and an increase in pressure. The remaining energy will be consumed by irreversible losses across the impeller and in the fan casing producing an additional increase in the temperature. The following measurements and calculations were done for each upcast shaft.

<u>Ventilation Shaft 1E (VS1E)</u>

Barometric pressure (B.P) = 88.83 kPa

Fan drift air temperature (td) = 21.0°C

Saturated vapour pressure (e) = 2.4861kPa

Actual density (ρ)

$$= \frac{P-0.378(e)}{0.287045(273.15+td)} \qquad (10)$$

$$= \frac{88.83-0.378(2.4861)}{0.287045(273.15+21.0)}$$

$$= \frac{87.89}{84.43}$$

= **1.041kg/m³**

Velocity pressure *(Pv)*

$$= \frac{v^2\rho}{2} \qquad (11)$$

$$v^2 = \frac{2Pv}{\rho}$$

$$v = \sqrt{\frac{2\ x\ Pv}{\rho}}$$

$$= \sqrt{\frac{2\ x\ 245}{1.041}}$$

= **21.42 m/s**

Air quantity

Average velocity = 21.42 m/s

Cross sectional area = 10.75 m^2

Quantity at ambient density = $A\ x\ u$

= **230.265 m^3/s**

Electrics

Current = 60 Amps

Voltage = 11kV

Motor Input Power

$$= \sqrt{3}\ x\ V\ x\ A\ x\ Pf \qquad (12)$$

= $\sqrt{3}$ x 11 x 60 x 0.72

= **823.071kW**

Fan pressure

Fan Static Pressure = 2.8kPa

Mean Static Air Power

= Pressure x Quantity (13)

= 2.8 x 230.265

= **644.742kW**

$$\text{Mechanical efficiency} = \frac{Air\ power\ x\ 100}{Input\ power} \quad (14)$$

$$= \frac{644.742\ x\ 100}{823.071}$$

$$= \mathbf{78.3\%}$$

The details for the rest of the uptake shafts is shown in Table A.3 in Appendix A.

4.2.2 Diesel loading

Estimation of airflows required within the work areas of a mine ventilation network is the most empirical aspect of modern ventilation planning. Konkola Copper Mine utilizes several loaders, dump trucks, drill rigs and other mobile equipment of various types and sizes for extraction of ore. Types of machines and their rated power used at Konkola Copper mines are shown in Table A.4 in appendix A. For these machines to operate efficiently and safely, adequate air must be supplied in all areas where they are operating. The quantity of air delivered to these areas must be capable of sweeping away heat and toxic gases generated from these machines.

The Zambian Mine Regulation stipulates that a mine should provide 0.05 m^3/s of ventilation air per kilowatt of engine power. However, typical mine ventilation requirements for acceptable operation of diesel equipment ranges from 0.03 to 0.08 m^3/s over the engine per kilowatt power. The calculations that were done for this study used 0.05 m^3/s as applied by Konkola and it is based on the diesel equipment rated power. The airflow requirements for machinery used at the mine are shown in Table 4.2.

Table 4.2 Airflow requirements for machinery

Machine name	Bancroft deep	Bancroft central	Bancroft north	Konkola extension	Konkola flats	Konkola east	Total	Rated power (kW)	Air quantity (m^3/s)
Face rigs	3	-	3	1	-	3	10	55	27.5
Support rigs	1	-	2	1	-	3	7	55	19.25
Long hole rigs	2	-	2	1	-	2	7	55	19.25
LHDs	4	-	4	2	-	3	13	186	120.9
Dump trucks	5	-	6	2	-	6	19	298	283.1
Scaler	2	-	2	1	-	2	7	55	19.25
Lub Truck	-	-	1	-	-	-	1	55	2.75
Scissor lifts	3	-	2	1	-	2	8	55	22
Tyre handler	1	-	1	-	-	-	2	55	5.5
ECU	-	-	1	-	-	-	1	55	2.75
Man carriers	-	-	-	1	-	1	2	55	5.5
Subtotal									**527.75**
Pump chambers, sumps and settlers and crusher chambers									300
Explosive magazine (by four)									120
Overall air volume requirement									**947.75**

4.2.3 Virgin rock temperatures

The geothermal gradient at Konkola Copper Mine are exceptionally low compared to the other areas in Zambia. The air temperatures at the mine, even at deeper levels (1050mL), are quite low ranging around 30 ^{o}C (dry bulb) while the rock temperatures at the other mines in Copperbelt, at similar depths can be as high as 50 ^{o}C.

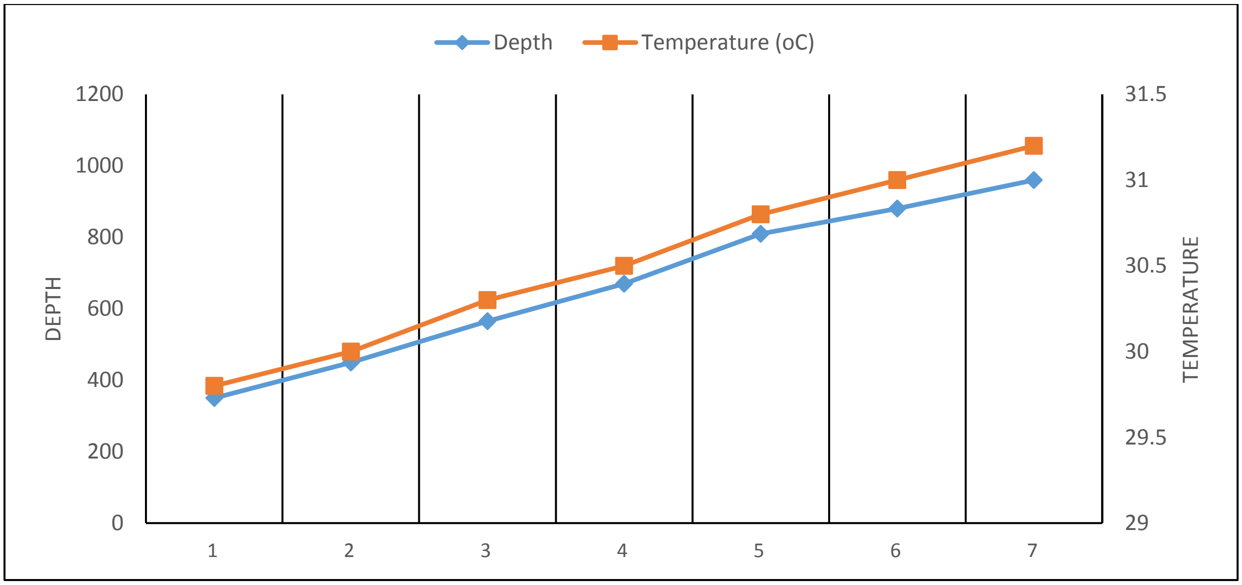


Figure 4.1 Temperature depth relationship at Konkola Copper Mine

Three boreholes that are located around Konkola Mine showed almost no geothermal gradient. The research conducted at the mine indicated that the apparent lack of geothermal gradient in the Konkola boreholes was due to downward movement of groundwater, probably near surface waters, resulting in measurement of temperature of moving water and undisturbed rock. Measurements that were collected at depths 319m and 800m (levels 900'L to 2650'L) below the surface showed unusual low temperatures for such depths ranging between 24 ^{o}C and 30.1 ^{o}C.

In general groundwater associated with stratigraphically older formations (footwall formations) were slightly warmer than water in younger formations (hanging wall formations). A number of drill holes were drilled at different mine levels, in order to determine true geothermal gradient in the mine area. A 6m long, 40 mm diameter boreholes were drilled perpendicular to the direction of the haulage in the Footwall Quartzite formation. The measured temperature versus depth was plotted as shown in Figure 4.1 and the dry rock temperature was determined. The measured values showing the effect of depth on temperature is shown in Table A.2 in Appendix A.

The measurements indicated that there is an extremely low geothermal gradient of 2.28K/km (or 1^{o}C/438m). The following are geothermal gradients in known mining areas further away from Konkola mine:

Nchanga - 17.8K/km (West orebody)
Mopani - 18K/km
Luanshya - 18K/km center of Mulyashi Syncline
-23K/km Basement Complex

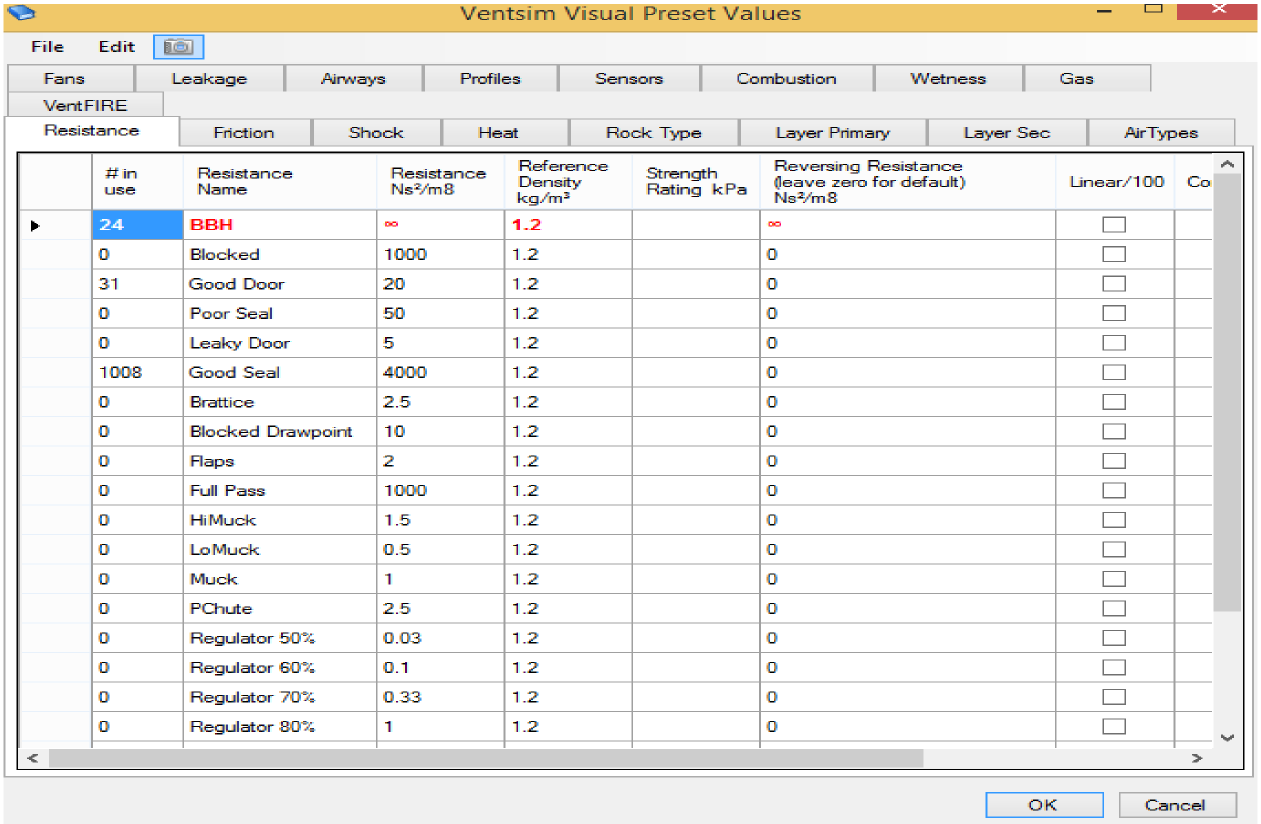
4.3 Building a ventilation model

Modelling of a cost-effective and efficient mine ventilation model depends upon the accuracy of the input data used. Konkola mine ventilation model was developed after an extensive data collection from the mine. The simulation of the Konkola Copper Mine ventilation system was performed using the computer software Ventsim Visual. The evaluation of airflow in Ventsim Visual is based on the Hardy Cross method, an iteration estimation method used to adjust the airflow until the estimation errors lie within acceptable limits.

4.3.1 Preset values

These are the values that provide a quick and convenient way to specify airway characteristics and parameters that are commonly used in the ventilation model. Examples of these parameters are airway sizes, airway profiles, resistances (such as doors or seals), common wall friction factors, shock losses, rock type, airway wetness and heat sources. This Preset Box provides access to model primary and secondary layer names and colors, as well as air types, tunnel profiles, fans, wetness fractions and numerous other parameters used in Ventsim simulation.

These values allow multiple editing when building the model. If any preset value is changed, this change would be applied to all the airways using that preset value. All the values required in the presets were entered before building the model and most of this data was acquired through mine ventilation survey and data obtained from various departments. Figure 4.2 shows the preset table options as presented in Ventsim.



# in use	Resistance Name	Resistance Ns²/m8	Reference Density kg/m³	Strength Rating kPa	Reversing Resistance (leave zero for default) Ns²/m8	Linear/100	Co
24	BBH	∞	1.2		∞	☐	
0	Blocked	1000	1.2		0	☐	
31	Good Door	20	1.2		0	☐	
0	Poor Seal	50	1.2		0	☐	
0	Leaky Door	5	1.2		0	☐	
1008	Good Seal	4000	1.2		0	☐	
0	Brattice	2.5	1.2		0	☐	
0	Blocked Drawpoint	10	1.2		0	☐	
0	Flaps	2	1.2		0	☐	
0	Full Pass	1000	1.2		0	☐	
0	HiMuck	1.5	1.2		0	☐	
0	LoMuck	0.5	1.2		0	☐	
0	Muck	1	1.2		0	☐	
0	PChute	2.5	1.2		0	☐	
0	Regulator 50%	0.03	1.2		0	☐	
0	Regulator 60%	0.1	1.2		0	☐	
0	Regulator 70%	0.33	1.2		0	☐	
0	Regulator 80%	1	1.2		0	☐	

Figure 4.2 Preset table options

4.3.1.1 Settings

Settings provided command over a large number of parameters used in Ventsim for simulation, graphical display and file handling. These were saved specifically for the file in which they could be modified but they could also be shared with other files using the inherit function, or the master link function.

4.3.1.2 Costing

The costing settings were entered and these defines the mining and ventilation cost components of the model. These figures were used in calculating optimum airway sizes, and total ventilation cost to run a modelled ventilation system. The US dollar currency was used due to its consistent stability. The costing used is shown in Figure 4.3.

