Alternate solutions for mine ventilation network to keep a pre-assigned fixed quantity in a working place

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Abstract  In underground constructions, a good ventilation design not only delivers fresh air to establish good working environment, but also provides a scientific and reliable basis to prevent disasters. In emergency cases, unexpected closure of the main airways may occur, providing the workers with alternative airways is substantial. This is important not only to sustain personnel lives, but also to prevent the mine ventilation system from damage. In this research, alternate solutions were introduced in case of failure in the underground construction to keep a pre-assigned fixed quantity in a working place for mine ventilation network. Eight different collapse scenarios were proposed to study their effect on the air quantity distribution among the branches in the ventilation circuit. From these scenarios, it is found that providing a sufficient air quantity in the working places could be achieved through modification of the network topology and adjusting the values of the regulators pressure. It is also indicated that the distance between the collapse and working places has a great effect on the amount of air delivered to it. A reduction in the power consumption could be done by re-arrange the installed regulators and decreasing the number of nodes and branches inside the network. A relationship representing the effect of changing the network topology on the total network power consumption was deduced through regression analysis. It is found that the total network power is quadratic dependent on the number of regulators and number of branches while it is directly dependent on the regulator power.

Keywords  Mine ventilation network · Power consumption through mine ventilation networks · Regulators adjustment · Nonlinear optimization · Air flow control

1 Introduction

A good mine ventilation design should maintain adequate airflow through mine working areas all the time even in case of emergency. It does not only conform to the safety and health standards and federal regulations, as defined by the Mine Safety and Health (MSHA), but also lower the cost of air supply (U.S. Code of Federal Regulations 2014). Providing continuous fresh air to the mine dilutes and removes noxious gas and dust. It also adjusts the climate in the underground mine workings, and consequently establishing a good working environment (Sui et al. 2011). Mining accidents may have a variety of causes, including leakage of poisonous gases (such as hydrogen sulfide) or explosive natural gases, especially firedamp or methane, or gas outburst or gas explosion, dust explosions, collapsing of minestopes, mining-induced seismicity, flooding, or common mechanical errors from improperly used or malfunctioning mining equipment (safety lamps or electrical equipment). The improper use of explosives underground can also cause methane and coal-dust explosions (Terazawa et al. 1985; Kucuker 2006).

Thousands of miners die from mining accidents each year, especially in the processes of coal and hard rock mining. Deaths nowadays not only occur in underdeveloped countries and their rural parts, but also in developing
The main objective of the nonlinear programming model is to minimize the overall air power consumed through the network.
mine ventilation network, $Z$. The air power is supplied by the fans and can be expressed as

$$ z = \sum_{j=1}^{B} t_j |q_j|, \quad (1) $$

where $B$, $q_j$, and $t_j$ are, number of branches, air quantity, and fan pressure in branch $j$, respectively. The overall air power is used to overcome branch and regulator pressure losses. Alternatively, it can be expressed as

$$ z = \sum_{j=1}^{B} \left( r_j q_j^2 |q_j| + s_j |q_j| \right) \quad (2) $$

where $r_j$ and $s_j$ are the resistance factor and regulator pressure in branch $j$, respectively.

### 2.2 Constraints from KVL and KCL

Mine ventilation system, as a network, must obey or comply with Kirchhoff’s current law (KCL) and Kirchhoff’s voltage law (KVL). Accordingly, the algebraic sum of all pressure drops in a closed loop must equal zero (Wang 1983).

$$ \sum_{j=1}^{B} a_{ij} q_j = 0, \quad i = 1, 2, \ldots, N - 1 \quad (3) $$

$$ \sum_{j=1}^{B} b_{ij} \left[ r_j |q_j| q_j + s_j t_j - H_j \right] = 0, \quad i = 1, 2, \ldots, M \quad (4) $$

where $a_{ij}$ is the element of the reduced-incident matrix; $N$ is the number of nodes; $b_{ij}$ is the element of the fundamental mesh matrix; $M$ is the number of the fundamental meshes $(M = B - N + 1)$ and $H_j$ is the natural ventilation pressure in branch $j$. $|q_j| q_j$ is used instead of $q_j^2$ in order to preserve negative values if present. An additional constraint is the required air flow in each branch; this could be formulated as follows:

$$ q_j^L > q_j > q_j^U \quad (5) $$

where $q_j^L$ and $q_j^U$ are lower and upper limits for air quantity flow in branch $j$, respectively.

