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A Prevention through Design Approach for the Environmental S&H Conditions and the Ventilation System at an Italian Underground Quarry

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Even if the number of the Italian underground quarrying operations is steadily growing, in many cases the safety criticalities are somehow underestimated, in spite of the regulations D.Lgs. 81/08 and D.Lgs. 624/96, Italian enforcements of the former European Directives 89/391/EEC, 92/91/EEC and 92/104/EEC.
Ventilation system is conceived to face very simplified requirements, whilst critical pollutants or emergency situations are not taken in due consideration. Asides, the ventilation system fault and availability analysis are seldom included in the project.
The paper deals with the results of a research work started some years ago at an underground quarry exploited through drift sublevel based on drill and blast technique, to identify criteria suitable to grant effective safety and health -S&H- conditions for the workers operating in the underground in the Prevention through Design approach.
Taken into account that the phases for an effective approach to the S&H problems in underground must follow a hierarchic method, in which the risk management should be faced from an effective hazard reduction to a minimum at the sources, and the ventilation should be considered only as a 4th level solution, the possibilities of control at the main pollution sources, i.e. the emission of pollutants due to the rock winning and mucking operations, have been examined.
The residual risk was then faced with both the original underground and airways layout definition for a new exploitation development, based on technical and efficiency considerations, and on fire emergency computer simulations.
Finally, the paper summarizes the results of an availability analysis of the ventilation system for normal operating conditions, and the emergencies management, on the basis of the results of Hazard Evaluation techniques, particularly Hazard and Operability Analysis and Fault Tree Analysis.

1. The Method

The control of the underground environment involves the adjustment, modification, alteration, or correction of an existing or incipient undesirable situation in order to attain or maintain safe working conditions (Bersano et al., 2010).
To carefully identify all the possible different conditions, the general underground layout in an Italian quarry (Figure 1) was analysed by means of a simulation software fed with input data directly collected, and some modifications were introduced, on the basis of the assumption that an upward flow has to be granted in any situation, and both the flow reversal risk and the presence of workers in areas polluted by fumes should be avoided at the very first stage of the ventilation layout, and fittings design (with special reference to the possible presence of workers in areas polluted by fire fumes; the residual risk not directly eliminated

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by the underground layout design must be managed in terms of organization, and, if necessary, with the introduction of rescue chambers).

