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Evaluating complex mine ventilation operational changes through simulations

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Abstract

Increasing the profitability of the mining industry is contingent on its ability to improve operational efficiency. Mine ventilation networks typically represent 25-50% of a mine's energy consumption and, therefore, exhibits scope for optimisation. Ventilation networks comprise numerous complex integrated airways, branches and ventilation fans. The most effective way to optimise and evaluate them is computer-aided simulations. However, no framework exists to clarify exactly how operational changes in ventilation networks should be evaluated. In this study, a scalable method was developed, implemented and analysed. The case study validation resulted in satisfying key performance indicators of both service delivery and operational energy costs, thereby increasing operational efficiency. The significance of the novel method is that it allows for improved operational decisions on mine ventilation networks. The value of the method was illustrated by the adoption of the method by the case study mining personnel to form the new norm of their procedures and standards.

Keywords: *Mining, optimisation, sustainable cost saving*

Highlights

- *Mine ventilation operational changes optimised and evaluated through simulations.*
- *Scalable method.*
- *Additional non-energy benefits.*

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1. Introduction

Mine ventilation networks are used to ensure that underground environmental conditions are conducive to safe and productive mining [1]. This is done by supplying sufficient airflow to the working areas to govern heat stress imposed on workers and to dilute and exhaust hazardous particulates to below statutory occupational exposure levels [2]. However, the dynamic nature of deep-level mining means that the engineering challenges faced include contending with ever-higher virgin rock temperatures because of increased depth, requiring more complex ventilation networks [3]. The costs associated with providing acceptable working conditions for reserves that are further and deeper away from ventilation shafts become a critical determinant of the feasibility of continued mining [2]. Operational efficiency is, therefore, the main contributing factor to increasing mine profitability, as shown by the industry's drive to improve upon the status quo [4, 5]. In modern mining, there has been a move towards adopting technological advances, to which the rapid development and increased production targets could be attributed [6]. Mines are, therefore, expanding operations vertically and horizontally to achieve these production targets in the most cost-effective manner possible. Research indicates that electricity is among the factors with the largest potential to increase operational efficiency on mines [7], so lowering the potential future cost of electricity is critically important.

Considering mine ventilation systems represent 25-50% of the energy consumed in a mining operation, large potential exists to realise electrical cost savings through optimisation [4, 8]. Typical backward-curved airfoil centrifugal fans employed on deep-level mines as main ventilation fans have installed capacities ranging from 500 kW to 2.1 MW per fan [4, 9]. Mine ventilation systems consist of hundreds of interconnected sections and applications, such as airways, raises, crosscuts, main shafts, ventilation shafts, sub-shafts, raise boreholes, ventilation doors, travelling ways, fans and regulators [8]. In view of the complexity of the system and mine development, it is easy to understand that inefficiencies such as short-circuits, insufficient air velocities, increasing temperatures and leakages will occur [1].

Mine ventilation networks are required to comply with occupational health and safety standards and regulations specified by the host country. In South Africa, two important factors affecting the operations of mine ventilation and subsequent working environments are the wet-bulb temperature (T_{wb}) and air cooling power (ACP) [10]. Legislation stipulates that work should not proceed underground when $T_{wb} \geq 32.5$ °C or the dry-bulb temperature (T_{db}) ≥ 37 °C [3, 10, 11]. Additionally, the ACP should be 300 W/m^2 as a minimum for acceptable working conditions [3, 10, 12].

Because of constrained resources, operational changes are not regularly and thoroughly evaluated on these complex systems in deep-level mines [9, 13]. Furthermore, decisions are often made with limited information, which increases both risks and likelihood of project failures. Consequently, deep-level mines require a reliable, scalable method to evaluate complex mine ventilation operational changes according to key performance indicators such as cost and service delivery [13].

1.1 Modelling and simulation of mine ventilation networks

Substantial research indicates that complex systems can only be thoroughly evaluated with the use of simulations [13, 14, 15, 16]. With the arrival of the digital age, simulation technologies have been incorporated to design large and complex mine ventilation networks [4]. To provide accurate results, these simulations nevertheless require an abundance of dedicated resources that are both labour-intensive and time-consuming [17]. Recent technological advancements coupled with innovative methods may, however, enable mines to evaluate operational changes more accurately and cost-effectively, resulting in improved decision-making capabilities. Several researchers have addressed techniques to model and optimise sections of mine ventilation networks [4, 16]. Acuna and Lowndes (2014) conducted a review of such studies, showing that there is still a knowledge deficit in addressing the effects of both cost and service delivery in ventilation optimisation techniques [16]. The techniques used in industry do not incorporate simulations, but include tedious manual calculations [16]. These techniques do not take the holistic effects of operational changes into account, but are narrowed to only consider single service delivery parameter evaluations [13].

Computational fluid dynamics simulation was used to optimise axial flow ventilation fan blade profiles [18]. This method holds promise for further research on airfoil and centrifugal ventilation fans in particular, but it is limited to component design and cannot be applied to optimise the branches of complex ventilation networks. Chatterjee developed a ventilation-on-demand (VOD) optimisation model that exploits the cyclical nature of mining to reduce ventilation fan-operating costs [19]. This model determines the optimal fan operating speeds during each hour of a day by considering the time-of-use electricity tariffs [11]. Although the premise of the model is well founded, it does not develop VOD methods that include network optimisation and inclusion of other techniques to achieve an integrated solution.

