# OPTIMIZATION OF COMPLEX MINE VENTILATION SYSTEMS WITH COMPUTER NETWORK MODELLING

**Euler De Souza**

*Department of Mining Engineering*
*Queen's University, Kingston, Ontario, Canada, K7L 3N6*

Abstract: In order to save on costs, modern mining operations constantly strive toward optimizing the operating efficiency of their ventilation systems. Typical mine ventilation systems are represented by complex networks of hundreds of airways; the optimization of such complex 3-dimensional networks can only be studied using computer models. This paper presents an overview of mathematical models and techniques used in computer programming and of ventilation network models currently used in industry. The complex procedures used to develop, calibrate, refine and validate the ventilation network for a mine are also introduced. Limitations of ventilation computer modeling that must be taken into consideration when making engineering decisions and establishing multi-million dollar implementation programs for a mine ventilation system are discussed.

Keywords: modelling, networks, verification, calibration, optimization

## 1. INTRODUCTION

The ventilation of underground mines represents approximately 50% of the total energy consumed by the mine operation and 25 to 40% of the total mining cost. Modern mining operations are committed to reducing the total energy consumption and operating costs, and the ventilation system constitutes a primary target.

Typical mine ventilation systems are represented by complex networks of hundreds of airways, with multiple branchings and a multitude of appliances, including fans, doors, stoppings, and regulators. The study and optimization of such complex systems can only be efficiently performed using computer models.

An review of mathematical models and techniques used in computer programming for the analysis of complex ventilation networks is presented. The method which has found the widest application is an iterative technique based on the Hardy Cross method. This method of network analysis involves making an initial estimate of the airflow distribution, calculating an approximate correction to be applied to each airway and repeating the correcting procedure iteratively until an acceptable degree of accuracy has been attained for each estimated airflow.

Features of ventilation network computer models currently used in industry are also presented. Circuit evaluation and analysis is important for accurate and economical planning of the mine ventilation system requirements in the short and long term. The complex procedures used to develop, calibrate, refine and validate the ventilation network for a mine are introduced. The calculation of the distribution of airflow in mine ventilation circuits requires that the circuit geometry, branch resistances, and fan position and characteristics be known. A number of techniques are used to determine the airflow redistribution when the mine ventilation layout or characteristics are changed. Changes in the mine ventilation circuit may result from mine expansion (e.g. driving of new roadways, raises, stopes, etc.), closing off of mined out areas, changing the positions or duties of fans, and moving, adding or removing doors and regulators.

Typical industrial applications used to develop, design and optimize the ventilation system of operating mines are presented. Discussions of model accuracy to be acceptably used in ventilation planning exercises and of model reliability for use as an engineering assessment tool are presented in conjunction with the industrial applications.

## 2. VENTILATION NETWORK ANALYSERS

A number of advanced ventilation modeling techniques have been developed over the years, including the Hardy Cross method, the critical path method and other more efficient approximation methods. Such modeling techniques have been optimized with advanced programming techniques to improve computing efficiency. Several mathematical models, based on the basic laws of mass, momentum and energy transport have also been developed and included in ventilation models to quantify the effect of gases and particulates in the mine environment, and the effect of heat and moisture on airflow. Such models include thermodynamic models, pollutant-dispersion modeling, and fire simulations. Several ventilation simulation packages are available to the user to help solve complex ventilation systems. A number of contributions to mine ventilation modeling are listed in the references.

## 3.VENTILATION CIRCUIT TERMINOLOGY

A mine ventilation circuit or network is a closed and interconnected system of branches (airways) through which air may flow. A junction or node is a point at which three or more airways (branches) meet. A branch is a single airway connecting two junctions. A mesh or loop is any closed path of connected branches within the circuit or network.

