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Evaluating the impact of auxiliary fan practices on localised subsurface ventilation

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ABSTRACT

Mines are continually expanding in size and depth, leading to an increased reliance on localised subsurface ventilation systems. The use of underground auxiliary fans is a favoured method to increase and control airflow in working areas. However, the effectiveness of auxiliary fans in this regard is not clear. This paper evaluated the performance of these underground fan systems in four different South African deep-level gold mines. A total auxiliary fan system efficiency of 5% was found across six systems, with the average fan efficiency of 33 fans at 38%. The results showed that these fans deviate significantly from their design operating points. Therefore, there are significant shortcomings in current underground fan practices. Our detailed investigations led to the conclusion that the assemblage of underground auxiliary fan systems results in significant energy inefficiencies. Therefore, maintaining good underground fan practice such as optimal fan selection, ducting design and maintenance is crucial for the efficacy of a mine ventilation network.

1. Introduction

The extraction of mineral resources has become increasingly more complex as easy to reach reserves are being depleted [1]. This has resulted in mines continually expanding in size and depth in order to reach new production zones [1]. To ensure a safe and productive mining environment, underground ventilation systems are used to provide adequate fresh air to parts of a mine where mine personnel and equipment travel and work [2]. However, due to the increasing expansion of mine networks there is a subsequent increase in ventilation network size and complexity, making fresh air distribution and management of the ventilation network challenging and energy intensive [3].

With increasing mine depth there is a subsequent increase in the airflow demand and system pressure [4]. These pressure demands become a concern when surface extraction fans can no longer supply the required suction pressure which ultimately restrains mine expansion [4]. Therefore, the use of smaller underground auxiliary fans is commonplace in deep-level mine ventilation systems in order to overcome these restrictions [3–6].

Various types of fans exist in deep-level mines as illustrated by the basic schematic of a mine ventilation network given in Fig. 1. Fig. 1 also illustrates the typical location and types of mine ventilation fans [6]:

(1) Primary fans are large fans that have a significant impact on the total mine airflow such as surface extraction fans.
(2) Booster fans are smaller fans that are in series with one or more primary fans. These fans are installed to assist the primary fans in overcoming mine airflow resistances.
(3) Development end fans are auxiliary fans used to ventilate a workplace with no air flowing through it.
(4) District or circuit fans are auxiliary fan assemblages that are used to direct air into a specific district or area. Typical districts can be one or more mining areas, underground bulk air coolers, raise boreholes, return airways, and up and downcast shafts.

Research on primary ventilation fans has shown that fan assemblages can have a major impact on the total performance of a fan installation [7]. De Souza found that up to 40%–80% of the energy consumed by primary ventilation fans, is used to overcome the resistances of fan assemblages components [7]. However, with proper engineering design and installation, these systems could operate at efficiencies above 80% resulting in an improvement of between 20% and 65% [7]. This leads us to the question of whether similar problems exist in other ventilation components such as underground auxiliary and district fan assemblages.

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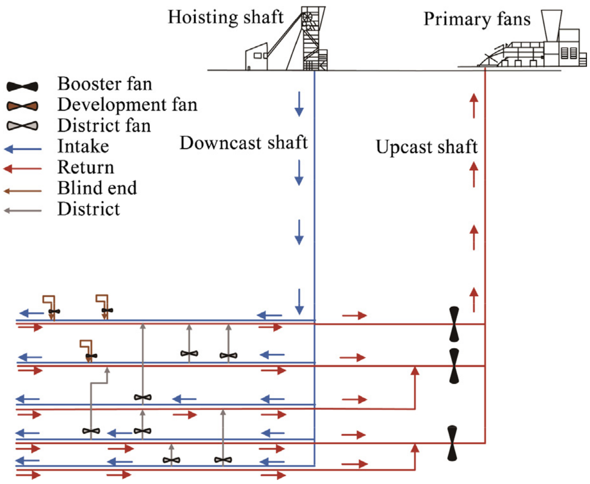

Fig. 1. Basic schematic of a typical underground ventilation network.

Literature describes various energy inefficiencies present in mine auxiliary fan assemblages such as ducting leakages, fan inefficiencies, door leaks, ducting pressure losses due to friction factors, poor fan performance and poor fan installations [7–11]. Levesque also highlighted the need for testing to determine leakage values that can be used for design purposes as well as assessment of the quality of fan assemblage installations [10]. It is thus evident that there exists a need to evaluate and understand the impact that underground auxiliary fan systems have on subsurface ventilation.

Underground district fan assemblages typically consist of axial fans, corrugated spiral-ducting, and airlocks (walls, seals or doors) [12,13]. This paper investigates the effective interaction between the components of district fan assemblages and the actual performance of these systems. Throughout this study, auxiliary fans will be considered as the fan only while district fans will be considered as the localised fan system which will include the fan and fan assemblage consisting of ducting and airlocks.

The novelty of this study is that it focuses on the efficiency of underground auxiliary fan assemblages. No literature is available that explicitly evaluates underground fan assemblage practices and how efficient the conversion of electrical energy to ventilation energy is. It is therefore of utmost importance for the mining industry and related mechanical engineering fields to understand the status of underground district fan assemblages and the implications of poor engineering practices.

1.1. The practice of underground district fan assemblages

District and auxiliary fans do not have a significant influence on the total airflow rate and ventilation pressure of a mine [12]. Total airflow is a function of the suction pressure created by the main ventilation fans while district and auxiliary fans distribute this airflow to the correct areas [6]. However, the efficacy of airflow distribution in any underground fan system is highly dependent on the quality of district and auxiliary fan installation, fan selection and assemblages maintenance [13]. Their performance plays a vital role in the safety of mine workers and subsequently production [14]. The design, planning, and monitoring of underground fans are therefore of utmost importance for an underground ventilation network to function. Diligent steps for underground ventilation controls' design, management, and monitoring are available in literature [15]. However, the efficacy of the design, management, and monitoring of ventilation controls is highly dependent on how well industry is adhering to available guidelines and practices.

