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DEVELOPING A NEW HYBRID MCDM METHOD FOR SELECTION OF THE OPTIMAL ALTERNATIVE OF MECHANICAL LONGITUDINAL VENTILATION OF TUNNEL POLLUTANTS DURING AUTOMOBILE ACCIDENTS

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Abstract. Breathable air inside the tunnel is an undeniable necessity and beside natural ventilation, the tunnel should be reliably organized, to automatically provide healthy air under different conditions. Among methods of tunnel ventilation, longitudinal and transverse modes are the most common mechanical methods. This research is focused on selection of the optimal method for mechanical longitudinal ventilation of tunnel pollutants from four presented models. In terms of this research, the authors used SWARA (*Step-wise Weight Assessment Ratio Analysis*) as one of the most versatile MCDM (*Multiple-Criteria Decision-Making*) methods for managerial decision making in complex situations with multiple and varied measures. Fourteen experts of different fields were involved. The research model was established based on expert ideas and the following criteria: smoke control (C_1), safety level (C_2), design complexity (C_3), investment costs (C_4), increasing concentration of pollutants until portal (C_5), smoke laden section (C_6) and simultaneous evacuation and fire fighting (C_7). SWARA method was applied to evaluate criteria while VIKOR (*VlseKriterijumska Optimizacija I Kompromisno Resenje*) method was used to evaluate and rank four alternatives of this research, namely: 1) jet fans with spot extraction by axial fans (A_1); 2) axial fans with Saccardo nozzle (A_2); 3) jet fans with shaft axial fans (A_3); 4) jet fans only (A_4). Final results illustrate that jet fans with spot extraction by axial fans is the best choice. Finally, the authors believe that this new hybrid model of MCDM methods can be useful as a new framework in different fields of research.

Keywords: roadway tunnel, longitudinal ventilation, pollutant discharge, vehicle, Step-wise Weight Assessment Ratio Analysis (SWARA), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Multiple-Criteria Decision-Making (MCDM).

Introduction

Tunnel ventilation – [evacuation of] air in digging or in exploiting – is one of the most important issues in tunnel introduction (Kurioka *et al.* 2003). In long tunnels, in which mechanical digging technology is used, ventilation is more important and sensitive and requires more sophisticated studies. A ventilation method must be determined to create a safe environment in a tunnel and, moreover, to secure breathable environment, especially in critical and climatic modes, such as: vehicle dysfunction, accidents, fires, ventilation incapacitation and electricity slack. Tunnel ventilation can be natural or mechanical (longitudinal, transverse, semi-transverse and two head half transverse) (Chow 1998; Carvel *et al.* 2001a; Atkinson, Wu 1996). Natural ventilation is used in tunnels which have a limited length between 250÷800 metres (depending on traffic intensity, number of lanes in each direction and other conditions) (Kurioka *et al.* 2003).

Various tunnel ventilation methods exist and longitudinal ventilation system is among the most popular ones (Li, Chow 2003). Different types of this system are described by the Company (Witt&Sohn 2011) that produces ventilation systems and techniques. The longitudinal ventilation system creates the longitudinal air flow as fresh air enters and smog air exits from limited holes within the tunnel. This system is the most effective method for one way traffic tunnels (Beard, Carvel 2011; Colella *et al.* 2009).

Experimental models such as wind tunnel were initially used to analyze air flow in tunnels. However, in order to determine the optimal method for discharging pollutants, the simulation and modelling methods in computational fluid dynamics (CFD) software were used in the analysis of air flow containing particles (Li, Chow 2003; Lai *et al.* 2003; Gehrke *et al.* 2003), which initially are mostly intended for fires in tunnels (Carvel *et al.* 2001b; Modic 2003, Casalé 2003). This alternative, which is based on one or two models, has been researched by many authors, including Sigl and Rieker (2000), Waterson and Lavedrine (2003), Gao *et al.* (2004), Ballesteros-Tajadura *et al.* (2006). Another method is based on economic estimates to justify the investment costs, which are mostly substantial. This method is time-consuming; besides, in terms of longitudinal ventilation of a tunnel, it considers some limited numbers of effective indexes.