## 4. AIRFLOW EQUATIONS USED IN CIRCUIT ANALYSIS

Consider the case of an air flow volume, Q ($m^3/s$), passing through an airway of resistance R ($N.s^2/m^8$). The air follows the basic law of airflow given by,

$$H = R\,Q^n\,w \qquad (1)$$

where, H is the frictional pressure drop along the airway (Pa), *w* is the air density ($kg/m^3$) and *n* is a constant for the range of flow conditions considered. For underground ventilation conditions, the index *n* lies between 1.8 and 2.2, although certain situations may develop where laminar conditions prevail and the value of *n* will decrease to 1.0. In routine mine ventilation planning, in which fully turbulent airflow conditions normally prevail, the assumption of the square law for all ventilated branches is, in general, adequate and will give an acceptable level of accuracy. Mathematically,

$$H \propto R\,Q^2\,w \qquad (2)$$

Friction pressure losses are caused by the resistance of the airway walls on the airstream. The constant of proportionality therefore depends upon the geometry and roughness of individual wall surfaces of the airway. The Atkinson Equation is used to determine the friction loss in mine ventilation,

$$H = \frac{kPLQ^2}{A^3} = RQ^2 \qquad (3)$$

where, H is the frictional pressure drop (Pa); Q is the airflow ($m^3/s$); k is the empirical friction factor ($N.s^2/m^4$); R is the airway resistance ($N.s^2/m^8$); P is the airway perimeter (m); L is the airway length (m); and A is the airway cross-sectional area ($m^2$). Atkinson equation is normally presented at standard air density.

## 5. AIRFLOW LAWS USED IN CIRCUIT ANALYSIS

Kirchhoff's First and Second Laws are used in solving ventilation network analysis.

Kirchhoff's First Law states that the algebraic sum of all mass flow rates ($M_i$) at any junction is zero. Mathematically,

$$\sum_{i=1}^{b} M_i = 0 \qquad (4)$$

where, $M_i = w_iQ_i$ (kg/s) and *i* represents a particular branch connected to the junction and *b* is the total number of branches connected to that junction.

Where changes in density are negligible or all characteristics have been corrected to a standard density, the above equation reduces to,

$$\sum_{i=1}^{b} Q_i = 0 \qquad (5)$$

In simple terms, the First Kirchhoff's Law states that the sum of all air volumes flowing towards a junction must equal the sum of all air volumes flowing away from that junction. When making air volume flow measurements underground, the observed values must follow the First Law.

Kirchhoff's Second Law states that the algebraic sum of all energy transforms which take place within the airflows in any closed mesh is zero. In order to simplify this statement and develop a simplified mathematical expression for use in ventilation calculations consider the case of one single branch, *i*. The following equation expresses the energy content of that branch,

$$\Delta\left[\frac{u_i^2}{2}\right] + \Delta z_i g + W_{fi} = \int_i VdP + F_i \qquad (6)$$

where, $\Delta[u_i^2/2]$ is the change in kinetic energy along the branch (Nm/kg); $\Delta z_i$ is the change in elevation along the branch (m); g is the acceleration of gravity ($m/s^2$); $W_{fi}$ is the work input of fans in the branch (Nm/kg); $\int_i VdP$ is the flow work along the branch (Nm/kg); and $F_i$ is the mechanical energy transformed to heat by turbulence within the branch (Nm/kg).

For a number, *m*, of branches forming a closed mesh,

$$\sum_{I=1}^{m} \Delta z_i g = 0 \qquad (7)$$

and

$\sum_{i=1}^{m} \int_i VdP$ is the natural ventilating energy, $(NVE)_m$.

Summing the terms of equation 6 around a closed mesh gives,

$$\sum_{i=1}^{m} \left[F_i - W_{fi} - \left(\Delta\,\frac{u_i^2}{2}\right)\right] - (NVE)_m = 0 \qquad (8)$$

The changes in kinetic energy are normally very small compared with the other terms and may, in general, be neglected.

