Optimization of mine ventilation fan speeds according to ventilation on demand and time of use tariff

Arnab Chatterjee*, Lijun Zhang, Xiaohua Xia

Department of Electrical, Electronic and Computer Engineering, University of Pretoria, Pretoria 0002, South Africa

Abstract

In the current situation of the energy crisis, the mining industry has been identified as a promising area for application of demand side management (DSM) techniques. This paper investigates the potential for energy-cost savings and actual energy savings, by implementation of variable speed drives to ventilation fans in underground mines. In particular, ventilation on demand is considered in the study, i.e., air volume is adjusted according to the demand at varying times. Two DSM strategies, energy efficiency (EE) and load management (LM), are formulated and analysed. By modelling the network with the aid of Kirchhoff's laws and Tellegen's theorem, a nonlinear constrained minimization model is developed, with the objective of achieving EE. The model is also made to adhere to the fan laws, such that the fan power at its operating points is found to achieve realistic results. LM is achieved by finding the optimal starting time of the mining schedule, according to the time of use (TOU) tariff. A case study is shown to demonstrate the effects of the optimization model. The study suggests that by combining load shifting and energy efficiency techniques, an annual energy saving of 2 540 035 kWh is possible, leading to an annual cost saving of 2 670 705 South African Rand.

Keywords: Energy efficiency, load management, mine ventilation, optimization, time of use tariff, ventilation on demand (VOD)

1. Introduction

Demand side management (DSM) programmes are introduced around the world as an effective and quick solution to the ever increasing energy concerns. These programmes seek to reduce the gap between power supply and demand broadly by energy efficiency improvement, energy conservation interventions, fuel switching, load expansion and self-generation, among which energy efficiency (EE) and load management (LM) are the most popularly used methods in the industrial sector [1]. The LM approach aims to reduce electricity demand at peak periods by giving monetary incentive to shift load to off-peak periods, e.g., in the form of the time of use (TOU) tariff or demand response [2, 3]. The EE approach aims to reduce overall electricity consumption by installing energy efficient equipment and/or optimizing industrial processes, e.g., by making use of variable speed drives (VSDs).

DSM techniques are applied in various industries as can be found in literature. Some applications consider load shifting by finding the optimal switching times of equipment or processes

---

according to the TOU tariff, e.g., controlling conveyor belts [4, 5], pumps [6, 7], geysers [8] and equipment that form part of a batch process [9]. These examples show significant cost saving compared to the baseline case, but actual energy saving is very little because the objective is focused on load shifting from peak periods. Considerable attention has also been drawn to EE improvement of industrial processes by the application of VSDs. In particular, the application of VSDs to fans and pumps have been studied [10, 11, 12], reasons being that VSDs offer more energy saving than a simple switching strategy [5, 10] and a small reduction in the speed can result in large energy savings [13, 14, 15]. However, these examples don't consider LM under the TOU tariff in order to shift load from peak time. Thus very few cases consider obtaining energy saving and peak load shifting with application of DSM techniques, simultaneously [16]. In particular, little evidence is found of application of VSDs to achieve both LM and EE in mining ventilation networks.

It is known that the industrial sector consumes about 37% of the world's total delivered energy, and out of this, the mining industry contributes about 9% [17]. Mine ventilation is crucial for safety reasons, because it is responsible for clearing out noxious and flammable gasses; and also provides a comfortable working environment underground. The rating of the fans that provide ventilation, depending on its use, can range from 100 kW [18, 19] to about 3000 kW [20, 21]. Thus, contribution by the ventilation fans towards the total power consumption is quite significant. Research suggests that, depending on the type of mine, up to 40% [22] of the total electricity used, and up to 60% [23] of mining operating cost can be attributed to ventilation underground.

Existing studies on mine ventilation networks vary in objectives. Some consider making use of computer programmes in conjunction with survey data to model the changes in the structures of the ventilation network to achieve safe and economic solutions [24, 25]. These cases do not consider LM or EE in any way. Other studies are performed with the objective of running the ventilation system more efficiently to reduce costs, e.g., in [21] a review is done at the beginning of every week to determine which levels will be inactive for the next week, such that the auxiliary fans in those levels can be switched off. This study considers EE but not by application of VSDs. Optimization techniques are sometimes employed, e.g., [26, 27] discuss the use of nonlinear programming methods to find the optimal flow rates in the branches such that the the rating of the fan, required to supply the network, is minimized; [28] shows the use of genetic algorithms (GA) to decide on the optimum number, location, and size of booster fans/regulators in the network; [20] makes use of mixed integer programming (MIP) to find the optimal angles of the auxiliary fan blades, in order to match the varying flow rates throughout the different stages in a mine. These studies are all performed with the objective of minimizing energy consumption and/or related costs, but there is no consideration for the TOU or the application of VSDs. The only studies that consider using VSDs to vary ventilation fan speeds in underground mining are presented in [19, 29, 30]. These studies explore the concept of ventilation on demand (VOD). The idea is to allow variable air flow by adjusting the speed of the fan over time (based on the demand), as opposed to running them at full capacity at all times. These studies perform EE measures, but there is no consideration for shifting load from peak times and the TOU tariff. Another limitation to those researches is that only auxiliary fans, instead of the main fan, are selected. This is done because changing the speed of the main fan will affect the entire network and is more complicated to control than the auxiliary fans.

To this end, this research focuses on applying optimization techniques to reduce energy consumption and the corresponding costs of mine ventilation fans. Specifically, energy consumption is minimized by determining an optimal speed profile for the main fan according to VOD. In addition,
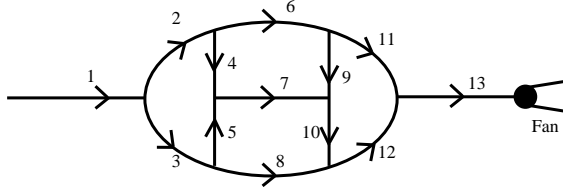
Figure 1: An example of a ventilation network (adapted from [26]).

