APPLICATION OF GENETIC ALGORITHMS TO DETERMINE THE BEST COMBINATION OF MAIN AND BOOSTER FANS

by

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ABSTRACT

One major challenge in mine ventilation is to determine the best combination of main and booster fan pressures to satisfy the airflow requirements and minimize the overall power consumption.

This study presents a genetic algorithm-based program to solve mine ventilation network problems. The program, written in C++ language, combines genetic algorithms (GAs, developed by MIT) and a ventilation simulator (xyz.c, developed by MVS Engineering). The program also known as GVENT is used to determine the best combination of main and booster fan pressures for a sample and a coal mine ventilation network.

For a sample network, the program generated the power requirement for two alternatives: 1. Single-fan system, 2. Two-fan systems. A comparison of the results shows that the second alternative reduces main fan pressure and leakages and consequently results in net savings of 487 kW (19%).

For the coal mine ventilation network, the program generated the power requirements for two alternatives: 1. three surface fan system and 2. three surface and two booster fan system. A comparison of the results shows that the second alternative (three surface and two booster fans) results in a net savings of 209 kW.

The results generated by this program were compared with those generated by a ventilation simulator, VnetPC, and found that these were within the 0.5% accuracy.

Using this new approach, the results were generated faster and with less human intervention than those generated by the simulator.

In addition to the GA-based program, two separate programs were developed to evaluate the network results for flow recirculation. These programs, based on search routines, were used to test the results of the sample network problem described previously. In each case, the outcomes were positive—no recirculation paths were found. The program identified the recirculation paths successfully.

In summary, this research study presents a GA-based fan selection program that can be used by mine operators to determine the best combination of fan pressures (surface and underground booster fans) that satisfies the mine flow requirements, reduces leakage, and minimizes the total power consumption.

This work is dedicated to my beloved father Chunni Lal, mother Sita, wife Archana, and daughter Malvika

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CHAPTER 1

INTRODUCTION

Adequate ventilation plays an important role in maintaining safe working conditions in underground mines. The objective of any mine ventilation system is to supply an adequate amount of fresh air to each working face at minimum cost. This Chapter 1 deals with a general overview of ventilation planning, statement of problem, hypothesis, research objectives, and scope of work.

1.1 General Overview

Ventilation planning includes selection of type and location of mine openings to surface (shafts, drifts and ramps); the shape, size, and number of openings; location of control devices; and selection and location of main fans. Well planned ventilation systems are always integrated with the mining methods and other local conditions specific to the mine site. A coal mine ventilation system must be designed to supply the required quantities of air to the mine and to maintain healthy and safe working conditions at all times. This quantity should be determined on the basis of number of workers, kinds of machinery used, production of gases, dust, heat, and humidity in the mine. Accurate air quantity estimation is an important aspect of mine ventilation systems. This must consider the leakage flow rates through the various control devices. Fan pressure and power losses in a mine are proportional to the square and cube of the flow quantity, respectively. Small errors in quantity estimates may lead to large errors in pressure and power estimates and affect the total mine ventilation, health and safety, and production rate. The number and size of airways required to course the required quantities of air to various workings are two other important parameters. These determine the velocity of air. Inadequate velocities can lead to the stratification of low density gases near the roof, such as the case of methane. On the other hand, higher velocities may lead to the entrainment of settled dust to the airstream, thus increasing the dust concentration. The pressure loss (P) in an airway is calculated using Atkinson's equation ($P = RQ^2$). In this equation, R is the airway resistance and Q is flow rate. A mine consists of multiple interconnected airways. Under this situation, the airflow – pressure distribution in the mine is governed by Kirchhoff's two laws: conservation of mass and conservation of energy. These equations are used to determine the mine resistance and fan operating points. Once the fan operating point is known, the selection of the suitable fan can be made. Depending upon the location of the fan, two cases can be distinguished: 1. surface fan system (fan located on surface) and 2. surface-booster fan system (where at least one fan is located underground).

1.2 Statement of Problem

As an underground mine goes deeper and deeper, or extends laterally, the ventilation system becomes more complex due to increased heat, humidity, and methane emissions, which affect the quality of air negatively. To overcome the problem, larger quantities of air are required. Sometimes, main fan alone can serve the purpose of meeting the flow requirements of a mine, but often deep and extensive mines require high fan pressures. These fans, when not installed adequately, can result in “Caught in Between” type safety hazards while operating high pressure airlock doors. Furthermore, high pressure fans may result in excessive leakage through stopping and high power consumption. Alternatives such as sinking new shafts or widening existing airways are not very popular because they require heavy capital investment and several months of construction time. Another alternative is the utilization of booster fans in addition to the main surface fans. A booster fan can be used to reduce the main fan pressure and reduce leakage and power consumption. However, the misuse of these fans can increase the potential of flow recirculation, build-up of contaminants, and the possibility of mine fires, especially when the fans are not sized and located properly.

One major challenge is to determine the optimal combination of main and booster fans for a mine while reducing the surface fan pressures and eliminating the onset of flow recirculation. The solution can be achieved using commercial software packages by trial and error. But the process is very lengthy, and often the optimal solution is not found. Therefore, a new approach to solve the problem is required.

1.3 Hypothesis

The proposed Genetic Algorithm-based fan selection program, once interfaced with a ventilation simulator, will eliminate the manual effort and reduce time to determine the best combination of main and booster fans for a mine.

1.4 Thesis Objectives

1. To develop a Genetic Algorithms-based C++ program to determine the best combination of main and booster fans pressure for underground mines, without flow recirculation.
2. To develop a routine in C++ to detect and quantify the flow recirculation.
3. To identify hazards and analyze the risk associated with booster fan utilization.
4. To develop a sound booster fan operation protocol and recommendations for safe and efficient use of booster fans.

1.5 Scope of Work

In the past, several attempts have been made to determine the optimum combination of main and booster fans (Calizaya et al. 1987; Yang et al. 1997, 1998; Lowndes et al. 2010; Acuña et al. 2010). But, none of these studies has accurately dealt with flow recirculation while optimizing the air power requirement. The commercial ventilation software can be used to determine the best combination of main and booster fans by a trial and error. The process is tedious and lengthy and often the optimal solution is not achieved. Commercial ventilation software such as VnetPC does not detect recirculation paths. Sometimes, detection of recirculation paths is done separately by evaluating the resulting flow quantity diagrams for flow reversal. The process can become tedious and inefficient for complex networks. Considering the impact of flow recirculation on the quality of air circulated through the workings, academic and industrial communities feel an urgent need of such a program to detect and quantify flow recirculation while determining the best combination of main and booster fans. Furthermore, hazard identification and risk analysis were not taken into account in the past. All of these issues can restrict or limit the use of booster fans and deprive the mining communities from their benefits.

Recent developments in ventilation network analyses have demonstrated that the total air power consumption can be minimized by properly selecting the size and location of booster fans compatible with the size and location of main surface fans and minimizing the regulator resistances. In order to ascertain the optimum system configuration, the ideal duties of booster fans and regulators must be determined. Mining is a dynamic process that alters the configuration of working faces as the exploitation of mineral deposit advances. Such a situation demands for a flexible solution, which may be achieved systematically by changing fan parameters and ventilation system configurations as the mining advances.

In this dissertation, a Genetic Algorithms-based program is first applied to determine the best combination of main and booster fans for a sample ventilation network and then tested in a coal mine ventilation network. A separate routine is developed to detect and quantify the recirculation for any ventilation network.

Hazards identification and risk analysis is also included to frame guidelines and recommendations for safe and efficient utilization of the booster fan.

CHAPTER 2

LITERATURE REVIEW

The study on the use of booster fans in underground coal mines is not a new topic, but an old one. In fact, the use of booster fans started in the United Kingdom in the early 1900s. Many researchers and scientists worked on topics such as sizing and locating booster fans under different ventilation conditions. Time was also spent on documenting the advantages and disadvantages of these fans. However, the application of this technique is not well understood. Proof of this is that the use of booster fans is not allowed in the U.S. coal mines. Critical factors associated with the design, installation, and operation of booster fans in coal mines are reviewed in this chapter.

2.1 Optimal Combination of Main and Booster Fans

Several studies were conducted in an attempt to determine the best combination of main and booster fans for underground mines.

Calizaya et al. (1987) proposed an algorithm based on the VnetPC software output and linear relationships between the fan pressure and regulator or added resistances. In this study, a sample network was investigated in two stages: (a) Single-fan system and (b) Two-fan system. In each stage, a set of feasible solutions were generated. These solutions consisted of fan pressures and an added resistance for each working area where a fixed quantity of air was required. Fan pressure and added resistance relationships were plotted and the resulting graphs evaluated for the optimum main fan pressure. The same procedure was repeated for different booster fan pressure to determine the best combination of two-fan pressures. This algorithm requires a ventilation simulator and skills to interpret the results graphically. To some degree, the solution to the problem, the best combination of fan pressures, is found by trial and error. Therefore, this approach is time consuming and tedious, particularly for the large network and multiple-fan ventilation network. Furthermore, if the booster fan location is predefined, the optimal solution is valid for the given location only.

O'Leary et al. (1989) proposed a modified method for optimizing the main and booster fans by incorporating the computer methodology and eliminated the manual trial and error method. She accomplished this task in four stages: first, by optimizing the single fan system for a set of fixed quantities and second by running the program for a set of main and fixed booster fan pressures and then evaluating the results for an optimal solution. For each working place, the computer program calculates the ratio of the desired flow requirement to the predicted airflow by the unregulated network analysis. The branch having the least regulator resistance is called the critical branch as this is the most difficult branch to ventilate. The network is reevaluated with the same fan pressure but for different fixed airflows. The process is repeated for different sets of main and booster fan pressures, the resulting added resistances are evaluated, and the optimal combination of fan pressures are determined. Once more, the results are reevaluated; if the insertion of a booster fan causes the optimum main fan pressure to increase, this means that the user has positioned the booster fan in an inappropriate place. With the main fan pressure optimized for the current fixed booster fan, the resistance of the added regulator in each of the fixed quantity branches is calculated. For the critical branch, the added resistance would be zero. In the third stage, to determine the optimum booster fan pressure, stage 2 is rerun for a wide range of booster fan pressures. The corresponding values of the main fan pressures are computed by the procedure followed in the first stage for each incremental value of booster fan pressures. The critical branch is determined for a wide range of booster fan pressures, starting from low to high. The change in a critical branch is used to indicate whether a booster fan pressure is above or below the optimum pressure. The linear relationship between a booster fan pressure and the regulator resistances is used to determine the change in the critical branch and to approximate the optimum booster fan pressure. In the fourth stage, evaluating each line representing the fixed quantity branches checks the undesired recirculation. The distortion in any line indicates flow recirculation. The limitation of this method is that the application of the program is restricted to a system of one booster fan only. Given the number of iterations involved, this method would be difficult to apply to achieve the optimal solution for a multiple booster fan ventilation network. Furthermore, tedious manual effort is involved to detect recirculation.

Moll et al. (1994) used the technique proposed by Calizaya et al. (1987) with little modification. This modification is based on the regression analysis of booster fan pressure and added regulator resistance to achieve an optimal combination of main and booster fan pressure. This technique improves and reduces the manual effort to some extent, but still it needs manual effort and skill to achieve an optimal solution. All the techniques as discussed above encounter difficulties and pose challenges in terms of manual effort and skill required to determine the best combination of main and booster fans for the ventilation network. To overcome these difficulties, some of the researchers have applied a genetic algorithm as discussed in the next section to achieve the optimal combination of main and booster fan pressures.

2.2 Application of Genetic Algorithms in Mine Ventilation

Yang et al. (1998a) applied a genetic algorithm to optimize ventilation networks. He used modular programs that combine the application of a genetic algorithm optimization technique with a ventilation network simulator. To apply this technique into a ventilation network, a binary string was created by encoding the three network variables: main fan pressure, booster fan pressure, and the location of a booster fan. He used a ventilation network simulator to calculate the fitness of the solution strings. The fitness of a solution string is measured in terms of total air power requirement by the network for the main fan and booster fan configuration. This is a preliminary area of research in the application of genetic algorithms in booster fan ventilation networks. This technique was applied successfully to determine the combination of main and booster fan pressure while eliminating the manual effort. However, the recirculation problem associated with improper design and the location of the booster fan is not dealt with properly while determining the best combination of main and booster fans in a network.

Yang et al. (1998a, 1998b) applied genetic algorithms into the optimization of fan power consumption for a large mine ventilation network. The genetic algorithm established the minimum airpower consumption of the given network by choosing the best main fan pressure, best booster fan pressure, and best booster fan location. Although their studies applied successfully to the network with single booster fans, the question of the application of two or more booster fans in such a network was not answered. In addition to that, the recirculation problem was not dealt with properly.

Yang et al. (2000) applied genetic algorithms to the optimization of the fan power consumption of a large U.K. coal mine ventilation network. The genetic algorithm established the minimum airpower consumption for the given network by choosing the best main fan pressure, best booster fan pressure, and best booster fan location. Although their studies were applied successfully to the proposed network with two and three booster fans, the recirculation problem was not elaborated in detail.

Lowndes et al. (2004) applied genetic algorithm optimization methods to the design of practical ventilation systems for multilevel metal mines He successfully applied this technique to determine 1. main fan pressure, 2. booster fan pressure, 3. number of booster fans, and 4. location of booster fans in two real mine ventilation networks for different periods of mining: short term, medium term, and long term planning. Lowndes et al. (2005) also applied GA to determine influence of a coding method and the population size to optimize the performance of a mine ventilation network. Simple binary coding performed better than the hybrid coding when using a population of 60 or 100. The two coding methods, however, produced very close performance when using a population size of 200. Taking all the three population sizes together, simple binary coding performed better than hybrid coding. This research work is an extensive study in booster fan optimization process. However, the multiple exhaust system networks were not studied to determine the best combination of main and booster fans. In addition to that, the recirculation problem was not investigated thoroughly.

All of the above studies did not address the recirculation problem while determining the best combination of main and booster fans.

Recent studies on the application of genetic algorithms into mine ventilation are discussed in the next section.

2.3 Recent Investigations Using GAs in Mine Ventilation

Genetic algorithms have been used to address many ventilation network problems with increasing levels of confidence and have been tested using sample ventilation networks (Lowndes 2004; Acuña 2010). However, when considering tools for global optimization, it must be acknowledged that genetic algorithms are only search routines. The solution space comprises many data points generated by a ventilation solver. These data points are combined by means of cross-over and mutation processes to generate off springs for the next generation. The process is repeated until the stopping criterion (fitness function) is reached and an optimal solution found.

Genetic algorithms have been applied into both semicontrolled and free splitting ventilation networks to determine the best combination of main and booster fan pressure. Recent studies done by Acuña et al. have been reviewed critically and documented here.

2.3.1 Free Splitting Approach

Acuña et al. (2010) applied genetic algorithms into solving practical mine ventilation problems using genetic algorithms for free splitting networks. The main objective was to determine the fan pressures to supply the airflow requirements. He used the square of the sum of the differences between the required and the predicted airflow delivered as a fitness function. As this function is asymmetrical with respect to airflow requirements, a preset large penalty value was added if an infeasible solution were produced. This penalty function increased the speed to produce improved feasible solutions.

To test the validity of the approach, the proposed procedure has been applied into a small network with three fixed quantity branches where the problem was to determine the main fan pressure. The results show that this fitness function does not always yield a unique solution, but a range of possible solutions instead. In fact, in this example the predicted fan pressure was lower than the optimal solution, indicating that the proposed fan cannot satisfy the flow requirements without the help of an additional booster fan.

2.3.2 Semicontrolled Flow Approach

Acuña (2010) in his Ph.D. thesis, "Multiple period mine ventilation and fan selection optimization," introduces a genetic algorithms (GAs) based fan selection method for underground mines. His main objective was to propose and validate an optimization methodology to determine the best combination of fan duties and regulator resistances for a ventilation network. At the beginning of his work, he noted that "three things must be done to solve a ventilation problem using genetic algorithms:

1. Define and represent the problem;
2. Define the genetic operators; and
3. Define the objective function to be optimized."

The author used a set of GAs integrated with a ventilation solver to evolve a population of potential solutions for the single- and multiple-period problem and suggests that such an operation can be used to determine the optimum location and combination of fan duties for a mine ventilation network. He used two different fitness functions to approach the solution: one based on airpower and another based on the square deviation from the airflow requirements. Through an example, he demonstrated the capacities of the approach to determine improved feasible solutions to a network problem in terms of air power and regulator resistances for different working areas with fixed quantities of air. For the same network conditions, he demonstrated that the airpower function is a better approach than the airflow deviation approach in terms of accuracy and the simulation time to reach the optimal solution. This work is directly related to mine ventilation optimization. However, neither the documentation for the program nor the code for the interface with the GA was published with the manuscript.

2.4 Investigations into Flow Recirculation

Airflow recirculation has been recognized as an undesirable event particularly in coal mines. Therefore, recirculation should be avoided when determining the best combination of main and booster fans in designing ventilation systems. Numerous studies have been conducted to establish the facts of pros and cons of flow recirculation, but very few studies have been conducted to develop means or methods to quantify the problem. Moreover, such methods are not coded in a computer program and tested in large and complex ventilation networks. The outcomes of two major studies are discussed herein to demonstrate their capabilities and limitations.

Calizaya et al. (1990) proposed two algorithms: maximum flow algorithm and cut-and-search algorithm. The first algorithm is based on finding the maximum flow for each path from a source to a sink. Nodes with residual capacities show the recirculation path and also show the quantity of recirculation. The second algorithm is based on deletion of the source and sink node while traversing a network. The remaining nodes, left after the deletion process, constitute the recirculation path(s). The two algorithms were tested in a small network to demonstrate their capabilities and limitations. Both algorithms were able to find the recirculation loops, but the first algorithm was faster than the second one. The algorithms were not tested using large ventilation networks particularly those with multiple intake and return airways. Furthermore, the first algorithm, based on a standard Operations Research routine, was found to have a drawback. It was unable to distinguish between weakly and strongly connected nodes, a common feature in multilevel ventilation networks in which a graph is said to be *strongly connected* if every vertex is reachable from every other vertex. The *strongly connected components* of an arbitrary directed graph may be partitioned into sub-graphs that are themselves strongly connected. It is possible to find all the strongly connected components of a graph. Such strongly connected components may consist of either a single vertex or group of vertices.

Acuña et al. (2012) presented a new algorithm to detect multiple recirculation paths at the 14th US Mine Ventilation Symposium. Based on this algorithm a new auxiliary graph initially with no nodes is generated. A node of the ventilation network is added. Then this is identified as source sink or saddle. All the source and sink nodes are deleted. The resultant graph is then evaluated starting from any node following a path to create a cycle. This cycle is then appended on to the original auxiliary graph. If the cycle has super nodes, then it is merged with the auxiliary graph. In the original network, the cycle is collapsed into a single super node by deleting the internal nodes and branches of the cycle. This algorithm has the capacity to identify the strongly connected components without including any branches that are not part of the component. A sample network was used to illustrate the major steps of this algorithm and to determine a set of recirculation paths. However, it was not tested using real mine ventilation networks with multiple intake and return airways. A precise recirculation path finding routine is needed to design recirculation-free ventilation systems in this field.

Properly planned and operated controlled recirculation can reduce the maximum general body gas concentration in a ventilation system (McPherson 1988). The use of booster fans may lead to the development of uncontrolled airflow recirculation, especially when the fans are not sited or sized properly. To reduce or eliminate the risk, a synchronized operation of booster fans, airlock doors, and environmental monitor is required. The fans and doors should be designed to allow an acceptable level of recirculation (± 10%), and the monitors must be placed to detect fire products and to allow the mine operator to stop recirculation and to return the area to one ventilated by the through flow ventilation system (Middleton 1985).

CHAPTER 3

BASICS OF MINE VENTILATION SYSTEMS

The mine ventilation systems consist of fans, airways, and control devices for air coursing (Hartman 1997). It includes the shape, size, and number of airways; location of control devices; and selection and location of fans. Well planned ventilation systems meet the requirement of air at the minimum cost. The prime objective of any mine ventilation is to supply enough air to dilute the contaminant concentrations to acceptable levels and to maintain the oxygen concentration above 19.5% by volume for making the workplace safe and comfortable. This chapter deals with the estimation of ventilation parameters to determine the size and number of fans to meet the airflow quantity requirements effectively and efficiently. It includes the governing principle for airflow in mines and network analysis. It also includes the standards and regulations for safe utilization of booster fans in coal mines.

3.1 Design Parameters of Ventilation Systems

Coal mine ventilation systems must be designed as to maintain all mine workings healthy and safe at all times (Hartman 1997). Before designing any mine ventilation systems, ventilation engineers must estimate or calculate the flow requirements, branch resistances, and all pressure losses. These parameters are useful to determine the size, number, and location of main and booster fans. They are also useful to determine the number and size of ventilation control devices. All the relevant design parameters required for ventilation planning are discussed below.

3.1.1 Airflow Requirements

Each underground mine operation requires a fixed quantity of air to dilute and remove the air contaminants, such as dust, toxic gases, heat, and humidity, and to maintain safe oxygen levels for mine workers. Correct estimation of the required quantity of air at each working is vital. The airflow requirements (Q_0) are determined based on following factors.

(a) Mine gasses

Various gasses such as CH_4, CO, CO_2, and H_2S are produced during mining. The flow requirements are determined based on the gas emission or production rates. Equation 3.1 is used to calculate the flow requirement to bring down the gas concentration to an acceptable level or TLV (Threshold Limit Value).

$$Q_0 = \frac{q}{TLV - B} \tag{3.1}$$

Where

q = Production of gas during mining, m³/s

TLV = Threshold Limit Value of a gas, %

B = Background gas concentration in intake airway, %

(b) Dust production

Dust is produced during the mining process. The airflow requirement is determined based on the dust production rate and the allowable concentration. Equation 3.2 is used to calculate the flow requirement.

$$Q_0 = \frac{G}{(TLV - B)} \tag{3.2}$$

Where

G = Dust production, milligram/s

TLV = Threshold Limit Value of dust in working area, mg/m^3

B = Background concentration of dust in intake airway, mg/m^3

(c) **Heat load**

Various electrical machineries are used during the mining process. These machineries produce heat. Airflow requirements are determined based on the production of heat. Equation 3.3 is used to calculate the airflow requirement.

$$Q_0 = \frac{q}{\rho(h_2 - h_1)} \tag{3.3}$$

Where

Q_0 *=Airflow requirement, m*^{3}*/sec*

q =Total heat load, kW/sec

ρ *= Density of air, kg/m*^{3}

h_1 =*Enthalpy of air at existing temperature*, *kW*

h_2 = *Enthalpy of air at desired temperature*, *kW*

(d) Regulatory requirements

The Mine Safety and Health Administration (MSHA) has prescribed the following minimum quantities of air for underground coal mines (30 CFR § 75.325 1977).

1. 1.42 m^3/s (3,000cfm) at face (Bituminous and Lignite mines)
2. 4.25 m^3/s (9,000cfm) at last open crosscut
3. 14.17 m^3/s (30,000cfm) for longwall or shortwall mining

3.1.2 Estimation of Resistances

The airway resistance (R) is calculated using Atkinson's resistance equation. This equation depends on the geometry (physical dimensions) of an airway and a roughness coefficient known as friction factor (K) measured or predicted. The Atkinson's resistance equation is given by

$$R = \frac{K * Per * L}{A^3} \tag{3.4}$$

Where

K=Friction factor, kg/m^3

Per =Cross-sectional perimeter, m

L =Airway length, m

A = Cross-sectional area, m^2

When the airway is not straight, instead it includes obstructions (bends, and sudden changes in cross-section) *L* is replaced by *Le* (equivalent length).

3.1.3 Estimation of Pressure Loss

The estimation of pressure loss is an important part of ventilation planning. Air flow in mine airways is governed by Bernoulli's equation (Equation 3.5) (McPherson 1993). This equation states that the total energy at any section in a moving fluid consists of the sum of the kinetic, potential, and work energy of that section. The total energy remains constant at any section, considering that the fluid is ideal, and proceeds along the conduit (airway) with no shear forces and no frictional losses, ignoring any thermal effects.

$$\frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g + \frac{P_1 - P_2}{\rho} = 0 \tag{3.5}$$

Where

P =Pressure, Pa.

ρ = Density of air, kg/m³

u = Velocity, m/s

Z =Elevation, m

g =gravity acceleration, m/s²

Mine airways possesses rough surface and irregular shape. Therefore, some mechanical energy will be transformed into much less useful heat energy. The loss of such energy is often termed as a frictional pressure drop. For the flow of real fluids, Equation 3.5 can be modified and rewritten by Equation 3.6 taking into account of frictional loss of mechanical energy (McPherson 1993).

$$\frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g + \frac{P_1 - P_2}{\rho} - P_l = 0 \tag{3.6}$$

Where

P_l =Pressure loss, Pa.

In general, the pressure loss in fluid flow is made up by two components: frictional loss (P_f) and shock loss (P_x). This can be expressed by Equation 3.7.

$$P_l = P_f + P_x \tag{3.7}$$

Frictional loss is the energy spent to move the fluid through a conduit of a uniform cross-sectional area, whereas shock loss is the energy spent to move the fluid through a conduit of a nonuniform cross section or obstructed by bends and sudden changes in cross section. Shock losses also occurs at the inlet and discharge of a system and at the split or junction of two or more air currents. The shock loss can be calculated from velocity pressure using Equation 3.8.

$$P_x = X\rho \frac{u^2}{2} \tag{3.8}$$

Where

X = Shock loss factor

The value of X depends upon the shape and type of airway obstructions (bend, sudden expansions, contractions, etc.). It can be calculated from pressure-quantity measurements, or read from shock loss charts reported in textbook (McPherson 1993).