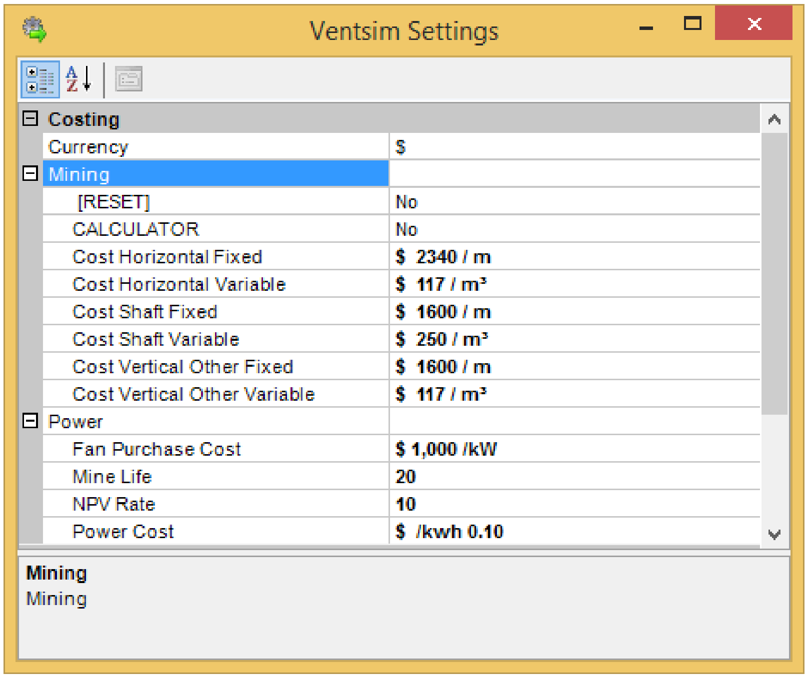


Figure 4.3 Mining and power costs

4.3.1.3 General

These are the factors that describe airway sizes and settings when first building a model, as well as file saving and loading behavior in Ventsim. The values used for this model are shown in Figure 4.4

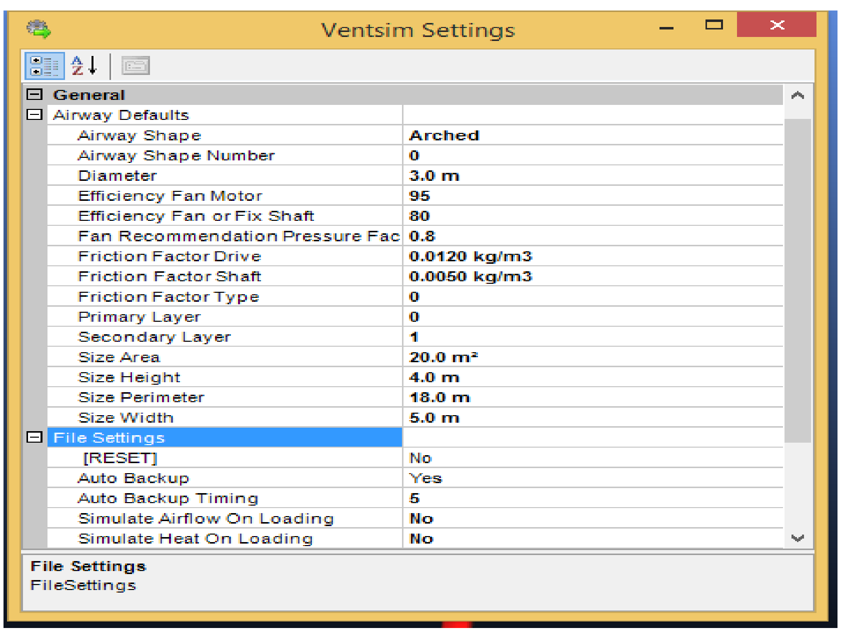
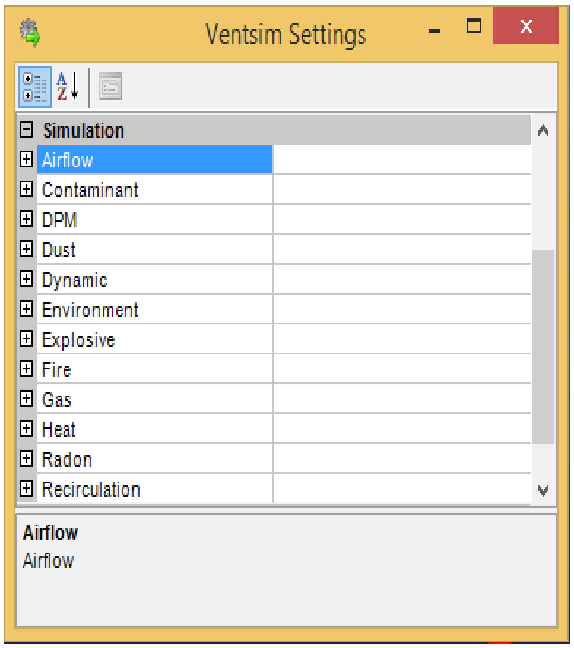


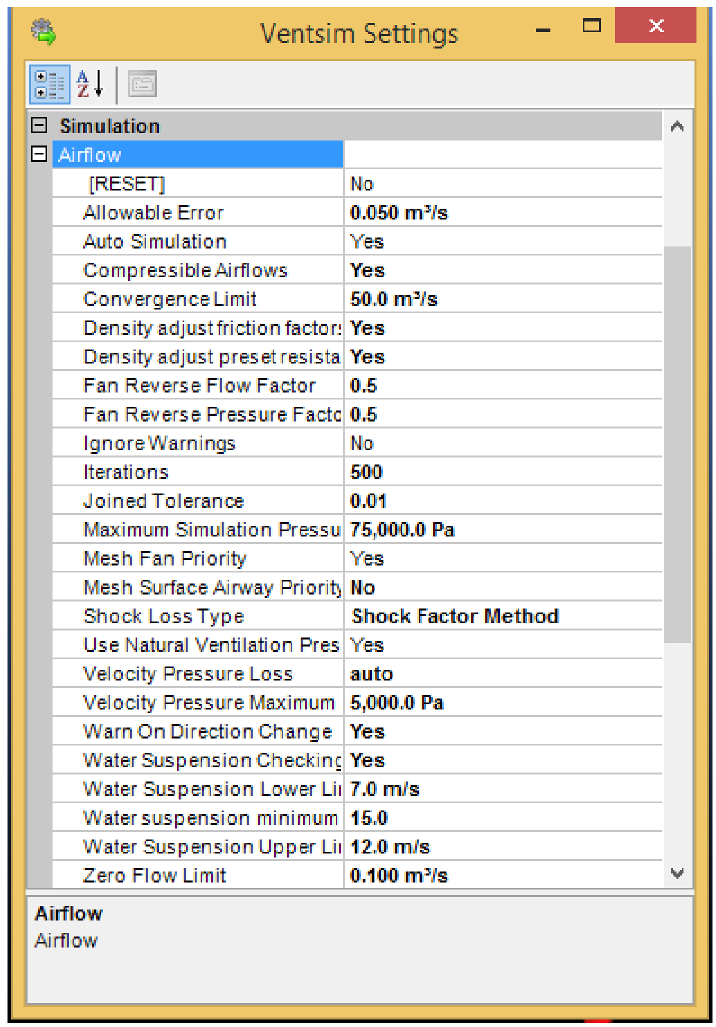
Figure 4.4 General settings for airways

4.3.1.4 Simulation

These settings directly influenced how the airflow simulation was operating. All the parameters affecting airflow, contaminant, Diesel Particulate Matter (DPM), dust, dynamic, environment, explosive, fire, gas, heat and recirculation were entered before building the model. These were influencing the level of accuracy Ventsim must resolve before an acceptable solution was displayed. These settings were commanding Ventsim Visual to ignore or not all warnings errors found during simulation. The simulation settings for airflow are shown in Figure 4.5.



(a)



(b)

(a) Simulation settings
(b) Simulation Airflow settings

Figure 4.5 Simulation settings

4.3.2 Importing data from Surpac, Autocad and Micro station

To produce a more accurate ventilation model, the actual mine designs were imported from Surpac, Autocad and Micro station into Ventsim Visual to use as a template to construct a true 3D to scale model. The airway coordinates data were collected from the survey department and captured in Microsoft Excel. It was saved in Character Separated Variables (csv) format which is compatible with Surpac. This format was very easy to import and export using the most common spreadsheet and database software packages.

CSV files were imported into Surpac software interface. This data in Surpac was then changed to string data (.str format) and then loaded in the main graphics to visualize the centerlines of the airways. The string files of the mine floor center lines were displayed in the software as shown in Figure 4.6.

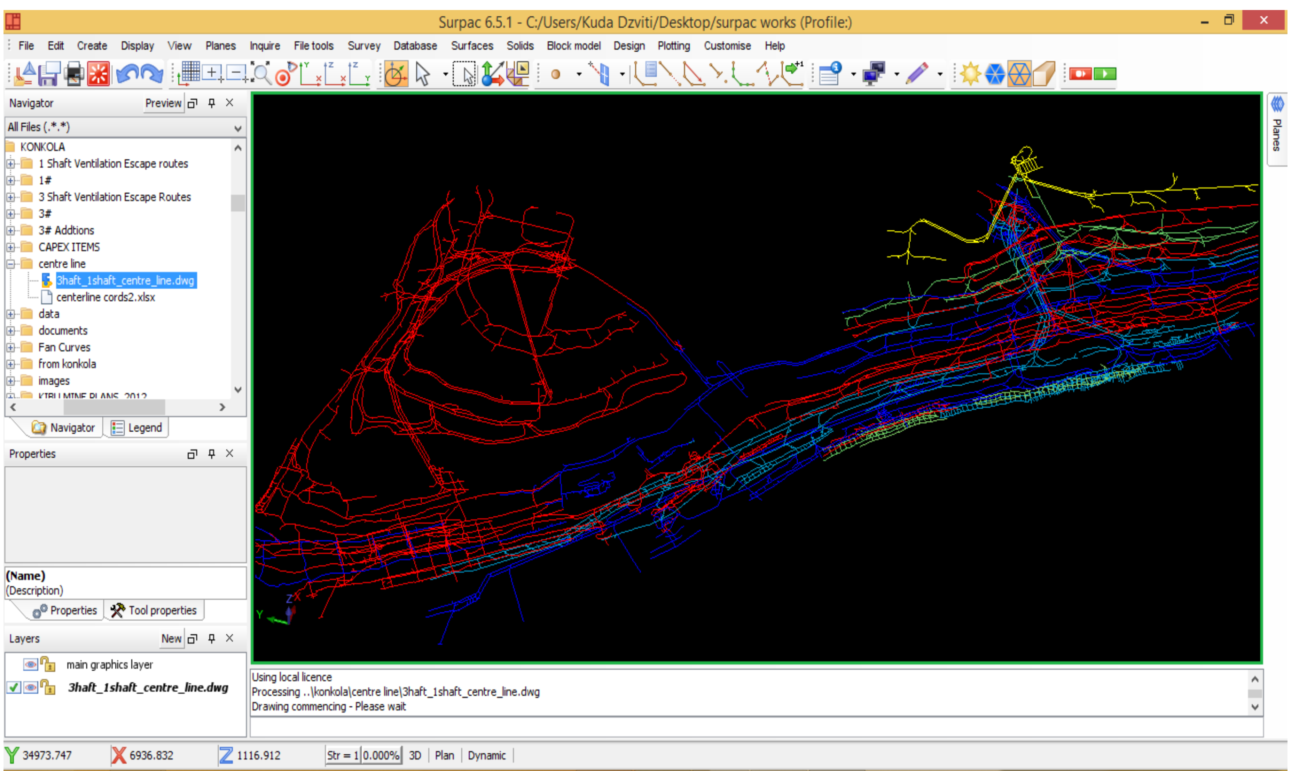


Figure 4.6 Imported csv files of airways

This data was saved in str format which was compatible with Ventsim Visual. Some of the coordinates data for the airways were not available from the survey department, hence mine ventilation plans drawn using Micro Station and Autocad were used and the output data obtained from these two software were imported as DWG and DXF files respectively into Ventsim Visual. The DXF files imported into Ventsim are shown in Figure 4.7 visualizing the skeleton of the mine.

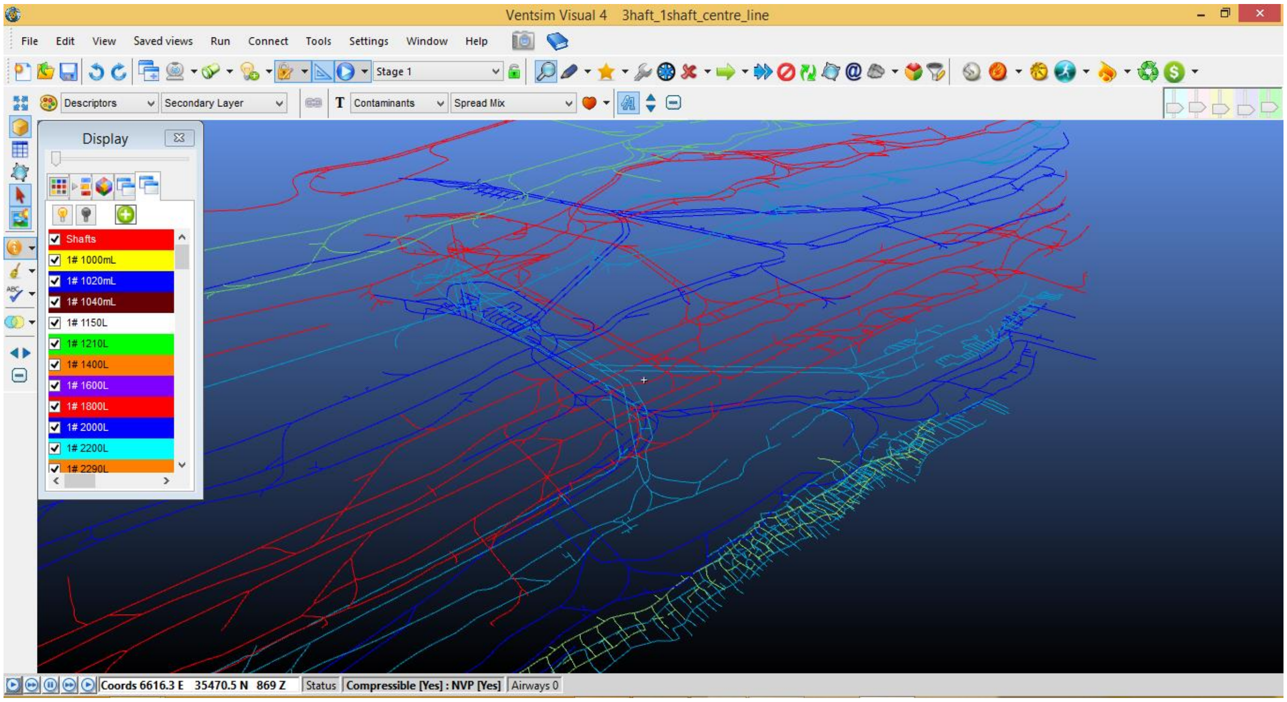


Figure 4.7 Imported DXF lines (Ventsim Visual)

These centerlines were then converted into airways for air movement using the "Convert to Airway" option as shown in Figure 4.8.

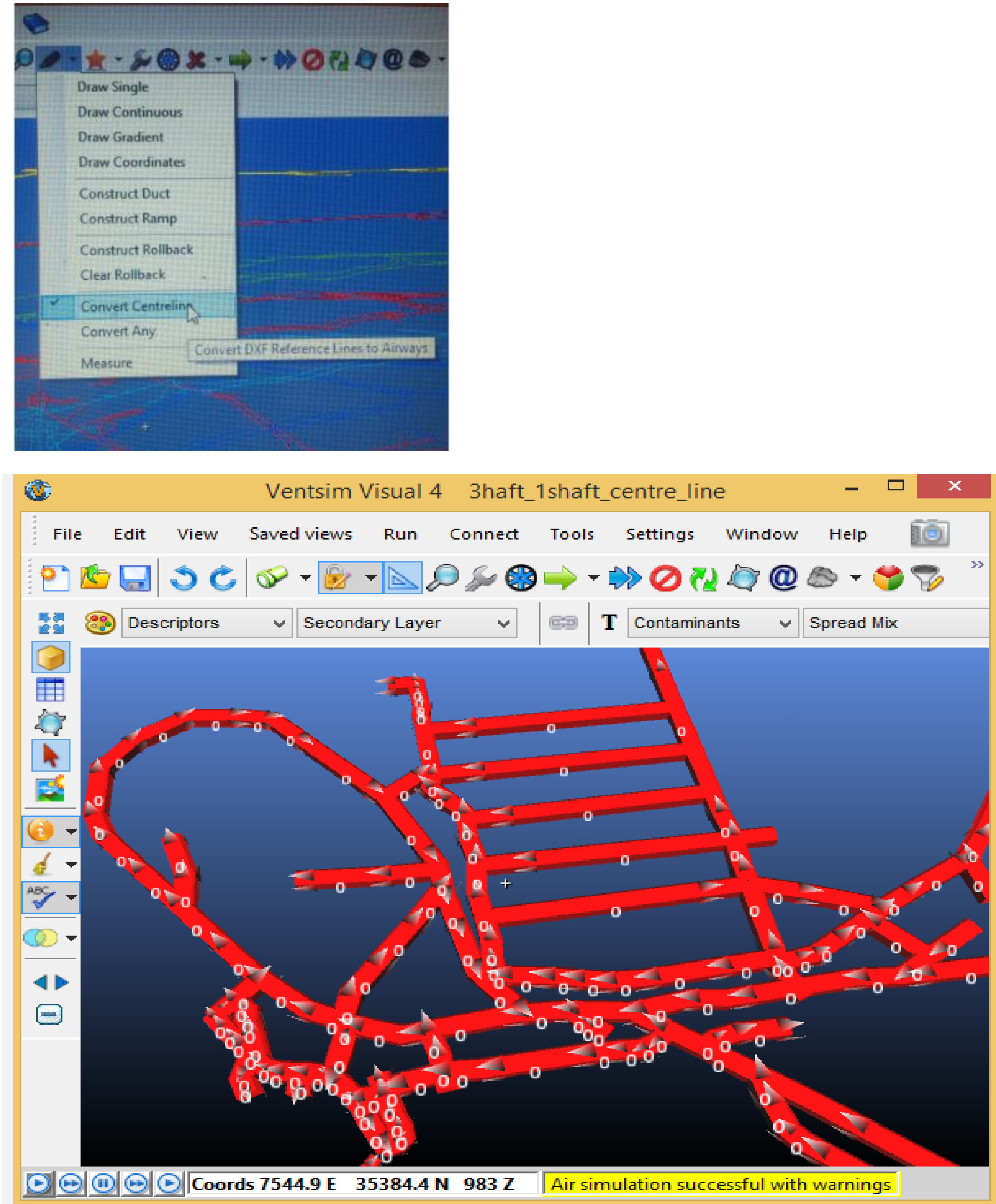


Figure 4.8 Conversion of DXF files

4.3.3 Modifying and validating import data

The program assigned default airways sizes and shapes to all the imported airways and these default sizes and shapes were inherited from the settings menu. This was done to prevent re-editing of all the airways sizes and shapes.