LM is introduced by optimizing the mine schedule considering the TOU tariff such that further energy cost reduction can be achieved for the mine. The ventilation network is first mathematically modelled by extending the work shown in [26, 27], whose main feature is modelling the network using Kirchhoff's current and voltage law. Then, the optimal schedule of a set of given mining processes is found by solving an optimization problem formulated. Thereafter, the fan speed optimization problem is solved to determine the optimal fan speed profile throughout the mining processes that matches the VOD and reduces energy consumption. For the fan speed optimization problem, the fan's operating point is correctly determined by incorporating the fan laws and the network's system curve to get a realistic figure of the savings [16, 31]. A case study is presented to demonstrate and verify the effectiveness of the optimization model built. The results show that by combining load shifting and energy efficiency techniques, an annual energy saving of 2 540 035 kWh is possible, leading to an annual cost saving of R 2 670 705 (R is the sign of South African Rand, the average exchange rate to US dollar in 2013 was $1=R9.64).

The rest of the paper is organized as follows. Section 2 presents the formulation of the ventilation problem. A case study is given in Section 5. Section 6 concludes this study.

2. Problem formulation

The problem is divided in two parts, EE and LM. For the EE case, the fan speed is adjusted according to the varying demand of air flow rate throughout the day. In the case of the LM, the optimal starting time of the mining schedule is found (according to the TOU tariff) that leads to minimum cost; and then the fan speed is adjusted accordingly.

For either case, the ventilation network needs to be modelled. To help understand the model better, an example of a simple network is presented. A path in a network can be defined as a directed chain from the inlet node to the outlet node. In addition, an assumption is made to simplify the model that says, the airflows in all branches contained in the path must have the same direction. The total number of paths in a network n_p is given by $n_p = n - m + 1$, where n is the number of branches and m is the number of nodes. In Fig. 1, there is 1 fan, 13 branches, 9 nodes, and thus, 5 paths.

Tellegen's theorem states that "the power provided to the system and the power consumed in the network must be equal" [32]. From a ventilation network point of view, it can be concluded that the sum of air power supplied by the fans must be equal to the sum of power losses incurred in the branches of the network.

The analogy of circuit theory is often used in modelling flow distribution networks by comparing the flow rate to current, and the voltages to the pressure [26, 27]. Thus Tellegen's theorem, along with Kirchhoff's laws form the basis to modelling an airflow distribution network.

The adaptation of Kirchhoff's current law is given by

3

$$\sum_{j=1}^{n} B_{ij} Q_j = 0, \text{ for } i = 1 \ldots m, \tag{1}$$

where j is the branch number, n is the total number of branches, Q_j is the flow rate of branch j, i is the node number, m is the total number of nodes, B_{ij} is the element of an $m \times n$ incidence matrix $B = [B_{ij}]$ that describes the node-to-branch incidence

$$B_{ij} = \begin{cases} 1, & \text{if flow in branch } j \text{ enters node } i; \\ -1, & \text{if flow in branch } j \text{ leaves node } i; \\ 1, & \text{if branch } j \text{ is not incident with node } i. \end{cases}$$

The adaptation of Kirchhoff's voltage law is applied to the paths in this case;

$$\sum_{j \in F} L_{pj} H_j - \sum_{j=1}^{n} L_{pj} h_j = 0, \text{ for } p = 1, \ldots, n_p, \tag{2}$$

where F is the set of branches containing a fan, H_j is the fan pressure in branch j, L_{pj} is element the path matrix $L = [L_{pj}]$, h_j is the pressure loss over the jth branch, p is the path number, and n_p is the total number of paths.

The path matrix L is an $n_p \times n$ matrix that describes the branch-to-path incidence and defined by

$$L_{pj} = \begin{cases} 1, & \text{if path } p \text{ contains branch } j; \\ 0, & \text{if path } p \text{ doesn't contain branch } j. \end{cases}$$

2.1. Atkinson Resistance

Unlike ohm's law, the relationship between pressure drop over a branch/pipe and the flow rate through it is not linear. It is derived from the Darcy-Weisbach equation [33] and is given by [26, 27]

$$h = RQ^2, \tag{3}$$

where h is the pressure drop over the pipe, Q is the flow rate through the pipe, and R is known as Atkinson resistance, given by

$$R = \frac{\rho \mu l}{2 D A^2}, \tag{4}$$

where ρ is the density of air, l is the length of the pipe, D is the diameter of the pipe, A is the cross-sectional area of the pipe, and μ is the Darcy friction factor, which is dependent on the material of the pipe.

This is a theoretical determination of the branch resistances. In practice, however, the resistance of a branch would be found by using data for the flow rate and pressure differences obtained from meters inside the mine, and solving eq. (3) for R.
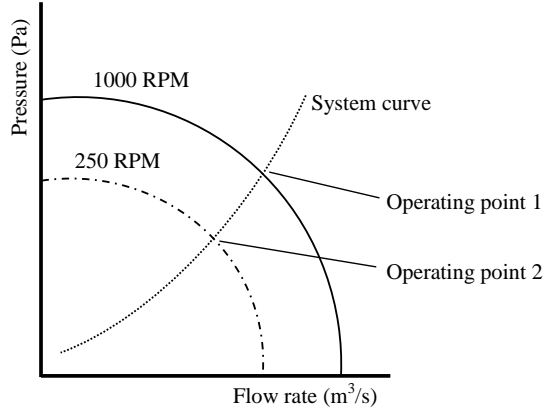
Figure 2: Operating points at different fan speeds

2.2. Fan Laws and Performance Curves

A particular fan can be characterized by its fan curve, i.e., how much pressure the fan needs to develop to supply a particular flow rate. A simple example of fan curves is shown in Fig. 2. It can be seen that a fan running at a particular speed has its corresponding fan curve, therefore changing the speed will result in a new curve. It can also be seen that as the speed reduces, a lower head/pressure is required to achieve the same flow rate. This means lower power is needed to supply the fan, since the air power is given as the product of the pressure and the flow rate. Thus less power is consumed at lower running speeds [13]. However, the question arises as to how to characterize the relationship between flow rate and power. This is solved by the Fan Laws, also known as the Affinity Laws.