Various mine ventilation simulation packages are available for initial mine planning and design [15, 16], but none of them are used for optimisation or evaluation studies [16, 20]. Many mines in the private sector do not optimise or evaluate operational changes at all [11]. These mines typically implement operational changes to continue with mine development without regard to ventilation, until stopped by law or ventilation-related accidents [20]. This emphasises the need to optimise and evaluate operational changes through simulations. New methods to lower the costs associated with analysing mine ventilation networks (such as simulation and optimisation) could encourage adoption within these mines.

In the 1960s, ventilation simulation packages incorporated the simple laws of incompressible flow for Newtonian fluids [20]. However, with the large variation in air density experienced in underground mines, these packages became obsolete. In the 1970s, mine ventilation simulation packages were developed to include the thermodynamic relationships for Newtonian fluids [21]. This principle forms the basis of most modern ventilation simulation packages, which utilise the thermodynamic principles, fluid dynamic properties and network mass balances, typically of fluids such as air, to simulate actual ventilation networks [13, 20].

Modern simulation packages have varying degrees of complexity and accuracy [16], which should make a flexible, cost-effective simulation package based on the nature of work desirable [13]. The scalable technique used in the present study satisfied this need by providing a means to select and use a ventilation simulation package to optimise and evaluate operational changes. This method has the potential of allowing for decisions that can improve operational efficiency and safety, while ensuring legal compliance.

1.2 Mine ventilation optimisation

Typically, in hard-rock mining, there are two critical mining shifts to be considered in ventilation optimisation [22]. The first is the drilling, charge-up and blasting shift and the second the loading shift (when broken rock is removed from production faces) [17]. The complex ventilation network is used to ventilate the underground working areas during these shifts, in order to ensure compliance with health and safety standards [3]. There is also a shaft clearance period between shifts, during which the hazardous particulates (toxic blasting gases and dust) are diluted and exhausted by the ventilation network.

Conventionally, after the drilling shift, miners retreat from the production face to the main shaft haulage area where fresh air intakes are available until the clearance period has subsided or the miners have left the mine [9, 17]. Even though mining is conducted on a cyclical basis, maximum ventilation is typically supplied during all operating hours [9]. Only in recent studies have techniques such as ventilation on demand prompted crucial questions regarding true ventilation requirements during each hour of a day, exploiting the cyclical nature to lower operational costs [9, 11].

It is clear from literature that simulation is a viable technique to optimise and evaluate complex mine ventilation networks [8, 13, 16], but most packages are only used to evaluate either cost or service delivery during initial mine planning [9]. These key performance indicators are seldom considered simultaneously, especially when operational changes are to be implemented on a mine ventilation network. Simulation packages are therefore not used to optimise or evaluate operational changes [20]. Other techniques have been presented in literature to optimise mine ventilation networks [4, 16]. Conversely, none of the reviewed techniques provided a single framework or method that describes the process of optimising and evaluating operational changes through simulations. The present study aims to satisfy this deficit by developing an innovative scalable method to describe how operational changes should be evaluated and optimised through simulations.

2. Methodology

In this section, the newly developed scalable method, as shown in Figure 1, was applied to a mining complex. Please refer to the supplementary information for model development.[1] The method is shown in a step-by-step manner to show the significance of each step from A to I.

The ventilation network of a typical deep-level South African mining complex was selected as a case study. Due to confidentiality agreements the complex is referred to as DK. At DK, narrow-reef conventional mining is conducted at a depth of ± 1.9 km, focussing on the south reef ore body. The operation has one production shaft, which acts as the main downcast intake shaft (fresh air enters the ventilation network), and one up cast vent shaft (return air is exhausted after ventilating the working areas). DK also has a sub-vent shaft on the northern side and is interconnected with another mine, CK on two levels namely, 90L and 106L with twin airways. Next to DK's main downcast intake shaft, is an up cast vent shaft, DK1A. This illustrates the complexity of mine ventilation systems.

DK vent shaft is installed with two 2.1 MW Fantecnic (Howden) WBF-390 main surface ventilation fans. Currently, both of these ventilation fans are operating to ensure that conditions are conducive to safe and legal mining. DK1A vent shaft is installed with three Artec Davidson main surface ventilation fans, two having an installed capacity of 1.01 MW and the other 1.3 MW. Currently, only one of the 1.01 MW rated ventilation fans is operational at DK1A vent shaft.

