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Air quality in underground mining

Suggested adjustments for the fulfilment of the Commission Directive 2017/164

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Declaration

I declare that this is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Resumo

A Diretiva (UE) 2017/164 da Comissão Europeia, lançada a 31 de janeiro de 2017, possui estabelecidos novos valores-limite indicativos de exposição profissional (IOELV) para agentes químicos. O sexto artigo está relacionado com a implementação de novos valores-limite para os gases CO, NO e NO_2 na indústria mineira em subterrâneo. Este estudo visa compreender os principais contribuintes destes gases tóxicos e possíveis medidas de mitigação.

Na Diretiva, não existe indicação de qual deverá ser a metodologia para obter os valores dos gases tóxicos. Consequentemente, foi desenvolvida uma proposta que pretende reunir dados relacionados com a qualidade do ar e a sua posterior análise. O método considera a avaliação de todos os locais e operações, adaptável a todas as minas. A metodologia de avaliação é dividida em três fases: caracterização da mina em análise, metodologia de medição e análise de dados.

Após o desenvolvimento da metodologia de avaliação, foi possível aplicá-la em dois casos de estudo. No primeiro, foi possível realizar medições diretas durante os meses de julho e agosto de 2019. Foram recolhidos dados de 20 situações, permitindo compreender a situação atual em todos os tipos de locais e operações da mina. No segundo, os dados foram fornecidos pela mina, para posterior análise. Neste caso, a metodologia foi implementada apenas parcialmente, e os dados analisados foram apenas relacionados no ciclo de limpeza.

Foram também analisados possíveis ajustes para atingir os IOELV da Diretiva e, consequentemente, aumentar a qualidade do ar, melhorando o ambiente ocupacional nos locais de trabalho em subterrâneo.

Palavras-Chave: Qualidade do ar, Indústria mineira em subterrâneo, Explosivos, Equipamento a diesel

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Abstract

The European Commission Directive (EU) 2017/164, published on the 31st of January 2017, has new Indicative Occupational Exposure Limit Values (IOELV) for chemical agents. The sixth article concerns the implementation of new limit-values for CO, NO and NO_2 gases in the underground mining industry. This study aims to understand the main contributors of these toxic gases and possible mitigation measures.

In the Directive, there is no indication of which methodology should be used to attain toxic gas' values. As a result, a method has been developed to gather air quality data and its further analysis. The developed method considers the assessment of all sites and operations, adaptable to all mines. The methodology is divided in three phases: characterization of the mine under analysis, measurement methodology and data analysis.

After the methodology was developed, it was applied in two case studies. In the first case, it was possible to perform direct measurements during the months of July and August 2019. Data was collected referring 20 situations allowing the understanding of the current situation in all types of sites and operations of the mine. In the second case, data was provided by the mine for further analysis. Here, the methodology was only partially implemented, and the data analysed was only related to the cleaning cycle.

Possible adjustments to meet the Directive's IOELVs and, consequently, to increase air quality by improving underground workplaces were also analysed.

Key-words: Air Quality, Underground Mining, Explosives, Diesel Equipment

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Abbreviation list

A

AN: ammonium nitrate

ANFO: Ammonium nitrate-fuel oil

C

CA: Confidential Attachment

$Ca(OH)_2$: Calcium Hydroxide

CH_4: methane, 9; Methane

CO: Carbon Monoxide

CO_2: Carbon dioxide

CPE: Collective protective equiptment

D

DOC: Diesel Oxidation Catalyst

DPM: Diesel particulate matter

E

EU: European Union

G

GEM: Gases Evaluation Methodology

H

H: Fan load

H_2: hydrogen

H_2O: Water

H_2S: Hydrogen sulphide

HC: Hydrocarbons

He: Helium

I

IOELV: Indicative Occupational Exposure Limit Values

L

LHD: Load-haul-dump

LNC: Lean NOx Catalyst

N

N: Nitrogen

NH_3: Ammonia

NH_4^+: Ammonium

NO: Nitrogen Monoxide

NO_2: Nitrogen Dioxide

NO_3^-: Nitrate

NO_x: Nitrogen oxides

NTP: Normal temperature and pressure

O

O_2: Oxygen

OELs: Occupational exposure limits

P

P: Fan Power

PPE: Personal protective equipment

Q

Q: Volume of air moved by the fan

R

RPM: Rotation Per Minute

S

SCR: Selective Catalyst Reduction

SO_2: Sulphur dioxide, 7; Sulphur Dioxide

STEL: Short-term exposure limit

T

TLV: Threshold limit values

TWA: Time-Weighted Average

Others

η: Fan efficiency

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1. Introduction

The present thesis was conducted in the scope of the 2018/2019 dissertation candidacy to obtain the masters' degree in Geological and Mining Engineering.