Each term in Equation 8 can be expressed as a pressure differential (rather than an energy transform) by multiplying each term by a standard density value ($w_{st} = 1.2\ kg/m^3$),

$$\sum_{i=1}^{m} [w_{st}F_i - w_{st}W_{fi}] - w_{st}(NVE)_m = 0 \qquad (9)$$

The three terms in Equation 9 may now be expressed using a more familiar terminology,

$w_{st}F_i = H_i$ = frictional pressure drop (Pa)
$w_{st}W_{fi} = H_{fi}$ = total pressure across the fan (Pa)
$w_{st}(NVE)_m = (NVP)_m$ = natural ventilation pressure (Pa)

and Kirchhoff's Second Law may be expressed as,

$$\sum_{i=1}^{m} (H_i - H_{fi}) - (NVP)_m = 0 \qquad (10)$$

The Second Kirchhoff's Law states that the algebraic sum of all frictional pressure drops around any closed mesh, less any fan and natural ventilation pressure, is equal to zero.

When applying the Second Law, one must consider the physical meaning of the negative signs before the $H_{fi}$ and NVP terms. For example, if a fan or a natural ventilation pressure in a mesh are assisting the flow, they are effectively sources of pressure rise in the direction of airflow and thus may be considered as negative pressure drops. The adoption of the following sign convention is normally used:

- The frictional pressure drop in a branch, $H_i$, is positive if the flow in that branch is clockwise, and vice-versa.

- The fan pressure, $H_{fi}$, in a mesh is positive if the flow in the branch it is located (or to be located) is clockwise, and vice-versa.

If the resulting sum of pressures (second law) is positive, a fan is required, if negative a regulator is required.

One should note that the Second Law as expressed in the form of Equation 10 is valid only when all terms are referred to the same standard density, $w_{st}$.

## 6. THE HARDY CROSS METHOD OF NETWORK ANALYSIS

Consider the simple case of an air flow volume passing through an airway. The characteristic of this simple circuit is illustrated in Figure 1.

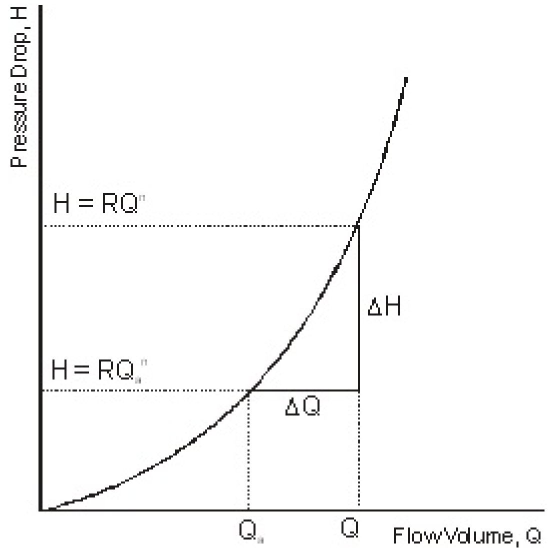

Fig. 1. Graphical depiction of the Hardy-Cross method

In order to determine the actual value of the airflow volume, Q, an estimated value, $Q_a$ is first assumed, such that,

$$Q = Q_a + \Delta Q \tag{11}$$

where ΔQ is the error involved in the initially assumed airflow quantity. Similarly, ΔH is the corresponding error in the frictional pressure drop, H. This is illustrated in Figure 1.

We now proceed in determining the correction, ΔQ, to be applied to the assumed airflow volume, $Q_a$.

From Figure 1, the slope of the system curve in the region of the actual air flow volume Q and the assumed quantity, $Q_a$, can be approximated by,

$\frac{\Delta H}{\Delta Q}$ or, in the limit by, $\frac{dH}{dQ}$.

Differentiating the law of airflow given by Equation 1,

$$\frac{dH}{dQ} = nRQ^{n-1} \tag{12}$$

or, $nRQ_a^{n-1}$, at the assumed quantity, $Q_a$.

We can thus write,

$$\frac{\Delta H}{\Delta Q} = nRQ_a^{n-1} \tag{13}$$

or,

$$\Delta Q = \frac{\Delta H}{nRQ_a^{n-1}} \tag{14}$$

Substituting,

$$\Delta H = RQ^n - {}^{Rqan} \tag{15}$$

$$\Delta Q = \frac{RQ^n - RQ_a^n}{nRQ_a^{n-1}} \tag{16}$$

The numerator in Equation 16 represents the out-of-balance pressure drop and the denominator is the slope of the HQ curve.

