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Application of VENTSIM 3D and mathematical programming to optimize underground mine ventilation network: A case study

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Abstract

Ventilation is a vital component of an underground mining operation, used to guarantee a safe atmosphere for workers and survive them from the hazardous and toxic gases. In the recent years, engineers have begun to apply new operation research techniques in order to optimize the ventilation systems to assist in achieving a regulatory compliance, reduce ventilation costs, and improve its efficiency. Airflow regulation optimization in mine ventilation networks is described as a minimization model whose objective function is a minimum number of regulators and energy consumption. In this work, all the previously accomplished works were first reviewed. Then a ventilation system was designed for the Western-Razmja coal mine by a manual method, and an axial fan was proposed. Subsequently, the same ventilation system was simulated using the VENTSIM 3D software. The results obtained by computer simulation showed that there was a reliable relation between the manual method and the simulation approach. In the final step, the GAMS software was used to solve a Mathematical Programming (MP) problem to minimize the overall cost of ventilation by determination of the optimum location for the fan and regulators. The final results of this work illustrated that not only the number of regulators were reduced through solving the MP model but also the total resistance of the Western-Razmja coal mine was reduced by 14% from 1.6 to 1.3. Furthermore, it was observed that the total efficiency of the proposed fan was increased.

Keywords: *Underground Mining, Mine Ventilation Network, Operation Research (OR), VENTSIM 3D, Mathematical Programming, GAMS.*

1. Introduction

The main purpose of mine ventilation is to provide a fresh and sufficient air for mine halls, dilute and eliminate all toxic and harmful gases and dust, and regulate the air quality, and as a result, create a safe and comfortable workplace for miners [1]. Mine ventilation networks are complex, and their investigation through analytical methods is a very hard issue. Hence, using computer simulation in order to control the mine ventilation system makes it easier to manage. Since a ventilation network contains numerous branches, a small error in the input data can cause main problems during simulation. Obtaining the required information from the mine ventilation network through a manual or 2D approach is problematic for people who are not familiar with the ventilation networks [2]. In other words, the designer has a perfect understanding of a complex ventilation system, although it will be so hard for other engineers to realize the designed networks in a 2D dimension. Therefore, using a 3D software, i.e. VENTSIM 3D, gives a great opportunity for people who do not have much experience in the field of mine ventilation network due to its user-friendly and capability to illustrate airways graphically with a high quality.

A coal mine main fan is one of the largest power-consuming facilities among various electrical and mechanical equipment. Its power consumption usually accounts for 20%-30% of the mine. One main reason for the main fan's high power consumption is its overall low efficiency, so the principal optimization problem associated with underground mine ventilation systems is to determine the number, location, and duty of the fans and regulators to deliver the required airflow and pressure distribution at the lowest fan power or energy consumption [3]. In this work, after simulation of the Western-Razmja coal mine, one of the Eastern Alborz coal mine Companies, a mathematical programming problem related to the ventilation network was used to optimize and determine the best locations for the fan and regulators. In what follows, a review of the previously research works regarding the mine ventilation design and optimization is presented.

2. Literature review

2.1. Mine ventilation design

With the development of computer techniques in mining industry, the design of ventilation networks for underground mines by computers has served as a reliable way. In other words, application of computers such as VENTSIM is a good alternative to the experimental and manual methods due to their simplicity and accuracy. Table 1 presents a summary of the previous research works on the mine ventilation system design.