### 3 Problem formulation

To study the effect of isolation of a part of a mine on the stability of mine ventilation system, a network shown in Fig. 1 was solved using LINGO optimization software, version 14.0.1.58. This network example (Huang and Wang 1993a, b) consists of 53 branches, 23 nodes and three main fans installed in branches 51, 52 and 53. The mathematical formulation for this problem is a NLP, which entails 4 linear and 64 non-linear variables. The total number of constraints for air quantity flows, regulators and fan power are 191, where 32 of them are nonlinear constraints.

Eight different scenarios were created. The first five (A, B, C, D and E) are failure scenarios at different nodes 6, 7, 8, 3 and 21 respectively as shown in Fig. 1. All scenarios are solved two times, firstly, when the collapse happened and secondly, to keep the air quantity fixed at branch number 26 to be 40 m$^3$/s. The total air quantity input to the network ($q_1$) is maintained fixed as in case before failure; $q_1 = 318.5$ m$^3$/s. This can be done by redistributing that air quantity among airways via changing the values of regulators installed in regulator branches as listed in Table 1. Delivering more quantities from the main fans or constructing new regulators in different airways, which may take a long time especially in case of emergencies, is not applicable. The air quantities in each branch in both cases for each scenario are shown in Fig. 2.

The last three scenarios Fig. 3 are designed to study the effect of the number of branches, nodes, regulators and regulator power, on the total power consumed by the main fans in the mine ventilation system. These three scenarios have been postulated by removing nodes 7, 12 and 17 and their associated branches respectively.

### 4 Results and discussion

#### 4.1 Effect of isolation of a part of a mine on the air quantity in a fixed quantity branch

Isolation of a part of a mine could be due to fire, a roof collapse, gas outburst, gas explosion or any kind of emergency. Obviously, Air flow delivered to the branches in the network will be affected by this isolation. Air flow distribution among different airways in the system in all scenarios is shown in Fig. 2. Removing node 8, scenario
Table 1 Data used and results for the scenarios