The Fan Laws are a set of governing equations that define the relationship between the speed of the fan (N), the pressure developed by the fan (H), and the input power to the fan (P). These laws are given as [34]

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2}, \tag{5}$$

$$\frac{H_1}{H_2} = (\frac{N_1}{N_2})^2, \tag{6}$$

$$\frac{P_1}{P_2} = (\frac{N_1}{N_2})^3. \tag{7}$$

In these equations, the variables with subscript 1 are those at the original condition, and the ones with subscript 2 are the resulting variable due to the change in speed. E.g., using the first formula, the new flow rate (Q_2) can be found, due to the change in speed, if the initial flow rate (Q_1) is known. The same idea can be applied to the other formulae regarding the pressure and power, respectively.

2.3. System Curves

The system curve represents the combination of all the aerodynamic resistances in the system, by simplifying the entire network into a single airway with an equivalent resistance, R_{eq}.
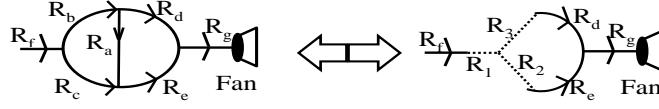
5

Figure 3: Delta to Wye Conversion

For instance, in Fig. 1, the system curve can be found by finding the equivalent resistance seen from the fan's point of view. Ideally, the system curve is characterised by a second order function in the same form as eq. (3). Practically, however, eq. (8) is taken as the general form to cater for offsets and disturbances.

$$H = b_2 Q^2 + b_1 Q + b_0. \tag{8}$$

In order to find the total equivalent resistance, some equivalent resistance simplifications are necessary. With the analogy from circuit theory, the following equations are derived.

For pipes in series [35]

$$R_{eq} = R_1 + R_2. \tag{9}$$

For parallel pipes,

$$\frac{1}{\sqrt{R_{eq}}} = \frac{1}{\sqrt{R_1}} + \frac{1}{\sqrt{R_2}}. \tag{10}$$

For a delta to wye conversion, with reference to Fig. 3, the following equations are derived from first principles

$$
\begin{aligned}
2R_1 = {} & \frac{R_c(R_a + R_b)}{R_a + R_b + R_c + 2\sqrt{R_c(R_a + R_b)}} \\
& + \frac{R_b(R_a + R_c)}{R_a + R_b + R_c + 2\sqrt{R_b(R_a + R_c)}} \\
& - \frac{R_a(R_b + R_c)}{R_a + R_b + R_c + 2\sqrt{R_a(R_b + R_c)}},
\end{aligned}
\tag{11}
$$

$$
\begin{aligned}
2R_2 = {} & \frac{R_a(R_b + R_c)}{R_a + R_b + R_c + 2\sqrt{R_a(R_b + R_c)}} \\
& + \frac{R_c(R_a + R_b)}{R_a + R_b + R_c + 2\sqrt{R_c(R_a + R_b)}} \\
& - \frac{R_b(R_a + R_c)}{R_a + R_b + R_c + 2\sqrt{R_b(R_a + R_c)}},
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
2R_3 = {} & \frac{R_a(R_b + R_c)}{R_a + R_b + R_c + 2\sqrt{R_a(R_b + R_c)}} \\
& + \frac{R_b(R_a + R_c)}{R_a + R_b + R_c + 2\sqrt{R_b(R_a + R_c)}} \\
& - \frac{R_c(R_a + R_b)}{R_a + R_b + R_c + 2\sqrt{R_c(R_a + R_b)}}.
\end{aligned}
\tag{13}
$$

Thus, the equivalent resistance as seen from the fan's point of view in Fig. 3 is calculated by

$$R_{eq} = R_f + R_1 + ((R_3 + R_d)||(R_2 + R_e)) + R_g. \tag{14}$$

Therefore, the coefficient b_2 in eq. (8) is found by the above calculations to be $b_2 = R_{eq}$. The other coefficients are considered to be 0 in this study, because an ideal case is assumed.

2.4. Fan Operating Point

When analyzing flow rate/pressure/power changes of a fan with respect to speed changes, often the fan/affinity laws are used. However, this is only valid when the fan is being analysed by itself. When considering the fan as part of a network, using only the fan laws will result in incorrect analysis, i.e., there is no guarantee that the fan will operate at the calculated flow rate/pressure. More importantly, a reduction in fan speed will often result in an overestimate of power savings [31]. When formed part of a network, the fan will operate at a steady state condition, which is known as the operating point of the fan. The operating point of the fan is given by the intersection point between a fan curve and system curve.

A simple example of this is shown in Fig. 2. It can be seen that if the fan is running at 1000 RPM, it will operate at point 1, and if it is running at 250 RPM, it will operate at point 2. This shows that every time the speed changes, there will be a new operating point.

Therefore, it is imperative that the affinity laws are used in conjunction with the system curve, such that the correct operating point is found.

In section 3, three equations are used as part of the objective and constraint functions, i.e., $P_k(N_k(t))$, $Q_k(N_k(t))$, and $H_k(N_k(t))$. These equations express the power, the flow rate, and the pressure as a function of the fan speed, respectively. The fan operating point $[H_k(N_k(t)), Q_k(N_k(t))]$ is time varying for VSDs and determines the power consumption of the fan $P_k(N_k(t))$.

It is noted that for ease of notation, the subscript k in the functions $P_k(N_k(t))$, $Q_k(N_k(t))$ and $H_k(N_k(t))$ is omitted in the remaining of this section. For each fan k, the same procedure as given here applies. To form the flow-speed function $Q(N(t))$, the fan curve of the highest speed is required. This curve can be described by a second order polynomial given by the generic form

$$H_{full} = a_2 Q_{full}^2 + a_1 Q_{full} + a_0, \tag{15}$$

where H_{full} is the pressure developed by the fan at full speed, Q_{full} is the flow rate delivered by the fan at full speed; a_2, a_1, and a_0 are constant parameters derived from the full speed fan curve.

By making use of the fan laws, and replacing eqs. (5) and (6) into eq. (15), the following equation is obtained

$$H = a_2 Q^2 + a_1 Q(\frac{N}{N_{full}}) + a_0(\frac{N}{N_{full}})^2 \tag{16}$$

where N_{full} is the rated full speed.