Knowing the resistance of the underground districts and the fan assemblages is crucial when designing or selecting underground fans. The criteria for underground fan selections are listed in literature [16–18]. However, the characteristics of the districts can change dynamically as the mine expands [18,19]. In addition, the pressure effects of nearby underground fans and natural ventilation pressure can influence the operating point of a fan significantly [5]. Further, energy lost due to inefficiency are directly induced into the air stream as thermal energy [20]. Ideally, a ventilation simulation model could thus assist personnel with the underground fan selection procedure [21].

Diligent steps are in place for the design and installation of surface extraction fans and their assemblages in the mining industry. However, there are fewer efforts on the design and installation of underground district fans [9]. Thus, underground district fans may have operational and financial implications when not correctly managed [9]. The thermal comfort and safety of mine personnel are also highly dependent on the effective airflow distribution of these fan systems [22]. Due to the impact on safety, there should be no compromise with the control and management of these underground mine ventilation fans.

A previous case study by Krog demonstrates the energy implications due to shock losses when underground fans are installed without any silencer [9]. Krog found that energy cost savings of up to 60% can be achieved when discharge cones for fan outlets are used rather than fans delivering airflow directly to the air stream. This is due to the reduction of shock losses, which are often neglected when underground fans are installed [9].

The measured operating points of underground fans often lie well off the manufacturer's curve due to various reasons [8]. The reasons why these underground fans are operating off their manufacturer's curves are however absent in literature. In deep-level mines, there is a significant number of district and auxiliary fans which absorb a large amount of electrical power [6]. The impact underground fan assemblages have on an underground ventilation network is therefore a topic worth investigating. Furthermore, various inefficiencies are present in underground fan assemblages, which can have a significant compounding effect on the overall fan system performance [5,7–9,20]. Thus, we investigate the impact of fan practices on underground district fan systems' performances and how well the electrical energy is converted to ventilation energy.

2. Method and materials

This study investigated the impact district fan assemblages have on an underground ventilation network. Ventilation data

Table 1
Airflow and fan assemblage measurements and equations.

	Parameters	Measuring instrumentation or calculation
1	Static pressure $\triangle P$ (kPa)	Delta Ohm HD2134P.2-manometer
2	Velocity V (m/s)	Tenmar 404-vane anemometer
3	Area A (m^2)	Bosch GLM 20 distance meter
4	Volumetric flow rate Q (m^3/s)	$Q = VA$
5	Barometric pressure BP (kPa)	Tenmar 404-barometer
6	Air wet-bulb temperature T_{wb} (°C)	Basic whirling hygrometer
7	Air dry-bulb temperature T_{db} (°C)	Basic whirling hygrometer
8	Density ρ (kg/m^3)	$\rho = f(T_{wb}, T_{db}, BP)$ [23]
9	Fan total pressure $\triangle P_T$ (kPa)	$\Delta P_T = \Delta P + \Delta\rho V^2/2$
10	Electrical power consumption P_{fan} (kW)	UNI-T UT204A clamp-multimeter
11	Airflow resistance R	$R = \Delta P/\rho Q^2$
12	Airpower P_{air} (kW)	$P_{air} = Q \times \Delta P_T$
13	Mass flow rate m (kg/s)	$\dot{m} = Q \times \rho$
14	Total efficiency η_{total}	$\eta_{total} = (P_{air}/P_{fan})$

was gathered from four different deep-level gold mines in South Africa referred to as Mine A, B, C, and D respectively. Table 1 shows the various parameters and the required instrumentation used for the research. A comprehensive investigation was conducted on six district fan assemblages on Mine A. Performance evaluations on the various components of these district fan assemblages were conducted. The fan assemblages include the fan ducting (corrugated spiral-ducting), the airlocks, and the fan itself. Furthermore, the performance of 33 underground auxiliary fans was measured across four deep-level mines in South Africa (Mine A, B, C, D).

2.1. District fan assemblage evaluation

A full system evaluation on six district fan assemblages was conducted. Fig. 2 is a basic schematic of a typical underground district fan assemblage with two fans, two corrugated spiral-ducting systems, and two airlocks. The system evaluation included an actual system performance evaluation, followed by an analysis of the fan performance and a performance evaluation of the ducting and airlocks of the fan assemblage. The purpose of the evaluations was to determine the actual performance of the fan system and to quantify the contributions of each component, fans, ducting and airlocks towards the total system performance.

2.2. System measurements

Fig. 2 indicates the proposed measuring points and the required measurements. The locations where pressure differences were required are also shown in Fig. 2 where ΔP denotes pressure difference.

Measurement point *A* is in the fresh air stream before the fan intakes. The necessary psychrometric parameters, the dry-bulb and wet-bulb air temperature, as well as barometric pressure were measured at point *A* for each system. Measurement point *D* also required the basic psychrometric parameters and barometric pressure, and was located downstream from the system outlet. In addition to the psychrometric parameters, the volumetric flow rate at point *D* was calculated and the average haulage velocity and estimated haulage areas were measured.

The average air velocity and ducting diameter were measured at measurement points *B* and *C*, which are located at the inlet and outlet of the fans' ducting, respectively. The total pressure and electrical input power of the fans was also measured. With the parameters measured, the actual performance of the fan systems was deterimned. A break down on the performance of the various fan assemblage components was also concluded.

2.3. Total system performance

The volumetric airflow rate delivered to the district, the fan system delivery pressure (the pressure difference across the airlocks), the temperature gained through the system, and the system efficiency were measured or calculated as illustrated and tabulated in Fig. 2 and Table 1. These parameters were used as critical performance indicators of the underground fan systems.

