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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

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states. On April 5, 2010: Upper Big Branch Mine disaster, West Virginia, United States. An explosion occurred in Massey Energy's Upper Big Branch coal. Twenty-nine out of thirty-one miners at the site were killed. November 19, 2010: Pike River Mine disaster in New Zealand. The coal mine exploded. Twenty-nine men underground died immediately, or shortly afterwards, from the blast or from the toxic atmosphere. May 13, 2014: Soma mine disaster took place in Soma, Turkey. The accident, called the worst mining accident ever in Turkey, and it is the worst mining accident in the 21st century so far. 301 people died and at least 80 workers were injured (Mining-Technology 2014; Retzer 2014; Schleifer 2014).

Distribution of air flow among the airways in mine ventilation systems may occur either naturally or by adding control devices (fans or regulators). Natural splitting occurs when the air flows in airways of a ventilation system divided among airways according to their aerodynamic resistance. For controlled splitting, a prescribed quantity of air flow is circulated through each or some of the airways. In practice, most mine ventilation systems utilize controlled splitting (Wang 1990). To eliminate the risk of mine ventilation hazards, novel optimization scheme alternatives for the complex network variables should be adopted to be rapidly applied in case of emergency to eliminate hazards. Therefore, determination of the locations and sizes of these ventilation control devices representa main challenge in design and analysis of mine ventilation systems (Wang et al. 1985; Wu and Topuz 1987).

Mathematically, a mine ventilation network problem is defined by a system of network equations and variables. The variables usually include air quantities, regulator pressure losses and fan pressures. The general rules for building an optimal mathematical model of a ventilation network are to satisfy: (i) Kirchhoff's current and voltage laws, and (ii) Atkinson's equation.

For a network that has N nodes and B branches, there will be at least B independent network equations in N variables. Several operations research methods have been applied to determine locations and sizes of ventilation control devices in the mine ventilation networks, including linear programming, network analysis, nonlinear programming, and simulation (Wang 1982, 1984; Bhamidipati and Topuz 1983; Wu and Topuz 1987; Hu and Longson 1990; Wu 1991; Kumar et al. 1995; El-Nagdy 2013; Nyaaba et al. 2014).

In this work, possible alternate solutions have been discussed in case of failure in the underground construction for a theoretical mine ventilation network. The effect of roof collapses or area isolation on the air quantity distribution among the branches in the ventilation circuit is also investigated. This work does not only study the effect of mine ventilation network topology changes on the power consumed but also sustaining the air quantity in the fixed quantity branch unchanged regardless the location and the size of failure. This can be done by modifying the topology and adjusting the regulators used according to the air quantity flow through them.

An ideal solution should satisfy the necessary air flow distribution and a predefined objective. The applicable objectives are minimizing the power consumption, accordingly, minimizing the overall cost of ventilation. The aims of this work are:

(1) To study the effects of isolating a part of a mine on the stability of mine ventilation system.
(2) To keep the air quantity unchanged in the fixed quantity branch while delivering a sufficient air quantity enough to sustain the workers lives in case of emergency.
(3) To minimize the power consumed.
(4) To formulate a relation between themine ventilation topology and the total power consumed through the network.

2 Research theory fundamental

In normal ventilation situation, the target is safe, economic and feasible. Safety and feasibility are usually reflected from the required airflow quantity, the lower and upper limit of airflow quantity and control variable and the controllability of branches. Thus, the objective function of optimum control problem usually considers economic aspect at first. That is, to make the ventilation fee as less as possible. During emergencies, the economic factor is minor and the difficulty of control facility installation is relatively important. So that, the optimization during mine crisis period mainly aims to make the number of control facilities as less as possible and the control quantity as lower as possible, which is convenient for temporary control measures. Because the control facility number is the calculated number of branches whose control variables are not zero. Then it is an object optimization problem about integer programming, which is difficult to get the result. In order to simplify the solving process, it is necessary to combine control variables and control facility number into one objective function and make the optimum scheme which is a kind of compromise between them. However, it is not easy to find an idea objective function (Wu and Li 1993). Depending upon these hypotheses the main objective function in this model will be a compromise to include economic and safety factors.