By equating eq. (16) to the system curve equation (8) and solving for Q, a function is obtained for the flow rate only in terms of the normalized speed (N/N_{full}) [36]. By curve fitting, this function can be approximated to a linear function given by [16]

$$Q(N(t)) = c_1 \frac{N(t)}{N_{full}} + c_0, \tag{17}$$

where c_1, and c_0 are constant parameters.

Thus, eq. (17) can be used to find the flow rate at the operating point corresponding to any given fan speed $N(t)$.

The pressure-speed function is obtained in a similar method, i.e., the same procedure is followed until eq. (16) is reached. Thereafter, eq. (16) and eq. (8) are each expressed in terms of the flow rate Q. These are then equated to each other, and then the resulting equation is solved for H. This will result in a function for the pressure developed by the fan expressed only in terms of the normalized speed. Again, by curve fitting, this function can be approximated to a second order polynomial given by the generic form [16]

$$H(N(t)) = d_2 \left(\frac{N(t)}{N_{full}}\right)^2 + d_1 \frac{N(t)}{N_{full}} + d_0. \tag{18}$$

Lastly, with the fan operating point find by eqs. (17) and (18), the power of the fan at the operating point is obtained by following a similar process to the flow-speed formulation. First, the power curve for the highest speed is expressed as a 3rd order polynomial; into which, eqs. (5) and (7) are replaced to yield the following equation

$$P = e_3 Q^3 + e_2 Q^2 \left(\frac{N}{N_{full}}\right) + e_1 Q \left(\frac{N}{N_{full}}\right)^2 + e_0 \left(\frac{N}{N_{full}}\right)^3. \tag{19}$$

Thereafter, by replacing eq. (17) into eq. (19), a function is obtained for the power only in terms of the normalized speed. By curve fitting, this function can be approximated to a 3rd order polynomial given by the generic form [16]

$$P(N(t)) = f_3 \left(\frac{N(t)}{N_{full}}\right)^3 + f_2 \left(\frac{N(t)}{N_{full}}\right)^2 + f_1 \frac{N(t)}{N_{full}} + f_0. \tag{20}$$

After eq. (20) is obtained, the power of the fan operating at different speeds can be calculated accurately with the fan's operating point accounted for.

3. Energy Efficiency

To find the optimal fan speeds that result in minimum energy cost, while adhering to the flow rate requirements, a generic mathematical formulation of the optimization model is given in this section.

The objective is to minimize the following discrete cost function

$$J = \sum_{k=1}^{K} \sum_{t=1}^{T} P_k(N_k(t)) C(t) \Delta t, \tag{21}$$

where K is the total number of fans, T is the total number time steps, $C(t)$ is the time of use tariff at time step t, and Δt is the length of time steps in hours.

$P_k(N)$ is a 3rd order polynomial that describes the power of the fan k as a function of its speed $N_k(t)$. It is detailed in section 2.4 and given in eq.(20).

Since the optimization variable is chosen to be the fans' speeds, the flow rates of the branches that contains a fan are defined by flow rates of that fan. This forms the first system constraint, given by

$$Q_j(t) = Q_k^j(N_k(t)), \text{for } j \in F, \tag{22}$$

8

where $Q_j(t)$ and $Q_k^j(N_f(t))$ are the flow rate of branch j and the flow rate of fan k that lie in branch j at time t, respectively.

$Q_k^j(N_k(t))$ is a linear equation that describes the flow rate of a fan k, as a function of its speed $N_k(t)$. It is given by eq. (17) in section 2.4.

The second constraint is based on the ventilation load of the mine. This is where the concept of VOD is used, i.e., the demand for airflow rate at each branch, at each time step forms the load to the system. This can be written as

$$Q_j^{min}(t) \leqslant Q_j(t) \leqslant Q_j^{max}(t), \tag{23}$$

where $Q_j^{min}(t)$ and $Q_j^{max}(t)$ are the minimum and maximum allowable airflow in branch j at time t. For the case where the demand is a fixed amount, $Q_j^{min}(t) = Q_j^{max}(t)$.

The rest of the constraints are formed based on the principles of conservation of mass and energy. The principle of conservation of mass is stated in eq. (1), but is shown here again including the time variable.

$$\sum_{j=1}^{n} B_{ij}Q_j(t) = 0 \text{ for } i = 1, \ldots, m. \tag{24}$$

The principles of conservation of energy is expanded from eq. (2) to give

$$\sum_{j \in F} L_{pj}H_j(t) - \sum_{j=1}^{n} L_{pj}r_j Q_j^2(t) = 0, \text{ for } p = 1...n_p, \tag{25}$$

where $H_j(t)$ is the fan pressure in branch j at time t. For a specific fan k, this is a second order polynomial that describes the pressure across fan as a function of its speed $N_k(t)$ at time t and denoted as $H_k(N_k(t))$, which is derived from the fan laws, and is presented in eq. (18) in section 2.4

Thus an optimization model can be completely described by the objective function, given by eq. (21), and the constraints, given by eqs. (22)-(25).

4. Load Management

To further investigate the potential of peak shaving and cost minimization by implementing LM strategy, the LM problem of the ventilation system is formulated. It is assumed that a schedule consists of N processes that follow each other. Therefore, the main idea of LM is to find an optimal starting point of these processes in view of the TOU tariff.