The introduction chapter aims to acknowledge the motivation behind the study, proceeded by the objectives proposed to be studied and the methodology that was followed.

1.1. Motivation

The mining industry is fundamental for the modern world. Everything we rely on is either made from minerals or depends on minerals for its production. Minerals are essential for basic infrastructures (such as hospitals, houses and roads), for the production of energy (from non-renewable to renewable sources), for transport facilities (as cars, trains and bicycles), for indispensable daily items (such as computers, telephones and hygiene products) and many other commodities and services. Technological advancements require a higher demand of minerals which are only possible to attain by mining. However, the need for minerals should not cease improvements to change this industry into a safer and more sustainable one.

Mine development can take place on the surface (open pit) or underground. Deposit depth and excavation costs are the decisive factors regarding the type of exploration decision. Although open pit mining is related with higher productivity, excavations costs of certain deposits may compensate the investment on an underground mine.

Underground mining is associated with high hazards, ranging from the quality of the air to the movements of the rock mass. For this reason, occupational safety is essential for workplace security and respective workers.

The upsurge concern with the environment and workers' health and safety, have been the two main factors for the increasingly stricter requirements from the governmental institutions. On the 31st of January, 2017, the European Union (EU) released the Commission Directive 2017/164 establishing the fourth list of indicative occupational exposure limit values (IOELV), with the purpose of increasing the health and safety of workers from risks related to the chemical agents at work. On the Directive is established new limit values for the carbon monoxide (CO), nitrogen monoxide (NO) and nitrogen dioxide (NO_2). The new limits for these gases present a challenge for the underground mining industry, and so, the Directive provides a transitional period ending on the 21st of August 2023. The difficulty of the mines to comply with the new limit values and the approach of the transitional period end, motivated a research regarding the required measures needed to achieve the Directive.

1.2. Objectives and Scope

The main objective of this investigation is to have a deep knowledge of the mine's current situation, in order to understand:

- Which are the main producers of toxic gases on underground mines;
- How the ventilation will influence the gases dilution;
- How the type of explosives used will affect the air quality;
- How adjustments in the machinery might decrease the toxic gases produced.

On the Directive there is no indication regarding the method of measurement to acquire the toxic gases values. Therefore, throughout this thesis will also be intended the design of a model for gathering the data related to the air quality and its further analysis, adaptive to all mines and considering all the locations and operations.

Posterior to the mine's characterization, the suggested adjustments will be approached, on underground mining sites, to achieve the Commission Directive 2017/164 IOELV and, consequently, increase the air quality, improving the work site for the miners.

1.3. Methodology

To achieve the objectives previously established this study is divided in four consecutive phases: theoretical framework, development of an evaluation model, validation (by applying it on case studies) and analysis of possible adjustments to comply with the Directive.

The theoretical framework will consist of a research to understand the importance of the Directive and a literature review to gain a detailed knowledge of the work that already exists on the thesis topic.

The evaluation plan aims to be adaptable to all types of mines, regardless of mining method, and including all situations on which the miners are exposed to the toxic gases specified by the Commission Directive 2017/164. It is also intended that, by using the model, it is possible to have a detailed analysis of the areas and operations that expose the workers to unsafe environments, allowing a posterior assessment of the necessary improvements for the mine being studied. To validate the model, it will be applied to practical cases.

The analysis of possible adjustments intends to gather solution that will dilute or decrease the toxic gases. The adjustments study will be divided into three categories, accordingly to the required investment.

2. Theoretical Framework

The underground mining environment is known for the presence of toxic gases. The existence of this type of gases in this work environment can be very dangerous to all workers *“Hazards, such as toxic chemicals in the workplace, need to be identified, and the risks associated with them from any possible exposure needs to be adequately controlled”* (Euromines, 2017). Throughout the years, many laws have been made with the purpose of improving the quality of the work environment and the health and safety of all workers.

