Economic modeling of Australian longwall ventilation

T.I. Mayes & A.D.S. Gillies
University of Queensland, Brisbane, Australia

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ABSTRACT: The goal of optimum longwall ventilation design can be seen as an integral part of the success and continuation of entire mining operations. The process of longwall ventilation design is ideally an integral process to the overall mine design development and implementation. To develop optimized longwall ventilation designs in this context an economic basis has been established to evaluate and undertake further design iterations to achieve the goal of design optimisation. Fundamental economic consideration of longwall ventilation design characteristics and operation through the analysis of current longwall ventilation practices is used to outline the basis for a generic economic longwall ventilation model. Some of these issues include gateroad development, sealing practices, labour utilisation, ventilation infrastructure, operational delay costing and consideration of alternate ventilation techniques such as booster fans and bleeder ventilation. The economic investigation of longwall ventilation draws on aspects of the established longwall ventilation practices from North America, Europe and Australia.

1 INTRODUCTION

Planning processes for establishing ventilation network details are widely used in many different generic forms. The longwall ventilation planning and design process is a subset of these established procedures. Usually these processes are developed as a result of the personal experience of the mining engineer involved with ventilation planning of a number of projects over a period of time. The methodology utilized in this process strives to arrive at a ventilation design that satisfies all criteria set including those of minimum ventilation requirements and minimizing cost. The solution to a given longwall ventilation scenario may then meet the criteria set but may be suboptimal dependant on the level of experience and expertise of the engineer involved in the design process. The knowledge based development of design methodologies exists in various forms, an example of which can be seen in Basu & Wala (1993).

It is proposed that the optimisation of these planning and design stages can be undertaken using an economic basis developed from considering existing practices in the context of economic fundamentals. This economic basis would then be used to form a methodology utilised in the longwall ventilation planning process.

2 ECONOMIC CONSIDERATIONS

In consideration of the development of an economic basis for a design methodology it is necessary to define a number of economic terms and their use in the derivation of economic considerations. The fundamentals listed below should not be considered as an exhaustive list of economic terms but a summary of already established concepts.

- Capital and operating costs.
- Deferred and non deferred costs.
- Fixed and variable costs.
- Time value of money and interest.
- Internal Rate of Return and Net Present Value.
- Depreciation and taxation implications.

These economic terms are defined in any number of economic and ventilation texts including Stermole & Stermole (1990).

3 LONGWALL VENTILATION CONSIDERATIONS

The consideration of fundamental design and economic issues involved in developing a robust ventilation design are discussed below.

3.1 *Specifications*

As a minimum sound engineering design and those legislative constraints imposed for the management of ventilation contaminants specify the minimum ventilation requirements. The management of ventilation contaminants has to consider respirable and explosible dust, toxic and explosible gases and heat. A comparison internationally of these features can enlighten the design process by highlighting different modes of thinking and tradition.

3.2 *Infrastructure*

Infrastructure used within the ventilation system forms the basic components or building blocks of the model. The major components of a ventilation network can be divided into the utilization of shafts and raisebores, roadway development, ventilation control devices or appliances and fans.

3.2.1 *Shafts/raisebores*

Recently with the advent of reliable and available raiseboring technologies the use of small diameter shafts/large diameter raisebores are used more widely to augment initially intake capacity and hence lower intake resistance. The extension of this application is considered in Section 7.2 where back return capabilities are considered and expanded on.

The economic consideration of these installations is traditionally focused on the summation of the operating costs of providing the necessary air power and the initial cost of shaft development. Ultimately with proper planning additional shaft installations can replace the original or existing upcasting or downcasting capacity. At this point savings are achieved by converting the Mains section between shafts into either all intake or all return. Leakage is totally eliminated and increased parallel roadways greatly reduces the effective resistance. In practice there are a few Australian examples of the implementation of this concept in varying stages of completion.

3.2.2 *Roadway development*

The most fundamental use of roadways is that for ventilation. When considering the costing of roadway development it may be possible to subsidize some development costs from other mining functions but this is usually not a significant consideration. Typical Australian practice for gateroad development utilizes two parallel headings. Fundamentally the cost of the second gateroad has to be attributed (certainly in full or maybe in part) to the ventilation system. With the recent use of three heading gateroads in one Australian colliery the additional costs over developing a two heading gateroad have to again be attributed to ventilation.