To do so, the following cost function is minimized

$$J = \sum_{i=t_s}^{\lambda_1-1} P_1C(i) + \sum_{i=\lambda_1}^{\lambda_2-1} P_2C(i) + \cdots + \sum_{i=\lambda_{N-1}}^{\lambda_N-1} P_NC(i), \tag{26}$$

where t_s is the starting time of the schedule, and the decision variable; $t_{p(1)}, \ldots, t_{p(N)}$ are the durations (hours) of the processes 1 to N; $P_1, \ldots, P_N$ are the power consumptions (kW) of processes 1 to N, at the specified flow rates, respectively; and $C(i)$ is the electricity cost (R/kWh) at time instant i, according to the TOU tariff; and

$$\lambda_y = t_s + \sum_{z=1}^{y} t_{p(z)}, \text{for } y = 1, \ldots, N. \tag{27}$$

5. Case study

5.1. Problem description

For demonstration purposes, a case study is presented. The example from Fig. 1 is used, and it is assumed that a schedule is followed over 24 hours with regard to the mining processes. The schedule is shown in chronological order, in Table 1, i.e., the processes have to follow each other as shown. For this example it is assumed that only branch 7 and 8 are being actively mined, and thus only these branches follow the schedule. Thus, there is no particular requirements for the other branches of the mine. Again, the problem is divided in two parts: energy efficiency and load shifting. For the first case, it is assumed that the schedule shown in Table 1 starts at the beginning of the day, i.e., no consideration is made towards the optimal starting time according to the TOU tariff. For the second case, the optimal starting time of the schedule is found that leads to the minimum cost, and then the optimal fan speeds are found accordingly. For both cases, the optimization period is for one day; 24 hours.

Table 1: Mining cycle and its requirements

Process	Duration	Min flow required
Drilling	8 hours	$15.2 m^3/s$
Explosive charge-up	3 hours	$10.3 m^3/s$
Blasting	6 hours	none
Cleaning & Mucking	7 hours	$25.5 m^3/s$

For either case, the system curve is needed. It is assumed that the resistance of each branch is known (see Table 2). Thus the procedure described in section 2.3 is followed, and it is found that the equivalent resistance seen by the fan is $R_{eq} = 0.2122 Ns^2/m^8$. Assuming no initial offset, the system curve is described by

$$H = 0.2122 Q^2. \tag{28}$$

Table 2: Resistance values for the example network (adapted from[26])

Branch no.	$R \ (Ns^2/m^8)$	Branch no.	$R \ (Ns^2/m^8)$
1	0.0225	8	1.35
2	0.1104	9	0.225
3	0.3	10	0.0551
4	0.168	11	4.5
5	3.6	12	0.0385
6	0.15	13	0.0585
7	0.072		

The data from the fan curves (given in Fig. 4) are used to obtain the power-speed, pressure-speed, and flow-speed functions. The data for this fan curve is obtained from an operating mine in South Africa.
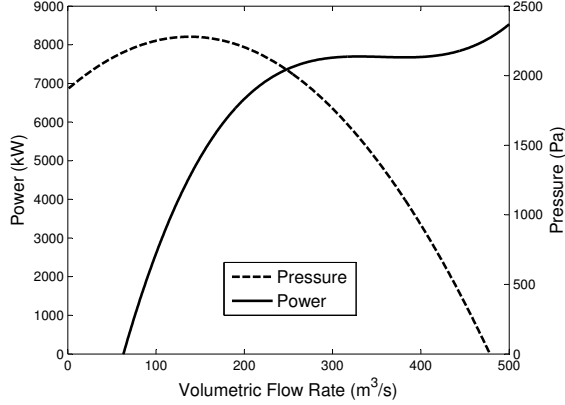
Figure 4: Fan power and performance curve

The power-speed, pressure-speed, and flow-speed functions are given by eqs. (29), (30), (31) respectively.

$$P(N) = 1796(\frac{N}{750})^3, \tag{29}$$

$$H(N) = 7973(\frac{N}{750})^2, \tag{30}$$

$$Q(N) = 194(\frac{N}{750}). \tag{31}$$

The incidence matrix and path matrix can be structured according to eqs. (1) and (2). They are not presented here to save space.

Table 3: Megaflex TOU tariff

Time of use	Tariff(R/kWh)
00:00 - 06:00 (off-peak)	0.348
06:00 - 07:00 (standard)	0.641
07:00 - 10:00 (peak)	2.116
10:00 - 18:00 (standard)	0.641
18:00 - 20:00 (peak)	2.116
20:00 - 22:00 (standard)	0.641
22:00 - 24:00 (off-peak)	0.348

5.2. Results and discussion

As per the requirements, only branchs 7 and 8 are limited to specific flow rates throughout the day. The flow rates for the rest of the branches are limited between $3m^3/s$ and an infinite amount, i.e., the model is allowed to choose any value that will minimize the cost, while maintaining the constraints. The tariff structure shown in Table 3 is used to calculate the energy cost.

5.2.1. Case 1: Energy Efficiency

The problem is a non-linear one, due to the non-linear equality constraint given by eq. (25). The problem is solved using the $fmincon$ solver in Matlab's optimization toolbox. The schedule

11

from Table 1 is followed, and started at 00:00. A safety margin of 3 m^3/s is kept, and no upper bounds of the flow rates are considered. Therefore the demand constraints for branches 7 and 8 are given by

$$
\begin{aligned}
Q_{7\&8}(t) &\geq 18.2 \quad \text{for} \quad 00:00 \leq t \leq 08:00, \\
Q_{7\&8}(t) &\geq 13.3 \quad \text{for} \quad 08:00 \leq t \leq 11:00, \\
Q_{7\&8}(t) &\geq 3.00 \quad \text{for} \quad 11:00 \leq t \leq 17:00, \\
Q_{7\&8}(t) &\geq 28.5 \quad \text{for} \quad 17:00 \leq t \leq 24:00.
\end{aligned}
\tag{32}
$$

The results include flow rates of branches 7 and 8, optimal fan speeds found and power profile of the fan, are presented in Figs. 5, 6, 7, and 8, respectively. It is noted that the solutions obtained might not lead to a global minimum, and therefore they may be referred to as sub-optimal solutions. As can be seen from Figs. 5 and 6, the minimum required flow rates of branches 7 and 8 are achieved over the 24 hour period, and the constraints are all satisfied. It is noted that the optimal flow rates of the branches, as determined by the model, are not less than the minimum requirements. Theoretically, the power of a fan can be reduced if the flow rates of the branches exactly equal to the minimum required values. However, that cannot be always satisfied due to physical limits. In other words, there is no possible solution that can satisfy exactly the minimum requirements for both branch 7 and 8.
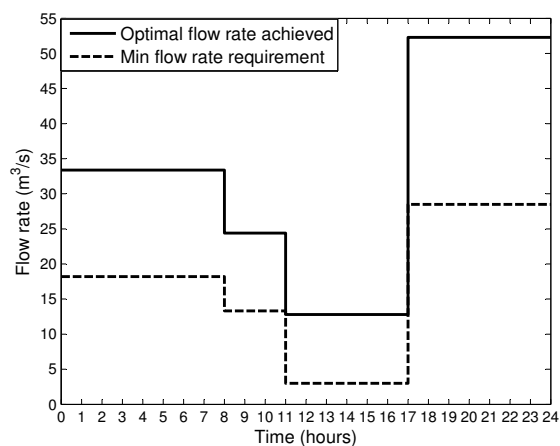