Technological advancements enhanced work conditions, by improving machinery, ventilation system as well as the advancing personal protective equipment (PPE) and collective protective equipment (CPE).

The Commission Directive 2017/164 presents a new list of limit values that attend to the protection of workers that work with certain chemical agents. Among this list, there are new threshold limit values (TLV), this is, the “*concentration within which personnel may be exposed without known adverse effects to their health or safety”* (Sifferlinger, 2017), for CO, NO and NO_2.

In order to have a deep knowledge to answer the research problem, it is necessary to characterize, examine and assess concepts regarding the thesis topic. Therefore, the present chapter is structured according to different subject matters regarding the objective: legislation, gas emissions consequences, gas emissions principal causes, measurements methods, ventilation and dilution of gases, explosives comparison, and, lastly, equipment alternatives.

2.1. Legislation

The concerns with the health and safety of workers in underground mining and in other work environments, in which are present chemical agents, are continuously addressed in legislations in many countries.

The European Union (EU) has established several directives to promote the achievement of better work environments for all the worker from the EU countries. *“A "directive" is a legislative act that sets out a goal that all EU countries must achieve. However, it is up to the individual countries to devise their own laws on how to reach these goals”* (EU, 2019). In order to protect the workers’ health, the occupational exposure limits (OEL) have been created. The OEL are proposed by taking into account scientific considerations or also the socio-economic and technical factors.

The Council Directive 89/391/EEC, of the 12th of June 1989, creates an “*introduction of measures to encourage improvements in the safety and health of workers at work”.* According to the article 16, point 1, the Commission must do individual directives in areas, such as: workplace, work equipment, personal protective equipment, among others. The article 17 states the directives should be revised considering the technical progress, since new technology will allow a progress on workers’ protection.

The Council Directive 98/24/EC, of the 7th of April 1998, aims to protect the health and safety of EU workers from risks related to chemical agents at work. Therefore, *"the Council shall adopt by means of Directives minimum requirements for encouraging improvements, especially in the working environment, to guarantee a better level of protection of the safety and health of workers"*. According to article 3, point 2, the European Commission should propose the indicative occupational exposure limit values, assisted by the Advisory Committee on Safety, Hygiene and Health protection at work.

Following the Directive 98/24/EC and considering article 17 from the Directive 89/391/EEC, throughout the years were released directives establishing lists of IOELVs: The Commission Directive 2000/3/EC in the 8th of July 2000, on which is established the first list of IOELVs; the Commission Directive 2006/15/EC presents the second list of IOELVs; and the Commission Directive 2009/161/EC in the 17th of December 2009, was issued with the third list of IOELVs (EU-OSHA, 2019).

The Commission Directive 2017/164 of the 31st of January 2017, establishes the fourth list of IOELVs revising and implementing new limits for thirty-three substances, contemplating the scientific considerations and the socio-economic and technical feasibility factors. The new IOELVs were established with the assistance and recommendation of the Scientific Committee on Occupational Exposure Limits; *"IOELVs are (…) derived from the most recent scientific data available and taking into account the availability of reliable measurement techniques"* (EU-OSHA, 2019). This most recent Directive attends to the "*protection of the health and safety of workers from the risks related to chemical agents at work*" (Commission Directive 2017/167, 2017). The Commission Directives 91/322/EEC, 2000/39/EC, 2006/15EC, 2009/161/EC and the Council Directive 98/24/EC, were rectified once this new Directive was applied. In the Commission Directive 2017/164 is specified that the member states should have applied the new IOELVs by the 21st of August 2018.

Another important factor is the relation between the limit values and the period of exposure on the Commission Directive 2017/164. The TLV limits were implemented considering the time of exposure, this is, the concentration to which the workers may be exposed over a certain time period without adverse effects; it was established a long-term exposure limit values of 8 hours, Time-Weighted Average (TWA) and a short-term exposure limit (STEL) of 15 minutes. The limits implemented should never be exceeded on the time periods considered, that is, the TWA limit should never be surpassed during the shift, however, in special situations, when the worker needs to be in a situation with higher values of the toxic gases, the exposition should never be more than 15 minutes and the values should never exceed the STEL limit. The Commission Directive 2017/164 features new entries on the IOELVs list, reduction of workplace exposure limits (new 8-hours TWAs limits and STEL limits) and skin notation.

