Accuracy and Confidence Prediction in Ventilation Models

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ABSTRACT

Ventilation models simulate underground pressures and flows based on data entered by the user, however it is not common knowledge the accuracy of the results can vary widely through different parts of a model regardless of the accuracy of the data entered. Depending on the structure of the ventilation system and the effect of natural ventilation pressures the results could vary ~~widely~~ significantly with only small input parameter changes. Modelled ~~areas~~ regions of a mine often cause considerable concern with ventilation professionals when simulated data does not match measured data or critical ventilation areas fail to meet expectations after design and implementation. This paper examines the causes of variability and inaccuracy in modelling results and where to expect lower confidence results in a ventilation system. Methods to improve confidence through more robust ventilation design and contingency are also discussed.

INTRODUCTION

Ventilation modelling has become a critical tool in most modern mine ventilation designs and relies on the mining professional to accurately design and input data into the modelling software to obtain accurate results. When done correctly, models can reliably confirm design assumptions and provide confidence in achieving planned airflow and environmental conditions.

The most critical input data for airflow modelling is the resistance of the model airways which includes assumptions of friction and shock losses. For existing mines, airway resistance data can be validated with actual resistance measurements in a mine, however measured data can also have error variability due to the survey methods used and constantly changing mine conditions during surveys. For future ventilation planning, assumptions must be made based on previous experience or theoretical data which will typically be less accurate than measured data. The accuracy of input data will have a direct impact on the accuracy of simulation results, however the impact of resistance errors can vary significantly, depending on the location in the model and the construction design of the interacting airways. The resultant variability in airflow may be much more than what the resistance variability would initially suggest.

In critical areas, where airflow or temperature must precisely be engineered, these variations can cause significant problems with health, safety, and lost productivity from reduced work output and delays.

This paper shows variations are greatly impacted by ventilation design structure, the accumulation and interaction of small errors, and the variable pressure of natural ventilation. Analysis of the key causes of large variability in ventilation model results will be discussed, and contingency plans raised about what can be done to identify and limit the variability in critical areas.

ANALYSIS OF VARIABILITY

The most common causes of variability of modelling airflow results compared to actual results are errors in resistance estimation and natural ventilation pressure changes (Griffith & Stewart 2019). As described in Equation 1, resistance errors can be caused by poor estimations of airway size, friction factor or shock loss. For example, variations between design and actual resistance can occur when the mining process causes overbreak and results in larger than expected airway sizes. If the engineer fails to survey the correct size and assumes design sizes, the resulting simulation may be incorrect.

Natural ventilation pressure variation is more difficult to identify. It is caused by heat changes in the mine (from mining activity, underground rock strata or surface temperature changes) creating pockets of more buoyant air in the mine, changing the balance of airflow at different times. Although well below the pressures normally applied by ventilation fans, small changes in pressure *balance* particularly in areas outside of the direct influence of fans can cause large changes of airflow without significantly affecting overall mine fan pressures or total airflow. This variability may cause unexpected changes in ventilation, particularly away from the influence of the primary ventilation circuit.

Resistance sensitivity

Atkinson's resistance equation for an airway (Equation 1) is dependent on the airway length, *L*, perimeter, *per*, cross-sectional area, *A*, and the friction factor, *k* (McPherson, 1993):

$$R = kL\frac{per}{A^3}. \qquad (1)$$

Where

R = Resistance (Ns^2*/m*^{8}*)*

k = Friction Factor (kg/m^3*)*

L = Length (m)

A = Area (m^2*)*

per = Perimeter (m)

Resistance can therefore be subject to the following errors in measurement or estimation including;

- Poor or incorrectly assumed measurement of size or friction factors underground.
- Deformation of the surrounding airway host rock causing size changes over time.
- Partial blockage of airways with pipes, ducts, conveyors or other obstructions that are not included in the model.
- Poorly considered shock losses around bends or contractions in the mine.
- Passing vehicles and machinery causing temporary blockages or a piston effect.