| No. ($r_j$) | $r_j$ (Ns/m^8) | Original solution | Scenario A failure @ node 6 | Scenario B failure @ node 7 | Scenario C failure @ node 8 |
|-------------|----------------|-------------------|-----------------------------|-----------------------------|-----------------------------|
|             |                |                   | Failure Fixed $q_{26}$      | Failure Fixed $q_{26}$      | Failure Fixed $q_{26}$      |
|             |                |                   | $q_j$ (m^3/s) $S_i$ (Pa) | $q_j$ (m^3/s) $S_i$ (Pa) | $q_j$ (m^3/s) $S_i$ (Pa) |
| 1           | 0              | 318.5 No          | 318.5 No 318.5 No          | 318.5 No 318.5 No          | 318.5 No 318.5 No          |
| 2           | 0.0308         | 93.5 No           | 87.7 No 89 No              | 104 No 104 No              | 97 No 100.7 No             |
| 3           | 0.0118         | 136 No            | 136.2 No 137 No            | 121.5 No 121.5 No          | 136.7 No 137.2 No          |
| 4           | 0.0415         | 89 No             | 94.6 No 92.5 No            | 93 No 93 No                | 84.9 No 80.6 No            |
| 5           | 0.0555         | 30.5 No           | 18.1 No 20.2 No            | 53.5 No 53.5 No            | 35.3 No 40.3 No            |
| 6           | 0.04           | 52.7 No           | 61.7 No 57.7 No            | 67.9 No 67.9 No            | 44.3 No 34.4 No            |
| 7           | 0.0617         | 44.1 No           | 91.8 No 94.7 No            | 61.3 No 61 No              | 48.9 No 51.6 No            |
| 8           | 0.0237         | 69 No             | 0.1 No 0.1 No              | 96.1 No 96.5 No            | 72.2 No 77.7 No            |
| 9           | 0.7            | 10.8 No           | 13.9 No 14.4 No            | 0.1 No 0.1 No              | 11.2 No 11.7 No            |
| 10          | 0.048          | 52.8 No           | 56.4 No 59.1 No            | 0.1 No 0.1 No              | 57.1 No 62.4 No            |
| 11          | 0.165          | 11.7 No           | 1 No 14.5 No               | 0.1 No 0.1 No              | 21.6 No 29.1 No            |
| 12          | 0.404          | 30 –1034 No       | 42.2 –659 No –1336          | 55.3 0 58.4 0              | 47.6 0 44.7 453            |
| 13          | 0.04           | 57.9 No           | 64.2 No 65.6 No            | 60.1 No 59.2 No            | 0.1 No 0.1 No              |
| 14          | 0.125          | 42.1 No           | 49 No 50.1 No              | 45.3 No 43.1 No            | 59.7 No 41.2 No            |
| 15          | 0.06           | 10.9 No           | 0 No 0 No                  | 14.8 No 12.1 No            | 19.8 No 18.7 No            |
| 16          | 0.075          | 20.3 No           | 0.1 No 0.1 No              | 0 No 0.1 No                | 22 No 24.9 No              |
| 17          | 0.111          | 27.9 No           | 34.9 No 35.8 No            | 31.8 No 28.9 No            | 0 No 0.1 No                |
| 18          | 0.425          | 25 –1009 No       | 38.7 0 41 0                | 43.7 0 47.1 0              | 39.5 0 46.6 0              |
| 19          | 0.75           | 30 No             | 53.1 No 53.8 No            | 32.4 No 25.9 No            | 29.2 No 23.8 No            |
| 20          | 0.65           | 40 –649 No        | 0.1 –1.2 0.1 –154          | 45.6 0 46.7 0              | 43.3 0 48.2 0              |
| 21          | 0.815          | 38.5 –105 No      | 0.1 –1.2 0.1 –66           | 0.1 0 37.8 0               | 31 0 35.7 0                |
| 22          | 1.75           | 20 –644 No        | 28.1 0 28.9 0              | 0.1 –1.3 0.1 –133          | 21.7 0 24.9 0              |
| 23          | 1.25           | 20 –874 No        | 18.9 –933 34.2 0           | 0.1 –1.3 0.1 –144          | 25.9 0 30 0                |
| 24          | 2.4            | 15 –877 No        | 24.2 0 24.8 0              | 0.1 –1.3 0 –1281           | 20.5 0 23.4 0              |
| 25          | 1.45           | 30 0              | 29.3 0 29.8 –45.3          | 28.3 0 30.3 0              | 0.1 –1.9 0 –1248           |
| 26          | 0.65           | 30 –838 No        | 45 0 45.9 0                | 42 0 32 –741               | 34.6 0 1.2 –1500           |
| 27          | 0.55           | 40 –431 No        | 38.9 –431 40 –431          | 35.2 –431 40 –431          | 25.1 –431 40 –431          |
| 28          | 0.35           | 9.6 No            | 31.8 No 31.4 No            | 24.4 No 24.5 No            | 16.7 No 16.7 No            |
| 29          | 0.3           | 10 No             | 1 No 1 No                  | 5.9 No 8.1 No              | 7.3 No 10.9 No             |
| 30          | 0.405          | 10.2 No           | 8.4 No 3.8 No              | 12.9 No 15.4 No            | 20.6 No 21.9 No            |
| 31          | 0.5            | 13.6 No           | 17.6 No 15.5 No            | 11.4 No 11.8 No            | 16.5 No 11.6 No            |
| 32          | 0.1975         | 45.4 No           | 60 No 63.3 No              | 51.7 No 48.6 No            | 52 No 53.6 No              |
Table 1 continued