3.2.3 *Ventilation appliances*

This category of ventilation control devices includes stoppings, seals, overcasts and regulators. The cost elements of these devices are that of purchase, installation, labour and consumables. The selection of appliances is now even more difficult with a larger range of devices available with the advent of legislation providing for a minimum overpressure performance but not specifically dealing with leakage characteristics. Ongoing costs of labour and consumables can be considered in the maintenance of such devices and is discussed in Section 3.3.3.

3.2.4 *Fans*

The selection of main fans is an important function in the economic operation of a ventilation system and can contribute to minimized capital and operating expenditure if undertaken properly.

3.3 *Operating costs*

A number of different factors contribute to the expense of operating a longwall panel. When considering ventilation the categories of expense include most notably power, labour and maintenance and can be fixed or variable in nature.

3.3.1 *Power*

The costs associated with power consumption in the ventilation network are attributed to the operation of fans. Given unique operating characteristics the power consumption can be calculated given a duty point. That is the load in terms of quantity and pressure required. It is usually easiest to consider the cost of electricity as the average cost per kWh and not worry about time dependent peak and off peak charging. The cost of running ventilation fans is continuous and hence averaging is possible.

A large consideration in the operation of fans is the presence of leakage in the mine. This leakage can be seen to exist most predominantly in older ventilation appliances that are usually the devices closer to the bottom of the upcast shaft and pit bottom in an exhausting mine. There are gains to be had in rectifying this problem increasing the system resistance and adjusting the duty of the fans.

3.3.2 *Labour*

The cost of labour in Australian mines is increasingly the subject of contracts with the utilisation of specialist contract labour. As a process this makes the associated costs more visible and easier to incorporate into planning functions.

3.3.3 *Maintenance*

Maintenance of a longwall ventilation network is necessary for a number of reasons including roof falls, excessive rib spalls, water and silt build up and convergence and general operational wear and tear on ventilation appliances. These maintenance functions can be separated into leakage minimization and resistance minimization. It is possible to utilize a method of evaluating the selection of different maintenance projects based on that proposed by Peterson (1993). It is emphasized that the solution to each potential ventilation problem is considered as a separate economic opportunity in this methodology. In the evaluation of maintenance projects a series of goals is set and the network is assessed based on pressure and quantity survey data.

Part of this maintenance function includes the expense of consumables such as sealing agents. In this example it can be seen that the application of sealing agents to ventilation appliances can improve the leakage characteristics but incurs material and labour expense during the actual application. The frequency of such applications must also be considered if, for example, convergence causes the ventilation appliance leakage characteristics to degrade rapidly. In this case the selection of more appropriate ventilation appliances and not necessarily the cheapest can be assessed against the ongoing maintenance costs.

3.4 *Operational delay costing*

Robust design and planning procedures ensure in the ideal case that the ventilation system is capable of dealing with all elements of contaminant ingress and management. In the case of a poorly designed ventilation system it is possible to delay mining operations due to ventilation reasons, such as gassing out of faces and the existence of uncontrolled or poorly controlled hazardous environments.

To establish the delay cost there are several methods that consider those that can be deferred and those that cannot be avoided such as labor. This represents a significant cost to be avoided irrespective of whether the cost of delays is considered the direct loss of revenue (with associated consideration for the fixed and variable costs) or the time value discounted cost due to revenue recovery at the end of the mine life. To approach this topic various work has been completed including a time discounted recovery of revenue based decision methodology for evaluating longwall transfers, developed by Johansen (1998). In this work Johansen proposed a basis for evaluating investment decisions for decreasing the longwall transfer period to minimize loss of production.

3.5 *Legislative cost implications*

Further to sound engineering design legislative constraints are imposed for a multitude of reasons. Sometimes it can be seen that these legislative requirements are in fact constraining the productivity and/or profitability of the operation. An example exists in the USA where it is legislated that the belt air cannot normally be used to ventilate a face and hence is used as a neutral roadway. This is discussed later but can be seen as an additional development and operating cost to the ventilation system.

An example in Queensland existed under the recently replaced regulation where intake air was not allowed to be routed past old workings. In this case it meant that a return roadway was placed along side the main seals of previously exhausted longwall panels, now sealed goaf's. In the case where a mine was extracting longwall panels on both sides of the Mains roadways the use of flanking returns or a sacrificial roadway was necessitated. With due consideration for the function this preformed by removing barometric behavior related gas contamination the additional expense incurred included additional stopping lines, balancing overcasts and the associated leakage. For some mines this may have been necessary to deal with large volume seal goaf areas but with the necessary monitoring and ventilation design this did not need to be an issue.

