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Rapid selection strategies for tunnel development auxiliary ventilation systems

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Abstract

Auxiliary ventilation system selection in tunnel development projects can be challenging depending on different site limitations, such as opening size and length, available power, environmental conditions, expected fleet, advance rates and equipment dimensions. This paper presents the technical and economic analysis study developed for various alternatives of auxiliary ventilation systems to support the development of mining tunnels. The represented variables are the different components of ventilation systems and five different tunnel drift cross-sections. The auxiliary ventilation system configurations considered in this study are in accordance with the legislated Chilean requirements, which are similar to Canadian regulations with regards to mining development. The methodology proposed in this paper consists of elaborate pre-calculated scenarios that allow a faster approach to the design of auxiliary ventilation systems in horizontal developments considering reduced cost of investment (CAPEX) and operations (OPEX) while complying with local regulations. The methodology used consisted of collecting the information available from the mine sites, and then a set of case studies for the calculations of the various parameters of the auxiliary ventilation systems. Technical and economic ranges are then estimated to select the ducting size, material roughness (friction or k factor) and geometrical parameters for the design of the mining tunnel auxiliary systems. This strategy provided ease and speed in the calculation and analysis of the costs associated with auxiliary ventilation systems, allowing for a faster convergence to a good solution when selecting a ventilation system for mining tunnel development.

Keywords: *auxiliary mine ventilation systems, rapid selection methodology, tunnel development*

1 Introduction

The problem targeted in this study is the lack of an adequate methodology to reduce the search range and pre-selection of auxiliary ventilation systems that are suitable for tunnel development within mining projects. The pre-selection of auxiliary ventilation systems must be supported by design criteria that are in accordance with the regulatory requirements of each country. This applies to any underground development, and to tunnel construction auxiliary ventilation systems.

It is common to find inadequate auxiliary ventilation systems with significant deficiencies that interfere with or delay mine development, and at the same time generate an increase in unnecessary energy usage. In addition, the installation of materials unsuitable for the construction of the auxiliary ventilation system also produces an increase in energy costs due to the fan oversizing that will most likely occur. Another consequence of the lack of clear design criteria and their proper implementation is reflected in excessive air leakage from the ducts, couplings, adapters and capping, creating sub-standard conditions in terms of the quantity and quality at the working face. This can then result in lower development rates due to longer blast clearance times and a poor environment for workers. Eventually, the sum of these issues results in unnecessarily high development costs and a failure to meet schedules.

Most of the literature identified for auxiliary ventilation systems has concentrated on advancing the understanding of such systems under different scenarios. This paper attempts to introduce a methodology to expedite the selection of auxiliary ventilation systems for different airflow requirements and duct conditions. A case study is presented to validate the proposed methodology.

2 Literature review

Auxiliary ventilation of tunnels have been studied by several authors, among them the work of Vutukuri (1984), who studies tunnel ventilation with the use of long-distance ducts and multiple series fan systems installed and spaced according to the system pressure drops. The objective of this study was to minimise leakage losses resulting from a high positive pressure generated by multiple fans at the entrance of the duct, by splitting the fans and their pressure input along the length of the duct. The study suggests evenly distributing the fans along the duct length and the fans pressure drop.

Other authors, such as Miller (1984), carried out studies into the calculation of correction factors for roughness in elbows using smooth wall pipes and the interference factors between elbow combinations in duct systems as a function of their turn radius and sharpness. McPherson (2009) stated that values of interference factors between elbows in series may be greater, or smaller, than the simple sum of two or more individual loss factors.

On the same research subject, Martinez and Contreras (1992) developed a computational analysis program to obtain the proper equipment selection for defined auxiliary ventilation systems in mining tunnel construction. Later, San Martín (2016) developed an analytical methodology for auxiliary ventilation system rapid selection applicable to under-construction tunnels.

In addition to the empirical relations made by Hartman (1982), Idelchik (1989) and Benedict (1980) established values for certain relations of flows, and circular and rectangular duct geometries. Miller (1984) conducted studies for various common-use geometries (tee and elbows), over a wide range of flow ratios and certain geometric relationships for circular ducts in two and three-way splits.