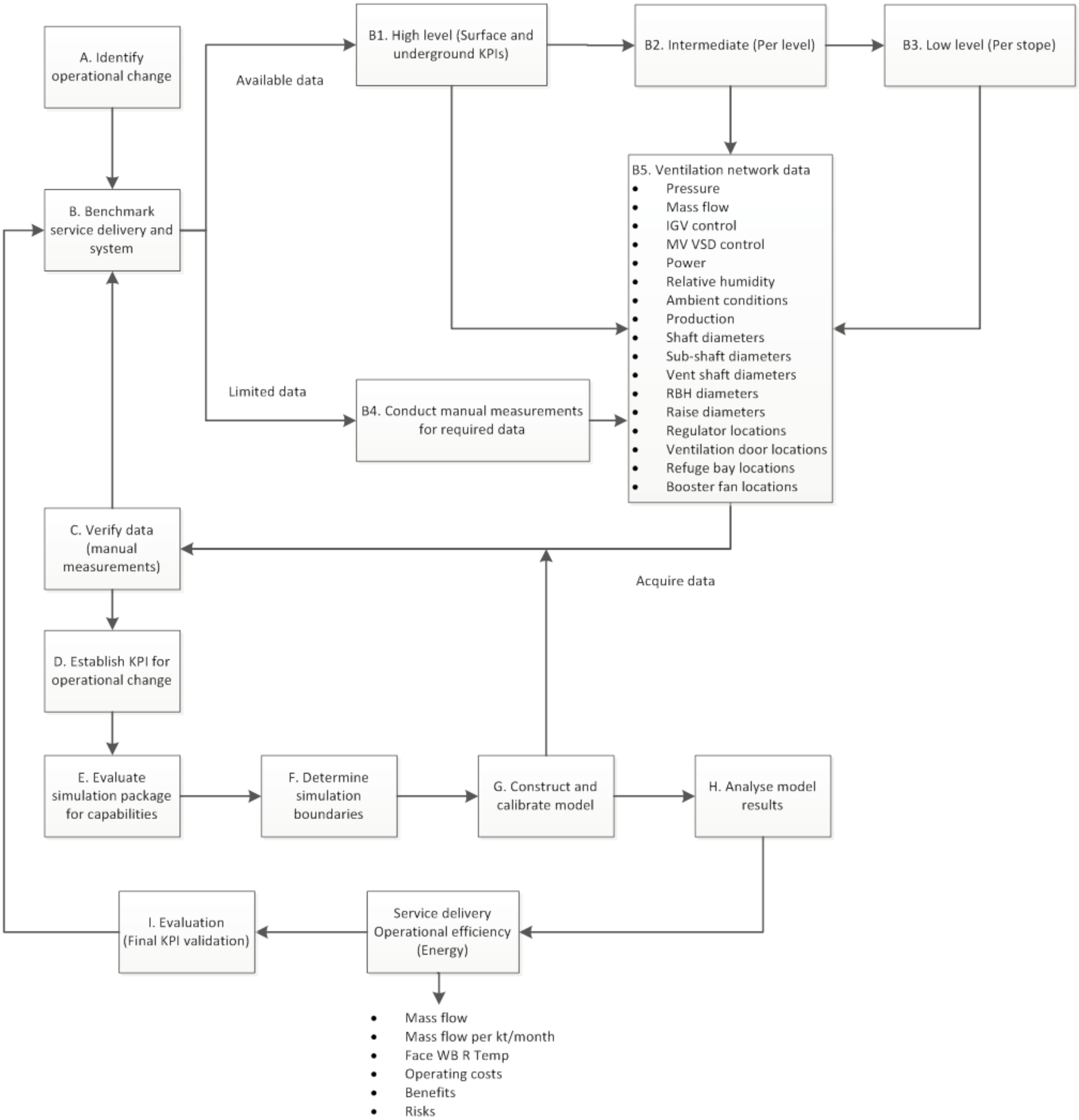


Figure1: Newly developed scalable method for mine ventilation networks.

The case study mining complex started to experience temperature constraints on the main production levels, 192L, 197L and 202L, which comprises the south reef section. The increasing temperatures were as a result of mine development. Mine personnel had to mitigate the increasing temperatures by implementing an operational change on the ventilation network. However, there were many operational changes available for implementation and mine personnel were challenged to determine the most feasible option. As a result, there was a need to apply the scalable method to address their problem and determine the most feasible option.

2.1 Operational changes (A)

As part of the scalable method (**A**), nine operational change scenarios were identified to be optimised and evaluated. Each operational change was simulated separately, but the simulations have similarities and three groups were considered, namely group 1 (scenario A to C), group 2 (scenario D to H) and group 3 (scenario I). The different operational change scenario groups are displayed in Figure 2. The operational changes were different for each scenario, and these differences are highlighted in the discussion below.