4.3.3.1 Filtering tools

Three filtering tools were used for cleaning of the design. Ventsim Visual considered every section between two points as a separate airway. To minimize the number of airways in the model, the simplification function was used to combine set lengths of airways to equivalent lengths. This function removed a lot of small airways and unnecessary detail to prevent slowing down the system graphics and simulation, resulting in a more unwieldy model. This did not alter the ventilation calculations but produced the same results with less clutter on the screen. For example, a nice smoothly rounded ramp produced many airway segments which were not required for accurate ventilation simulation. The Simplify function in Ventsim Visual, was used to sort, identify unnecessary detail and remove them without adversely affecting simulation.

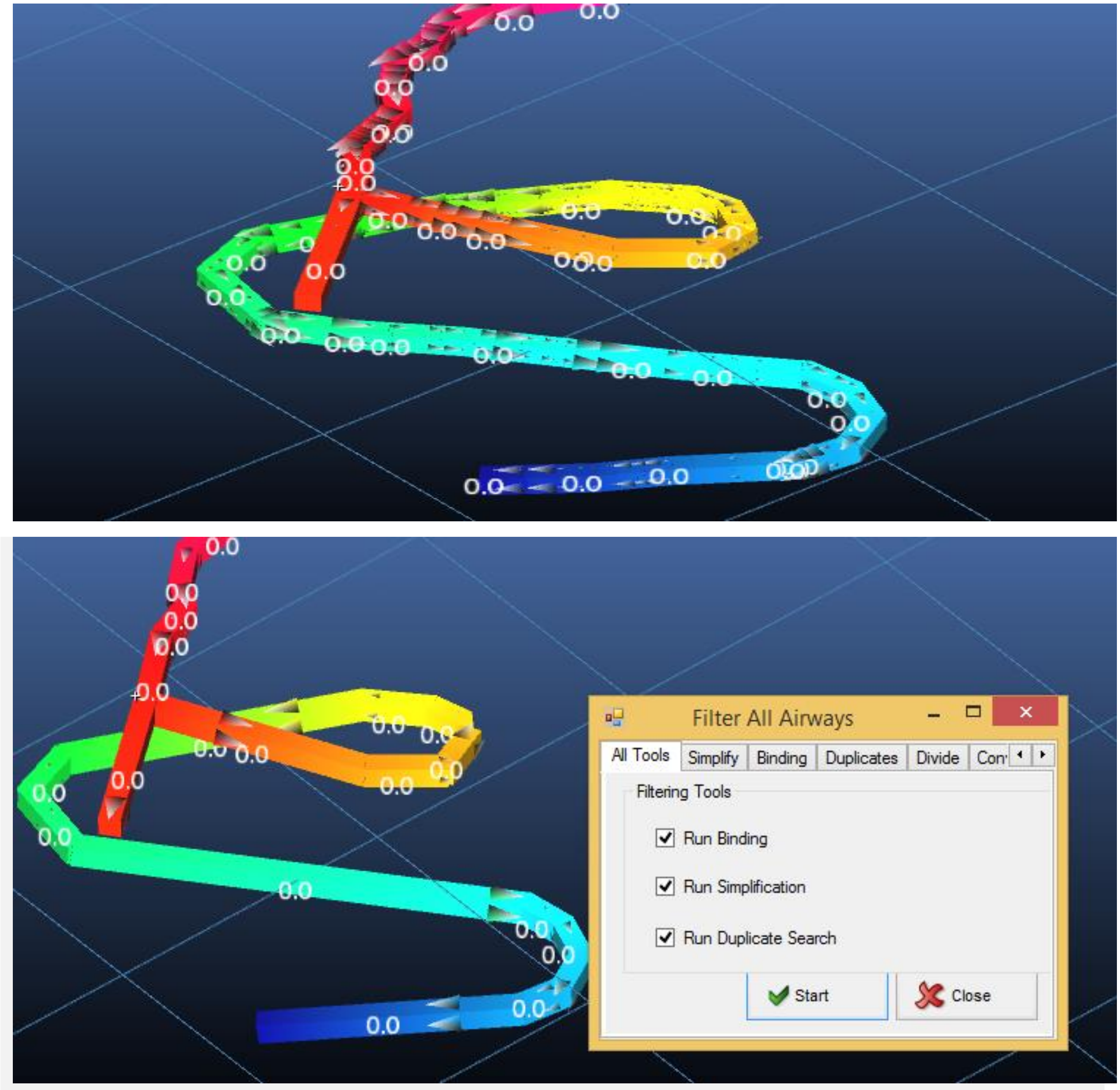


Figure 4.9 The effect of the Simplify Function to reduce airway data

The binding filter connected all airways whose ends were close to each other in a value up to 5m distance set by the user in the software. The third filtering tool removed duplicate airways and points to eliminate the possibility of running calculations for the same heading twice. These three tools were run quickly to prepare the model for simulation.

4.3.4 Creating pressure for flow

For air to flow in the model, there must be a pressure in the model. There are three different methods of creating pressure in the model and these are:

- Fans: It utilizes fan curve to establish an accurate working flows and pressure in a ventilation model.
- Fixed pressures: It uses a consistent pressure to induce an airflow in a ventilation model. The airflow in the airway varies based on resistance encountered by the pressure.
- Fixed airflows: It uses a consistent airflow to induce flow through a model. Pressure required will be adjusted to the required value to produce the airflow.

4.3.4.1 Fans

A fan database was constructed in Ventsim Visual using all the existing fan manufacturers' curve to input all the fans used in the mine. This was done using the Digitizer button on the main fan entry sheet. This tool allowed the user to directly copy a fan sheet into Ventsim, and then digitize (move and click) the mouse directly over the fan curves to enter the fan points as shown in Figure 4.10. The red line in the diagram shows the path traced on the curve being digitized.

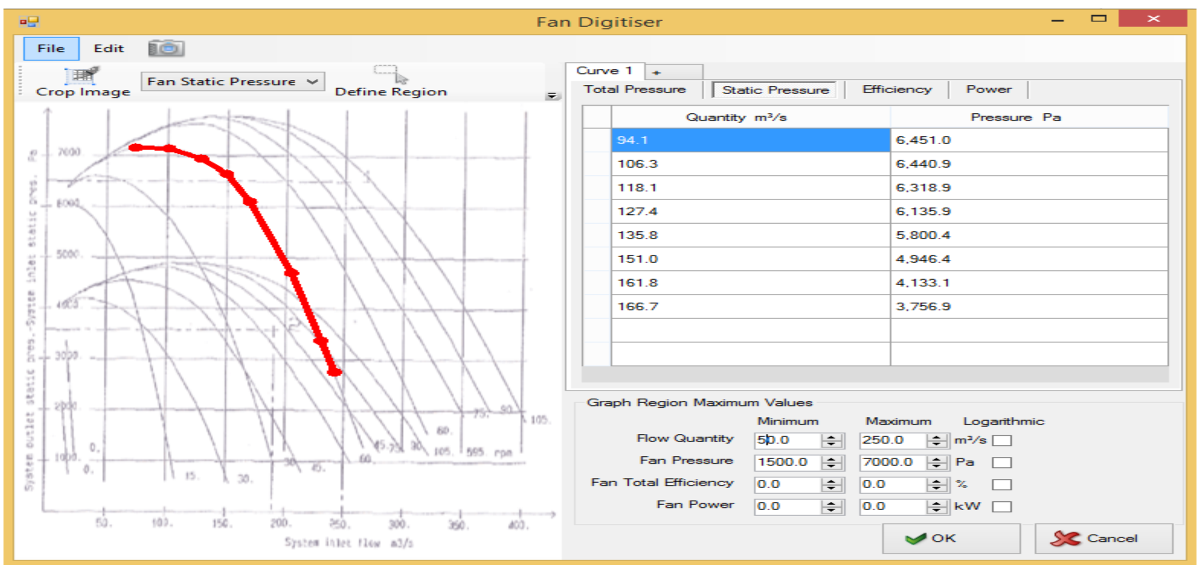


Figure 4.10 Digitizing fan on top of a fan curve

The digitized fans were stored in the fan database and several fan characteristics (maximum power, blade angle and revolutions per minute) were entered to make the fan operate in a similar manner as installed fans at the mine. These fan curves were automatically modified for local air density in a model and power, efficiency and the fan duty were calculated and provided in the Edit Box. Figure 4.11 shows the fan performance curve and its characteristics after digitizing.

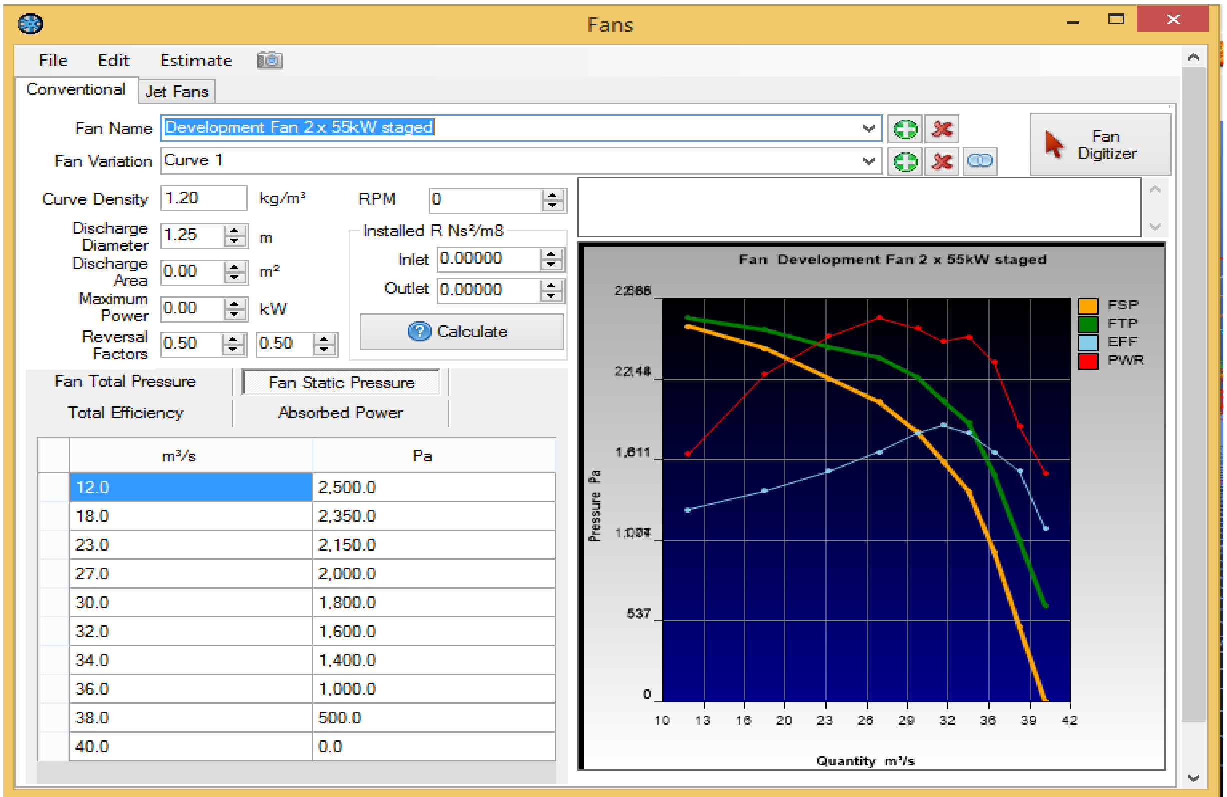


Figure 4.11 Fan performance curve and its characteristic

The mixed pressure method was used for modelling as it allows both pressure types (static pressure and total pressure) to be used for the fans. This method did not consider system velocity pressure exit losses. The main fans (ABB Axial fans and centrifugal fans) were installed on the upcast shafts in preparation for simulation. Figure 4.12 shows three ABB axial fans installed on top of an upcast #3 ventilation shaft. The main fan performance curves are shown in Figure A.4 in Appendix A. Currently the mine is operating two fans at this shaft and the other one is on standby. Ventsim Visual shows the operating fans in green color and the one on standby in blue indicating that it was switched off.

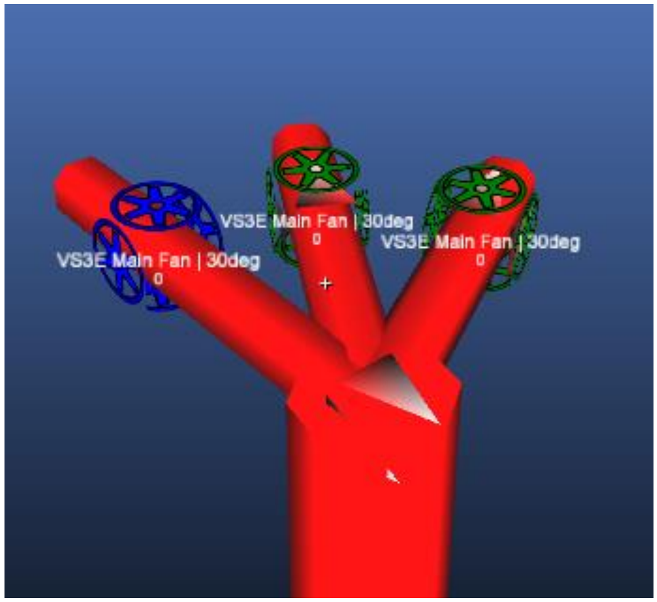


Figure 4.12 #3 exhaust ventilation shaft fans

Alstom booster fans were installed in series with the main surface fans to boost the air pressure by the surface main fan passing through it. An airway was selected in the edit mode, and the proper fan selected from the fan database to place it in that airway. For the Alstom booster fans, a 1016 mm diameter match piece was constructed in form of a ventilation duct and the fan installed on that duct to allow airflow to the return raise. The same principle was used for the installation of Alstom auxiliary fans to ventilate developing or dead ends. The construction of ventilation duct was done using the drop down option drawing tool in Ventsim, Construct Duct, and 760mm diameter ducts were constructed outside and parallel to the selected series of airways to make them visible.

This function was used to edit the diameter of the duct, leakage intervals, friction factor and the offset distance from the center of the airway. Figure 4.13 shows how booster fans and auxiliary fans were installed to ventilate different mining districts and developing or dead ends.

