A PRAGMATIC METHODOLOGY FOR MINE VENTILATION PLANNING

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ABSTRACT

A ventilation planning framework, which integrates the mine production plan with the ventilation plan, is introduced as a means of formulating an optimal engineering design solution which meets long range ventilation planning activities at producing mine sites. The framework was developed to overcome a common problem whereby the mine plan is created without consideration of ventilation, and thus the ventilation plan must be the most economic while also having zero input to the mine production plan. The ventilation planning framework charts a path whereby a production plan is turned into a ventilation model, the future airflows are scrutinized against design acceptability criteria, and solutions are evaluated and ranked to determine the best future design. One novel feature of the methodology is the use of the value-ease method to quickly focus efforts rather than working in an iterative loop in its attempt to arrive at the most practical and economic ventilation design recommendation.

KEYWORDS

Ventilation planning, Ventilation modelling, Optimization

INTRODUCTION

Mine production planning is a process used to schedule the best sequence of all required mining events, carried out using available resources, to maximize a mine's value. Ventilation planning is a subset of this process, and must be well developed and correlated with production planning in order to comply with the various health and safety regulations that the need to be met in the field. These planning activities are inherently difficult as operational realities may not allow the schedule to be completed at the same rate as planned, economics may change the resources available to complete work, and the design of what is being scheduled is in constant flux as new information is brought into the plan and the rough outlines of a long-range plan are refined into detailed short-range designs for execution.

In many cases the mine production plan is developed without consideration of ventilation, and thus the ventilation plan must be developed to meet all planned production activities yet without affecting the mine production plan. Typically, in this case, the ventilation plan is developed in a tedious iterative process to arrive at an acceptable design. In such case, the developed ventilation plan is neither optimal nor in many cases cost-effective.

A framework for ventilation planning, with a particular focus on integrating the production plan at an active mine, and planning to the end of mine life is introduced.

The framework reconciles the mine production plan with the ventilation plan by creating design acceptability criteria, and from these, minimum airflow requirements for the production plan are set. The framework continues with the development of a ventilation model that is extrapolated forward, and the predicted future flows are tested against the ventilation acceptability criteria and the model is also checked for other bottlenecks and inefficiencies. Where gaps exist between the available and required ventilation, ideas are generated and ranked rapidly according to the value-ease principle and preliminary modelling. Those potential solutions which appear most likely to succeed are then modelled in detail before a fuller economic analysis is undertaken, a recommendation arrived at, and final optimizations made.

The proposed ventilation planning framework greatly differs from those methods commonly used within industry; it smartly correlates with the mine production plan, and utilizes the value-ease method to quickly focus efforts rather than working in an iterative loop. In this case, solutions are evaluated and ranked to determine the best path forward in order to select the optimal project scope to meet the ventilation requirements of the mine production plan.

THE CONVENTIONAL VENTILATION PLANNING PROCESS

The design process of a mine ventilation plan requires a number of assumptions to determine the airflow volume required, and the factors causing and resisting this flow underground, allowing a ventilation design to be completed. These assumptions will likely change with time as the underground expands, equipment is added and replaced, and production blocks open and close over the life of mine. Yet the data available to make these assumptions will be limited and imperfect, and the mine plan will inevitably change. However, the design must always comply with appropriate health and safety legislation, while being efficient, economic, and practical. This is the ventilation engineer's dilemma: how to efficiently deliver the required airflow for a mine plan that is always being revised. This is where the question of robustness arises, providing excess capacity without negatively affecting efficiency to create flexibility.

The level of detail in a mine ventilation plan will therefore need to match the level of detail in the mine production plan. Short range plans are 'locked-in' and have a very high level of detail, while preliminary feasibility studies are very general and are not made for executing. As a mine or mining blocks move from exploration, through feasibility and into short range plans for execution (Figure 1), assumptions become estimates, estimates become known parameters, and detail is added. In the cyclical nature of mine planning where the long, medium, and short-range plans are constantly revisited, revised, and refined the ventilation plan is built up in tandem.