The relationship between pressure, airflow and resistance is defined by Atkinson's equation (Equation 2) or it's variation (Equation 3).

$$P = RQ^2 \qquad (2)$$

$$Q = \sqrt{\frac{P}{R}} \qquad (3)$$

$$\frac{1}{\sqrt{Rt}} = \frac{1}{\sqrt{R1}} + \frac{1}{\sqrt{R2}} + \frac{1}{\sqrt{Rn....}} \qquad (4)$$

Where

P = Pressure (Pa)

Q = Quantity (m^3*/s)*

Rt=Combined resistance of parallel airways (Ns^2*/m*^{8}*)*

In the case of a single airway leading to a pressure source, if resistance (*R*) varies and pressure (P) remains the same, then airflow (*Q*) according to Atkinsons equation should theoretically vary by the square root of the resistance change percentage (Equation 3). For example, a 10% change in resistance should only cause a 3% change in airflow if fan pressure remains constant. However, as most mines are driven by ventilation fans defined by pressure/~~volume~~quantity curves, the change in airflow may be more than this.

In the case of multiple parallel airways ventilated by the same fan pressure, a variation in resistance applied to either parallel airway will result in a change only in that airflow, with the combined flow changing by a lesser percentage than a single airway (Equation 4). If multiple random changes are made to multiple parallel airways, then the combined resistance change will always be less than a single airway.

However, in the case of connecting airways between multiple parallel airways a much less predictable result may occur as demonstrated in Figure 1. If two parallel airways with identical resistance (Airways A and B) exist with a connecting airway (Airway C) at the same point along the airways, then no flow will occur between the connecting airway. If the resistance is increased in Airway A relative to Airway B then the connecting airway will flow towards Airway B, and vice versa. In summary the flow in the connecting airway may change magnitude and direction as the airflow tries to find the path of least resistance. It is this configuration that causes the greatest uncertainty in model design.

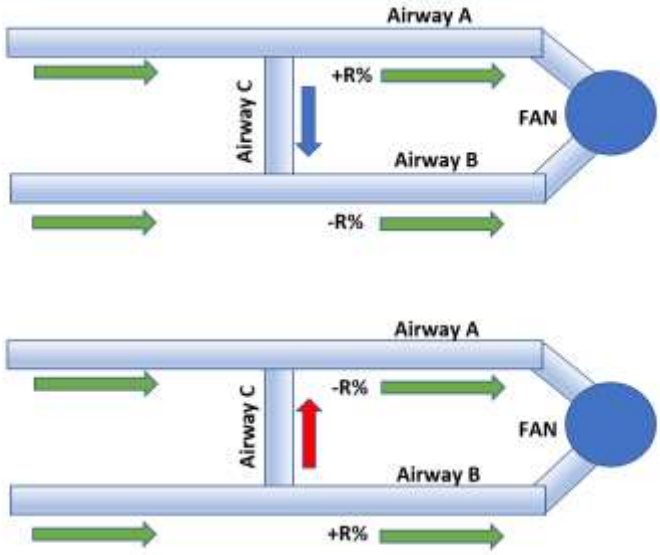

Figure 1 Connections Between Parallel Airways

Methodology of Resistance Sensitivity

Small errors in resistance estimation are unavoidable, therefore a proposed method of examining the effect of resistance errors is to deliberately apply a series of randomised errors to produce multiple variations of the model. ~~Similar to~~Like the Monte Carlo approach of statistical analysis, a method can be applied where the resistance of each airway is modified by applying a random factor, ε, of maximum size, ε_{max} as described in equation (5). Every simulation will result in slightly different airflows depending on the variations in resistances in the model.

$$(1-\epsilon_{max}) \le \epsilon \le (1+\epsilon_{max}), \qquad (5)$$

An algorithm can be derived as follows;

- A variation factor of 1/3 or 33% provides a reasonable random variation to each airway resistance in the model.
- A significant number of iterations of variable simulations can be performed to provide a statistically significant average. One hundred (100) iterations is suggested, however larger models may need to be satisfied with fewer iterations due to simulation time constraints.
- The simulation results will provide a mean airflow $\bar{Q}$, the airflow standard deviation σ_Q and the frequency of airway airflow directions changes for each airway.
- Further statistical properties can be determined including the mean standard error, $\frac{\sigma_Q}{\sqrt{n}}$, the deviation of the mean airflow from the current simulated airflow, Q, and the airflow quantity confidence, *C*.
- The quantity confidence, expressed as a percentage, is given by equation (6) which is useful in highlighting any airways with large deviations from the mean, but will also highlight low flow airways with small, but relatively large, deviations.

$$C = 100 \times \left(1 - \left|\frac{(Q-\bar{Q})}{\bar{Q}}\right|\right). \qquad (6)$$

It is important to note the method cannot estimate the likely actual variation of resistance or airflow in a real mine. Instead, the method is testing the resilience of the airway flows in the model to change because of variations in resistance. If the airflows do not change any more than the amount predicted by Atkinson's equation (Equation 2 and 3), then the confidence of the model airflow matching the inputted resistance is considered 100%. If, however the airflow variation is greater than expected by the simple variation in resistance, then it is likely the structural configuration of the model (in particular airway connections between parallel airways) is likely causing the variability and therefore the airflow magnitude and direction should be treated with more caution.