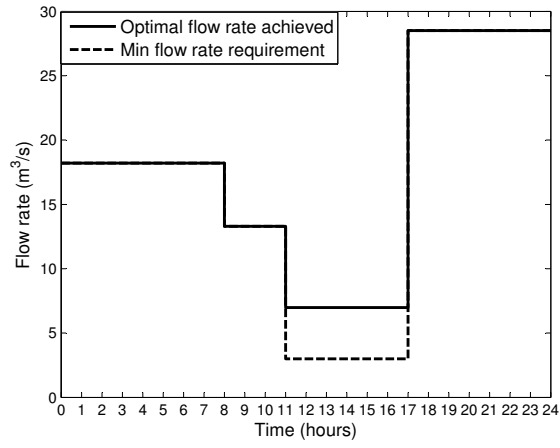Figure 5: Flow Rate in Branch 7 for Case 1
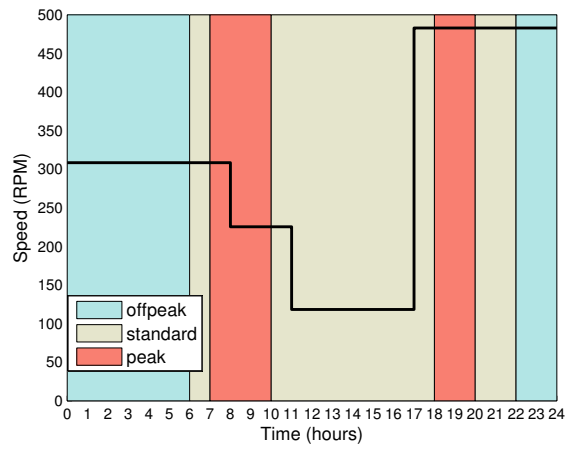
Figure 6: Flow Rate in Branch 8 for Case 1

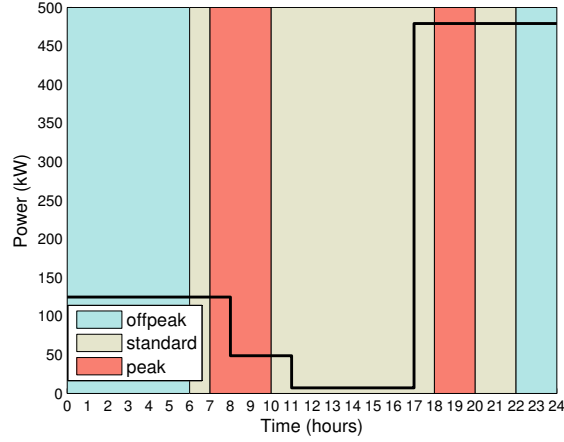Figure 7: Optimal Fan Speed for Case 1

Figure 8: Power Consumption of Main Fan for Case 1

Fig. 7 shows that the fan speed is varied throughout the day, and this means that the power consumption will vary as well, reflected in Fig. 8. The non-linear relationship is clearly visible, whereby dropping the speed from 300 rpm to about 225 rpm reduces the power consumption from 125 kW to about 50 kW.

The optimized fan speed results in energy cost of R4 151 per day. Comparing this to a situation where the fan needs to be run at full capacity at all times to supply the maximum flow rate of 28.5 m^3/s to branches 7 and 8, the cost of energy would be R9 781 per day. This leads to a cost saving of R5 630 per day, which adds up to R2 054 950 cost saving per year (assuming the same cycle throughout the year).

In terms of energy savings, keeping a constant speed leads to daily energy consumption of 11 499 kWh; whereas varying the speed results in the daily consumption to be 4 540 kWh. This leads to daily savings of 6 959 kWh, which translates to savings of 2 540 035 kWh per year.

5.2.2. Case 2: Energy Efficiency and Load Management

For this case, the optimal starting time is first found by solving the model shown in section 4. To solve this problem, the genetic algorithm (GA) solver in Matlab is used, because of the integer constraint on the decision variable. The TOU tariff that is followed is shown in Table 3[1]. Thereafter, the schedule shown in Table 1 is followed and the optimal fan speeds are found.

After minimization of the objective, it is found that the minimum cost over a 24 hour period occurs when the cycle is started at 05:00. It is noted that changing the schedule will result in a change in the working hours for the workers. Since this is a preliminary study, the social effects vs. economic benefits of the change are not considered.

Keeping a safety margin of 3 m^3/s, the demand constraints are given by

$$
\begin{aligned}
Q_{7\&8}(t) &\geq 18.2 \quad \text{for} \quad 05:00 \leq t \leq 13:00 \\
Q_{7\&8}(t) &\geq 13.3 \quad \text{for} \quad 13:00 \leq t \leq 16:00 \\
Q_{7\&8}(t) &\geq 3.00 \quad \text{for} \quad 16:00 \leq t \leq 22:00 \\
Q_{7\&8}(t) &\geq 28.5 \quad \text{for} \quad 22:00 \leq t \leq 05:00
\end{aligned}
\tag{33}
$$