The equations developed above were for the case of a single airway. Consider now a more general case where a series of *b* branches form a closed mesh within a network. In this case, the mean out-of-balance pressure drop is given by,

$$\Delta H = \frac{\sum_{i=1}^{b} (R_iQ_i^{ni} - R_iQ_{ia}^{ni})}{b} \tag{17}$$

and the mean slope of the HQ curve can be written as,

$$\frac{\sum_{i=1}^{b} nR_iQ_{ia}^{ni-1}}{b} \tag{18}$$

When these two expressions are combined in the form of Equation 16, a composite value of flow correction $\Delta Q_m$, known as the mesh correction factor, is obtained,

$$\Delta Q_m = \frac{\sum_{i=1}^{b} (R_iQ_i^{ni} - R_iQ_{ia}^{ni})}{\sum_{i=1}^{b} n_iR_iQ_{ia}^{ni-1}} \tag{19}$$

The frictional pressure drop along branch *i* is,

$$H_i = R_i Q_i^{ni} \qquad (20)$$

at the actual quantity $Q_i$.

When summing the pressure drops in the numerator, $R_i Q_{ia}^{ni}$, the sign must not be overlooked if it is remembered that the frictional pressure drop is always positive in the direction of flow (when no fans are present). The slope of the HQ curve, represented in the denominator by $n_i R_i Q_{ia}^{ni-1}$, is always positive, and the sign in the denominator is not accounted for. For each mesh forming the network, a sign convention is chosen for referencing the branch airflows around the mesh; it is suggested to choose a clockwise direction around each mesh to be positive.

Mechanical ventilation (fans) and natural ventilation pressure in each mesh are included in the analysis by using the complete form of Kirchhoff's Second Law in the numerator of Equation 20 and the slope of the fan characteristic in the denominator,

$$\Delta Q_m = \frac{-\left[\sum_{i=1}^{b} (R_i Q_{ia}^{ni} - H_{fi}) - (NVP)_m\right]}{\sum_{i=1}^{b} (n_i R_i Q_{ia}^{ni-1} - S_{fi})} \qquad (21)$$

where, $H_{fi}$ and $S_{fi}$ are the pressure and slope of the fan characteristic located in branch *i* at a assumed flow volume of $Q_{ia}$.

One should note that, because of the approximations made in the derivation of Equation 21, the use of the mesh correction factors, $\Delta Q_m$, in the network will not result immediately in an exact balanced flow pattern. The technique has to be applied repeatedly until all the mesh correction factors approach the desired required level of accuracy (close to zero). For this reason, the analysis of complex networks can be performed only with the use of computers.

The Hardy Cross formula given in Equation 21is in its most general form and is valid for branches with different values of *n*, i.e. different flow conditions. Also, as previously mentioned, in routine mine ventilation planning, the assumption of the square law for all ventilated branches is, in general, adequate and will give an acceptable level of accuracy. Thus, Equation 21 can be expressed as,

$$\Delta Q_m = \frac{-\left[\sum_{i=1}^{b} (R_i Q_{ia} |Q_{ia}| - H_{fi}) - (NVP)_m\right]}{\sum_{i=1}^{b} (2 R_i |Q_{ia}| - S_{fi})} \qquad (22)$$

where, $|Q_{ia}|$ is the absolute value of $Q_{ia}$.

When using Equation 22 for correcting the flows for each branch forming a mesh, a sign convention for referencing the branch airflows around the mesh must be followed. It is suggested to choose a clockwise direction around each mesh to be positive, as follows,

- The branch flow $Q_{ia}$ is positive if its direction within the mesh is clockwise, and vice-versa.

- The fan pressure, $H_{fi}$, in a mesh is positive if the flow in the branch it is located is clockwise, and vice-versa.
- The natural ventilation pressure, $(NVP)_m$, in a mesh is positive if it acts in a clockwise direction, and vice-versa.