(1) Total electrical power input: the total fan power input (P_{fan}(kW)) of the fan systems was measured.
(2) The system delivered airflow rate: the volumetric airflow rate, Q (m^3/s), after the fan system into the district (measurements D) was calculated for each fan system (parameter 4 in Table 1).
(3) Total system delivery pressure: the sum of the barometric pressure difference and velocity pressure difference between measurements D and A yields the total delivery pressure, ΔP_T (Pa) of the fan system.
(4) System air power: the actual air power (P_{air} (kW)) induced into the ventilation network by the fan system, is equivalent to the product of the system delivery volumetric airflow rate and total delivered pressure (parameter 12 in Table 1).
(5) Dry-bulb and wet-bulb temperature gains: the air dry-bulb and wet-bulb temperature differences between measuring points *D* and A were calculated to quantify the effect that the fan system has on the underground air thermal conditions.
(6) System efficiencies: the actual system efficiency, η_{system}, is the ratio between the system air, (kW), P_{air} and total fan electrical power input, P_{fan} (kW), as described in Eq. (1). The system efficiency was calculated for each fan system and used as the system's key performance indicator.

$$\eta_{system} = \frac{P_{fan}(kW)}{P_{air}(kW)} \tag{1}$$

2.4. Fan performances

The performances of the fans were determined to quantify their contributions towards the fan system's performance. The fan elec-

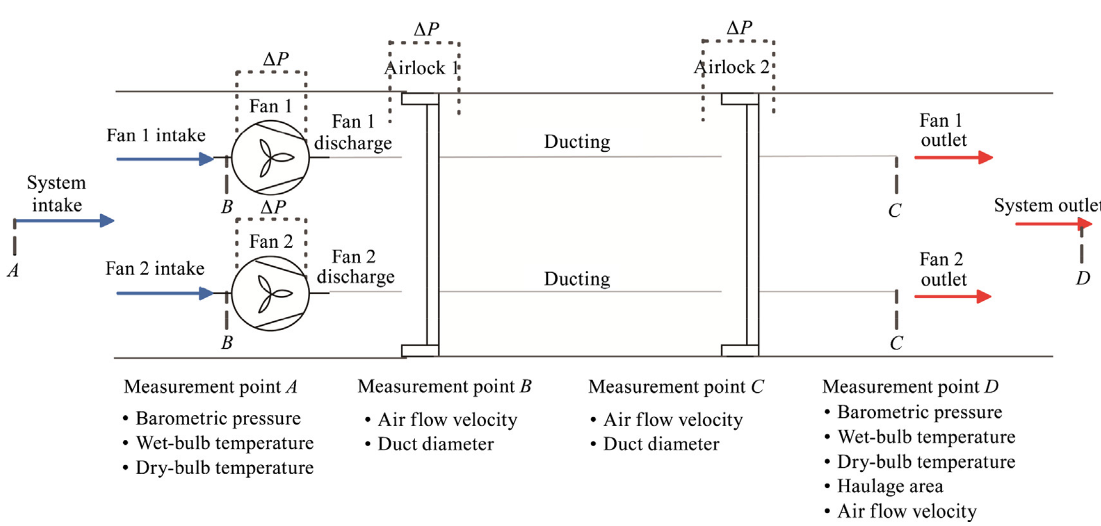

Fig. 2. District fan assemblage measurement guideline.

trical power input, intake volumetric airflow rate, fan pressure difference, fan air power, and fan efficiency were measured or calculated for each fan in the fan assemblage as illustrated and tabulated in Fig. 2 and Table 1.

(1) Fan electrical power: the fan power input (P_{fan} (kW)) of each fan was measured.
(2) Fan intake volumetric airflow rate: the total fan intake volumetric airflow rate (Q (m^3/s)) at measuring point B was determined at each fan intake.
(3) Fan total pressure difference: the total pressure difference (ΔP_T (Pa)) between the discharge and intake of each fan was measured.
(4) Fan air power: the fan air power (P_{air} (kW)) was calculated for each of the fans in the fan system. The fan air power is equivalent to the product of the intake volumetric airflow rate and total pressure difference across the fan.
(5) Fan efficiency: the fan efficiency, η_{fan}, as described in Eq. (2), was calculated for each of the fans in the fan systems. The fan efficiency is the ratio between the fan air power, P_{air}, and fan input electrical power.

$$\eta_{fan} = \left(\frac{P_{air}}{P_{fan}}\right) = \left(\frac{\Delta P_{fan} \times Q_{fan}}{P_{fan}}\right) \tag{2}$$

The efficiency of a fan, represented by η_{fan}, as illustrated by Eq. (2), is equivalent to the amount of air power, P_{air}, generated from the electrical power input P_{fan}. Therefore, the motor efficiency is accounted for in the fan efficiency. (Refer to parameters 10 and 12 in Table 1).

The air power (P_{air}) is equivalent to the product of the total pressure (ΔP_T), which is the static pressure measured across the fan, velocity pressure at inlet and outlet, as well as volumetric airflow rate (Q_{fan}) of the fan. As tabulated in Table 1, parameter 12. Moreover, the electrical power input (P_{fan}) is measured for each fan with a multi-meter.

2.5. Ducting performances

The ducting pressure loss, air leaks, and efficiency were calculated for each fan assemblage. The quantity of leaks through the airlocks, and airlock efficiency was also determined. These performances were compared in order to quantify the effect each of these components that have on an underground fan system. The required parameters were measured, as shown in Fig. 2.

(1) Total ducting intake volumetric airflow rate: the total intake airflow rate into the ducting is equivalent to the corresponding fan's intake volumetric airflow rate (measuring point *B*).
(2) Ducting leaks: the quantity of leaks through the ducting was determined by subtracting the fan intake volumetric airflow rate, measuring point *B*, with the ducting outlet volumetric airflow rate, measuring point *C* ($Q_{ducting}$).
(3) Ducting pressure loss: the difference between the total pressure at the fan outlet and system delivery pressure is equivalent to the ducting pressure loss (($\Delta P_{delivery}$). The ducting pressure loss was calculated for each fan in the fan system.
(4) Ducting efficiency: the ducting efficiency was calculated for each section of ducting and was equivalent to the ratio of air power delivered to the district through the ducting, and the fan air power as described in Eq. (3).

$$\eta_{ducting} = \left(\frac{\Delta P_{delivery} \times Q_{ducting}}{\Delta P_{fan} \times Q_{fan}}\right) \tag{3}$$

2.5.1. Airlock performances

Airlocks air leaks: the amount of air lost through the airlocks was determined as the difference between the fan systems delivered volumetric airflow rate, measured at point *D*, and the fan volumetric airflow rate delivered through the ducting, measured at point *C*.