For any given ventilation network, the total pressure loss (pressure difference) consists of two components: static pressure (P_s) and velocity pressure (P_v). For complex mine ventilation networks, with several intake and return airways and multiple working areas, the total static pressure is difficult to calculate. It can only be determined by means of a ventilation simulator. The mine velocity pressure is equivalent to the loss of kinetic energy at the fan discharged. When the fan is not equipped with a discharged cone (evasée), a great portion of this energy is lost to the atmosphere. The total mine pressure (P_t) or fan pressure can be determined by Equation 3.9.

$$P_t = P_s + P_v \tag{3.9}$$

Ventilation planning must be integrated with production objectives. It must begin in the early stage of mine planning. In existing mines, the first step of ventilation planning is to conduct a ventilation survey and establish a database in a basic network file. The next step is to update the file to include the new workings and determine the fan duties. This is usually accomplished by means of ventilations simulators.

3.2 Coal Mine Ventilation Planning

All worked-out areas should be either ventilated or sealed completely (30 CFR § 75.334 1977). In case of ventilating, it is required to keep the methane air mixture and other air contaminants from the worked-out area diluted and routed into return airways. This is known as a *bleeder ventilation system*. An effective bleeder ventilation system removes the methane and other contaminants sufficiently far from the active pillar line or working areas so that a temporary ventilation interruption or sudden atmospheric drop should not cause a large influx of gas from the gob. This is achieved by placing regulators at strategic locations at both panel ends. When the mined-out area is sealed, this is known as a *bleeder-less ventilation system*. Seals must be constructed to withstand prescribed pressure-standards (30 CFR § 75.335 1977).

The mining method influences the mine ventilation system. Depending upon the mining method used, the ventilation system in a coal mine can be divided into three groups: longwall, shortwall, and room and pillar ventilation systems.

3.2.1 Longwall Ventilation

The development of a longwall face consists of two sets of parallel entries with two, three, or four entries in each set (Ramani 2011). The amount of air required in a longwall face is determined based on the methane emission rates during mining and conveying. The total cross-sectional area of the face is determined by the height of the coal cut and the distance from the face to the gob line. In the United States, longwall retreating is more common than advancing. In this system, fresh (intake) air is supplied through the headgate entries and splits at the headgate to ventilate the longwall face

(Bessinger 2011). An adequate volume of air is allowed to flow behind the face at the headgate to ventilate the perimeter of the gob. Along the face and at the tailgate, air is allowed to bleed into the gob and tailgate to ventilate the methane to fuel-lean levels. This is the most common ventilation system used in the United States.

The alternative to bleeder ventilation is bleederless ventilation. The major difference between the bleederless and bleeder ventilation systems is that in the bleederless system seals are built in headgate crosscuts immediately inby the face in order to progressively seal the gob and exclude oxygen as the longwall retreats.

The most commonly used ventilation system in a double entry longwall is the modified U-tube ventilation system. In this case, the airflow through the head gate splits mostly to the longwall face and partially to the bleeder system to ventilate the gob. In the Y ventilation system, intake air is supplied through all the head gate and tailgate entries. The air supplied from the tailgate side is to push gob gases away from the tailgate corner (Hartman 1997). Intake air supplied through the tailgate and the headgate is forced back into the gob. All the air supplied to the face is allowed to join the return airway and discharged through the exhaust fan.

3.2.2 Shortwall Ventilation

A shortwall layout is very similar to that of a longwall panel. The main difference is that the shortwall face generally consists of 45 to 75 meters. In shortwall, a continuous miner cuts only in one direction. Then it is backed up to the headgate, and another cut is started. The airflow is maintained from the head gate to the tailgate, keeping the operator's place flushed with fresh air and away from dust produced by the machine.

3.2.3 Room and Pillar Ventilation

Depending upon the direction of airflow in multiple openings, the ventilation may be either unidirectional flow or bidirectional flow. In *unidirectional flow*, the direction of airflows is the same in all adjacent openings, and consequently air is entirely fresh or exhausts air. On the contrary, in *bidirectional flow*, the direction of airflow in adjacent airways is opposite, and consequently air is partly used and partly fresh. In bidirectional flow, stoppings and overcasts are erected to separate the return air from fresh air. These control devices are considered as a great source of leakage flows. Leakage is a problem in a bidirectional flow (Hartman 1993). During development work, bidirectional flow may be either through one or double splits. Figure 3.1 shows examples of single and double split ventilation systems.

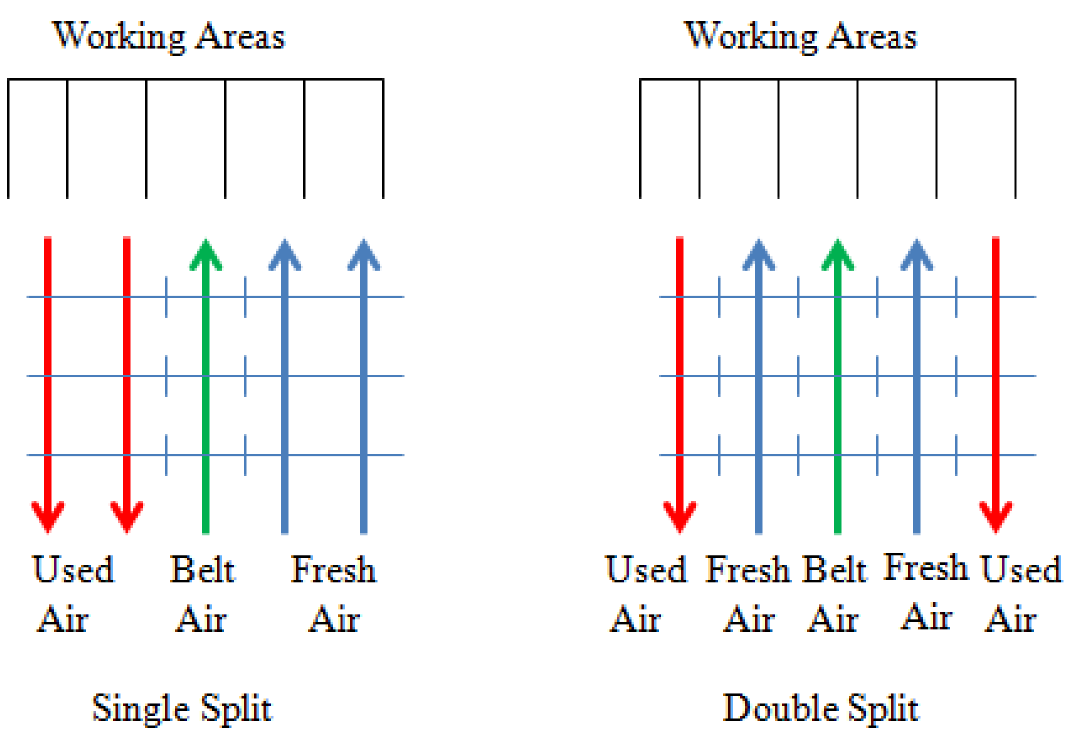


FIGURE 3.1 Example of single and double split systems

In the single split system, a high velocity air stream ventilates the faces of all the entries in a series. It is applicable if the mine generates low methane. In a double split arrangement, the fresh air at the last open cross-cut splits in two different directions to ventilate working places independently. It is applicable if rooms are driven on both sides simultaneously or if the mine generates more methane.

3.3 Ventilation Control Devices

A mine ventilation system is equipped with various control devices such as stoppings, doors, seals, overcasts, regulators, and auxiliary fans to course the air in a desired quantity and quality to a workplace. All the control devices must be made of incombustible material. The main functions of all the control devices are explained below.

- **Stopping**. A stopping is a physical barriers placed between the intake and return airways to prevent mixing into each other. It may be temporary or permanent in nature depending upon purpose and length of service. A temporary stopping may consist of jute fabric or a PVC (Poly Vinyl Chloride) barrier. It is used in active working areas where frequent change in airflow is required. A permanent stopping is installed to provide long term control of airflow. It may consist of prefabricated cinder blocks, metal, or masonry, lined from the high pressure side.
- **Seal**. A seal is a special type of stopping used to isolate abandoned workings or fire. Seals must be constructed to withstand prescribed pressure standards (30 CFR § 75.335 1977).

- **Door**. A door is a hinged stopping or movable partitioned stopping to permit the passage of personnel or pieces of equipment. It may be constructed of sheet metal covered with sealants. It can be a manual or automatic self-closing door. Airlock doors are sets of two or more doors placed in a series to minimize the pressure required to open them.
- **Overcast**. Overcast is an air bridge that allows the intake and return airflows to cross without mixing. It prevents mixing of intake and return air. It is generally of a larger area to minimize the pressure loss and is made of substantial incombustible material.
- **Regulator**. A regulator is an opening in a stopping in an airway and is equipped with adjustable or sliding door. It is used to control and redistribute the quantity of air in each split.
- **Auxiliary fan**. An auxiliary fan is smaller size fan and is used to create a local pressure difference to allow the desired flow of air in workplace.
- **Booster fan**. It is a main fan installed in a mine airway (intake or return) and used to handle the total quantity of air required in a working district. It is sized and installed to assist the main surface fan.

3.4 Mine Ventilation Network

A mine ventilation network consists of various components, such as fans, airways, and flow control devices such as stoppings, regulators, doors, and overcasts. The problem consists in determining the size of these components to satisfy the airflow requirements to dilute and remove the air contaminants generated at the workings as explained earlier.

Figure 3.2 shows a sample ventilation network used in this study. It includes 65 branches, 45 nodes, two intake airways, one return airway, and six working areas where the flow requirements are 47, 15, 40, 33, 33, and 20 m^3/s, respectively. It addition, it includes one surface main fan, one underground booster fan, and several control devices. An airway is characterized by two nodes (a start and an end) and one parameter (airway resistance, usually).

The fresh air, flowing through the intake airways, is directed to the working areas and used to dilute the air contaminants, including mine gasses and dust. The contaminated air is directed to the return airways and exhausted through the up-cast shafts. Various control devices are used to course the air to the working areas and remove the contaminants. The air cannot be circulated through the workings unless some pressure difference is created in the ventilation system. This is accomplished by means of main fans and booster fans. Therefore, it is essential to pressurize the air to create a constant flow and overcome energy losses. Mostly, the air is pressurized by mechanical ventilation, i.e., by means of main fans.

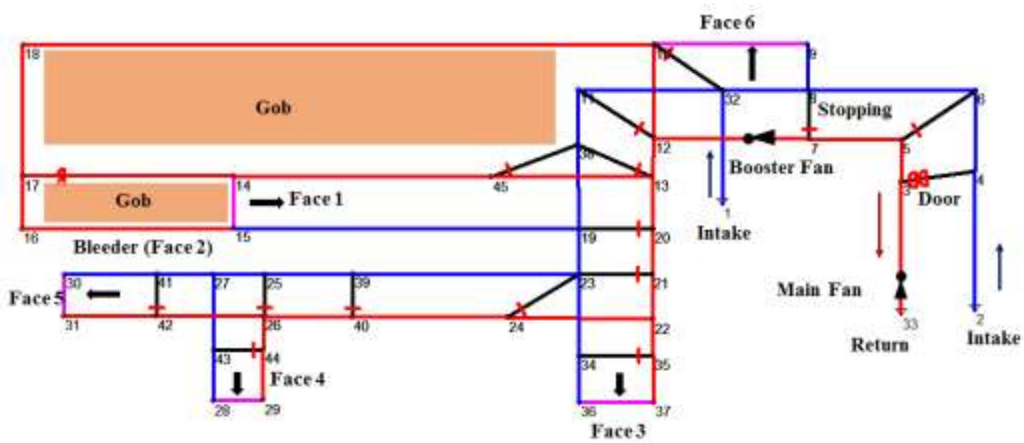


FIGURE 3.2 Ventilation network details

Natural ventilation pressure, created by thermal energy exchange with the strata, depends on the elevation differences and air temperature differences between the surface and the mine workings. In most mines, natural ventilation pressure is not strong enough to fulfill the flow requirements. Moreover, the direction of natural ventilation changes seasonally and diurnally. For these reasons, mine management cannot rely on the natural ventilation pressure alone. A fan is a device that utilizes the mechanical energy of a rotating impeller to produce both movement of the air and changes in its total pressure (McPherson 1993). Fans are recognized as the major sources of pressure energy used to ventilate mine workings.

3.5 Ventilation Network Analysis

Ventilation network analysis is a very important tool in predicting the effects of changes in air pressure on the flow distribution in a ventilation network. The objective of a ventilation network analysis is to simulate reality as closely as possible, to help in planning, and to evaluate safe alternatives in cases of emergency or unexpected situations that may occur in a mine. Any ventilation network analysis follows three basic laws: Atkinson’s law and Kirchhoff’s first and second laws.

1. **Atkinson’s law**: This law establishes a relationship between pressure loss and flow quantity. It can be written mathematically as

$$P = RQ^2 \tag{3.10}$$

Where

R = Resistance of roadways, Ns^2/m^8

Q = Quantity of air traversing the section of roadway, m^3/s

P = Pressure loss along the roadway, Pa

In existing mines, pressure losses and quantities can be measured, but resistances are usually calculated.

2. **Kirchhoff's first law**: It states that the mass flow entering a junction(j) equals the mass flow leaving that junction or mathematically,

$$\sum_j M = 0 \tag{3.11}$$

Where M is the mass flow, positive or negative, entering the junction.

In terms of volume flow, this can be rewritten

$$\sum_j \rho Q = 0 \tag{3.12}$$

However, in ventilation network analysis, the flows are considered incompressible; therefore, the density of air remains constant. Then Equation 3.12 can be rewritten as

$$\sum_j Q = 0 \tag{3.13}$$

This equation is valid at every junction or intersection of airways.

3. **Kirchhoff's second law**: It states that the algebraic sum of all the pressure

drops around a closed path, or mesh in the network must be zero, having taken into account the effects of fans and natural ventilating pressures.

$$\sum_i P_i - P_f - NVP = 0 \tag{3.14}$$

The pressure drop along an air path depends on the flow direction; therefore, the pressure drop can be positive (clockwise) and negative (counterclockwise).

Four methods can be employed for solving ventilation network problems (McPherson 1993). The first of these involves the compounding of series and parallel airway arrangements into a single airway of equivalent resistance. The second method is the analytical solution of equations obtained by the above three laws. The third is the use of physical models or analogous to represent the mine ventilation system and, finally, the fourth is the method of successive approximations that have come to forefront with the evolution of digital computers. The method chosen for a particular problem depends upon the complexity of the network to be analyzed. The second and fourth methods are also known as direct analysis and iterative techniques, respectively.

3.5.1 Direct Analysis (Manual Method)

For a network, containing *b* branches and *j* junctions, this technique involves formulating and solving three sets of equations for *2b* unknowns. The first set is formulated based on Atkinson's law. A set of *b* equations can be formulated using this law (one for each branch). The second set is formulated based on Kirchhoff's first law. A set of j equations can be generated using this law (one for each node). However, only $j-1$ of these is independent; the flow at the i^{th} junction is already defined by the flows of other junctions. These equations are of linear type. The third set is formulated based on Kirchhoff's second law. A set of $b - j + 1$ equations can be formulated using this law. Each pressure difference of this set can be expressed in terms of airway resistance and flow quantity using Atkinson's law. Therefore, these equations are transformed into quadratic equations. These equations are of nonlinear type.

For the sample network ($b = 65$, and $j = 45$), there would be $2b = 130$ equations to solve: 65 based on Atkinson's law (nonlinear), 44 based on Kirchhoff's first law (linear) and 21 based on Kirchhoff's second law (nonlinear). For complex networks, solving nonlinear type equations becomes a difficult task. Therefore, this approach is not suitable for solving complex networks. Techniques other than analytical ones are required to solve real mine ventilation network problems.

3.5.2 Iterative Technique (Hardy Cross Method)

This method enables the user to solve a ventilation network problem iteratively. It is based on initial estimates of airflow rates for all branches of the network. These are then adjusted by calculating an approximate correction for each branch flow and repeating the correcting procedure iteratively until an acceptable level of accuracy has been attained. The iterative technique, currently used by most fluid flow simulators, was originally developed by Professor Hardy Cross. The technique, originally developed for water distribution systems, has been modified to improve its efficiency in solving mine ventilation network problems. The details of a modified Hardy Cross method are given in most mine ventilation handbooks (McPherson 1993; Hartman 1997).

One variation of this method that is used in mine ventilation is referred to as semicontrolled splitting. In this case, the flow rates of a selected number of branches of a network are predefined (working areas of a mine). For any given fan(s), the quantity-pressure distribution in the network, including the predefined flow rates can be obtained using this method iteratively. Booster fans, regulators, and others can be used in solving semicontrolled ventilation networks problems.

3.6 Regulatory Requirements of Booster Fans

Each country has its own regulation on the use of booster fan. In this section, statutory regulations on the use of booster fans of three countries are summarized.

3.6.1 Federal Underground Coal Mine Standard (United States)

Each coal mines shall be ventilated by one or more main fans. Booster fans shall not be installed underground to assist the main mine fan except in anthracite mines (30 CFR § 75.302 1977). In anthracite mines, booster fans are installed in the main air current or split of the main air current and may be used with the prior approval of the Mine Safety and Health Administration (MSHA).

3.6.2 The 1956 Coal and Other Mines (United Kingdom)

The 1956 Mining Law allows the U.K. coal mine operators to use booster fans provided that certain conditions are met. Two of such conditions are listed below (Part 28):

1. "No fan (not being an auxiliary fan) shall be installed at any place below ground in a mine, unless the manager is satisfied that it is necessary or expedient to install it at that place for the proper ventilation of the mine…"
2. "If any such fan is installed at any place below ground the manager shall forthwith give notice thereof to the inspector for the district, attaching thereto particulars of the survey and a copy of the report made in relation to that installation…"

In addition, the following standards are imposed:

1. **Planning**. The plan must specify the size and location of the proposed fan and give predictions as to its effect on all parts of the mine.
2. **Half-Hourly Inspection**. The fan installation must be inspected at 30 minute intervals and for the instrumentation (sensor) readings to be recorded every 2 hours.
3. **Electrical**. There must a dedicated power supply from the surface substation to the fan with an alternative supply available.

The installation of a booster fan requires a thorough ventilation survey and planning. The report and all other details of such survey must be sent to the District Inspector for approval. The Mines Inspector has the ability to impose whatever conditions and requirements it seems fit to further enhance safety.

3.6.3 Australian Coal Mine Regulations

In Australia, booster fans are used in two coal mining states: New South Wales and Queensland. In both states, the installation of booster fans requires a thorough evaluation and risk analysis and a management plan demonstrating adoption of best practice that must be submitted to the state inspectorate for approvals. Some specific state requirements are listed below.

1. **Queensland - Coal Mining Safety and Health Regulation, 2001 Part 11 Division 5:**

   353 **Using fans underground**: "(3) The mine must have a standard operating procedure for using the following fans if the fans are used in the mine's ventilation system—(a) auxiliary fans, (b) booster fans; (c) scrubber fans …"

   354 **Provision for fans in principal hazard management plan for ventilation**: The mine's principal hazard management plan for ventilation must state— "(b) if a booster fan is used at the mine— (i) the procedures for using the fan; and (ii) the action to be taken if a methane detector monitoring the air passing through the fan activates a visible alarm."

   358 Dealing with underground auxiliary and booster fans: "(1) A person must not deal with a fan ventilating a place below ground at an underground mine unless the person—

   (a) is the ERZ (Explosion Risk Zone) controller for the place; or

   (b) is authorized by the ventilation officer to deal with the fan …"

2. **New South Wales - Coal Mines (Underground) Regulation, 1999**

Part 4 Ventilation, Division 5 Fan installations

93 Installation of monitoring system: “A system must be installed and maintained to monitor the operation of the main ventilation fan or fans at a mine. The system must provide for the giving of an alarm at the surface of the mine if the fan or fans stop.”

95 Booster fans: “A booster fan must not be installed or used underground at a mine unless the installation and use of the fan is approved.”

Booster fans are located in the return airways with their motors and electrical components in intake air. As part of the safety management plan all underground booster fans are equipped with environmental and fan condition monitors, and electrical interlocking systems. The possibility of mine fires is the major design parameter.

CHAPTER 4

APLICATION OF GENETIC ALGORITHMS IN MINE VENTILATION

Genetic algorithms (GAs) were developed in 1975 by John Holland, his colleagues, and his students at the University of Michigan. They investigated algorithms based on the mechanics of natural selection and natural genetics, where each individual is assigned a fitness value based on a fitness function to test its survival rate in a competitive environment. In GAs, individuals of lower fitness value will die out in such an environment, but those of higher fitness value will survive and become eligible parents for the next generation. This process is repeated for a desired number of generations. Evolution occurs as a gradual process of reproduction in which an algorithm is used to select the fit individuals for survival. The population of the modern world can be recognized as a result of successive development of generations similar to those used in GAs to optimize an objective function. In this dissertation, genetic algorithms have been applied in a ventilation network to determine the best combination of main and booster fans to minimize the air power, leakages, and, consequently, the ventilation cost. This chapter deals with the GAs program to determine the best combination of main and booster fan pressures in multiple ventilation networks. This program essentially consists of a GAs library (developed by MIT) interfaced with a ventilation simulator VnetPC (developed by MVS Inc.). This program was used successfully to solve a sample network as well as a coal mine ventilation problem.

4.1 Mechanism of GAs

GAs' working mechanism is very simple. Figure 4.1 shows the general functioning of GAs, which start with initial populations of potential solutions to a problem. Each individual population is represented by a set of parameters. These parameters are regarded as the genes of a chromosome. An individual population is evaluated by a fitness function with assigned specific fitness value. Such a population can be represented by different sizes of circles depending upon the fitness value. The highest fitness value is categorized an elite and is transferred as a child to the next generation. Only higher fitness value populations are selected as eligible parents to cross over and produce children for the next generation, and the others are rejected. Out of those children, only a small fraction of the population undergoes mutation to mimic the diversity among the children. In every generation, a new set of individuals (strings) are created using bits and pieces of the fittest ones. Throughout genetic evolution, fitter chromosomes have better chances to produce good quality offspring, which means a better solution to a problem. Genetic Algorithms are based on random numbers, but this is not a simple random walk problem. All the historical information is stored and utilized subsequently to predict new outcomes with improved overall performance. In addition, Genetic Algorithms offer greater flexibility to provide robust searches in complex spaces.

The real world of search is mostly suitable to discontinuities and vast multimodal, noisy search spaces. Random search algorithms have gained increasing popularity by the

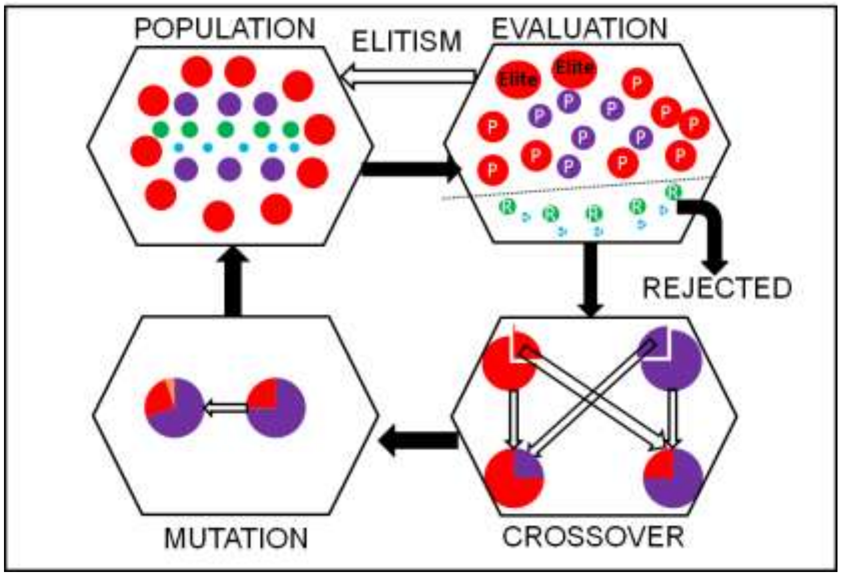


FIGURE 4.1 Mechanism of GAs

fact that researchers have recognized the shortcomings of calculus-based and other enumerative schemes. GAs are different from more normal optimization and search procedures in four ways (Goldberg 1989). First, GAs start with coding of the parameter sets, not the parameters themselves. Second, they search for a solution of a problem from the multiple populations, not a single point. Third, GAs require payoff (objective function) information, not the derivatives or other auxiliary information. Fourth, they use probabilistic transition rules, not deterministic rules. An effective search is principally based on an improved structure. This characteristic makes GAs a more canonical method than several search schemes.

4.1.1 GAs Parameters

A genetic algorithm that yields good results to many practical problems depends on the wise selection of three parametric values: Reproduction (Selection), Crossover, and Mutation. These are briefly described below.

4.1.1.1 Reproduction (Selection)

Reproduction is a process in which individual strings are copied as an eligible parent according to their objective function, often recognized as a fitness value. The value is a measure of a profit or goodness that we want to maximize. Copying strings according to their fitness values suggests that a string with a higher value possesses higher probability of contributing one or more offspring to the next generation. This is an artificial operator that measures the potential of parents in producing the next generation. Reproduction operators can be implemented in algorithmic form in a number of ways. Perhaps the easiest way is to select parents based on the Roulette Wheel Selection algorithm, which provides wheel slots to each current string in the population in proportion to its fitness value. Although this selection procedure is random, each parent's chance of being selected for reproduction is directly proportional to its fitness. On balance, over a number of generations this algorithm will drive out the least fit members and contribute to the spread of the genetic material in the fittest population members. The purpose of the parent selection process is to provide more reproductive chances, on the whole, to most fit.

4.1.1.2 Crossover

A crossover operator is used to recombine two strings to yield a better string. In this operation, recombination creates different individuals in successive order by combining materials from two individuals of the previous generation (Mathew 2010).