Hargreaves and Lowndes (2006) performed simulations using steady-state computational fluid dynamics (CFD) models to replicate the ventilation flow patterns seen on the tunnel fronts during the various stages of a mining cycle. The results of the simulations were compared with data obtained from a series of large-scale ventilation experiments carried out within a rapid development tunnel of a representative British coal mine. They concluded that CFD models can be used successfully to identify the ventilation characteristics associated with the various auxiliary ventilation systems during a cycle.

In subsequent years, Toraño et al. (2009) carried out studies in coal mines measuring the behaviour of airflows and methane concentrations, then modelling this behaviour in ventilated dead-ends headings with CFD. His study concluded that there may be some areas of the tunnel in which the methane concentration is higher than the regulation values. This was due to the airflow and methane behaviour in the tunnel, the presence of dead zones and the fact that only a portion of the airflow provided by the fan reaches the working face. Its contribution, using CFD modelling, provides an understanding as to in which areas of the tunnel it may be necessary to reinforce the forced ventilation by additional systems to prevent methane accumulation.

In his research, De Souza (2009) developed calculations for the preliminary design of ventilation in dead-end headings, obtaining ranges of flows and velocities required to ventilate different situations within tunnels.

As indicated earlier, most of the published research has concentrated on the modelling of auxiliary ventilation systems. This study concentrates on the development of a methodology that can profit from those results to propose the adequate auxiliary ventilation according to different development constraints.

3 Proposed methodology

A methodology is proposed that allows the prompt selection or an approximation of the auxiliary ventilation system based on the particular local parameters of each project. The output is variable depending on the geometry, geopolitics and economics of each installation. This methodology is split into a sequence of steps. Figure 1 presents a diagram with the methodology.

1. The first stage of the study consists of a collection of information corresponding to the ventilation study, including projects in current and recently built developments to provide technical and economic parameters used for ventilation system construction in local mines. The current local legal regulations that govern ventilation systems for underground mining and occupational health and safety are also considered (e.g. Chile in this instance).

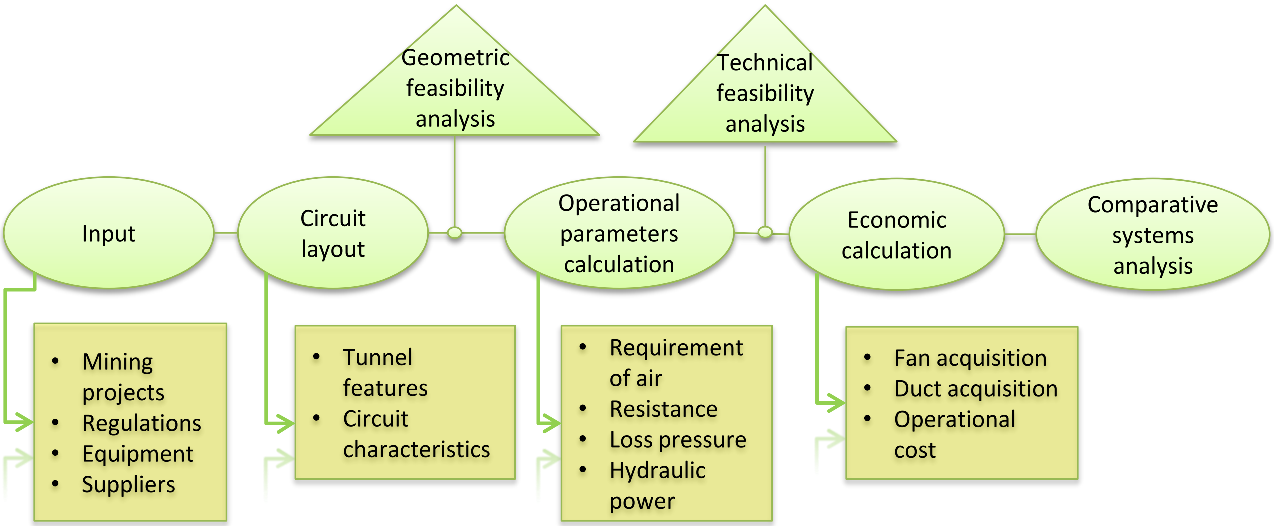

Figure 1 Study methodology

2. Perform a comparative analysis of the ducting characteristics provided by different suppliers, focusing mainly on the construction material, drift cross-section lengths and diameter sizes of the duct, roughness factor, types of fittings, and price. Figures 2 to 5 provide examples of ducts used for assessment in this study.