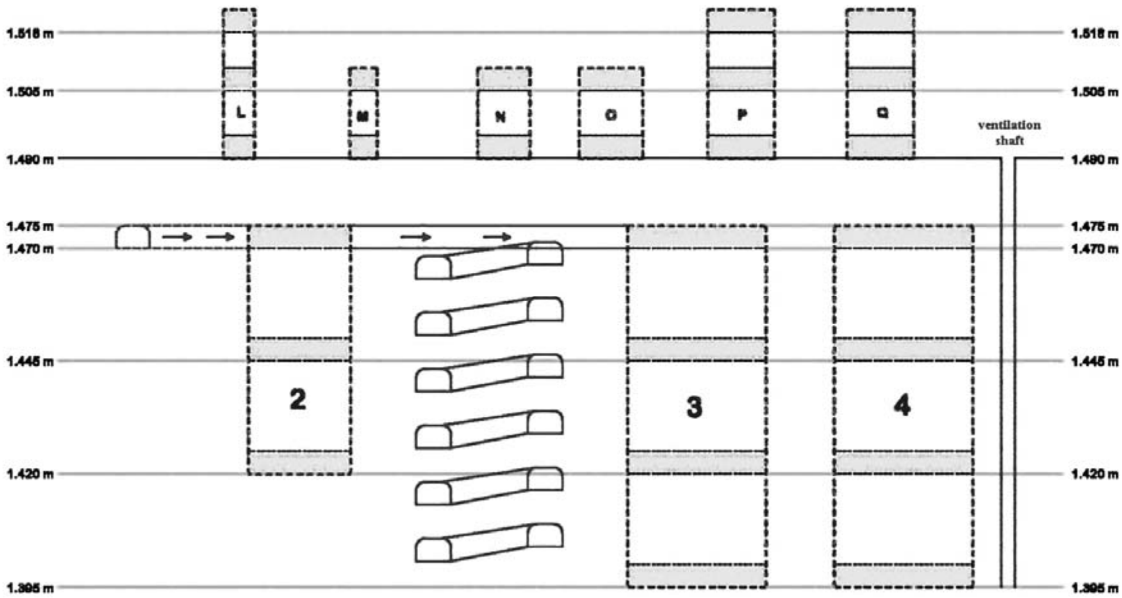

Figure 1: Section of the quarry sub level exploitation, with the old (L, M, M, O, P, Q), and the new (2, 3, 4) rooms.

The first step consisted in the direct measurement of the pressure (in terms of pressure difference along the airways) and flow-rate (from velocity and airway cross section) in 17 representative stations along the main airways[1]: a series of measurement campaigns carried out in different seasonal conditions made available the different ranges of the values of the aforesaid parameters due to the different natural draft, and to the thermal contribution of the mining equipment and machineries, often sufficient to overcome the head losses. It must be underlined that the latter statement involves the risk of natural descending ventilation, with the possibility of flow reversal in case of fire: such a situation can be managed only by the adoption of a mechanized ventilation system including a fan located at the higher level (1530 m), to grant a constant ascending flow from the clean air entrance (1490 m) in all seasonal, weather and underground condition.

2. The Numerical Simulation

The use of numerical tools for fire safety engineering has significantly grown in the last years. The most common applications of these tools are the analysis of fire scenarios in buildings (Rein et al. 2009) and tunnels (Carvel and Beard, 2011). CFD models are often used since they allow one to account for the phenomena occurring in the area where fire develops and smoke propagates, as well as to obtain detailed information about the conditions (temperature, concentration of contaminants, etc.) in the fire nearby or in the evacuation routes. The use of CFD implies the requirement of large computational resources, which may constitute a limitation in the case of complex systems and/or large number of scenarios to be analysed.

In the case of systems as rail and road tunnels, subways or quarries, the use of multi-scale techniques can be adopted to avoid the huge computational cost of the full CFD representation. The basic idea is to consider, where possible, the tunnel as a system where the fluid is behaving as fully developed as any flow through a pipe. Non fully developed flows are encountered in some regions like near the portals, shaft or downstream fans and fire source and, in the case of subways, in the stations. The flow here follows 3D patterns. These are the regions where CFD techniques are required. Far away from the disturbances, the temperature and velocity gradients tend to disappear and the flow starts to behave again almost as fully developed. In these regions the one-dimensional model is able to produce accurate results.

[1] The spot data resulting from the campaigns where confirmed by routine simplified measurements systematically carried out by the underground supervisors.

Pressures and temperatures at the boundaries are obtained from the 1D model and imposed as the boundary conditions to the 3D model. Velocities are obtained from the 3D model and imposed as the boundary conditions to the 1D model. This requires that boundary conditions are adjusted at each iteration.

A simplified procedure can be obtained by modelling the global fluid dynamic behaviour of the entire structure using a 1D model. Pressures and temperatures at the cross sections that identify the domain to be modelled using the 3D model are obtained. These values are imposed as the boundary conditions to the 3D domain. The velocities calculated at these boundaries using the 3D model and the 1D model must be compared. Alternatively, mass flow rates can be imposed as boundary conditions instead of pressures (except for one section, where pressure must be mandatorily imposed).

Multi-scale techniques allow a significant reduction of the computational time because the more time consuming tools are not applied to the entire domain but just to the regions where it is needed.