In Commission Directive 2017/164, it is considered the specifically the underground mining industry and the tunnelling industry. The Advisory Committee on health and safety at work "*recognised that there were concerns regarding the technical feasibility of the proposed IOEVL's for nitrogen monoxide and nitrogen dioxide in underground mining and tunnelling, and for carbon monoxide in underground mining*" (Commission Directive 2017/164, 2017). Therefore, on the 6th article is specified for underground mining and tunnelling there will be a transitional period ending on the 21st of August

2023, concerning the limit values established for nitrogen monoxide, nitrogen dioxide and carbon monoxide. The mining industry has the same concern: *“New NO_x limits are not easy to achieve in the underground environment, hence long transition periods are required”* (Euromines, 2017). By the end of this period, both of these work environments must apply the limit values present in this Directive (table 1).

Table 1 - Indicative Occupational Exposure Limit Values Commission Directive 2017/164

EC No (1)	CAS No (2)	Name of the Chemical Agent	Limit values			
			TWA (3)		STEL (4)	
			mg/m³	ppm (5)	mg/m³	ppm
211-128-3	630-08-0	Carbon monoxide	23	20	117	100
233-271-0	10102-43-9	Nitrogen monoxide	2.5	2	-	-
233-272-6	10102-44-0	Nitrogen dioxide	0,96	0,5	1,91	1

Until the end of the transitional period the member states should continue applying:

- Regarding the carbon monoxide and the nitrogen dioxide, the limit values are implemented in compliance with the national limits.
- Concerning the nitrogen monoxide, the limit values should follow the Directive 91/322/EEC.

Following are examples portraying the limit values applied during the transitional period for two countries in the EU: Portugal (table 2) and Spain (table 3).

Table 2 - Previous Indicative Occupational Exposure Limit Values for Portugal (Diogo, 2017)

EC No	CAS No	Name of the Chemical Agent	Limit values				Directive/National law
			TWA		STEL		
			mg/m³	ppm	mg/m³	ppm	
211-128-3	630-08-0	Carbon monoxide	-	25	-	-	NP 1796:2014
233-271-0	10102-43-9	Nitrogen monoxide	30	25	-	-	91/322/EEC
233-272-6	10102-44-0	Nitrogen dioxide	-	0,2	-	-	NP 1796:2014

(1) EC No: European Community number, the numerical identifier for substances within the European Union

(2) CAS No: Chemical Abstract Service Registry Number

(3) TWA: Measured or calculated in relation to a reference period of 8 hours time-weighted average

(4) Short-term exposure limit (STEL): a limit value above which exposure should not occur and which is related to a 15-minute period unless otherwise specified.

(5) ppm: parts per million by volume in air (ml/m³)

Table 3 - Previous Indicative Occupational Exposure Limit Values for Spain (Diogo, 2017)

EC No	CAS No	Name of the Chemical Agent	Limit values				Directive/National law
			TWA		STEL		
			mg/m^3	ppm	mg/m^3	ppm	
211-128-3	630-08-0	Carbon monoxide	29	25	-	-	-
233-271-0	10102-43-9	Nitrogen monoxide	30	25	-	-	91/322EEC
233-272-6	10102-44-0	Nitrogen dioxide	5,7	3	-	-	-

The IOELVs for Portugal and Spain are very similar regarding the TWA limit values of CO and NO. However, the NO_2 TWA limit values are distinct.

Although the CO's TWA limit values are defined by national law, for Portugal and Spain the IOELVs are equal in ppm (25 ppm); in Spain the TWA limits values of CO are also defined in mg/m^3, however, in Portugal the values are not defined in these units. The NO's TWA limit values are both defined by the same Directive, therefore, both countries present the same TWA's IOELV.

The limit values defined for the NO_2 are imposed by each country national law and, in this case, are distinct. The Portuguese law is more restrictive than the Spanish law and the Commission Directive 2017/164 regarding the measures in ppm's but does not present limits in mg/m^3. Nonetheless, the Spanish law is in agreement with the majority of the other European countries (Austria - 3 ppm, Belgium - 3 ppm, France - 3 ppm (Sifferlinger, 2017)).