4 TRADITIONAL ECONOMIC EVALUATION METHODS

Traditional economic evaluation of ventilation systems has been confined to the stand alone assessment of shaft installations and number of roadways selection. Examples of these can be seen in most ventilation texts including Le Roux (1990), Lambrechts (1989), McPherson (1993) and Tien (1999). An applied example is provided by Krishna (1997). This analysis considers the air power operating cost in addition to the cost of developing that particular infrastructure item. These costs functions are identified and then the optimum selection is based on, for example, a graphical solution, as can be seen in Figure 1. The solution of capital and operating cost functions for a shaft installation can be found where the summation is at a minimum total cost.

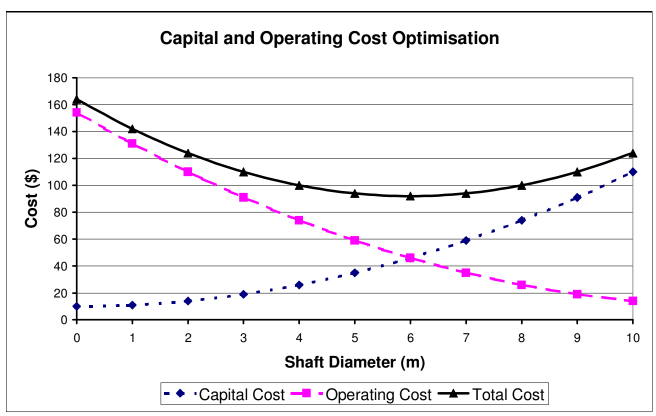

Figure 1. Theoretical example capital and operating cost function optimisation with minimum total cost indicating optimum selection of shaft diameter.

5 RISK CONSIDERATION

The uncertainty or risk associated with the processes of longwall ventilation is considered in a number of different ways as it pertains to the development of an economic basis for longwall ventilation design methodologies.

5.1 *Economic risk*

In constructing the economic basis for future modeling it is important to consider the methods for dealing with economic risk. This is considered a part of the methodology of investing in the mining industry and for dealing with uncertainty with aspects of the developed economic model. Uncertainty or risk and return form the basis for investment decision making processes. This can be dealt with in terms of setting higher hurdle rates for investments dealing with uncertainty. Economic risk is dealt with in detail in Runge (1998).

5.2 *Ventilation environment risk*

Risk also exists due to the hazardous nature of underground coal mine environments and the resulting interaction with induced ventilation. Ventilation systems are designed to fulfill a set of criteria to manage the inherent hazards present. This is to prevent the possibility existing where, for example, a spontaneous combustion event or explosible atmosphere exists.

In the longwall ventilation design methodology utilised it is proposed that the various designs being considered are evaluated according to the economic factors identified to produce a preferred ventilation design. The design is then assessed with respect to the ventilation environment risks present to identify whether the risk consideration of the hazards present are manageable in the ventilation design and management plan. If that particular design is not acceptable then the process is repeated in an iteration to consider the next most suitable design.

In the planning process limits are utilised to control the perceived hazards. These limits are based to a degree on sound engineering design and actual mining experience within that mine, set of conditions and/or particular seam and location. The best example of this is the restriction of pressure differential that is induced across ventilation appliances and through the actual mine (i.e. coal pillars, overburden, sealed goaf's) to prevent the possibility of a spontaneous combustion event occurring. When considering this hazard additional controls may be implemented such as rib injection to minimize leakage paths and hence oxygen transport. These controls are however less effective and reliable compared to engineering design to prevent a situation occurring as utilised in the typical risk minimization process and the implementation of controls.

Another strategy that can be adopted for the operation of longwall ventilation systems is the consideration of real time monitoring of all ventilation parameters and the control of ventilation appliances. Work being undertaken by Gillies et al. (2002) describes the use of monitoring technologies as part of the implementation of real time monitoring of the ventilation airflows within both metalliferous and coal mines. Previous work undertaken and international efforts in this area are referenced in this publication.

5.2.1 *Risk evaluation and management*

The fundamentals of risk evaluation and management are based on the closed loop process of hazard identification, risk assessment, development and implementation of procedures and monitoring the effectiveness of the developed procedures (Oberholzer, 1996). Various developed methods for dealing with risk evaluation and management exist and can be applied to the design iteration proposed after having selected the most attractive economic model developed and assessed.