Figure 2 Oval duct installed

Figure 3 Smooth duct installed

Figure 4 Steel duct

Figure 5 Smooth duct (duo) installed

Three ducting materials were considered for the case study, namely rough duct, smooth duct, and metallic duct. The rough duct is made with a spiral-shaped reinforcement that covers the entire length of the duct. This product has more resistance to airflow than the smooth duct, but also the benefit of greater flexibility for the case of tunnel corners, and it deteriorates less over time. It has a friction factor of 0.011 kg/m^3. This duct can be used for systems with positive and negative internal pressures. The smooth duct has a friction factor of 0.0037 kg/m^3 and presents resistance to the rupture by expansion. This duct is used in systems with positive internal pressures. The metal duct is characterised by its high strength and rigidity, and it has the lowest friction factor (0.0021 kg/m^3). This type of duct is used for systems with positive and negative pressures. All three friction factors are according to McPherson (2009).

The auxiliary ventilation systems considered in this study are push, pull and forward systems. The push system is based on the injection of fresh air from the duct to the dead-end heading (positive pressure). Figure 6 presents the push ventilation system diagram.

Figure 6 Push auxiliary ventilation system

The pull system considers exhausting through the ducting from the dead-end heading, for which a negative pressure must be generated at the outlet of the duct where the fan is usually located. Figure 7 presents the pull ventilation diagram.

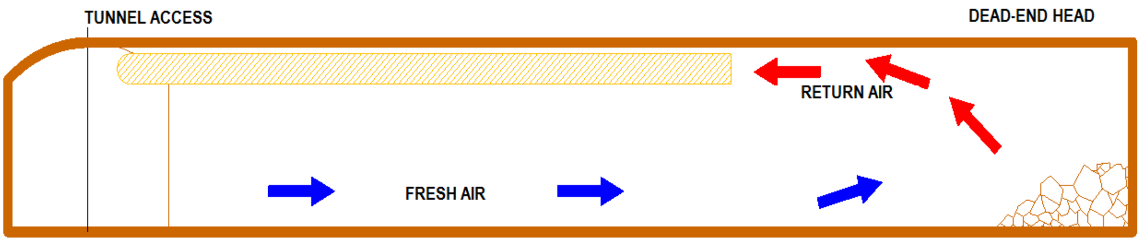

Figure 7 Pull auxiliary ventilation system

The forward system is a version of a pull system, consisting of the continuous displacement of the fan location that generates the differential pressure and flow, which will progressively advance in the direction of the developing front as the working face advances. Figure 8 shows the forward ventilation scheme.

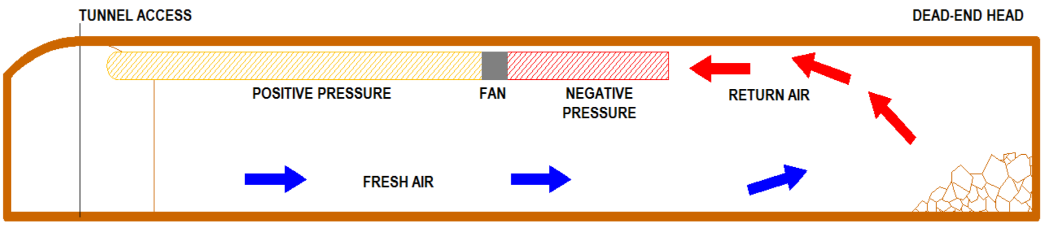

Figure 8 **Forward auxiliary ventilation system**

3. Review and select the different feasible types carried out for auxiliary ventilation systems suitable for the tunnel's construction. The geometrical characteristics of the tunnel and construction characteristics must be taken into account. Figures 9 and 10 are examples of tunnel designs including rock handling equipment and an auxiliary ventilation duct. In both instances, it can be observed that the minimum safety distance of 0.5 m between equipment and pipeline is respected, and is required to avoid equipment movement damaging the duct.