New strings are created by exchanging information among strings in the mating pool. The two strings participating in the crossover operation are known as parent strings, and the resulting strings are known as child strings. It is clear from this construction that good substrings from parent strings can be combined in order to form a better child string if an appropriate site is chosen. With a random site, the produced children strings may or may not have a combination of good substrings. It is also clear from this discussion that crossover may be detrimental or beneficial. Therefore, in order to preserve some of the good strings in the mating pool, few strings are not used in the crossover process. They are called elite population. Such elite individuals transfer directly to the next generation. Various crossover operators are available in the literature. One site and two site crossover operators are mainly responsible for the search of new strings. In most cases, two strings are picked randomly from the mating pool. A one site crossover operation is performed by randomly choosing a crossing site along the string and by exchanging all bits on the right side of the crossing site to form new strings. One-site crossover is more suitable when the string lengths are small, while a two-site crossover is more suitable for large strings. Table 4.1 shows one-site crossover at a third bit place.

On the one hand, the first three bits of String 1will combines with the later five bits of String 2 and produce a first child. On the other hand, the first three bits of String 2 will combines with the later five bits of String 1 and produce a second child.

4.1.1.3 Mutation

Mutation adds extra information in a random way to the genetic search to avoid getting trapped at local minima (Mathew 2010). It is an operator that introduces diversity

TABLE 4.1 One site crossovers (3rd bit place)

Before Crossover (Parents)		After Crossover (Children)	
String 1	01101100	String 1	01111001
String 2	11011001	String 2	11001100

in the population whenever the population becomes homogeneous due to repeated use of reproduction and crossover. Mutation may cause the individuals' chromosomes to be different from those of their parents. Mutation is, in a way, the process of randomly disturbing genetic information. Mutations operate at the bit level, when the bits are being copied from the current string to the next string. However, the probability of mutation is usually a small value, called the mutation probability. When the generated random number is less than the mutation probability, then the bit is inverted so that the zero becomes one and one becomes zero. On one hand, this helps to introduce diversity to the population. On the other hand, it might produce a weak individual that will never be selected for further operations. The need for mutation is to create a point in the neighborhood of the current point, thereby achieving a local optimum around the current solution.

For example, consider the following four strings for a local search.

01101011
00111101
00010110
01111100

A quick inspection shows that all four strings have a 0 in the left-most bit position. If the true optimum solution requires 1 in that position, then neither reproduction nor crossover operator described above will be able to create a 1 in that position.

4.1.2 Evaluation of Population

In general, fitness function is first derived from the objective function and used in successive genetic operations. Fitness in a biological sense is a quality value that measures the reproductive efficiency of the chromosomes. In a genetic algorithm, fitness is used to allocate reproductive traits to individuals in the population and as a measure of goodness of fit. This means that individuals with higher fitness values will have a higher probability of being selected as potential parents for further examination. The process helps to recognize the population as an elite, eligible parent or rejected population. The fitness function may be either the environment or physical capacity.

4.2 GVENT Fan Selection Program

The GVENT fan selection program is a modular program written in C++ language. It combines GAs routines (developed by MIT) and a ventilation simulator. It is used to solve a ventilation network problem for fan pressures and their locations to optimize a fitness function. It requires a ventilation network, a set of airways with fixed flow requirements at working areas, fan locations, an objective function, and practical constraints. In addition, it requires a set of GA routines that are embedded in the program.

The GAs library (GAlib, developed by MIT) is interfaced with the ventilation simulator (Wall 1996). Interfacing the two programs is an important step in producing feasible solutions to a problem. For a given fan pressure, the simulator is used to solve the ventilation network for a set of flow rates and regulator resistances that satisfy the airflow requirements at the mine workings.

Upon execution, the program generates an output file showing the fan pressures, flow quantities, total air power, and regulator resistances for all working areas. These results are then evaluated against a fitness function and a set of constraints until the optimal or near optimal solution is achieved.

This program essentially consists of the following seven building blocks:

1. Ventilation network
2. GAs parameters
3. GAs routines
4. Ventilation simulator
5. Fitness function
6. Practical Constraints
7. Evaluation

A summary of each block is presented below.

4.2.1 Ventilation Network

This is a collection of branches and nodes. A branch represents an airway, i.e., a drift, shaft, or active working. A node is an intersection of two or more branches. In ventilation, four types of branches are distinguished: fan branch, fixed quantity branch, normal branch, and a leakage branch. A fan branch represents an airway where a fan is located. A fixed quantity branch represents a working area or an underground facility where a fixed quantity of air is required. A leakage branch represents a high resistance airway, intentionally kept blocked (door or stopping), and a normal branch represents any other airways used for ventilation. To run this program, a network file is required. This file should be prepared in Sample.csv format (Appendix A) and include the following fields:

1. **Model Data**: It includes project title, fan efficiency, power cost, air density, reference junction number, units of measurement, execution date and time, and number of iterations.
2. **Branch Data:** It includes branch ID, From junction ID, To junction ID, type, flag number, surface state, airway resistance, total resistance, total quantity results, pressure results, air power, operating cost, square law quantity exponent, and branch description.
3. **Junction Data:** It includes junction number, X-coordinate, Y-coordinate, Z-coordinate, surface connection (In Atmosphere), and relative pressure.
4. **Fan Data:** It includes fan ID, From junction ID, To junction ID, pressure, and number of fan curve points.
5. **Fixed Quantity Data:** It includes fixed quantity ID, branch ID, From junction ID, To junction ID, fixed quantity, and gas flow rate (inject/reject).
6. **Fan Results:** It includes branch ID, From junction ID, To junction ID, fan pressure, fan quantity, air power, and operation cost.

Upon the execution, network results are generated, and these are stored in an output file. This output file is very similar to the input file except for a few parameters that are replaced by new values. These changes are highlighted in their corresponding fields in Table 4.2.

4.2.2 GAs Parameters

The GA parameters play an important role in controlling the population size, number of generations, and also the way how the individuals of a population are created. The following GA parameters are used in this program.

Size of population (n):	100
Number of generation (N):	30
Crossover rate (X):	0.26
Mutation rate (m):	0.015

These parameters were determined based on parametric studies conducted on sample ventilation models.

TABLE 4.2 Output template updates

Field	Parameters replaced by new values, when output file is created				
a. Model Data	Iteration Date	Iteration Time	Number of Iteration	----	----
b. Branch Data	Total resistance	Quantity Results	Pressure	Airpower	Operating Cost
c. Junction Data	Relative Pressure	----	----	----	----
d. Fixed Q Data	----	----	----	----	----
e. Fan pressure	Fan Pressure				
f. Fan Results	Fan Pressure	Quantity	Airpower		

4.2.3 GAs Routines

The following three libraries and three functions are used for interfacing the ventilation simulator and the search engine of this program:

1. **#include<ga/GASimpleGA.h>:** This algorithm is used to create nonoverlapping individuals of a population. An initial population is created by cloning the individuals' properties that are passed onto them. For each generation, the algorithm creates an entirely new population of individuals by selecting fitted genes from the previous population then matting these to produce new offspring for the new population. This process continues until the stopping criteria are met.

2. **#include<ga/GA1DArrayGenome.h>:** This is a 1D resizable array of objects. It is a template derived from the GA genome class. Each element in the array is a gene. The values of the genes are determined by the type of the genome. For example, an array of "int" may have integer values whereas an array of "double" may have floating point values.

3. **#include<ga/GA2DArrayGenome.h>:** A genome is a set of genes that contains an arbitrary number of lists that could be easily modified. This file is a two dimensional array of genomes derived from a two-dimensional array genome class. It shares the same characteristics as those of current genomes, but adds the feature of previous genomes. Each genome is generated with specified width and height.

Some of following functions are also used in this routine.

1. GARandomSeed (seed): It is called to generate random numbers.

2. float Objective(GAGenome &): It is called to define the objective function.
3. void myinitializer(GAGenome& g); It is called to generate random fan pressure for the given ranges.

Currently, all these routines reside in the MIT GAlib library (Wall 1995).

4.2.4 Ventilation Simulator

A ventilation simulator is used to solve the network for airflow rates, regulator resistances, and airpower. As any ventilation simulator, this is governed by three basic laws: Atkinson's square law ($P = R*Q^2$), Kirchhoff's first law (conservation of mass) and Kirchhoff's second law (conservation of energy). In addition, the simulator includes a mesh selection routine and the Hardy Cross' network solution algorithm (Hartman 1997). An executable "xyz.c" program, developed by Mine Ventilation Services Inc (MVS 2013), is used in this study.

The fan selection program also works well without the ventilation simulator for small network problems provided that a mesh selection routine is appended.

4.2.5 Fitness Function

In ventilation planning, the main objective is to determine the best combination of fan duties and regulator resistances to satisfy a set of flow requirements. The air power (AP), calculated by multiplying the fan pressure (P) by its flow rate and (Q), the main function to be optimized. For multiple fans, the total air power is determined as the sum of individual fan air powers. In the GVENT program, total airpower is used as the fitness function. Equation 4.1 shows this function for a multiple fan ventilation system.

$$T.A.P. = \sum_{j=1}^{N} P_j Q_j \tag{4.1}$$

Where

T.A.P. = *Total air power, kW*

P_j = *Pressure of fan j, kPa*

Q_j = *Quantity of fan j, m^3/s*

N = *Number of fans.*

This is the function that is minimized to obtain the solution to the problem.

4.2.6 Practical Constraints

The air, once contaminated, by law, must not be allowed to recirculate through the workings. Therefore, a constraint is required to ensure that there is no leakage from a return airway to any intake airway. This constraint can be satisfied by 1. using surface fans only and 2. by using properly sized surface and booster fans.

Another constraint is maintaining positive regulator resistances in all airways with fixed flow rates. A negative regulator resistance implies the need of a booster fan. If this constraint is violated, the probability of recirculation is high. In the GAs-based program, this problem can be reduced by assigning a very large default value to the fitness function. Using this approach, the probability of selecting an individual fan that yields negative regulator resistances is very small. In addition, the fitness function is assigned a very large preset value when the corresponding combination of main and booster fans is not able to meet the flow requirements. The main goal of solving a ventilation network problem is to determine the best combination of fan duties that meets the flow requirements at different working areas and minimizes the total airpower while satisfying all the practical constraints.

4.2.7 Evaluation

The generated fan pressures are evaluated for regulator resistances (R_R), leakage through stoppings (Q_{SL}), and air power (AP). The regulator resistances are evaluated against a preset regulator resistance ($\geq$ 0.005 Ns^2/m^8.) A negative regulator resistance implies the need for a booster fan, and such a solution is rejected. For an individual population, alternative solutions with positive regulator resistances are evaluated, and the air power is minimized (local minimum).

4.3 Methodology

Figure 4.2 shows a schematic of the GVENT fan selection program. The program starts by generating the individuals (entities) of the initial populations. In this case, an entity is represented by an array of main and booster fan pressures (in the 0–6 kPa range), and a population by a set of entities with their corresponding attributes. Next, the program is executed to determine the flow distribution in the network, and then the results are evaluated against a fitness function. The fit individuals are preserved for the next generation, and the others are rejected. The elite individuals go directly to the next generation.

The GVENT program continues to generate other populations randomly for the next generation. The newly generated fan pressures are used to update the input file and to solve the ventilation network for regulator resistances (RR), leakage flow rates through

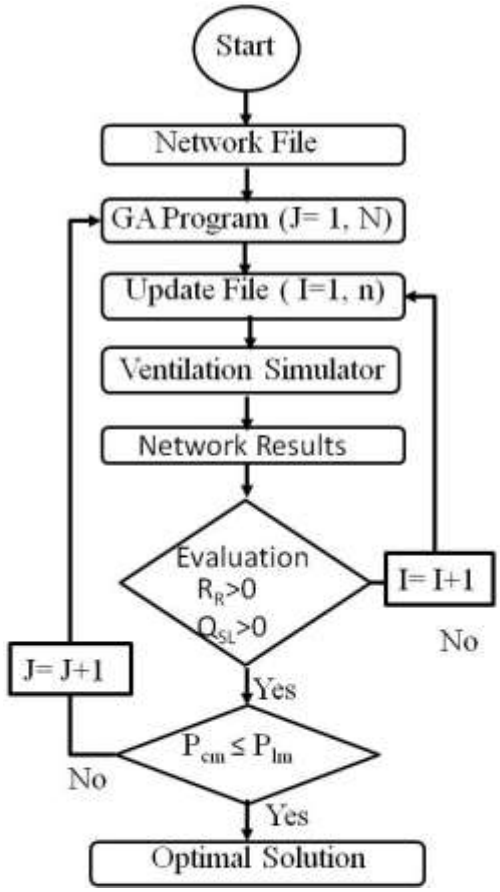


FIGURE 4.2 Schematic of GVENT program

stopping (Q_L), and air power (AP). The regulator resistances are evaluated against a preset value of regulator resistance = 0.005 Ns^2/m^8. A negative regulator resistance implies the need for a booster fan, and such a solution is rejected. For an individual population, alternative solutions with positive regulator resistances are evaluated, and the air power is minimized (local minimum). The procedure is repeated for all the entities of the population (n = 100) and the preset number of generations (N = 30). The local minimum (P_{lm}) of each generation is stored in a file. The minimum (P_{cm}) of the current generation is compared to the local minimum of the previous generation. This procedure is repeated until the global minimum of the fitness function is obtained. If the search process does not show any improvement in power reduction, the program is terminated and the current total air power is labeled as the global minimum.

The objective of this program is to determine the best entity (combination of fan pressures) that fulfills the flow rate requirements and minimizes the input power while maintaining the regulator resistances positives.

Broadly, the GVENT fan selection program consists of the following three steps:

1. Step 1. A ventilation network input file is created. This file consists of six fields: model data, branch data, junction data, fixed quantity data, fan data, and model results. The GAs-based program successively updates this file for new, randomly generated, fan pressures (0–6 kPa).
2. Step 2. The program is initialized with a set of GA parameters (crossover rate, mutation rate, population size, and number of generations). These parameters are used to generate the population of fan pressures (0 to 6 kPa) for the first generation. Then the program is activated to call an input file, to calculate the flow rates and regulator resistances, and to update the output file.
3. Step 3. The output file of each population is evaluated against the fitness function and other constraints, and the optimal or near optimal solution is found. At this stage, all regulator resistances must be positive at the minimum air power. If any population does not satisfy this criterion, then a lower fitness value is assigned to this population. Only higher fitness value populations are preserved, and the others are discarded. This procedure is repeated for all the populations and for all the generations.

For each fit population, the program generates a score. This score is upgraded whenever an improved solution is achieved. This procedure is repeated until the program reaches the optimal solution or terminating criteria.

4.4 Application of GVENT into Mine Ventilation

A sample ventilation network problem has been solved using this program. The network problem was first solved for a single surface fan system and then for a two-fan system.

4.4.1 Sample Problem

Figure 4.3 shows the mine ventilation network used to illustrate the major steps of this program. The network includes 65 branches, 45 nodes, one surface main fan, one booster fan (when needed), six working areas, one return airway, and two intake airways. Table 4.3 shows the airflow requirements. The problem is to determine the best operating pressure for the surface fan, if only one fan is used, and the best combination of main and booster fan pressures if two fans are used. In each case, the solution must satisfy the airflow requirements without causing any unwanted recirculation. The airway resistances and other network parameters are shown in Appendix B. The sample problem is solved for the fan pressures and their corresponding airpower and regulator resistances, first using a ventilation simulator (VnetPC) and then using a GAs-based GVENT program. In each case, two scenarios are considered: a single surface fan system and a two-fan system that includes a booster fan.

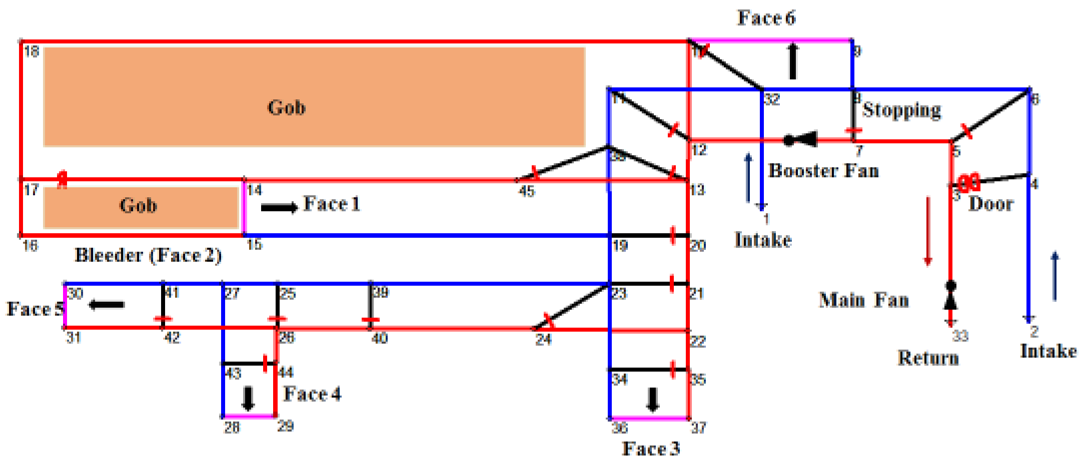


FIGURE 4.3 Sample network

TABLE 4.3 Flow requirements

Item	Branch	Airflow requirements, m^3/s	Working areas
1	15-14	47	Face 1
2	15-16	15	Face 2
3	36-37	40	Face 3
4	28-29	33	Face 4
5	30-31	33	Face 5
6	9-10	20	Face 6

4.4.2 VnetPC Approach

A network data file is first created in VnetPC and then solved iteratively for two ventilation scenarios: 1. using a surface fan only and 2. using two fans, one surface and one booster fan. In each case, the fan pressure is determined to satisfy the airflow requirements and minimize the power consumption.

4.4.2.1 Single-fan system

For this system, the network was solved in three steps. First, the fan pressure was initialized and the network solved for regulator resistances. Next, the regulator resistances were sorted, and then the critical branch (minimum resistance) was identified. If all the regulator resistances are positive, the trial pressure is decreased by a fixed amount (step size); otherwise, this pressure is increased. This procedure is repeated until the resistance of the critical branch is close to the predefined positive value (0.005 Ns^2/m^8). When this condition is satisfied, the optimal solution is found. Table 4.4 shows an optimal solution for the single fan system.

A quick evaluation of Table 4.4 shows that a high-pressure fan (5.72 kPa) is needed to meet the total requirements of air (188 m^3/s). Furthermore, at this pressure, a significant amount of fresh air (58% of total quantity) is short-circuited to surface

TABLE 4.4 Optimal solution for single-fan system—VnetPC Approach

Description	P, kPa	Q, m^3/s	AP, kW	Total AP., kW	Q_L, m^3/s
Single Fan System					
Main Fan	5.72	442.60	2532	2532	255

(leakage flows) before reaching the workings.

4.4.2.2 Two-fan system

In this case, the single-fan system was modified by adding a booster fan in the main return airway (branch 12-7 in Figure 4.3). The reason for choosing this location was to reduce the possibility of drastic changes in pressure at or near the working places when the booster fan was stopped. The operation of the booster fan introduced a new dimension to the design problem. Now the major challenge was to determine the optimal combination of two fan pressures (main, and booster). In an attempt to solve the problem, the booster fan pressure was set at 200 Pa, and the main fan pressure was decreased successively from 5720 Pa to 3000 Pa to meet the flow rate requirements. The total air power for this combination was recorded. This procedure was repeated for other booster fan pressures in the 200–3000 Pa range while minimizing the main fan pressure. For each combination of main and booster fan pressures the total airpower was recorded.

Figure 4.4 shows the booster fan pressure - total air power relationship. The optimal combination of main and booster fan pressures was determined graphically as the minimum of the total air power function.

Table 4.5 shows a summary of results for the two-fan system. In this case, the best combination of fan pressures was given by 2.63 kPa for the main fan and 2.60 kPa for the booster fan. Under these conditions, as compared to the single fan system, the quantity of air circulated through the system decreased from 433 m^3/s to 399 m^3/s, and the total power requirement decreased from 2532 kW to 2016 kW.

An evaluation of results of these two scenarios (Table 4.4 and Table 4.5) shows

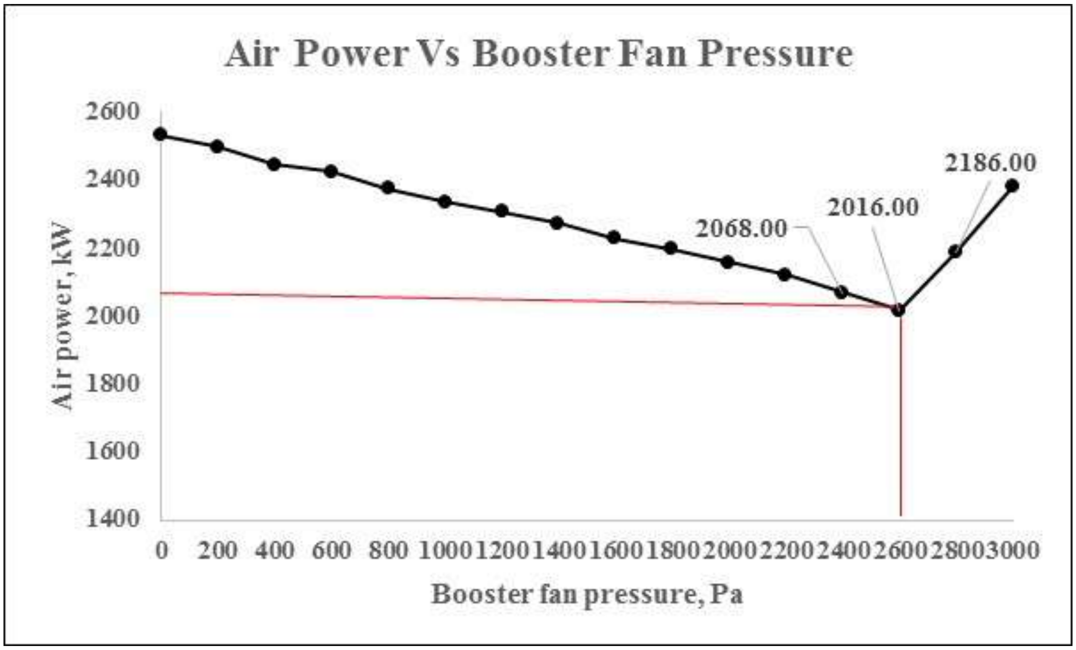


FIGURE 4.4 Optimal solution for single-fan system—VnetPC Approach

TABLE 4.5 Optimal solutions for two-fan system—VnetPC Approach

Fan System	P, kPa	Q, m^3/s	A. P., kW	Total A. P., kW	Q_L, m^3/s
Two-Fan System					
Main Fan	2.630	399	1049	2016	211
Booster Fan	2.600	372	967		

that the two-fan system requires a lower pressure surface fan and lower total input power than the single-fan system.

In addition, because of the lower fan pressure, the leakage quantity is reduced from 255 to 211 m^3/s. These results show some of the benefits that can be gained by using booster fans in a ventilation system.

4.4.3 GVENT Approach

As in the previous section, to solve the sample network problem, two input files were created, one for the single-fan system and another for the two-fan system. In addition, based on trial tests and experience gained from other researchers (Yang et al. 1998), the following GAs parameters were chosen:

1. population size: 100
2. cross-over rate: 0.26
3. mutation rate: 0.015
4. number of generations: 30
5. pressure range: 0 to 6 kPa

The reason for selecting a large population size and large number of generations was to enable the program to cover a wide range of alternatives for the proposed ventilation network, irrespective of the size and shape of the mine.

4.4.3.1 Single-fan system

In this case, first, the input file was updated to include GAs parameters, and then the GVENT program executed. In the process, for each trial fan pressure, a set of regulator resistances were generated. These were then evaluated. Only the trial pressures with positive regulator resistances were preserved and evaluated against the objective function (air power); the others were discarded. The process was repeated for all the individuals of the population. In each generation, to balance the population size, new individuals were generated and the evaluation procedure repeated until the optimal or near optimal solution was found. Figure 4.5 shows a screenshot (optimal solution) of the program showing the final results in SI units. Table 4.6 shows a summary of results generated by this program for a single-fan network problem. Figure 4.6 shows the fan pressure – number of generation convergence diagram before the solution to the problem is achieved. The fan pressure convergences at 2533 Pa in 10 generations and remains fairly constant thereafter.