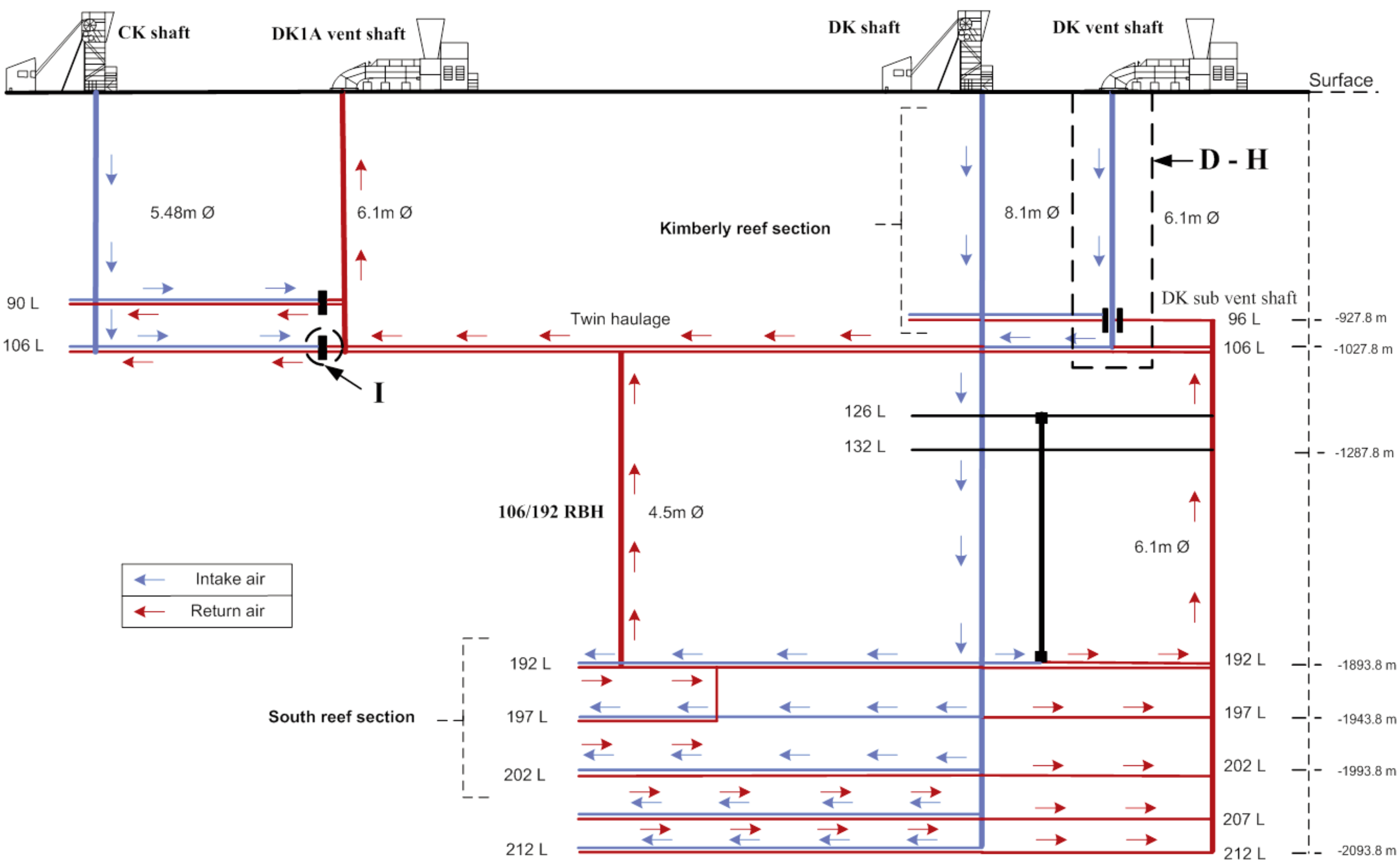
Group 1 (scenario A to C), DK vent shaft was converted to a down cast shaft and the return from CK to DK1A closed off, converting DK1A to the main up cast shaft. In scenario A, both the 1.01 MW ventilation fans and the larger 1.3 MW ventilation fans were operating at DK1A, with no fans operating at DK vent shaft. In scenario B, the two 2.1 MW ventilation fans originally situated at DK vent shaft were moved to operate at DK1A. In scenario C, the operating fan configuration was the same as in scenario B but the airway between DK and the 106/192 RBH was enlarged.

Group 2 (scenario D to H), DK vent shaft was kept as the main up cast shaft while only operating one of the 2.1 MW ventilation fans. This operational difference is indicated by the dotted rectangle in Figure 2. The fresh air intake for group 1 therefore changes to a return airway for group 2. Additionally, the returns from CK to DK1A were closed and DK1A utilised as the second up cast shaft for DK operations. In scenario D to H, one 1.01 MW ventilation fan and the larger 1.3 MW ventilation fan were operating at DK1A. In scenario E, the RBH diameter was enlarged from 4.1 m to 4.5 m. In scenario F, one of the twin airways between the RBH and DK1A was enlarged on 106L from 11.25 m^2 to 20 m^2. In scenario G, two 1.01 MW ventilation fans were operating at DK1A, and one of the twin airways was enlarged (as discussed for scenario F). In scenario H, both 2.1 MW ventilation fans were operating at DK vent shaft, with only the 1.3 MW ventilation fan operating at DK1A.

Group 3 (scenario I) is shown in Figure 2. DK vent shaft was kept as the main up cast shaft, as in the case of group 2. However, a maximum return air mass flow of 150 kg/s was maintained from CK to DK1A. The air mass flow control point is indicated by the dotted circle in Figure 2.

2.2 Benchmark (B)

The methodology was implemented on a low level for the purpose of the study to illustrate the scalability and accuracy possible with the use of simulations. As part of the methodology (B), the ventilation network operations of the mining complex were benchmarked to include detailed data on a per stope basis. This included acquiring ventilation network data from the mine such as air mass flow, temperature, relative humidity, pressure, area and tons of reef mined on a per stope basis (B3, 5). Any missing data was manually measured with calibrated measuring equipment on a per stope basis as part of the methodology (B4).



RBH = raise bore hole; Ø = diameter; L = level; D-H = group 2; I = group 3.