This simulation technique is applied here: 1) 1D simulation of the whole quarry is used to evaluate the airflows in the entire system and to identify the best layout and ventilation hardware (fan, monitoring and regulation devices, etc...). Inputs for this model are obtained on the basis of the data acquired through the measurement campaigns (Figure 2), 2) Computational Fluid Dynamics (CFD) in different areas of the underground using the results of the 1D model as the boundary conditions to obtain local distributions of velocity, temperature, smoke, etc. Different fire emergency scenarios corresponding with 10 MW fire have been considered. The 1D simulations have been developed using a software developed at Politecnico di Torino (Borchiellini et al., 2011), while CFD simulations have been conducted using the software FDS (Baum et al. 2007).

Finally, to optimize and simplify the layout of the airways, and properly simulate the possible interventions necessary to manage the natural draft, the boundary condition of total closure of a shaft connecting the 1518 m level to abandoned underground exploitations at higher levels was assumed (so avoiding short circuits in the general ventilation net).

The results of the computer analyses can be summarized as follows:

a) the most critical situation corresponds to a fire located in the node “N20” at 1490 m level (Figure 3), which represents the main point of distribution of the fresh air to the whole underground, so that further detailed analysis appeared advisable;
b) the 1D analysis put in evidence the risk of convective movements of polluted air: in particular in an hypothetical scenario of fire in the node “N20”, it was possible to verify such a situation between the already exploited rooms “N”, “P”, “Q” and “R”. This phenomenon can only worsen the conditions during an emergency, substantially contributing to the rapid pollution of the whole interested levels (Figure 4). It should be moreover emphasized that also a saturation of the available air volumes can occur, leading to incomplete combustion and production of under-oxidised gases. Some modifications in the ventilation layout were then hypothesized, in particular with the exclusion from the ventilation net of all the already exploited rooms located at the 1490 m level together with the "R24", "R47" and "R48" branches: the proposed modified layout grants a substantial reduction of uncontrolled -and unnecessary- air movements, and appeared to be suitable for a well-defined analysis and management of the underground ventilation in both normal and critical conditions.

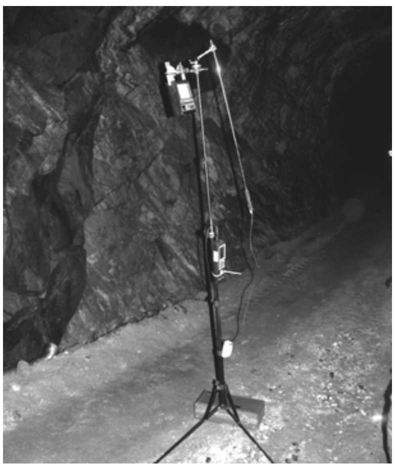
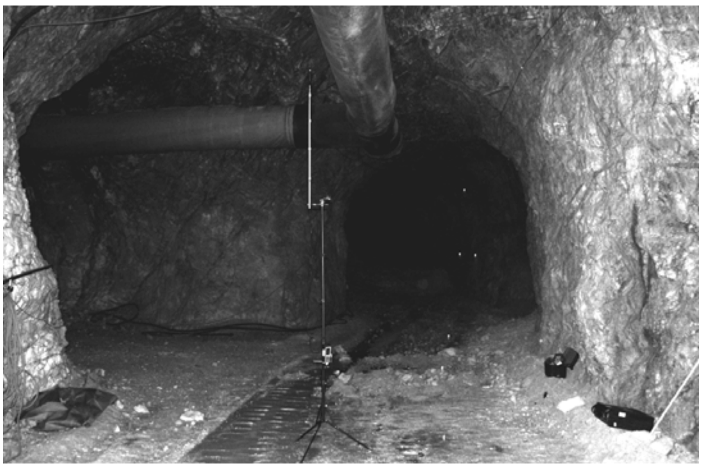

Figure 2, 3: measurement of the air flow in underground by means of an anemometer at node “N20”