4.4.3.2. Two-fan system

In this case, the GVENT randomly generate a population of pairs of fan pressures (one pressure for each fan). As in the previous case, the booster fan was placed in branch 12-7 (Figure 4.3). Once the input file was updated, the program was executed, and the results evaluated against the fitness function.

```
Main fan pressure (branch 8-38) is: 5.72239
Main fan flow rate is : 442.66
Main fan air power:  2532.90

Total air power is: 2532.9
Regulator resistance for branch  14-45 is: 0.23644
Regulator resistance for branch  15-16 is: 4.2865
Regulator resistance for branch  37-35 is: 0.7523
Regulator resistance for branch  29-44 is: 0.01634
Regulator resistance for branch  31-42 is:0.00551
Regulator resistance for branch  9-10 is:4.75919
```

FIGURE 4.5 Screenshot of solution for single-fan system—GVENT Approach

TABLE 4.6 Optimal solution for single-fan system—GVENT Approach

Fan System	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Q_L, m^3/s
Single Fan System					
Main Fan	5.722	442.66	2533	2533	255

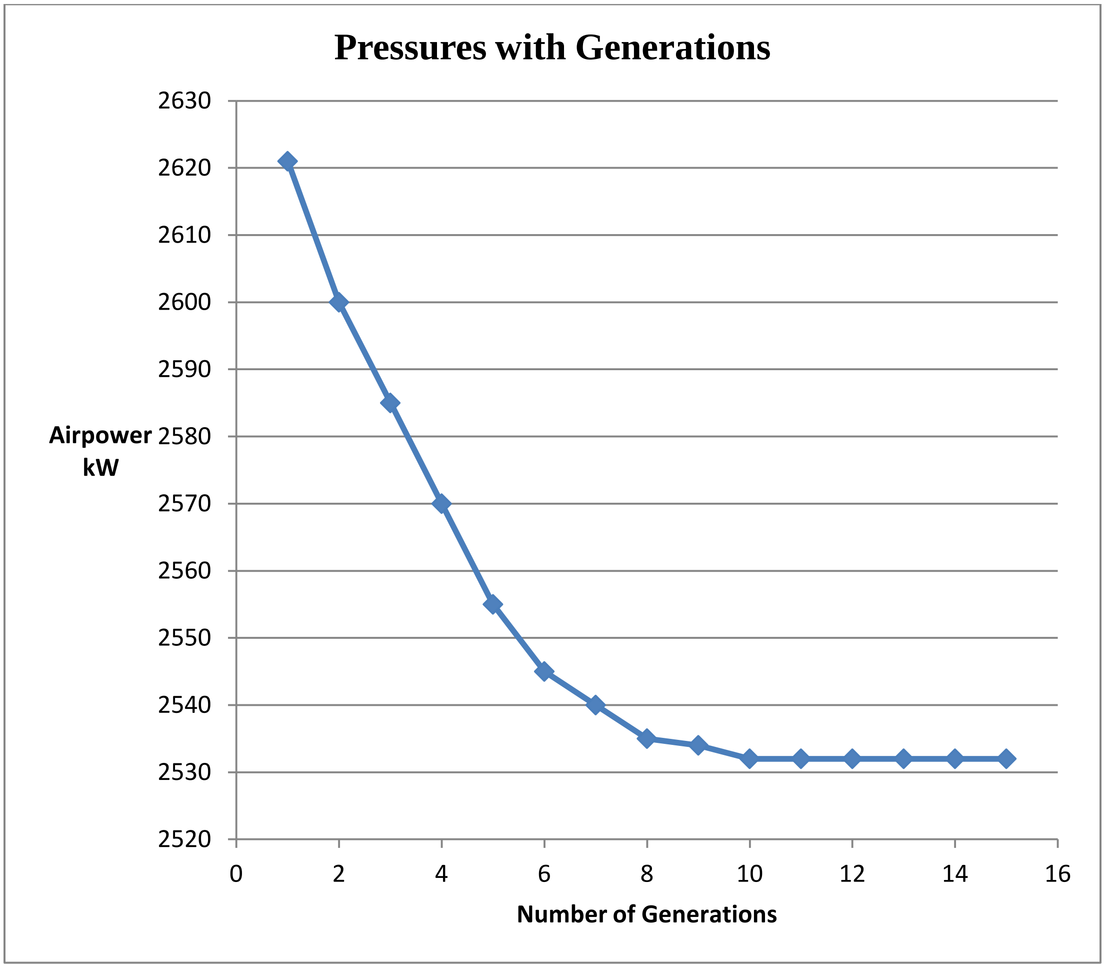


FIGURE 4.6 Convergence of single-fan system—GVENT Approach

The procedure of updating and solving the network for flow rates and regulator resistances was repeated for different individuals of a population and for different generations until an optimal or near optimal solution was found. Figure 4.7 shows a screenshot (optimal solution) of the GVENT program. Table 4.7 shows the optimal solution to the problem using this approach.

A quick evaluation of the results of the two scenarios (Table 4.6 and Table 4.7) shows that the two fan scenario yields lower surface fan pressure and total power requirement than the single fan scenario. These results are similar to those generated by the VnetPC simulator, but obtained rapidly.

4.5 Concluding Remarks

A comparison of results of the two approaches (VnetPC and GVENT) used to solve the same network problem shows that the GVENT program was able to replicate the results generated by the VnetPC within an accuracy of 0.5% for flow rates rapidly. Using VnetPC, these results were achieved after several trials and correlation studies, which in this case took about 3 days. Using the GVENT program, it took less than 1 hour to achieve practically the same results with very little manual involvement. The GVENT is an efficient and effective fan selection tool. The results are very convincing and appealing not only for small network problems, but for coal mine ventilation networks, as it will be shown in the next chapter.

```
Main fan pressure (branch 3-33) is: 2.65595
Main fan flow rate is : 400.65
Main fan air power:  1064.13
Booster fan pressure (branch 12-7) is: 2.62778
Booster fan flow rate:  373.58
Booster fan air power:  981.77

Total air power is: 2045.9
Regulator resistance for branch  14-45 is: 0.24332
Regulator resistance for branch  15-16 is: 4.36208
Regulator resistance for branch  37-35 is: 0.76468
Regulator resistance for branch  29-44 is: 0.0244
Regulator resistance for branch  31-42 is:0.01354
Regulator resistance for branch  9-10 is:4.81754
```

FIGURE 4.7 Screenshot of solution for two-fan system—GVENT Approach

Table 4.7 Optimal solutions for two-fan system—GVENT Approach

Fan System	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Q_L, m^3/s
Two Fan System (One Main and One Booster Fan)					
Main Fan	2.65595	400.65	1064	2046	213
Booster Fan	2.62778	373.58	982		

CHAPTER 5

APLICATION OF THE GVENT TO A MINE VENTILATION NETWORK

A ventilation network from an operating coal mine was used to demonstrate the capabilities of the GVENT program described in Chapter 4. This program was used for determining the optimal fan duties under two cases, one with multiple surface fans only, and the other with multiple surface fans and two booster fans together. This chapter discusses the results of the GVENT program.

5.1 A Coal Mine Ventilation Network

5.1.1 Mine Description

The ventilation network used for this example is from a mine located in Colorado, United States. This mine operates three working sections: one longwall and two continuous miner sections. The longwall panel is 305 m wide and 4.8 km long. A 15-m slice of coal is removed from the panel each day. In addition to the longwall, this mine also operates two continuous miners in development headings, each with an advance rate of about 61 m per shift. On the average, the mine produces about 22,000 tons of coal per day. Figure 5.1 shows the ventilation network of this mine. The encircled part shows the possible locations for booster fans. Appendix C shows airways resistance for the network.

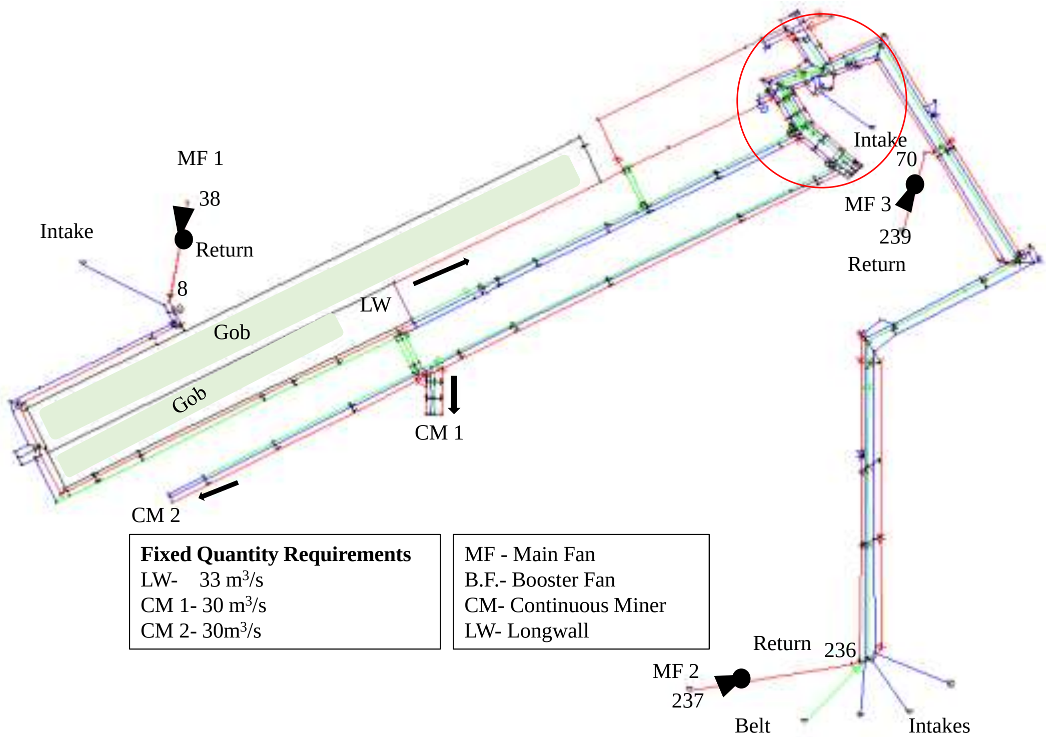


FIGURE 5.1 Coal mine ventilation network

5.1.2 Ventilation System

The mine is ventilated by a U-tube ventilation system that includes three working areas with fixed quantity requirements, five intake airways, and three exhaust shafts equipped with surface fans. Fan 1 is used to ventilate the longwall gob, fan 2 to ventilate mined-out areas that are not sealed yet, and fan 3 to ventilate the three working sections. The surface main fans are located in the following branches: 8-38, 236-237, and 70-239, respectively.

5.1.3 Airflow Requirements

Based on the coal strata characteristics and the mining methods used and assuming that the liberation of methane at each section is constant, the following airflow requirements were estimated: 33 m^3/s for the longwall and 30 m^3/s for each continuous miner section as per the data provided by the mine. Table 5.1 shows details of the airflow requirements for each section. CM1 section consists of three small quantities to ventilate properly.

The above quantities were determined based on the methane emission rates, coal production rates, and the threshold limit values stated in the *Code of Federal Regulations* (30CFR §75.321 1977). In the development sections the flow requirements were maintained at the main return, while in longwall panel, they were maintained at the tailgate.

5.2 Statement of Problem

Based on the mine ventilation network of Figure 5.1, the airway resistances shown in Appendix C, and the flow requirements of Table 5.1, the problem is to determine the best combination of fan pressures that fulfill the flow requirements and minimizes the total power consumption. The problem is to be investigated using the GVENT program for two fan configurations: 1. using three surface fans only and 2. using three surface fans and two booster fans together.

TABLE 5.1 Airflow requirements for coal mine network

Working area	Airflow requirements, m^3/s
LW	33
CM1	30
CM2	30

5.3 Solution Approach

The GVENT program was used to determine the optimal solution to the problem for each case. As described in Chapter 4, the process was started by creating an input data file, initializing the GA parameters, and running the program. The solutions were then checked using the VnetPC program and examined for flow recirculation. The formulation details and the calculated fan pressures for each case are presented below.

5.3.1 Case A: Three Surface Fan System

In this case, the problem was to optimize the total air power while determining the fan duties. The GVENT program was used to determine the fan duties to meet the air flow requirements and minimize the total air power.

Prior to running the GVENT program, an input file for the network problem was created, and the GA parameters initialized as explained in Chapter 4, These were used to generate the initial population of fan pressures. These fan pressures determined the flow distribution, airpower, and regulator resistances. These fan pressures were then evaluated against a fitness function—the total airpower, and a set of constraints—the need to have positive regulator resistances for all fixed quantity branches. The main goal of this program was to determine the best combination of fan pressures for the network while satisfying the flow requirements and minimizing the total power consumption.

Figure 5.2 shows a screenshot of the solution file created by the GVENT program. In this figure, the calculated values are expressed in SI units. For example, fan pressures are in kPa, quantities are in m^3/s, airpower is in kW, and regulator resistances are in Ns^2/m^8. Table 5.2 shows a summary of key results for this problem.

```
Main fan pressure (branch 8-38) is: 1.50081
Main fan flow rate is : 26.20
Main fan air power:  39.33
Main fan pressure (branch 236-237) is: 0.702196
Main fan flow rate:  65.90
Main fan air power:  46.26
Main fan pressure (branch 70-239) is: 3.71845
BMain fan flow rate:  352.11
Main fan air power:  1309.14

Total air power is: 1394.73
Regulator resistance for branch  169-294 is: 0.02338
Regulator resistance for branch  220-219 is: 0.38429
Regulator resistance for branch  290-1291 is: 1.30337
Regulator resistance for branch  226-164 is: 1.27264
Regulator resistance for branch  189-215 is:0.01003
```

FIGURE 5.2 GVENT solutions for three fans system

TABLE 5.2 Summary of GVENT solution—Three surface fan system

Surface Fan Number	Branch Number	Pressure kPa	Quantity, m^3/s	Airpower kW	Total Airpower kW
1	8-38	1.50	26.20	39.33	
2	236-237	0.70	65.90	46.26	1395
3	70-239	3.72	352.11	1309.14	

An evaluation of the results shown in Table 5.2 shows that the airpower is optimized at 1395 kW when the three surface fans are rated at 1.50, 0.70, and 3.72 kPa, respectively. For these pressures, all the regulator resistances were positive, indicating that no additional booster fans are needed; therefore, this is a feasible solution to the problem.

To check the results for flow recirculation, the fan pressures generated by the GVENT program were used to solve the network problem using the VnetPC simulator. The results were then evaluated for flow reversal and recirculation. No unwanted recirculation loops were detected. Therefore, the results shown in Table 5.2 indeed represent the optimal solution to the problem.

5.3.2 Case B: Three Surface and Two Booster Fans System

In this case, the location of three surface fans and flow rate requirements were unchanged. Booster fans were located in branches 5-150 and 171-159. Figure 5.3 shows the details of booster fan locations for the mine ventilation network. Here again, the problem was to determine the optimal combination fan duties for the new fan locations in the network. The GVENT program was used to determine the fan duties to meet the air flow requirements and minimize the total air power.

Prior to running the GVENT program, an input file was created for the network problem, and the GA parameters initialized as explained in Chapter 4. These were used to generate the initial population of fan pressures including the booster fans. These were used to determine the flow rates, regulator resistances, and the total airpower. These results were then evaluated against the same fitness function and constraints as in the

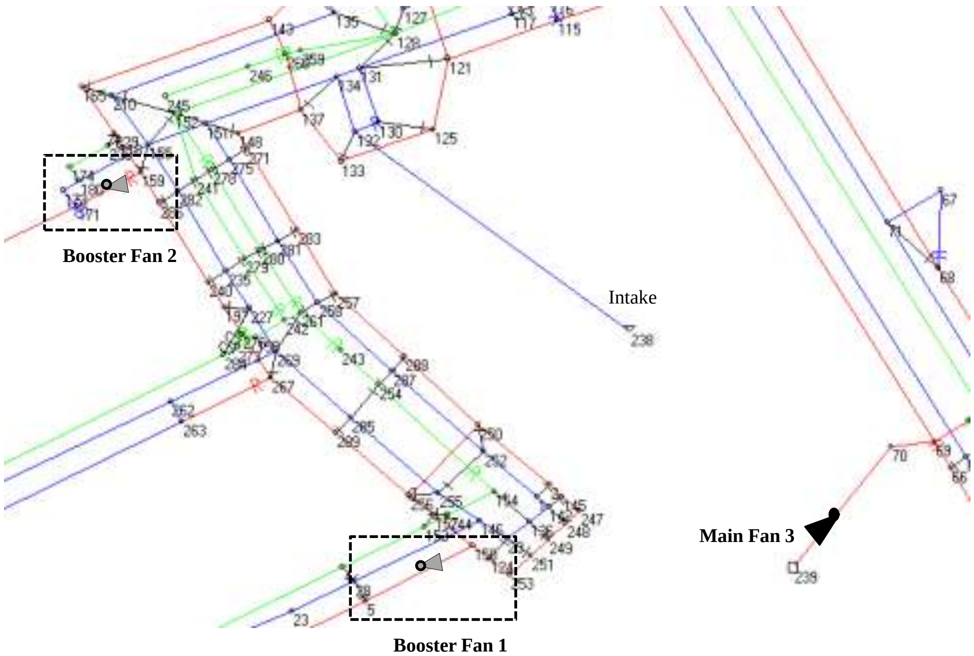


FIGURE 5.3 Locations of booster fans in a coal mine ventilation network

previous case. The main goal of this program was to determine the best combination of fan pressures for the network while satisfying the flow requirements and minimizing the total power consumption. Figure 5.4 shows a screenshot of the solution file created by the GVENT program. As mentioned preciously, the calculated values are expressed in SI units.

Table 5.3 shows a summary of key results for this problem. An evaluation of the above results shows that the airpower is optimized at 1186 kW, when the fan pressures are rated at 2.62, 1.33, and 2.67 kPa for the three surface fans and at 0.69 and1.29 kPa for the two booster fans. Under these conditions, all regulator resistances were positive, indicating that no additional booster fans were needed.

To check the results for flow recirculation, the fan pressures generated by the GVENT program were again fed to the VnetPC simulator, and the network problem

```
Main fan pressure (branch 8-38) is: 2.62484
Main fan flow rate is : 46.00
Main fan air power:  120.75
Main fan pressure (branch 236-237) is: 1.32828
Main fan flow rate:  98.88
Main fan air power:  131.31
Main fan pressure (branch 70-239) is: 2.67503
Main fan flow rate:  302.83
Main fan air power:  810.07
Booster fan pressure (branch 5-150) is: 0.688327
Booster fan flow rate:  75.99
Booster fan air power:  52.28
Booster fan pressure (branch 171-159) is: 1.29295
Booster fan flow rate:  55.72
Booster fan air power:  72.05

Total air power is: 1186.46
Regulator resistance for branch  169-294 is: 0.01623
Regulator resistance for branch  220-219 is: 0.45357
Regulator resistance for branch  290-291 is: 1.49762
Regulator resistance for branch  226-164 is: 1.47378
Regulator resistance for branch  189-215 is:0.05387
```

FIGURE 5.4 GVENT solutions for three surface and two booster fans

TABLE 5.3 Summary of GVENT solution—Three surface and two booster fans

Surface Fan Booster Fan	Branch Number	Pressure kPa	Quantity m^3/s	Airpower kW	Total Airpower kW
MF-1	8-38	2.62	46.00	120.75	
MF-2	236-237	1.33	98.88	131.31	
MF-3	70-239	2.67	302.83	810.07	1186
BF-1	5-150	0.69	76.00	52.28	
BF-2	171-159	1.29	55.72	72.05	

solved for flow rates and regulator resistances. The results were then evaluated for flow reversal and recirculation. No unwanted recirculation was found. Therefore, the results shown in Table 5.3 indeed represent the optimal solution to the problem.

5.4 Concluding Remarks

A comparison of the results generated by the GVENT program for the two ventilation scenarios (Table 5.2 and Table 5.3) shows that the five-fan scenario (three surface fans and two booster fans) yields a lower air power requirement than the three surface fan scenario (1186 kW vs. 1395 kW), resulting in a net saving of 209 kW. Furthermore, when five fans are used, the largest surface fan pressure decreased from 3.72 to 2.67 kPa. These results show two advantages that can be achieved by using booster fans in coal mines: 1. reducing the total power requirement and 2. reducing the main fan pressure. Further evaluation of the results found no flow recirculation for either of the two ventilation scenarios. Therefore, the GVENT program can be used to determine the optimal combination of fan pressures to complex network problems with multiple fans.

CHAPTER 6

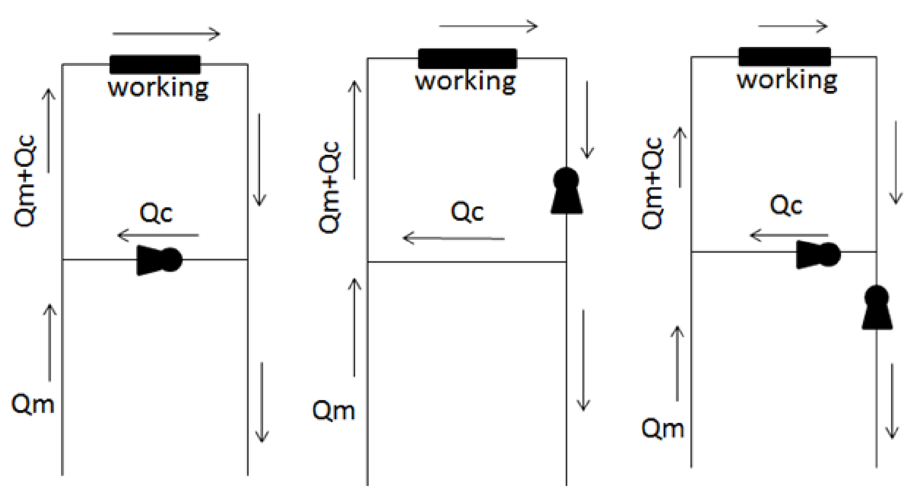
FLOW RECIRCULATION

Flow recirculation is defined as the movement of ventilation where air passes through the same point more than once (Jones 1987). Recirculation is prohibited in many coal mining countries because of the fear that the reuse of return air would allow the build-up of air contaminants at the workings. This chapter deals with the various aspects of flow recirculation. An algorithm-based program was designed to detect and quantify the recirculation in booster fan ventilation networks. Two types of recirculation exist in a mine: controlled recirculation and uncontrolled recirculation.

6.1 Controlled Recirculation

Controlled recirculation occurs in a circuit purposefully, following a design that allows a certain quantity of recirculation air to the working area, increasing the quantity of air without adversely affecting ventilation variables. Proper sizing of the booster fans and locating them correctly in either intake or return air can achieve this. It is an economical way to improve workplace conditions that increases the face air velocity and allows effective dilution of contaminants. It is also considered beneficial in mines in cold climates, where heating of air is required, and in deep or extensive mines when the working areas are far from the surface connections, where cooling of air is required.

Depending upon the configurations of booster fan locations in district ventilation, the controlled recirculation can be classified into three categories: crosscut, in-line, and combined systems. Figure 6.1 shows the configurations of booster fans in each type of recirculation system. A fan may be placed in the crosscut to minimize the required pressure-volume duty (hence the operating cost). However, such a configuration of booster fans reduces the total through flow air. A fan may also be placed either in the intake or return to achieve more flow at the face. The choice of booster fan position either in the intake or return is governed by the mineral transportation route. Considering the climatic conditions of a mine, the booster fan may be placed in return to dissipate heat at the return. The first category of recirculation is the simplest one because it locates the booster at the crosscut to allow free travel in the intake and return. The second category locates the booster fan in-line with the main fan and offers obstructions for free travel. The third category is a combination of both crosscut and in-line circulations with main fans.



(a) Crosscut (b) In-line (c) Combined

FIGURE 6.1 Controlled recirculation (McPherson 1993)

There are benefits to both types of recirculation. However, considering the air flow and resistance of airways as constant, the airpower consumed by the system would be the same, irrespective of the location of fans (McPherson 1993). In practice, differences in the efficiencies of the fans will affect the required total electrical input to the fan motors.

In each case, the system maintains a constant fresh airflow (Q_m) with recirculation flow (Q_c), increasing total airflow at the working place by recirculation flow quantity. The ratio of the recirculation flow to total airflow at the working face is known as the recirculation fraction (F). Equation 6.1 is used to calculate recirculation fractions for ventilation circuits when recirculation occurs at the immediate crosscut near the working area.

$$F = \frac{Q_C}{Q_m + Q_c} \tag{6.1}$$

The recirculation fraction varies from zero to one (no recirculation to 100% recirculation). The controlled recirculation is dictated by the value of the recirculation fraction.

Research on controlled recirculation has shown numerous benefits, especially applicable to deep or extensive underground mines (Calizaya 1989; McPherson 1993). However, the potential benefits depend upon the efficacy of booster fan design, a reliable atmospheric monitoring system, and a sound booster fan operation protocol.

6.2 Uncontrolled Recirculation

When a booster fan is not sized and located properly, it can create uncontrolled recirculation. Uncontrolled recirculation is an unintentional use of return air that is due mainly to an improper design, location, or operation of the booster fan. It can create unsafe work conditions by building up high concentrations of air contaminants. Therefore, an elimination of uncontrolled recirculation is an important step at the design stage. In some cases, the risks involved could be so high that the use of this technology is restricted, especially in coal mines. The use of a booster fan may lead to the development of uncontrolled recirculation if this fan is not installed, maintained, operated, rated, or located correctly. Uncontrolled recirculation is viewed as an undesirable event, and therefore it is avoided when determining the best combination of main and booster fans. Uncontrolled recirculation is recognized as a safety hazard that may prohibit the use of booster fans in coal mines, further preventing the potential benefits of such use, especially in deep or extensive coal mines.

6.3 Statement of Problem

The proper design and location of booster fans eliminate the safety hazards associated with high main fan pressure. Conversely, the incorrect design of booster fans in any ventilation network can create unsafe conditions due to uncontrolled recirculation. The currently available ventilation simulation programs do not give much information about recirculation. The current approach to investigating recirculation using simulation software requires manual effort, i.e., traversing from node to node in the output from the simulator, while keeping tracks of all the nodes that form recirculation paths. This is an easy task in a simple ventilation network, but it becomes tedious and sometimes very confusing in a complex and large network. Moreover, the presence of multiple recirculation paths makes the manual effort more complex and difficult, especially in separating multiple loops that are connected together. Thus, there is a need for a more efficient computational method that will detect and quantify the recirculation efficiently, determining the best combinations of both main and booster fans in a ventilation network.

6.4 Mathematical Formulation of the Problem

The detection and quantification of recirculation in a sample network is based on graph theory. Therefore, it is very important to walk through the basic concepts of a graph representation of any network. A *graph* is a collection of vertices and edges: vertices are simple objects that can have names and properties; an edge is a connection between two vertices. A path from vertex u to v in a graph is a list of vertices in which successive vertices are connected by edges in the graph. A graph is connected if there is a path from every node to every other node in the graph. A simple path is a path in which no vertex is repeated. A cycle is a path that is simple except that the first and last vertices are the same. A graph with no cycles is a tree. A directed graph is a graph with directed edges. It consists of a nonempty finite set of elements called vertices and a finite set of ordered pairs of distinct vertices called edges. A ventilation network can be recognized as a *directed graph*. The vertices are termed *nodes*, and the edges are termed as *branches*. These branches describe the flow in the network. An adjacency matrix is a mathematical representation of the network that shows whether any two nodes are connected or not. The matrix shows a 1 when nodes are connected and a 0 when nodes are not connected.

Similarly, a flow matrix shows flow rates between connected nodes, with values of 0 between unconnected nodes (Sedgewick 1992).