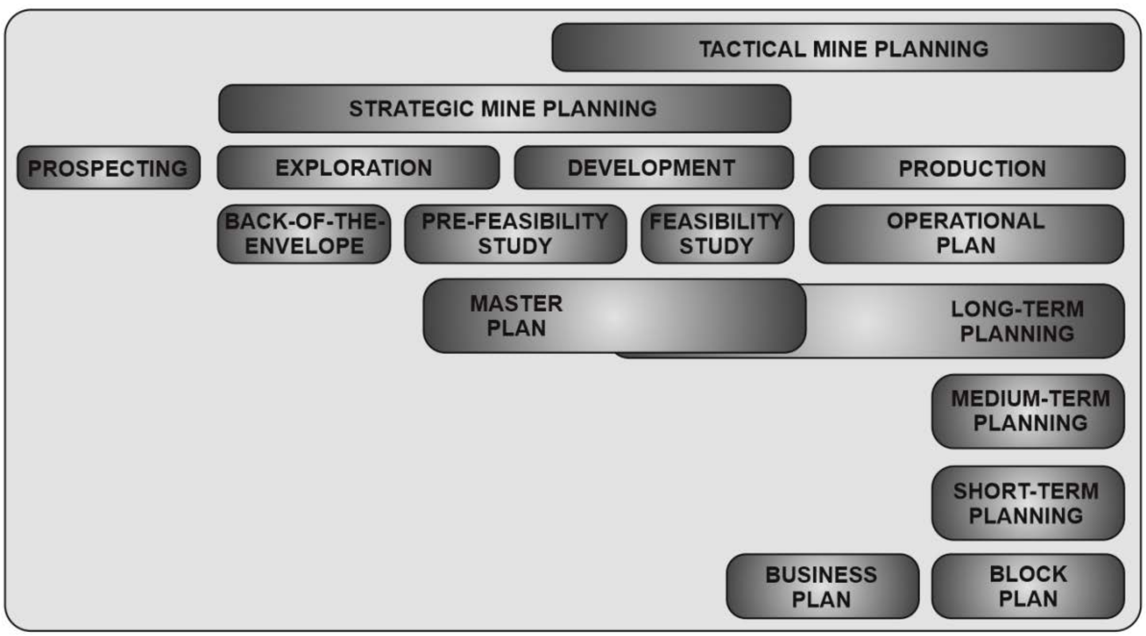

Figure 1. Example layout of mine planning activities from the business' perspective (De Souza, 2015)

For example, a preliminary economic assessment study may calculate the total fresh airflow volume with rule-of-thumb values based on airflow volume requirements per tonne of production, select surface fans, rough-in some vertical development, and assume a $/t cost for auxiliary ventilation. Some simple modelling with average ventilation factors and a few stages representing the major changes over the mine life may even occur. A long range (5 year) plan would utilize the fresh airflow available for the budgeted fleet in the mine plan, and estimate annual costs for fans, power, and ducting, and also include preliminary annual project budgets for vertical development and ventilation infrastructure. In the long-range plan ventilation modelling should be looking for outlier periods or conditions where demand could be greater than availability, both locally and mine wide. This is the focus of this paper. The long-range plan is the first opportunity for detail to be added that may conflict with other parts of the mine plan. A medium range (or budget) plan will estimate the month when raises are blasted or fans are installed, and this is where capital projects are scoped, quoted, and argued for. Ventilation modelling in the medium range plan is repeating the work of the long-range plan, but with greater granularity and certainty of the production plan. This is the last opportunity to catch large primary ventilation problems before they are experienced underground. Within short range (3 month to 2 week) plans the medium range and budget plans are converted into detailed plans for execution. Ventilation planning in the short-range plan exists only to consider how small disruptions will affect the greater airflows (taking a fan offline for a short period, a breakthrough before a bulkhead is built, etc.), how regulators should be adjusted, and what changes to the auxiliary ventilation may be required. These long-medium-short range ventilation plans are both a part of, and (ideally) created in tandem with, the production plan. Ventilation allows production, and production requires ventilation. Therefore, sometimes the ventilation plan adjusts for what the production plan requires, and sometimes the production plan adjusts for what the ventilation plan allows.

It is common that the first pass of the mine plan creates a skeleton schedule of development meters and production tonnes. Detail is then added by building the construction project schedule on top (including raisebores, ventilation raises, ore passes, pump stations, etc.). The long-range ventilation plan is then created given the existing infrastructure and existing ventilation project plan. Any additional alterations to the ventilation network required to meet the design acceptability criteria are then considered. As good solutions are found they are rolled into the working version of the long-range mine plan. If no good solutions are found, a discussion to adjust the mine plan is necessary. Regardless, the findings of the ventilation plan are communicated out to the engineering group and operations leaders, and the outcome feeds into the next iteration of the long-range plan.