2.2. Mine ventilation optimization

In the recent years, several research works have been accomplished regarding mine ventilation optimization. Calizaya et al. [4] have used a hybrid solution method to study mine ventilation optimization. Their method applies a set of linear calculations to the branch resistance, and as a result, a minimum fan power is measured by this linear technique and the regulator resistance curves. Barnes [5] has developed a new algorithm based on non-linear programming in order to seek an improvement solution for airflow distribution and evaluation of pressure. The algorithm establishes a set of possible flows and improves the flows while maintaining feasibility. Wu and Topuz [6] have developed a new model to distribute the airflow considering a minimum power consumption. They solved their optimization model in three separate classes including the linear programming method (Simplex Method), Critical Path Method (CPM), and application of the CPM and cut-set techniques. Wang [7] has utilized the Newton-Raphson iterative method to optimize the ventilation system. The methodology of this algorithm is based upon a specific routine by dividing the main problem into dependent and independent variables for the air pressure and air flow. This method leads the system to allocate the ventilation equipment such as fans and regulators. Jacques [8] has introduced a heuristic algorithm with an objective function based on minimizing the airflow deviation rather than air power minimization. Although this method was unable to locate the required fans and regulators, it could determine the distribution of airflow considering the Kirchhoff's second law. Huang and Wang [9] have proposed a new optimization method based on Generated Reduced Gradient (GRG), which minimizes the total air power by applying two steps: 1) determination of search direction 2) calculation of the fan and regulator pressures. They implemented their model on a ventilation system consisting of 9 nodes and 18 branches. Kumar et al. [10] have presented an algorithm consisting of two main approaches. In the first approach, they determined the best performance and location of the main fans using CPM to establish the largest pressure drop of the ventilation network. In the second approach, identification of the pressure for underground booster fans was carried out using a heuristic algorithm including Fibonacci and the cyclic search method. Wu and Topuz [11] have developed a new algorithm based on the mathematical programming, branch, and bound technique. Due to the fact that their model followed a non-linear programming model, they transformed the algorithm to a linear programming problem. The final results of their proposed model illustrated that it was able to determine the required airflow distribution. Lowndes and Yang [12] and Lowndes et al. [13] have developed a new Genetic Algorithm (GA) based on the search method in order to find out the location and pressure of the booster fans in underground mines. Their optimization model was implemented on the Chilean El Indio mine. The results of their implementation showed that the algorithm was able to perform an optimum solution with 3 of 16 underground booster fans. Li Jiang et al. [14] have established a non-linear mathematical programming with the objective of minimizing the energy consumption in a simple ventilation system. The results of this study demonstrated that it had a 3% decreasing rate. Zhao Dan et al. [15] have introduced a new heuristic algorithm named Powell. An integration of this algorithm was carried out into a GA to produce a Hybrid Genetic Algorithm (HGA) in order to optimize the ventilation network. The objective function was minimizing the costs. After implementation of a ventilation network, they found that HGA was able to remove the main GA drawbacks. GYWCY Jichao [16] have presented the particle swarm algorithm to minimize the overall energy consumption considering the balance conditions for air quantity and pressure. They examined their model on an example of mine ventilation network and showed that the performance of their model was very high compared to the other intelligent optimization models. Table 2 shows a summary of the previously accomplished works on mine ventilation optimization.

3. Case study

The Western-Razmja coal mine, one of the main mines in Eastern Alborz Coal Mines Company, is selected as a case study for this research work. This mine is located 80 km from the city of Shahrood in Alborz Mountains (Figure 1). Longwall mining was applied for this mine in order to extract coal from the K5, K8, K13, and K19 seams. According to the exploration reports, the host rocks of this mine are related to the upper Triassic and lower Jurassic periods [51]. The Western-Razmja coal mine ventilation has been performed by natural ventilation and several booster fans. However, with the development and expansion of the network, it is required to establish an appropriate ventilation design, which is discussed in this study.

Figure 1. Western-Razmja coal mine location.

4. Manual design

The design of air conditioning for underground mines is based upon several principals including preparation of mine maps, identification of mine branches and ventilation nodes, calculation of resistance and airflow for each branch, measurement of pressure drop for each branch of a grid, network adjustment, and selection of the main fan and regulators.

4.1. Air flow

In the first step, According to the characteristics of the Western-Razmja coal mine, the essential parameters consisting of the number of workers in stopes, coal seam radiation, blasting operations, and the minimum air speed are utilized for stopes, which are under preparation and extraction conditions [52]. Tables 3 and 4 show the measured values for airflow in the stopes under preparation and extraction, respectively. Figure 2 illustrates the airflow distribution for the entire ventilation network.

4.2. Fan and regulator selection

In order to regulate the pressure drop in the ventilation network, it is necessary to identify the direction and value of airflow in every branch. For this reason, each node should have the same input and output airflow. After that, it can be interpreted into meshes and critical paths. In this work, using the manual method and considering the fact that the pressure drop should be equal to zero in each mesh (Equation 1), locations of the fans and regulators were determined through ensuing conditions [53]:

1: if the pressure drop is greater than zero ($\sum \pm P\Delta i > 0$), it is required to locate regulator in the negative direction or fan in the positive direction.

2: if the pressure drop is equal to zero ($\sum \pm P\Delta i = 0$), it is not required to locate any regulator or fan in any branch.

3: if the pressure drop is lower than zero ($\sum \pm P\Delta i < 0$), it is required to locate fan in the negative direction or regulator in the positive direction.

$$\sum_{i=1}^{i=n} \Delta P_i = \sum_{i=1}^{i=n} R_i Q_i^2 \quad (1)$$

Based upon these conditions, 1 fan and 10 regulators are located in the Western-Razmja mine ventilation network, which are shown in Figure 3. The calculations results show that the approximate diameter of the fan is equal to 1.459 m and the resistance of the interior equipment is equal to 0.074 Kmorg. Furthermore, the main fan should satisfy 19.57 (m^3/s) for airflow and 81.65 (mmH_2O) in pressure. Considering the characteristics of Russian fans, which are commonly used in Iranian coal mines, a special axial fan type (VOD16) [54] with 16° blade angle is performed for this ventilation network. The main specifications of this fan are shown in Table 5.

Table 1. A summary of previous research works related to mine ventilation design.