A recirculation path in a ventilation network is considered the same as a cycle in a graph. Depending upon the configuration of a directed graph, multiple cycles may also exist. These multiple cycles may have certain vertices and edges in common and thus be loosely connected. In the mathematical theory of a directed graph, a graph is said to be *strongly connected* if every vertex is reachable from every other vertex. The *strongly connected components* of an arbitrary directed graph may be partitioned into subgraphs that are themselves strongly connected. It is possible to find all the strongly connected components of a graph. Such strongly connected components may consist of either a single vertex or a group of vertices. The single vertex consists of a single node. Therefore, one can say that every vertex must be part of one strongly connected component. However, a single vertex is recognized as trivial, and a group of vertices is recognized as nontrivial. The presence of each nontrivial strongly connected component forms a recirculation path within a ventilation network. Therefore the main objective in an analysis of a ventilation network using graph theory is to identify all the nontrivial, strongly connected components in the network.

6.5 Recirculation Algorithms

In an attempt to implement algorithms to detect and quantify the recirculation in mine ventilation networks, it is very important to understand the categorization of nodes. Nodes are classified as source, sink, and saddle nodes. A source is defined as a node that has only outgoing branches. A sink is defined as a node that has only incoming branches.

A saddle node has both outgoing and incoming branches. Two algorithms were coded in C++ to detect and quantify recirculation. First, the recirculation detection algorithm iteratively identifies and deletes source and sink nodes. The remaining saddle nodes show where recirculation may occur. Second, the recirculation quantification algorithm is based on the quantity of maximum flow, which is determined by the maximum capacity of each path selected while traversing from source to sink nodes. These two programs were used independently to allow the detection and quantification of recirculation, eliminating the need for manual input. The resulting process is efficient and fast.

6.5.1 Recirculation Detection Algorithm

The recirculation detection algorithm consists of seven steps.

1. Step 1: Prepare the adjacency matrix of [N] [N] for the sample network, where N represents the number of nodes in the network.
2. Step 2: Identify the source and sink nodes and delete the columns and rows associated with these nodes.
3. Step 3: Update and resize the matrix while preserving the original node numbers by applying a tracking node system.
4. Step 4: Repeat steps 2 and 3, until all the source and sink nodes are deleted.
5. Step 5: Check for the residual adjacency matrix. If it is a nonempty matrix, the network contains at least one recirculation cycle. A null matrix shows no recirculation.
6. Step 6: Check for nontrivial, strongly connected nodes, identifying the

multiple connected cycles that may allow recirculation.

7. Step 7: Display the output list of recirculation cycles.

To use the algorithm and corresponding program, an input file is prepared from the branch results of a standard VnetPC simulation to get an adjacency matrix for the given network. This input file consists of three values for each branch: *from*, *to*, and *flow rate*. Flow rates may be positive or negative. For any branch with a negative flow, the nodes are swapped. This procedure is repeated for all the negative flows.

6.5.2 Recirculation Quantification Algorithm

This recirculation quantification algorithm consists of five steps.

1. Step 1: Prepare the flow and residual capacity adjacency matrix.
2. Step 2: Determine the maximum flow capacity for each path while traversing from source to sink node.
3. Step 3: Update the current residual matrix by subtracting the maximum flow.
4. Step 4: Repeat steps 2 and 3 for all possible paths from source to sink nodes.
5. Step 5: Check for the residual capacity matrix. A nonempty matrix will show recirculation quantities; a null residual matrix shows that no recirculation will occur.

The adjacency flow matrix is prepared from the result of a VnetPC simulation, as described above.

Based on the above algorithms, two computer programs, Detection.C and

Quantification.C, were developed and used to detect and quantify flow recirculation loops and quantities in ventilation networks.

6.6 Sample Network and Recirculation

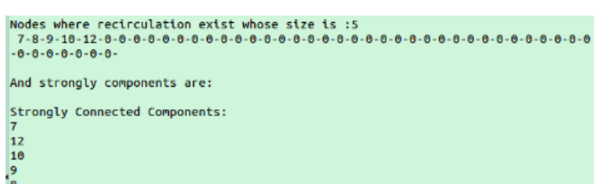
To demonstrate the capabilities of the recirculation programs, a sample network was analyzed. The description of each network and the implementations of both algorithms are given below.

The **s**ample network discussed in Chapter 4 was used to demonstrate the capability of the program for detection and quantification of recirculation. One of the fixed quantities for the working place (8-9) was increased purposefully from 20 to 66 m^3/sec, and the main and booster fans were operated at pressures of 3.0 kPa and 2.8 kPa, respectively, to ensure that recirculation would occur.

6.6.1 Detection of Recirculation

An input file was prepared for the sample network as discussed above. Appendix D shows the details of an input file. Figure 6.2 shows a screenshot of the output of the reticulation detection program.

A quick evaluation of the output shows that the final residual matrix consists of five nodes, namely 7-8-9-10-12. It also shows that there is recirculation among them. The


```
Nodes where recirculation exist whose size is :5
 7-8-9-10-12-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0-0
-0-0-0-0-0-0-0-

And strongly components are:

Strongly Connected Components:
7
12
10
9
8
```

FIGURE 6.2 Screenshot of recirculation detection for the sample network

output also shows that the matrix consists of single strongly connected components. These conclusions were also validated with VnetPC results, which showed identical results.

6.6.2 Quantification of Recirculation

An input file was again prepared. The resulting output file shows the quantity of recirculation. Appendix D shows the details of an input file. Figure 6.3 shows a screenshot of the output of the reticulation quantification program.

Again, the output shows that the final residual matrix consists of five nodes, namely 7-8-9-10-12. The quantity of recirculation is 4.27 m^3/s among them. This result was also validated with VnetPc results. This validation test showed that the two programs can detect and quantify recirculation efficiently and effectively.

```
The branch where recirculation exist: 7-8
Recirculation amount is: 4.27
The branch where recirculation exist: 8-9
Recirculation amount is: 4.27
The branch where recirculation exist: 9-10
Recirculation amount is: 4.27
The branch where recirculation exist: 10-12
Recirculation amount is: 4.28

The branch where recirculation exist: 12-7
Recirculation amount is: 4.28
```

FIGURE 6.3 Screenshot of recirculation quantification for a sample network

6.7 Effect of Recirculation on Methane Concentrations

To evaluate the effect of recirculation on the ventilation system, a ventilation engineer must determine the methane concentrations in the intake and return airways. Consider the simple ventilation circuit shown in Figure 6.4a. It consists of one working face, one intake, and one return airway. The working face is assumed to be a point source of methane. Assuming initial methane concentration X_i is in the intake air of Q_i, with the constant make of methane (q) at the working face, methane concentrations at various points may be calculated as shown below.

Concentration of methane in intake air at C is

$$X_c = X_i \tag{6.2}$$

Concentration of methane in return air at D is (McPherson 1993)

$$X_d = \frac{Q_i X_i + q}{Q_i + q} \tag{6.3}$$

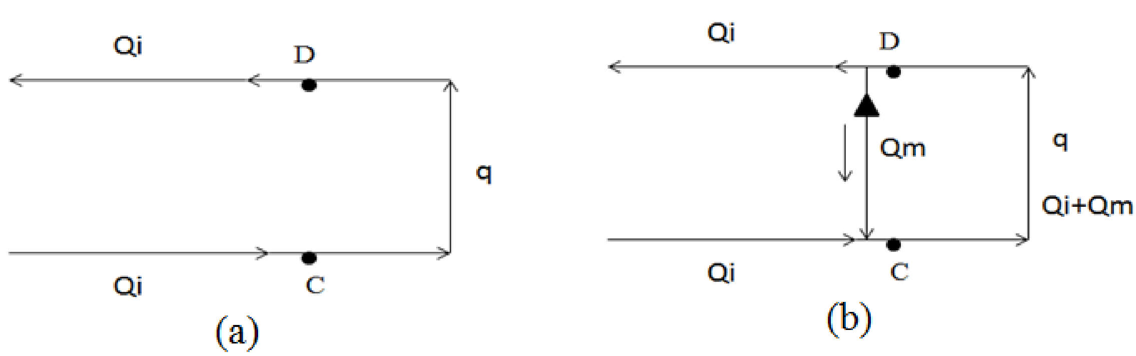


FIGURE 6.4 Effect of recirculation on concentration of methane (a) without recirculation, (b) with recirculation

If additional air is desired in the working face without increasing the amount of fresh air, then a recirculation circuit can be set up (Figure 6.4b), placing a booster fan in a crosscut through which recirculation of Q_m is allowed.

Now, the concentration of methane in intake air at C is given by

$$X_i = \frac{Q_i X_i + Q_m X_d}{Q_i + Q_m} \tag{6.4}$$

Similarly, the concentration of methane in return air at D is

$$X_d = \frac{Q_i X_i + Q_m X_d + q}{Q_i + Q_m + q}$$

It can be rewritten as follows

$$X_d = \frac{Q_i X_i + q}{Q_i + q} \tag{6.5}$$

Equation 6.5 shows that recirculation does not change the contamination level in the return airway. However, the concentration of methane in the intake, inby the crosscut in which the booster fan is located, will be higher than the initial concentration without recirculation, but less than the concentration in the return airway. It can be concluded that if mixing methane is uniform and fast, the concentration of methane at the face can increase slightly.

Intuitively, it seems that the buildup of methane at the face will cease when a steady state condition is attained, and also that, at that same time, the maximum concentration at the face will be the same as in the return air. This supposition can be proved by an analysis that considers the recirculation fraction (F), a constant make of methane (q) during mining, and uniform mixing of methane in air in successive cycles of recirculation. The total make of methane in each cycle in return air can be calculated as follows (McPherson 1988):

0th cycle: $q_1 = q$ (without recirculation)

1st cycle: $q_1 = Fq + q$ (with recirculation)

2nd cycle: $q_2 = F^2 q + Fq + q$

3rd cycle: $q_3 = F^3 q + F^2 q + Fq + q$

4th cycle: $q_4 = F^4 q + F^3 q + F^2 q + Fq + q$

nth cycle: $q_n = F^n q + F^{n-1} q + F^{n-3} q + \ldots\ldots\ldots\ldots F^3 q + F^2 q + Fq + q$

$$q_n = q(1 + F + F^2 + F^3 + \ldots\ldots\ldots\ldots F^n)$$

$$q_n = \frac{1 - F^n}{1 - F}$$

$$q_\infty = \frac{1}{1 - F} \tag{6.6}$$

The methane makeup increases in each successive recirculation cycle, but increments become smaller and smaller, eventually becoming insignificant in the fifth cycle. For an example, when the value of F = 0.20, q_n goes to 1.25q, where q_n is the total methane increase in return air during mining operations. However, methane can also be diluted to its normal limits without recirculation by mixing with the total available air at the face. Thus, when recirculation is allowed, the concentration of methane in the return air can be calculated using the following relationship, where the variables are defined as in Equation 6.7,

$$X_d = \frac{1.25q}{Q_i + Q_m} \tag{6.7}$$

The concentration of methane in the face air varies slightly when recirculation takes place in a crosscut further out-bye than the first crosscut from the face. This is because the methane in the recirculation air will leak from the intake to the return through the various crosscuts existing between the recirculation crosscut and the face. When recirculation takes place far away from face, less methane reaches the face, making safer the recirculation that takes place through the immediate crosscut. The actual make of the methane at the face can be calculated by Equation 6.8:

$$q_n = \frac{q}{1 - F'} \tag{6.8}$$

Where F’ is the effective recirculation fraction. It can be defined as follows:

$$F' = \frac{\text{Re}\,circulated}{Total\,(Fresh + \text{Re}\,circulated\,)}\,Air \tag{6.9}$$

This F’ is used to calculate the makeup of methane at the face in the case of recirculation, which takes place at some distance outby from the face. F’ is less than that of F depending upon the leakages though the various crosscuts between the recirculation crosscut and the face. As leakage quantity increases, leakage of methane also increases, and less methane reaches the face. This fact can be verified using the sample network, shown in Figures 6.5 and 6.6. The network consists of 16 nodes and 16 branches with multiple crosscuts between intake and return airway. It has one working face with a flow requirement of 45 m^3/s. The emission of methane from the face is assumed to be constant (1 m^3/s). The main fan is located at branch 15-16. The two scenarios are discussed to demonstrate the two facts: one, that for recirculation near the working face through the branch 10-7 and second, that for recirculation away from the face through the branch 13-4.

6.7.1 Case 1: Recirculation Near the Face

When a booster fan is placed in branch 10-7 and rated with pressure of 0.725 kPa in addition to the main fan rated with a pressure of 0.755 kPa, recirculation occurs through the immediate crosscut near the working face. Figure 6.5 shows the schematic flow distribution in a network. Table 6.1 shows fan duties for a sample network (Case 1). After a careful analysis, recirculation fraction (F) can be calculated using a recirculation

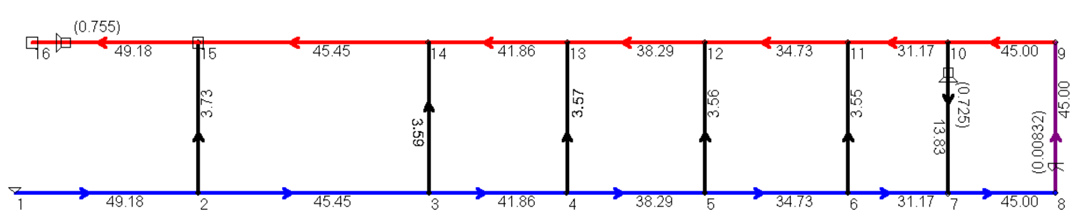


FIGURE 6.5 Sample network—Case 1

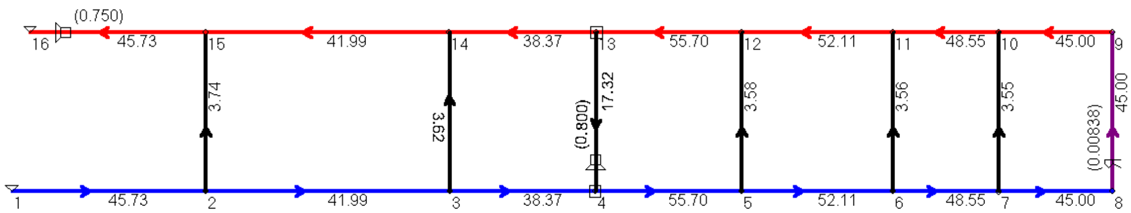


FIGURE 6.6 Sample network—Case 2

TABLE 6.1 Fan duties for a sample network—Case 1

Two Fan System	P, kPa	Q, m^3/s	AP, kW	Total AP, kW
Main Fan	0.755	49.18	37.13	47.16
Booster Fan	0.725	13.83	10.03	

amount of 13.38 m^3/s and total face quantity of 45.00 m^3/s. The value of F was found to be 0.31, approximately. The recirculation amount of methane can also be calculated using a recirculation fraction. It was found to be 0.31 m^3/s. This is the amount of methane mixed with fresh air. Since leakages do not occur through crosscuts between mixing point and face, therefore, the recirculation part of methane is the same as reaching at face. In such cases, the value of F and F' would be the same.

<u>6.7.2 Case 2: Recirculation Far from the Face</u>

When a booster fan is placed in branch 13-4 and rated with a pressure of 0.800 kPa, in addition to the main fan rated with pressure of 0.750 kPa, recirculation occurs far from the working face. Figure 6.6 shows the schematic flow distribution in a network. Table 6.2 shows the fan duties for a sample network (Case 2).

TABLE 6.2 Fan duties for a sample network—Case 2

Two Fan System	P, kPa	Q, m^3/s	A. P., kW	Total A. P., kW
Main Fan	0.750	45.73	34.30	48.16
Booster Fan	0.800	17.32	13.86	

After a careful analysis, recirculation fraction (F) can be calculated using the recirculation amount of 17.32 m^3/s and total face quantity of 45.00 m^3/s. The value of F was found to be 0.38, approximately. The effective recirculation fraction (F') can be calculated using the recirculation amount of 17.32 m^3/s and total mixed quantity of air (fresh air + recirculation air) of 55.70 m^3/s. The value of F' was found to be 0.31, approximately. The recirculation amount of methane can be also calculated using effective recirculation fraction (F'). It was found to be 0.31 m^3/s. This is the recirculation amount of methane. Leakages occur through all the crosscuts between recirculation crosscut and face. A part of methane (0.059 m^3/s) proportional to total leakage quantities leaks through the crosscuts between the recirculation crosscut and the working face. The remaining part of the methane (0.25 m^3/s) reaches to the working face.

Considering the recirculation, a booster fan should be placed in crosscut away from the working face. This effective recirculation fraction (F') is less than the value of the recirculation fraction (F) as defined in the textbook (McPherson 1993). The difference in value is dependent on the leakage quantity through the crosscuts before reaching the working face. This fact is applicable wherever recirculation exists far from the working face.

CHAPTER 7

HAZARD IDENTIFICATION AND RISK ANALYSIS

Often, the booster fan is installed in a return airway, isolated from the intake airways by a set of stoppings and airlock doors. The obvious reason for this location is to avoid obstruction to safe travel in the intakes and to dissipate heat from the fan in return air. A booster fan requires a monitoring system with control interlocks to function safely and effectively in a ventilation network.

Adequate selection, installation, commission, maintenance, and operation of a booster fan will decrease main fan pressure, leakage, and power consumption. However, an inadequate installation can increase the likelihood of the buildup of air contaminants due to flow recirculation, leading to fires from the buildup of heat or sparks. In most coal mining countries, identification of hazards and risk analysis are a part of the planning process undertaken before installation and operation of a booster fan. In the United States, the regulations of the Mine Safety and Health Administration (MSHA) require mine operators to apply general hazard awareness and control in all operations, but do not require a comprehensive risk management program. This chapter deals with identifying the hazards associated with each stage of booster fan utilization and with applying risk analysis tools like Work Place Risk Assessment and Control (WRAC), Failure Modes and Effects Analysis (FMEA), and Fault Tree Analysis (FTA) to mitigate the associated risks to acceptable levels. This chapter also includes the guidelines for the safe uses of booster fans in a mine ventilation network.

7.1 Booster Fan System

A part of a typical ventilation network for a coal mine is used to demonstrate both the location of various ventilation control devices and the issues of risk associated with the booster fan systems. Figure 7.1 shows a typical arrangement of a booster fan system. Efficient utilization of a booster fan depends upon the comprehensive understanding and implementation of the following planning and operation parameters.

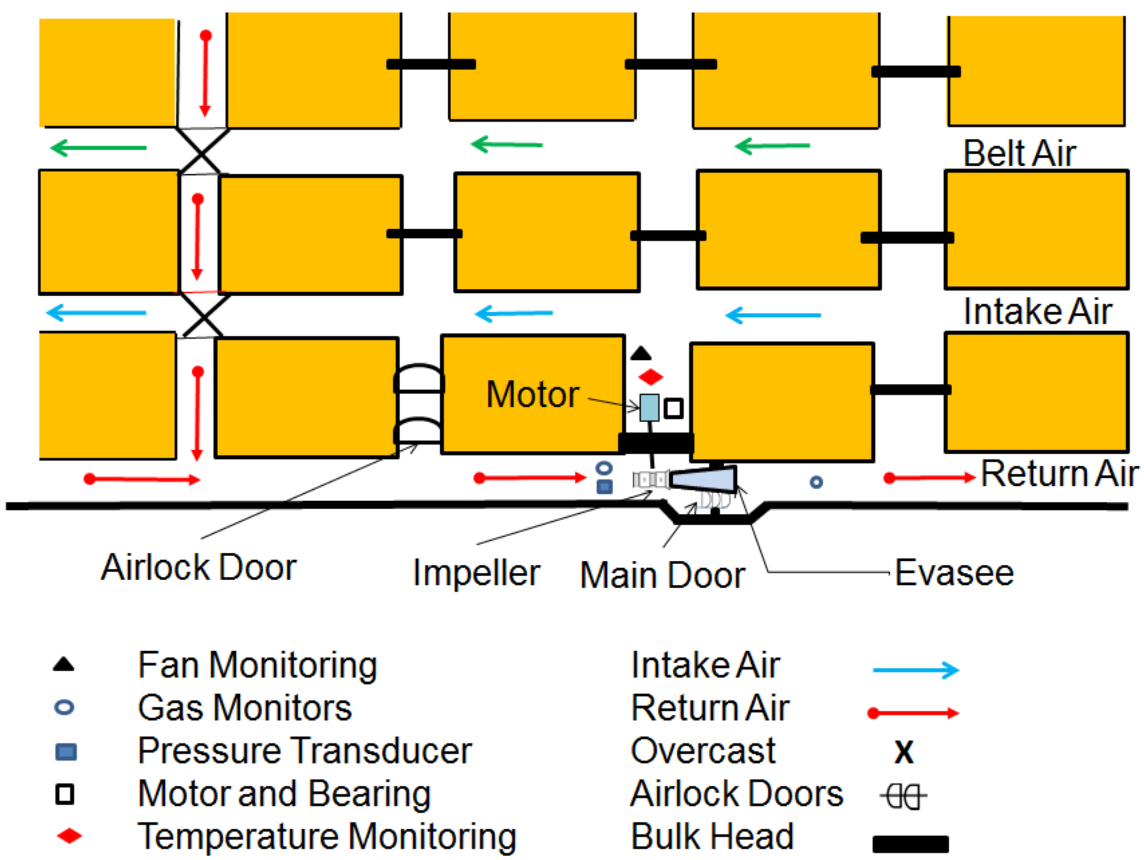


FIGURE 7.1 Typical arrangement of a booster fan system

7.1.1 Fan Selection

Once the fan duties are specified, the next step is to determine the type, size, and number of fans for the system. The main objective is to select a fan or set of fans that meets the flow requirements. The booster fans may be of either centrifugal or axial type, depending on the air pressure that develops and the size of the airways. The main reason for selecting a centrifugal fan is to have the fan motor and starter in an intake airway and the fan housing in a return airway, thus minimizing risks from the heat and sparks that may occur. The alternative is to have an axial fan equipped with a flameproof enclosure installed in a return airway.

7.1.2 Installation, Testing, and Commissioning

Site preparation and fan installation are two main tasks that precede the operation of a booster fan. Site preparation often involves the widening of an existing drift or developing a bypass drift to house the fan and the airlock doors. To reduce leakage and flow recirculation, the fan must be installed in a concrete bulkhead and equipped with an effective airlock system and an environmental monitoring system. Installation requires the construction of foundations for the fan housing, motor, and airlock doors, and the construction of a bulkhead. In addition, to minimize the risk of fire, a fan and environmental monitoring system must be installed.

A further task during fan installation is testing and commissioning. Normally, a booster fan is tested for its stability and performance. This is accomplished by running the fan first under no-load conditions, with the airlock doors kept wide open, then under half load with the doors are partially open, and finally under full load with the doors are fully closed. The fan's operating parameters, including vibration and motor and bearing temperatures, are measured during each test. The results are then evaluated against pre-established standards given by the fan manufacturing company and legislative bodies. Table 7.1 shows some of the common threshold limit values used in the industry. The booster fan is commissioned only when the measure parameters are consistently at or below these limits.

7.1.3 Fan Operation

Main and booster fans must be operated whenever workers are present in an underground mine. The monitoring system measures all the relevant parameters, including the concentrations of air contaminants. The booster fan is equipped with an interlock system. Two of the main function of which are to cut off power to the fan in the event of main fan failure, and to de-energize inby equipment and open airlock doors if the booster fan fails for any reason. The former condition also requires the de-energizing of all underground equipment; the latter is intended to prevent the buildup of air contaminants.

TABLE 7.1 Standards of fan parameters (Calizaya 2014)

Fan Parameters	Allowable Limits
Vibration	5.5 mm/s
Motor Temperature	85º C
Shaft Alignment	0.05 mm
Fan Duty	± 5% of designed value
Bearing Temperature	85º C

When the main fan fails, the whole system must be shut down and an alarm must be generated either automatically or by a management procedure. Workers must be trained to understand that in the instance of such an alarm, the mine's emergency evacuation procedure is initiated. An established fan start-stop protocol must be followed in restoring power after any power stoppage, including those scheduled for changing the fan duties.

7.1.4 Maintenance

Adequate maintenance of the fans, monitoring system, and interlocks are equally important in making the ventilation systems safe and effective.

7.2 Hazard Identification

7.2.1 Planning and Design

The location, size, and type of the fan are determined during the planning and design stage of the ventilation system. The associated hazards are identified to ensure that the system components and controls are all in place. Some of the critical hazards are identified and presented below.

1. **Oversizing the Booster Fan.** Oversizing the booster fan in comparison with the main fan may lead to uncontrolled recirculation, which in turn can lead to the buildup of air contaminants at the working face. Determining the best combination of main and booster fan pressures using ventilation simulators may reduce these hazards.

2. **Inadequate Maintenance of the Monitoring System.** Although mine

monitoring systems are assembled and installed to operate under harsh conditions, they are subject to wear and tear and malfunction. The system components should be maintained regularly, and the sensors must be calibrated against primary standards. Furthermore, the system must be equipped with redundant units. If the system provides erroneous readings, fan conditions cannot be predicted and the failures modes cannot be avoided.

3. **Poor Design of the Airlock Doors and Bulkheads.** The airlock doors and bulkheads are provided to direct the air to where it is needed and to minimize short circuits and flow recirculation. The doors must be designed and installed to operate at high pressures. Poor installation and maintenance will lead to leakage and flow recirculation, thus reducing the efficiency of the ventilation system. Furthermore, poorly maintained doors can lead to struck by and caught between type accidents.

4. **Poor Design of the Fan Foundation.** A booster fan requires a strong foundation. Misalignment and excessive vibration can lead to a number of unwanted events. The foundation design for the fan motor and casing must be site-specific and include provisions to facilitate fan repair and maintenance.

7.2.2 Installation and Commissioning

Inadequate installation and commissioning of the fan may also lead to hazardous situations. Some of the hazards during this stage are identified and presented below.