Finally, the choice of meshes will determine the rapidity with which the flow pattern converges towards balance. Also, high resistance branches increase the number of iterations required for convergence. For increased efficiency, the meshes should be selected so that each high resistance branch appears in one mesh only and that no mesh contain more than one high resistance branch.

## 7. PROCEDURE FOR NETWORK ANALYSIS USING THE HARDY CROSS METHOD

A procedure is described for the application of the Hardy Cross method in computer programming.

- Using updated mine ventilation plans, draw the equivalent ventilation network. Locate all fans, doors, regulators and other ventilation control devices. Define and number the joints and branches. Determine the natural ventilation pressure and the air density at each branch. Determine the resistance of each branch and make corrections to a standard air density:

$$R_{i\,st} = \frac{w_{st}}{w_{i\,o}} R_{i\,o}$$

where, $R_{i\,st}$ is the standardized resistance for branch *i*, $R_{i\,o}$ is the observed branch resistance, $w_{i\,o}$ is the observed air density in the branch and $w_{st}$ is the reference standard density (1.2 Kg/m$^3$).

- Estimate the airflow volume flowing though each branch of the network and the pressures developed by the fans. When making airflow estimates the following factors should be considered. The Kirchhoff's First Law should be followed at each junction, i.e. the sum of the flow rates into the junction must equal the flow out.

- Divide the network into a series of meshes. The minimum number of meshes is given by,

$$M = B - J + 1$$

where, *M* is the minimum number of meshes, *B* is the number of branches and *J* the number of junctions or nodes in the network. The selected pattern meshes should represent the complete network system. Also, no mesh should contain more than one high resistance branch and such a branch should not appear in more than one mesh.

- For each mesh, evaluate the mesh correction factor using Equation 22.

- Correct the flow in each branch. When correcting the flows for each branch forming a mesh, a sign convention for referencing the branch airflows around the mesh must be followed. It is suggested to choose a clockwise direction around each mesh to be positive.

- Repeat the process until all values of $\Delta Q_m$ become negligibly small or are below a prescribed level. At this point a satisfactory airflow balance will be reached.

## 8. COMPUTER SOFTWARE TO SOLVE VENTILATION NETWORKS

Ventilation simulation programs are used to predict airflows, frictional head losses, air power losses, fan operating points and contaminant distribution and concentrations. Typical software assumes incompressible flow and is based on Kirchoff's laws. The Hardy-Cross iterative technique is used to converge to solutions.

Computer programs can simulate existing ventilation networks such that fan operating points, airflow quantities, and frictional pressure drops approximate those of the actual system. This is accomplished using data from ventilation surveys together with information determined from known airway dimensions and characteristics.

The use of ventilation network programs eliminate the need for any manual calculating procedures and enables ventilation personnel to concentrate their efforts on data collection and analysis of computed results. Several simulations can be easily and rapidly performed in a single set of data input; from the results the most practical and economical solutions can be selected. The complete mine layout and ventilation network can be stored and easily updated, either on a daily basis, as mining progresses, or used for accurate long term planning.

Proposed underground facilities may also be designed using ventilation software. Such simulations are conducted by incorporating physical input data from conceptual plans with documented design parameters used to determine estimated resistance of airways in the network. The range of fan duties required, airflows, pressure drops, operating costs, and the location of ventilation controls may then be ascertained for the entire duration of a project by conducting time-phase exercises.

A number of programs have been developed and widely used by mining organisations. A description of typical features found in ventilation network software are listed below.

Options within commercial software allow for the display of on-screen schematics, production of listings, output files, and plots of input and output data so that the modeling procedure can be thoroughly documented.

Typical software is full-colour, interactive and capable of producing 3D network schematics. Network views by plan, cross-section or longitudinal section can also be generated.