Year	Author	Design Method			Description
		Manual	Software		
			2D	3D	
2001	Widzyk-Capehart and Watson [17]		●		Due to the increase in mining depth, the development of ventilation system was studied using VENTSIM.
	Widzyk-Capehart and Fawcett [18]			●	The Bronzewing mine ventilation system simulated and optimized in VENTSIM and long-term planning was investigated.
	Madani and Osgoui [19]	●	●		The primary design of ventilation system was studied during the preparation step in Galanderoud mine.
2002	Marx and Belle [20]			●	Simulation of a coal mine was carried out using VUMA by the trial-and-error approach to optimize the ventilation system.
2003	Gashtasbi et al. [21]	●	●		The ventilation system in Razi coal mine was designed, and finally, measured values were validated using Tahvie.
	Madani and Mofti [22]	●			Due to the expansion of Kiasar coal mine and existence of main problems, the ventilation system was investigated carefully.
2006	Exikis and Kapageridis [23]			●	The ventilation network of an underground mine was simulated in a computer and the location of fans was determined under emergency conditions.
	Madani et al. [24]	●	●		Due to several problems in the Heshuni mine ventilation system, the re-design and evaluation of effective parameters were investigated.
2008	Anemangoli et al. [25]		●		In this study, the eastern Kelariz mine was simulated using VENTSIM.
2011	Wei et al. [26]			●	VENTSIM 3D was used to manage the Donghai ventilation system due to its size and complexity.
	Gusat et al. [27]	●	●		This study presented the main advantages of simulation in mine ventilation networks.
2012	Lilic et al. [28]	●			Long-term planning for ventilation and optimization process was discussed for the Omerler mine.
	suvar et al. [29]			●	The problem of complex ventilation networks was investigated using VENTSIM Visual Advanced.
	Chaoqun [30]			●	Mine ventilation system re-designed in Tongxing mine and the existing problems were discussed to optimize the ventilation network.
	Ghazvivni and Aghjani [31]	●		●	In this study, a ventilation network was designed using VENTSIM 3D in Eastern-Yourt coal mine.
	Elahi zeini and Rabiei nejhad [32]		●		The dilution of harmful gases was applied in the Western-Razmja coal mine using artificial ventilation and determination of main fan.
	Elahi zeini and Rabiei nejhad [33]		●		The dilution of harmful gases was applied in Eastern-Kelariz coal mine using artificial ventilation and determination of main fan.
2013	Felsner [34]			●	Using VENTSIM, based on the existing condition of Erzberg mine, the ventilation system was designed.
	Pazin fushazde [35]	●	●		The ventilation system for the Anguran underground mine was studied using VENTSIM.
	Akande and Moshood [36]	●			The design of Okaba coal mine was carried out using Auto-CAD, and the locations of auxiliary fans were specified.
2014	Stewart [37]			●	In this study, the ventilation of blasted region was accomplished in an underground mine.
	Haghighat [38]			●	In this study, the underground mine ventilation network was analyzed carefully, and the installation of the main and auxiliary fans was determined in VENTSIM.
	Cioclea et al. [39]			●	The various effects of harmful gases produced by blasting operations were discussed in underground mines.
	Elahi zeini [40]	●			The manual design of Takht coal mine was investigated, and the intensity of air flow was proposed as well.
	Zariei darmeian et al. [41]	●	●		The design of ventilation network for the Tabas mine was designed during the drilling process.
	Bagher zadeh et al. [42]	●			In this study, the design of ventilation system for Tabas Parvadeh Coal Mine was performed.
2015	Acunaa and Wallace [43]			●	In this study, based on the predicted production rate, the design of ventilation system for Teniente mine was carried out considering the sensitivity analysis.
	Sethi [44]			●	This study examines the amount of pressure and air quality for Nandira coal mine using VENTSIM.
2016	Zhang and SUO [46]			●	In order to overcome the high resistance of Majiagou coal mine, its network was simulated in VENTSIM and analyzed carefully.
	Elahi zeini et al. [45]	●			In this study, the conditions of Tunnel-8 coal mine were simulated in VENTSIM, and the distribution of current was evaluated in the entire system.

Table 2. A summary of previous research works related to mine ventilation optimization.

Year	Author	Solution Method	Optimality
1987	Calizaya et al. [4]	Gaussian elimination and linear optimization	●
1988	Barnes [5]	Non-linear programming	●
1989	Wu and Topuz [6]	Linear programming & CPM	●
1989	Wang [7]	Newton-Raphson	
1991	Jacques [8]	Heuristic	●
1993	Huang and Wang [9]	GRG	●
1995	Kumar et al. [10]	CPM & Fibonacci algorithm	●
1998	Wu and Topuz [11]	Branch & Bound–Linear Programming	●
2004	Lowndes and Yang [12]	GA	
2005	Lowndes et al. [13]	GA	
2007	Li Jiang et al. [14]	Non-linear programming	
2009	Zhao Dan et al. [15]	HGA	●
2010	Acuña et al. [47]	GA & ventilation solver	
2013	GYWCY Jichao [16]	Particle swarm algorithm	●
2015	Nyaaba, W et al. [48]	First-order Lagrangian (FOL) algorithm	●
2016	Sotoudeh et al. [49]	MIP	●
2017	Xu, G et al. [50]	Calibrated non-linear programming	

Table 3. Required airflow in stopes under preparation.