2.1 Objective function

The main objective of the nonlinear programming model is to minimize the overall air power consumed through the mine ventilation network, Z. The air power is supplied by the fans and can be expressed as

$$z = \sum_{j=1}^{B} t_j |q_j|. \tag{1}$$

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

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

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).

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

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

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:

$$q_j^L > q_j > q_j^U \tag{5}$$

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.

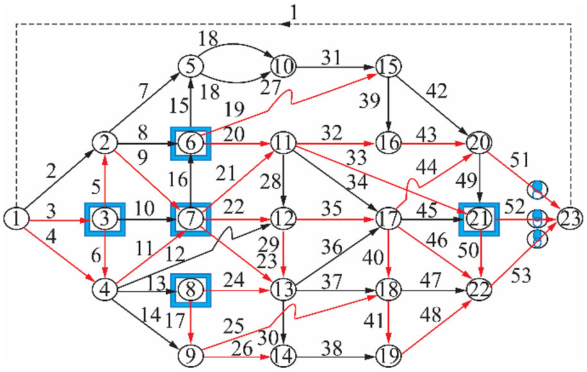

Fig. 1 Network layout with collapse at suggested node shown

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^2/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}	
		Air flow q_j (m^3/s)	Regulator S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	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	42.2	−659	20	−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	38.7	0	41	0	43.7	0	47.1	0	39.5	0	46.6	0
18\	0.75	30	No	53.1	No	53.8	No	32.4	No	25.9	No	29.2	No	23.8	No
19	0.65	40	−649	0.1	−1.2	0.1	−154	45.6	0	46.7	0	43.3	0	48.2	0
20	0.815	38.5	−105	0.1	−1.2	0.1	−66	0.1	0	37.8	0	31	0	35.7	0
21	1.75	20	−644	28.1	0	28.9	0	0.1	−1.3	0.1	−133	21.7	0	24.9	0
22	1.25	20	−874	18.9	−933	34.2	0	0.1	−1.3	0.1	−144	25.9	0	30	0
23	2.4	15	−877	24.2	0	24.8	0	0.1	−1.3	0	−1281	20.5	0	23.4	0
24	1.45	30	0	29.3	0	29.8	−45.3	28.3	0	30.3	0	0.1	−1.9	0	−1248
25	0.65	30	−838	45	0	45.9	0	42	0	32	−741	34.6	0	1.2	−1500
26	0.55	40	−431	38.9	−431	40	−431	35.2	−431	40	−431	25.1	−431	40	−431
27	0.35	9.6	No	31.8	No	31.4	No	24.4	No	24.5	No	16.7	No	16.7	No
28	0.3	10	No	1	No	1	No	5.9	No	8.1	No	7.3	No	10.9	No
29	0.405	10.2	No	8.4	No	3.8	No	12.9	No	15.4	No	20.6	No	21.9	No
30	0.5	13.6	No	17.6	No	15.5	No	11.4	No	11.8	No	16.5	No	11.6	No
31	0.1975	45.4	No	60	No	63.3	No	51.7	No	48.6	No	52	No	53.6	No
32	1	20.4	No	19.4	No	21.5	No	19.4	No	17.6	No	22.1	No	23	No