Airlocks efficiency: the airlock efficiency, Eq. (4), is merely the ratio between the total airflow through the ducting measured at points *D* ($Q_{delivery}$), and the total airflow rate into the district measured at point C ($Q_{ducting}$).

$$\eta_{door} = \left(\frac{Q_{delivery}}{Q_{ducting}}\right) \tag{4}$$

2.5.2. Fan system efficiency breakdown

An energy analysis was conducted to quantify the impact of the various components on an underground district fan assemblage. The efficiency of each component was evaluated and compared to quantify the impact of each fan assemblage component. The total system efficiency can be derived from Eq. (5), which is a combination of the previous equations and simplifies to the ratio of energy delivered to the airflow ($P_{delivery}$) and the energy provided to the fan (P_{fan}).

$$\begin{aligned} \eta_{system} &= \left(\eta_{fan}\right)\left(\eta_{ducting}\right)\left(\eta_{door}\right) \\ \eta_{system} &= \left(\frac{\Delta P_{fan} \times Q_{fan}}{P_{fan}}\right)\left(\frac{\Delta P_{delivery} \times Q_{ducting}}{\Delta P_{fan} \times Q_{fan}}\right)\left(\frac{Q_{delivery}}{Q_{ducting}}\right) \\ \eta_{system} &= \left(\frac{P_{delivery}}{P_{fan}}\right) \end{aligned} \tag{5}$$

2.5.3. System volumetric efficiency

System volumetric efficiency: the system volumetric efficiency, $\eta_{volumetric}$, as described in Eq. (6), was calculated for each fan system. The system volumetric efficiency is the ratio between the total intake airflow rate, Q_{fans} measured at measuring point *B*, and the volumetric airflow rate into the district, $Q_{delivered}$ measured at point *D*.

$$\eta_{volumetric} = \frac{Q_{fans}}{Q_{delivered}} \tag{6}$$

2.6. Ideal underground fan system performance

The results of the six district fan systems were compared with the performance of an ideal underground fan system. The performance of this system is based on the following assumptions:

(1) Intake dry-bulb and wet-bulb air temperatures of 28 and 25 °C at 112 kPa respectively (typical underground conditions).
(2) Two 45 kW rated fans each operating at 1500 Pa and 12 m^3/s, with a total fan efficiency of 70%, which we found to be the typical manufacturer designed operating point.
(3) The fan assemblage's airlocks have only 3% leaks, which were the best performers of the measured airlocks. Therefore, an airlock efficiency of 97% is assumed for the ideal system.
(4) The fan assemblage's ducting has no air leaks, which would be achievable with proper maintenance.
(5) The ducting has a total length of 35 m, the average of the six measured fan assemblages.

(6) The ducting pressure loss is calculated with the actual friction factor of the corrugated spiral-ducting [24]. Assuming no additional shock losses and no ducting bends. The ducting pressure loss is therefore estimated at 270 Pa.

2.7. Fan performance evaluation

2.7.1. Fan efficiencies

The efficiency of 33 underground auxiliary fans (excluding assemblage) across four deep-level mines was determined, as described in Eq. (2). The measurement of the static pressure across the bulkheads of an underground fan is rarely done correctly [9]. The incorrect measuring of fans leads some mine operators and engineers to believe that the fans operate at a considerably lower operating point. Measuring the pressure difference across a fan is only correct when assuming the dynamic pressure remains the same throughout the system, the inlet and outlet duct and fan diameter is constant, and there are no shock losses [9]. Therefore, when the pressure over the underground fans was measured, the velocity pressure of the fans was accounted for.

2.7.2. Fan operating points

Measurements on two sets of axial 45 kW fans were made. The operating points, static pressure, and volume airflow rate relation of the measured fans were plotted against their characteristic curves. The curves were assumed to be at a constant density of 1.3 kg/s as per manufacturer curves.

2.7.3. Fans system responses

The fan system resistance (*R*), as described by parameter 12, Table 1, was calculated for each of the measured fans. The actual deviation in responses was determined and used to create a 99% confidence system response interval. The interval was then used to evaluate whether the use of universal underground fans is viable at deep-level mines.

3. Results

3.1. District fan assemblage evaluation

An initial study on Mine A, where the total performance of 18 district fan systems was evaluated, yielded a total system efficiency of 11%, based on their rated electrical power. These underground fan systems alone added 1 MW of heat to the ventilation system. However, the root cause of these in-efficiencies is not clear. Therefore, a thorough investigation was launched to determine the performance of various components of such district fan assemblages. The results thereof should give a clear indication of what fan assemblage practices are causes for concern in deep-level mines.

A full analysis as described in Section 2.1 was conducted on six district fan systems, systems A to F, on Mine A. The overall performance of the fan systems, the performance of the fans, and the ducting and airlocks performance were evaluated. These fan systems all had a 45 kW fan in parallel with another 45 kW fan or a 15 kW fan, as illustrated in Fig. 2.

3.1.1. Total system performances

Table 2 summarises the system performance regarding the electrical input power, the volumetric airflow rate and pressure delivered to the district, and air power generated by the fan system, the system efficiency, and air temperature gain of the fan systems. The overall performance of the system considers the performance of the fans, the ducting, and the airlocks.

It is evident from Table 2 that the systems have poor performance with an average system efficiency of 5%. Therefore, these fan assemblages have major flaws since they are extremely inefficient. The result of this inefficiency was an average wet-bulb temperature gain of 1.3 °C. This is particularly concerning when considering one of the main functions of the ventilation system is ensuring adequate temperatures that are maintained at the underground workplaces [2]. In large deep-level mines, where large quantities of auxiliary and district fans are present, such inefficiencies could contribute a significant amount of unwanted heat to a system.