Stopes (advancing)	No. of workers (m^3/min)	Gas Radiation (m^3/min)	Blasting (m^3/min)	Min. air speed (m/min)	Max. air flow (m^3/min)	Safety factor	Final air flow (m^3/s)
K19-west (+2152)	18	50	161.53	90	161.53	1.2	3.23
K19-west (+2200)	18	50	203.09	90	203.09	1.2	4.06
K8-west (+2090)	18	50	145.01	90	145.01	1.2	2.09

Table 4. Required airflow in stopes under extraction.

Stopes (advancing)	No. of workers (m^3/min)	Gas Radiation (m^3/min)	Min. air speed (m/min)	Max. air flow (m^3/min)	Safety factor	Final air flow (m^3/s)
K13-east (+2152 to +2090)	42	167.83	36.45	167.83	1.2	3.36
K19-west (+2276 to +2200)	42	201.39	36.45	201.39	1.2	4.03
K19-east (+2200 to +2152)	42	201.39	36.45	201.39	1.2	4.03
K5-west (+2120 to +2152)	42	130.23	36.45	130.23	1.2	2.61
K8-west (+2152 to +2090)	42	147.55	36.45	147.55	1.2	2.95

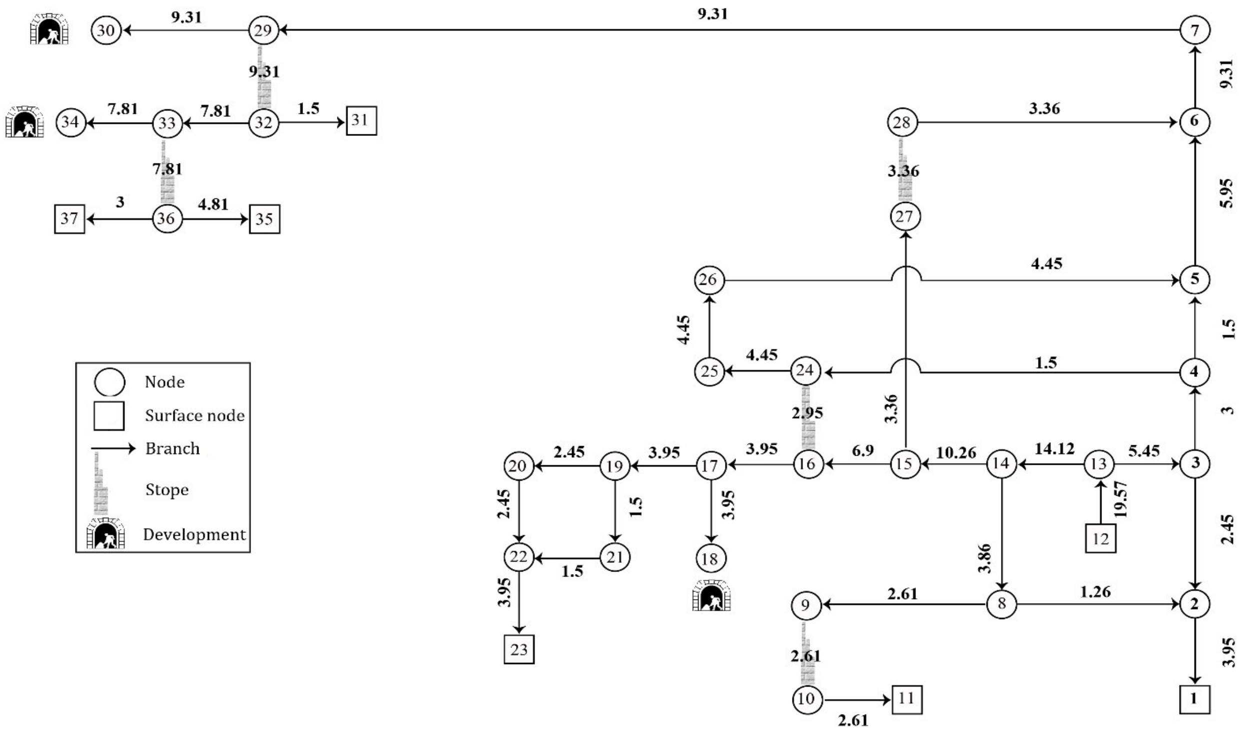

Figure 2. Airflow distribution for entire mine ventilation network (m^3/s).