Table 1 continued

No. (r_j)	r_j (Ns^2/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}	
		Air flow q_j (m^3/s)	Regulator S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j(m^3/s)	S_i (Pa)	q_j(m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)
33	1.3	22.7	No	25.2	No	24	No	21.3	No	22	No	23.2	No	24.9	No
34	0.667	15	No	14.4	No	13.8	No	13.6	No	14.8	No	16.8	No	18.6	No
35	0.048	49.8	No	53.7	No	51.4	No	48.5	No	51.2	No	60.1	No	63.7	No
36	0.5	12.4	No	14.8	No	15.6	No	9.5	No	7.7	No	1	No	1	No
37	0.24	29.2	No	29.5	No	27.3	No	20.3	No	26.3	No	23.7	No	32.7	No
38	0.08	53.6	No	56.5	No	55.5	No	46.6	No	51.8	No	41.6	No	51.6	No
39	0.0305	36.3	No	24	No	24.9	No	42.5	No	42	No	40.7	No	43.6	No
40	4	5.6	No	5	No	3.8	No	3.7	No	5,8	No	5.8	No	8	No
41	1	10.9	No	14.2	No	13.7	No	11.8	No	10.9	No	11.8	No	4.8	No
42	0.056	49.2	No	36.2	No	38.5	No	54.9	No	53.3	No	54.7	No	58.2	No
43	0.0297	56.6	No	43.3	No	46.4	No	61.9	No	59.6	No	62.7	No	66.6	No
44	1.625	14.9	No	13.4	No	15.7	No	15	No	12.9	No	16	No	16.3	No
45	0.25	45.6	No	52.5	No	50.1	No	43.1	No	43.9	No	45.3	No	47.9	No
46	3	11	No	12.1	No	11.2	No	9.8	No	11	No	10.9	No	11.1	No
47	0.08	54	No	65.2	No	63.3	No	54.1	No	53.3	No	52.3	No	37.2	No
48	0.0277	64.5	No	70.7	No	69.2	No	58.4	No	62.7	No	53.5	No	56.4	No
49	0.6	16.3	No	25.7	No	19.4	No	12.9	No	18.8	No	12.7	No	15.6	No
50	0.25	25.3	No	31.6	No	31.5	No	26.7	No	21.8	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	106.4	2038	117.2	2469
53	0.035	104.1	2586	113.3	2800	112.2	2800	95.7	2317	105.1	2612	91.5	2033	75.8	2295

No. (r_j)	r_j (Ns^2/m^8)	Original solution		Scenario D failure @ node 3				Scenario E failure @ node 21			
				Failure		Fixed q_{26}		Failure		Fixed q_{26}	
		Air flow q_j (m^3/s)	Regulator S_i (Pa)	q_j (m^3/s)	S_i (Pa)	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
2	0.0308	93.5	No	165	No	173	No	95.9	No	99.1	No
3	0.0118	136	No	0.1	No	0.1	No	136.4	No	136.5	No
4	0.0415	89	No	153.4	No	145.4	No	86.2	No	83	No
5	0.0555	30.5	No	0	No	0	No	33.9	No	38.5	No
6	0.04	52.7	No	0	No	0	No	47.1	No	40.6	No
7	0.0617	44.1	No	58.2	No	70.5	No	48.3	No	51.1	No
8	0.0237	69	No	90.2	No	89.3	No	70.5	No	76.2	No

Table 1 continued

No. (r_j)	r_j (Ns^2/m^8)	Original solution		Scenario D failure @ node 3				Scenario E failure @ node 21			
				Failure		Fixed q_{26}		Failure		Fixed q_{26}	
		Air flow q_j (m^3/s)	Regulator S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)
9	0.7	10.8	No	16.6	No	13.2	No	10.9	No	10.3	No
10	0.048	52.8	No	0.1	No	0.1	No	55.5	No	57.3	No
11	0.165	11.7	No	18.2	No	31.8	No	18.9	No	23.5	No
12	0.404	30	−1034	46.6	0	54	0	23.5	−595	1	−1262
13	0.04	57.9	No	50.5	No	34.8	No	51.4	No	57	No
14	0.125	42.1	No	38.1	No	24.9	No	39.4	No	42.1	No
15	0.06	10.9	No	16.3	No	44.2	No	20.8	No	19.7	No
16	0.075	20.3	No	1	No	29.7	No	21.3	No	28.9	No
17	0.111	27.9	No	26.8	No	16.1	No	28.3	No	28.6	No
18	0.425	25	−1009	38.9	0	11.9	0	40.5	0	46.3	0
18\	0.75	30	No	35.6	No	102.8	No	28.5	No	24.4	No
19	0.65	40	−649	43.1	0	42.7	0	50.2	0	51.1	0
20	0.815	38.5	−105	31.8	0	32	0	20.8	−371	34.3	0
21	1.75	20	−644	3.4	−803	7.6	−802	20.8	0	24.2	0
22	1.25	20	−874	11.6	−656	1	−1012	24.6	0	15.6	−867
23	2.4	15	−877	19	0	6.9	−1046	18.5	0	22.5	0
24	1.45	30	0	23.7	0	18.6	−775	23.2	0	28.4	0
25	0.65	30	−838	36.8	0	1	−1499	37.8	0	30.7	−820
26	0.55	40	−431	28.1	−431	40	−431	28.8	−431	40	−431
27	0.35	9.6	No	21.7	No	43.4	No	1	No	8.7	No
28	0.3	10	No	1	No	19.2	No	1.3	No	22.1	No
29	0.405	10.2	No	10	No	19	No	12.6	No	9.9	No
30	0.5	13.6	No	16	No	11.2	No	21.5	No	21.5	No
31	0.1975	45.4	No	52.8	No	71.3	No	68.1	No	62.1	No
32	1	20.4	No	20.9	No	20.6	No	31.4	No	28.3	No
33	1.3	22.7	No	21.7	No	23.6	No	0	No	0	No
34	0.667	15	No	13.2	No	19.6	No	9.9	No	16.7	No
35	0.048	49.8	No	49.2	No	55.3	No	36.8	No	28.8	No
36	0.5	12.4	No	12.3	No	1	No	1	No	1	No
37	0.24	29.2	No	24.3	No	32.3	No	31.8	No	38.3	No
38	0.08	53.6	No	44.1	No	51.2	No	51.4	No	61.5	No
39	0.0305	36.3	No	41.3	No	50.4	No	49.2	No	47.6	No
40	4	5.6	No	4.1	No	7.9	No	7.8	No	9.4	No