1. **Misalignment of Shafts**. During fan installation, it is essential to have the fan and motor shafts aligned properly. Misalignment can result in excessive vibration, shaft fatigue, and irregular bearing wear, leading to excessive friction. This can act as a source of ignition and trigger a mine fire. Alignment tests must be conducted periodically and after any major repair.

2. **Fan Performance Tests.** During testing, the fan is usually operated under three different conditions: no load, half load, and full load. For a no load condition, the airlock doors are kept open, then partially closed for a half load, and totally closed for full load. Fan parameters (such as motor temperature and vibration) are measured for each condition. These are compared against a set of standard values, as shown in Table 7.1. The fan is commissioned only when all the fan specifications are met.

7.2.3 Operation

Hazards may also exist during the operation stage. Some of these are identified and listed below:

1. **Power Failure to the Mine Site:** A power failure to mine site will result in the buildup of air contaminants and a reduction in the total quantity of air delivered. Controls should be in place to de-energize the mining equipment and to reduce the gas emissions in the mine when mine power fails.

2. **Failure of the Main Fan:** The main fan can fail due to mechanical or

electrical problems. If the booster fan is left running, uncontrolled recirculation and a buildup of contaminants can create unsafe conditions. To mitigate this hazard, the booster fan and all underground equipment must be de-energized immediately upon main fan failure. For most major equipment, including the booster fan, this is accomplished by an electrical interlock system.

3. **Failure of the Booster Fan:** As soon as the booster fan failure is detected, the airlock doors must be opened and the quality of air at the workings re-evaluated. Although a booster fan stoppage reduces the quantity of air directed to a section, the opening of the doors will allow part of the air circulated by the main fan to reach the workings. If this quantity is not sufficient to dilute the contaminants, the work load in the section should be reduced.

4. **Failure of the Interlocking Mechanism:** If for any reason, the main fan stops, the booster fan must also stop. The malfunctioning of the interlock that controls this action may lead to airflow recirculation and the buildup of air contaminants.

5. **Failure of the Monitoring System**: Gas sensors, pressure transducers, and other devices used with a monitoring system are subject to wear and malfunction. Workplace assessment using faulty units can result in unsafe and unhealthy conditions. To avoid this problem, transducers should be calibrated frequently. Redundant units and uninterruptable power supplies should be provided for critical monitors.

6. **Failure of the Fan Motor or Bearings**: The fan motor or bearings may fail under loads greater than their respective rated capacities. Motor and bearing temperatures are key indicators of the fan health. When the fan is installed properly, with the right alignment, these temperatures should never exceed the alarm level, which is typically 85ºC. However, these temperatures may vary with weather conditions.

7. **Spontaneous Combustion and Fire**: Although the likelihood of spontaneous combustion near the fan installation is low, it can occur in low rank coal mines, when the coal comes in contact with oxygen through the cracks around the periphery of the fan bulkhead. This may lead to a fire in the fan housing. To control the problem, the fan drift should be covered with inert material. An alternative is to install the fan in a drift drive in the overlaying strata.

7.3 Risk Assessment

Risk assessment is the process by which the outcomes of risk analysis are compared against the risk acceptance criteria established to this purpose and understood by all parties. Identification of potential hazards and evaluation of risks associated with the utilization of booster fans in coal mines are two major steps of risk assessment for the use of booster fans. If requirements are not met, changes to the system should be made and the process repeated. Figure 7.2 shows a flow chart of the risk assessment process used in this study. The process starts with the inventory of hazards and a list of unwanted event. Then, these are compared against the risk acceptance criteria. A risk matrix is used

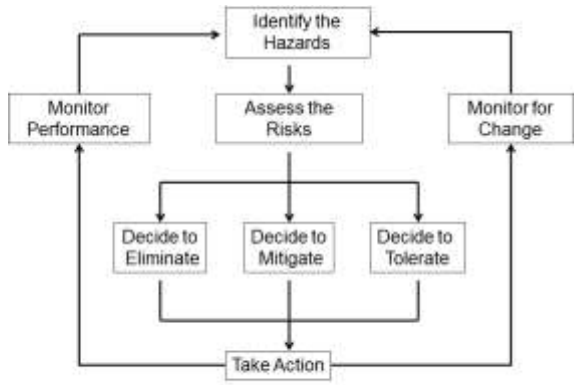


FIGURE 7.2 Process of risk assessment

to determine the critical hazards.

7.3.1 Risk Assessment Team

Before any analysis, a team must be formed. The members must be familiar with the hazards to be investigated. They must also be capable of identifying the vulnerabilities of the process or facility being evaluated, analyzing the results, and developing action plans to mitigate the consequences of failures. A team of experts formed specially to conduct the risk assessment is described here.

7.3.2 Risk Matrices

The risk matrix is an evaluation tool used to rank the risk of potential hazards in terms of the likelihood (L) and consequence (C) of the undesired event. It increases the visibility of the risk and assists the management in making timely, informed decisions (Chapanis 1986; Grayson 2001; Joy 2009). Table 7.2 shows the risk matrix used in this study.

TABLE 7.2 Risk matrices

Severity / Likelihood	1 Insignificant	2 Minor	3 Moderate	4 Major	5 Catastrophic
	Risk Rating				
5 Most certain	5	10	15	20	25
4 Likely	4	8	12	16	20
3 Possible	3	6	9	12	15
2 Unlikely	2	4	6	8	10
1 Rare	1	2	3	4	5

Risk Rating	Legends	Guidelines for risk matrix
13 to 25	(Ex): Extreme	Implement action plan
9 to 12	(H): High	Proactive manage
4 to 8	(M): Medium	Actively manage
1 to 3	(L): Low	Monitor & manage

Categories of harm severity
Catastrophic – Multiple deaths
Critical – One death or multiple severe injuries
Moderate – One to three severe injuries
Minor – One severe injury or multiple minor injuries
Insignificant – One minor injury

Categories of harm likelihood
Most Certain – Event occurs once or twice in a year
Likely – Event occurs less than once in a year
Possible – Event occurs or may reoccur in 10 years
Unlikely – Event could happen in 20 years
Rare – Event has never happened

7.4 Workplace Risk Assessment and Control

Workplace Risk Assessment and Control (WRAC) is a qualitative risk ranking method. It breaks down the work into steps in a process map and evaluates each unwanted event using a risk matrix (Joy 2009). In the booster fan case, the analysis is performed during three stages: planning and design, installation and commissioning, and operation. Risk ranks are determined and postevaluation control measures established.

A WRAC was performed for the installation and use of booster fans. The risk assessment team included a mechanic, an electrician, a ventilation engineer, and a manager. Table 7.3 shows the WRAC for the design, installation, and operation of the fans.

7.4.1 Interpretation of WRAC Outcomes

The inventories of hazards and unwanted events were identified for each of the stages described above. Major hazards and related unwanted events were addressed, existing controls evaluated, and risk rankings established. These were used to determine critical hazards. Based on this study, fire and flow recirculation were identified as the major hazards that require special attention. These were followed by the hazards from the failure of the electrical interlock mechanism. Finally, mitigation controls were established for each critical hazard.

The recommended measures, if implemented correctly, can reduce the risk to a tolerable level. WRAC includes a list of all the potential hazards with their existing controls, risk ranks, and recommended control measures. This table also shows the outcomes of the analysis using the WRAC method. The L and C values for each of the

TABLE 7.3 WRAC analysis and outcomes

Steps in process	Unwanted event	Current controls	L	C	R	Recommendation
During design stage						
Oversizing and poor location of booster fan	Recirculation and fire	Use vent simulator to size and site fans	2	4	8	Check for recirculation before implementing the design
Failure to design monitoring system	Undetected fire and recirculation	Use handheld units to monitor CO	3	4	12	Follow the good practices as adopted in other countries
Failure to design airlock doors and bulkheads	Airlock doors fails to open, or close	Test airlock doors for stability	2	4	8	Follow the good practice as adopted in other countries
During installation and commissioning stage						
Fan guarding and testing	caught between moving parts	Fencing around the fan	1	5	5	Install safety screen and good illumination
Misalignment of motor and fan shafts	Excessive vibration can damage fan	Follow vendor's guidelines	3	3	9	Check alignment manually
Failure to measure vibration and temperature	Damage to motor and fan parts	Fan monitoring system	2	4	8	Check manually for redundant sensors.
Failure to follow SOP	Fan breaks down frequently	Training	2	4	8	Refresher training
During operation stage						
Mechanical or electrical fault	Failure of electrical interlocks	Fans installed in same circuit	1	5	5	Independent power sources for main and booster fans
	Failure of monitoring system	Check air quality manually	2	4	8	Install redundant monitoring
	Failure of motor or bearings	Regular maintenance	2	4	8	Keep spare motor and fan parts in hot room
Chemical	Fire and self-heating of coal	Eliminate ignition sources	3	5	15	Shotcrete fan drift and equip fan with firefighting units
	Buildup of air contaminants	Avoid flow recirculation	3	5	15	Provide fan with a good monitoring system
	Dust and smoke buildup on blades	Use water spraying during cutting	1	5	5	Frequent maintenance
	Recirculation	Constant monitoring	2	5	10	Evaluate CO and cut power to downside equipment

*L - Likely to occur, *C - Consequences, *R - Risk rate hazards were assessed by the risk assessment team, and risk rate (R) was calculated as the product of L and C.

7.5 Failure Mode Effects and Criticality Analysis

Failure Mode Effects and Criticality Analysis (FMECA) is used for evaluating the effects of potential failure modes of subsystems, assembly components, or functions (Ericson 2005). It is a bottom-up evaluation technique that evaluates the effects of failure modes on the system and other items using the current and recommended control measures. Severity and probability evaluations of failure modes provide the user a prioritized list of corrective actions. While FMECA is usually used to identify single component failure modes, hazards can be the result of multiple failure modes. For this reason, this tool should only be used in conjunction with other tools, such as Job Safety Analysis (JSA) and Safe Operating Procedures (SOPs). FMECA is used exclusively during the operation stage. During the operation of a booster fan, three groups of failure modes were distinguished: electrical, mechanical, and physical. The effects of each mode on the system were evaluated, the risks ranked, and postevaluation control measures recommended. Table 7.4 shows the results of the risk analysis of hazards associated with the operation of booster fans using FMECA.

7.5.1 Interpretations of FMECA Outcomes

Table 7.4 shows three critical hazards associated with the operation of booster fans: power failure to the mine site, failure of the monitoring system, and failure to detect flow recirculation. It also shows that the booster fan system, when equipped with reliable

TABLE 7.4 FMECA analysis and outcomes

Failure mode	Effects		L	C	R	Control
	Other item	System				
Electrical						
1. Failure to detect fan condition or air contaminants	Undetected buildup of fire products, Change in vibration and temperature	Undetected spontaneous heating and fire Overheating of motor	3	5	15	Equip monitoring system with redundant and calibrated sensors
2. Power failure to mine site	Main and booster fans stoppage	Whole ventilation system is down	3	5	15	Provide system components with uninterruptable power supply (UPS)
Mechanical						
1. Failure of main fan	Mining equipment is down	Mine air quality deterioration	2	5	10	Stop booster fan and downside equipment, open airlock doors and evacuate mine personnel
2. Failure of booster fan	Booster fan is down	Section air quality deteriorated	2	4	8	Stop downside equipment
3. Failure of airlock doors to open while booster fan is down	Flow through ventilation not restored	Potential for gas buildup	2	4	8	Inspect door conditions regularly
4. Failure to monitor recirculation	Buildup of contaminants	Fire or explosion	3	5	15	Monitor flow quantity and flow direction
5. Failure of couplings	Booster fan is down	Air quality deteriorated	1	5	5	Examine bearing temperature and maintain couplings
Physical						
1. Roof and rib failure	Damage the fan	Mine ventilation system disrupted	2	3	6	Reinforce roof and walls and perform convergence tests
2. Failure of fan foundation	Damage the fan motor	Mine vent system disrupted	2	3	6	Regular measurement of vibration and noise
3. Failure of bulkhead and man doors	Decrease of fan efficiency	Increased local recirculation	2	3	6	Monitor pressure drop across the bulkhead

airlock doors and fire sensors, can be operated safely. A power failure to the main fan while the booster fan is still operating may result in buildup of air contaminants. This problem can be overcome by activating the interlocking system. During the analysis described here, two critical failure modes were identified: failure to monitor fire products and power failure to the mine site. The recommended control measures, if implemented, can reduce the associated risks to tolerable levels. This study points out all the potential hazards, risk ranks, and recommended control measures required to reduce or eliminate the hazards associated with the safe operation of a booster fan in an underground coal mine.

7.6 Fault Tree Analysis

Fault tree analysis (FTA) is a safety analysis technique that determines the root causes and probabilities of occurrences of specified undesired events (Ericson 2005). Fault trees are graphical models of fault events with logic gates and are used to model the cause-effect relationships involved in causing the undesired event. FTA is also applicable to the evaluation of large, complex, dynamic systems to identify potential safety problems. FTA provides all the information required by system analysts to model and analyze the unique combinations of fault events that can cause an undesired event to occur. FTA is deductive in that it develops with the logical fault path from a single undesired event at the top to all of the possible root causes at the bottom. The most commonly used application is the proactive FTA, performed during system development to influence design by predicting and preventing future problems. The other application is reactive FTA, performed after an incident or mishap has occurred.

A fault tree analysis can be used for both quantitative and qualitative analysis of risks. Quantitative analysis of risk is generally preferred, but requires more time, experienced personnel, and knowledge of component failure rate data and can be very expensive. In most circumstances, a qualitative evaluation of the fault tree yields effective results at a reduced cost.

7.6.1 Cut Set Analysis

When the development of the fault tree is complete, it can be evaluated to determine the critical cut sets. A cut set is a set of events that together cause a given top, or unwanted event (UE), to occur. A cut set is also referred to as a fault path. Cut sets are one of the key products from FTA. They identify both the component failures and events and the combinations that can cause the various UEs associated with the system being analyzed. Cut sets also provide one mechanism for calculating the probability of the UEs and can reveal the critical and weak links in a system design by identifying critical safety-related components.

Cut sets are generated using the rules of Boolean algebra; many different algorithms exist for their generation. A minimal cut set is one that has been reduced to the minimum number of events that can cause a given UE to occur. A cut set for a given UE cannot be further reduced and still guarantee occurrence of the top UE. Analysis is required to determine the contributing elements and the significance of each.

Of all the identified risks, fire and air recirculation are recognized as high potential hazard factors that must be evaluated to determine their respective impacts on the normal functioning of the mine. This study was restricted to proactive fault tree analysis for the fire and recirculation as a result of a malfunctioning of a booster fan system. FTA was applied separately to fire and recirculation analysis. The FTA for initiation of an underground fire requires analysis of two elements (excluding one element) in the fire triangle. Thus, the FTA for fire included combustible material and ignition sources and excluded supply of oxygen. The FTA of recirculation has incorporated all the associated aspects.

7.6.2 Mine Fire

Mine fire is a safety issue that requires careful attention from the mine operator. Three elements constitute the well-known fire triangle: combustible material, an ignition source, and a supply of oxygen. It is understood that a fire will initiate only when all three are present in appropriate amounts.

7.6.2.1 Combustible material

In addition to coal, combustible material likely to be present in a coal mine includes diesel fuel, methane, lubricant oils, and timber scraps. The management of combustible materials is very important. The presence of coal in the form of airborne dust is very hazardous, and that dust may form a mixture that will explode when ignited. Roof falls and bad housekeeping may lead to the presence of airborne coal dust. Diesel fuel is very volatile and highly inflammable. The improper transportation, storage, and use of diesel may lead to a fire. Both solid and liquid lubricants are also flammable and are widely used in underground mines. Methane is highly flammable and forms an explosive mixture with air in the range of 5–15%. Methane is frequently associated with coal formation and may be liberated with the extraction of coal. The mining method exerts a big influence on the liberation and subsequent concentration of methane. Methane is liberated from the gob, the coal itself, and the roof and floor strata. In some cases, methane may be liberated directly from coal and other strata as soon as those materials are exposed to the air. In other cases, methane is released when the coal fractures and the fissures develop. Timber scraps are also a potential source of combustible material.

7.6.2.2 Ignition sources

There are five primary sources of ignition in an underground coal mine, namely heat from friction or combustion in the mining equipment; spontaneous heating of coal; electric arcs from short-circuiting, loose connections; and sparks generated by the interaction of machinery and rock surfaces.

7.6.2.3 Supply of oxygen

Maintaining the required availability of oxygen is an important function of the ventilation system. Oxygen, as a component of the ventilation air, is required for worker respiration and for the operation of internal combustion engines on some mine equipment. Thus, oxygen cannot be eliminated from the environment of an active part of an underground coal mine. However, it can be eliminated or limited in certain parts of the mine, such as the gob areas. Therefore, the supply of oxygen was not taken into consideration for this FTA.

For the purpose of this analysis, the existence of combustible material (at admittedly varying levels) and ignition sources are taken into consideration. A booster fan provides a new, potential ignition source in addition to those already present in the mine. Each element that contributes to fires was considered in the FTA study presented in Figure 7.3.

7.6.2.4 Cut set analysis for fire

Two types of failures are recognized in a cut set analysis: single and multiple point failure.

1. Single point failure: Single point failure is not found in the analysis for fire. There are no cut sets with only one element (single point failures) in the cut sets. This is good because a single point failure is the most difficult to manage and control.
2. Multiple point failure: Multiple point failures are common in the analysis of fire. Table 7.5 shows multipoint failures.

There are several multiple point failures that, when they occur, will lead to the occurrence of the UE (initiation of a fire). The shortest cut sets are made of events 5, 6, 7, 8, 9, 10, 11, and 12. Management and control of events, thus, require special care to avoid the occurrence of combinations leading to initiation of a fire.

The FTA showed that there are multiple point failures that can lead to a mine fire, including combinations of friable strata, poor support, human error, management error, power failure, mechanical failure, overloading and overrunning of machines, poor methane drainage, and a poor ventilation system. Methane, coal, diesel, and timber scraps are the major sources of combustible material. Heat from equipment, the spontaneous heating of coal, electrical arcs, and sparks from metal/rock interaction are the major ignition sources. The management of all these elements is required to make the mine safe.

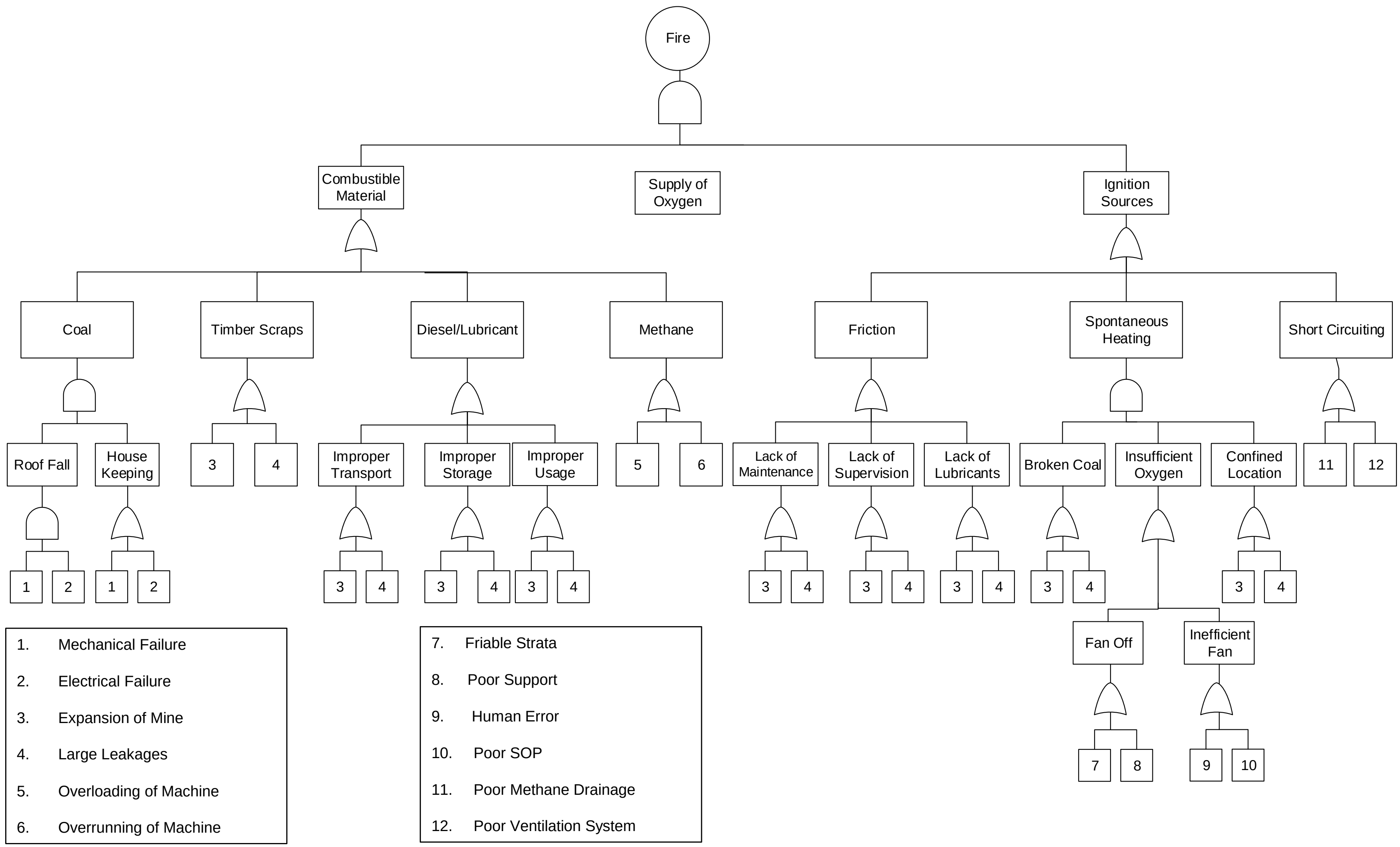


FIGURE 7.3 Fault tree for fire initiation

TABLE 7.5 Cut sets of mine fire

Cut Sets				
1	2	3	7	9
1	2	3	7	10
1	2	3	8	9
1	2	3	8	10
1	2	3	8	11
1	2	3	8	12
1	2	4	7	9
1	2	4	7	10
1	2	4	8	9
1	2	4	8	10
1	2	4	8	11
1	2	4	8	12
5	7	9		
5	7	10		
5	8	9		
5	8	10		
5	8	11		
5	8	12		
6	7	9		
6	7	10		
6	8	9		
6	8	10		
6	8	11		
6	8	12		

7.6.3 Recirculation of Mine Air

Air recirculation is another important issue. It requires constant attention because in a coal mine, the probability of its occurrence is higher when a booster fan is used. Figure 7.4 shows an FTA applied to recirculation of air. Recirculation is defined as partial reuse of air, whether intentionally or unintentionally. The two types of recirculation may be found in a coal mine, controlled and uncontrolled. In controlled recirculation, 5–10% of the air is reused intentionally in a controlled manner so that the concentrations of contaminants (methane, dust, etc.) stay below the limits prescribed by the regulating authority. Hazards are always associated with uncontrolled recirculation, which can lead to buildup of contaminants beyond the prescribed limits and create disastrous conditions in the mine.

The recirculation of mine air may result from any of the following conditions:

1. The main fan is off and booster fan is on.
2. The booster fan is not sized or located properly.
3. Bulk head and stopping are poorly designed or constructed or are constructed with unsuitable materials.

A cut-set analysis was performed on the FTA for recirculation to determine the factors contributing to recirculation. This is explained further for illustration.

7.6.3.1 Cut set analysis of recirculation

As in the previous analysis, single-point failure is considered here. The cut-set analysis for the FTA relating to recirculation resulted in several single-point failures. As noted earlier, a system with single-point failures is potentially very hazardous, so

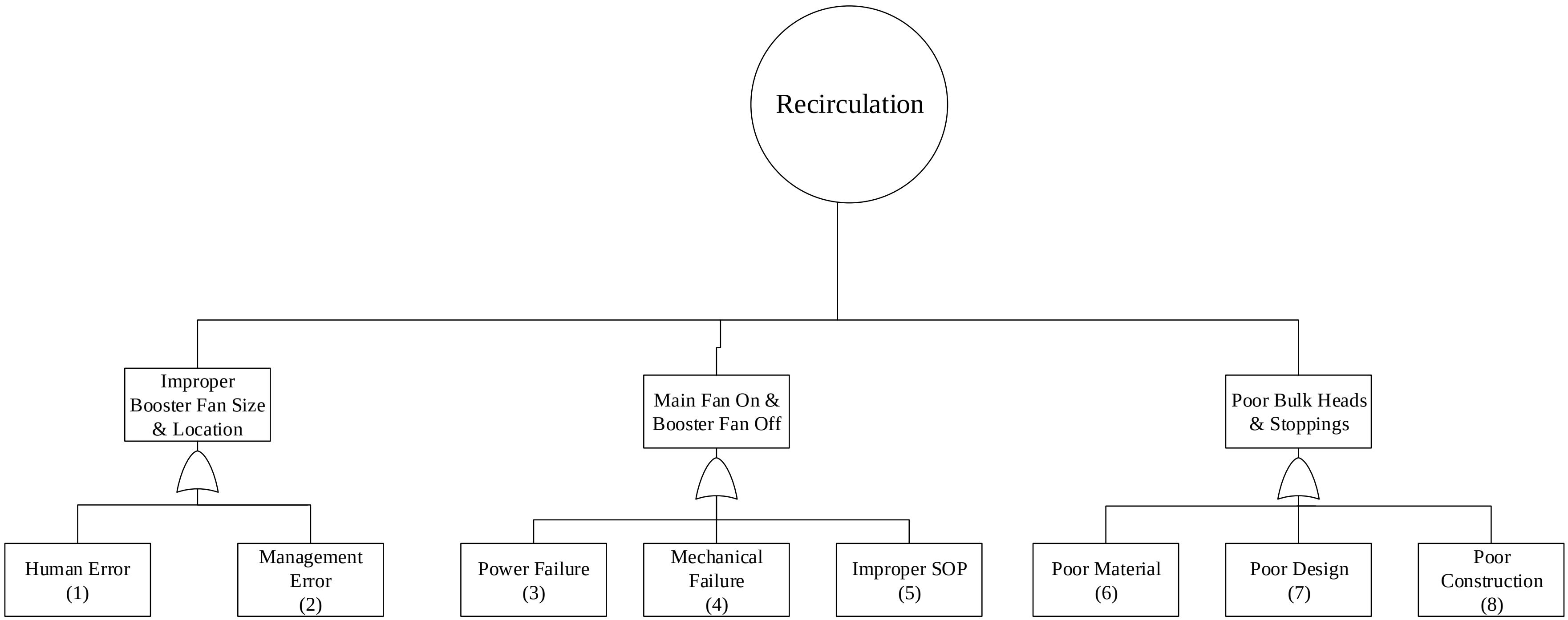


FIGURE 7.4 Fault tree for recirculation of mine air

redundant sensor and safety features are important. Table 7.6 shows the single point failure cut set for air recirculation.