| No. (rj) | rj (Ns²/m⁸) | Original solution | Scenario A failure @ node 6 | Scenario B failure @ node 7 | Scenario C failure @ node 8 |
|----------|-------------|-------------------|-----------------------------|-----------------------------|-----------------------------|
|          |             |                   | Failure Fixed q₂₆           | Failure Fixed q₂₆           | Failure Fixed q₂₆           |
|          |             |                   | qj (m³/s) Sj (Pa)           | qj (m³/s) Sj (Pa)           | qj (m³/s) Sj (Pa)           |
| 33       | 1.3         | 22.7              | No 25.2 No 24 No           | No 21.3 No 22 No           | No 23.2 No 24.9 No         |
| 34       | 0.667       | 15                | No 14.4 No 13.8 No         | No 13.6 No 14.8 No         | No 16.8 No 18.6 No         |
| 35       | 0.048       | 49.8              | No 53.7 No 51.4 No         | No 48.5 No 51.2 No         | No 60.1 No 63.7 No         |
| 36       | 0.5         | 12.4              | No 14.8 No 15.6 No         | No 9.5 No 7.7 No           | No 1 No 1 No              |
| 37       | 0.24        | 29.2              | No 29.5 No 27.3 No         | No 20.3 No 26.3 No         | No 23.7 No 32.7 No         |
| 38       | 0.08        | 53.6              | No 56.5 No 55.5 No         | No 46.6 No 51.8 No         | No 41.6 No 51.6 No         |
| 39       | 0.0305      | 36.3              | No 24 No 24.9 No           | No 42.5 No 42 No           | No 40.7 No 43.6 No         |
| 40       | 4           | 5.6               | No 5 No 3.8 No             | No 3.7 No 5.8 No           | No 5.8 No 8 No             |
| 41       | 1           | 10.9              | No 14.2 No 13.7 No         | No 11.8 No 10.9 No         | No 11.8 No 4.8 No          |
| 42       | 0.056       | 49.2              | No 36.2 No 38.5 No         | No 54.9 No 53.3 No         | No 54.7 No 58.2 No         |
| 43       | 0.0297      | 56.6              | No 43.3 No 46.4 No         | No 61.9 No 59.6 No         | No 62.7 No 66.6 No         |
| 44       | 1.625       | 14.9              | No 13.4 No 15.7 No         | No 15 No 12.9 No           | No 16 No 16.3 No           |
| 45       | 0.25        | 45.6              | No 52.5 No 50.1 No         | No 43.1 No 43.9 No         | No 45.3 No 47.9 No         |
| 46       | 3           | 11                | No 12.1 No 11.2 No         | No 9.8 No 11 No           | No 10.9 No 11.1 No         |
| 47       | 0.08        | 54                | No 65.2 No 63.3 No         | No 54.1 No 53.3 No         | No 52.3 No 37.2 No         |
| 48       | 0.0277      | 64.5              | No 70.7 No 69.2 No         | No 58.4 No 62.7 No         | No 53.5 No 56.4 No         |
| 49       | 0.6         | 16.3              | No 25.7 No 19.4 No         | No 12.9 No 18.8 No         | No 12.7 No 15.6 No         |
| 50       | 0.25        | 25.3              | No 31.6 No 31.5 No         | No 26.7 No 21.8 No         | No 25.2 No 28.8 No         |
| 51       | 0.0159      | 104.4             | 2380 67.2 2251 81.2 2486   | 118.8 2299 106.9           | 2313 120.6 2033 125.5 2404 |
| 52       | 0.0123      | 110               | 2515 135 2800 125.1 2800   | 104 2307 106.5 2484        | 2484 106.4 2038 117.2 2469 |
| 53       | 0.035       | 104.1             | 2586 113.3 2800 112.2 2800 | 95.7 2317 105.1 2612       | 2612 91.5 2033 75.8 2295  |