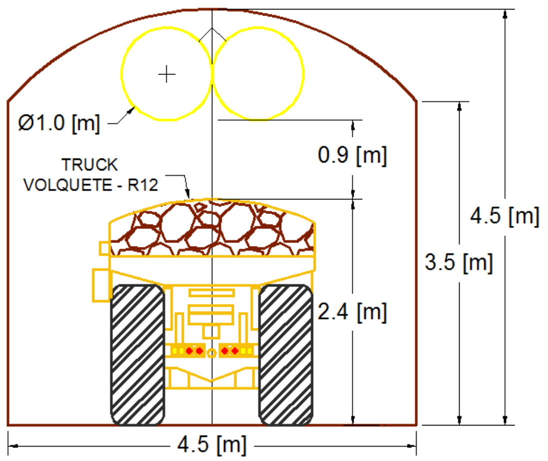

Figure 9 **Duo duct with 1 m diameter and drift cross-section of 4.5 × 4.5 m**

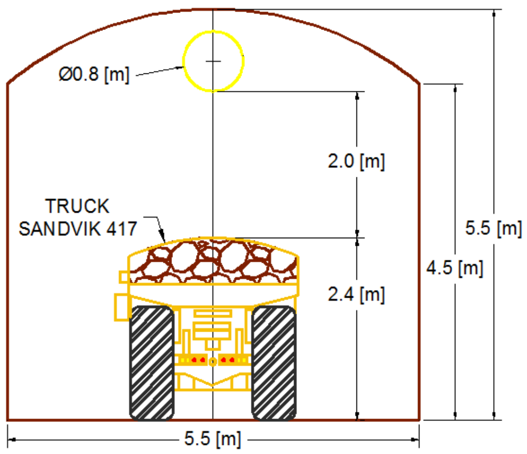

Figure 10 **Simple duct with 1 m diameter and drift cross-section of 5.5 × 5.5 m**

4. Perform an analysis of the technical feasibility of construction for the different proposed systems, including a critical review with respect to mine constructability factors (considering mining cycles, ground control constraints and mine designs, among others).

5. Determine the fresh air requirement according to the local regulations. In Chile, the law requires 2.83 m^3/min (100 cfm/BHP) of fresh air per brake horsepower of diesel equipment and 3 m^3/min for each individual in the exposed area.

6. The calculation of resistance and pressure drop of the system using Atkinson's equation is performed:

$$\Delta Pe = \frac{K\ L\ O\ Q^2}{A^3} \tag{1}$$

where:

K = Friction coefficient (kg/m^3).

L = Length of tunnel (m).

A = Duct area (m^2).

O = Duct perimeter (m).

Q = Mass flow (m^3/s).

7. The tunnel construction time is estimated by applying an average development rate of 150 m of advance every month. This is based on the work of Navarro and Vargas (2012), which analysed dozens of mining projects.
8. The pressure drop generated by the shock losses in the ventilation pipe considers losses due to duct entry, duct exit, adapters, elbows and curves, and is developed as follows:

$$\Delta Px = \frac{X \rho v^2}{2} \quad (2)$$

where:

X = Shock loss factor.

v = Air velocity.

ρ = Air density (1.2 kg/m^3 is used for this investigation).

9. Calculation of total air power loss for the duct. For purposes of economic calculations, a motor efficiency of 90% is assumed, which allows the estimation of electric power and energy consumed through time.
10. Analysis of the economic variables included in the study for the mining auxiliary ventilation systems, such as construction costs and operating costs. The cost of auxiliary ventilation for the tunnel construction is given by:
    a. Fan supply cost.
    b. Flexible duct, elbows, regulators and adapters supply costs.
    c. Installation cost.
    d. Maintenance cost.
    e. Energy cost.

The supply cost for the ventilation equipment is calculated from the cost projected by the fan suppliers, plus an installation cost based on the power of the fan. The supply and installation cost is estimated at USD 239.40 for each kW of installed power.