Figure 2: Operational change scenario A to I

2.3 Data verification (C)

The acquired data was verified (**C**) with manual measurements to ensure the accuracy of the data and subsequent simulation. Considering the latest life-of-mine plan, it was determined that the highest production rate planned for the specific mining complex was ±120 kilotons (kt) per month. In South Africa's deep-level mines, the average typical volumetric flow range is 3–6 m^3/s per kt of rock mined per month or 0.12 m^3/s per ton mined per day[17]. For this study, an average air mass flow of 4 kg/s was presumed to be sufficient in order to maintain production face wet-bulb temperatures of ±29.5°C for the south reef sections.

2.4 Key performance indicators selection (D)

The key performance indicators (KPIs) that were selected for the case study are shown below, categorised according to the data types (D):

- Service delivery KPIs – wet-bulb temperatures, air volumetric flow, air mass flow, air pressure.
- Operational KPIs – energy, maintenance.
- Technical KPI – air mass flow per kiloton production planned per month.

It was crucial to select applicable KPIs relating to the objective of the evaluation, as they form the basis on which the simulation and subsequent evaluation results were analysed. For this study, the aim was to improve the operational efficiency of the system, thereby reducing the energy costs while satisfying the service delivery requirements. Therefore, in terms of service delivery, the wet-bulb temperatures had to be within acceptable limits and the energy costs had to be kept as low as possible. Ultimately, the selected KPIs would indicate the success of the newly developed methodology, by comparing the pre- and post-implementation effects of the KPIs.

Based on this, the detailed simulation KPIs for the case study were determined and prioritised to be:

- Maintain production face return wet-bulb temperatures of ±29.5°C for the south reef sections.
- Optimise each operational change scenario for increased operational efficiency.
- Determine the suitability of existing infrastructures. Referring to existing main ventilation fans situated at DK vent shaft and DK1A vent shaft, minimum and maximum intake and return airway dimensions as well as the 106/192 RBH dimensions.

2.5 Software selection (E)

Commercially available simulation packages were evaluated (E) and a package incorporating a thermal hydraulic solver was selected to meet the detailed, per stope, simulation capabilities. Vuma 3D, a simulation package specifically designed to model complex mine ventilation networks, was already available on site and proved adequate.

2.6 Simulation boundaries (F)

The next step in the methodology was to determine the ventilation network boundaries per KPI, as defined per data type category (F). At that time, the air handling capacity of DK was limited by the main down cast shaft for a maximum down cast volume of 600 m^3/s, at an air velocity of 12 m/s. The collective up cast volume capacity of DK vent shaft and DK1A vent shaft was estimated at 1000 m^3/s. Previous studies indicated that a minimum airflow volume of 470 m^3/s was required to effectively ventilate the south reef sections. Since no mining was planned for the Kimberly reef sections, above 106L, it was excluded from the critical KPI simulation boundaries. The most critical simulation boundaries were established from the acquired data, as shown in Table 1.

Table 1: Critical KPI simulation boundaries.

Simulation boundaries	*Parameters*
Surface temperatures [°C WB/DB]	18/28
DK main shaft diameter [m]	8.1
Main intake and return airway [m^2]	11.55 (3.5 x 3.5)
Intake airway velocities [m/s]	6 – 8
Main return airway velocities [m/s]	10 – 12
Design air density [kg/m^3]	0.95
DK vent shaft diameter [m]	6.1

WB = wet bulb; DB = dry bulb

2.7 Simulation calibration (G)

As part of the method (G), the simulation was constructed for the complex mine ventilation network by incorporating the acquired data per stope and simulation boundaries. The simulation was iteratively calibrated by comparing the actual verified dataset with the simulation results on a per stope basis. Therefore, referring to Figure 1, the actual and simulation data for 192L's stope 5 west were compared. The simulation was therefore constructed to include all nodes where actual verified data were available or measured. The actual and simulated data showed an overall resulting correlation of 8%. The identified operational change scenarios were then simulated individually, to be optimised and evaluated.

2.8 Simulating operational change analysis (H)

The different operational change scenarios were simulated and optimised. Conforming to the method (H), the results were analysed according to the KPIs of each data type category. Each operational change scenario had to satisfy the service delivery and operational efficiency KPIs. Figure 1 shows the south reef section where the temperature constraints were experienced as a result of mine development, indicated by 192L, 197L and 202L. The air mass flows were therefore critical on these levels to mitigate the effects of the increasing temperatures. The south reef air mass flow is defined as the sum of the air mass flows on the main production levels before the air is returned through the up cast sub shaft and 106/192 RBH. The simulation air mass flow results for each of the scenarios are shown in Table 2.

Table 2 indicates that all of the operational change scenarios satisfied the air mass flow requirement. However, in order to evaluate and optimise the operational change scenarios, the service delivery constraints had to be satisfied and adhered to by each for all the KPIs. Furthermore, it was critical that the ventilation network resulted in wet-bulb temperatures conducive to safe and legal mining operations as this was the most important KPI [3]. All the simulation scenarios were therefore analysed to satisfy and maintain production face return wet-bulb temperatures of ±29.5°C.

The average production face wet-bulb return temperatures of the simulation scenarios are illustrated in Figure 3. The average standard deviation between the nine simulation scenarios was calculated as. As a result of this small standard deviation, one can conclude that each scenario satisfied the most critical service delivery KPI.