To determine the optimal ventilation system that could be used in case of a traffic accident, some indexes could be derived to compare different methods. To determine these indexes, applicable secondary incidental elements, such as reduction of visibility and breathable air, should be analyzed (Yuan, You 2007). It should be considered that inability to control and discharge smoke may result in reduction of visibility for drivers and rescue workers as well as harden the breathing of people inside such tunnels (Atkinson, Wu 1996). Therefore, more research is required in terms of each element when selecting the optimal method.

The purpose of this research is to identify criteria that are significant in terms of mechanical longitudinal ventilation of tunnel pollutants and to select the best option from available mechanical alternatives.

To identify and evaluate more effective criteria, the authors used the *Step-wise Weight Assessment Ratio Analysis* (SWARA). Meanwhile, *VlseKriterijumska Optimizacija I Kompromisno Resenje* (VIKOR) was applied to evaluate alternatives and rank them.

This new methodology, which is based on SWARA and VIKOR, can be useful as a new framework for demanding decision making cases.

1. Introducing Types of Mechanical Longitudinal Ventilation of Tunnel Pollutants

1.1. Mechanical Longitudinal Ventilation Methods in Tunnels

Based on existing studies and regulations effectual in different countries, such as USA and France, four common methods of mechanical longitudinal ventilation systems for tunnels are presented in order to compare and select the most optimal alternative. These methods are: jet fan with longitudinal discharge with central fans, jet fan with shaft vertical fans, central fans with Saccardo nozzle and jet fan without additional systems (Witt&Sohn 2011). These methods are discussed below.

1.2. Jet Fans with Shaft Axial Fans

Whenever possible to dig shafts in the roof of a tunnel, it may be possible to install jet fans to direct pollution and to install a central fan in shafts (Fig. 1) to supply fresh air into the tunnel and extract polluted air from the tunnel. This method is used in tunnels with shaft digging possibility (Lai *et al.* 2003).

1.3. Axial Fans with Saccardo Nozzle

Saccardo nozzle is responsible for fast injection of air into a tunnel (Fig. 2). Usually, such injection is per-

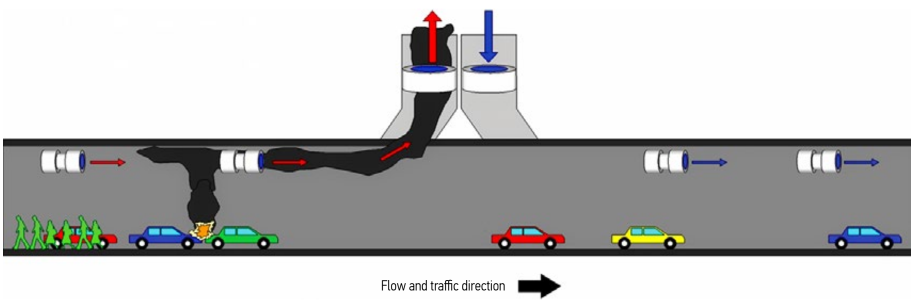

Fig. 1. Operating jet fans and central shaft fans

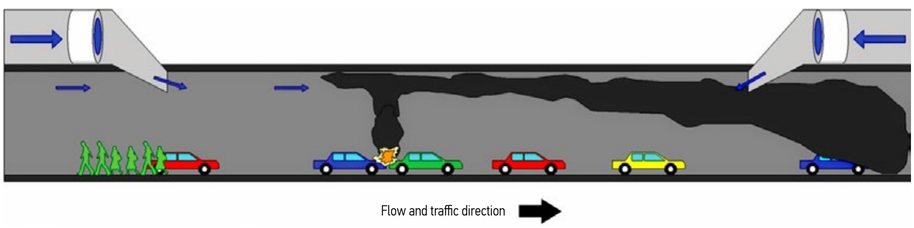

Fig. 2. Operating central fans equipped with Saccadro nozzle

formed based on traffic direction. The discharge action is usually performed with a very close angle to tunnel axis to create proper longitudinal air movement.