There are multiple case studies on mine ventilation studies and improvements that have been carried out that have been presented at the North American Mine Ventilation Symposia (Ponce Aguirre, 2006) (Wallace, Jr., et al., 2012) and other industry conferences. These present the challenges faced and solutions found to overcome problems, but these do not present methodologies for use by other professionals, or if they do they are overly simplistic. As well there are ventilation planning methodologies available in textbooks. These are fuller and have some iteration loops included. However, they may be said to have poor correlation with the production plan, are designed for feasibility stage projects, and do not specifically consider how to narrow a multitude of possible solutions down to the most economic recommendation. This is where a robust ventilation planning framework, which integrates the mine production plan with the ventilation plan, is introduced in this paper.

PROPOSED METHODOLOGY FOR VENTILATION PLANNING

The proposed methodology was developed for use by operating mines to guide long range ventilation planning activities at a producing mine site, though it may provide value for feasibility stage planning. The framework was designed to overcome a common problem whereby the mine plan is created without consideration of ventilation, and thus the ventilation plan must be the most economic while also having zero input to the mine production plan. Each process step of the proposed methodology, illustrated in Figure 2, is described below.

Prepare inputs

1. Simplify the Mine Development and Production Plan

The first step of the proposed framework is to bring the various components of a mine plan together into a single chart of activity by period for each ventilation zone. To create this ‘Simplified Activity Plan’ the ventilation engineer must select the size of ventilation zones (ex. drift, level, block, area), determine the appropriate time scale (ex. month, quarter, year), and then assign the major activity that defines the ventilation requirements. It may be as straightforward as defining each level as either inactive, waste development, ore development, ore production, or backfill. Alternatively a mining block may be assigned a fixed airflow volume given a known or estimated work cycle.

In the feasibility stage work would have been completed to determine the ideal combination of daily ore and waste tonnes, tunnel size, method of material movement, and fleet to maximize the project's Net Present Value (NPV). In an operation planning for closure in 10 years or less, the inputs which were variable early on are instead fixed: the main ramps are developed, the fleet size has peaked and will eventually shrink as equipment reaches the end of serviceable life, and the payback period for a shaft/conveyor/rail/electric-truck system is longer than the life of the mine (or is too disruptive). In these late stage operations, the annual production rate will eventually fall as the resource is eliminated. Growth is not the goal, but sustaining mining rates through to the end is. These late stage projects have different challenges than the 'blank slate' of a pre-feasibility study. In these old mines, ventilation can become an afterthought. The production plan in this situation may be created assuming ventilation can be provided as long as the raises and tunnels carrying airflows are extended with the mining front, which would seem to be a fair assumption as no expansion of the fleet is expected, so all else being equal sufficient air should be delivered underground to create a safe working environment for the production plan. The reason the assumption that ventilation is not a constraint to the future production plans in mines nearing the end of mine life is incorrect is that, as the resource shrinks, so do the areas that work occurs in. This may in some cases cause a concentration of people and equipment into a smaller area which may not be set up for such an airflow quantity. Alternatively, the production area may become spread out as pillars and remnants are targeted, and again the ventilation system may not be set up for such an irregular airflow regime. Regardless, a detailed mine development and production plan is the first requirement for a mine ventilation plan.

2. Determine Design Acceptability Criteria and Estimate Airflow Requirements

The second stage must determine the criteria which the final ventilation plan must meet. These criteria are the mine parameters, environmental parameters, and legal requirements that one would consider to create the minimum design acceptability criteria. Suggested ranges for these parameters for early stage projects are available in the standard mining textbooks, and older mines would have a fixed fleet and knowledge of the environmental parameters. These design acceptability criteria are then applied to the simplified activity plan to estimate the airflow requirements for the mine. These criteria need to be defensible, comply with at a minimum with internal company policies as well as provincial and federal laws, and ought to also be consistent with industry best practice.