Heat sensitivity

A second cause of variability of airflow in model predictions is the distribution of heat and natural ventilation pressures throughout a model. If natural ventilation pressure is considered (~~and~~ in most cases it should be considered) then the simulation and distribution of temperature and air density is an important part of the calculation. Figure 2 demonstrates the effect on temperature changes and natural ventilation pressures causing airflow changes between what would be otherwise stagnant airway connections between parallel airways.

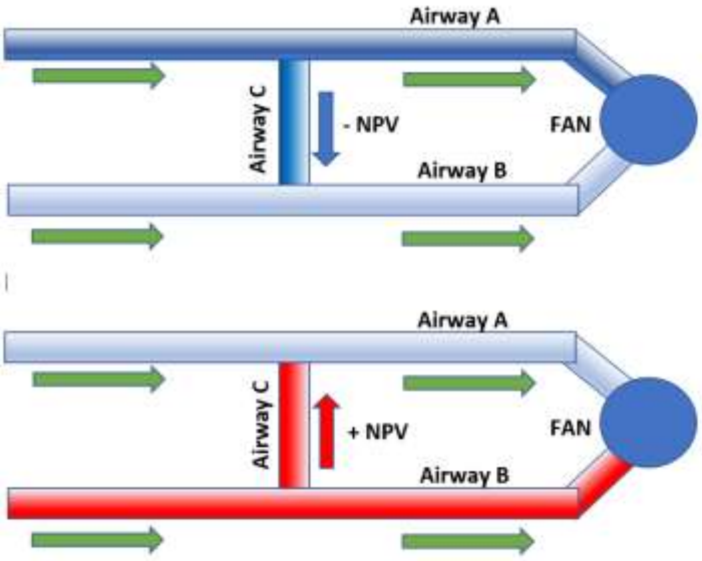

Figure 2 Variable Temperatures (shown as Red and Blue) cause natural ventilation pressures and flow changes between parallel airways

Most ventilation modelling is performed using steady state analysis. In this case, the distribution of heat through a model is predetermined and considered constant for an indefinite period. A simplified approach to calculating the effect of natural ventilation pressures is to use prior airflow simulations to predict heat flow distribution through a mine, and then use the heat flow distribution to predict natural ventilation effects which influence subsequent airflow simulations. This coupled approach will provide different steady state solutions every iteration which may or may not eventually converge to a steady solution.

A more sophisticated approach is to couple the flow and heat distribution into the energy balance equations used to solve airflow distribution (Danko 2017), ~~however despite being a steady state approach, in reality even this~~however any method using a steady state approach is only valid for a single moment in time and real mines will be constantly disturbed by subtle changes in heat distribution due to changing surface conditions or moving heat sources (for example machinery) underground.

The first simplified approach is more likely to provide an indication of the stability of a model due to changing heat distribution for each iteration being considered for subsequent iterations. While this approach does not simulate actual likely variance of heat throughout a mine (because the ultimate steady state solution between each iteration would be interrupted before completion in a real mine), is does provide an indication of the ~~likelihood~~ possibility of airflow variance due to changing heat distribution. Another approach would be to simply change the temperatures (and therefore air density) randomly throughout the model (much as the resistance was changed randomly in the previous section), however this would require a more sophisticated distribution mechanism to consider the initial heat distribution and how the heat flowing from one random change would flow into downstream areas.

Methodology of Heat Distribution Sensitivity

Using the simplified iterative steady state method described above;

1. A model with no temperature variation is run to provide initial airflow distribution
2. A thermodynamic heat simulation is run to distribute heat along the pathways determined by the airflow simulation.
3. The air density and natural ventilation pressure is calculated for the new heat distribution in every airway.
4. Another airflow simulation is performed taking into consideration the temperature and density changes causing new natural ventilation pressures.
5. The iteration loops back to Step 2 and repeats a statistically significant number of times.