6 MODELING

Based on the established economic considerations it is then possible to construct a model to include the different relationships present for each of the key elements present in the ventilation system. One of the most critical elements of such modeling is consideration for the life of each of the ventilation system components. That is, the scope of the ventilation model is important to the economic decision making process.

The opportunity exists to establish a methodology for assessing the entire ventilation system based on the economic factors identified. With the availability of software based ventilation simulations it is very easy to consider various variations within the ventilation system and compare the entire ventilation network solutions to establish the wider relationships. This augments the stand alone economic consideration already mentioned of shaft sizing and number of roadways selection by looking at a network based solution.

7 ALTERNATIVE VENTILATION METHODS

With an economic basis outlined it is then possible to extend the analysis of longwall ventilation designs to include consideration for alternative ventilation techniques that are not utilised currently in Australia. The assessment and discussion of these techniques draws on observations and comparisons of international longwall ventilation practice primarily from Europe and North America.

7.1 *Booster fans*

Booster fans have historically had little application in Australian underground coal mines and no use in recent times. The exception to this is the current installation at West Cliff Colliery located in the southern coalfields of the Sydney coal basin. In this case a booster fan has been installed in each of two headings in the Mains returns in parallel. This installation was justified on the basis of moving the longwall operations to a new district with set ventilation requirements over the life of the new district. The current ventilation system was unable to satisfy the future ventilation requirements and hence booster fans were considered and implemented (Benson, 2001).

At a point in the mines life where the main fans are operating close to their stall point or an unstable region of the operating curve several options must be considered to prolong the operation's life or provide the option to extend workings into new areas. This includes consideration of the ability to increase the duty of the main fan installation with an associated increase in power consumption, whether new main fans are required or use of additional ventilation infrastructure such as a new shaft or an increased number of roadways underground. Each of these options can be assessed in terms of required capital and operating revenues. At this point booster fans can be considered and have in reality been used to extend the life of longwall operations, as can be seen in the English longwall mining industry. An example of this is provided by Jobling et al (2001).

It should also be considered that the use of regulation in longwall operations represents significant additional cost to that required to actually satisfy ventilation requirements. Consider the following example adapted from Carruthers et al. (1993). The following assumed conditions exist in a longwall operation:

- Flow through the high resistance district 95m³/s
- Pressure loss in the high resistance district 1.37kPa
- Flow through other parallel circuits 142m³/s
- Pressure loss in the other parallel circuits if unrestricted 0.62kPa
- Artificial restriction 0.75kPa
- Pressure loss of the main intake and return airways 0.38kPa
- Surface fan duty with no booster fan 237m³/s@1.75kPa
- Total power requirement with all 237m³/s being artificially restricted and a fan efficiency of 75% 554kW

If a booster fan was installed in the high resistance path and the regulators in the low resistance paths were removed then the new fan duties and power requirements would be:

- Main fan - 237m³/s@1.0kPa = 313kW
- Booster fan - 95m³/s@0.75kPa = 94kW

The total being 407kW or a power saving of 147kW. Assuming a power cost of \$0.05/kWh this represents an annual power saving of approximately \$64,000. It can be seen that based on the operating costs that booster fan utilisation can result in power cost savings. At this point it is then necessary to consider the capital costs of the installation and the controls necessary to minimize induced risks such as local recirculation. Due to the more even pressure distribution within the ventilation system there may be a resultant increased level of overall safety through spontaneous combustion risk management. The savings identified would actually be increased due to reduced pressure differentials applied to ventilation appliances in the network and hence less leakage would be experienced.

It should also be recognized that with booster fan installations monitoring and control of each installation must be maintained at the surface and that the necessary operating procedures must exist including interlocking of all the mine fans. There also exists the need for site preparation to minimize the local recirculation hazard.

In the USA the use of booster fans is prohibited based on a fear that the operation of a booster fan installation could not be adequately controlled from outside the mine and could lead to abnormal recirculation conditions or other potential hazardous situations (Kennedy, 1999). It can be seen that with the use of available technologies booster fan installations have been operated in a controlled and safe manner, as can be seen in England, and that such legislative restrictions could force the closure of sub economic operations. The use of booster fans has far greater savings than those demonstrated in the above example if their use facilitates the continued operation of the longwall operation. These factors should be considered as part of a complete economic assessment of existing or proposed ventilation designs.

7.2 *Sub Mains roadways behind longwall*

Historically there has been some use of bleeder roadways in longwall ventilation design in Australia but this practice was discontinued due to the need to manage the possibility of spontaneous combustion within most Australian coal seams.