The supply, installation and maintenance cost of the duct line will be the product of the duct length (m) and the linear cost (USD/m) depending on the type of pipeline used. The combined cost of duct is determined from a local market analysis of suppliers and is shown in Figure 11. The simple duct term is used in Chile to reference what might also be known as the single duct in other regions. In a similar way the duo term for duct may also be known as dual duct.

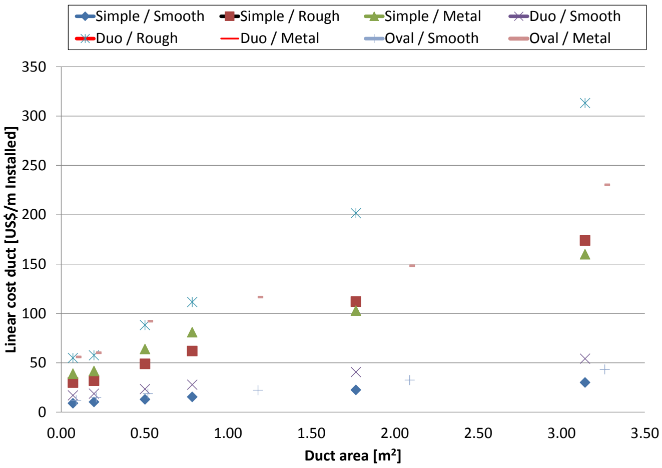

Figure 11 Duct lineal cost per duct area

The comparative analysis of the different methods is carried out from an economic and technical point of view (construction feasibility). In particular, the feasibility analysis, in a simple way, reduced the number of case studies for the later economic evaluation of the systems. It is worth mentioning that the reduction process limited the number of cases for study from 450 initially, to the 103 final cases to be analysed. Figure 12 shows the result of the feasibility analysis, where the grey cells are those systems that are not geometrically feasible, the red cells represent the auxiliary ventilation systems that are not technically feasible, and the remaining green cells represent the systems that are feasible to construct.

The technical feasibility analysis discards those auxiliary ventilation systems that have a pressure loss greater than 15,000 Pa (three fans in series with a pressure drop of 5,000 Pa each). This is due to auxiliary fan and power availability limitations.