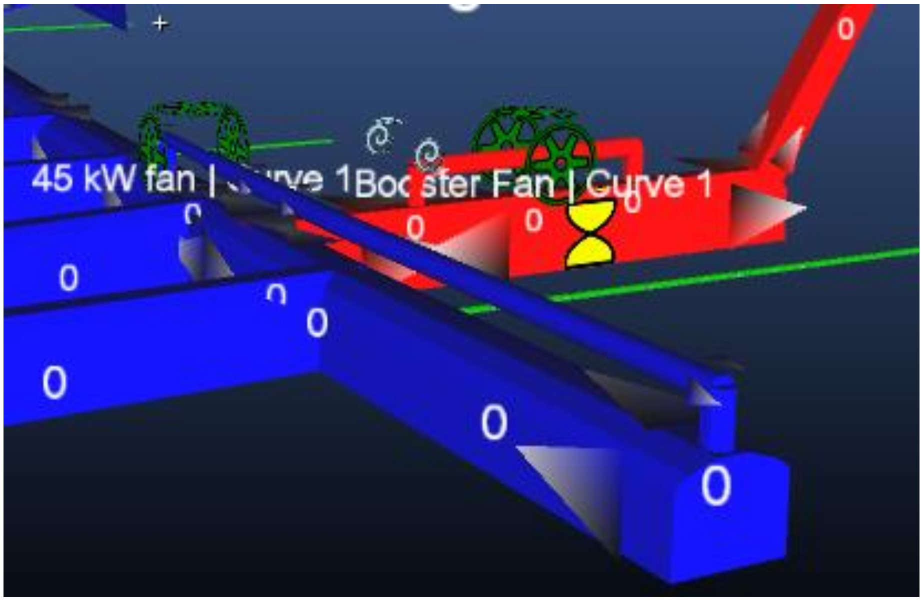
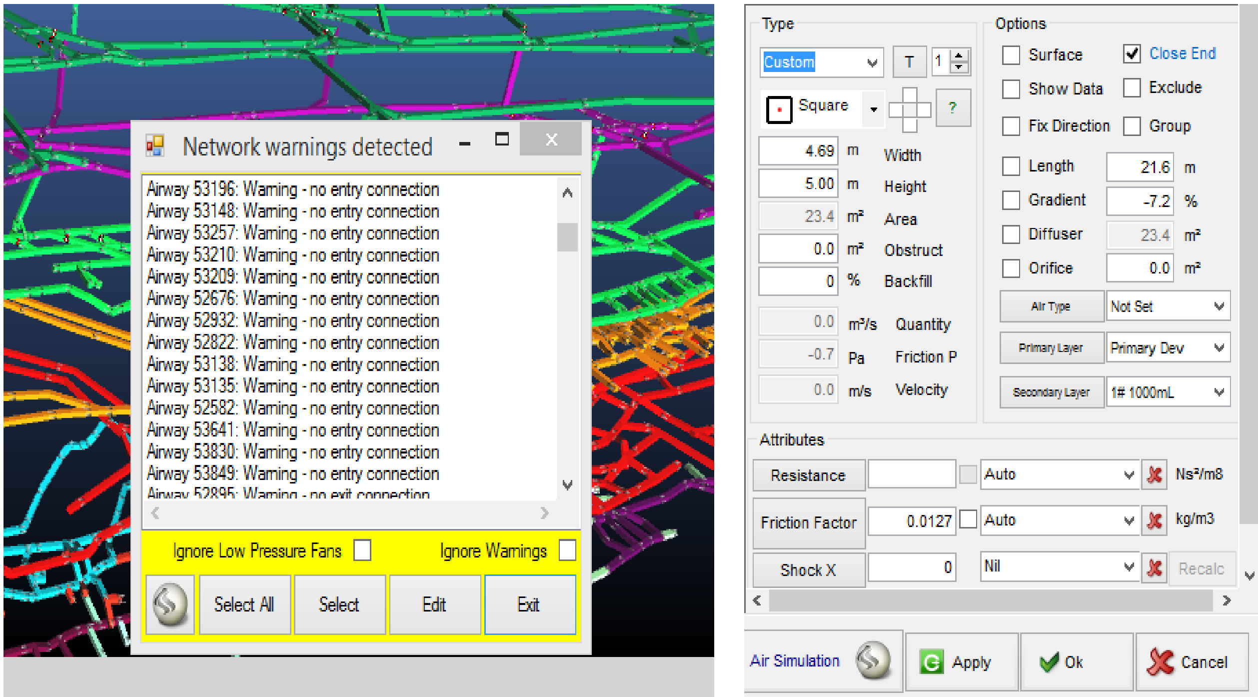


Figure 4.13 75 kW Booster fan and 45kW forcing fan installation

Airflow simulation was done on the model to quickly sort and validate (check) the imported airways. The model at this stage did not correctly simulate but this function was used to check the airways for duplicates and unconnected airways ends, to speed up the process of establishing a working model. Most of the errors resulted from airways not exactly joined into other airways, or remaining unconnected as dead ends, resulting in no exit or entry errors. These type of errors were corrected by editing all the airways showing no exit or entry error. Figure 4.14 shows how these errors were displayed in Ventsim Visual.



(a) **(b)**

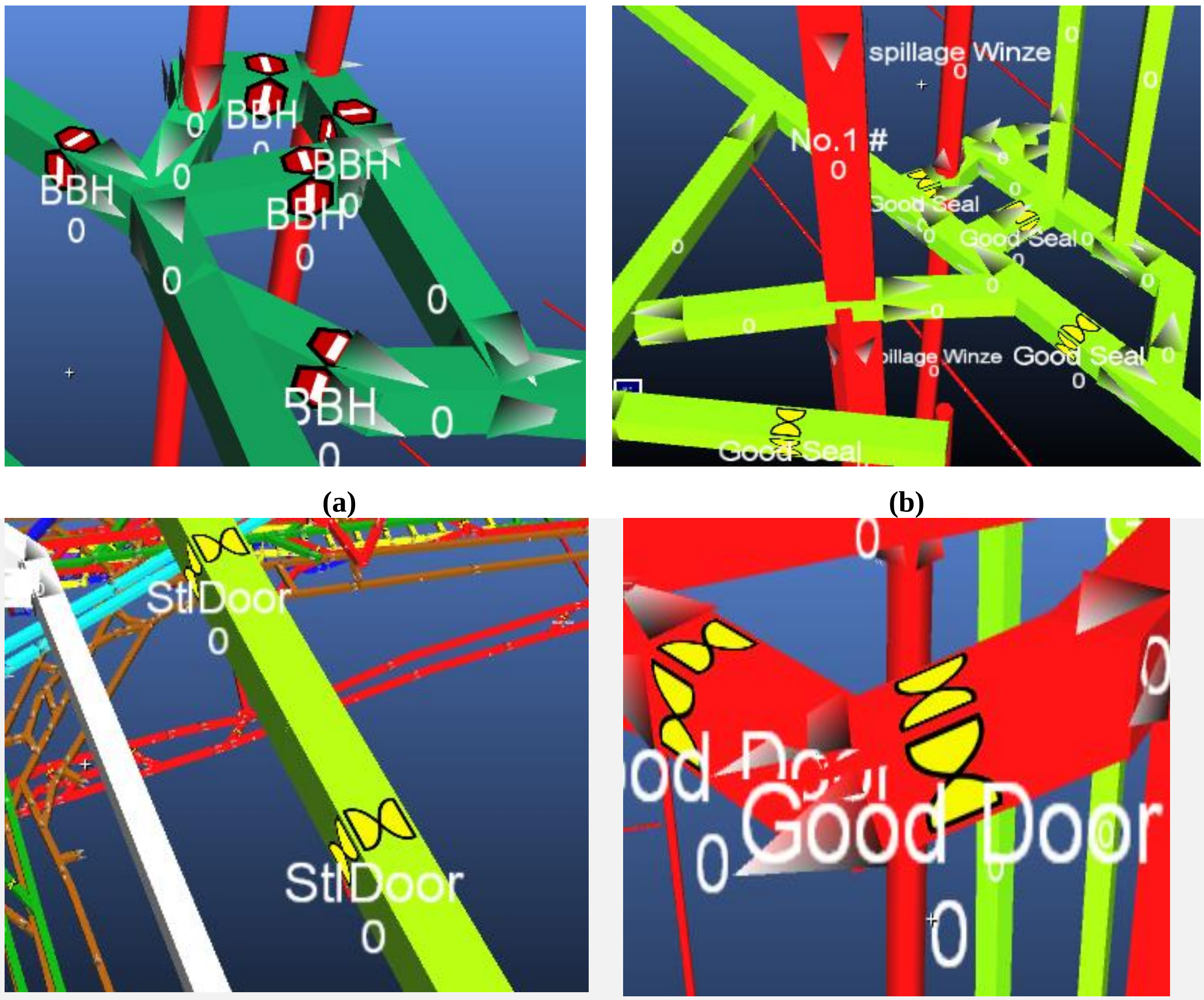
(a) No exit or entry errors (b) Edit box

Figure 4.14 No entry or exit connection errors

These errors were corrected by following each and every airway checking if they are connected to other airways. Clicking on the airway errors shown displayed the airway on the graphics window, highlighted in a different color to allow the user to edit it. The toolbar move function was used to move the airway end onto the other junction ends if a connection existed in the real mine. For all the airways which are not connected to other airways or connected to the surface such as dead end, blind developing heading or undeveloped heading, the Edit Box was used to correct them.

The Close End option was clicked to allow Ventsim Visual to assume the airways were dead end without connection to other airways or to the surface. The simulation process assumed this path is blocked and no airflow was allowed along the airway. For airways that are connected to the surface, the Surface option was used. The Surface option was clicked to connect the airway to the surface, allowing it to freely exhaust and intake air from the surface atmosphere. The exit to the surface was assumed to be at the elevation of the airway end. The barometric pressures at this point were adjusted for any difference in height between the airway elevation and the defined surface elevation in the settings.

After these corrections, airflow was directed to the right places in right quantities using controls such as steel doors, flaps, brick walls and other different types of regulators. This was achieved by going through the whole model level by level with the assistance of ventilation officers installing the controls at the right places with the correct resistances. The Edit Box was used to select the controls from the presets entered before model building. Figure 4.15 shows different types of controls that were used in the model.



(a) **(b)**

(c) **(d)**

(a) Bulkhead **(b) Good seal**

(c) Steel doors **(d) Good door**

Figure 4.15 Ventilation controls

Several ventilation controls were installed and these were displayed as icons on the airways. These controls were used to apply resistance in that specific airway. The yellow icons represented Good seal (according to the mine these are properly constructed brick walls with a maximum leakage of 0.4m^3/s), Steel doors, Good doors and the red icon represented the bulkheads (total seal where there is no leakage). During this process the airflows in the airways were approaching the real quantities measured underground. To easily edit the model, layers were developed to be able to identify and view parts of the model separately from other parts of the model. By doing this, unnecessary details were turned off so that only airways of interest were viewed. This was achieved by utilizing the Display Manager to be able to activate layers of interest. Figure 4.16 shows the secondary layers in the Display Manager while Figure 4.17 shows the complete ventilation model.

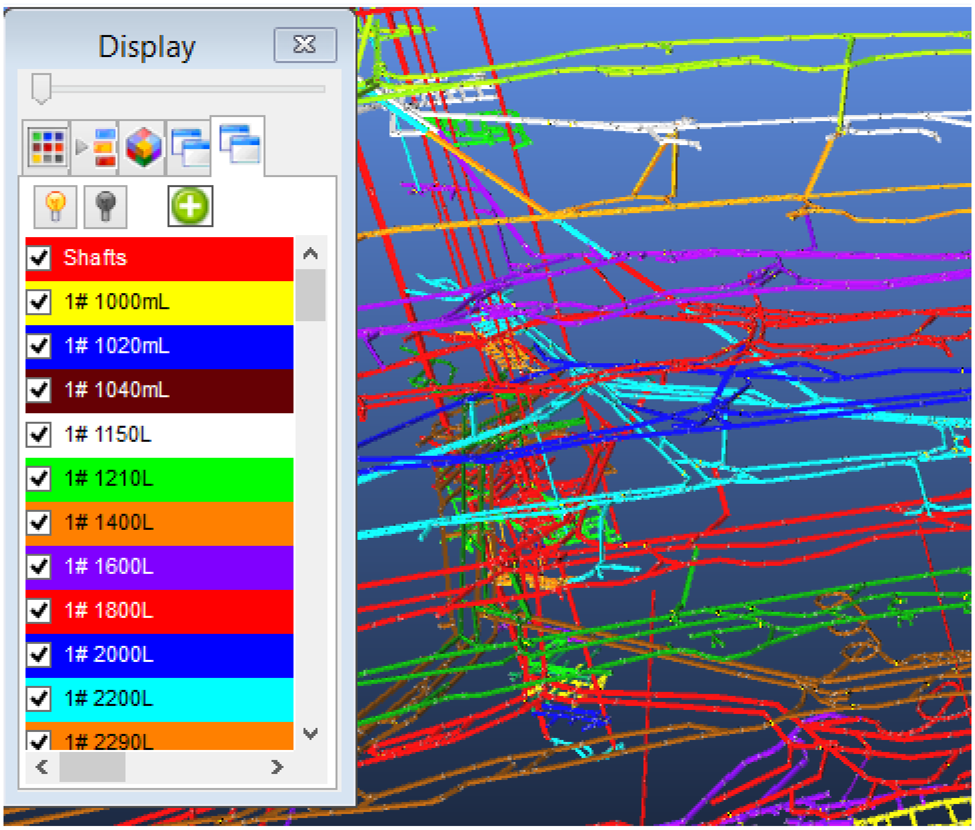


Figure 4.16 Secondary layers in Display Manager

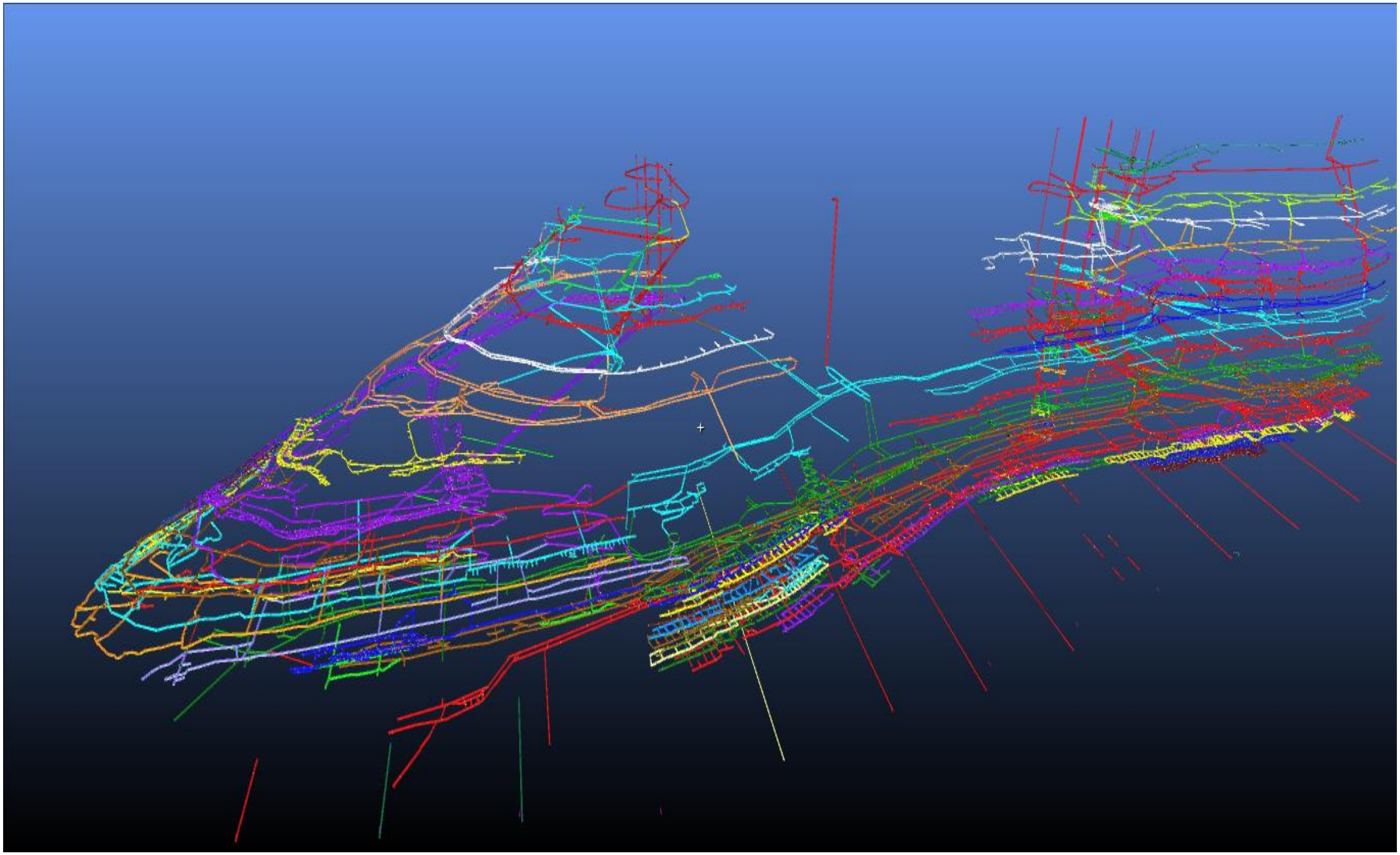


Figure 4.17 Konkola Copper Mine complete ventilation model

CHAPTER 5 DATA ANALYSIS AND INTERPRETATION

5.1 Introduction

This chapter presents an analysis of the model developed in chapter 4 through the methodological framework mentioned in Chapter 3. It discusses the research findings and answers the questions raised in the first chapter.