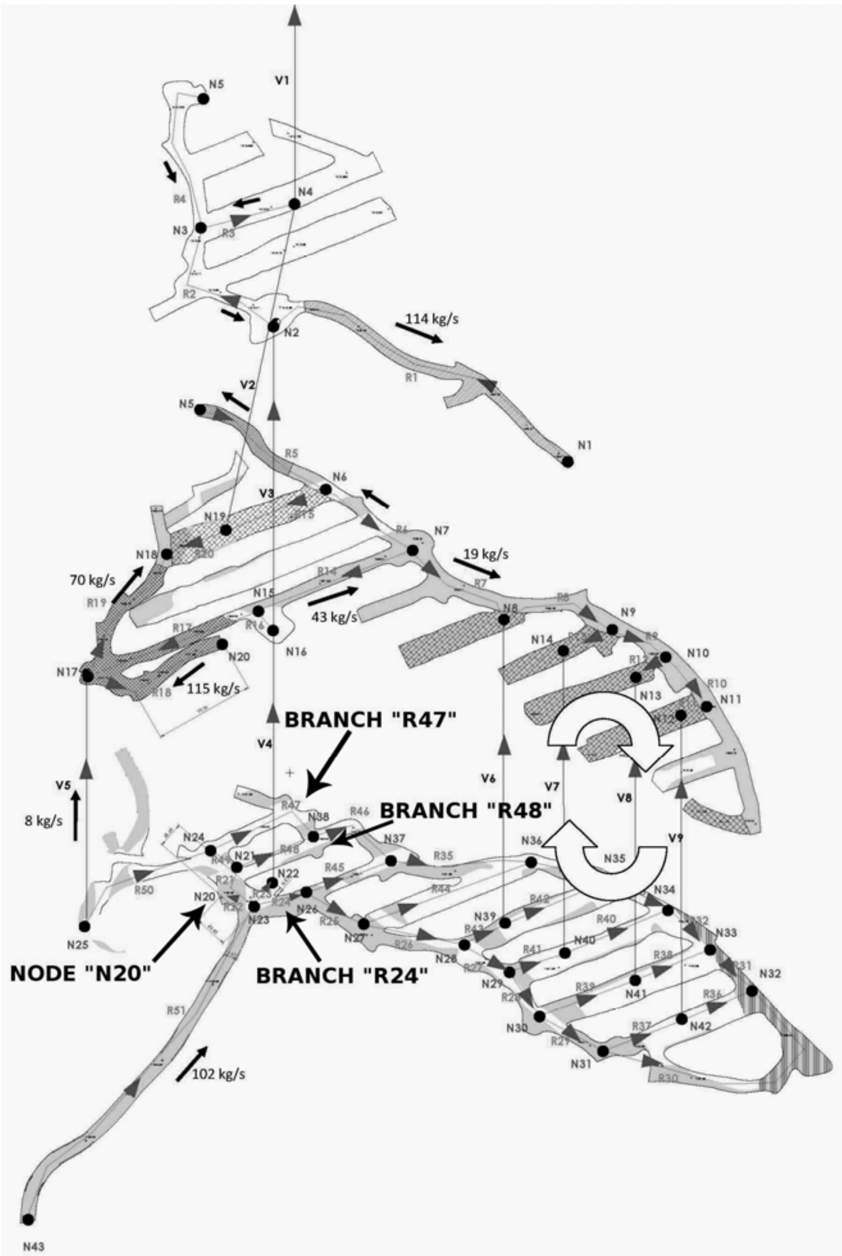

Figure 4: underground levels layout adopted in the simulations carried out with a 1D nodal points software to evaluate the direction and amount of the airflow after a fire accident in "N20" at level 1490 m. The arrows show the possible areas of convective movement

c) the CFD analysis applied in the node "N20" confirmed, as shown in Figures 5 e 6, the criticality of this node, and provided detailed information on the possible development -step by step along the time- of a 10 MW fire In terms of air temperature and velocity.

On the basis of the aforesaid results, the ventilation layout was confirmed, and it was possible to define the most suitable characteristics of the fan to be introduced.