Circuit				Section					Circuit				Section				
Type	Material	System	Ø	3.5×3.0	3.8×3.8	4.5×4.5	5.5×5.5	6.5×6.5	Type	Material	System	Ø	3.5×3.0	3.8×3.8	4.5×4.5	5.5×5.5	6.5×6.5
Simple	Smooth	Push	0,3						Duo	Smooth	Forward	1,0					
Simple	Smooth	Push	0,5						Duo	Smooth	Forward	1,5					
Simple	Smooth	Push	0,8						Duo	Smooth	Forward	2,0					
Simple	Smooth	Push	1,0						Duo	Rough	Push	0,3					
Simple	Smooth	Push	1,5						Duo	Rough	Push	0,5					
Simple	Smooth	Push	2,0						Duo	Rough	Push	0,8					
Simple	Smooth	Forward	0,3						Duo	Rough	Push	1,0					
Simple	Smooth	Forward	0,5						Duo	Rough	Push	1,5					
Simple	Smooth	Forward	0,8						Duo	Rough	Push	2,0					
Simple	Smooth	Forward	1,0						Duo	Rough	Pull	0,3					
Simple	Smooth	Forward	1,5						Duo	Rough	Pull	0,5					
Simple	Smooth	Forward	2,0						Duo	Rough	Pull	0,8					
Simple	Rough	Push	0,3						Duo	Rough	Pull	1,0					
Simple	Rough	Push	0,5						Duo	Rough	Pull	1,5					
Simple	Rough	Push	0,8						Duo	Rough	Pull	2,0					
Simple	Rough	Push	1,0						Duo	Metal	Push	0,3					
Simple	Rough	Push	1,5						Duo	Metal	Push	0,5					
Simple	Rough	Push	2,0						Duo	Metal	Push	0,8					
Simple	Rough	Pull	0,3						Duo	Metal	Push	1,0					
Simple	Rough	Pull	0,5						Duo	Metal	Push	1,5					
Simple	Rough	Pull	0,8						Duo	Metal	Push	2,0					
Simple	Rough	Pull	1,0						Duo	Metal	Pull	0,3					
Simple	Rough	Pull	1,5						Duo	Metal	Pull	0,5					
Simple	Rough	Pull	2,0						Duo	Metal	Pull	0,8					
Simple	Metal	Push	0,3						Duo	Metal	Pull	1,0					
Simple	Metal	Push	0,5						Duo	Metal	Pull	1,5					
Simple	Metal	Push	0,8						Duo	Metal	Pull	2,0					
Simple	Metal	Push	1,0						Oval	Smooth	Push	0,4 × 0,3					
Simple	Metal	Push	1,5						Oval	Smooth	Push	0,6 × 0,4					
Simple	Metal	Push	2,0						Oval	Smooth	Push	1,0 × 0,6					
Simple	Metal	Pull	0,3						Oval	Smooth	Push	1,5 × 0,9					
Simple	Metal	Pull	0,5						Oval	Smooth	Push	2,0 × 1,2					
Simple	Metal	Pull	0,8						Oval	Smooth	Push	2,5 × 1,5					
Simple	Metal	Pull	1,0						Oval	Metal	Push	0,4 × 0,3					
Simple	Metal	Pull	1,5						Oval	Metal	Push	0,6 × 0,4					
Simple	Metal	Pull	2,0						Oval	Metal	Push	1,0 × 0,6					
Duo	Smooth	Push	0,3						Oval	Metal	Push	1,5 × 0,9					
Duo	Smooth	Push	0,5						Oval	Metal	Push	2,0 × 1,2					
Duo	Smooth	Push	0,8						Oval	Metal	Push	2,5 × 1,5					
Duo	Smooth	Push	1,0						Oval	Metal	Pull	0,4 × 0,3					
Duo	Smooth	Push	1,5						Oval	Metal	Pull	0,6 × 0,4					
Duo	Smooth	Push	2,0						Oval	Metal	Pull	1,0 × 0,6					
Duo	Smooth	Forward	0,3						Oval	Metal	Pull	1,5 × 0,9					
Duo	Smooth	Forward	0,5						Oval	Metal	Pull	2,0 × 1,2					
Duo	Smooth	Forward	0,8						Oval	Metal	Pull	2,5 × 1,5					

Figure 12 Feasibility analysis results. The grey cells are those auxiliary ventilation systems that are not geometrically feasible, the red cells represent the auxiliary ventilation systems that are not technically feasible and the green cells represent the auxiliary ventilation systems that are feasible to construct (drift cross-section and ϕ (diameter) units are metres)

4 Results

4.1 General values per drift cross-section

For the drift section dimensions that have been used, and the partial and total costs considered, it has been possible to produce Figure 13. It shows the more convenient ventilation systems according to the dimensions of the drift, in terms of cost per metre of development. From this figure, several important observations can be obtained, such as:

- In small dimension drifts, energy costs are high, but these decrease as the drift cross-section increases. This is due to the pressure that must be supplied to overcome the load losses in smaller duct areas.
- The bigger drift dimensions increase the cost of ducts significantly, due to the increase of the drift cross-sectional area that has to be accommodated.
- The cost of the fan to supply a specific volume tends to decrease in the larger sized drifts. The reason for this is the larger duct that has to be accommodated, and the lower working pressures that are required for the fans.
- Finally, the total cost tends to decrease with larger ducting or lower airflow volumes, which indicates that power is a dominant factor. However, depending on the time frame considered, it may or may not be the most dominant one compared to the other costs, in particular the duct cost.