Table 5. Specifications of selected fan for Western-Razmja coal mine [52].

Fan type (VOD-16)	
Parameter	**Value**
Airflow (m^3/s)	12-67
Pressure (mmH_2O)	92-438
Speed (RPM)	1000
Diameter (m)	1.6
Power (KW)	40-270
Efficiency (%)	77-79

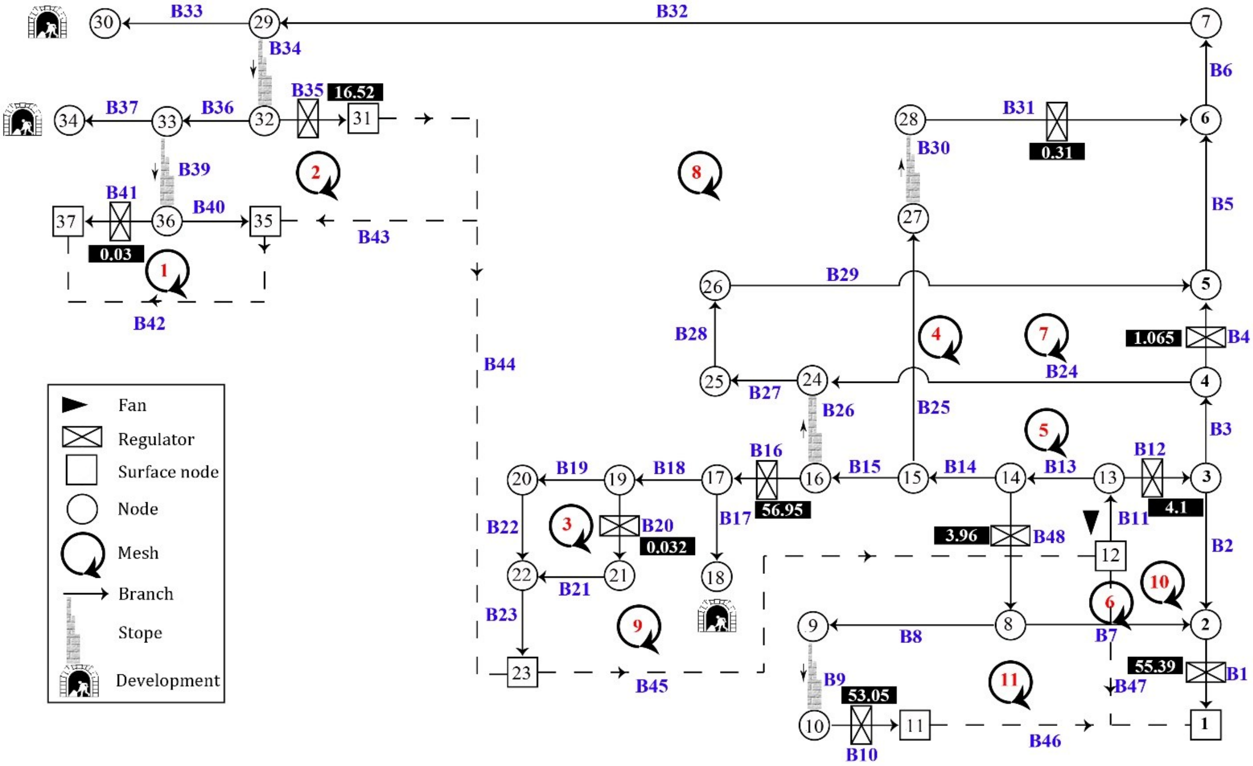

Figure 3. Locations of fan and regulators in Western-Razmja coal mine.

5. VENTSIM simulation

According to the latest network of the Razmja coal mine, the AutoCAD software is used to define the airflow ways entire the branches and stopes using a central line. Then the constructed file, which is in a DXF format, is introduced to VENTSIM as an input file in order to simulate the air ways. Furthermore, several Parameters consisting of the length of branches, cross area, friction factor, etc. are defined for VENTSIM to regulate and simulate the airflow for the entire network considering the locations of fans and regulators. After implementation of these parameters, 2000 iterations were carried out to simulate the airflow distribution for the entire branches and stopes (Figure 4). The results obtained from VENTSIM are shown in Table 6. Also a comparison of airflow distribution through the manual method and 3D simulation is illustrated in Table 7. According to this table, it is evident that the simulation results are very analogous to the simulation results.