1.4. Jet Fans with Spot Extraction by Axial Fans

This method is flexible to change the direction of air intake and discharge. This is useful both in normal conditions and during traffic accidents. The description of method application is described below (Fig. 3):

- ***Normal mode:*** only longitudinal jet fans are operational in ventilating air pollutants that result from vehicle combustion; it has the same application as jet fans of the jet fans only alternative (without the system).
- ***Crisis mode:*** as presented in Fig. 3, during accidents, the operation of the ventilation system changes as longitudinal jet fans become responsible for change of the intake and blowing the smoke from a traffic accident to the closest inlet in order to lead the smoke to the discharge channel and out to the open environment (Witt&Sohn 2011; Buchman 2006; NCHRP 2006).

1.5. Jet Fans Only

Several pairs of jet fans installed at a specified distance, which is determined by the designer of the method, move all of the required air inside a tunnel longitudinally at a constant velocity. This creates an air flow inside a tunnel, which helps to lead pollution outwards. Jet fans (Fig. 4) create an ejection stream, i.e. the first jet fan intakes air to pass it into the next jet fan and this way all along the entire tunnel. This intake and discharge action inside a tunnel is continuously performed by jet fans mounted at specified distances on the ceiling or sides of the tunnel, which causes the air flow and finally discharges tunnel air pollution (Witt&Sohn 2011; Lai *et al.* 2003; NCHRP 2006).

2. Advantages and Disadvantages of Each Method

The advantages and disadvantages of each method as well as experts opinions are offered in Tables 1–4.

Table 1. Jet fans with spot extraction by axial fans (A_1)

Advantages	Disadvantages
• Capacity to concentrate discharge at the location of fire; • Simultaneous Evacuation and Fire Fighting or SEFF; • Excellent smoke control on port; • Highest safety level	• High investment costs; • Complex design; • Increasing concentration of pollutants

Table 2. Axial fans with Saccardo nozzle (A_2)

Advantages	Disadvantages
• Excellent smoke control (no smoke outside the fire source); • Average safety level	• High investment costs; • Complex design; • Increasing pollutant concentration up to the port; • Tunnel gets filled with smoke; • Requires room to inverse air flow

Table 3. Jet fans with shaft axial fans (A_3)

Advantages	Disadvantages
• Increasing concentration decreases before the port (50%); • Sections in full smoke (50%); • Excellent smoke control (50%), tunnel discharged of smoke; • Highest safety level	• High investment costs; • Complex design

Table 4. Jet fans only (A_4)

Advantages	Disadvantages
• Excellent smoke control; • (no smoke outside the fire source); • Average safety level; • Low investment costs; • Simple design	• Increasing pollutant concentration up to the port; • Tunnel gets filled with smoke

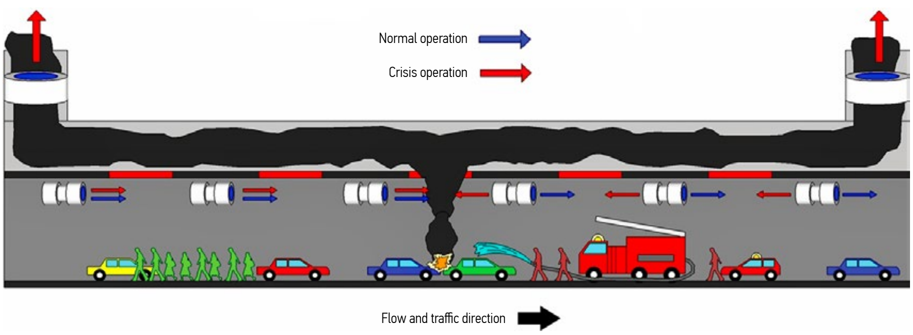

Fig. 3. Longitudinal discharge jet fans with central fans operating in crisis and under normal conditions

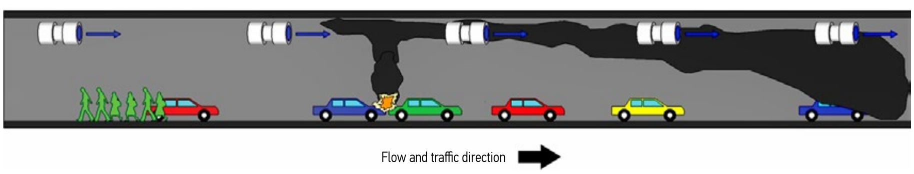

Fig. 4. Operation of jet fans only

3. Determining effective indexes for selection

Effective indexes for selection of the best alternative were identified during interviews with experts of the field. To increase accuracy, criteria or decision-making measures consisted of safety, economical and feasibility properties as presented in Table 5. If more information is available, more and better criteria can be chosen. However, to implement this method, the following steps must be taken.