The mine ventilation model was developed from the data collected through several ventilation surveys. The ventilation model produced was used for a wide variety of purposes including:

- Fault-finding of a problem area in a mine and options analysis for resolution of such problems,
- A complete review or optimization exercise of an entire mine's ventilation system (assessment of different options),
- A much longer life-of-mine type of study

This model will be used by the mine to operate its mine ventilation system efficiently and effectively at the lowest possible net present cost. It will be able to solve ventilation problem or assess a new or modified ventilation design using the model before committing large sums of money.

5.2 Network summary

Figure 5.1 represents a summary of the model network displayed by the software. The summary includes details of how the model was built. For this model, compressible airflows was used to allow Ventsim to adjust air densities, volumes and fan curves according to airway depth and corresponding density.

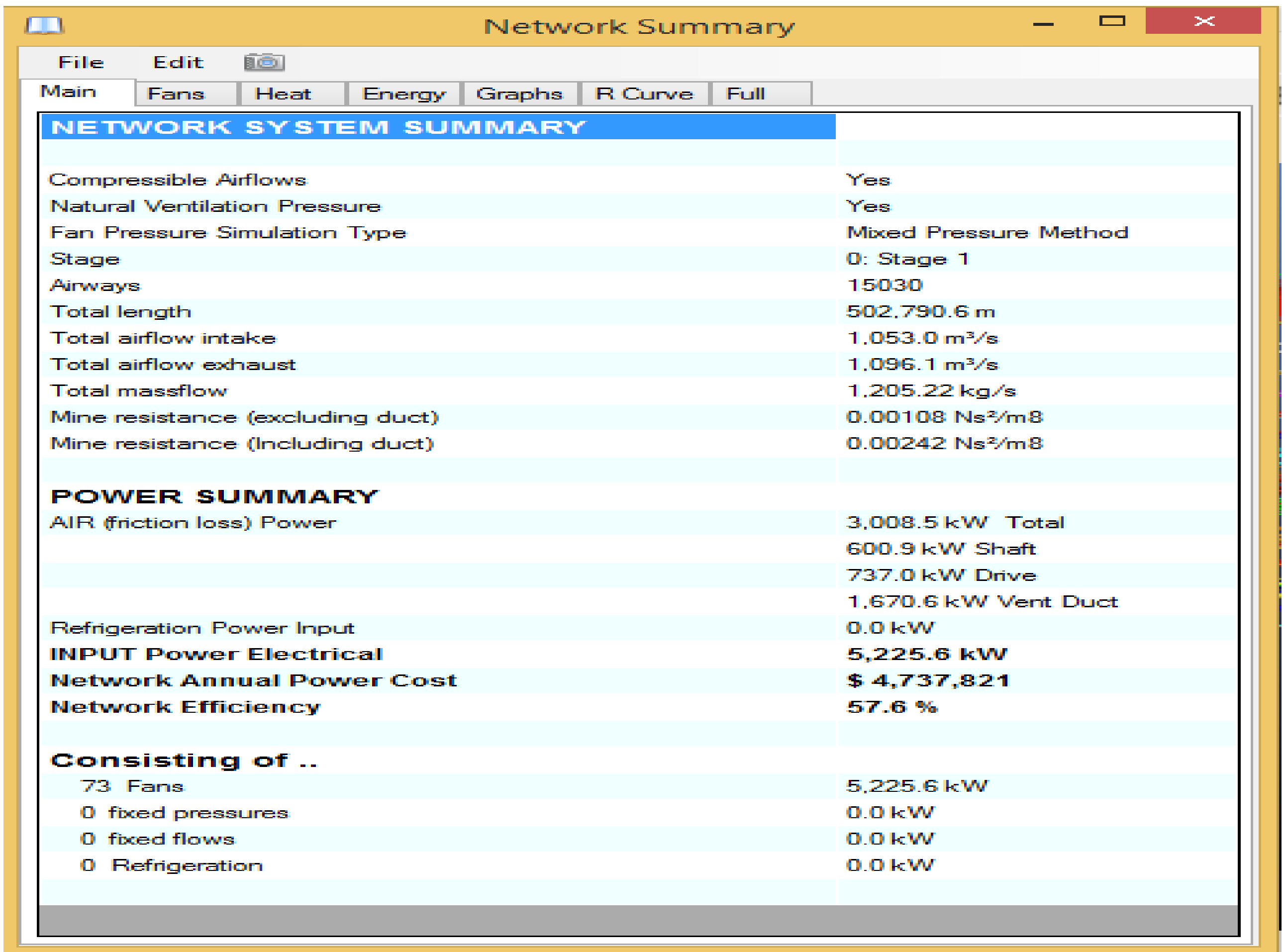


Figure 5.1 Summary of the model network

Temperature effects on density were also taken into account when Heat simulation was run in conjunction with air simulation. Natural ventilation pressures were also set at yes to force Ventsim to calculate natural ventilation pressure derived from air heat and density differences in the model. The mixed pressure method was used which allows Ventsim to use both pressure types (static and total) for fans in the model. This method does not consider system velocity pressure exit losses hence it is regarded a least consistent method to use but it was used due to the unavailability of some static or total pressure curves and the user did not want to estimate curves.

The total quantity of intake and exhaust air, total mass flow and total mine resistance (excluding and including ducts) were displayed. The power summary (including the network efficiency) was also included showing how much is being needed to influence airflow in the model and the number of fans that were in the model were shown. Figure 5.2 shows mine resistance curves (with and without duct) and the annual cost of ventilating the model. The mine resistance graph shows two curves, the lower red curve without auxiliary ventilation duct included and the green curve including auxiliary ventilation duct. The mine resistance was calculated based on the established airflow airways set by resistances and fans. Any airflow change in the model was assumed to universally and equally change across the entire model.

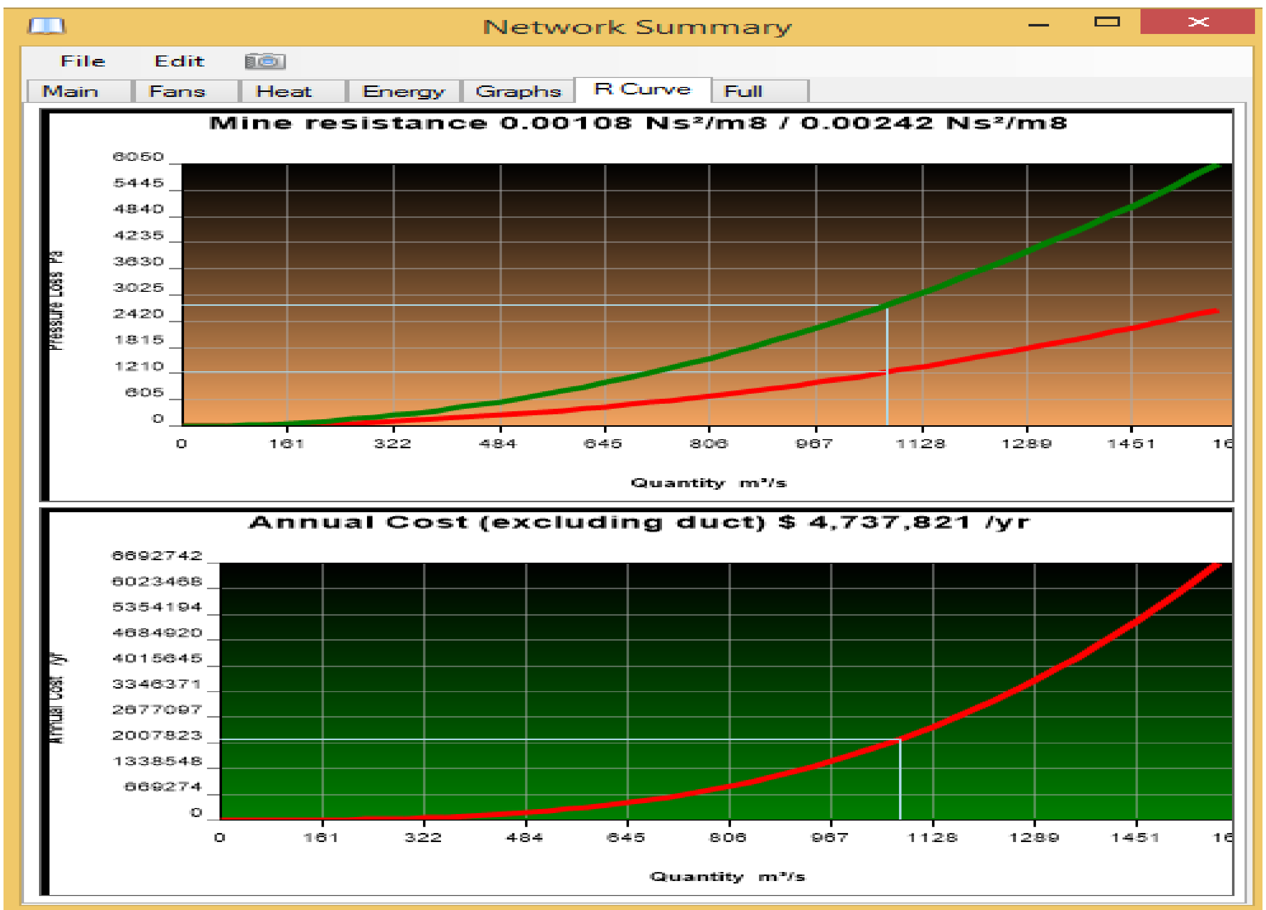


Figure 5.2 Total mine resistance and annual cost

5.2.1 Energy losses

Figure 5.3 shows a graphical representation and percentage of energy losses in the model. The graph represented loss of input electrical energy into various ventilation losses such as wall friction, shock losses, regulator losses, orifice losses and exit losses.

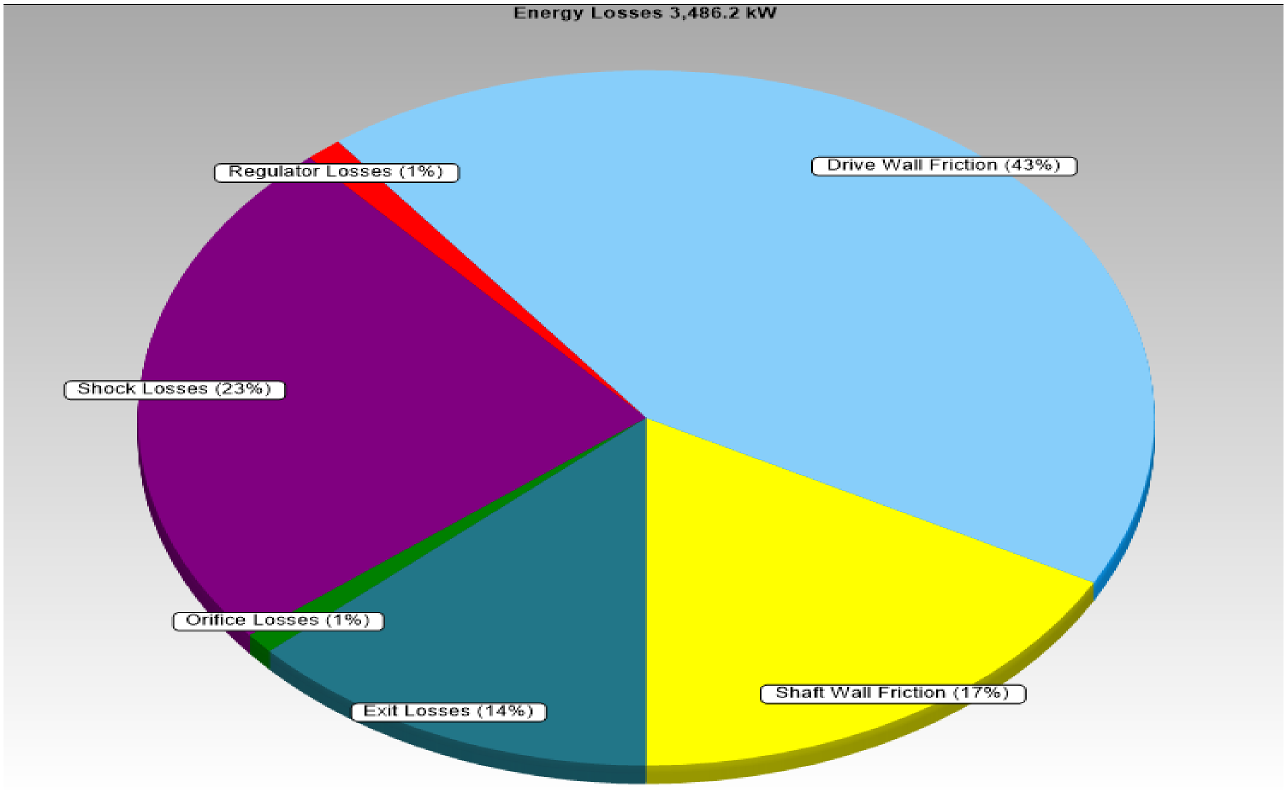


Figure 5.3 Energy losses

The exit losses displayed power lost due to the velocity of ejection of exhaust air into the atmosphere. These exit losses can be recovered into useful fan static pressure by increasing diffuser size of the main surface fan hence reducing exit velocities. This means that Ventsim can be used to design an optimum diffuser size for the main surface fans by assessing different options of diffuser sizes in the model hence reducing energy losses of the ventilation system.

5.2.2 Heat gain/ losses

Figure 5.4 shows the quantity of heat added and removed from the mine atmosphere. From the graph it is clear that auto compression is the major contributor of heat into the mine due to the depth of the mine, but this heat is removed when air travels back to the surface through upcast shafts.

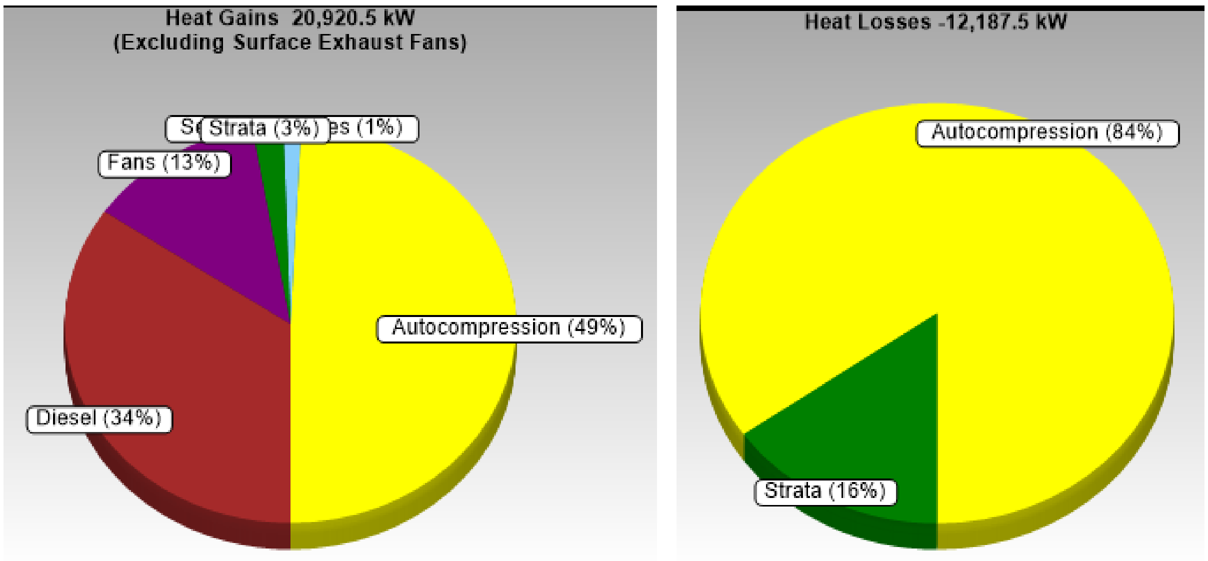


Figure 5.4 Heat gains and losses

Heat removal as air ascend upcast shafts is referred to as de-auto compression. The second major contributor of heat in the model are the diesel machines. This is because the mine is mechanized and most of its operations are done by machines. The mine increased its fleet size and the size of machinery underground to boost production as they try to counteract the fluctuating copper prices. By so doing the machines are increasing the burden on the ventilation system.