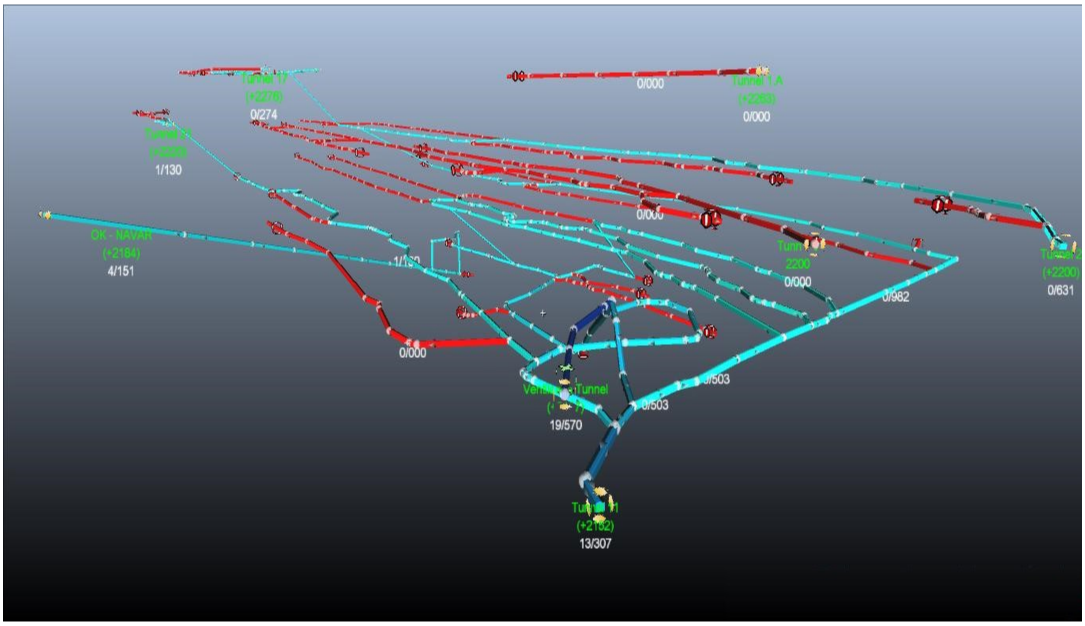

Figure 4. Airflow distribution in Western-Razmja coal mine (VENTSIM 3D).

Table 6. A summary of simulation results obtained from VENTSIM simulation.

Network System Summary	
Natural Ventilation Pressure	No
Airways	675
Total Length	16950 (m)
Total Airflow Intake	20 (m^3/s)
Total Airflow Exhaust	20 (m^3/s)
Total Massflow	24 kg/s
Mine Resistance (excluding duct)	1.6 Ns^2/m^8
Mine Resistance (including duct)	1.6 Ns^2/m^8
Air (friction loss) Power - Total	13 (kW)
Air (friction loss) Power - Shaft	1.5 (kW)
Air (friction loss) Power - Drive	12 (kW)

Table 7. Airflow values for preparation and extraction stopes using VENTSIM simulation.

Stopes (advancing)	Required Airflow (m^3/s)	Airflow Simulation (m^3/s)
Stopes (Extraction)		
K13-east (+2152 to +2090)	3.36	3.37
K19-west (+2276 to +2200)	4.03	9.2
K19-east (+2200 to +2152)	4.03	7.71
K5-west (+2120 to +2152)	2.61	2.78
K8-west (+2152 to +2090)	2.95	2.99
Stopes (Preparation)		
K19-west (+2152)	3.23	9.7
K19-west (+2200)	2.09	7.71
K8-west (+2090)	4.04	4.18

6. Mathematical modeling

The main goal of optimization in mine ventilation network is determination of the optimum locations for fans and regulators and minimization of overall power costs. As shown in Figures 2 and 3, stopes and airways are represented as lines (branches) and the connected points as nodes in an underground mine ventilation network. Like an electrical network, a mine ventilation network must satisfy the Kirchhoff's Current Law (KCL) [11]: the airflow of any node is equal to the flow into that node. The mathematical model of this law can be shown as Equation 2.

$$\sum_{j=1}^{b} a_{ij} Q_j = 0 \quad i = 1,2,3, \ldots, n \quad \text{Or:} \quad AQ=0 \tag{2}$$

Where A is a linearly independent matrix of order (n-1) × b and A = a_{ij}; the a_{ij} values are defines as:

$$\begin{cases} 1 & \text{If branch } j \text{ is connected to node } i \text{ and the airflow goes away node } i \\ \text{-1} & \text{If branch } j \text{ is connected to node } i \text{ and the airflow goes into node } i \\ 0 & \text{If branch } j \text{ is not connected to node } i \end{cases}$$

Q_j is the airflow quantity through branch j, and b and n are the numbers of branches and nodes in the ventilation network, respectively.