Table 5. Important indexes for evaluation of different longitudinal ventilation methods used in tunnels

	Important indexes for evaluation of different longitudinal ventilation methods used in tunnels
C_1	Smoke control (SC)
C_2	Safety level (SL)
C_3	Design complexity (DC)
C_4	Investment costs (IC)
C_5	Increasing Concentration of Pollutants until Portal (ICPP)
C_6	Smoke Laden Section (SLS)
C_7	Simultaneous Evacuation and Fire Fighting (SEFF)

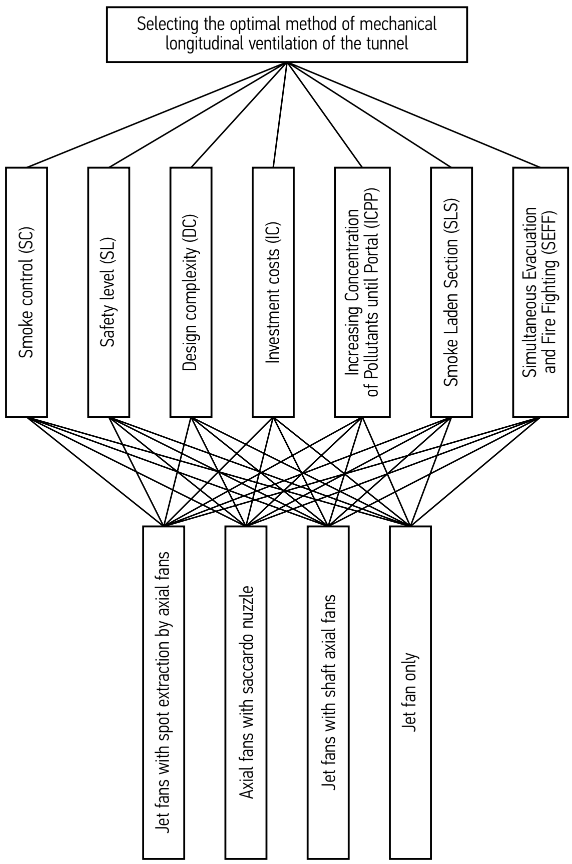

Fig. 5. Graphically represented selection of the optimal mechanical longitudinal ventilation method

Expert Information. The first step of the research involved the most experienced road construction managers and a group of experts in civil engineering, construction management and technology, and economy to determine seven important criteria for evaluation of different longitudinal ventilation methods used in tunnels, which are listed in Table 5. Information on experts is provided Table 6. Ideas suggested by experts were compared during the process of research.

The hierarchical tree is the graphical representation of the problem (purposes, measures and alternative options) is presented in Fig. 5.

Table 6. Background information of experts

Groups	Items	No	Groups	Items	No
1) Civil Engineering	Bachelor	0	3) Construction Management and Technology	Bachelor	0
	Master	4		Master	1
	Ph.D.	2		Ph.D.	1
2) Economic Experts	Bachelor	0	4) Top Managers	Bachelor	0
	Master	0		Master	3
	Ph.D.	2		Ph.D.	1

4. Methodology

4.1. A Step-Wise Weight Assessment Ratio Analysis (SWARA) Method

Various approaches can be used to assess weights (Zavadskas *et al.* 2010a, 2010b), e.g. the eigenvector method, SWARA (Keršulienė *et al.* 2010), expert method (Zavadskas, Vilutienė 2006), analytic hierarchy process (AHP) (Saaty 1977, 1980), FARE (Ginevičius 2011), Entropy method, and etc. (Keršulienė, Turskis 2011).

In SWARA method, each expert first of all prioritizes and ranks criteria. The most significant criterion is ranked first, and the least significant criterion is ranked last. The overall ranks of the entire group of experts are determined according to the average value of ranks (Keršulienė, Turskis 2011). The step-wise weight assessment ratio analysis (SWARA) (Keršulienė *et al.* 2010) methodology was developed in 2010. This methodology was applied for the selection of rational dispute resolution (Keršulienė, Turskis 2011). The procedure for determination of criteria weights is presented in Fig. 6.