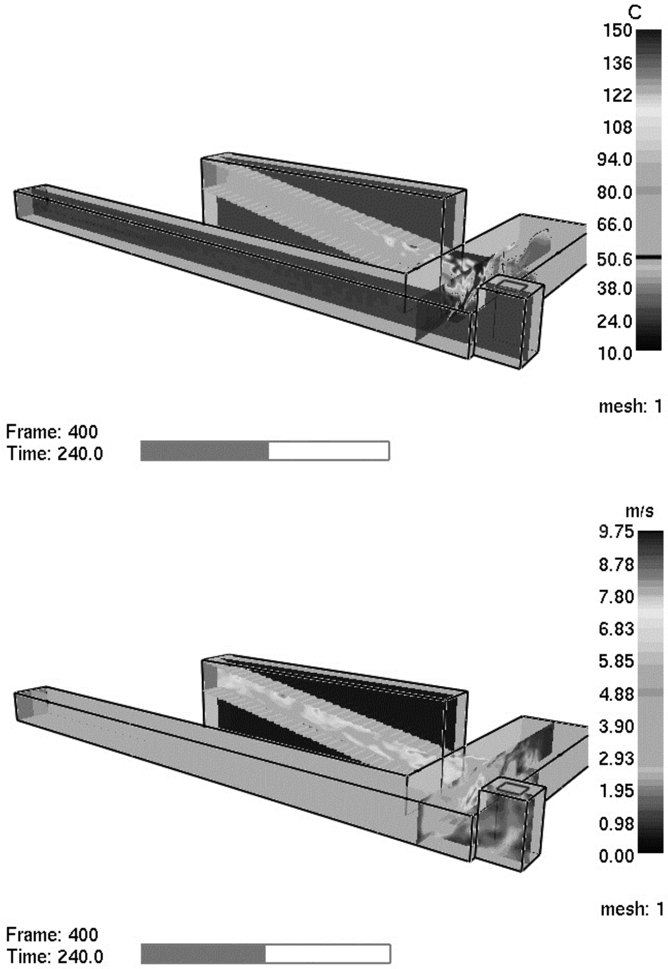

Figure 5, 6: temperature and velocity at 240 seconds during a 10 MW power fire at node "N20"

3. The definition of the characteristics of the main Fan

The main fan to be located at 1530 m level was dimensioned to fulfil the following requirements:

- the management of the seasonal variations of the natural draft, so that an upward air flow is in any case granted, taken into account that the computer simulations suggested a maximum value of the possible downward natural flow movement of ≈ 80,000 m^3/h;
- the capability of an effective management of the diesel fumes emitted by the mining equipment[2]: basically the trucks used for the ore transportation at the 1490 m base level (see Table 1);
- the regulations on the minimum/maximum (0.1 m/s - 6 m/s) air velocity in the underground according to the Italian regulation D.P.R. 128/59, art. 261.

Such an approach was considered acceptable, provided that a) no exploitation areas are ventilated in series, b) the fresh air intake way is different from the ore transportation way, c) a special risk assessment and management is carried out to grant safe conditions on the basis of organization, and, if necessary, of rescue chambers for the fire emergency situations.

Considering the co-presence in the underground of two or three 300 kW diesel machines, and the following very simplified assumptions related to the combustion diesel reaction:

- diesel fuel formula = n-Dodecan: $C_{12}H_{26}$ ≈ Dodecan-cycle $C_{12}H_{24}$
- mixture strength[3] = 1.4;

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[2] The fire load is preliminarily minimized, and exclusively approved diesel machines are allowed into the underground.

[3] combustion air volume / stoichiometric combustion air volume.

- fumes temperature = 473 K;
- reaction granting a total combustion;

it was possible to roughly estimate the quantity of produced fumes of ≈ 10,800 m^3/h ≈ 3 m^3/s.

In practice, the fumes can show different concentrations of highly noxious substances, such as nitrogen oxides (NO_X), carbon oxides (CO and CO_2) and, according to the Institut de recherche Robert-Sauvé en santé et en sécurité du travail (2001) and Bertolatti et al. (2011), a not negligible amount of air dispersed particulate matter.