Fortunately, the poor energy efficiency of these systems presents considerable energy savings opportunities for deep-level mines. Therefore, identifying the root cause of inefficiencies on these fan systems would be worthwhile. Thus, we conducted a full analysis, as described in Section 2.1, on the various assemblage components (fans, ducting and airlocks) to conclude on the total system performance.

3.1.2. Fan performances

The efficiency of the fans of these assemblages was evaluated to quantify how large an effect the fans have on these low system efficiencies. The results of the measured fans are tabulated in Table 3. These results include the fan total delivery pressure difference, intake volumetric airflow rate, the air power of the fans, the electrical power of the fans and the actual fan efficiencies.

From Table 3 it is evident that these fans have poor performance, with an average fan efficiency of 27%. Therefore, on average 63% of the electrical energy is wasted due to fan inefficiencies. However, it is known that fans are sensitive towards the condition of the fan assembly due to the resistance these impart on the system [7]. Thus, to obtain a comprehensive understanding of the performance of these underground fan systems, the ducting and airlock performances should also be considered. After all, the condition of these components has a direct influence on the fan system response and therefore the fan performance and operating point [7].

3.1.3. Fan performances ducting and airlock performances

Apart from fan inefficiencies, leakages through the airlocks, leakages through ducting and ducting pressure loss are other contributors towards the system inefficiencies. The ducting leaks, pressure losses, and door leaks are tabulated in Table 4 along with the efficiencies of the airlocks and the system volume efficiency.

From Table 4 it is evident that the systems have an average volumetric efficiency of 66%. Therefore 34% of the air intake is wasted due to leaks through the ducting systems and the doors. The volumetric efficiency is considerably higher than the actual efficiency of the systems. However, the system efficiency is a more comprehensive illustration of how well the fan input power is being converted to air power by the fan system.

The average ducting efficiency of the measured fan assemblages is 33%, and for an ideal system with no air leaks, a ducting efficiency of 82% can be expected. More than half of the air power delivered to the ducting system is lost due to leaks and pressure losses in the ducting system. Leaks have an adverse effect on ductwork's pressure balance, ultimately hindering the efficiency of the ducting.

The condition of underground ducting systems has a significant influence on a fan system's overall efficiency. Poor joint integrity, dents, holes, dust and rubble build-up inside the ducting and unnecessary bends are all controllable factors which have a substantial contribution on ducting pressure losses and leaks. Fig. 3 illustrates typical poor ducting misalignment and connections in underground fan assemblages. Fortunately, most of these

Table 2
Systems' performance summary.

Parameter	System A	System B	System C	System D	System E	System F	Systems average
Electrical power input (kW) (P_{fan})	70.6	71.0	75.0	56.0	54.5	59.0	64.4
System delivery volumetric airflow rate (m^3/s) ($Q_{delivered}$)	9.0	17.3	11.4	5.3	10.9	11.2	10.9
Total system delivery pressure (Pa) ($\Delta P_{delivered}$)	120.0	110.0	300.0	200.0	610.0	600.0	323.3
Air power (kW) (P_{air})	1.1	1.9	3.4	1.1	4.0	6.7	3.1
Dry-bulb temperature gain (°C)	2.7	1.6	2.0	3.0	2.0	1.7	2.2
Wet-bulb temperature gain (°C)	1.0	1.1	1.6	2.2	1.3	0.8	1.3
Overall fan system efficiency (η_{system})	2%	3%	5%	2%	7%	11%	5%

Table 3
Systems' fans performance summary.

Parameter	System A		System B		System C		System D		System E		System F		Average fan	Ideal system	
	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2		Fan 1	Fan 2
Fan electrical input power (kW)	35.6	35.0	36.0	35.0	36.0	39.0	15.0	41.0	40.5	14.0	44.0	15.0	34.5	25.7	25.7
Fan intake volumetric airflow rate (m^3/s)	6.8	6.9	10.9	9.8	7.6	10.4	5.5	3	10.1	4.8	9.3	5.2	8.4	12.0	12.0
Fan pressure difference (kPa)	0.5	0.7	0.9	0.7	1.7	1.5	1.0	1.5	1.3	1.0	1.9	1.1	1.2	1.5	1.5
Fan air power (kW)	3.5	4.9	9.6	7.0	13.0	15.7	5.3	4.5	13.3	4.6	17.8	5.5	10.4	18	18
Fan efficiency	10%	14%	27%	20%	36%	40%	35%	11%	33%	33%	40%	37%	30%	70%	70%

Table 4
Fan system performance summary.

Parameter	System A		System B		System C		System D		System E		System F		Average system		Ideal system	
	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2	Fan 1	Fan 2
Total volumetric intake (m^3/s)	13.7		20.7		18		8.5		14.9		14.5		15.1		24.0	
Ducting leak (m^3/s)	0.5	1.1	2.0	1.2	3.5	1.9	1.4	0.5	4.6	0.1	0.4	0.1	2.1	0.8	0.0	0.0
Ducting pressure loss (kPa)	0.28	0.48	0.66	0.49	1.30	1.10	0.65	1.20	0.59	0.23	1.20	0.35	0.78	0.64	0.3	0.3
Ducting efficiency	42%	27%	21%	27%	13%	22%	24%	17%	30%	75%	35%	66%	28%	39%	82%	82%
Total ducting leak (m^3/s)	1.6		3.2		5.4		1.9		4.7		0.5		2.9		0.0	
Ducting length (m)	18.0		20.0		44.0		35.0		25.0		66.0		35.0		35.0	
Airlocks air leak (m^3/s)	3.1		0.5		1.3		1.3		3.7		2.8		2.1		0.8	
Airlocks efficiency	75%		97%		90%		80%		64%		80%		81%		97%	
Actual district volumetric airflow rate (m^3/s)	9.0		16.9		11.4		5.3		6.5		11.2		10.1		23.3	
System volumetric efficiency	66%		82%		63%		62%		44%		77%		66%		97%	

Fig. 3. Left-poor duct connection, right-ducting leaks.

inefficiencies can be solved with better design prior to implementation and sustained maintenance after implementation.