Table 1 continued

No. (r_j)	r_j (Ns^2/m^8)	Original solution		Scenario D failure @ node 3				Scenario E failure @ node 21			
				Failure		Fixed q_{26}		Failure		Fixed q_{26}	
		Air flow q_j (m^3/s)	Regulator S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)	q_j (m^3/s)	S_i (Pa)
41	1	10.9	No	11.9	No	4.6	No	14.2	No	13.5	No
42	0.056	49.2	No	54.6	No	63.6	No	69.1	No	65.5	No
43	0.0297	56.6	No	63.3	No	70.9	No	80.7	No	75.9	No
44	1.625	14.9	No	16.4	No	13.9	No	26.2	No	22	No
45	0.25	45.6	No	44.4	No	43.1	No	0.1	No	0.1	No
46	3	11	No	9.9	No	10.9	No	13.7	No	15.1	No
47	0.08	54	No	53.3	No	36.6	No	63.2	No	64.9	No
48	0.0277	64.5	No	56	No	55.8	No	65.6	No	74.9	No
49	0.6	16.3	No	9.7	No	15.8	No	0	No	0	No
50	0.25	25.3	No	28.3	No	20.7	No	0	No	0	No
51	0.0159	104.4	2380	123.5	2651	132.7	2800	175.9	2800	163.5	2800
52	0.0123	110	2515	104	2597	103.2	2800	0.1	0	0.1	0
53	0.035	104.1	2586	91	2553	82.6	2800	142.5	1043	154.9	1435