The main feature of the SWARA method is the possibility to estimate opinions of experts or stakeholder groups regarding the significance ratio of the criteria in the process of their weight determination (Keršulienė *et al.* 2010). This method is useful for coordinating and gathering data from experts. The use of SWARA is uncomplicated and experts of various fields can easily understand the general idea.

The following decision-making models were developed based on SWARA method – Keršulienė *et al.* (2010) in selection of rational dispute resolution method, Keršulienė and Turskis (2011) for architect selection.

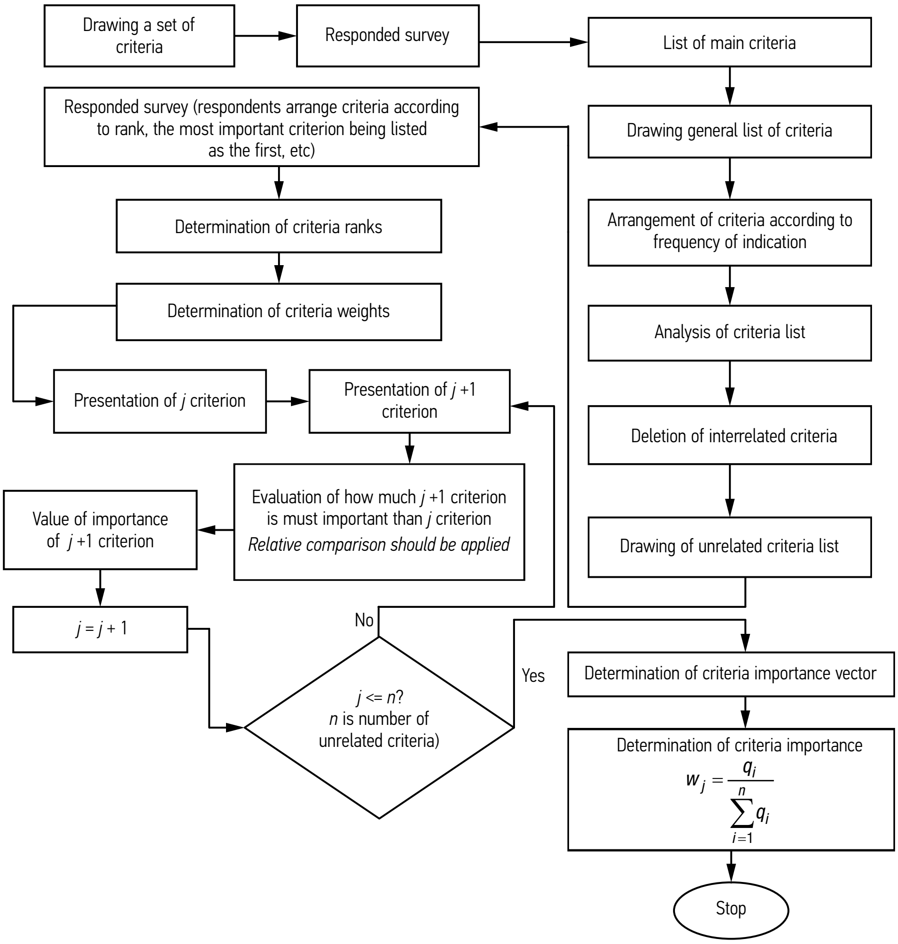

Fig 6. Determining the criteria weights based on (Keršulienė, Turskis 2011)

4.2. VIKOR Method

4.2.1. Introduction to VIKOR

The VIKOR method is a compromised MADM method, developed by Opricovic and Tzeng (2002) started from the form of L_p-metric:

$$L_{pi} = \left(\sum_{j=1}^{n} \left(w_j \frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right)^p \right)^{(1/p)} ; \quad (1)$$

$$1 \le p \le +\infty ;$$

$$i = 1, 2, ..., i .$$

The VIKOR method can provide a maximum 'group utility' for the 'majority' and a minimum of an individual regret for the 'opponent' (Opricovic, Tzeng 2002, 2004).