Typical commercial software incorporates a number of tabular views, used to facilitate rapid data entry, and allow the user to copy and paste data between Windows applications. Drawing views, fully interactive with the mouse, are normally available to allow the user to easily develop and manipulate networks. Data import features, DXF import, allows networks to be developed as Lines, Polylines, and Text, and to be imported into the program as levels/groups of data, or as an entire mine. Fan curve and fan file managers are used to enter fan curves in a tabular format and to identify combined fan operations.

The data input requirements include 3D junction coordinates, airway branch properties (resistances or dimensions) and fan curve data (pressure and flow). Output of the various ventilation parameters is provided in graphical and tabular representations.

It is important to note that the analysis, conclusions and recommendations presented in any design project is dependent on the proper validation of the mine ventilation layouts, quality of ventilation survey data available and on the validation of the operating conditions of all mine fans. Any decisions to be made from computer based designs should always be backed by other methods of engineering analysis and design calculations.

## 9. CASE APPLICATIONS

The use of network analysis is illustrated in Figure 2. Ventilation surveys are first performed to evaluate airflows, pressures, resistances, natural ventilation, air densities and air quality. This data is used to update the ventilation plans and also forms the input data for a ventilation network program. The engineer will then prepare several ventilation strategies and than simulate those plans using the computer for short and long term planning and decide the most effective, practical and economical alternative. As the mine continues to develop, ventilation surveys are updated and the process is repeated for updating the developed ventilation plans and strategies. This approach to ventilation planning is simple and if properly applied will undoubtedly improve the efficiency of a mine ventilation department.

The author has been involved on a series of projects aimed at designing new ventilation systems or at improving existing systems for mines throughout North America. Typical applications include ventilation system expansion, the design of ventilation airways, and the design of new fan installations.

Figure 3 presents the ventilation network developed for an operating mine. The study program for this operating mine was established to improve the ventilation layout to a system capable of safely sustaining current mining operations. A study of system upgrade requirements indicated that the flow volume supply to the mine had to be doubled. Major changes to the ventilation infrastructure had to be designed and modelled.

Standard procedures were used to develop the ventilation network. To develop the model, the latest ventilation survey plans compiled by the mine personnel were reviewed. Initially, a basic framework was developed based on the detailed mine block plans. Branches and junctions were established and numbered and coordinates were assigned for each junction. Ventilation properties for each branch were also compiled based on previous studies.

To assess the model's accuracy, the basic network models results were compared to ventilation survey results performed at the mine. Two parameters were used for comparison purposes, the airflow in key branches and the operating point of the surface and underground booster fans.

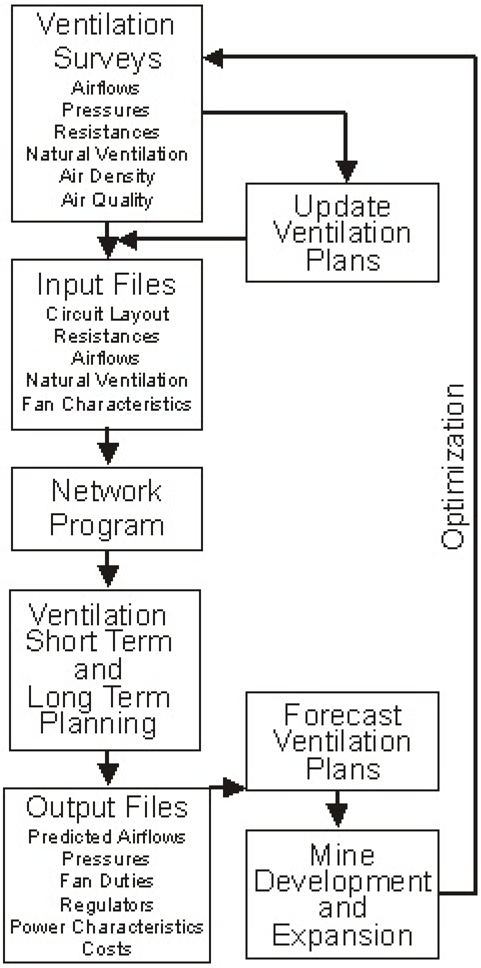

Fig. 2. Network analysis in ventilation design.