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| No. ($r_j$) | $r_j$ (Ns²/m⁸) | Original solution | Scenario D failure @ node 3 | Scenario E failure @ node 21 |
|-------------|----------------|------------------|----------------------------|----------------------------|
|             |                | Air flow $q_j$ (m³/s) | Regulator $S_i$ (Pa) | Failure | Fixed $q_{26}$ | Failure | Fixed $q_{26}$ |
| 9           | 0.7            | 10.8             | No                        | 16.6  | No  | 13.2  | No  | 10.9  | No  |
| 10          | 0.048          | 52.8             | No                        | 0.1   | No  | 0.1   | No  | 55.5  | No  |
| 11          | 0.165          | 11.7             | No                        | 18.2  | No  | 31.8  | No  | 18.9  | No  |
| 12          | 0.404          | 30               | −1034                     | 46.6  | 0   | 54    | 0   | 23.5  | −595 |
| 13          | 0.04           | 57.9             | No                        | 50.5  | No  | 34.8  | No  | 51.4  | No  |
| 14          | 0.125          | 42.1             | No                        | 38.1  | No  | 24.9  | No  | 39.4  | No  |
| 15          | 0.06           | 10.9             | No                        | 16.3  | No  | 44.2  | No  | 20.8  | No  |
| 16          | 0.075          | 20.3             | No                        | 1     | No  | 29.7  | No  | 21.3  | No  |
| 17          | 0.111          | 27.9             | No                        | 26.8  | No  | 16.1  | No  | 28.3  | No  |
| 18          | 0.425          | 26               | −1009                     | 38.9  | 0   | 11.9  | 0   | 40.5  | 0   |
| 19          | 0.75           | 30               | No                        | 35.6  | No  | 102.8 | No  | 28.5  | No  |
| 19          | 0.65           | 40               | −649                      | 43.1  | 0   | 42.7  | 0   | 50.2  | 0   |
| 20          | 0.815          | 38.5             | −105                      | 31.8  | 0   | 32    | 0   | 20.8  | −371 |
| 21          | 1.75           | 20               | −644                      | 3.4   | −803| 7.6   | −802| 20.8  | 0   |
| 22          | 1.25           | 20               | −874                      | 11.6  | −656| 1     | −1012| 24.6  | 0   |
| 23          | 2.4            | 15               | −877                      | 19    | 0   | 6.9   | −1046| 18.5  | 0   |
| 24          | 1.45           | 30               | 0                         | 23.7  | 0   | 18.6  | −775| 23.2  | 0   |
| 25          | 0.65           | 30               | −838                      | 36.8  | 0   | 1     | −1499| 37.8  | 0   |
| 26          | 0.55           | 40               | −431                      | 28.1  | −431| 40    | −431| 28.8  | −431|
| 27          | 0.35           | 9.6              | No                        | 21.7  | No  | 43.4  | No  | 1     | No  |
| 28          | 0.3            | 10               | No                        | 1     | No  | 19.2  | No  | 1.3   | No  |
| 29          | 0.405          | 10.2             | No                        | 10    | No  | 19    | No  | 12.6  | No  |
| 30          | 0.5            | 13.6             | No                        | 16    | No  | 11.2  | No  | 21.5  | No  |
| 31          | 0.1975         | 45.4             | No                        | 52.8  | No  | 71.3  | No  | 68.1  | No  |
| 32          | 1              | 20.4             | No                        | 20.9  | No  | 20.6  | No  | 31.4  | No  |
| 33          | 1.3            | 22.7             | No                        | 21.7  | No  | 23.6  | No  | 0     | No  |
| 34          | 0.667          | 15               | No                        | 13.2  | No  | 19.6  | No  | 9.9   | No  |
| 35          | 0.048          | 49.8             | No                        | 49.2  | No  | 55.3  | No  | 36.8  | No  |
| 36          | 0.5            | 12.4             | No                        | 12.3  | No  | 1     | No  | 1     | No  |
| 37          | 0.24           | 29.2             | No                        | 24.3  | No  | 32.3  | No  | 31.8  | No  |
| 38          | 0.08           | 53.6             | No                        | 44.1  | No  | 51.2  | No  | 51.4  | No  |
| 39          | 0.0305         | 36.3             | No                        | 41.3  | No  | 50.4  | No  | 49.2  | No  |
| 40          | 4              | 5.6              | No                        | 4.1   | No  | 7.9   | No  | 7.8   | No  |
C, represents the closest failure node to branch 26 while removing node 6, scenario A, is the furthest distance as shown in Fig. 1. It should be recognized that, the total air quantity delivered through the whole system is fixed (318.5 m$^3$/s) in all scenarios. Figure 4 shows the air quantity in branch 26 in all failure scenarios. Air quantity in branch 26 dropped from 40 m$^3$/s in the main scenario, before failure, to 25.1 m$^3$/s when the failure happened at node 8. This indicates the extent of the risk that workers might be confronted if the collapse is close to workplaces. On the other hand, a small drop in the air quantity, 38.9 m$^3$/s, happened when the collapse occurred in node 6. Failure at entrance or exit of the mine has almost the same effect on the air quantity of branch 26 (around 28 m$^3$/s), as shown in scenarios D and E in the same figure.