4.2.2. VIKOR steps

1) ***Calculate the normalized value:***

$$f_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{n} x_{ij}^2}} ; \; i = 1, 2, ..., m ; \; j = 1, 2, ..., n . \quad (2)$$

2) ***Determine the best and worst values:***

For all the attribute functions the best value was f_j^+ and the worst value was f_j^- that is, for attribute j = 1 – n, we get formulas (3) and (4):

$$f_j^+ = \max f_{ij} ; \; i = 1, 2, ..., m; \quad (3)$$

$$f_j^- = \min f_{ij} ; \; i = 1, 2, ..., m, \quad (4)$$

where: f_j^+ is the positive ideal solution for the j-th criteria; f_j^- is the negative ideal solution for the j-th criteria. If one associates all f_j^+ one will have the optimal combination, which gets the highest scores, the same as f_j^-.

3) ***Determine the weights of attributes:***

The weights of attributes should be calculated to express their relative importance.

4) ***Compute the distance of alternatives to ideal solution:***

This step is to calculate the distance from each alternative to the positive ideal solution and then get the sum to obtain the final value according to formula (5) and (6):

$$S_i = \sum_{j=1}^{n} w_j \frac{f_j^+ - f_{ij}}{f_j^+ - f_j^-} ; \quad (5)$$

$$R_i = \max\left(w_j \frac{f_j^+ - f_{ij}}{f_j^+ - f_j^-} \right), \quad (6)$$

where: S_i represents the distance rate of the ith alternative to the positive ideal solution (best combination); R_i represents the distance rate of the i-th alternative to the negative ideal solution (worst combination). The excellence ranking will be based on S_i values and the worst rankings will be based on R_i values. In other words, S_i, R_i indicate L_{1i} and L_{0i} of L_p – metric respectively.

5) ***Calculate the VIKOR values* for *i* = 1, 2, ... , *m*, *which are defined as:***

$$Q_i = v\left(\frac{S_i - S^+}{S^- - S^*} \right) + (1-v)\left(\frac{R_i - R^+}{R^- - R^*} \right), \quad (7)$$

where: $S^- = \max S_i$; $S^+ = \min S_i$; $R^- = \max R_i$; $R^+ = \min R_i$; v is the weight of the strategy of 'the majority of criteria' (or 'the maximum group utility'). $\left(\left(S_i - S^+ \right) / \left(S^- - S^+ \right) \right)$ represents the distance rate from the positive ideal solution of the i-th alternative's achievements. In other words, the majority agrees to use the rate of the i-th. $\left(\left(R_i - R^+ \right) / \left(R^- - R^+ \right) \right)$ represents the distance rate from the negative ideal solution of the i-th alternative; this means the majority disagree with the rate of the i-th alternative. Thus, when the v is larger (> 0.5), the index of Q_i will tend to majority agreement; when v is less (< 0.5), the index Q_i will indicate majority negative attitude; in general, v = 0.5, i.e. compromise attitude of evaluation experts.

6) ***Rank the alternatives by Q_i values:***

According to the Q_i values calculated by step (4), we can rank the alternatives and to make-decision.

The recent developments of decision making models based on VIKOR method are listed below:

- Fouladgar *et al.* (2012) in project portfolio selection;
- Yücenur and Demirel (2012) for insurance company selection;
- Wang and Tzeng (2012) for creating brand value;
- Liu *et al.* (2012) in improvement of tourism policy implementation;
- Wu *et al.* (2012) for ranking universities;
- Antuchevičienė *et al.* (2011) in ranking of building redevelopment alternatives.

5. Results

5.1. SWARA Result

Due to methodology of this research, SWARA is applied in prioritizing and calculating relative importance of each criterion and results are shown in Table 7.

Based on SWARA methodology, criteria, which were first prioritized by experts, weights and relative importance of each criterion were calculated. Based on results, which were somewhat predictable, smoke control (C_1) was found to be the most important criterion and its value was calculated based on SWARA method 0.211.

5.2. VIKOR Result

This section describes how, according to the results of SWARA, VIKOR was applied for final ranking and evaluation of mechanical longitudinal ventilation methods in tunnels, namely:

- jet fans with spot extraction by axial fans (A_1);
- axial fans with Saccardo nozzle (A_2);
- jet fans with shaft axial fans (A_3);
- jet fans only (A_4).