For example, some design acceptability criteria may be:

- Airflow quantities will meet minimum reasonable requirements for maximum diesel power operating in a ventilation zone for each activity.
- Auxiliary fans will not recirculate.
- Airflow from production areas must be directed to exhaust airways without reuse.
- Leakage will occur from fresh air to exhaust air.
- Minimum and maximum airflow velocities where personnel are present.

3. Prepare Calibrated Ventilation Model

The third step of the proposed framework is to build a calibrated ventilation model using data from field investigations. The goal of this step is to build an accurate model of the current system such that the airflow modelled matches the airflow and pressures measured underground (without forcing the solution by fixing airflows or pressures), and so that any extrapolation forward or alternative configuration would be an accurate prediction of the future outcome. A brief synopsis of the steps involved in building a model is presented in Table 1.

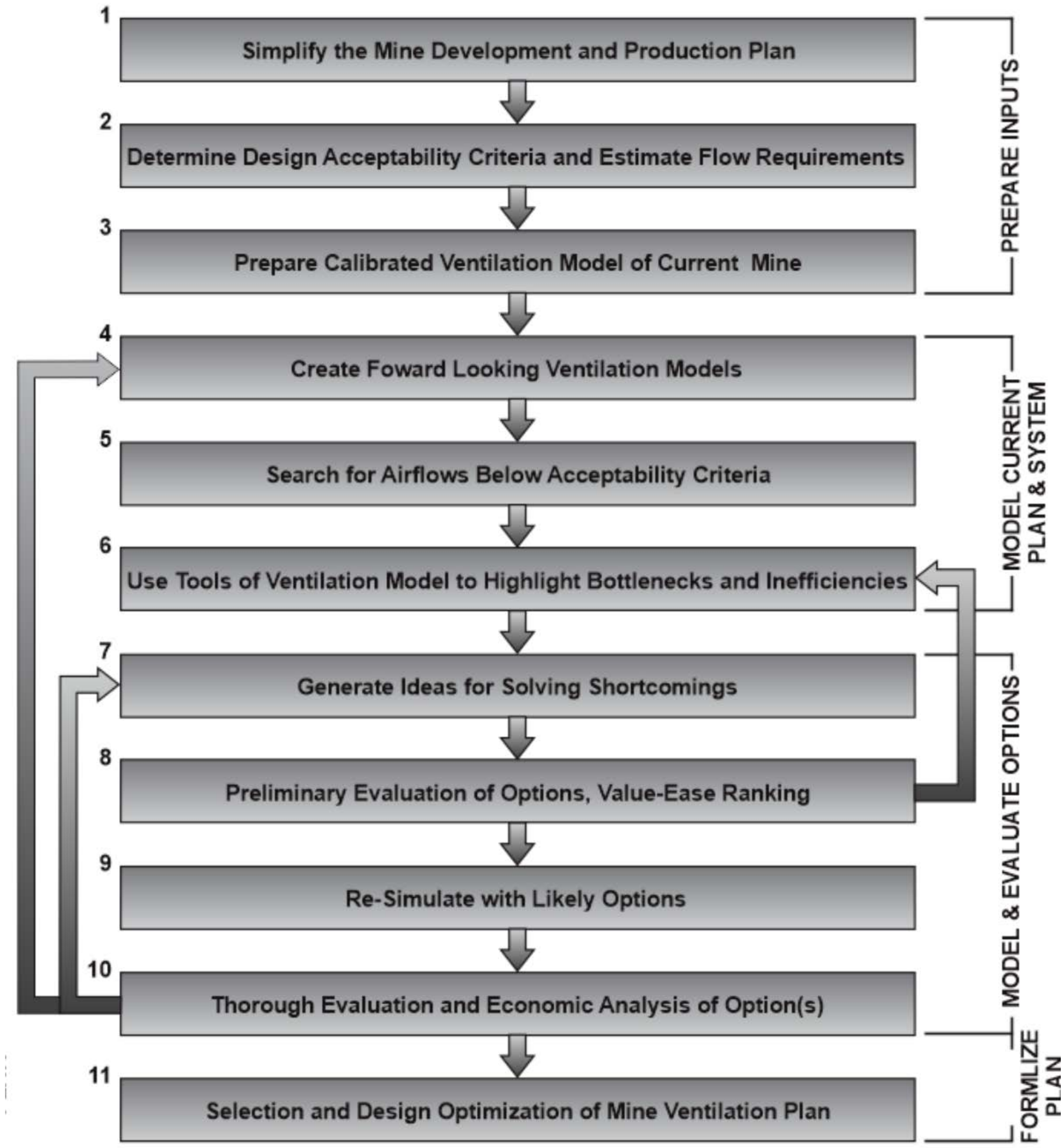

Figure 2. Proposed methodology of long range ventilation planning

Table 1. Typical steps involved in building a calibrated ventilation model

Step	Action
1	Perform a ventilation survey of airflows and balance these within 10%
2	Determine branch Atkinson Resistance and friction factors with a volume-pressure survey, or use published average friction factors if at a feasibility stage
3	Import design centerlines into the modelling software (use life-of-mine design), simplify and clean up
4	Populate branches with basic information regarding: size and shape, friction/resistance information if available, PQ survey data if available, and specify branches that open to surface or are dead ends, etc.
5	Insert ventilation controls such as: bulkheads, brattices, regulators, doors, and obstructions. These may be modelled as open areas, as an Atkinsons Resistance number derived from pressure-quantity data, or as standard values often available in the software
6	Insert shock losses where the drifts abruptly change direction or size with a significant air speed (usually above 5 m/s)
7	Insert fans including main intake, exhaust and booster fans and include fan shock losses
8	Check model against field measurements and confirm validity

Model current plan & system

4. Create Ventilation Model of Production Plan at each Stage/Period

With a calibrated model the fourth step is to complete the extrapolation of the model from Step 3 into future time periods. For each period being planned a copy of the calibrated model is set up and adjusted to match the approved mine plan future layout. Ambient temperature and approved ventilation projects should be included. The goal is to create an accurate ventilation model of each future period of the current mine plan.

5. Search for Constraints, Insufficient Airflow, and Recirculation in Primary Ventilation Circuits.