In conclusion, trough a comparison with the suggested Limit Values -Tables 1 and 2-, and taken into account the possible seasonal situations of downward natural draft, a suitable fan should be characterized by prevalence values in the range 1,000 ÷ 3,000 Pa, and a flow value of at least 250,000 m^3/h.

Table 1: Threshold Limit Values in a 8 hours Time Weighted Average (TLV-TWA) (American Conference of Governmental Industrial Hygienist, 2012)

substance [n° CAS] (publishing date)	*TLV-TWA*
Carbon Dioxide [124-38-9] (1983)	5,000 ppm
Carbon Monoxide [630-08-0] (1989)	1 ppm
Nitrogen Oxide [10102-43-9] (1992)	25 ppm
Particulate Matter (provided that no substances with an applicable TLV are present ([4]))	10 mg/m^3 (inhalable) 3 mg/m^3 (respirable)

Table 2: Permissible Exposure Level (PEL) in a 8 hours time weighted average for Diesel Particulate Matter in underground mining operations (Mine Safety and Health Administration, 2008)

substance	PEL
Total Carbon (D_{50} = 0,2 μm)	160 $\mu g/m^3$

In the hypothesis that a special risk analysis and management is carried out to grant safe conditions of the workers, on the basis of organization and, where necessary, of rescue chambers, such a fan can be considered suitable to manage also the emergency situations. Obviously, taken into account the important seasonal variations in the natural draft, special care should be devoted to the underground environment automatic monitoring and fan regulation, both to save energy and to grant a correct response also in case of emergency.

4. The Hazard Identification Technique Selected to evaluate the Availability of the system

According to the results of a research work carried out by the Authors (Bersano et al., 2011), the Hazard and Operability Analysis -HAZOP- and the Fault Tree Analysis -FTA- (Table 3) techniques have been employed in combination to identify and analyze the criticality of ventilation systems in underground operations.

Table 3: Hazard Identification techniques selected

Technique	*Description*
HAZard and OPerability analysis (HAZOP)	*A structured and systematic method, in which the operating problems of a planned or existing process, that may represent risks to personnel, or equipment, or prevent efficient operation, are identified using a series of guide words, to investigate the deviations (EVENTS causing upset to the system).*
Fault Tree Analysis (FTA)	*A failure analysis technique, in which a pre-identified particular accident or main system failure -TOP EVENT- is analyzed using boolean logic to combine a series intermediate events down to the very Root Causes, thus providing a method for assessing and evaluating the causes sequence leading to the accident in a probabilistic approach.*

[4] The presence of crystalline silica is systematically monitored by the quarry technicians, and the Author were informed that it is play a critical role in the ventilation flow rate definition, in comparison with the diesel fumes.

Moreover, an investigation on the failure probabilities of the different components of the ventilation system (Table 4) should be started, to collect numerical data usable in the provisional failure evaluations.

Table 4: subsystems, parts and components of the ventilation system

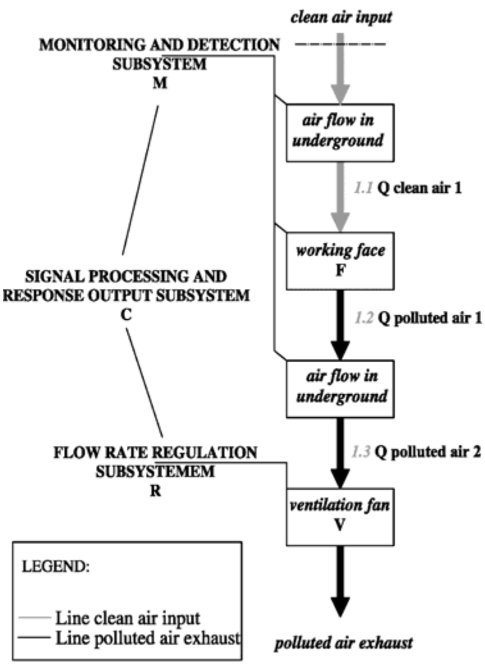
SUBSYSTEM	*PARTS*	*COMPONENTS*
V - ventilation	*Air movement activators*	*Fans, their motors (usually electric), rpm variators, etc.*
R - ventilation flow regulation	*Regulation devices*	*PLC*
C - signal processing and response output	*Signal interpretation system*	*COMPUTER*
M - monitoring and detection	*Ventilation performance monitoring devices*	*Fan rpm, water gauge and flow rate monitoring at the fans*
	Underground pollutant measurement devices	*Pollutant detectors*
	Signal transmission systems	*Signal transmission lines and connectors*