Similar to the resistance sensitivity method, the mean airflow, $\bar{Q}$, the airflow standard deviation, σ, and the percentage of samples in which the airflow direction changed, X, for each airway can be recorded. In addition, the mean dry-bulb temperature, $\bar{T}$, and the standard deviation, σ_T can be recorded, as well as the temperature mean standard error, $\frac{\sigma_T}{\sqrt{n}}$, and the deviation of the mean dry-bulb temperature from the currently simulated dry-bulb temperature are calculated. Sections of the mine that do not converge to a solution after repeated heat and airflow simulations are detected by observing airways with low airflow and direction confidences.

RESULTS

The proposed methods and algorithms were tested in VentSim Design to provide visual feedback of results. These methods have now been incorporated into tools in the software for users to test their own designs.

Resistance sensitivity

Figure 3 ~~(Figure 3 needs the colour legend made larger so it can be more easily read)~~ ~~shows~~shows a metalliferous mine design with fresh air entering the mine via a ramp and shaft system on the right-hand side. Whilst most areas on the design show confidence of 100%, where resistance variations will not affect airflow any more significantly than defined by Atkinsons equation (Equations 2 and 3), several areas show significantly less confidence where airways branching off the main ramps show in yellow and green, suggesting a confidence level of 90% or below. A deeper airway in the model design traversing across the design shows a blue colour with a confidence level of only 50%.

This does not mean the airflow results in the real mine could vary by this amount. However, it does indicate the model results in these areas are being easily influenced by small resistance changes locally and elsewhere in the model. Any errors in data input and assumptions for airway friction factors or sizes are more likely to have a strong effect on these airways. Conversely, areas of full confidence are less likely to be affected and can be considered more reliable predictors of actual airflow.