In addition, a mine ventilation network should satisfy the Kirchhoff‘s Voltage Law (KVL): the sum of pressure drops around any mesh in the network must be equal to zero [11]. The mathematical model of this law can be shown as Equation 3.

$$\sum_{j=1}^{b} b_{ij} H_j = 0 \quad \text{i = 1,2,3, ... , m} \quad \text{Or: BH=0}$$
$$H_j = HL_j + HR_j - HF_j - HN_j \tag{3}$$

where B is a fundamental mesh matrix, B = b_{ij}; the elements b_{ij} are defined as:

$$\begin{cases} 1 & \text{If branch } j \text{ is contained in mesh } i \text{ and has a same direction} \\ \text{-1} & \text{If branch } j \text{ is contained in mesh } i \text{ and has a opposite direction} \\ 0 & \text{If branch } j \text{ is not contained in mesh } i \end{cases}$$

HL_j is the pressure for branch j, R is the resistance factor for branch j, HR_j is the pressure drop of the regulator in branch j, HF_j is the fan pressure in branch j, and HN_j is the natural ventilation pressure across branch j.

Consequently, with consideration of C_p for the annual energy cost, C_j for maintenance and purchase cost, d_j for the upper bound of HF_j, and Y_j that is a binary variable, the objective function can be represented as Equation 4:

$$Minimize\ \ Z = \sum_{j \in L} a_j HF_j + \sum_{j \in L} C_j Y_j$$
$$C_p q_j = a_j \tag{4}$$

Regarding the Kirchhoff‘s laws, investigated before, the constraints of this model can be described as follow:

$$\sum_{j=1}^{L} b_{ij} (R_j |Q_j| Q_j + HR_j - HF_j - HN_j = 0 \qquad \text{i = 1,2,3, ... , L}$$

$$HF \le d_j Y_j \qquad \text{j} \in \text{L}$$
$$\text{HR} \ge 0 \ \ , \ \ \text{HF}_j \ge 0 \qquad \text{j = 1,2,3, ... , b}$$
$$Y_j = \begin{cases} 1, & \text{HF}_j > 0 \\ 0 & \text{otherwise} \end{cases}$$

6.1. Real model (Western-Razmja Mine)

As described in Section 6, the required matrix (bij) was introduced to identify the sign of pressure drop in the mathematical model. This matrix consisting of 11 rows and 48 columns, which are representatives of the Western-Razmja ventilation network meshes and branches, is shown in Figure 5. In the next step, the mathematical modeling for this mine is carried out using the formulas mentioned in Section 6 considering 6000 \$/power for C_p and 2500 \$/power for C_j. The problem was solved using the GAMS software. The results of mathematical modeling show that 4 regulators are removed from the main ventilation networks (branches 20, 31, 41, and 48) and 1 fan is located in branch 11. Furthermore, the total resistance of this mine, measured in Section 5, was reduced by 14%. In other words, its value decreased from 1.6 Ns^2/m^8 to 1.5 Ns^2/m^8. Also in addition to minimizing the overall ventilation costs, it is observed that the total efficiency is increased as well.

7. Discussion

The airflow in mine ventilation is realized with the aid of ventilation control devices such as fans and regulators. The optimal determination of location and size of these control equipment is the most important problem in the design and analysis of mine ventilation systems. According to the results obtained from the optimization process through the mathematical model, it can be concluded that the number of regulators have been reduced due to minimization of the mining costs. Simulation of the mathematical model outputs in VENTSIM show that the values for airflows have changed, and it has been able to satisfy the required airflow in the preparation and extraction stopes. Figure 6 shows a brief comparison regarding the total efficiency values into the two manual and mathematical modeling approaches. According to this figure, it can be observed that the fan efficiency is increased from 58% to 65%. Therefore, through the mathematical model and formulation of ventilation network as a mixed integer, programming is a useful way to obtain an optimal solution.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	1	-1	0	0
4	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
5	0	0	-1	0	0	0	0	0	0	0	0	-1	1	1	1	0	0	0	0	0	0	0	0	-1
6	0	1	0	0	0	0	-1	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0
7	0	0	-1	-1	-1	0	0	0	0	0	0	-1	1	1	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	1	1	0	1	1	0	0	1	1	0
9	0	0	0	0	0	0	0	0	0	0	-1	0	-1	-1	-1	-1	0	-1	0	-1	-1	0	-1	0
10	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
11	1	0	0	0	0	0	1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	1	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	-1	-1	0	0	1	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
7	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	-1	0	0	0	0	-1	-1	-1	0	-1	-1	0	0	0	0	0	0	0	0	-1	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0

Figure 5. Matrix [bij] for Western-Razmja coal mine.