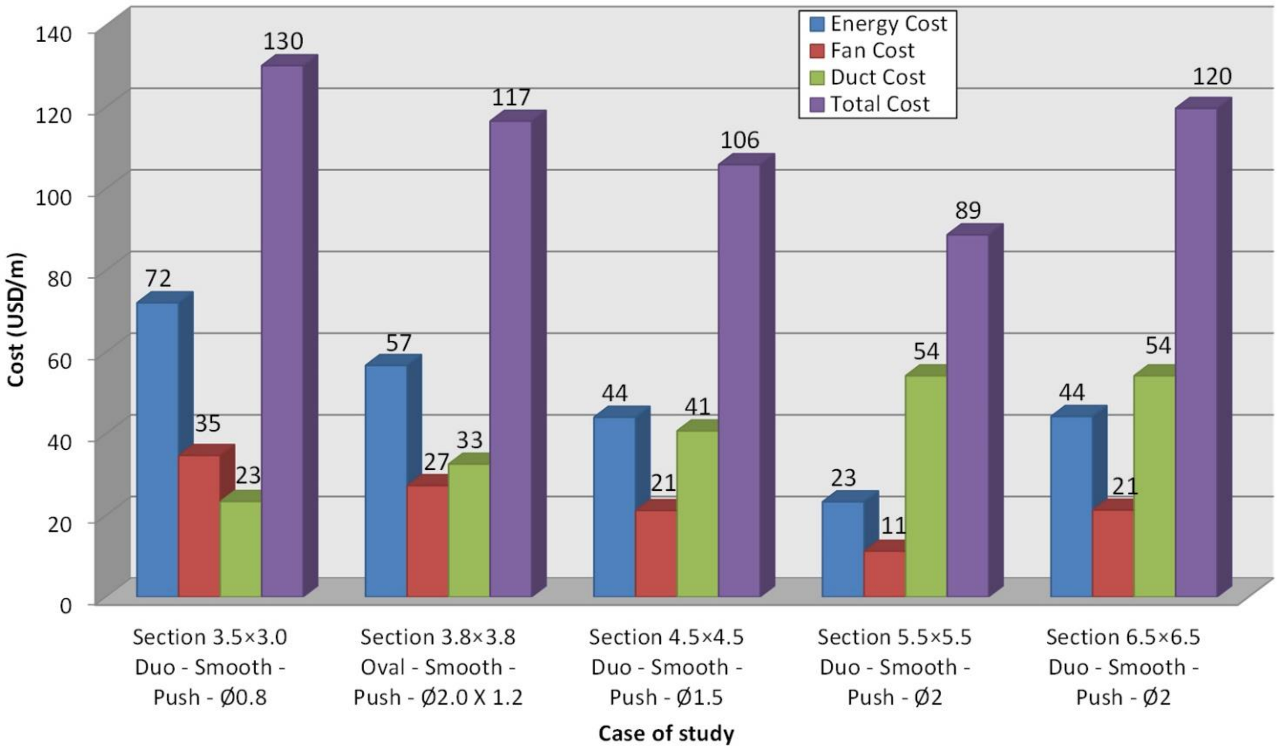

Figure 13 Cost summary for most favourable cases per drift cross-section

The calculation of the power requirements for the different constructible system options indicates that the ducts that have the largest open area (diameter or cross-section) are those that present the lowest energy consumption for the system. These are typically the single duct systems, followed by the oval options, and lastly, the dual systems. Additionally, the type of material plays a direct role in the results of this item.

4.2 Case study

To demonstrate the methodology a case study was developed. The scenario considered consists of:

- Drift dimensions, width and height: 4.5 × 4.5 m.
- Ground support: rock bolts and welded mesh.
- Tunnel length: 1,000 m.

The equipment used for the construction is a 250 HP (186 kW) diesel scoop (load–haul–dump unit), a 300 HP (224 kW) diesel truck, an electrical lifting unit with an electric motor and electric scaling equipment.

- Personnel working in parallel: 10 workers.
- Number of days to finalise the work: 200 days (two shifts, 12 hours each).

The results of the calculation for the case study are summarised in Tables 1 to 5.