From the results seen in Table 4, the average airlock efficiency, which includes both ventilation doors, is 81% and therefore on average 19% of the ventilation air is leaked through the doors. It should however be noted when pressure over doors increases, the quantity of air leaks will also increase and subsequently the inefficiency of the airlock. Thus, to maintain proper underground fan practice, it is recommended to investigate airlock performance regularly.

3.1.4. Fan system efficiency breakdown

It is evident that the total fan system efficiency is sensitive towards all the components of the fan assembly. Due to the accumulating effect of the inefficiencies of the various components, the average system efficiency of the measured fan systems was only 5% as shown in Table 5. However, our research indicates that there is significant scope for improvement on these assemblages when considering that the theoretical ideal efficiency of such systems could be as high as 56% as shown in Table 5. Therefore, it is important to investigate how this efficiency improvement could be achieved.

Fig. 4 illustrates the compounding effect of the various component inefficiencies on the total system efficiency. Fig. 4a shows the average power fraction breakdown of the six measured district fan systems showing that the majority of air power is lost due to fan

Table 5
Efficiency breakdown of measured fan systems and ideal fan system.

Fan system component	Average measured efficiency	Ideal efficiency
Fans (total)	28%	70%
Ducting (total)	20%	82%
Airlocks	81%	97%
Total system	5%	56%

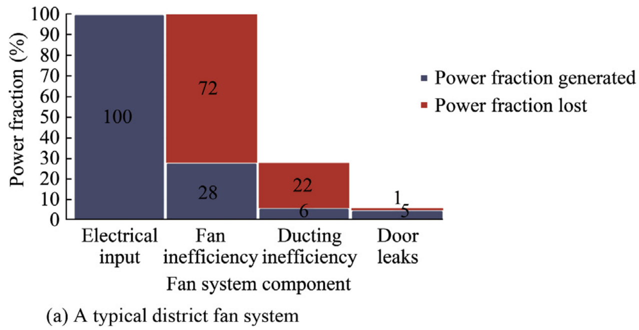

Fig. 4. Comparison of power distribution between a typical district fan system and an ideal system showing the maximum fan power which could be delivered to the air by underground fan assemblages after all inefficiencies in the rightmost bar graph.

(28% efficient) and ducting (20% efficient) inefficiencies. Therefore, due to the interconnected nature of the systems, both efficiencies will have to be rectified to achieve a total efficiency improvement. For instance, if the power delivered to the ducting system is increased due to a more efficient fan the ducting power loss in absolute terms will subsequently increase.

It is evident that all fan assemblage components' inefficiencies should be considered when evaluating an underground fan system. Fig. 4b illustrates the power fraction breakdown of an ideal underground fan system as described in the research. This ideal system should realistically be achievable in the current mining environment through proper fan selection and design, craftsmanship and maintenance of fan ducting.

3.2. Fan performance

In order to determine the status of fan selection in underground mining districts, we investigated 33 district and auxiliary fans across four deep-level mines. Measurements on two different types of 45 kW fans in the four deep-level mines were made. Table 6 tabulates the measured performance of these fans. Only the fans were measured and not the fan assemblage. The results are summarised in Table 6.

The average fan efficiency of the 33 measured fans was 38%. Therefore, on average 62% of electrical energy was lost due to fan and motor inefficiencies. These inefficiencies induce heat in the underground mine ventilation network. The average system resistance for these fans was 15.7, however with significant deviations. This deviation in the system supports the fact that fans should be selected based on the fans' actual operating conditions and application, even in underground environments [16].

3.2.1. Fan operating points

Fig. 5 displays the fan characteristic curves of the two different 45 kW axial fans. Fig. 5 also displays the operating points of the 33 measured fans. The operating points of these fans should be an accurate reflection of the actual performance of these fans.

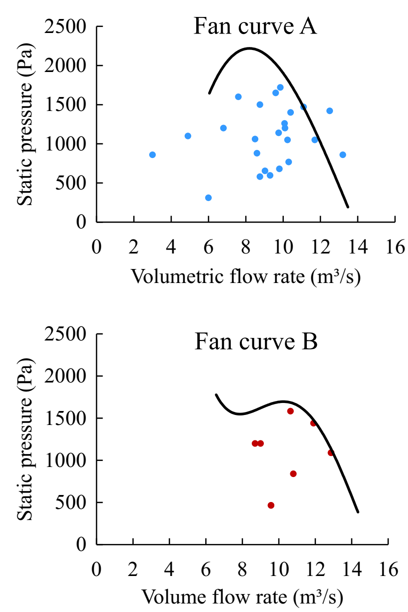

Fig. 5. Fan characteristic curves and operating points.

From Fig. 5, it is evident that most of these fans do not run on their respective characteristic curves. This confirms the findings by Rowland that underground fans tend to run off their characteristic curves [8]. The likely reasons for this are poor fan configuration, damaged impellers, inlet or outlet blockages and shock losses [9]. Harsh underground conditions further exacerbate these issues.

The exact reason for poor performance can mostly be determined with visual inspections. Of the measured fans, numerous had poor fan installation (misalignment of inlet and outlet ducting) and blockages. Furthermore, the effect high humidity and dust have on underground fan impellers are also worth investigating.

Table 6
Summary of measured fans performances.