Model calibration was performed in an iterative process, making one change at a time, so that the correlation between the model and survey results were within 10% for the majority of the parameters.

A series of ventilation modeling scenarios were the developed as part of the mine upgrade ventilation study. An optimum layout was arrived through an evaluation of alternatives in which the most practical and economical system was selected. The recommended implementations were successfully performed at the mine and the model was validated for use in future ventilation planning exercises.

## 10. CONCLUSIONS

Procedures for the successful development of computer based ventilation network models have been presented in this paper. Computer models can be used to aid in the design and optimization of future ventilation system requirements at an operating mine. Simulations for long term plans can be developed to size and distribute any required appliances (fans, doors, regulators, etc.) in the network in order to meet airflow and health and safety requirements during different stages of the mine life.

Users of ventilation modeling software should be aware that incorrect use of computer models could result in serious implications. A calibrated model needs to be continually refined, maintained and updated as the mine ventilation system changes, in order to be acceptably used in ventilation planning exercises.

## REFERENCES

Abbas, S.F. and Scheck, D.E. (1991). Enhanced ventilation simulators. In: *5th US Mine Ventilation Symposium* (Y.J. Wang, Ed.). pp. 551-555. SME, Littleton.

Bhamidipati, S.S. and Procarione, J.A. (1985). Linear analysis for the solution of flow distribution problems in mine ventilation networks. In: *2nd US Mine Ventilation Symposium* (P. Mousset-Jones, Ed.). pp. 645-654. A.A. Balkema, The Netherlands.

Burrows, J., Hemp, R., Holding, W. and Stroh, R.M. (1989). *Environmental Engineering in South African Mines*. Mine Ventilation Society of South Africa.

Hardy, R.J. and Heasley, K.A. (2006). Ventilation simulation programs Mine Vent and MFIRE: Updates to advance the technology of simulation programming. In: *11th U.S./North American Mine Ventilation Symposium* (J.M. Mutmansky and R.V. Ramani, Eds.). pp. 477-482. Taylor & Francis, The Netherlands.

Marx, W.M. (1999). Environ 2.5 - A mine ventilation and cooling network simulation tool. In:*8th US Mine Ventilation Symposium* (J.C. Tien, Ed.). pp. 565-570. UMR, Missouri.

Marx, W.M., von Glehn, F.H., Bluhm, S.J. and Biffi, M. (2001). Vuma - a mine ventilation and cooling network simulation tool. In:*7th International Mine Ventilation Symposium* (S. Wasilewski, Ed.). pp. 317-324. EMAG, Poland.

McPherson, M.J. (1993). *Subsurface ventilation and environmental engineering*. Chapman & Hall, London.

Mutmansky, J.M. and Kim, J. (1993). A study of mesh ordering techniques for mine ventilation network solution methods. In: *6th US Mine Ventilation Symposium* (R. Bhaskar, Ed.). pp. 163-170. SME, Littleton.

Ramani, R.V. (1982). Application of computers to ventilation. In: *Mine Ventilation and Air Conditioning* (H.L. Hartman, J.M. Mutmansky and Y.J. Wang, Eds.). pp. 517-545. John Wiley & Sons.

Sasaki, K. and Dindiwe, C. (2002). An integrated mine ventilation simulator "MIVENA Ver.6" with applications. In: *North American/Ninth US Mine Ventilation Symposium* (E. De Souza, Ed.). pp. 243-251. Swets & Zeitlinger, The Netherlands.

Wang, Y.J. (1982). Ventilation Network theory. In: *Mine Ventilation and Air Conditioning* (H.L. Hartman, J.M. Mutmansky and Y.J. Wang, Eds.). pp. 483-516. John Wiley & Sons.

Wang, Y.J., Hartman, H.L. and Mutmansky, J.M. (1985). Recent developments in mine ventilation network theory and analysis. In:*2nd US Mine Ventilation Symposium* (P. Mousset-Jones, Ed.). pp. 667-676. A.A. Balkema, The Netherlands.