The mine workings are advancing far away from the shafts, hence the booster and auxiliary fans number has increased. This results in a significant quantity of heat addition to airflow from the fans as shown in Figure 5.4. This heat is generated from motor and transmission losses and compression of air between the blades of the fans. The percentage of heat gain from strata is very low due to low geothermal gradient at Konkola Copper mine (2.28K/km). Sensible sources indicated 1% heat release into the atmosphere and these are pump stations in the mine. This is so because these pumps are electrically powered and most of the input power is converted into useful power and they do not release latent heat. Ventsim excluded exhaust fan heat on surface fans from the summary as this heat does not directly affect underground atmosphere.

5.3 Financial Optimization

The model developed was used to analyze and develop strategies to reduce the operating costs of the mine ventilation system. The total cost of the mine ventilation was considered as a combination of the following costs;

- Direct operating cost (such as power consumed or maintenance and upkeep of ventilation system),
- Direct capital infrastructure cost (which includes the development and infrastructure mined and fans purchased), and
- Indirect cost which factors productivity gains and losses due to ventilations conditions.

The main fans, booster fans and auxiliary fans used at the mine were electrically powered. These were the main components in the ventilation system that required optimization to reduce the ventilation system operating costs. According to the data collected at the mine the operating expenses of the fans are as shown in Figure 5.5.

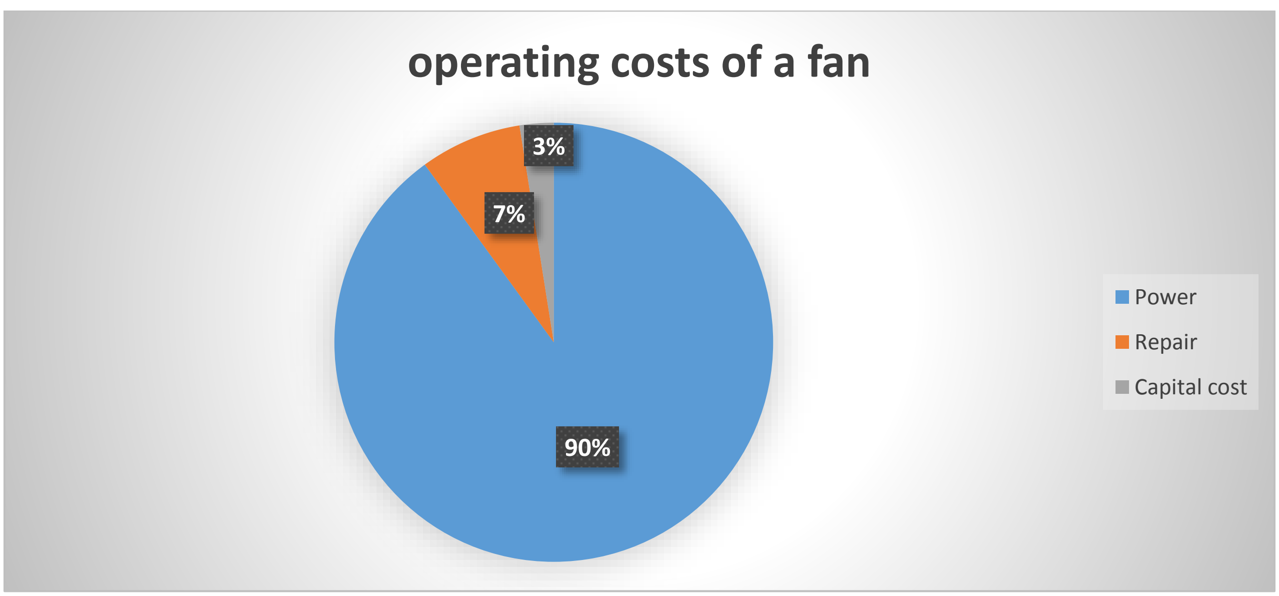


Figure 5.5 Operating costs of a fan

The pie chart shows that power absorbed by the fans constitute a greater percentage of its operating costs. This is mostly caused by operating fans at low efficiency whereby a fan is operated below its design duty point. The model developed was used to assess the performance of all the fans underground with the intention of improving their efficiencies.

5.3.1 Financial Simulation

Ventsim Visual provided a function to quickly estimate optimum ventilation infrastructure size, by considering mining costs as well as life of mine ventilation operating costs. 10, 20 and 30 years life of mine were used for financial simulation to check how ventilation costs can be reduced. The simulation helped to optimize airway sizes and save substantial money over the life of a mine. Ventsim Visual consists of three different options for financial optimization that is Quick, Selection and Global but the researcher used only one option which is Global Optimization. Global optimization recommend larger than original size airways, as recommending smaller sizes often ignores the reality that mine airway sizes are designed for minimum sized passage of men or machinery. The simulation only reported airways which were over-restricted and potential cost savings exist by making the airway larger. Global financial simulation checked and reported on all airways within a mine model on their suitability to carry the simulated air. It utilized the default cost settings entered in the Preset box to determine cost of airflow through each airway for the life of the mine.

The cost components considered in this simulation are the mining cost, and fan capital cost component and a lifetime discounted power cost to provide ventilation in the mine. Three different scenarios were considered and involved altering the life of mine from 10, 20 and 30 years. This was done due to the fact that mine life extends far beyond initial estimations as further ore resources are found. Figure 5.6 shows 10 years mine life for financial global optimization.

5.3.1.1 Scenario 1: 10 years mine life

Ventsim Visual found that 46 airways can be optimized in this scenario. The optimization of these airways will result in the total potential cost savings of $ 953, 379 and an annual power savings of $288,176.

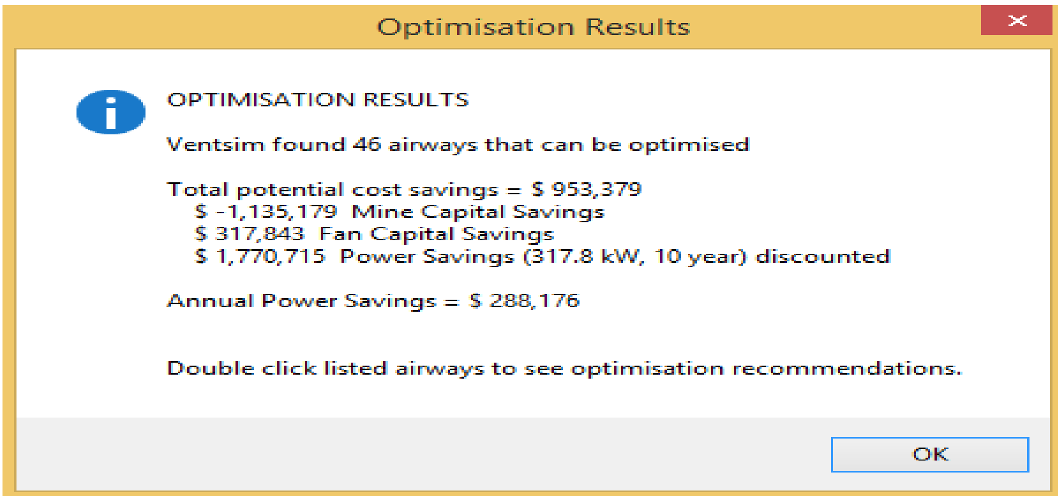


Figure 5.6 Financial Global Optimization

The mine capital savings were displayed as a negative value (-$1,135 179) because all the airways were recommended to be made larger as they were restricting airflow. This created additional mining costs, and this was further exacerbated by the time value of money which dictates that a dollar saved in mining costs now is worth more than a dollar saved in ventilation costs in the future. Increasing airway dimensions is the easiest way to reduce frictional pressure losses resulting in low ventilation costs of passing airflow in these airways. The reduction in the ventilating cost of the airways out ways the mining costs incurred hence resulting in the power savings of $1,770,715 for the mine.

The period in which the airway was required to handle air was considered as it affects how much ventilation cost can be saved in the future. All temporary airways were ignored to avoid incurring additional mining costs for temporary infrastructure and all airways resulting in power saving of less than $50,000 were left out. Ventsim provided the option to check each and every airway to evaluate the recommended size for that airway and the potential saving that exist.

By double clicking the displayed airway, Ventsim Visual highlighted the airway in blue and displayed the breakdown of all the related costs. Figure 5.7 shows the recommended shaft size for an upcast ventilation shaft 3A (VS3A) and the corresponding costs.

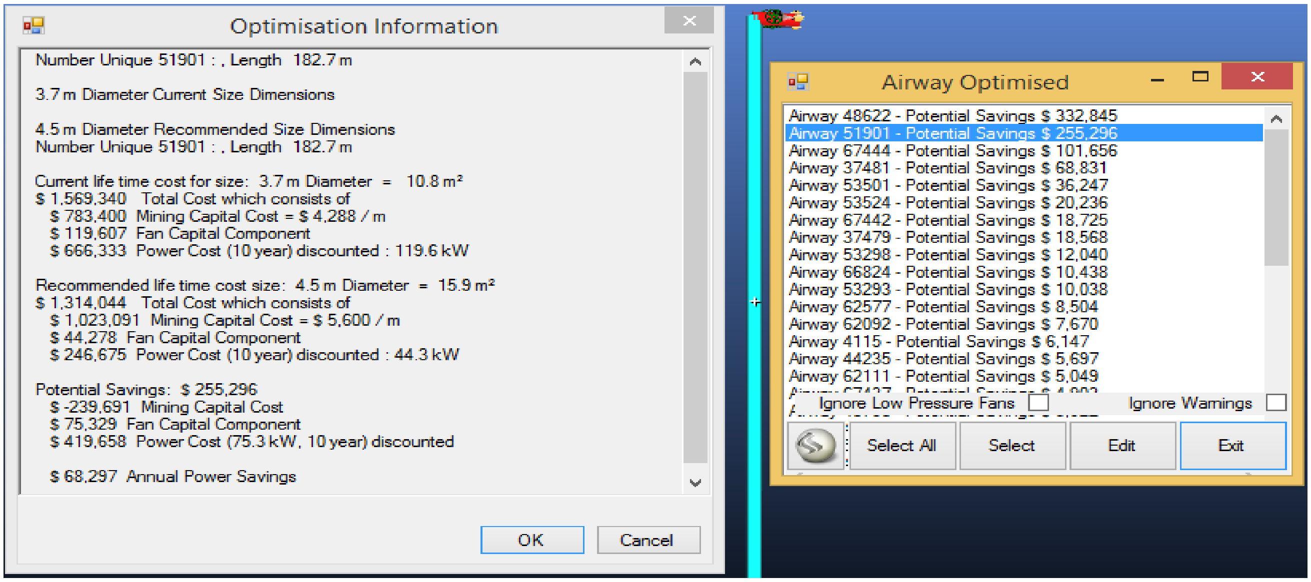


Figure 5.7 Recommended airway dimensions and corresponding costs

The current dimensions of the airway and life time cost of passing airflow through this airway, the recommended size and life time costs and the potential savings were displayed. By optimizing this airway, the mine has a potential of saving $ 68,297 on power annually. The power cost of passing air through this airway was discounted using the cost of capital 10 % assigned in the Preset Box. Table 5-1 shows a summary of the Global Optimization results for 10 years life of mine. The table shows the amount of power that can be saved by the mine if it considers enlarging airways to the recommended sizes.

Table 5.1 Summary of Financial Global Optimization (10 years mine life)

	Current		Recommended		Power saving ($)	Annual power saving ($)	Power saving (%)
Airway unique No.	**Dimension (m)**	**Power cost ($)**	**Dimension (m)**	**Power cost ($)**			
48622	3.7 diameter	867,008	4.5 diameter	320,964	546,044	88,866	63
51901	3.7 diameter	666,333	4.5 diameter	246,675	419,658	68,297	63
67444	5.0 x 5.0	259,236	6.1 x 6.1	94,862	164,374	26,751	63
37481	5.0 x 5.0	175,176	6.1 x 6.1	63, 569	111,607	18,163	64
53501	2.0 x 2.0	70,063	2.6 x 2.6	19,846	50,217	8,173	72
53524	2.0 x 2.0	36,377	2.6 x 2.6	9,393	26,984	4,392	74
67442	5.0 x 5.0	164,621	5.5 x 5.5	105,454	59,166	9,629	36
37479	5.0 x 5.0	164,248	5.4 x 5.4	106,324	57,924	9.427	35

5.3.1.2 Scenario 2: 20 years mine life

In this scenario 60 airways were found that can be optimized to reduce the operating costs of the ventilation system. The total potential cost of savings was found to be $1,715,158 and an annual power savings of $355,659.

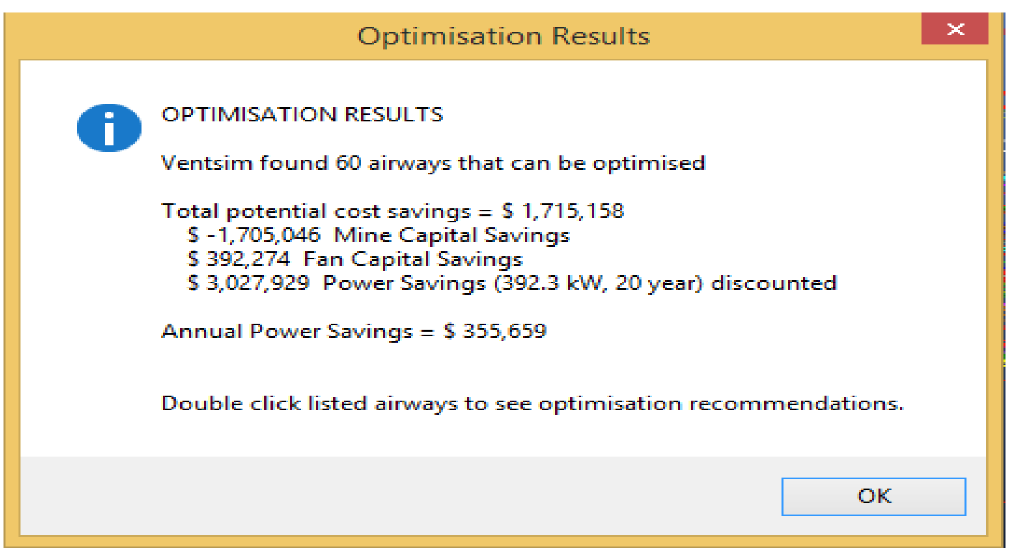


Figure 5.8 Financial Global Optimization

Table 5.2 gives a summary of the Financial Global Optimization done for 20 years mine life. Out of the 60 suggested airways, only those airways that result in power savings of not less than $50,000 was considered.

Table 5.2 Summary of Financial Global Optimization (20 years mine life)

	Current		Recommended		Power saving ($)	Annual power saving ($)	Power saving (%)
Airway unique No.	**Dimension (m)**	**Power cost ($)**	**Dimension (m)**	**Power cost ($)**			
48622	3.7 diameter	1,201,278	4.7 diameter	361,880	839,397	98,595	70
51901	3.7 diameter	923,233	4.7 diameter	278,120	645,113	75,775	70
67444	5.0 x 5.0	359,183	6.4 x 6.4	106,704	252,478	29,656	70
37481	5.0 x 5.0	242,714	6.4 x 6.4	72,104	170,609	20,040	70
53501	2.0 x 2.0	97,075	2.7 x 2.7	21,949	75,126	8,824	77
67442	5.0 x 5.0	228,089	5.7 x 5.7	119,517	108,572	12,753	48
37479	5.0 x 5.0	227,573	5.7 x 5.7	120,405	107,167	12,588	47
4115	5.0 x 5.0	271,971	5.4 x 5.4	180,321	91,651	10,765	34
53298	2.4 diameter	112,658	2.7 diameter	55,611	57,046	6,701	51
53293	2.4 diameter	109,951	2.7 diameter	57,209	52,743	6,195	48
44235	5.0 x 5.0	197,683	5.5 x 5.5	126,722	70,961	8,335	36
4112	5.0 x 5.0	174,092	5.4 x 5.4	115,425	58,667	6,891	34
44231	5.0 x 5.0	270,631	5.3 x 5.3	199,380	71,251	8,369	26

5.3.1.3 Scenario 3: 30 years mine life

In this case 64 airways were found that can be optimized to reduce the ventilation costs. By implementing the recommended sizes, the mine can realize a total potential cost of $2,054,961 and an annual power savings of $388,325.