2.9 Evaluating operational changes (I)

Following the satisfaction of the wet-bulb temperature KPI, the evaluation of the individual operational change scenarios commenced (I). The evaluation was done according to the specified KPI categories. The individual operational change scenario's average face wet-bulb return temperatures, indicated by the bar chart, and air mass flows, indicated by the line chart, are illustrated in Figure. 4.

On first inspection, the results of the operational change scenarios showed that scenarios A, B, C and G had the lowest average face return temperatures displayed in the bar chart. The simulation results thus indicated that these scenarios were the most sensible operational changes for future mine development to contend with the increasing rock-face temperatures experienced on the south reef section. However, as part of the method, the other KPIs must also be satisfied and evaluated. Hence, considering the average simulation air mass flow design of 4 kg/s for a typical deep-level South African mine, scenario A, D, E and G had the closest correlation results. These scenarios therefore ensured that sufficient air mass flow was provided to satisfy future production requirements.

At that stage in the method, further analysis was required for the ventilation network to evaluate the operational change simulations in an integrated comprehensive manner. The next step in the method was to consider the KPI of operational efficiency, by evaluating the operational change scenario energy costs indicated by the bar chart, and total air mass flow indicated by the line chart, as illustrated in Figure 5. The energy cost for the case study was determined for each operational change scenario by multiplying the ventilation fans' energy consumption in kilowatt-hours for each scenario

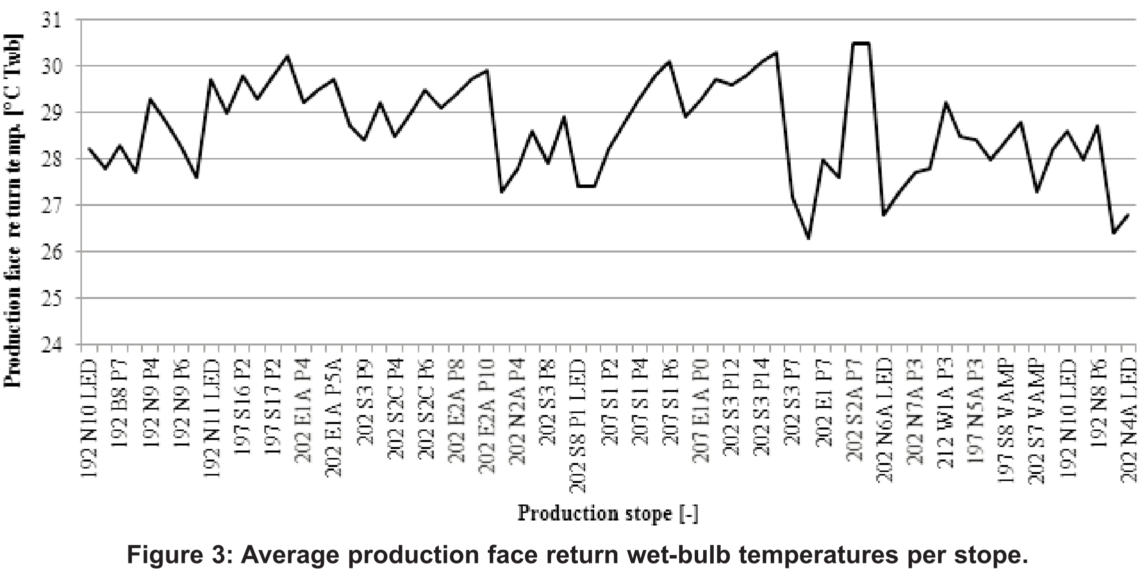


Figure 3: Average production face return wet-bulb temperatures per stope.

Table 2: Operational change scenario south reef air mass flow simulation results

Scenario	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*
Mass flow [kg/s]	455.3	509.5	532.6	470.6	475.9	491.2	473.8	533.0	480.5
Air flow [kg/s per kiloton/month]	3.94	4.41	4.61	4.07	4.12	4.25	4.10	4.61	4.16

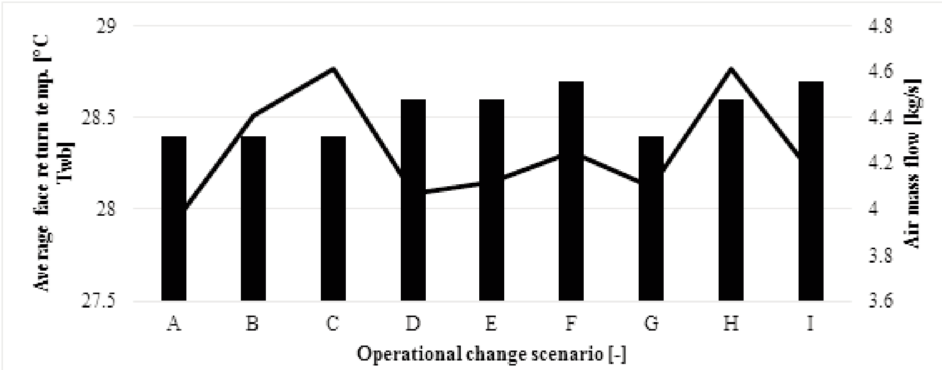


Figure 4: Average production face wet-bulb return temperatures (bar) and average air mass flow rates (line) per operational change scenario.