Table 1 Tunnel and duct geometric parameters

Geometric parameters				
ID	**Area (m^2)**	**Perimeter (m)**	**K (kg/m^3)**	**Length (m)**
Drift	18.85	15.57	0.0121	1,000
Duo duct	1.77 (each)	4.71 (each)	0.0037	1,000

Table 2 Required airflow volume

Airflow requirements	
ID	**Airflow (m^3/s)**
Airflow requirements	33.0
Leakage	7.5
Total airflow	40.1

Table 3 Tunnel and duct calculated resistances result

Resistance				
ID	**Wall (Ns^2/m^8)**	**Shock (Ns^2/m^8)**	**Total (Ns^2/m^8)**	**Unit (Ns^2/m^8)**
Drift	0.028	0.003	0.031	0.000
Duo duct	0.783	0.078	0.861	0.086
Total			0.892	0.089

Table 4 Calculated fan operational point

Operational point			
Airflow (m^3/s)	**Pressure (Pa)**	**Power (kW)**	
		Airflow	**Electric**
40.1	1,434	58	98

Table 5 Auxiliary ventilation cost summary

Costs summary		
Item	**Total cost (USD)**	**Unit cost (USD/m)**
Fan supply	21,183	21.2
Duct supply	40,680	40.7
CAPEX	61,863	61.9
Energy	44,027	44.0
OPEX	44,027	44.0
Project total (ventilation)	105,890	105.9

Figure 14 presents the comparison graphic resulting from the costs presented in Table 5. The result of the resistance calculation for the different auxiliary ventilation systems shows similar tendencies for those cases in which the same type of material is used. This is because the drift cross-section generates a negligible resistance compared to the resistance of the auxiliary ventilation ducts.

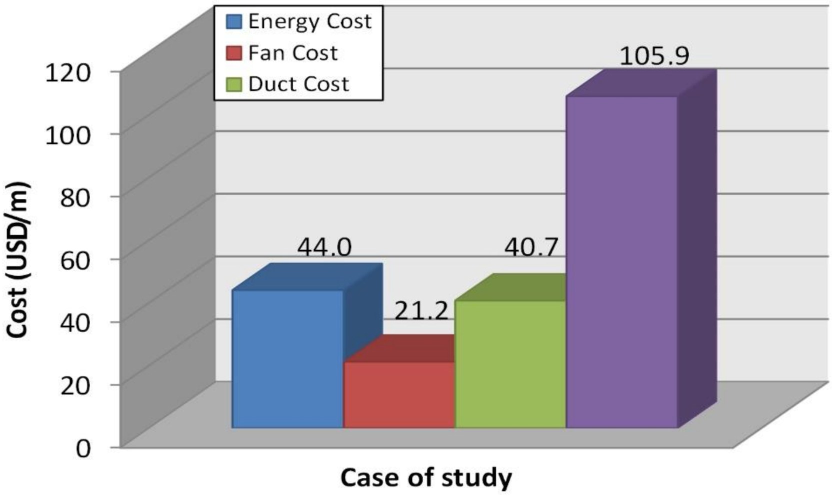

Figure 14 Case study cost summary

5 Conclusion

This study suggests a practical methodology for the rapid selection of auxiliary ventilation systems for tunnel construction. The methodology first helps to quickly reduce the universe of alternatives available after looking at all the practical constraints, such as electrical power available, fan sizes, duct sizes, and drift size, and then allows one to define the most economical alternative based on the cost structure.

The development of a case study was used to successfully demonstrate the applicability of the proposed methodology. As expected, the methodology confirmed well-known results such as larger dimension tunnel and duct sections having lower energy and fan supply cost for the same airflow requirement, due to the feasibility of installing a duct of larger area.

The duct material also plays an important role in the energy consumption, however, less important than the drift cross-section, but also linear proportion. The most relevant conclusion is that even if the duct cost tends to increase with larger drift cross-sections, as larger ducting can be properly fitted in the drift cross-section, the overall cost still tends to decrease. Even if this result might appear to be obvious, it is not necessarily the case depending on the duct cost structure and when considering shorter time span. This last conclusion is not necessarily intuitive, and emphasises the importance of a well-sized opening for the equipment, and the ventilation duct to be used in each development.

Further work is required to assess the impact of incorporating the cost of developing different drift cross-section sizes coupled with the proposed methodology as the ventilation cost for development might not be significant enough to unbalance the results of the also well-known economical drift cross-section analysis to define drift cross-sections. Using this methodology, the selection of the economical auxiliary ventilation system to be used for the case study was quicker than when not using the methodology. It also helped to ensure that only feasible solutions were considered, and to ensure that the most relevant alternatives were reviewed and compared.

Acknowledgement

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