With a calibrated ventilation model which was extrapolated forward according to the mine plan, the framework then requires the engineer to search for working areas where the airflow modelled is less than the requirement as per the design acceptability criteria from Step 2. It is recommended that a spreadsheet be created to track all the significant airflows from each stage of the base case model, and the spreadsheet be analyzed for shortfalls.

6. Use Tools of Ventilation Model to Highlight Bottlenecks and Inefficiencies

The framework continues with an efficiency focussed investigation. Ventilation is a significant cost for the modern underground mine, therefore the responsible engineer must not only ensure that the requisite occupational health and safety legislature is being met, but that it is done so in as efficient a manner as possible. There are several situations to look out for, and ventilation modelling software has tools available to assist, such as high airflow velocity and thus high shock and friction losses.

It is assumed in this framework that the responsible person at site is capable of finding inefficiencies that exist in the existing system through field investigations. These include, for example, air leakage and recirculation in a circuit, as well as head losses that are excessive for the type of drift. Fan operating points that are far outside the optimal efficiency range, and installations missing inlet bells and evasees are obvious candidates for improvement. In such cases where standard fan accessories are missing, calculations would show that fan losses are responsible for a significant portion of the fan total pressure, meaning that a lot of the work the fan is performing is being done to overcome the inefficiency of its own installation. A comparison of airflow volume per power unit (m^3/s per kW) is useful to create a local ranking of fans. Those fans expending the most power creating pressure have the lowest airflow volume per power unit; thus, large diameter-low pressure fans are always more efficient at airflow movement per input power. These are generalizations, the cost-benefit comparison and design requirements will be different at each operation, and there are applications where high-pressure booster fans are ideal.

With a completed model the first sign of inefficient airflows is excessive air speed. There are published tables with recommended ranges for permissible airflow speeds (De Souza, 2015). Alternatively, primary airways where the air velocity is too low may present an opportunity for improvement.

Other tools available include:
- recirculation finders: airflow recirculation is not only against Mines Regulations, but is also very inefficient in hot mines where air conditioners are required and can lead to added exposure to dust and diesel particulate matter.
- restricted fans: fans that are not adding pressure to the system and may be restricting flow.
- friction cost/L - ventilation modelling software can change the colour of drifts to identify the friction cost per length, a very good indicator for inefficient airflow.
- shock loss: ventilation modelling software can highlight where shock losses are occurring.