7.6.3.2 Analysis of cut sets for recirculation

In an FTA, all single point failures are equally important and require careful attention. That is the case for each element shown in Table 7.6. Elements 1 and 2 are concerned with human error and management error, respectively.

Elements 3, 4, 5, 6, 7, 8 are related to power failure, mechanical failure, improper Standard Operating Procedure (SOP), and poor material, construction, and design of bulkheads and stoppings, respectively. The FTA analysis showed that eight single-point failures can lead to uncontrolled air recirculation. Systems that show single-point failures should be fitted with redundant controls and interlocks to reduce the probability of a failure.

TABLE 7.6 Cut sets of recirculation of mine air

1	Human Error
2	Management Error
3	Power Failure
4	Mechanical Failure
5	Improper Standard Operating Procedures
6	Poor Material for Bulkheads and Stoppings
7	Poor Design for Bulkheads and Stoppings
8	Poor Construction for Bulkheads and Stoppings

7.7 Fan Protocol

Mine operators must be very familiar with the procedures followed for the safe and efficient utilization of booster fans in mine ventilation. The following are critical situations that may arise while booster fans are utilized.

7.7.1 Stoppage of the Main Fan

In this case, the booster fan and all the inby equipment must be stopped immediately. When the main fan is stopped by a power, if normal ventilation is not restored within 15 minutes, the mine evacuation procedure must be initiated.

7.7.2 Booster Fan Stoppage

In this case, the airlock doors must be opened and the power shut off for all inby equipment. If the booster fan is stopped by an outrage of power, work must be stopped until power is restored, either from the main power line or from a backup generator. If the booster fan fails mechanically, it must be replaced.

7.8 Guidelines for Safe Installation and Operation of Booster Fans

1. Proper sizing and location of a booster fan must be determined using ventilation simulators, to eliminate the recirculation.
2. An adequate monitoring system with proper maintenance must be in place to reduce the failure rate of any components.
3. Proper design of airlock doors and bulkheads must be determined to

eliminate the recirculation.

4. Proper fan foundation design and fan installation are critical, and alignment of shafts is particularly important.
5. The fan housing should be made of inert material to eliminate risks from overheating.
6. Electrical interlocks must be in place to stop the booster fan when the main fan is stopped.
7. Proper fan tests must be performed before the operation of a booster fan.
8. Methane must be controlled by appropriate measures, including methane drainage, a properly designed ventilation system, and an adequate methane monitoring system.
9. Generation of airborne coal dust in combustible quantities should be avoided by correct application of diluting materials, prevention of roof falls, dust control during the cutting of coal, and good housekeeping practices.
10. Human and management error should be eliminated by a modern safety management system that includes training, reporting, monitoring, rewards, and other proven components.
11. Spontaneous heating of coal must be minimized or eliminated by proper ventilation to prevent buildup of the heat.
12. Electrical arcing, equipment heating, and spark generation when cutting coal or rock must be controlled by careful inspection, maintenance, and supervision of equipment and correct equipment operation.

13. Electrical backup power for the fans should be considered for use in the case of power failure.

14. A skilled and experienced design team should size and locate the booster fan to prevent recirculation.

15. Bulkheads and stoppings should be correctly designed and constructed using appropriate materials. Proper maintenance of ventilation control devices is equally important.

16. Mechanical failure should be reduced by adopting standard operating procedures and maintenance schedules.

17. Overloading of equipment must be avoided by proper supervision and maintenance.

The risk assessment tools used here are proven to be effective for analyzing and ranking the risks in any other application when applied correctly. The fan operation protocol presented will control the identified risks and keep the mine safe when unplanned fan stoppages occur. The guidelines developed will mitigate the risks associated with the use of booster fans.

CHAPTER 8

DISCUSSION

The application of GAs in sample ventilation networks and in a coal mine ventilation network has been demonstrated successfully in Chapters 4 and 5, respectively. Other aspects of GAs application in mine ventilation still need to be investigated. This chapter includes additional aspects of GAs application, namely, the selection of the most economical alternative from a number of competing alternatives, application of multiple booster fans, and a push-pull system in a sample network. The chapter also includes the computation of the optimal booster fan pressure in addition to three surface fans in a coal mine ventilation network.

With reference to a sample network (Figure 4.3) as discussed in Chapter 4, GVENT was used to determine the optimal solution for a two-fan system (one main and one booster fan), when a booster fan was located in branch 12-7 in addition to a main fan located at branch 3-33. Based on this solution, one cannot claim that the chosen location was optimal until other locations for the booster fan were tested in terms of power requirement. In this chapter, the other possible booster fan locations will be tested to determine the best location for the fan. This chapter will also include the application of GVENT for two and three booster fans with their alternative locations. In addition, this study will include the optimal fan selection for a push-pull system. All the above studies will be done in the sample network as used in Chapter 4 with little modifications. Such modification will be explained accordingly in the corresponding section.

With reference to coal mine ventilation network as discussed in Chapter 5, GVENT was used to determine an optimal solution for three multiple surface fans combined with two booster fans. Based on this solution, one cannot claim that this was an optimal solution until the combination of three multiple surface fans with one booster fan was tested for other possible locations and an optimal solution for the system found.

8.1 Sample Network

Figure 8.1 shows the same network as used in Chapter 4 except for the booster fan locations. The network has six working areas with the same flow requirements. It has two intakes and one return airway. The same network was used to explore the potential aspects of other locations, number of booster fans, and a push pull system.

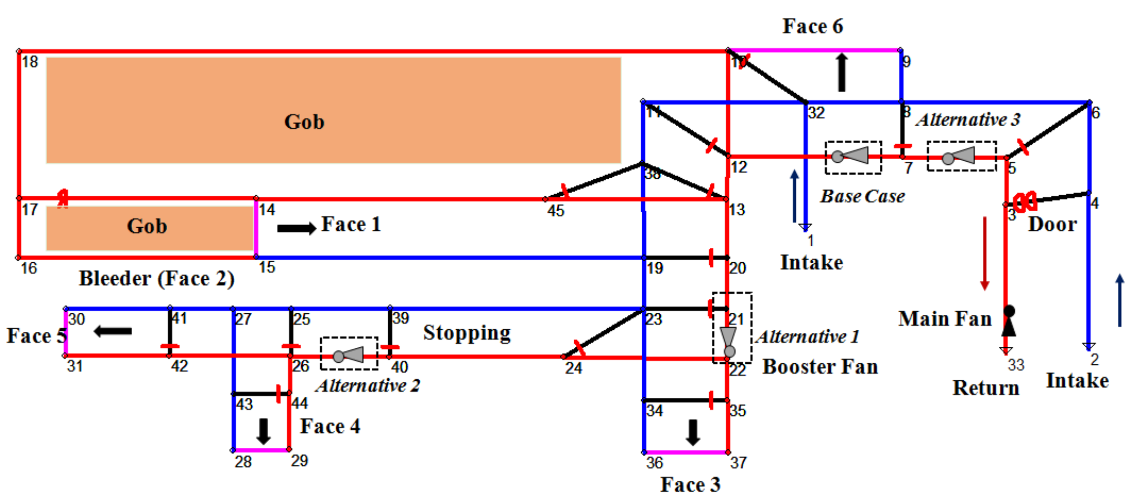


FIGURE 8.1 Sample network (one main and one booster fans)

8.1.1 Locations of One Booster Fan (B.F.)

The optimal solution for a booster fan location at branch 12-7 was determined in Chapter 4. In this study, three alternative booster fan locations were considered:

1. Alternative 1: BF located in branch 22-21 and used to assist Face 3, Face 4 and Face 5.
2. Alternative 2: BF located in branch 26-40 and used to assist Face 4 and Face 5.
3. Alternative 3: BF located in branch 7-5 and used to assist all the working areas.

These alternative fan locations were chosen based on the geometry of the model and the specific need of each section or working area.

The GVENT approach was used to determine the fan pressure and airpower for the three alternative locations. Table 8.1 shows details of solutions for each booster fan location including base case (branch 12-7). A quick evaluation of the results shown in Table 8.1 shows that the optimal solution was found when the booster fan was located in branch 26-40 (alternative 2) with an airpower of 1515 kW. Appendix E shows a screenshot of the optimal solution.

A comparison of the current solution (booster fan at branch 26-40) and the previous solution (booster fan at branch 12-7) shows a large difference in airpower between these two alternatives (2046 vs 1515 kW). Therefore, installing the booster fan in branch 26-40 rather than locating in branch 12-7 can result in net savings of 531 kW in airpower.

For the new optimal location of a booster fan, the main fan pressure increased

TABLE 8.1 Optimal solutions for each set of B.F. location—Sample network

Locations	Fan Duty	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Leakage, m^3/s
A. Base Case						
3-33	Main Fan	2.65595	400.65	1064.13	**2045.90**	**213**
12-7	Booster Fan	2.62778	373.58	981.77		
B. Alternative 1						
3-33	Main Fan	4.43741	408.52	1812.60	1999.72	221
22-21	Booster Fan	1.04071	179.75	187.12		
C. Alternative 2						
3-33	Main Fan	3.86123	376.95	1455.40	**1514.99**	**189**
26-40	Booster Fan	0.684078	87.12	59.59		
D. Alternative 3						
3-33	Main Fan	1.90147	407.03	773.76	2196.72	219
7-5	Booster Fan	3.58809	396.59	1422.96		

from 2.65 kPa to 3.86 kPa, the booster fan pressure decreased from 2.60 kPa to 0.68 kPa, and the total leakage decreased from 213 to 189 m^3/s. However, from a safety point of view, the location of a booster fan in branch 12-7 is more practical and fail-safe than locating in branch 26-40. When the booster fan is stopped, the main fan can still ventilate all of the workings, although with less quantity in some working areas. Locating the booster fan in branch 26-40 can only assist two of the three working sections of the mine. If the booster fan stops, the quantity of air in two sections would decrease drastically, thus inducing uncontrolled recirculation and allowing the buildup of air contaminants in these sections.

8.1.2 Application of Two and Three Booster Fans

Further studies have been done to explore the possibility of using two and three booster fans in the same sample network (Cases 1 and 2). Two and three booster fans are also tested for alternative locations to determine an optimal solution for the two cases so that the best locations can be determined.

8.1.2.1 Case 1: Two booster fans

GVENT approach was used to determine an optimal solution when two booster fans were placed at four alternative locations. Table 8.2 shows an optimal solution for each set of alternative locations. A quick evaluation of all alternatives shows that an optimal solution was found when two booster fans were placed in branches 26-40 and 13-12 (alternative 3) with an airpower of 1265 kW.

An evaluation of the solutions shown for the two cases, one main and one booster fan (Table 8.1) and one main and two booster (Table 8.2), shows that the network with two booster fans (alternative 3) yields a lower air power requirement than the network with one booster fan (alternative 2) (1265 kW vs. 1515 kW), resulting in a net saving of 250 kW of airpower. The leakage is reduced from 189 to 167 m^3/s. The main fan pressure is also decreased from 3.86 to 3.23 kPa.

8.1.2.2 Case 2: Three booster fans

GVENT approach was used to determine an optimal solution for the network problem, when three booster fans were located at four alternative locations. Table 8.3 shows an optimal solution for each set of BF locations.

TABLE 8.2 Optimal solutions for each set of B.F. location—Sample network

Locations	Fan	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Leakages, m^3/s
A. Alternative 1						
3-33	Main Fan	2.01724	347.63	701.17	1288.61	160
26-40	Booster Fan	0.873834	90.49	79.09		
12-7	Booster Fan	1.57361	324.68	512.02		
B. Alternative 2						
3-33	Main Fan	1.85571	357.88	664.23	1378.11	170
26-40	Booster Fan	0.859088	90.24	77.52		
7-5	Booster Fan	1.87564	339.21	636.36		
C. Alternative 3						
3-33	Main Fan	3.22632	354.58	1143.88	**1265.08**	**167**
26-40	Booster Fan	0.804319	87.79	70.58		
13-12	Booster Fan	0.202684	249.38	50.62		
D. Alternative 4						
3-33	Main Fan	3.49812	362.52	1268.09	1364.53	175
26-40	Booster Fan	0.825599	87.94	72.64		
45-13	Booster Fan	0.38534	61.83	23.80		

TABLE 8.3 Optimal solutions for each set of B.F. location—Sample network

Locations	Fan	P, kPa	Q, m^3/s	A.P., kW	A. P., kW	Leakages, m^3/s
A. Alternative 1						
3-33	Main Fan	1.30917	332.16	434.80	**1149.67**	**144**
26-40	Booster Fan	0.78470	86.86	68.19		
45-13	Booster Fan	0.4544	62.06	28.18		
7-5	Booster Fan	1.92115	321.97	618.50		
B. Alternative 2						
3-33	Main Fan	1.83997	334.16	614.85	1165.17	146
26-40	Booster Fan	0.799558	87.72	70.18		
45-13	Booster Fan	0.476036	62.50	29.75		
12-7	Booster Fan	1.44007	312.77	450.39		
C. Alternative 3						
3-33	Main Fan	2.2385	369.23	826.71	1496.01	181
26-40	Booster Fan	0.834536	91.52	76.42		
21-20	Booster Fan	0.130246	176.33	22.92		
7-5	Booster Fan	1.64824	345.85	569.96		
D. Alternative 4						
3-33	Main Fan	2.09265	355.38	743.81	1383.34	167
26-40	Booster Fan	0.760035	89.84	68.28		
45-13	Booster Fan	0	174.03	0		
12-7	Booster Fan	1.72515	331.16	571.25		

A quick evaluation of Table 8.3 shows the optimal solution was found when three booster fans were located in branches 26-40, 45-13 and 7-5, respectively (Alternative 1). A comparison of the results shown in Tables 8.3 and 8.2 (3 booster fan and 2 booster fan cases) shows that the three booster fan case yields lower total airpower than the two booster fans (1150 kW vs. 1265 kW), resulting in a net saving of 115 kW. Furthermore, when three booster fans are used, the main fan pressure is reduced from 3.23 to 1.31 kPa, and the leakage quantity from 167 to 144 m^3/s. These results show the advantages of using three booster fans instead of two to solve the problem.

8.1.3 Push-Pull System

The push-pull system of ventilation is another way of ventilating mines in which the fans are positioned at the intake and return end of the system. Referring to the sample network (Figure 8.1), each intake airway was equipped with a blower fan and the return airway with an exhaust fan. In practice, the blower fan is often installed in a bypass drift to allow the access of mining machinery and personnel through the intake drift. However, to avoid recirculation, the intake drift is equipped with heavy duty airlock doors, but in this study, it was assumed that airlock doors were airtight and there was neither leakage nor recirculation.

The GVENT program was used to solve the network problem and to determine the optimal combination of fan pressures for the push pull system. Figure 8.2 shows a screenshot of the output generated by the program. For the three fans, the optimal combination of fan pressures is given by 3.20 kPa for the main fan 1, and 2.67 and 3.04 kPa for main fan 2 and main fan 3, respectively. The total quantity of air delivered by the

```
Main fan pressure (branch 3-33) is: 2.66587
Main fan flow rate is : 443.38
Main fan air power:  1182.05
Main fan pressure (branch 1-32) is: 3.04651
Main fan flow rate:  345.88
Main fan air power:  1053.90
Main fan pressure (branch 2-4) is: 3.2058
Main fan flow rate:  97.49
Main fan air power:  312.55

Total air power is: 2548.5
Regulator resistance for branch  14-45 is: 0.23927
Regulator resistance for branch  15-16 is: 4.3176
Regulator resistance for branch  37-35 is: 0.75739
Regulator resistance for branch  29-44 is: 0.01962
Regulator resistance for branch  31-42 is:0.00878
Regulator resistance for branch  9-10 is:4.78163
Running time in seconds :5.285
```

FIGURE 8.2 Screenshot of solution for push-pull system

system is 443 m^3/s with a total power requirement of 2548 kW.

An overall evaluation of all alternative solutions for the sample network (Tables 8.1, 8.2 and 8.3) shows that the best alternative is the one that requires one main and three booster fans with a total power requirement of 1150 kW (case 2, alternative A). Under these conditions, the main fan pressure is reduced to the minimum (1.31 kPa), the leakage quantity is minimized, and no recirculation is detected; therefore this is the best solution to the problem.

8.2 Coal Mine Ventilation Network

Figure 8.3 shows the ventilation network of a coal mine as described in Chapter 5. It has three working areas where the airflow requirements are 33, 30, and 30 m^3/s respectively. In Chapter 5, the problem was solved under two conditions: 1. when the system is equipped with three surface fans only, and 2. when the system is equipped with three surface fans and two booster fans. Of these two scenarios, the second had the lesser power requirement. However, based on these results alone, one cannot claim for

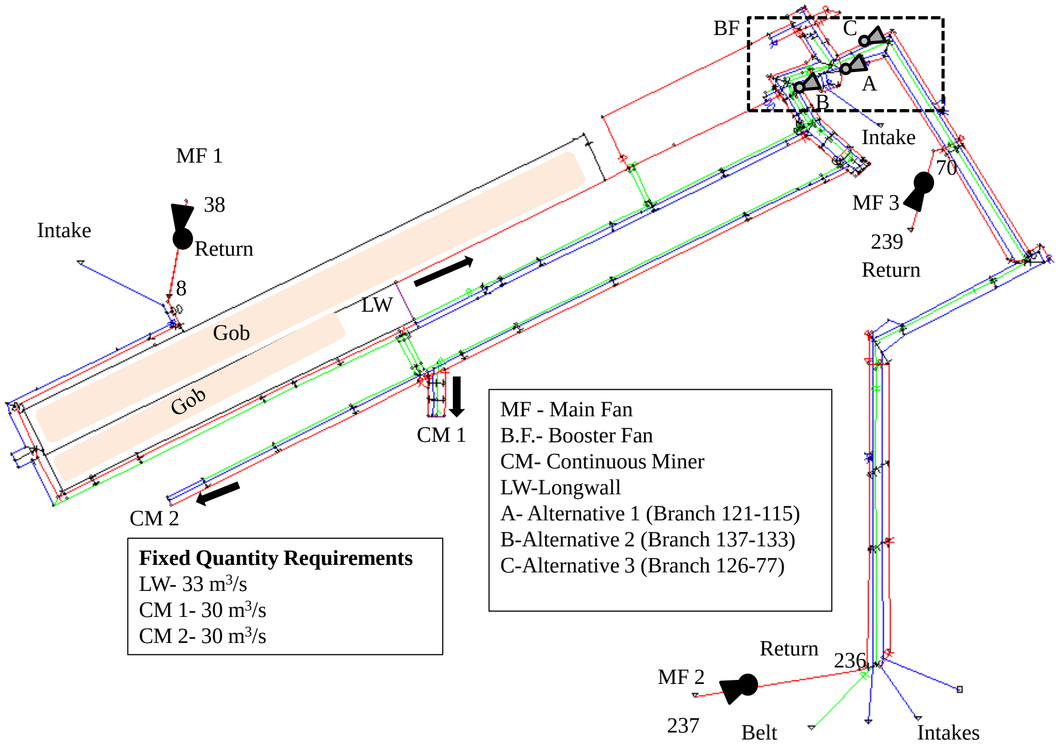


FIGURE 8.3 Coal mine ventilation network (Three main and one booster fans)

optimality unless other feasible alternatives are evaluated. In this case, the ventilation system was modified to include four fans: three surface fans and one booster fan. Three alternative booster fan locations were investigated: initially, the booster fan was located in branch 121-115, and then changed to branch 137-133 and to branch 126-77. In each case, the problem was the same, to determine the best combination of fan pressures to satisfy the flow requirements and to minimize the total air power.

8.2.1 Three Surface and One Booster Fan

GVENT program was used to solve the problem and to determine the best combination of fan pressures for each alternative. Table 8.4 shows a summary of results for each alternative. A quick evaluation of these results shows that an optimal solution

TABLE 8.4 Optimal solutions for each set of B.F. location—Coal mine network

Location	Fans System	P, kPa	Q, m^3/s	AP, kW	Total AP, kW	Leakages, m^3/s
A. Alternative 1						
8-38	Main Fan 1	1.27805	21.61	27.62	1342.58	317
236-237	Main Fan 2	0.39819	44.77	17.82		
70-239	Main Fan 3	2.94997	343.93	1014.59		
121-115	Booster Fan	1.34609	209.92	282.55		
B. Alternative 2						
8-38	Main Fan 1	1.98592	36.18	71.85	1345.99	286
236-237	Main Fan 2	0.120151	1.38	0.17		
70-239	Main Fan 3	2.9485	341.22	1006.26		
137-133	Booster Fan	1.27653	209.64	267.71		
C. Alternative 3						
8-38	Main Fan 1	1.59968	29.10	46.56	1363.20	297
236-237	Main Fan 2	0.161751	12.69	2.06		
70-239	Main Fan 3	3.26099	348.09	1135.12		
126-77	Booster Fan	1.27805	140.50	179.56		

was found when the booster fan is located in branch 121-115 (alternative 1). Under these conditions, the total airpower is minimized. The results generated for the alternative of this case (Table 8.4) were compared with those generated in Chapter 5 for similar conditions using two booster fans (Table 5.3).

Such comparison showed that, in terms of power requirement, the four fan system (current case, with one booster) is less effective than the five fan system (previous case, with two booster fans). In terms of airpower, for the same network conditions, the one booster fan case would require more input power than the two booster fan case (1343 kW vs. 1186 kW).

GVENT approach was very effective in determining the best combination of fan pressures for various ventilation scenarios, for both sample network problems and real mine ventilation problems. The results were very convincing and inspiring, especially for large network problems with multiple main and booster fans. As the number of booster fans increases, the power optimization problem becomes more difficult to solve using currently available ventilation simulators. Using a GA-based program, this task can be simplified considerably.

Furthermore, alternate main and booster fan locations can be investigated quickly and efficiently. However, this requires a good coordination between ventilation personnel and mine management, especially at the planning stage, when decisions are made on number and size of main airways, fans, and ventilation control devices. Furthermore, the approach does not always yield a recirculation-free solution. The generated solution still needs to be evaluated for this hazard. A separate program coded in C++ was developed to check the optimal solution for recirculation.

CHAPTER 9

CONCLUSIONS

The GVENT program, which combines genetic algorithm routines with a ventilation simulator, is a very effective tool in determining fan pressures for a wide range of ventilation network problems, i.e., from single-fan networks to complex multiple-fan coal mine ventilation networks. When booster fans are used in coal mines, flow recirculation is a major concern. The recirculation routine, developed based on the algorithms, is another important tool that detects and quantifies the flow recirculation in complex networks. Now, mine ventilation engineers are equipped with a tool that can be used to design a recirculation-free ventilation system that satisfies the flow requirements and minimizes the total power consumption. Risk analysis is another tool used to minimize the effects of flow recirculation in coal mines. Both major hazards associated with the utilization of booster fans and control measures that should be taken during various stages of booster fan utilization are addressed in this thesis.

9.1 Application of GVENT Program into Ventilation Network

The GVENT program was applied successfully to mine ventilation networks to determine the best combination of fan pressures while both satisfying the flow requirements in the mine and minimizing the total power consumption. This program was tested effectively and rapidly using sample network problems with one or two booster fans. The results were very close (within 0.5% accuracy) to those generated by a ventilation simulator.

This program was also tested effectively using real mine ventilation networks with three surface fans and two booster fans. Tests were repeated for different main and booster fan locations. In every case, the program was used to determine the best combination of fan pressures and minimize the total power consumption. The results showed that as the number of booster fans increases, the airpower requirement decreases to some extent provided that these are properly rated and located in the network.

Based on the above validation tests, the followings conclusions were drawn:

1. The program can be used to determine the best combination of fan pressures and regulator resistances for any size ventilation network problem. The solutions generated by the GVENT program were tested using a ventilation simulator (VnetPC), and results were found within an accuracy of 0.5 %.
2. The program can determine the optimal solution to a network problem with multiple booster fans, i.e., the program can determine the best combination of fan pressures for any given network with fixed fan locations. This information is useful during the planning stage because it allows the ventilation engineer to choose the most economic alternative from a number of competing alternatives.
3. The program produces the optimal solution to a ventilation network

problem faster than the ventilation simulator. For a real mine ventilation problem, when using this program, the optimal solution was found in less than 3 hours. Using a simulator, this task took a great number of trials and more than 1 week of a ventilation expert's time.

9.2 Application of Flow Recirculation Program

As part of this study, two independent programs were developed to detect and quantify the airflow recirculation in ventilation networks. For a set of directed airways, the first program enables the user to identify the saddle nodes, or those that show where recirculation may occur. The second program evaluates the results of the first program and determines the recirculation capacity of each closed loop. These, written in C++, were tested successfully using both sample networks with one or two recirculation loops and complex networks with multiple recirculation loops. The results generated by the GVENT program to various network problems were tested using these programs, and no recirculation loops were found.