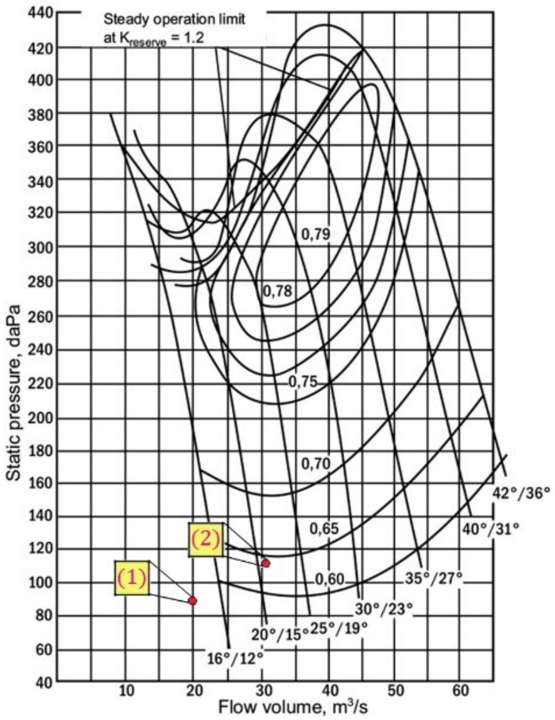

Figure 6. Total efficiency of fan 1: manual method 2: mathematical formulation.

8. Conclusions

This paper presents the application of VENTSIM and a common mathematical programming model in the Western-Razmja coal mine to optimize a defined problem consisting of an objective function, which is minimization of the overall costs and determination of the best location for fans and regulators. In order to reach this goal, the preliminary design was carried out by the manual method, and as a result, 1 fan and 10 regulators were determined considering the values 20 m^3/s and 1.6 Ns^2/m^8 for the airflow and resistance, respectively. In the second step, the results obtained from the manual design were imported to VENTSIM and simulated precisely. The outputs illustrated that the airflow distributed very well and satisfied the required airflow for the entire ventilation network. The main purpose of the simulation was to design the airflow distribution for the entire ventilation network, and the overall costs and optimum locations were not considered in this approach, while the mathematical programming for mine ventilation network was able to not only guarantee the optimum location for ventilation equipment but also reduce the operating costs. Therefore, a mathematical model, which satisfies Kirchhoff's laws, was proposed and solved using the GAMS software for the Western-Razmja coal mine. It was concluded that the regulators located in branches 20, 31, 41, and 48 should be removed. Then this modification was applied on VENTSIM and simulated like the first step. The final results illustrated that the total exiting resistance was reduced by 14.37% from 1.6 Ns^2/m^8 to 1.5 Ns^2/m^8. Also the total efficiency was increased by eliminating 4 regulators in the ventilation network.

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بهینه‌سازی شبکه تهویه معادن زیرزمینی با استفاده از نرم‌افزار VENTSIM 3D و برنامه‌ریزی ریاضی؛ مطالعه موردی

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چکیده:

تهویه یکی از مهم‌ترین عملیات معدنکاری زیرزمینی به منظور تضمین فضای ایمن برای کارگران و پاک‌سازی گازهای خطرناک و سمی به شمار می‌رود. در سال‌های اخیر، تکنیک‌های تحقیق در عملیات برای بهینه‌سازی سیستم‌های تهویه به منظور کمک به دستیابی به الزامات قانونی و کاهش هزینه‌های ناشی از تهویه و افزایش کارایی آن به کار برده شده‌اند. در تهویه شبکه‌های معادن زیرزمینی، بهینه‌سازی تنظیم جریان هوا به عنوان یک مدل کمینه‌سازی توصیف شده است که تابع هدف آن حداقل‌سازی تعداد فن‌ها و رگلاتورهای مورد نیاز و مصرف انرژی است. در این پژوهش، تحقیقات پیشین شبیه‌سازی و بهینه‌سازی تهویه معادن زیرزمینی مورد بررسی قرار گرفته‌اند. سپس، با بررسی سیستم تهویه معدن رزمجای غربی و طراحی دستی آن، فن مورد نظر پیشنهاد شده است. پس از آن، این سیستم تهویه در نرم‌افزار VENTSIM به صورت سه بعدی شبیه‌سازی شده است. نتایج حاصل از شبیه‌سازی کامپیوتری نشان دادند که رابطه قابل اعتمادتری بین روش دستی و شبیه‌سازی وجود دارد. در نهایت، با استفاده از برنامه‌ریزی عدد صحیح مختلط، مدل ریاضی ساخته شده با تابع هدف کمینه‌سازی هزینه‌های تهویه و جانمایی فن‌ها و درهای تنظیم‌کننده، در نرم‌افزار GAMS حل شد. نتایج نهایی حاصل از این پژوهش نشان داد که نه تنها تعدادی از درهای تنظیم کننده پس از حل مدل ریاضی حذف شده‌اند، بلکه مقاومت کلی شبکه تهویه معدن نیز از مقدار ۱/۶ به ۱/۳ (۱۴ درصد) کاهش یافته است. همچنین، مشاهده شد که تهویه صورت گرفته با مدل‌سازی ریاضی توانسته است بازده کلی فن را نیز بهبود بخشد.

کلمات کلیدی: معدن زیرزمینی، شبکه تهویه معدن، تحقیق در عملیات، VENTSIM 3D، برنامه‌ریزی ریاضی، GAMS.