Model & Evaluate Options

7. Generate Ideas for Solving Shortcomings

In this step of the framework ideas are generated to bring all airway branches up to the design acceptability criteria. The most common problem is insufficient airflow for the planned work, this being either to exhaust the contaminants or expel the heat. General solutions may be grouped as:
- sealing unwanted air leakage and eliminating recirculation.
- regulating airflows from an over-supplied to an under-supplied area.
- increasing booster/primary fan power (ex. change blade angle, fan motor, or fan), results in increasing operating cost.
- decreasing system resistance to increase operating point airflow volume (ex. decrease air speed to reduce friction head and increase fan flow, usually by using parallel drifts or raises), is normally associated with a significant capital cost.

Alternatively, if the problem is heat stress other solutions may be required. This step is best accomplished with a group of representatives from: short and long range mine planning, projects/construction, electrical engineering, geotechnical engineering, and operations.

8. Preliminary Evaluation of Options

Given the ideas brought forward, Step 8 ranks the various options in terms of value and ease. It is recommended this occur immediately after Step 7, and with the same group of people. The Value-Ease analysis allows engineers to quickly rank all the ideas independently in terms of how easy (a self-directed definition of time/effort/money) they are to implement, and how valuable (in this case effective in reaching the design acceptability criteria) they appear to be. Where the value is hard to estimate, quick modelling to look at the effect on one or two parameters (and not on the whole mine) at larger intervals is recommended. The ranking will indicate which ideas deserve the effort to develop, as shown in Figure 3. The ideas that are both easy to implement and have a high value are obviously the first to receive attention. Next those that are high-ease but low-value and low-ease but high value are pitted against one another for attention. Ideas that appear to be low value and difficult to implement are put aside right away. It may be that several less valuable projects are easier to implement than one large project to reach an equal result.

The application of a Value-Ease analysis is novel for a ventilation planning methodology and it accepts that some factors are fixed in the mine plan. The Value-Ease analysis moves all the idea generating to the front-end of the process and reduces the pool of ideas down to a single plan through detailed design, modelling, and economic analysis. In a more typical ventilation planning methodology the full design-model-economic analysis is completed and then compared against the design criteria, and the idea generating happens at the end of the process as an iterative loop attempting to find the optimal outcome, which can create much more work.

When considering how to implement an idea, it often happens that even more ideas are generated as one is being thought through; for example, if there are two methods to achieve one outcome one would need to consider the ease of each method. A return to Step 6 after the first pass of this step is recommended to consider bottlenecks and inefficiencies of the ideas under consideration.

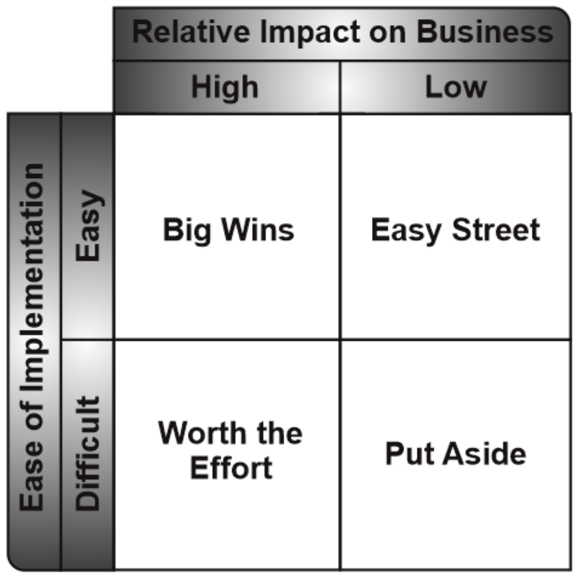

Figure 3. Value-Ease chart

9. Re-simulate with Potential Options

With all the ideas collected and the best options identified the framework moves forward to simulate these in great detail for each period of the mine plan. A spreadsheet to track the airflows of concern through all the model's time periods is highly recommended. If there are 18 periods being analyzed, and three ideas being tested, 54 new models are required. It is important at this junction to have an error-free model, as inaccurate or incomplete information in the base model will contaminate all the results, requiring a return to Step 4 and significant rework.