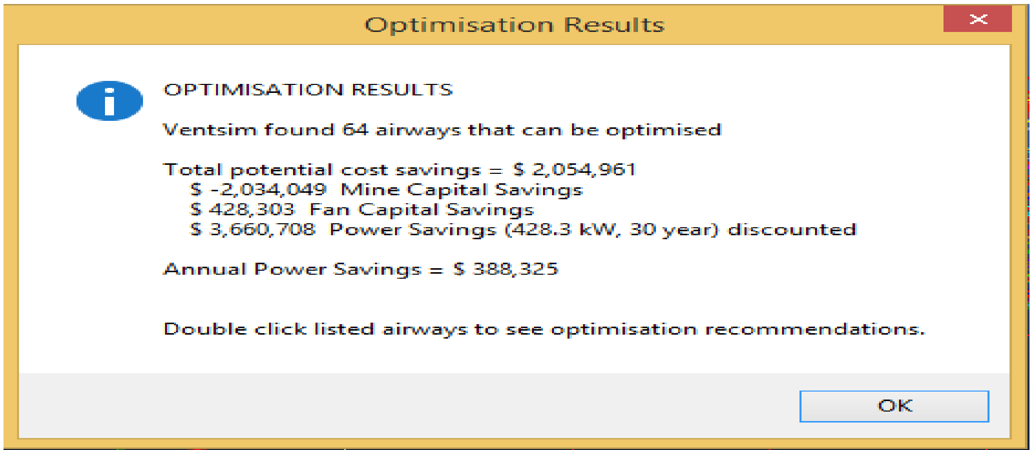


Figure 5.9 Financial Global Optimization

Table 5-3 gives a summary of the Financial Global Optimization done for 30 years mine life and only airways producing not less than $50,000 power savings were included in the table.

Table 5.3 Summary of Financial Global Optimization (30 years mine life)

	Current		Recommended		Power saving ($)	Annual power saving ($)	Power saving (%)
Airway unique No.	**Dimension (m)**	**Power cost ($)**	**Dimension (m)**	**Power cost ($)**			
48622	3.7 diameter	1,330,153	4.7 diameter	379,873	950,279	100,805	71
51901	3.7 diameter	1,022,279	4.7 diameter	291,949	730,330	77,473	71
67444	5.0 x 5.0	397,717	6.4 x 6.4	111,183	286,534	30,395	72
37481	5.0 x 5.0	268,752	6.4 x 6.4	75,131	193,622	20,539	72
53501	2.0 x 2.0	107,490	2.7 x 2.7	23,287	84,203	8,932	78
67442	5.0 x 5.0	252,559	5.7 x 5.7	124,584	127,584	13,534	51
37479	5.0 x 5.0	251,987	5.7 x 5.7	124,692	127,295	13,503	51
4115	5.0 x 5.0	301,149	5.5 x 5.5	186,732	114,416	12,137	38
53298	2.4 diameter	124,744	2.8 diameter	55,603	69,141	7,334	55
44235	5.0 x 5.0	218,890	5.5 x 5.5	131,344	87,546	9,287	40
53293	2.4 diameter	121,747	2.8 diameter	57,079	64,668	6,860	53
4112	5.0 x 5.0	192,769	5.5 x 5.5	119,529	73,239	7,769	38
44231	5.0 x 5.0	299,665	5.4 x 5.4	209,017	90,648	9,616	30
44232	5.0 x 5.0	154,393	5.5 x 5.5	94,688	59,705	6,333	39

All the scenarios discussed above shows that there is a negative correlation between airway dimensions and the power to pass airflow through that airflow. As the size of an airway is increased, the resistance to airflow in that airway decreases also and hence the ventilation operating costs will decrease for that airway. The results obtained from the Ventsim Visual shows that it is possible to use the model to reduce the ventilation operating costs without extensive mathematical calculations. These results can be used as a guideline by the ventilation team to make substantial decisions in running a cost-effective and technically efficient mine ventilation system.

5.4 Uncontrolled recirculation

Uncontrolled recirculation is when a quantity of air leaks from the return airways to the intake airways unintentionally as a result of high pressures in the return airways than that in the intake airways. Recirculation has the potential to increase the contaminant concentration in the intake air forming a hazardous mine atmosphere. The model was used to examine paths which were recirculating airflow in the mine and the percentage or recirculated air in each airway reported. Using a recirculation checker, Ventsim Visual displayed all the paths where airflow was recirculated as shown in Figure 5.10.

To prevent trivial reporting of recirculating air such as minor leakages of air through mine seals, a default tolerance of $1m^3/s$ recirculation was used. A list of recirculation loops were displayed in the software and sixty nine different recirculation loops were identified by Ventsim Visual. By double clicking the listed recirculation loop, the software zoomed in were that loop was located in the model. This provided an easy way for locating and rectifying recirculation in the mine. The recirculation checker helped the mine to identify collapsed or damaged brick walls in the mine and also airways that required to be blocked to prevent air recirculation.

Some of the loops highlighted proved the use of booster fans as potential source of recirculation. These cannot be substituted, as they improve the efficiency of the ventilation system. The locations of the booster fan and the blade angle setting have the most effect on recirculation (Wempen, 2012). So to limit the potential for system recirculation, the location and size of booster fans can be assessed using the model before the installation in the real mine.

The model can be used to resolve recirculation by reducing the number of booster fans used. This can be done by assessing how main surface fans can be set in terms of blade angle and rotational speed to deliver the required quantity of air to the working areas. The power absorbed by changing the quantity delivered by the main surface fans must be compared with that of using booster fans so that the operating costs of the main fans does not increase. Controlling recirculation resulted in providing quality air to the working areas and making the mine atmosphere safe and comfortable for the workers.

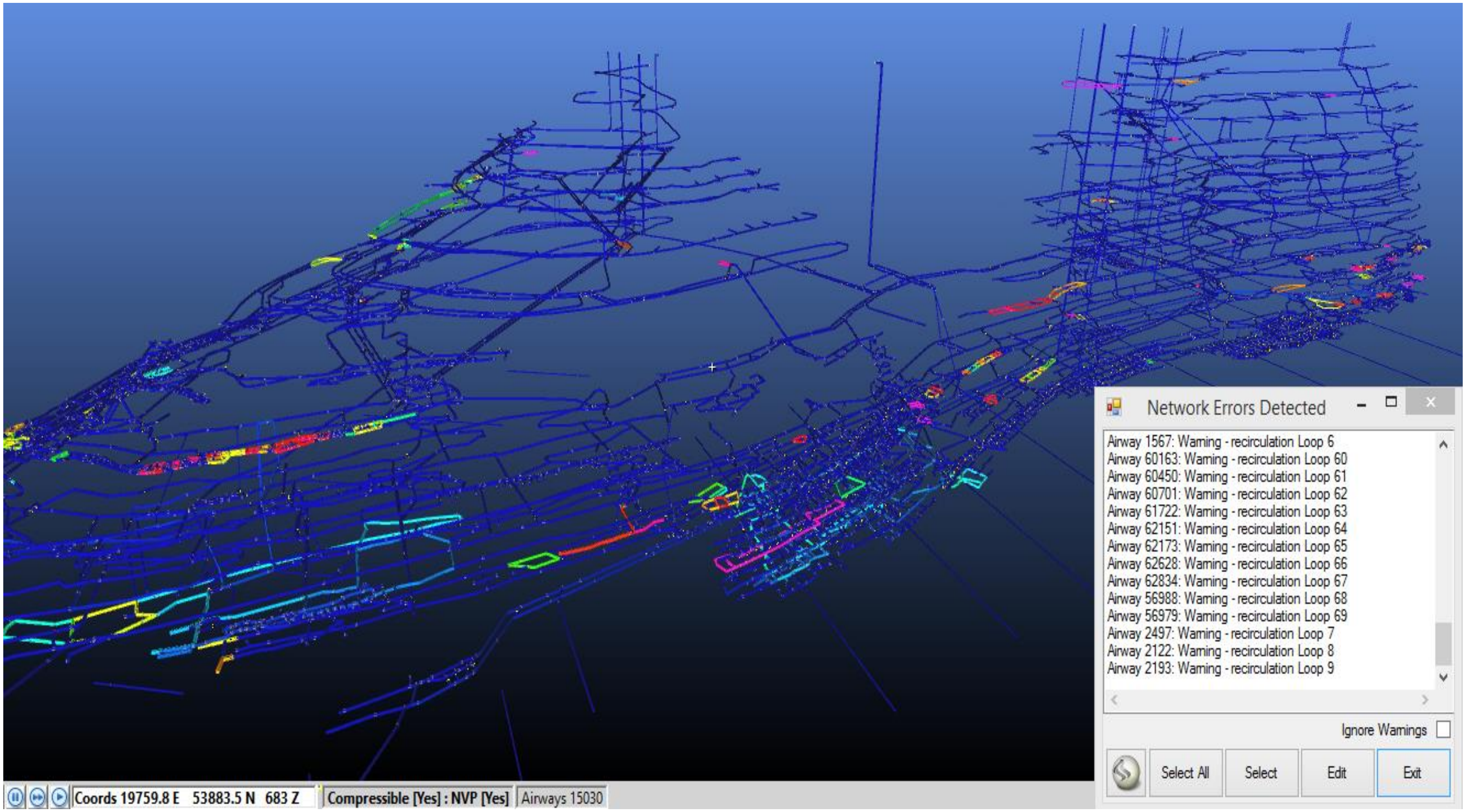


Figure 5.10 Recirculation loops shown by Ventsim Visual

5.5 Contaminant simulation

There are two different types of simulation that can be used for contaminant, gases, DPM and heat and these are steady state simulation and dynamic simulation. The main difference between steady state and dynamic simulation is that in the later, changing ventilation conditions and contaminants can be tracked through the mine at specific times. Furthermore the Ventsim model can be dynamically changed for example different levels of contaminants can be changed, or the model airflows, resistances or fans can be altered to see the effect on contaminant flow. Only dynamic simulation was discussed in this thesis.

5.5.1 Dynamic simulation

This is a specialized simulation method that shows a time based simulation that can be dynamically viewed and changed during the simulation. It can be applied to contaminants, gases, DPM and heat. The simulation results are shown dynamically on the screen as the simulation progresses or alternatively by placing a monitor in the airway to observe and record the simulation. It is performed to improve blast clearance times, production design and assist in emergency planning.

Figure 5.11 shows a dynamic contaminant simulation that was performed to simulate the concentration and distribution of contaminants from a blast zone in Konkola Flats section. 1000 kg of explosives was placed in the airway end and a monitor was placed at a refuge chamber closer to the Quartzite haulage. The dispersion rate of contaminants from the blast zone was assigned as 5 (moderate). The dispersion rate is the logarithmic factor at which contaminants will be dispersed. It depends upon the efficiency of the ventilation flow to access and remove all fumes from the blast zone. This factor does not affect the mass volume of contaminant entering the model but rather the rate at which it escapes into the model airflow.

The distribution of contaminants from this blast zone is shown in Figure 5.11 and the pink color shows the path followed by the contaminants from the blasting area. This shows that Ventsim can be used to track and visualize all the areas that will be affected when this end is blasted. The same principle can be applied to several ends in the mine to visualize all paths that will be followed by contaminants. The monitor placed at the refugee chamber produced results shown in Figure 5.12. The graph shows that blasting fumes started to report at the monitor location after 6 minutes and a peak contaminant of 1600 ppm was recorded.

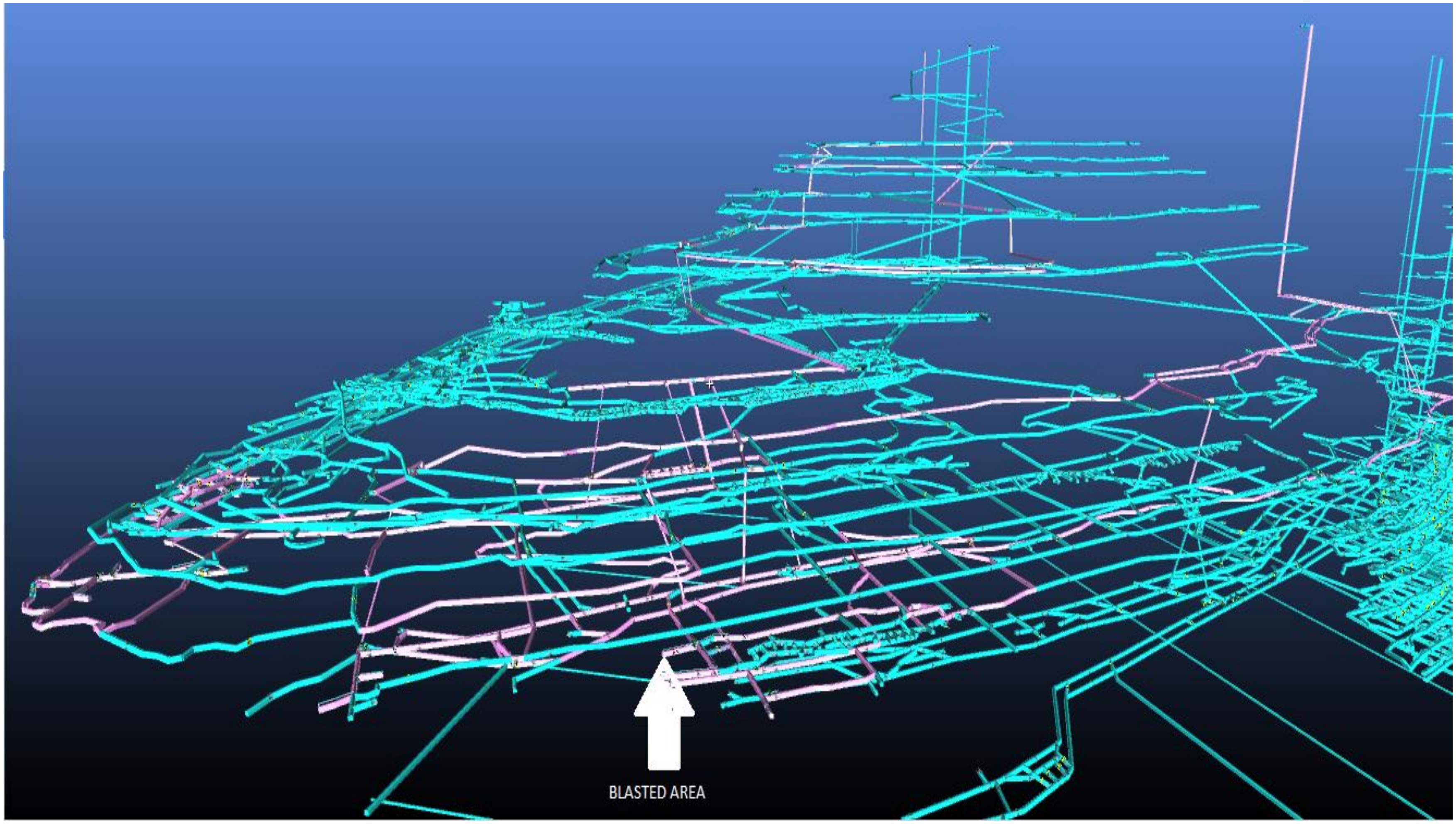


Figure 5.11 Contaminant simulation showing the distribution of blast fumes from Bancroft Flats