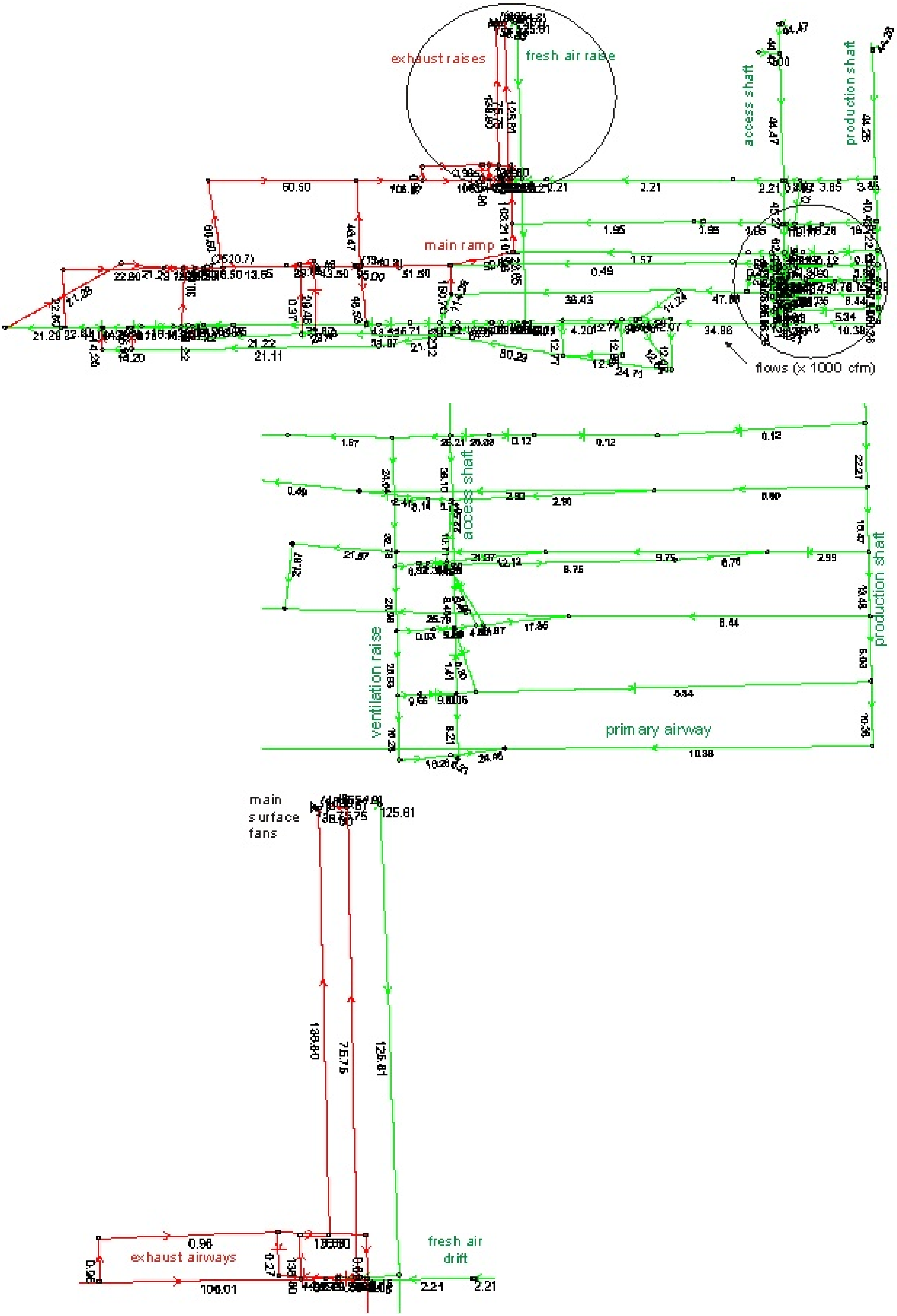

Fig. 3. Computer ventilation network model for an operating underground mine.