4.1 HAZOP – Hazard and Operability Analysis

The first step of the Hazard Identification was the implementation of a systematic analysis HAZOP on the complex ventilation - detection, to highlight the possible deviations, put in evidence the unwanted events (Top Events) and draft a hierarchical order of the criticalities.

The more critical event identified was *the rapid filling of smoke of some areas of the underground*, due to a fire not correctly managed by the ventilation system (Table 5).

Table 5: HAZOP analysis



Process	*Parameter*	*Deviation*	*Cause*	*Effects (worst credible case)*
Ventilation V	Q clean air 1	No	Improper response of the ventilation to an emergency alarm	Rapid filling of smoke not faced by the ventilation system
		Less	Improper response of the ventilation to an emergency alarm	Filling of smoke not completely contrasted by the ventilation
		More	Improper response of the ventilation to an emergency alarm	A not particularly critical situation, provided that correct organization and, if necessary, rescue chambers are available

4.2 FTA – Fault Tree analysis

To analyze the qualitative interactions among the identified initiator Events, the FTA technique was used. The Top Event being a rapid filling of smoke in some underground areas (Figure 7).

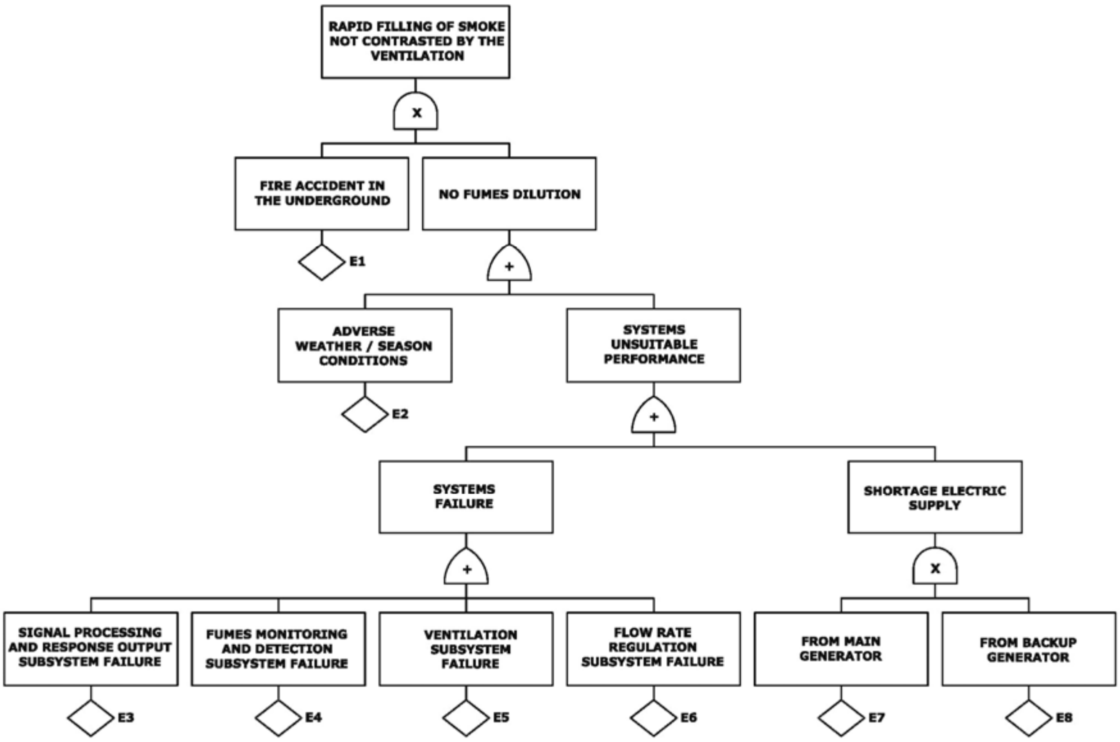


Figure 7: qualitative Fault Tree Analysis of the ventilation system

The qualitative FTA confirmed the importance of maintenance, management strategies, indispensable in any sector and without which the analysis of the availability of mechanical components becomes useless.

5. Analysis of the fumes resulting from the blasting operations

The fumes of an explosion are certainly unbreathable for the very low or nil oxygen content, but there is also concern of their toxicity, in particular in underground, where the renewal of air is not so rapid and complete as in open pit quarrying (some underestimated problems can arise, as discussed in Berry et al. (1993)).

The analysis of fumes produced by detonating explosives can be helpful to control the environmental condition in underground mining. Ideally, the detonation products of explosives could be water (H_2O), carbon dioxide (CO_2) and nitrogen (N_2); but, due to the kinetics of the chemical reaction, also toxic fumes, such as nitrogen dioxide (NO_2), nitric oxide (NO), carbon monoxide (CO) and, in relation to the type of explosive, sulphur dioxide (SO_2), ammonia (NH_3) and others, are produced.

The quantity of oxygen leads the explosives to a positive or negative balance: an excess of oxygen increases the production NO_x, while a deficiency facilitates the CO production.