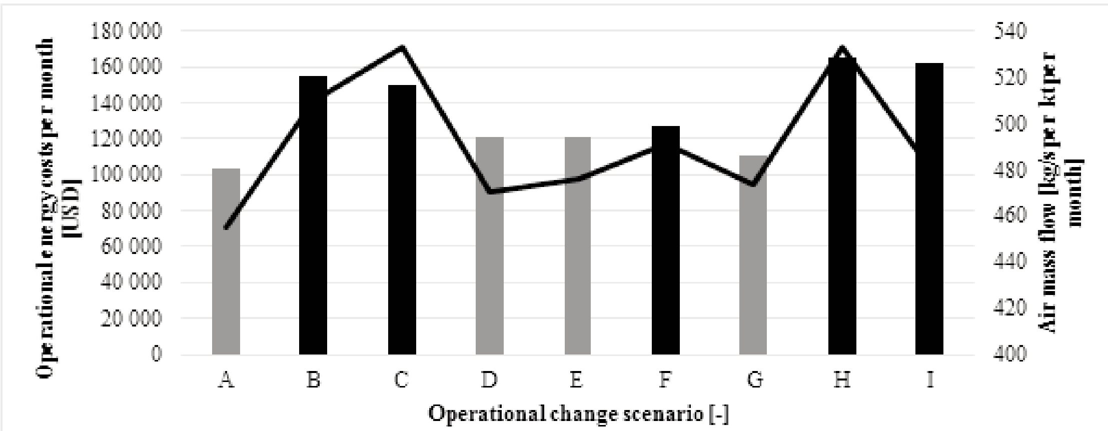


Figure 5: Operational costs per month in US dollars (bar) and total air mass flow rates (line) per operational change scenario.

per month, with the power utility's 2015/2016 electricity tariff.

Operational change scenarios A, D, E and G resulted in the lowest operational energy costs, as shown by Figure 5. This correlated to the average air mass flow utilised by the south reef section, as the operating costs were directly proportional to the up cast ventilation fans' electricity usage. Only two operational change scenarios, A and G, resulted in the lowest energy costs, thereby increasing the operational efficiency and satisfying the KPIs of the second data category.

The other operational change scenarios, in contrast, had shortcomings in at least one KPI. Therefore, only operational change scenarios A and G satisfied the KPIs of all three data categories. However, in order to proceed with the scalable methodology, the benefits and risks had to be analysed. The inclusion of the benefits and risks of each operational change scenario was incorporated in the method to make provision for a comprehensive, thorough evaluation. Although most benefits or risks cannot necessarily be quantified to a monetary value, they should still form part of the final evaluation [23].

Benefits

Scenario A had the lowest operating costs by only operating the DK1A ventilation fans. Scenario A also provided a means to convert the DK vent shaft to a second escape route for shaft egress. Scenario B provided flexibility to the network in the form of different ventilation fan operating configurations, flexibility in the up cast airflow capacities and a means to ventilate the old Kimberly reef section if required in future.

Risks

Scenario A had no flexibility or redundancy in the ventilation fans. If any of the DK1A ventilation fans experienced a breakdown, work in the south reef must be halted, according to legal standards and compliance. In scenario A, the DK1A vent shaft limited the total up cast airflow capacity. There was also no flexibility to ventilate the old Kimberly reef section in future. In scenario G, the DK vent shafts limited the down cast airflow capacity.

As mentioned previously, the only operational change scenarios which satisfied the KPIs of the three categories were A and G. Although scenario A had the lowest operational energy cost, the risks involved could have dire consequences for the mining complex and underground miners. Not all benefits and risks could be quantified to a monetary value, but should be included in the final evaluation of the operational changes. Therefore, following the evaluation and simulation analysis, operational change scenario G was implemented to achieve the desired results (**I**). The final simulation results for scenario G showed, by applying the methodology, that scenario G satisfied the most critical service delivery KPIs. The operational energy saving would therefore be realised by operating a 1.01 MW ventilation fan at DK1A vent shaft, instead of the 2.1 MW ventilation fan at DK vent shaft. This would result in a cumulative energy efficiency saving of ±9.64 GWh per annum. This figure was determined by multiplying the average energy saving per hour in kWh with 24 hours over a one-year period.

3. Validation

The operational change scenario G was implemented on the mining complex and was monitored for a period of 12 months. During this period, the cumulative energy efficiency saving measured through calibrated Schneider-Electric Powerlogic ION7330 power meters amounted to 8.50 GWh. This resulted in an energy saving of 23% on the ventilation network through implementing the most appropriate operational change identified by the scalable method. However, the total energy saving achieved was less than the simulation results indicated. The difference was attributed to the sealing of the return from CK shaft to DK shaft, which failed as a result of a temporary wooden seal. This was solved by the installation of a permanent seal, constructed from vermiculite bricks and cement packing.

As part of the method's final KPI validation, the simulated and actual results were compared. This provided an indication of the accuracy and success of the newly developed method. For that reason, the most important KPIs of the main production levels on the south reef section were analysed, as reported in Table 3. The average daily simulation KPI results were compared to the actual average daily KPI values, measured over the 12-month period. This indicated the accuracy of the calibrated simulation to forecast the effects of implementing an operational change. The average standard deviation of the daily wet-bulb temperatures was calculated to be,.