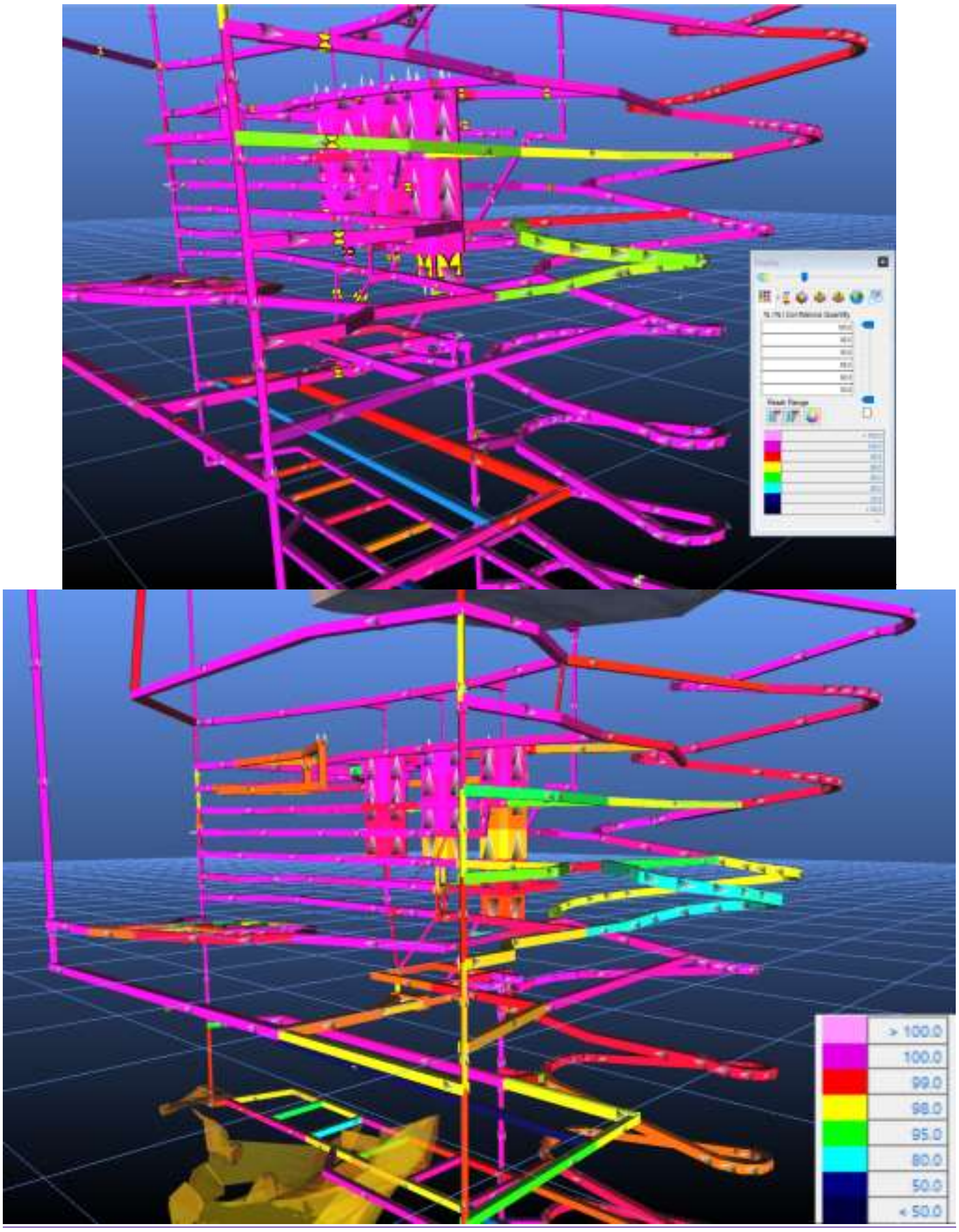

Figure 3 Airflow quantity confidence (%). Cooler (green and blue) indicate higher variability.

Airways with low quantity confidence will often also have low direction confidence. An airway prone to airflow reversal can cause numerous safety and productivity issues as the expected direction of gases, blasting fumes and heat cannot be guaranteed. The resistance sensitivity analysis will often highlight connecting airways between parallel zones sourcing air to or from a common pressure source as low confidence, whereas airways leading from or to major fans will show as high confidence.

Heat sensitivity

The same model was simulated for heat sensitivity with the results shown in Figure 4~~. (Figure 4 needs the colour legend made larger so it can be more easily read).~~