---

[1]Eskom, Schedule of standard prices for Eskom tariffs, 2013

The results are presented in Figs. 9, 10, 11, and 12. Again, the minimum required flow rates are achieved for branches 7 and 8. However this time it can be seen that the higher demand has been shifted to the off-peak times, and thus less energy is consumed during peak times, as shown in Fig. 12. If the optimal speed is followed, the energy cost (according to the TOU tariff) in 24 hours results to R2 464. Compared to case 1, this leads to a further R1 687 saving per day. Thus the annual energy-cost saving, when taking into account energy efficiency and load shifting, is R2 670 705.
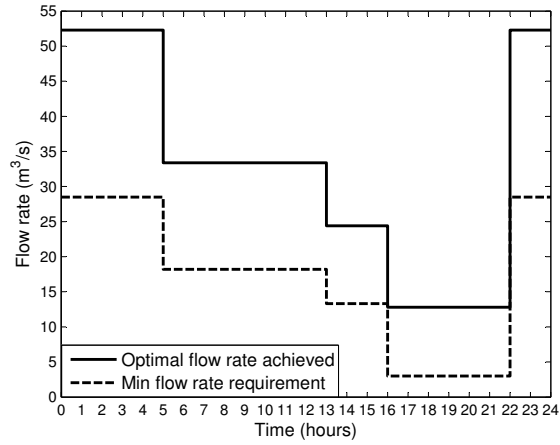

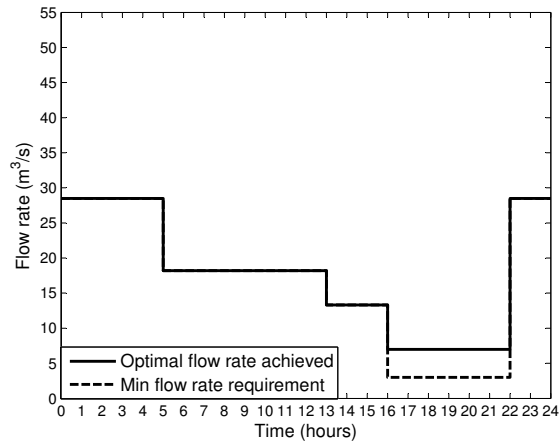Figure 9: Flow Rate in Branch 7 for Case 2

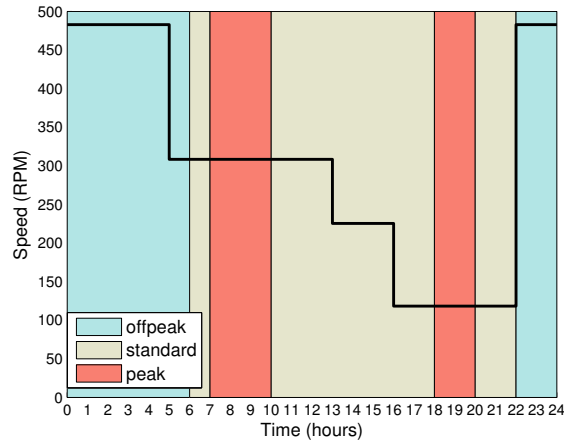Figure 10: Flow Rate in Branch 8 for Case 2
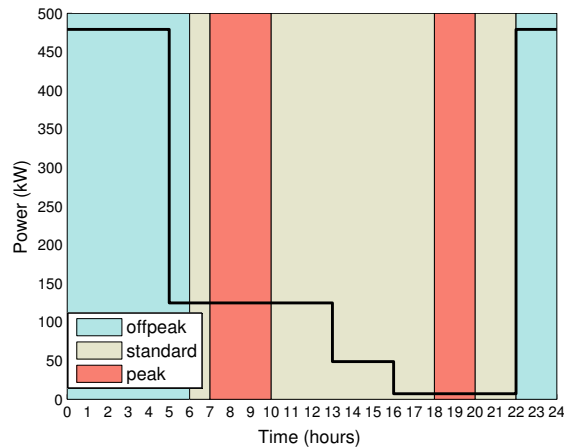
Figure 11: Optimal Fan Speed for Case 2

Figure 12: Power Consumption of Main Fan for Case 2

It must be noted that when compared to case 1, the energy savings in this case stays the same, i.e., 2 540 035 kWh per year. This is because the load is just shifted according to the TOU tariff, and the total demand still remains the same.

6. Conclusion

Different activities in a mine throughout the day lead to varying airflow requirements for the ventilation system. In view of this, ventilation on demand (VOD), which supplies the ventilation air quantity as it is required by at a specific location and time of the mine, is introduced. To realise VOD, fan speeds in the ventilation network must be adjusted accordingly to save energy and cost. An optimization model is built in this study to determine the optimal fan speeds that lead to minimum energy cost. Energy efficiency and load management strategies are investigated. It has been shown in a case study that a combination of energy efficiency and load shifting can lead to an annual energy saving of 2 540 035 kWh and an annual cost saving of R2 670 705. It

must be noted that the 74.8% cost saving and 60.5% energy saving may seem impressive, but this is only an indication of the maximum possible savings that can be achieved for this particular case. Various factors can affect this figure, such as the resistances of the branches, the characteristics of the fan, the TOU tariff, and the requirements of the flow rates. Thus, it has been shown that there is significant opportunity for energy and energy-cost savings in an underground mine ventilation network, and this paper provides a foundation for further research which will consider factors such as multiple fans, leakages, and efficiencies of the drives/motors etc.

7. Acknowledgement

References

[1] Gellings, C.. The concept of demand-side management for electric utilities. Proceedings of the IEEE 1985;73(10):1468–1470.

[2] Eissa, M.. Demand side management program evaluation based on industrial and commercial field data. Energy Policy 2011;39(10):5961 – 5969. Sustainability of biofuels.

[3] Saini, S.. Conservation v. generation: The significance of demand-side management (dsm), its tools and techniques. Refocus 2004;5(3):52 – 54.

[4] Middelberg, A., Zhang, J., Xia, X.. An optimal control model for load shifting with application in the energy management of a colliery. Applied Energy 2009;86(78):1266 – 1273.

[5] Zhang, S., Xia, X.. Optimal control of operation efficiency of belt conveyor systems. Applied Energy 2010;87(6):1929 – 1937.

[6] van Staden, A.J., Zhang, J., Xia, X.. A model predictive control strategy for load shifting in a water pumping scheme with maximum demand charges. Applied Energy 2011;88(12):4785 – 4794.

[7] Tang, Y., Zheng, G., Zhang, S.. Optimal control approaches of pumping stations to achieve energy efficiency and load shifting. International Journal of Electrical Power & Energy Systems 2014;55(0):572 – 580.