Moreover, it was observed that the confinement of a charge considerably influences the production of NO_x and CO; this is due to the oxidation of NO to NO_2, that depends mainly on the initial concentration of NO in the environment. A reduced confinement, on the contrary, allows the gases to propagate immediately after the blast at a very high temperature, due to the little work they have done: to limit this effect it is advisable to leave a 10 diameters length of uncharged hole.

The formation of CO, even if in some way influenced by confinement, depends on the oxygen balance.

In order to evaluate the actual risk of exposure of the operators, the performance of the explosive and the physico-chemical characteristics of the gases, on-site sampling of gases was performed. The

measurements of concentration of pollutants was focused in particular in the mucks and in the abandoned branches before blasting, and three hours after the smoke cleaning in four identified points with a Drager detector. These measures were carried out too, especially in the case of loading, where the operation requires the staff to stay close to the source of pollutant.
The explosive used in the quarry is a waterproof dynamite (GD) with an amount of harmful gases released lower than 22.7 l/kg of explosive, in order to quickly re-establish the proper conditions after the detonation.
The measurements showed that the concentrations of pollutants were maintained below the limits of sensitivity of the instrument: only nitrogen oxides (NO_x) and carbon dioxide (CO_2) reached concentrations sufficient to be detected, although systematically lower than TLV-TWA values.

6. Conclusion

Assumed the need of a Prevention through Design approach in underground mining activities, the results of the present study confirm the possibilities of effective improvements in the Safety and Health conditions achievable by the use of computer models and Fault Analysis techniques.
Some basic research was carried out to provide suggestions on the possibilities of reduction of the blasting fumes through the optimization of the performance of the explosives in terms of blasting plan and new materials, whilst the total Diesel power was already reduced to what strictly necessary, and the associate fire loads correctly managed.
The ventilation system design and layout were then defined with the support of numerical simulations, taken into account both normal and emergency situations: in particular, the expectable amount of exhaust gases due to the use of diesel machines and explosives was considered, together with the criticalities due to fire situations in different nodes and branches of the underground airways.
Finally, the ventilation system and parts response were analyzed by means of a combination of Hazard and Operability Analysis and Fault Tree Analysis, both in normal and emergency situations.

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