4.2 Effect of isolation of a part of a mine on the values of regulators pressure

Although regulators are installed in mine ventilation networks to control the distribution of air quantities among airways, they may increase the total pressure in the network. Consequently, this may increase the power delivered from the fans. Thus, a good mine ventilation design has an adequate number of regulators installed to deliver the pre-assigned values of air quantities (Wang et al. 1985). Figure 5 shows the sum of the values of the consumed pressure through regulators in each scenario to keep the air quantity fixed at branch 26 as in the main case. An improvement in the value of the pressure consumed through regulators is recognized in all scenarios. The main case represents the worst pressure consumed (~4742 Pa), while scenario with failure at node 6 represents the best, ~1556 Pa. This reduction in the consumed pressure may be due to the reduction in the number of airways resulting from the collapse.

4.3 Effect of isolation of a part of a mine on the power consumed

As shown in Fig. 6, the first five scenarios are not enough to study the effect of the network topology on the power consumed through the mine ventilation networks. The relation between the power in the main case (794 kW) before failure and the power in case of failure is not clear. It sometimes increases, as in scenarios A and D, or decreases as in scenarios C and E. In other cases, it may be almost the same as in scenario B. On the other hand, there is a recognized rise in the power consumption between all the cases of failure and that in cases of fixing...
air quantity at branch 26 at each node. In case of failure, the total power increased from 846.5, 734.8, 648.0, 829.8 and 641.1 kW to 866.3, 786.3, 765.0, 891.8 and 680.1 kW for a fixed quantity at branch 26 in scenarios A, B, C, D and E respectively. Therefore, three more scenarios have been introduced as shown in Fig. 3 to study the effect of changing the number of nodes and their associated branches on the power consumed through the mine ventilation networks. In these new scenarios, the number of airway branches have been reduced from 53 to 48, 45 and then to 41 by removing nodes 7, 12 and 17 respectively. Reducing the number of nodes and their connected branches has a great effect on reducing the power consumed through the network as shown in Fig. 7. The reduction in power may reach 50 % from the 53 branches (the main case) to the case of 41 branches.

On the other hand, there is a recognized saving in the power when more regulators are allowed to be installed in the network to keep the same air quantity passing through branch 26. A relation representing the effect of independent variables (number of branches; $B$, number of regulators; $N_r$, and power losses through the regulator, $S$ on the total power consumption, $Z$ for the network in kW has been developed through regression analysis of the real data as following:

$$Z = B(1.86B - 12.43N_r - 73.18) + N_r(332.79 + 16.36N_r) - 0.07S + 605.02$$

$R^2$ for the introduced correlation was found to be 0.97. That introduced correlation has been extracted from output results for networks of 53, 48 and 45 branches. An additional case of 41 branches has been taken to test and validate that correlation. The crossplots representing the predicted versus real values for total power at various number of branches, with different number of regulators and regulator power is shown in Fig. 8. It could be seen from this figure that there is an excellent agreements between models predicted values and real data. The plotted data points obtained by the new
correlations are quite close to the perfect correlations of the 45° line. This shows that the introduced correlation is able to predict the total power consumed at different number of branches, number of regulators and power consumed through regulators (Lazic 2004).

Fig. 3 Network layouts for scenarios 6, 7 and 8, respectively

Fig. 4 Effect of distance from collapse on the air quantity in branch

Fig. 5 Sum of the regulators pressure installed in each scenario

Fig. 6 Power consumed in each scenario

Fig. 7 Effect of changing the topology of the network on the consumed power
5 Conclusions

Based on the air distribution requirements of the underground ventilation network, an optimization program is introduced, using LINGO optimization software, version 14.0.1.58. The effect of roof collapse and other kinds of failure on the stability of mine ventilation system have been studied using a theoretical mine ventilation network. Eight different scenarios were designed to study the effect of mine ventilation topology on the power consumption. This study verified that: a fixed air quantity can be held in the working place by adjusting the amount of regulators in the regulator branches, without any change in the total amount of air delivered to the mine or installing any new regulators. These adjustments in regulators quantities not only deliver the required amount of air to the working places but also reduce the power required through the mine ventilation network. An equation representing the effect of number of branches, number of regulators and power losses through them, on the total power consumption for the network has been given.

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