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

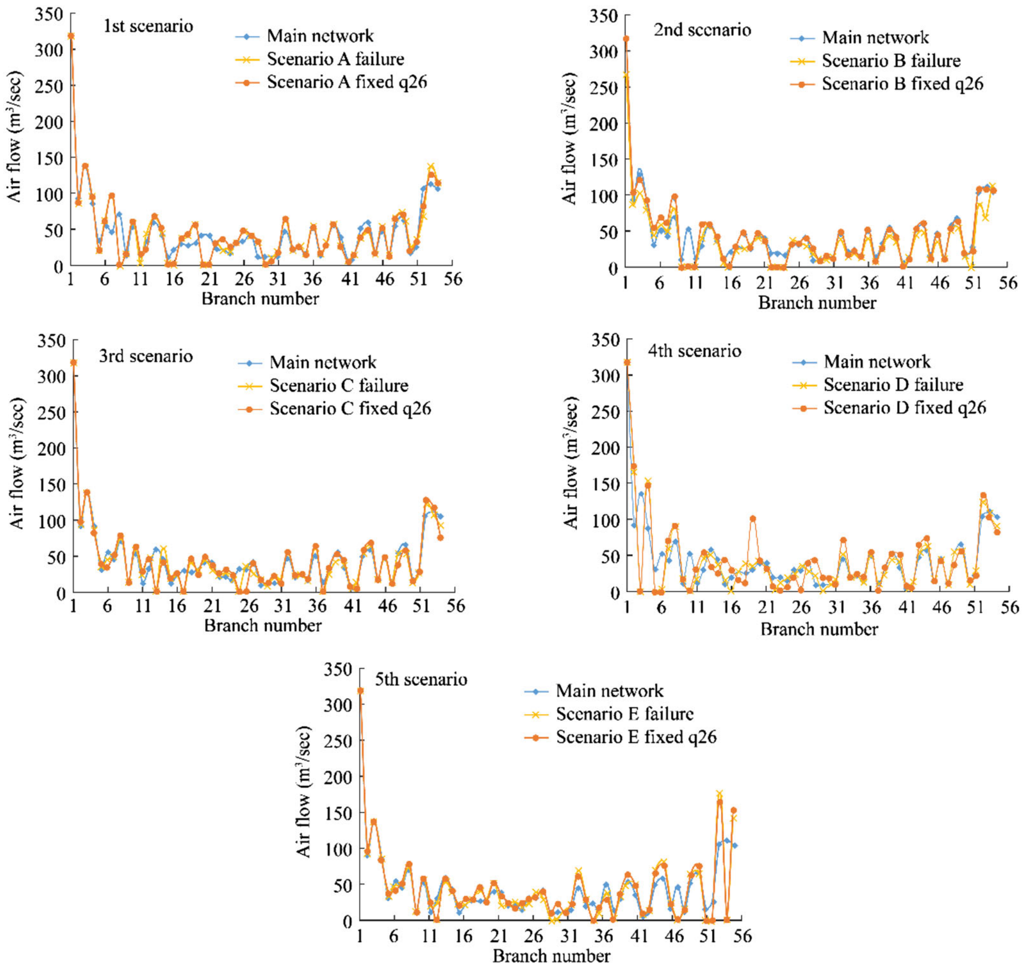

Fig. 2 Air quantity distributions

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 braches.

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:

$$\begin{aligned} Z = {} & B(1.86B - 12.43N_{\mathrm{r}} - 73.18) \\ & + N_{\mathrm{r}}(332.79 + 16.36N_{\mathrm{r}}) - 0.07S + 605.02 \end{aligned}$$