[8] Zhang, J., Xia, X.. Best switching time of hot water cylinderswitched optimal control approach. In: Proceedings of the 8th IEEE AFRICON conference. Namibia; 2007, p. 1–7.

[9] Ashok, S.. Peak-load management in steel plants. Applied Energy 2006;83(5):413 – 424.

[10] Teitel, M., Levi, A., Zhao, Y., Barak, M., Bar-lev, E., Shmuel, D.. Energy saving in agricultural buildings through fan motor control by variable frequency drives. Energy and Buildings 2008;40(6):953 – 960.

[11] Plessis, G.E.D., Liebenberg, L., Mathews, E.H.. The use of variable speed drives for cost-effective energy savings in south african mine cooling systems. Applied Energy 2013;111(0):16 – 27.

[12] Ozdemir, E.. Energy conservation opportunities with a variable speed controller in a boiler house. Applied Thermal Engineering 2004;24(7):981 – 993.

[13] Eliason, J.R., Fisher, B.S.. Large adjustable speed fan drives including static converter developments for cement plants. IEEE Transactions on Industry Applications 1977;IA-13(6):557–562.

[14] Al-Bahadly, I.. Energy saving with variable speed drives in industry applications. In: Proceedings of the 2007 WSEAS Int. Conference on Circuits, Systems, Signal and Telecommunications. Gold Coast, Australia; 2007, p. 53–58.

[15] Saidur, R., Mekhilef, S., Ali, M., Safari, A., Mohammed, H.. Applications of variable speed drive (VSD) in electrical motors energy savings. Renewable and Sustainable Energy Reviews 2012;16(1):543 – 550.

[16] Zhang, H., Xia, X., Zhang, J.. Optimal sizing and operation of pumping systems to achieve energy efficiency and load shifting. Electric Power Systems Research 2012;86(0):41 – 50.

[17] Abdelaziz, E., Saidur, R., Mekhilef, S.. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews 2011;15(1):150 – 168.

[18] Cheng, G., Qi, M., Zhang, J., Wang, W., Cheng, Y.. Analysis of the stability of the ventilation system in baishan coalmine. Procedia Engineering 2012;45(0):311 – 316.

[19] O'Connor, D.. Ventilation on demand (VOD) auxiliary fan project - vale inco limited, creighton mine. In: proceedings of the 12th U.S./North American Mine Ventilation Symposium. Nevada, USA; 2008, p. 41–44.

[20] Acuña, E., Hall, S., Hardcastle, S., Fava, L.. The application of a MIP model to select the optimum auxiliary fan and operational settings for multiple period duties. INFOR: Information Systems and Operational Research 2010;48(2):95–102.

[21] Hardcastle, S., Kocsis, C., Li, G., Hortin, K.. Analyzing ventilation requirements and the utilization efficiency of kidd creek mine ventilation system. In: Proceedings of the 12th U.S./North American Mine Ventilation Symposium. Nevada, USA; 2008, p. 27–36.

[22] Medved, M., Ristovic, I., Roser, J., Vulic, M.. An overview of two years of continuous energy optimization at the velenje coal mine. Energies 2012;5(6):2017–2029.

[23] Kurnia, J.C., Sasmito, A.P., Mujumdar, A.S.. Simulation of a novel intermittent ventilation system for underground mines. Tunnelling and Underground Space Technology 2014;42(0):206 – 215.

[24] Wallace, G., Codoceo, O.. Ventilation planning at the El Indio mine. In: Proceedings of the 6th International Mine Ventilation Congress. Pennsylvania, USA; 1997, p. 5–9.

[25] Wallace Jr., K., Tessier, M., Pahkala, M., Sletmoen, L.. Optimization of the red lake mine ventilation system. In: Proceedings of the 11th U.S./North American Mine Ventilation Symposium. Pennsylvania, USA; 2006, p. 61–66.

[26] Hu, W., Longson, I.. The optimization of airflow distribution in ventilation networks using a nonlinear programming method. Mining Science and Technology 1990;10(2):209 – 219.

[27] She, X., Sun, Y.. Research on optimization algorithm wind quantity distribution in ventilation networks based on generic algorithm. In: 2010 Second International Conference on Computational Intelligence and Natural Computing Proceedings; vol. 1. Wuhan, China; 2010, p. 154–158.

[28] Lowndes, I., Yang, Z.. The application of GA optimisation methods to the design of practical ventilation systems for multi-level metal mine operations. Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology 2004;113(1):43–58.

[29] Allen, C., Keen, B.. Ventilation on demand (VOD) project - vale inco ltd. coleman mine. In: proceedings of the 12th U.S./North American Mine Ventilation Symposium. Nevada, USA; 2008, p. 45–49.

[30] O'Connor, D., Hardcastle, S., Kocsis, C.. Justifying ventilation-on-demand in a canadian mine and the need for process based simulations. In: proceedings of the 11th U.S./North American Mine Ventilation Symposium. Pennsylvania, USA; 2006, p. 15–27.

[31] Carlson, R.. The correct method of calculating energy savings to justify adjustable frequency drives on pumps. In: Industry Applications Society 46th Annual Petroleum and Chemical Industry Conference. San Diego, CA; 1999, p. 275–283.

[32] Hu, W., Longson, I.. A computer method for the generalized controlled flow problem in ventilation networks. Mining Science and Technology 1989;8(2):153 – 167.

[33] A. Chadwick, J.M., Borthwick, M.. Hydraulic in Civil and Environmental Engineering. Oxfordshire, England: Spon Press; 4 ed.; 2004.

[34] Papar, R., Szady, A., Huffer, W., Martin, V., Mckane, A.. Increasing energy efficiency in mine ventilation systems. Tech. Rep.; Lawrence Berkeley National Laboratory, University of California; 1999.

[35] Hartman, H., Mutmansky, J.M., Ramani, R.V., Wang, Y.J.. Mine Ventilation and Air Conditioning. Wiley; 3 ed.; 1997. ISBN 978-0-471-11635-6.

[36] Shim, G., Song, L., Wang, G.. Comparison of different fan control strategies on a variable air volume systems through simulations and experiments. Building and Environment 2014;72(0):212 – 222.