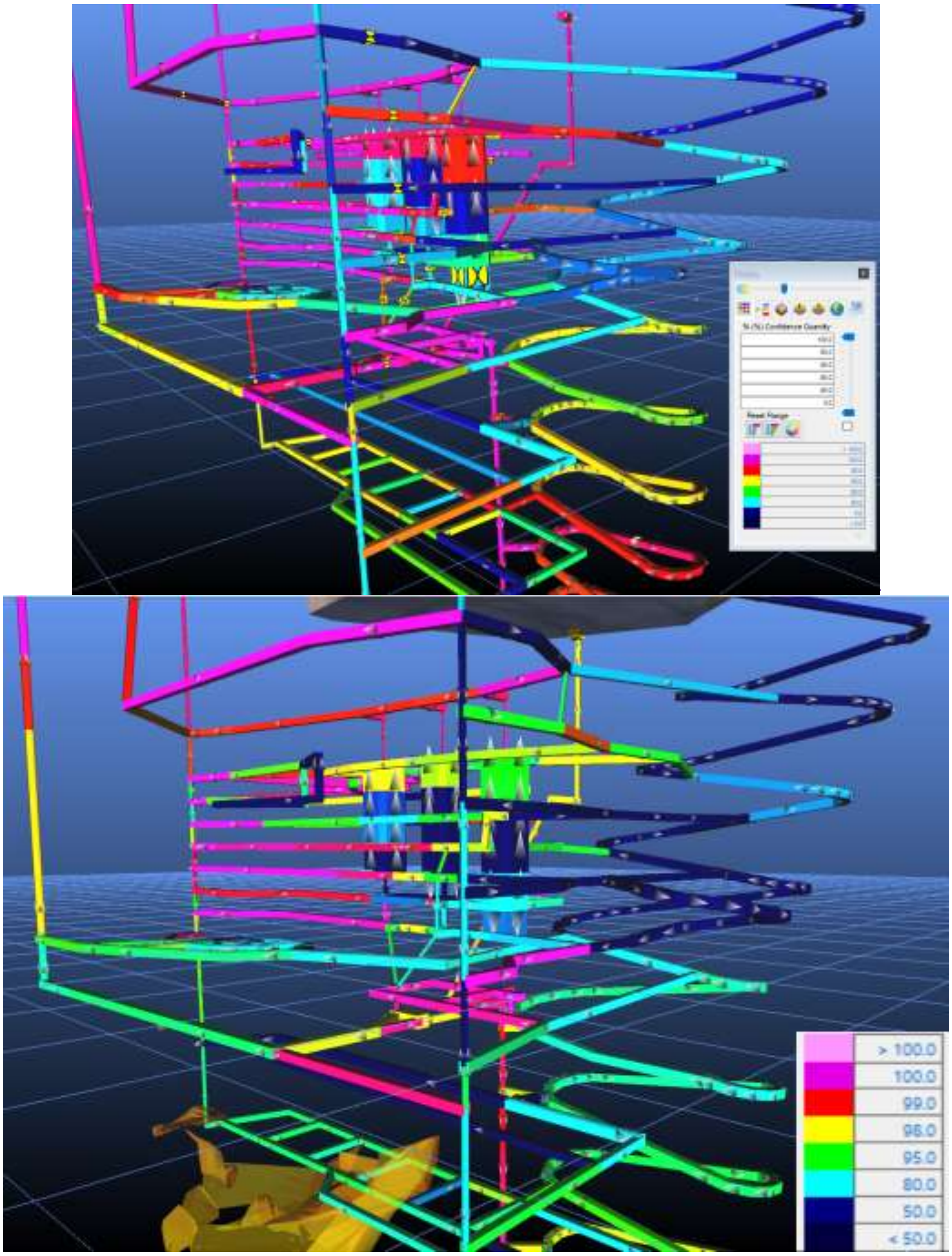

Figure 4 Heat sensitivity effects. Cooler colours (green and blue) show increased variability and reduced confidence

Considerable variability is demonstrated in this case with large sections of the upper main ramp on the right (away from the main fans and near multiple other surface connections) showing poor airflow confidence. Areas under the direct influence of a fan show good confidence with little susceptibility to natural ventilation pressure variations. The low confidence areas also showed a high risk of airflow reversal, a significant concern if a guaranteed ventilation direction is required for safety or productivity purposes.

DISCUSSION

The example model presented in Figures 3 and 4 ~~is~~ shows a poorly designed ventilation system, producing variable results in some areas from the sensitivity analysis. The model consists of many interconnected parallel pathway connections to primary ventilation fans and to surface connections, a configuration previously discussed as being more likely to cause variation in predicted airflow with subtle changes to resistance and heat distribution. The author notes there are many mines designed in this manner, and normal steady state simulation results may therefore be misleading as they perhaps incorrectly infer adequate airflow and correct directions to all critical areas.

The larger variations appear more likely to occur in regions a long distance from the direct influence of a main ventilation fan, or between parallel ventilation circuits driven by the same fan pressures. If primary airflows and directions can be easily influenced by small changes to airway sizes, resistance or heat, or by even parking or moving obstructions, such as vehicles, through these zones, then the ventilation cannot be considered robust and may require redesign in critical areas.

Engineers and ventilation officers are often perturbed about why some areas of their ventilation models perform poorly against measured results. Sensitivity analysis can also assist in identifying these areas and help allay (or confirm) fears of model inaccuracy or measurement mistakes. The same variability factors and sensitivity mean that it is common for the sensitive areas to show a high variability in actual measured results as well, with ventilation surveys on one date being substantially different to surveys taken on other dates. Trying to improve a model that performs poorly in a non-critical area shown to have high sensitivity could therefore be dismissed as a waste of effort and engineers could focus on more important parts of a model or ventilation design.

Critical areas that should not be exposed to the possibility of airflow variation (production zones, workshops, crushers, explosive magazines or fuel stores) should be checked more closely for variability. If the analysis shows the areas are sensitive, there may be a need for additional ventilation controls or engineering redesign to ensure guaranteed airflow. The causes of variation in models and real mines can often be overcome by utilizing fans dedicated to ventilating only one region, or by adjustable regulators that can be quickly changed to respond if undesirable ventilation variations are detected.

CONCLUSIONS

Sensitivity analysis using variable resistance and heat inputs may be a valuable method to determine the reliability and robustness of a ventilation design toward a given application. If strong variations are shown likely to occur in critical regions, ventilation professionals can take proactive steps to prevent them by improving ventilation design. Model sensitivity analysis will assist engineers in developing better and more robust designs that ensure safe conditions and that meet regulatory and productivity requirements in all circumstances.

~~(whilst being mindful of ensuring the paper doesn't appear to be a sales pitch for the software it isn't clear to the reader that these analyses have been done as a one off for a research project or whether anyone can run such analysis on the software themselves. To benefit the audience I believe this should be included in the paper somehow)~~

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