The greatest potential for Sub Mains utilisation is when used in conjunction with a back return system. An example of a back return system with upcasting return shaft in the Sub Mains as utilized in a generic ventilation district model can be seen in Figure 2. With increasing gas emissions from working faces at depth, the goaf and rib emissions are becoming more critical in the ventilation system design. To augment the return capabilities of the Mains roadways it is possible to consider the use of a back return shaft/raisebore. This is then an exercise involving economic consideration of pressure distribution and loads on existing infrastructure and costs associated with development of Sub Mains roadways, shaft/raisebores and possible additional fan installations. The advantages of such an inclusion can be seen to present an opportunity to more evenly distribute pressure differentials within the mine and in sealed areas. This solution can provide a more robust ventilation solution preventing possible downtime due to gassing out of working faces and general unsafe conditions.

The exception in bleeder ventilation in Australia is in two collieries in the southern coalfields of the Sydney coal basin in which a "Z" layout longwall ventilation approach has been utilised. In this case there has been a demonstrated history of no spontaneous combustion events in the high insitu gas content coal formation. The Sub Mains roadways are used to intentionally ventilate the goaf to induce a pressure differential to draw gas away from the longwall face. Again with reference to the cost of operational delays the cost of developing, ventilating and operating these Sub Main roadways can be analyzed in the system context.

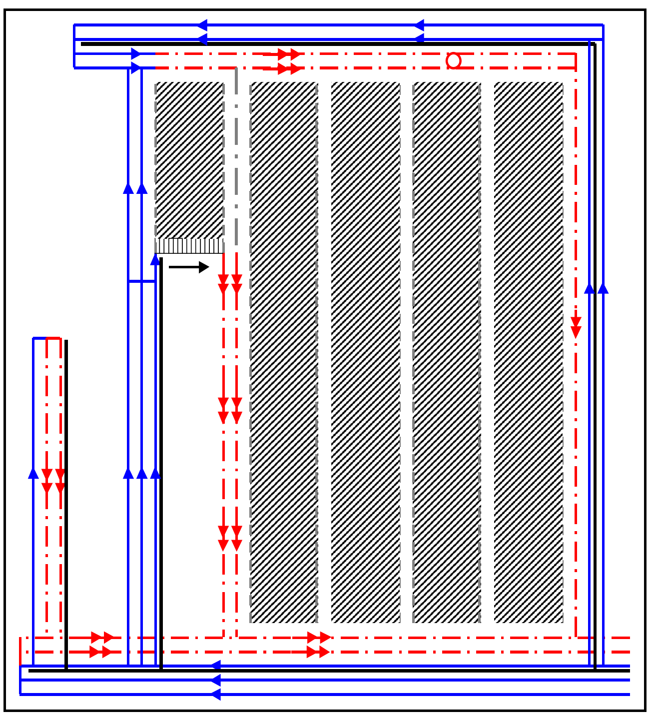

Figure 2. Generic longwall ventilation district model.

7.3 *Gateroad headings*

As already discussed there are examples of "number of roadways" selection derived from the summation of air power operating costs based on resistance calculations verses the cost of developing the roadways. International practices have seen European mines justifying single entry multiuse gateroads and Australian mines justifying two entry gateroads with a recent move to three entry gateroads for ventilation resistance reduction over extended gateroad lengths. In North America there is a regulatory minimum of three headings with the frequent use of additional entries.

Factors considered in determining the economic number of entries in general include regulatory requirements for neutral roadways (present in the USA), expected or observed degradation of roadway quality and hence the establishment of a time dependant resistance relationship and probably most importantly the life of the ventilation infrastructure. It can also be considered that using different development methods or equipment might allow some consideration for the dimensions of these roadways to be optimized. In this case there are certain fixed costs, such as the supply of services, semi-variable costs, such as required geotechnical support and variable costs, such as production related costs. To be considered also is the gateroad rate of advance given a set number of entries of a certain cross sectional area and associated development requirement.

Part of this assessment should include the consideration that longwall production is the lowest cost per tonne and that with an increased number of roadways more coal is sterilized in pillars and hence overall recovery of the resource is reduced.

An issue contradicting this analysis is, for example, the potential for legislation to stipulate minimum ventilation quantities required for diesel equipment operating in a particular roadway. Regulatory bodies in the USA are considering this requirement that would force the optimisation process to consider fewer roadways to increase quantities and hence operating cost.