Site	Total fans measured	Fan velocity (m/s)	Fan total pressure ΔP_T (Pa)	Fan volume airflow rate Q (m^3/s)	Fan air power P_{air} (kW)	Fan electrical power (kW)	Fan efficiency (%)	Total resistance (R)
Mine A	7	18.9	1286.4	8.6	11.3	38.1	30%	26.1
Mine B	8	20.3	974.8	9.2	9.7	33.3	29%	14.2
Mine C	4	22.0	1214.7	10.0	12.4	35.7	38%	11.5
Mine D	14	24.8	1552.0	11.3	17.9	34.1	54%	11.0
Average		21.5	1257.0	9.8	12.8	35.3	38%	15.7

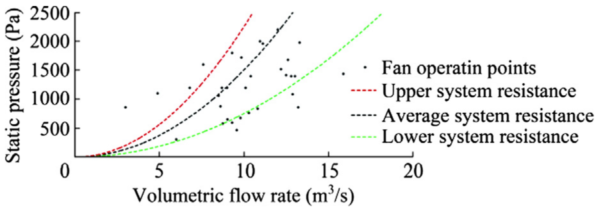

Fig. 6. Fan operating points and typical system resistance curves.

3.2.2. Fan system response

Since we found that the majority of fans were deviating significantly from their characteristic curves we further investigated the effect of the system resistance on fan operation. Fig. 6 displays the operating points of all the measured fans and the average system resistance. The upper and lower system resistance curves are also shown in Fig. 6. The upper and lower system resistance curves were determined within a 99% confidence interval over the 33 measured fan resistance curves.

From Fig. 6 it is evident that the fans' responses differ significantly. The upper and lower system resistances for these fans differ by 67%. Therefore, selecting a universal fan for underground use can cause fans to operate at very low efficiencies. Thus, the uniqueness of the response of each fan system and district should be considered when designing fans for underground use.

Fans are designed and selected based on their specific application. Therefore, knowing the system response, which includes the resistance of the fan assemblage and the fan district, is crucial. A mine ventilation network is a very complex system consisting of multiple junctions and districts, each having a different response. In addition, the effect of nearby underground fans has an influence on underground fan operating points and must be quantified. The response of any underground fan system is therefore unique. The response of an underground fan is also sensitive toward the condition of the fan assemblage's components. Therefore, fan assemblages must be designed and selected with great care and proper engineering practices as it is crucial to the success of an underground fan system.

4. Discussion

From literature we found that there was a need to investigate and evaluate the compounding effect that underground fan assemblage components have on the overall fan system performance. We found that there is clearly a significant amount of energy being lost through inefficiencies in fan assemblages. The results ultimately showed that the major efficiency losses in underground district fan assemblages were fan and ducting inefficiencies. Therefore, when selecting fans, the fan system response, district response, and effect of nearby fans have to be taken into account [16]. Furthermore, a fans' performance is sensitive towards the quality of the components of the fan assemblage.

It is evident that the response of each fan in an underground environment is unique. Therefore, the design of each fan assemblage should also be unique. Ideally unique fan design and selection would be recommended in large deep-level mines. However, due to the complexity and dynamic nature of the underground mining environment it is unlikely to be economically feasible to design fans as required. Thus, solutions might rather include installing variable frequency drives on fans to adjust fan speeds to supply airflow close to minimum requirements [10,25].

Installation of fans and fan assembly is another area of concern in deep-level mines. De Souza showed the significant efficiency effect poor fan assembly has on mine main fans [7]. This study made similar findings on underground district fans. Although underground fan assemblages are unique in geometry and characteristics, maintaining good underground fan practice such as regular investigation, monitoring, cleaning and maintenance of underground fan assemblages is required to ensure ventilation efficacy. Systems such as that described by Shriwas and Calizaya might also be adapted to indicate when assemblage performance is poor [26].

From the results, it is evident that poor ducting craftsmanship and maintenance is a significant contributor towards the fan system inefficiencies. The importance of proper craftsmanship with ducting systems should always be a priority. This is an area which could easily be improved upon by adopting adequate maintenance procedures or installing lower friction factor ducting [10].

Future work should include in-depth investigations where fan assemblages are refurbished and redesigned based on the findings from this study. Further, corrugated ducting should be replaced with ducting made from hard plastics and fans should be controlled with VSD's. Such a study should then compare the optimised fan assemblage systems with the existing systems in order to recommend future best practices for underground mine fan assemblages. This work could further be supported by the introduction of a mine ventilation management program based on the work of De Souza in combination with an integrated monitoring system [27–29]. Lastly, good practice would be to simulate intended changes before commissioning and purchasing equipment to ensure that the desired effect will be obtained [29].

An additional observation from the results of this study is that current poor fan practices can add a significant amount of heat into an underground mine ventilation network. If one considers a typical deep-level mine with 1.8 MW of installed district and auxiliary fans and system efficiency of 5% (as found in this study) then only 0.1 MW is converted to air power while the remainder is ultimately converted to direct heat. Now consider the scenario where the efficiency of the underground fan systems is improved to 56% (ideal case, Table 2). This can be achieved when the fan efficiency and ducting efficiencies are improved to 82%, which is the ideal case with no air leaks through the ducting system. For the same air power, 0.1 MW, only 0.2 MW of electrical power is now required, resulting in an 80% energy cost savings. In addition to this, only 0.1 MW of heat is gained through the ventilation system. Other than improved underground conditions, improving underground fan practices can pose a significant amount of opportunity for energy savings.

Although the performances of 33 underground fans were evaluated, only six underground fan assemblages were evaluated. Therefore, generalising the results was found to be difficult. However, considering the poor performance of the underground fans, a massive potential for improvement in underground fan practice and engineering was identified. Our research shows that solving the problem could be relatively easy, only requiring some capital expenditure from the mine. Unfortunately, the current constrained economic environment for South African deep mines prohibits mine management from making forward looking decisions [30,31]. Therefore, further research is highly recommended on finding a generalised solution to improve poor underground fan assemblage performances.

5. Conclusions

In literature the impact of poor district fan practices on mine ventilation networks is typically overlooked. We investigated the performance of six underground district fan assemblages in a South African deep-mine. It was found that the average assemblage efficiency was 5%. The fans had a total fan efficiency of 28%, while the ducting systems had efficiencies of 20%, and the airlocks maintained an average efficiency of 81%. A further investigation was conducted on 33 auxiliary and district fans across four deep-level mines which showed that these fans deviated significantly from design operating points and resulted in an average fan efficiency of 33%.