9.3 Hazard Identification and Risk Analysis

Hazards associated with the utilization of booster fans in coal mines were identified, the control measures used in coal mining countries listed, and the risks evaluated. When booster fans are used, hazards are found during three stages: installation, commissioning, and operation. These should be identified and the appropriate control measures implemented accordingly. The associated risks were analyzed using three methods: workplace risk assessment and control (WRAC), failure modes effects and criticality analysis (FMECA), and fault tree analysis (FTA). The hazards were evaluated using these tools independently and the outcomes analyzed, the risks ranked, and the recommended mitigation measures listed. If the recommended measures are implemented, the risks can be reduced to an acceptable level and booster fans can be used in coal mines safely.

Overall, the outcomes of this study can be used to produce sound ventilation systems using both surface and underground booster fans and enable coal mine operators to ventilate deep, extensive, or undersea coal mines where other alternatives are not feasible.

APPENDIX A

INPUT FILE FORMAT FOR GVENT PROGRAM

The input file for the sample problem is created in Sample.csv format. It includes six sections: model data, branch data, junction data, fixed quantity data, fan data, and fan results (in SI unit). Each section is described by two rows of data in table format. The first row shows the numbers used to describe all the required parameters and the second row, the actual value of parameters used. For example, for the sample network, the **Model Data** includes 2 rows with 9 columns of information and the **Branch Data** includes 2 rows with 14 column, etc. A detailed description of each section is presented below.

A.1 Input File Format for GVENT Program

a. Model Data

1.Title, 2. Fan efficiency, 3. Power Cost, 4. Air Density, 5. Reference Junction, 6. Measurement, 7. Execution Date, 8. Execution Time and 9. Number of Iteration

1	2	3	4	5	6	7	8	9
Sample 2014	65.00	0.2	1.2	1	1	04/25/2013	06:00:49	33

b. Branch Data

1.Branch ID, 2. From Junction ID, 3. To Junction ID, 4. Branch Type, 5. Flag, 6. Surface State, 7. Resistance, 8. Total Resistance, 9. Q Results, 10. P Results, 11. Air Power, 12. Operating Cost, 13. Q Exponents and 14. Description.

1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	7	5	0	0	0	0.006	0	0	0	0	0	2.0	R

//Define branch type
#define BRANCH_TYPE REGULAR = 0
#define BRANCH_TYPE PRESSURE QUNATITY = 1
#define BRANCH_TYPE KFACTOR = 2
#define BRANCHTYPE_RESIATCNSE PERIMETER LENGTH = 3
#define BRANCH_TYPE FIXED QAUNTITY= 4
// define branch flag
#define Branch Flag FANINBRANCH = 1

```
#define Branch Flag FIXINBRANCH = 2
#define Branch Flag IRBRANCH = 4
#define Branch Flag BOOSTERRANCH = 10
#define Branch Flag REGULATORBRANCH = 18
//Surface State
#define SURFACE NEITHER = 0
#define SURFACE INTAKE = 1
#define SURFACE EXHAUST = 2
```

c. Junction Data

1.Junction Number, 2. X-Coordinates, 3. Y-Coordinates, 4. Z-Coordinates, 5. In Atmosphere, 6. Relative Pressure.

1	2	3	4	5	6
1	11927	-5	0	1	0

In Atmosphere is assigned code 1, if junction is connected to atmosphere. Relative pressure is assigned code 0

d. **Fixed Quantity Data**

1. Fixed Q ID, 2. Branch ID, 3. From Junction ID, 4. To Junction ID, 5. Fixed Quantity, 6. Inject/Reject

Use 0 for Inject/Reject which means neither injection nor rejection in given network

1	2	3	4	5	6
1	53	14	45	47.00	0

e. Fan Data

1. Fan ID, 2. From Junction ID, 3. To Junction ID, 4. Fixed Pressure, 5. Number of Curve Points

1	2	3	4	5
1	3	33	2.0	0

f. Fan Results

1. Fan ID, 2. From Junction ID, 3. To Junction ID, 4. Pressure, 5. Quantity, 6. Operation Cost, 7. Fan curve 8. No. of Fan, 9. Series/Parallel

1	2	3	4	5	6	7	8	9
1	3	33	0.0	0.0	0.0	1	1	1

APPENDIX B

AIRWAYS RESISTANCE FOR SAMPLE NETWORK

This Table B.1 consists of three columns. The first and second columns show the description of the node. The third column shows airways resistances.

TABLE B.1 Airway resistance of sample network (Ns^2/m^8)

From Node	To Node	Resistance Ns^2/m^8	From Node	To Node	Resistance Ns^2/m^8
7	5	0.006	2	4	0.09
6	8	0.006	32	11	0.0015
10	12	0.1	12	7	0.0015
1	32	0.006	11	12	6
3	33	0.006	5	3	0.0015
13	12	0.001	4	6	0.0015
20	13	0.001	18	10	0.0015
21	20	0.001	17	18	0.0015
22	21	0.001	23	39	0.04989
14	17	5	23	24	6
25	27	0.0015	35	22	0.01
24	22	0.0015	34	35	6
26	40	0.03488	34	36	0.05
4	3	6	37	35	0.01
6	5	6	36	37	0.25
8	7	6	23	34	0.0015
19	20	6	38	13	6
8	32	0.0015	11	38	0.001
30	31	0.25	38	19	0.002
16	17	0.0015	14	45	0.04821
15	16	1	39	25	0.03011
15	14	0.25	40	24	0.04512
28	29	0.25	39	40	6
25	26	6	41	30	0.00095
19	23	0.0015	42	26	0.00548
23	21	6	41	42	6
19	15	0.08	43	28	0.00057
8	9	0.08	44	26	0.00066
9	10	0.2	43	44	6
27	41	0.00055	45	13	0.01949
31	42	0.00481	38	45	6
27	43	0.00093	32	10	6
29	44	0.00084			

APPENDIX C

COAL MINE VENTILATION NETWORK FILE

Table C.1 consists of four columns and 524 rows. The first three columns are used to identify a branch within the network (Branch, From, To), and the fourth columns are used to characterize a branch by its resistance in SI units.

TABLE C.1 Airway resistance of coal mine network (Ns^2/m^8)

Branch	From	To	Resistance	Branch	From	To	Resistance
1	72	87	0.00855	34	105	114	0.02635
2	92	87	0.00058	35	114	111	14.42598
3	102	95	212.43402	36	105	111	223.6148
4	102	113	29.90244	37	83	84	0.1044
5	101	102	0.00516	38	99	107	0.26463
6	94	95	0.15701	39	106	110	0.02192
7	91	92	0.01506	40	110	112	0.22752
8	92	95	195.66306	41	107	106	0.00056
9	92	80	0.0126	42	106	82	0.10917
10	80	33	0.05942	43	82	75	0.10235
11	88	81	3.4681	44	74	75	0.27175
12	88	97	212.43402	45	73	74	1.25498
13	97	103	2.06728	46	90	73	0.00108
14	103	108	37.89149	47	99	74	1.16438
15	108	113	0.02579	48	90	99	0.16301
16	87	88	0.00513	49	105	107	0.02287
17	102	103	0.03026	50	107	75	0.02702
18	95	97	0.17816	51	99	231	0.00467
19	88	89	0.00612	52	73	55	0.00415
20	89	83	14.32532	53	55	56	166.81665
21	81	83	0.13844	54	57	56	29.11651
22	89	98	2.01874	55	75	57	0.0217
23	98	104	1.52182	56	74	56	23.20005
24	104	109	7.51928	57	55	47	0.00612
25	109	108	0.03906	58	47	49	0.0042
26	103	104	0.01575	59	49	51	0.00437
27	97	98	0.34459	60	51	52	6.27742
28	89	90	0.01076	61	56	52	0.10567
29	90	84	41.01905	62	57	53	0.01585
30	84	232	0.82429	63	53	51	37.73498
31	112	111	0.0294	64	52	54	227.46137
32	111	109	0.00093	65	53	54	25.18468
33	104	105	0.00078	66	53	52	2292.515
67	47	52	3.22005	108	133	125	0.00695
68	47	46	3.01334	109	125	121	0.00033
69	46	48	0.16392	110	121	115	0.00924
70	48	50	0.06993	111	132	133	1400.38771
71	51	50	138.64118	112	130	125	224.06203

TABLE C.1 continued

72	49	48	150.28517	113	121	126	1.63417
73	53	65	0.19142	114	126	77	0.01288
74	65	66	34.66029	115	79	234	0.01492
75	66	69	13.13856	116	127	126	1173.97771
76	69	70	0.001	117	127	128	16.77111
77	62	233	0.00426	118	131	128	223.6148
78	61	62	3.35682	119	131	121	1196.33917
79	63	61	41.04893	120	134	137	244.57869
80	63	64	10.50989	121	143	138	0.00987
81	65	64	4.25458	122	143	260	0.01034
82	54	66	0.2687	123	134	151	0.0054
83	51	63	0.02073	124	151	155	0.00266
84	50	61	0.05667	125	135	128	16.77095
85	52	64	0.03054	126	135	138	224.3136
86	65	85	0.21779	127	128	152	0.00599
87	85	86	904.39763	128	155	152	100.62662
88	86	69	0.01952	129	155	159	307.47035
89	64	78	0.09193	130	152	278	0.31341
90	63	71	0.00652	131	286	159	0.00793
91	71	67	0.03882	132	159	118	0.00842
92	67	68	92.24111	133	165	143	0.04372
93	71	68	163.65646	134	151	275	0.00189
94	77	68	0.03466	135	271	148	0.00113
95	68	62	0.01438	136	148	137	0.00437
96	71	79	0.05183	137	151	148	347.84525
97	79	77	345.20536	138	151	152	55.82092
98	85	116	0.01118	139	155	282	0.0012
99	116	115	20.1415	140	79	78	0.08603
100	115	86	0.00337	141	78	128	0.05731
101	116	117	156.53054	142	85	78	0.18267
102	131	117	0.00759	143	173	171	18.35329
103	130	131	3.57784	144	171	159	0.37208
104	132	130	0.50355	145	180	174	0.00056
105	132	134	0.01025	146	208	207	0.00264
106	134	131	0.00107	147	207	194	0.00733
107	137	133	0.00433	148	127	195	0.00103
149	139	129	0.00578	190	20	313	0.00193
150	139	3	0.00265	191	313	325	0.00079
151	140	139	412.44509	192	325	10	0.00235
152	147	144	0.00435	193	326	42	0.01972

TABLE C.1 continued

153	138	147	0.02508	194	319	304	647.09311
154	178	135	0.00578	195	328	301	40.80971
155	60	141	8530.3924	196	321	329	0.00983
156	98	231	0.35443	197	322	331	0.01604
157	232	112	0.04907	198	322	321	0.00071
158	231	232	0.19225	199	295	324	0.00165
159	233	69	0.00135	200	322	324	85.30392
160	64	233	27.69304	201	314	321	0.00515
161	234	127	0.00356	202	316	314	85.30392
162	117	234	0.00305	203	317	316	341.2157
163	113	236	0.00994	204	317	318	0.1789
164	236	237	0.00011	205	315	322	0.0065
165	238	132	0.00101	206	296	314	0.00817
166	70	239	0.00011	207	297	296	85.30392
167	329	320	0.00401	208	297	298	85.30392
168	331	323	0.00851	209	317	298	0.08443
169	310	295	0.00179	210	297	315	0.01808
170	323	310	85.30392	211	263	296	0.01141
171	323	320	85.30392	212	124	253	0.00581
172	323	311	0.00216	213	255	256	8530.3924
173	331	295	85.30392	214	252	250	16.77095
174	331	329	85.30392	215	247	145	0.00487
175	320	309	0.00993	216	248	247	0.00413
176	311	309	85.30392	217	249	248	0.00516
177	311	312	85.30392	218	251	249	0.00535
178	312	310	0	219	253	251	0.0061
179	330	20	0.00095	220	255	146	0.00097
180	21	330	0.00198	221	136	249	2292.515
181	299	21	0.00567	222	252	1	0.00307
182	300	299	0.00194	223	289	267	0.01868
183	308	206	0.00995	224	269	285	0.00418
184	305	300	0.02089	225	243	254	0.01132
185	206	306	950.08338	226	258	287	0.00444
186	303	304	0.00973	227	250	288	0.02198
187	304	306	0.00181	228	257	283	0.0166
188	306	307	0.00177	229	275	271	1207.51995
189	301	302	40.80971	230	275	278	402.50646
231	282	241	234.79559	272	33	88	0.00158
232	282	286	368.96445	273	8	38	0.14775
233	282	235	0.00518	274	93	76	161.77328

TABLE C.1 continued

234	278	280	0.0205	275	160	76	0.02695
235	275	281	0.00414	276	156	161	83.85555
236	269	262	0.00475	277	93	96	83.85555
237	298	284	0.09031	278	140	205	0.00205
238	261	242	0.00292	279	100	149	0.12404
239	284	273	0.00269	280	119	35	0.00251
240	227	284	16177.3278	281	18	119	0.00408
241	276	197	0.00673	282	140	120	6.20233
242	267	276	0.01179	283	122	120	0.00148
243	324	318	0.04312	284	17	18	8530.3924
244	6	318	0.00244	285	17	100	59.04198
245	7	199	0.00552	286	149	204	0.00745
246	305	303	3354.22203	287	144	149	0.00648
247	206	305	10.54018	288	156	93	0.0572
248	194	171	0.01632	289	58	162	0.00557
249	269	267	34.21307	290	160	156	161.77328
250	258	261	162.12071	291	59	172	0.03979
251	258	257	1134.84507	292	311	209	0.01
252	269	261	206.84385	293	212	58	0.0079
253	3	213	0.0219	294	184	11	647.09311
254	198	208	0	295	229	165	0.01238
255	317	7	0.00246	296	174	230	0.00702
256	7	6	8532.629	297	230	229	8530.3924
257	273	276	8.67888	298	175	312	0.92241
258	307	8	0.2748	299	302	319	4.4723
259	9	308	0.14041	300	214	203	139.75925
260	319	303	2929.35399	301	184	328	40.80971
261	10	326	0.00493	302	189	327	83.85555
262	10	11	8530.3924	303	14	327	83.85555
263	313	11	341.2157	304	96	14	83.85555
264	11	12	0.01508	305	93	15	0.03574
265	330	12	7.04387	306	76	16	0.01696
266	13	303	0.03129	307	19	34	0.04976
267	12	13	0.17016	308	34	42	342.11034
268	300	13	3023.27232	309	15	19	1118.3
269	129	22	0.00398	310	16	44	0.00298
270	22	3	0.00848	311	42	44	0.00992
271	33	81	2.67443	312	44	19	0
313	34	11	0.00967	354	153	4	0.01502
314	35	122	0.00355	355	254	154	0.15969

TABLE C.1 continued

315	123	139	0.00362	356	154	244	0.00865
316	120	123	0.00138	357	157	256	0.00702
317	23	24	0.00279	358	153	157	4473.2
318	24	31	0.01165	359	215	208	0.01401
319	26	25	85.30392	360	19	14	647.09311
320	25	45	0.00992	361	1	142	0.00066
321	43	27	0.04939	362	2	250	0.02055
322	327	184	83.85555	363	1	2	341.2157
323	28	23	0.00284	364	252	255	8530.3924
324	28	5	341.2157	365	218	168	0.00446
325	31	37	0.02948	366	166	191	0.00946
326	4	32	0.06857	367	170	169	0.00087
327	32	31	44.732	368	169	294	0.00645
328	36	5	0.01383	369	216	176	0.00361
329	31	36	341.2157	370	192	181	0.057
330	37	41	0.02183	371	182	211	0.07622
331	32	39	0.11823	372	186	183	0.00081
332	39	37	44.732	373	183	168	0.00055
333	40	36	0.02355	374	168	176	0.00623
334	37	40	44.732	375	176	167	0.00623
335	41	26	0.01155	376	228	185	85.30392
336	39	43	0.08416	377	185	167	0.00054
337	45	40	0.01686	378	185	186	0.00078
338	26	27	44.732	379	186	176	0.00622
339	4	28	44.732	380	170	179	0.00788
340	43	45	8530.3924	381	187	292	0.00994
341	29	251	2292.515	382	179	293	0.03161
342	150	124	0.00454	383	187	188	341.2157
343	124	29	8530.3924	384	190	193	0.0138
344	136	154	8530.3924	385	187	190	341.2157
345	136	29	0.00055	386	191	187	0.01086
346	142	248	8530.3924	387	188	192	0.06917
347	142	136	0.00048	388	192	191	341.2157
348	145	2	0.00378	389	193	291	0.01129
349	142	145	8530.3924	390	191	193	341.2157
350	29	146	0.00062	391	181	166	341.2157
351	146	28	0.00568	392	166	164	341.2157
352	150	157	0.01101	393	256	250	0.00323
353	5	150	0.00395	394	189	215	0.1234
395	309	196	0.00465	436	27	222	0.0643

TABLE C.1 continued

396	198	6	0.02782	437	163	217	0.00085
397	199	207	31.09643	438	222	217	0.01228
398	199	198	0.00398	439	225	217	0.02009
399	201	202	0.02374	440	163	167	0.00362
400	202	200	0.08821	441	216	163	0.00623
401	302	203	139.75925	442	218	216	8530.3924
402	215	214	111.8074	443	181	225	0.02009
403	204	3	0.01053	444	216	225	0.00322
404	205	17	0.00316	445	161	96	0
405	205	119	223.66	446	175	161	83.85555
406	205	149	223.66	447	58	59	161.77328
407	208	201	4.09082	448	162	160	0.01728
408	200	18	0.01	449	172	156	0.15467
409	155	180	0	450	162	172	161.77328
410	118	229	0.00055	451	30	140	0.00186
411	230	118	8530.3924	452	30	60	0.00106
412	135	210	0.01042	453	178	144	341.2157
413	210	155	0.00264	454	60	178	0.00139
414	211	59	0.05597	455	141	128	0.02624
415	183	212	0.07055	456	180	173	0.00047
416	211	212	161.77328	457	227	269	0.00221
417	182	186	161.77328	458	209	182	0.69252
418	177	166	0.00627	459	196	228	0.03515
419	181	218	0.00368	460	228	209	0.00008
420	195	30	0.00069	461	241	278	85.30392
421	213	126	0.01942	462	152	241	0.01148
422	195	213	27.9575	463	242	158	0.0056
423	152	210	82.73754	464	241	279	0.01511
424	210	165	371.75964	465	261	243	0.05252
425	221	222	0.01625	466	244	153	0.00425
426	221	220	8530.3924	467	244	157	4473.2
427	220	219	0.16574	468	152	245	0.00313
428	223	224	0.00179	469	245	246	0.0145
429	224	226	8530.3924	470	128	259	0.01555
430	226	164	0.32111	471	260	137	0.01072
431	224	221	8530.3924	472	246	260	11.183
432	164	219	0.00298	473	259	260	11.183
433	219	25	0.00344	474	262	297	0.01398
434	26	223	0.00397	475	263	267	14.72379
435	223	177	0.00626	476	262	263	0.00061

TABLE C.1 continued

484	270	274	8530.3924	524	285	289	44.732
485	270	266	0.00046				
486	266	264	8530.3924				
487	224	270	0.00213				
488	274	290	0.00169				
489	266	221	0.01312				
490	264	220	0.00261				
491	290	226	0.0009				
492	291	164	0.00167				
493	290	291	0.24425				
494	292	170	0.00505				
495	293	188	0.06335				
496	292	293	0.00622				
497	294	190	0.01254				
498	292	294	85.30392				
499	175	189	0.09243				
500	209	175	0.00048				
501	41	43	44.732				
502	158	273	28.29846				
503	158	276	3.14427				
504	197	240	0.00663				
505	227	197	44.732				
506	235	227	0.0019				
507	240	286	0.02063				
508	235	240	44.732				
509	279	242	0.17463				
510	235	279	44.732				
511	280	261	0.14038				
512	279	280	44.732				
513	281	258	0.00322				
514	283	271	0.02102				
515	281	283	44.732				
516	281	280	44.732				
517	285	255	0.00503				
518	285	254	44.732				
519	287	252	0.00532				
520	288	257	0.02055				
521	287	288	44.732				
522	287	254	44.732				
523	256	289	0.02114				

APPENDIX D

INPUT FILE FOR RECIRCULATION

Appendix D shows an input file for the sample network used to detect and quantity the recirculation. It consists of four columns and represent description of Branch, From, To, and Quantities. Table D.1 is used to create an input file for detection and quantification of recirculation.

TABLE D.1 Input file for detection and quantification program

Br.	From	To	Q, m³/s	Br.	From	To	Q, m³/s	Br.	From	To	Q, m³/s
3	7	5	407.48	26	19	23	7.31	47	37	35	40
4	6	8	61.16	27	23	21	190.74	48	36	37	40
5	10	12	99.81	28	19	15	17.35	49	23	34	57.02
6	1	32	346.32	29	8	9	65.31	50	38	13	18.67
7	3	33	433.82	30	9	10	66	51	11	38	310.79
8	13	12	292.48	31	27	41	66	52	38	19	273.84
9	20	13	208.52	32	31	42	40.09	53	14	45	47
10	21	20	190.74	33	27	43	33	54	39	25	87.58
11	22	21	173.39	34	29	44	40.17	55	40	24	99.26
12	14	17	3.31	35	2	4	33	56	39	40	11.69
13	25	27	80.26	36	32	11	87.5	57	41	30	33
14	24	22	116.37	37	12	7	330.26	58	42	26	40.09
15	26	40	87.58	38	11	12	411.75	59	41	42	7.09
16	4	3	14.03	39	5	3	19.46	60	43	28	33
17	6	5	12.31	40	4	6	419.79	61	44	26	40.17
18	7	8	4.27	41	18	10	73.47	62	43	44	7.17
19	19	20	17.78	42	17	18	18.31	63	45	13	65.29
20	32	8	0.57	43	23	39	18.31	64	38	45	18.29
21	30	31	33	45	23	24	99.26	65	32	10	15.49
22	16	17	15	46	35	22	17.11				
23	15	16	15	47	34	35	57.02				
24	15	14	50.31	45	23	24	17.02				
25	28	29	33	46	34	36	40				

APPENDIX E

SCREENSHOT RESULTS (GVENT APPROACH)

Appendix E shows screenshot results of the GVENT approach for a sample and coal mine ventilation network. These results consist of fan pressures (kPa), flow rate (m^3/s), air power (kW), and regulator resistances (Ns^2/m^8). Figure E.1 shows an optimal solution of one main and one booster fan for sample network. Figure E.2 shows an optimal solution of one main and two booster fans for sample network. Figure E.3 shows an optimal solution of one main and three booster fans for sample network. Figure E.4 shows an optimal solution of three surface fans and one booster fan for the coal mine ventilation network.

```
Main fan pressure (branch 3-33) is: 3.86123
Main fan flow rate is : 376.95
Main fan air power:  1455.40
Booster fan pressure (branch 26-40) is: 0.684078
Booster fan flow rate:  87.12
Booster fan air power:  59.59

Total air power is: 1514.99
Regulator resistance for branch  14-45 is: 0.00186
Regulator resistance for branch  15-16 is: 1.50914
Regulator resistance for branch  37-35 is: 0.2514
Regulator resistance for branch  29-44 is: 0.02023
Regulator resistance for branch  31-42 is:0.00939
Regulator resistance for branch  9-10 is:2.70632
```

FIGURE E.1 Fan duties and regulator resistances (one main and one booster fan)

```
Main fan pressure (branch 3-33) is: 3.22632
Main fan flow rate is : 354.58
Main fan air power:  1143.88
Booster fan pressure (branch 26-40) is: 0.804319
Booster fan flow rate:  87.79
Booster fan air power:  70.58
Booster fan pressure (branch 13-12) is: 0.202684
Booster fan flow rate:  249.38
Booster fan air power:  50.62

Total air power is: 1265.08
Regulator resistance for branch  14-45 is: 0.01744
Regulator resistance for branch  15-16 is: 0.51478
Regulator resistance for branch  37-35 is: 0.1738
Regulator resistance for branch  29-44 is: 0.03759
Regulator resistance for branch  31-42 is:0.02667
Regulator resistance for branch  9-10 is:1.95239
```

FIGURE E.2 Fan duties and regulator resistance (one main and two booster fans)

```
Main fan pressure (branch 3-33) is: 1.30917
Main fan flow rate is : 332.16
Main fan air power:  434.80
Booster fan pressure (branch 26-40) is: 0.784707
Booster fan flow rate:  86.86
Booster fan air power:  68.19
Booster fan pressure (branch 45-13) is: 0.4544
Booster fan flow rate:  62.06
Booster fan air power:  28.18
Booster fan pressure (branch 7-5) is: 1.92115
Booster fan flow rate:  321.97
Booster fan air power:  618.50

Total air power is: 1149.67
Regulator resistance for branch  14-45 is: 0.17062
Regulator resistance for branch  15-16 is: 0.99388
Regulator resistance for branch  37-35 is: 0.14323
Regulator resistance for branch  29-44 is: 0.01364
Regulator resistance for branch  31-42 is:0.00282
Regulator resistance for branch  9-10 is:2.26674
```

FIGURE E.3 Fan duties and regulator resistances (one main and three booster fans)

```
Main fan pressure (branch 8-38) is: 1.27805
Main fan flow rate is : 21.61
Main fan air power:  27.62
Main fan pressure (branch 236-237) is: 0.39819
Main fan flow rate:  44.77
Main fan air power:  17.82
Main fan pressure (branch 70-239) is: 2.94997
Main fan flow rate:  343.93
Main fan air power:  1014.59
Booster fan pressure (branch 121-115) is: 1.34609
Booster fan flow rate:  209.92
Booster fan air power:  282.55

Total air power is: 1342.58
Regulator resistance for branch  169-294 is: 0.05307
Regulator resistance for branch  220-219 is: 0.55198
Regulator resistance for branch  290-291 is: 1.82265
Regulator resistance for branch  226-164 is: 1.79289
Regulator resistance for branch  189-215 is:0.01176
Running time in seconds :9.173
```

FIGURE E.4 Fan duties and regulator resistances (three surface and one booster fans)

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