The information on the decision matrix of VIKOR method is provided in Table 8 and final results and ranking of alternatives based on VIKOR are given in Table 9.

Subsequent to analysis and creation of judgment matrixes, the following results were obtained as listed in Table 9.

Based on Table 8 and observations obtain during the study, it can be stated that the method of jet fans with spot extraction by axial fans is the optimal mechanical longitudinal ventilation alternative. It should be mentioned that previous studies by Witt&Sohn (2011) suggested that jet fans with spot extraction by axial fans demonstrate better performance results; therefore, the current study supports and validities previous evaluations.

Table 7. Final results of SWARA method in weighting criteria

Criterion	Comparative importance of average value s_j	Coefficient $k_j = s_j + 1$	Recalculated weight $w_j = \frac{x_{j-1}}{k_j}$	Weight $q_j = \frac{w_j}{\sum w_j}$
C_1		1	1	0.211
C_2	0.137	1.137	0.879	0.186
C_6	0.156	1.156	0.760	0.160
C_5	0.175	1.175	0.646	0.136
C_4	0.131	1.131	0.571	0.120
C_7	0.20	1.2	0.475	0.100
C_3	0.162	1.162	0.408	0.087

Table 8. Decision matrix of alternatives

	C_1 (max)	C_2 (max)	C_3 (min)	C_4 (min)	C_5 (max)	C_6 (min)	C_7 (max)
W_i	0.211	0.186	0.087	0.120	0.136	0.160	0.100
A_1	8	9	8	8	8	4	8
A_2	5	6	5	4	5	7	5
A_3	7	8	7	7	8	5	7
A_4	5	5	4	3	5	8	4

$f^* =$ [0.626, 0.627, 0.322, 0.255, 0.599, 0.322, 0.644];

$f^- =$ [0.391, 0.348, 0.644. 0.681, 0.374, 0.644, 0.322].

Table 9. Ultimate results and ranking of alternatives

Alternatives	S_i	R_i	V_i	Q_i	Ranking
A_1	0.207	0.120	0.5	0	1
A_2	0.583	0.139	0.5	0.425	2
A_3	0.480	0.211	0.5	0.732	3
A_4	0.793	0.211	0.5	1	4

Conclusion

1. To determine the best mechanical ventilation method for tunnels, simulation and modelling dynamic (CFD) methods were used involving air pollutant. Economical estimation was also used to measure justification of investments. This method was found to be very expensive and time consuming. In case significant information is available, decision-making and reconciliation of result can become very complex. Considering the aforementioned, two MCDM methods were applied during this research to create a new hybrid model of MCDM methods based on SWARA and VIKOR. SWARA method was applied to evaluate criteria and calculate relative importance and values of each criterion, while VIKOR method was used to evaluate and rank alternatives.
2. 14 experts of four different fields participated in this research: top managers experienced in road construction, civil engineering experts, construction management and technology specialists, and economists. Seven important criteria were selected and a model of research was established. The following important criteria were chosen: smoke control (C_1), safety level (C_2), design complexity (C_3), investment costs (C_4), increasing concentration of pollutants up to the portal (C_5), smoke laden section (C_6) and simultaneous evacuation and fire fighting (C_7) as illustrated in Table 5.
3. SWARA method was applied for evaluation of these criteria; the results and importance of each criterion are illustrated in Table 7. Smoke control is the most important criterion, followed by the safety level criterion, next followed by smoke laden section and increasing concentration of pollutants up to the portal, investment costs, simultaneous and fire fighting, and design complexity.
4. Four mechanical longitudinal ventilation methods in tunnels were selected for this research, namely: 1) jet fans with spot extraction by axial fans (A_1); 2) axial fans with Saccardo nozzle (A_2); 3) jet fans with shaft axial fans (A_3); 4) jet fans only (A_4).
5. VIKOR method was applied for evaluation and ranking of four alternatives of this research and the evaluation was based on results of SWARA as well as importance of criteria. The existing research, which was focused on the mechanical longitudinal ventilation method used is tunnels, indicated that the jet fans with spot extraction by axial fans was the most optimal alternative from among the proposed methods.
6. This new methodology can be used as a new framework in other areas of research. For future research, authors proposed a comparison of this new methodology with other hybrid models such as AHP-TOPSIS or AHP-VIKOR.

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