Therefore, maintaining good underground fan practices such as optimal fan selection and ducting design, and maintenance is crucial for the efficacy of mine ventilation networks. The method used in the study can however be used to evaluate the efficiency of underground district fan systems and subsequently suggest a solution.

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References

[1] Hermanus M. Mining redesigned - innovation and technology needs for the future – a South African perspective. J South African Inst Min Metall 2017;117:811–8.
[2] McPherson M. Ventilation surveys. In: Subsurface ventilation and environmental engineering. Dordrecht: Springer; 1993. p. 322–65.
[3] Wallace K, Prosser B, Stinnette JD. The practice of mine ventilation engineering. Int J Min Sci Technol 2015;25:165–9.
[4] Wempen JM, Calizaya F, Peterson RD, Nelson MG. Evaluating the use of booster fans in two underground coal mines. Min Eng 2011;63:115–9.
[5] Habibi A, Gilllies AD. Effect of booster fan in ventilation networks – computational and experimental approaches. In: Proceedings of the 14th U.S./North American mine ventilation symposium. Salt Lake City: University of Utah; 2012. p. 83–9.
[6] Brake DJ, Nixon CA. Design and operational aspects in the use of booster, circuit and auxiliary fan systems. In: Proceedings of the 11th U.S./North American mine ventilation symposium. Pennsylvania: Pennsylvania State University; 2006. p. 543–53.
[7] De Souza E. Improving the energy efficiency of mine fan assemblages. Appl Therm Eng 2015;90:1092–7.
[8] Rowland JA. Ventilation surveys and modelling – execution and suggested outputs. In: Proceedings of the 11th underground coal operators conference, Wollongong. University of Wollongong & the Australasian Institute of Mining and Metallurgy; 2011. p. 214–24.
[9] Krog RB. Selection of underground booster fans. In: Proceedings of the 9th U.S./North American mine ventilation symposium. Kingston: CRC Press; 2002. p. 153–9.
[10] Levesque M. An improved energy management methodology for the mining industry. Laurentian University of Sudbury; 2015. PhD disseration.
[11] Gou Y, Shi X, Zhou J, Qiu X, Chen X. Characterization and effects of the shock losses in a parallel fan station in the underground mine. Energies 2017;10:785.
[12] Krog R, Grau R, Mucho T, Robertson S. Ventilation planning layouts for large opening mines. In: Proceedings of the society for mining, metallurgy and exploration annual meeting. Denver: ,Society for Mining, Metallurgy, and Exploration; 2004. p. 1–9.
[13] Greenheck.. Understanding fan system effects. In: Product Application Guide-FA/101-99. Schofield: Greenheck; 2017. p. 1–6.
[14] Man LI, Wang XR. Performance evaluation methods and instrumentation for mine ventilation fans. Min Sci Technol 2009;19:819–23.
[15] du Plessis JJL. Ventilation and occupational environment engineering in mines. 3rd ed. Johannesburg: Mine Ventilation Society of South Africa; 2014.
[16] Kursunoglu N, Onder M. Selection of an appropriate fan for an underground coal mine using the Analytic Hierarchy Process. Tunn Undergr Sp Technol 2015;48:101–9.
[17] Evans JB. Fan selection and sizing to reduce inefficiency and low frequency noise generation. In: Fan Noise 2003. Senlis: CETIM; 2003. p. 1–7.
[18] El-Nagdy KA. Stability of multiple fans in mine ventilation networks. Int J Min Sci Technol 2013;23:569–71.
[19] Hartman HL, Ramani RV, Mutmansky JM, Wang YJ. Mine ventilation and airconditioning. 3rd ed. New York: John Whiley & Sons; 1997.
[20] Le Roux WL. Mine ventilation notes for beginners. 1st ed. Johannesburg: Mine Ventilation Society of South Africa; 1979.
[21] Gillies S, Slaughter C, Wu HW. Booster fans–some considerations for their usage in underground coal mines. In: Proceedings of the 13th U.S./North American mine ventilation symposium. Sudbury: MIRARCO; 2010. p. 511–8.
[22] Roghanchi P, Kocsis KC, Sunkpal M. Sensitivity analysis of the effect of airflow velocity on the thermal comfort in underground mines. J Sustain Min 2016;15:175–80.
[23] Singh AK, Singh H, Singh SP, Sawhney RL. Numerical calculation of psychrometric properties on a calculator. Build Environ 2002;37:415–9.
[24] Kulkarni D, Khaire S, Idem S. Pressure loss of corrugated spiral duct. ASHRAE Trans 2009;115:28–34.
[25] Johnson D, Fourie CJS. An overview of energy efficiency in South African hard rock mining. In: Proceedings of the South African energy efficiency convention. Johannesburg: Institute of Electrical and Electronics Engineers; 2012. p. 1–6.
[26] Shriwas M, Calizaya F. Automation in detection of recirculation in a booster fan ventilation network. Int J Min Sci Technol 2018;28:513–7.
[27] Pretorius JG, Mathews MJ, Maré P, Kleingeld M, Van Rensburg J. Implementing a DIKW model on a deep mine cooling system. Int J Min Sci Technol 2019;29:319–26.
[28] Moridi MA, Kawamura Y, Sharifzadeh M, Chanda EK, Wagner M, Jang H, et al. Development of underground mine monitoring and communication system integrated ZigBee and GIS. Int J Min Sci Technol 2015;25:811–8.
[29] Nel AJH, Vosloo JC, Mathews MJ. Evaluating complex mine ventilation operational changes through simulations. J Energy South Africa 2018;29:22–32.
[30] Lane A, Guzek J, van Antwerpen W. Tough choices facing the South African mining industry. J South African Inst Min Metall 2015;115:471–9.
[31] Neingo PN, Tholana T. Trends in productivity in the South African gold mining industry. J South African Inst Min Metall 2016;116:283–90.