8 EVALUATION

The evaluation of longwall ventilation networks can be separated into two distinct considerations. The first is of the actual ventilation network based on ventilation fundamentals. The second evaluation is of the economic assessment process and includes the criteria set and validation of the modeling process to provide a high level of confidence in the modeling results. These two aspects of evaluating the ventilation design process can be seen as complimentary as the goals are similar.

8.1 *Ventilation system evaluation*

When appraising a longwall ventilation system it has been proposed by Kennedy (1999) that the following aspects should be considered:

1 Assessing the pressure distribution and load on the main fans. The reasons for high pressure requirements of a mine is to overcome leakage or frictional resistance. To address leakage if more air is required then an increase in pressure will result in even more leakage. The problem of frictional impedance can be dealt with through design and/or maintenance. Again if more air is required the pressure increase will follow the square law resulting in less airflow increase than pressure increase.
2 Assessing the ratio of Mains to gateroad air course lengths. In this case the ventilation costs associated with the Mains development is constant where as the costs associated with gateroad developments are constantly changing and are only ventilated in their fully developed state for a fraction of gateroad life.
3 Assessing the load on the ventilation system as a result of barometric pressure changes. During a rapidly dropping barometric pressure change event the extent of sealed areas will "breath" out contaminating the airflow against the sealed areas.
4 Assessing the ratio of air available at the last open cut through to total air being moved by the fan. Ideally mines have achieved efficiencies of up to 80%. Where this efficiency is lower increases in airflow requirements again require a square law increase in pressure and cubed relationship increase in power demands and hence cost.
5 Assessing the quantity of ventilation required. This is a value arrived at from assessing the various functions of the ventilation system and the required ventilation and contaminant criteria set.
6 Assessment of the location and quantity of leakage present. Identification of the location of leakage should be undertaken with consideration for the oldest ventilation appliances having the largest pressure differentials applied. Identifying the quantity of leakage on a section by section basis can establish normal and abnormal condition parameters and assist with the assessment of leakage characteristics.

It can be seen that practically these assessment criteria can be used to judge the condition of a ventilation system. More importantly these aspects can be considered in the planning and design stages with due consideration for the economic implications and relationships that exist.

8.2 *Economic evaluation*

Based on the proposed modeling basis it is then necessary during the iterative design process to evaluate the economic criteria set and review the performance of the modeling solutions. This can be undertaken by modeling existing ventilation networks with varying levels of system complexity to compare predicted results with the observed real results. In this way a feedback loop can be closed to refine the economic modeling process.

This is important for the application of the developed economic model to hybrid ventilation systems incorporating alternatives not used currently in Australia. This is an important step despite these alternative practices being utilised internationally to evaluate these options in an Australian context. This may also lead to greater understanding of the application of these methods internationally.

The final step is the application of the developed economic model to ventilation systems that are not currently used. An example of which can be seen in Figure 3. In this way consideration of ventilation systems is possible with a degree of confidence in the predicted results.

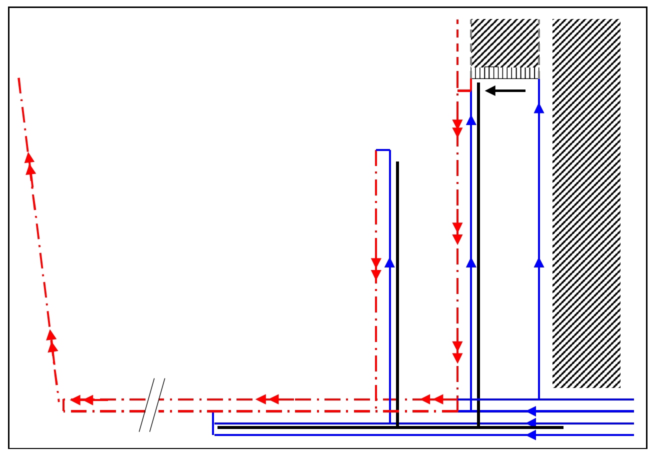

Figure 3. Alternative ventilation method utilizing flow through ventilation with returns and upcasting shaft predeveloped.

9 CONCLUSIONS

It can be seen that through the application of already established fundamental economic decision making tools that it is possible to establish the key aspects of all the components of a longwall ventilation system. In this economic context it is then possible to augment the planning process and provide a basis from which to optimize the ventilation designs constructed. The application of this work will directly benefit future endeavors to establish comprehensive ventilation system economic models that consider the many factors involved in ventilation design decisions.

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