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

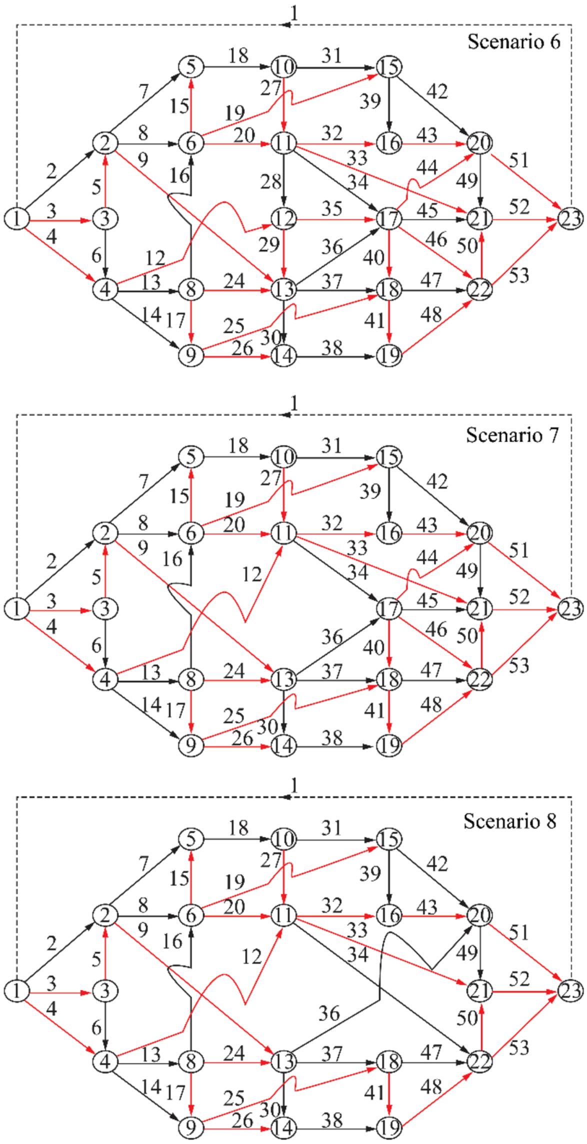

Fig. 3 Network layouts for scenarios 6, 7 and 8, respectively

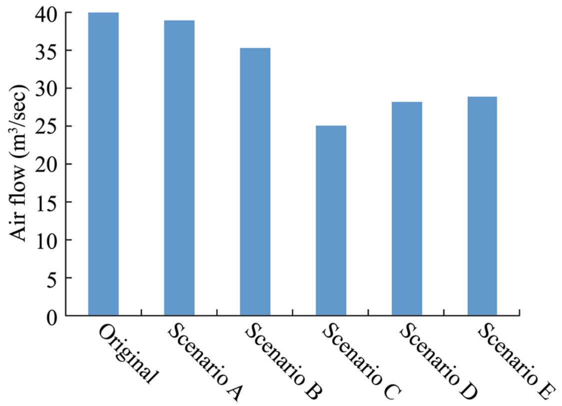

Fig. 4 Effect of distance from collapse on the air quantity in branch 26

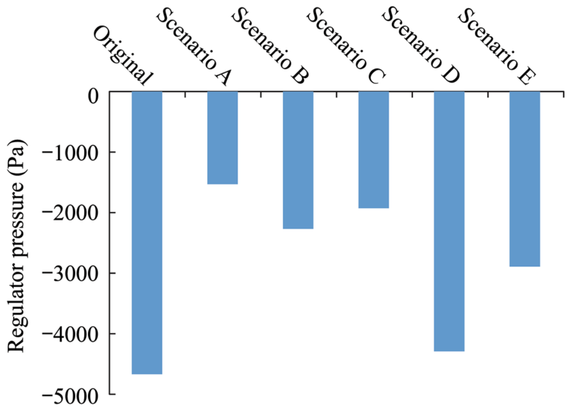

Fig. 5 Sum of the regulators pressure installed in each scenario

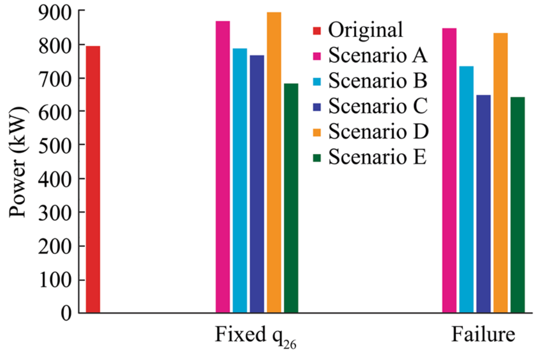

Fig. 6 Power consumed in each scenario

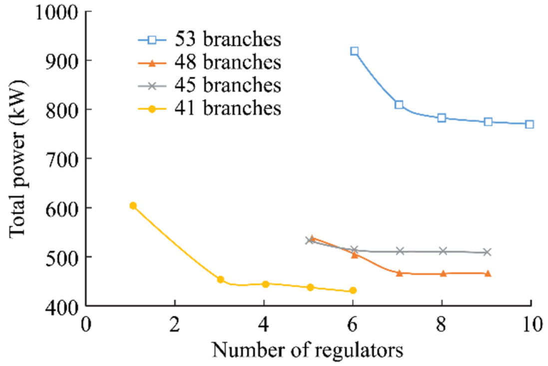

Fig. 7 Effect of changing the topology of the network on the consumed power

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).

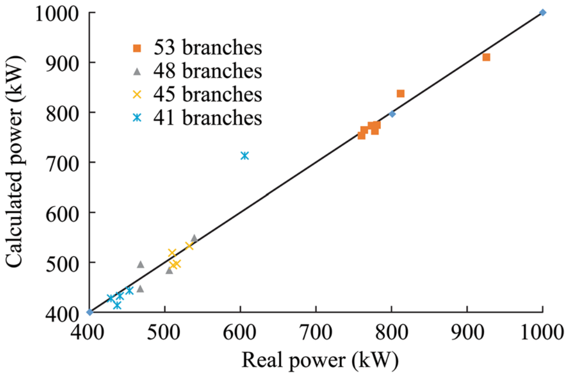

Fig. 8 Crossplot for total power representing predicted and real total power

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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