10. Thorough Evaluation and Economic Analysis of Options

At this stage, there should be one or more projects, or combinations of projects, that meet the design acceptability criteria. The results of the first-pass study in Step 9 brings an increased understanding of the model to the designer, necessitating a return to Step 4 to adjust the model, and to Step 7 with additional ideas, which has been included in the framework. This tenth step of the methodology develops the acceptable options to create preliminary capital budgets with operating costs, implements schedules, makes assumptions on technical details, and identifies critical path work. In the most extreme cases it may be necessary to change the production plan if an economic ventilation plan cannot be identified. Such plans may be generally said to require more ventilation than the primary circuit has available, necessitating an expansion to increase primary airflows.

Formalize Plan

11. Selection and Design Optimization of Mine Ventilation Plan

At this stage, the user should have at least one good option and be able to make the business case for any recommendation to their superiors and co-workers who participated in the idea generating session in Step 7. This recommendation ought to be a decision based on economics. The present value of all capital and operating costs are tabulated for the project selection, and other details (schedule, intermediate setups, outcome, flexibility…) noted. The business case will highlight the limits of the current system without investment, and how the design acceptability criteria mandate the required airflows for the mine plan. The project recommendations are finalized, and the budgets, operating costs, implementation schedules, and critical path that were roughed in for the preliminary comparison are made concrete for the final project approval.

DISCUSSION

The proposed methodology is a guide for engineers familiar with the principles of mine ventilation and the mine being assessed, and relies on the user to find the most efficient solutions through testing various ideas. To use the methodology to create a robust and optimal ventilation plan it is critical that the mine plan be reasonably accurate and ventilation model be correct. The optimal solution is the most efficient, the robust solution is one that can handle the future changes to the plan that will inevitably occur, usually by creating excess capacity by oversizing fan motors to allow for flexibility. Should the best solution not come up in the idea generating session, or be discovered during subsequent modelling work, or if it is eliminated erroneously during Value-Ease ranking, then this fatal flaw cripples the plan. The engineer also ought to recognize the value in teamwork and include stakeholders early in the process, particularly for the idea generating and value-ease ranking steps. The value of consulting related teams is so that all possible options are identified early in the process, and so that all construction obstacles are recognized in the preliminary analysis.

This methodology is best suited for the long-term master plan and block plans. While it is certainly possible to perform this level of work in a feasibility study, there are generally more important areas to focus energy upon (such as orebody knowledge). If using this methodology for quarterly schedules or shorter, then the proactive methodology is unsuitable and the ventilation engineer is working in a reactive manner; the outcome is not worth the effort.

Finally, to create a robust ventilation plan a good mine plan is required, but robust also means the ability to adjust for changes to the mine plan, usually by providing excess capacity to create flexibility. This can be done by over-sizing motors for the optimal fan selection, or using VFDs to operate fans at lower speeds. A good mine plan is one that is both easy enough that it will be achieved, but difficult enough that it will stretch the mine operations team, however one should still expect the plan to change. The long-range mine plan is not supposed to be executed as presented, and that is why intermediate and short-range planners are brought on to refine, revise, and revisit the mine plan on many occasions before it is issued. On top of this there are the market fundamentals which apply external pressure and inevitably change the long-range mine plan. Accordingly the mine plan must reflect the activity carried out across the mine if it is to be a useful document for ventilation planning. Should this not be the case then the ventilation plan may not be valid for the work executed underground.

CONCLUSIONS

A framework for ventilation planning with a particular focus on planning to the end of mine life has been presented. The framework is used to reconcile the mine production plan with the ventilation plan by creating design acceptability criteria, and from these criteria minimum airflow requirements for the production plan are assessed. A ventilation model is then developed and extrapolated forward, future flows are tested against these ventilation acceptability criteria, and the model is tested for other bottlenecks and inefficiencies. Where gaps exist between the available and required ventilation conditions, ideas are generated for closing these gaps, which are ranked according to the Value-Ease principle and preliminary modelling. Those potential solutions which appeared most likely to succeed are modelled in detail and a fuller economic analysis is undertaken, a recommendation is arrived at, and final optimizations are completed.

The novelty of this methodology was the development of a pragmatic framework for ventilation planning which integrates production planning in the ventilation planning and design process and which selects, from a multitude of possible design solutions, the most practical and economic recommendation. As well, the methodology takes a staged approach, formalizing the idea generation stage to gather a large pool of ideas early on, and required options to pass a Value-Ease analysis and preliminary modelling exercise before a complete financial comparison is made, and only then is a full fan selection exercise undertaken.

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