The most important objective of implementing the operational change was to ensure acceptable working conditions conducive to safe and productive mining at the highest operational efficiency, thereby lowest operational energy costs. From Table 3, the actual and simulated average daily wet-bulb temperatures correlate to within 9%. Moreover, the average daily airflow to each production level was sufficient to ensure acceptable working conditions and, in some cases, to supply supplementary airflow capacity. The service delivery KPIs were therefore satisfied for the main production levels.

Additionally, to accurately compare the results, other average daily KPIs for the integrated complex ventilation network were considered, as shown in Table 4. The average daily simulation air mass flows were compared to the actual average daily air mass flows, measured over the 12 month period. The absolute error of the average daily air mass flows are presented in Table 4 to indicate the level of simulation accuracy. Considering the average daily air mass flow results comparison in the table, the difference in air mass flow for each of the service delivery KPIs could be ascribed to variations in the data used to construct the simulations, as well as external factors such as air leaks and underground configuration changes that had an influence on the network. Due to the complexity of the ventilation network, these small differences between the simulated and actual results were negligible and the method was validated in terms of service delivery.

Another factor to consider as part of the KPI validation was operational efficiency. It was extremely important to illustrate the energy cost benefit realised as a result of implementation. Moreover,

Table 3: Post-implementation average daily KPI validation for main production levels

Level	*Simulated temp.*	*Actual temp*	*Temp error*	*Simulated airflow*	*Actual airflow*	*Airflow error*
	T_{wb}^{*} [°C]	T_{wb} [°C]	*Absolute* [%]	*Mass flow* [kg/s]	*Mass flow* [kg/s]	*Absolute* [%]
192	29.5	29.2	1	47.5	51	7
197	28.5	26.5	8	9.5	11.4	17
202	25.5	23.4	9	114	104.5	9

* *wb = wet bulb.*

Table 4: Post-implementation average daily KPI validation for the integrated, complex mine ventilation network.

Section	*Simulated mass flow* [kg/s]	*Actual mass flow* [kg/s]	*Absolute error* [%]
South Reef	473.8	478.0	1
192/106 Raise bore hole	185.0	165.0	12
DK vent surface fans	298.6	340.0	12
DK1A vent surface fans	299.9	313.0	4

the implementation costs were also included in the analysis. Therefore, the costs to install and close the return from CK shaft to DK shaft amounted to USD 3 312 (ZAR:USD exchange rate as on 13 November 2017). The costs to reduce the RBH and seal the old Kimberly reef sections amounted to USD 3 450. The cost to increase one of the return airways on 106L amounted to USD 2 070. The total cost of implementing operational change scenario G, amounted to USD 8 832. The time taken to complete the operational change was 1.5 months – it would have been much shorter had it not been for extended lead times for constructing the underground seals.

4. Results and discussion

The operational change was implemented and active for a period of 18 months during the time this study was compiled. The total energy savings, measured by the calibrated meters for this period amounted to 13.32 GWh which, if converted to costs according to the tariffs as mentioned earlier, resulted in an energy cost saving of ±USD 0.7 million.

The significance of this method lies in that it enables mine personnel to make improved decisions regarding operational changes on mine ventilation networks through simulations. The importance of this method was emphasised by the validation, in which scenarios A, B, C and G satisfied one KPI. However, if scenario B or C had been implemented, the operational costs would have been much higher than for scenario G. Likewise, the resulting air mass flow of scenario B and C would have proved to be unnecessary for this project. Furthermore, if scenario A had been implemented, the mine would have had a much larger risk of losing production or experiencing an underground working fatality as a result.

This method was easily implemented and was specifically developed to be scalable. This scalability is extremely important in successfully implementing and utilising it. The versatility of the method to conduct high, medium and low level evaluation studies provided mine personnel with new insights on operational changes. The author has observed a new vigour in mine personnel where the method was applied, as it was a new tool to be used for improving underground conditions and for increasing the profitability of deep-level mines. The importance of the method was underlined by its adoption by industry practising professionals as the norm of their mining standards.

This scalable method was developed according to a continuous improvement process. This enables the method to be incorporated and still be relevant in future developments such as cases where industry 4.0 and the 'internet of things' technologies are applied to the mining industry [13]. Mine personnel can develop a digital simulation twin of the entire ventilation network to be evaluated on a continuous basis, incorporating these new technologies.

5. Conclusions

This paper presented a scalable method to optimise and evaluate mine ventilation networks through simulations. Nine operational change scenarios were optimised and evaluated on a deep-level mining complex. The method was used to determine the most feasible option. The most feasible option was implemented successfully, resulting in a 23% energy saving.

Mine personnel had been challenged with making a decision of which operational change to implement, selecting from a vast array of operational changes. The method provided a means for selecting the best alternative, based on a comprehensive evaluation. The true value of the method is that it allows for improved and traceable decisions regarding operational changes – as illustrated by the adoption of the method by mining professionals as part of their own standards and procedures after successful validation.

The method promotes improved safety, better underground working conditions, legal compliance and mine productivity, as a result of a thorough evaluation which was not previously available. Its versatility and scalability makes it applicable to all ventilation networks, including future developments such as industry 4.0 or internet of things technologies.

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Note

1. Supplementary material can be found at https://journals.assaf.org.za/jesa/article/view/4445.

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