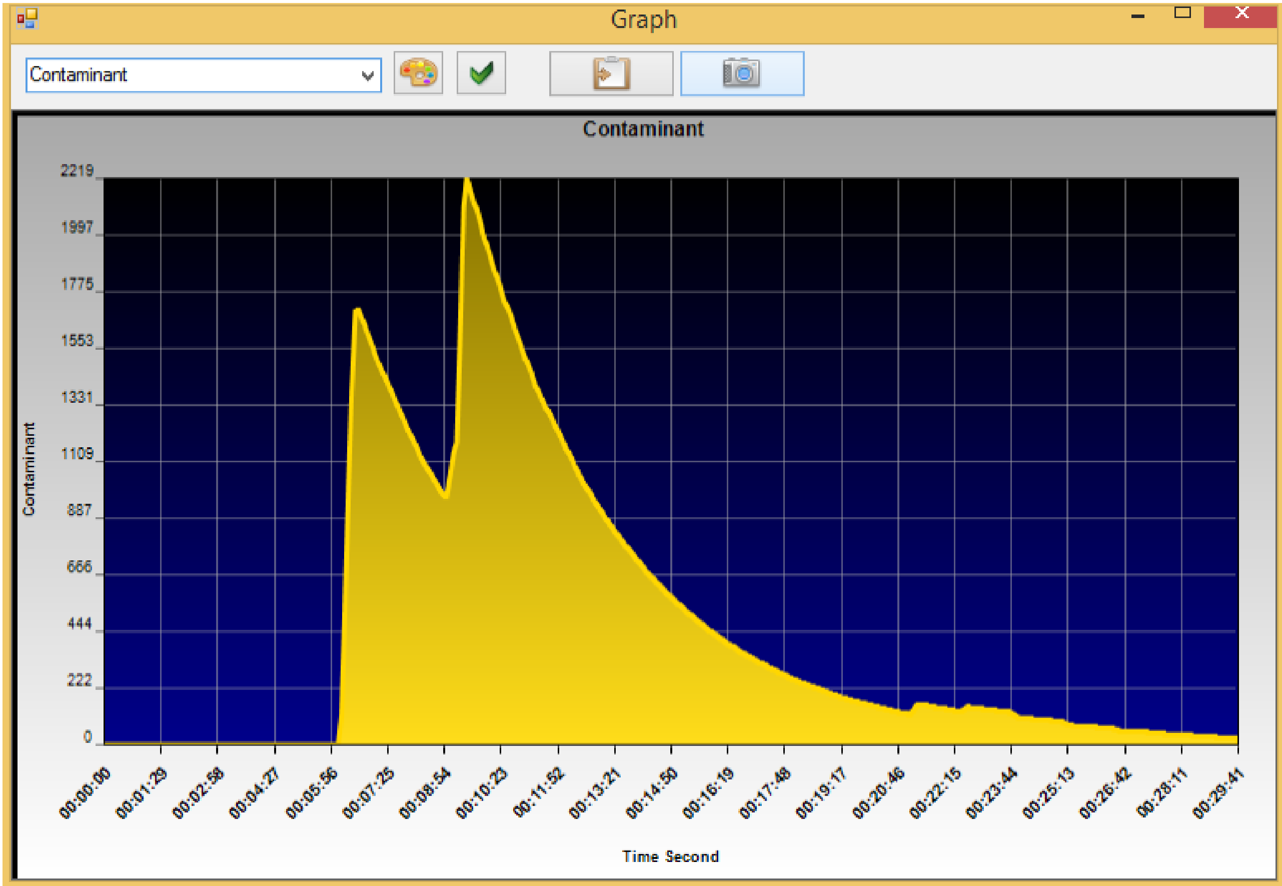


Figure 5.12 Blasting fumes at a monitor location (refugee chamber)

The concentration of fumes then decreased for the next 2 minutes as fresh air was diluting the fumes. Another peak concentration was recorded as blasting fumes from another end registered at the monitor location. The concentration of fumes then decreased logarithmically as it was swept away by fresh air. The monitor shows the time based simulation of contaminants from the blasted zone. This shows that Ventsim can be used to monitor clearance time of blasting and give a guideline of re-entry time for the mine.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. The existing ventilation system of Konkola mine has been reviewed. Results of study indicate that in its current form the ventilation system cannot meet the mechanization drive currently underway because of the ever increasing ventilation loads and networks.
2. An efficient mine ventilation system has been designed and simulation conducted using the Ventsim software.
3. The mine model ventilation has shown that it is possible to significantly reduce the mine ventilation operation costs without compromising the exposure levels of workers. Using scenario 2 involving 20 years mine life for example shows that 60 airways can be optimized to reduce cost with potential saving of about $ 1,715,518 and annual power saving of $355,659 dollars.
4. The ventilation model has provided the ability to visualize entire mine ventilation system in true to scale animated 3D. This model will be used to assess different options and communicate designs more clearly before taking on the risks, technical, financial or otherwise-of actual construction. Using Ventsim Visual, different scenarios can be examined by simulating potential changes such as reducing or turning off of fans.

Recommendations

The following are the main recommendations:

- Location and sizing of booster fans must be assessed using the model developed to find ways of reducing their number in use to reduce the operating costs of the ventilation system and reduce recirculation of air.
- Heat simulation must be performed to identify areas that are susceptible to high temperatures. Due to the low geothermal gradient at Konkola Copper Mines, heat problems can be solved by proper channeling of fresh air to where it is needed and by reducing recirculation of foul air to the working faces which results in rise in temperatures.
- The dispersion rate of blasting fumes must be determined by the gas detection meter so that a contaminant simulation of the whole blasting areas can be performed to identify areas

that will be polluted during blasting. This will help to check the effectiveness of the ventilation system to sweep away blasting fumes and adjustments can be done on the model to improve the ventilation system. By so doing the dispersion rate can be improved to reduce the re-entry time of the mine.

- To reduce the operating costs of the ventilation system, the recommended airway sizes shown during financial optimization in Chapter 5 must be implemented. This will also help to reduce the risk of incurring higher cost of developing the ventilation system in the future as the mine will be growing laterally and deeper.

Further work

The outcomes of the research has raised the prospect of further study on how air quality and temperature can be controlled to ventilate only specific areas when needed such as after blasting or before the re-entry to the area by miners.

References

Anna, F., 2013. *Application of Ventsim Visual at the show mine Erzberg,* University of Leoben: Mining Engineering & Mineral economics.

Brickey, A. J., 2015. *Underground production scheduling optimization with ventilation constraints,* Colorado: Colorado School of Mines.

CEMI, 2009. *Investigation of current research related to reduction of energy usage in mines through recycling, reuse, and other means,* Johannesburg: LCG Energy Management Group.

Chasm Consulting, 2012. *Ventsim Visual User Guide,* Queensland: Ventsim Visual.

Cristian, F. G., 2010. *The influence of ventilation modelling on production planning,* Ontario.

Cross, H., 1986. *Analysis of flows in networks of conduits or conductors,* Univ I11,Bull.286.

Feng, W., Fangping, Z. & Huiqing, L., 2011. *The use of 3D simulation system in mine ventilation management.* Beijing, Elsevier, pp. 1370 - 1379.

Gangal. M, G. M., 2002. An Overview of Regulations to Control Diesel Emissions In Canadian Mines. *Proceedings of the 9th U.S. Mine Ventilation Symposium*, 8-12 June, pp. 427-432.

Ganguli, R. & Bandopadhyay, S., 2004. *Mine Ventilation.* New York, A.A.Balkema.

Gillies, A., Habibi, A. & Kramer, R. B., 2013. *Comprehensive heat study at a Wyoming underground Trona Mine,* Rolla: Rock Mechanics and Explosives Research Center.

Hardcastle, S., Kocsis, C., Bissiri, Y. & Baiden, G., 2005. *Optimizing Mine Ventilation Through the Use of Life-Cycle Production Models.* Brisbane, AUSIMM, pp. 373-361.

Jing, G. & Cheng, Y., 2016. *Study of coal mine ventilation system optimization based on Ventsim.* Beijing, EDP Sciences, pp. 145-153.

Kapagendis, I. K., 2005. *The future of mine planning software- New tools and innovations.* Kozani, pp. 275- 281.

Karoly-Charles Kocsis, P., 2009. *New ventilation design criteria for underground metal mines based upon the life-cycle airflow demand schedule,* Vancouver: University of British Columbia.

McPherson, M., 1993. *Subsurface ventilation and environmental engineering.* London: Chapman and Hall.

Ramani, R. & Owili-Eger, R., 1990. *Engineering aspects of coal mine ventilation systems,* Pennsylvania.

Reid, B. J. R., 2011. *Design of an experimental mine simulator for the development of a procedure for utilization of multiple tracer gases in underground mines,* Blacksburg.

Robbins, R., 2000. Mechanization of underground mining:a quick look backward and forward. *international Journal of Rock Mechanics and Mining Sciences,* pp. 413-421.

Scott, R., Hinsley, F. & Hudson, R., 1953. A calculator for the Solution of Ventilation Networks Problems. *Trans.Inst.Mine,* Volume 112, p. 623.

Wempen, J. M., 2012. *Characterization of Air Recirculation in Multiple Fan Ventilation systems,* University of Utah, USA: Masters thesis, Department of Mining Engineering.

Widzyk-Capehart, E. & Fawcett, C., 2002. *Life of mine ventilation requirements for Bronzewing mine using Ventsim.* Kalgoorlie, Curtin University of Technology, pp. 815-822.

Widzyk-Capehart, E. & Watson, B., 2004. *Agnew gold mine expansion mine ventilation evaluation using Ventsim.* Kalgoorlie, Western Australian School of mines, pp. 345-352.

Appendix A

Table A.1: Maximum permitted quantities of certain gases. (Regulation 902(2) (b))

Column 1	Column 2
Description of gas	**Maximum permitted quantity of gas in parts per million**
1. Carbon Dioxide	7,500
2. Carbon Monoxide	100
3. Nitrous Fumes	10
4. Sulphur Dioxide	20
5. Hydrogen Sulphide	20

Table A.2: Effect of depth on temperature

Depth (m)	Mine level (ft)	Temperature (ºC)
350	1150	29.8
450	1480	30.0
565	1850	30.3
670	2200	30.5
810	2650	30.8
880	2900	31.0
960	3150	31.2

Table *A*.3: Main fan performance

PARAMETER	VS1A	VS1C	VS3A	VS3E FAN A	VS3E FAN B	VS3E FAN C	VS3C
Barometric pressure (kPa)	88.83	88.88	88.87	88.86	88.86	88.88	88.85
Fan drift air temperature (^oC)	22.0 saturated	19.0 saturated	20.0 saturated	23.0 saturated	23.0 saturated	22.0 saturated	20.0 saturated
Saturated vapour pressure (kPa)	2.6431	2.1964	2.3373	2.8086	2.8086	2.6431	2.3373
Actual density (kg/m^3)	1.04	1.05	1.033	1.03	1.03	1.04	1.05
Air quantity							
Average velocity (m/s)	21.48	21.11	21.57	33.86	34.41	29.0	20.46
Cross sectional area (m^2)	10.75	10.75	10.75	8.68	8.68	8.68	10.75
Quantity at ambient density (m^3/s)	231.0	227.0	231.88	294.0	298.68	251.72	220.0
Electrics							
Current (Amps)	45	60	64	53.5	56.1	45	60
Voltage (kV)	11	11	11	11	11	11	11
Motor input power (kW)	662.65	903.1	767.8	853.14	801.613	465.03	903.06
Fan pressure							
Fan static pressure (kPa)	2.3	3.0	2.45	2.45	2.4	1.5	3.3
Mean static air power (kW)	531.3	681.0	568.106	720.3	701.9	377.58	699.6
Mechanical efficiency (%)	80.2	75.4	74.0	84.4	87.6	81.2	77.5

Table *A*.4 Diesel rating and airflow requirements

Unit	Power (kW)	Air Quantity (m^3/s)
Boomer	53	2.65
Clayton	49.98	2.499
Normet	49.98	2.499
Air Loader	18.64	0.932
CAESAR LIFTER	30	1.5
EJC 130D	136	6.8
TORO 400D	158	7.9
Ejc 210	172.2	8.61
Simba H252	53	2.65
Toro 250D	102	5.1
Elphinston R1500	201	10.05
Ejc 60D	57.7	2.885
Elphinston R1600	172.2	8.61
Simba H126	53	2.65
Grader(GR) 01	87	4.35
MT5020 (50t)	485	24.25
MT6020 (60t)	567	28.35
MT436LP (30.65t)	298	14.9
MT2010 (20.5t)	224	11.2
MT431B (20.128t)	298	14.9
ST7 (6.8t)	144	7.2
ST7LP (6.8t)	144	7.2
ST14 (14t)	250	12.5
ST600LP (6t)	136	6.8
ST710 (6.5)	149	7.45
ST1030 (10t)	186	9.3
ST1030LP (10t)	186	9.3
ST1520 (15t)	198	9.9
EST2D (3.629)	56	2.8
EST 3.5 (6t)	74.6	3.73
ST3.5 (6t)	136	6.8

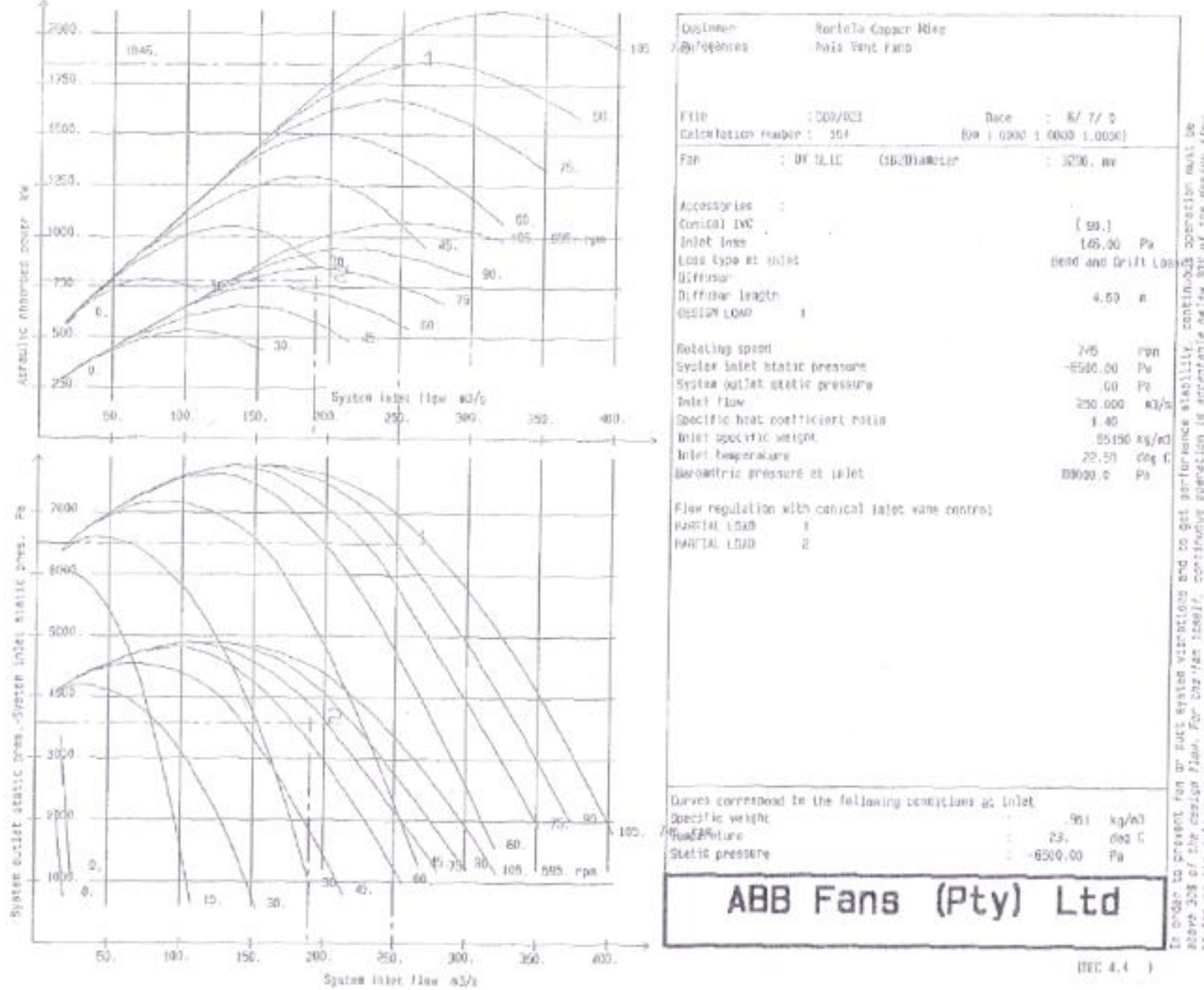


Figure A.4 Konkola ABB main fan curves