Regarding the STEL limit values, it is possible to verify that currently there are no limits established on the countries under analysis. However, on the Commission Directive 2017/164 are established STEL's for the CO and NO_2. This new criterion takes into consideration situations where the TWA values are surpassed and workers might be exposed to a threatening situation; on these cases the workers should not be exposed for more than 15 minutes, in order to not be in risk. Therefore, these limits should never be exceeded.

In table 4 are shown the reduction, in percentage (considering the values in ppm), necessary for CO, NO and NO_2 values on the two countries mentioned before (Portugal and Spain).

Table 4 - Reduction in percentage

EC No	CAS No	Name of the Chemical Agent	Reduction in %	
			Portugal	Spain
211-128-3	630-08-0	Carbon monoxide	20	20
233-271-0	10102-43-9	Nitrogen monoxide	92	92
233-272-6	10102-44-0	Nitrogen dioxide	-[(6)]	83.33

The reduction that presents the greater challenge is the NO. The CO reduction, although relatively smaller, it still presents challenges. Concerning the NO_2 reduction, for Portugal, this does not seem to translate into a problem (since the new IOVELs is higher than the present limit value) for Spain, and most of Europe, the reduction is also very significative and can be translated in a challenge to fulfil the new limit values.

The great reductions displayed in table 4, verify the challenges that the Commission Directive 2017/164 present for the underground mining industry.

2.2. Consequences of Gas Emissions

In normal temperature and pressure (NTP) conditions, the fresh air is composed by 78% of nitrogen (N_2), 21% of oxygen (O_2) and around 1% of other gases, such has carbon dioxide (CO_2), helium (He), methane (CH_4), carbon monoxide (CO), among others.

In underground mining environment the temperature and pressure conditions are different, and the gases can be present in higher percentages than in NTP, becoming toxic. Gases, such as, carbon monoxide, carbon dioxide, sulphur dioxide (SO_2), nitrogen oxides (NO_x) hydrogen sulphide (H_2S), represent this hazard. The presence of these gases in certain concentrations can cause health issues and sometimes be lethal.

As mentioned previously, the Commission Directive 2017/164 focus on the CO, NO and NO_2. For this reason, these gases will be in the focal point of this thesis.

The CO is present in fresh air with a percentage around 0,000025% (0.25 ppm). As reported by IMRC (2016), the effects of CO start to be experienced at about 0,02% (200 ppm); if the air contains 0,2% (2000 ppm) of this gas, it can be fatal after one to two hours of exposure. The inhalation of this gas presents several symptoms, from a headache to breathlessness and finally loss of consciousness. The poisoning by CO occurs by the formation of carboxyhaemoglobin in the bloodstream, which blocks the haemoglobin in the blood, in other words, it causes a reduction of red cells and consequently less molecules to transport oxygen. This gas is colourless, odourless and tasteless, which makes it extremely hard to detect and *"can be determined reliably only with measuring equipment"* (Sifferlinger, 2017).

[(6)] For Portugal there is no reduction of the NO_2 limit value, in fact there is an increase.

The NO and the NO_2 are from the family of nitrogen oxides. The NO_2 is originated through the NO's oxidation: *"The NO gas will in air be slowly oxidized to NO_2 gas"* (Vestre, 2005), as shown in equation (1):

$$2NO + O_2 \rightleftharpoons 2NO_2 \quad (1)$$

These gases present a yellow to brown colour and have a very strong and fetid smell. The intake of these gases leads to the lung's destruction. Although their inhalation has the same effects the *"NO_2 is approximately 10 times more toxic than NO and about 17 times more toxic than CO"* (Harris *et al.*, 2003).

Although the Commission Directive 1614/2017 does not mention the values of oxygen, the presence of this gas will affect not only the miner's health, but also the function of explosives and even machinery. The low concentration of this gas can lead to several health issues and even death. As mention before, the fresh air is composed by 21% of O_2; a concentration around 13,5% can lead to difficulty in breathing and if it reaches a concentration below 10% can be fatal (Sifferlinger, 2017). The concentration of O_2 can only be measured with equipment, but if an open flame extinguishes, it is an indication that the concentration of this gas is below 16%. Low concentration of O_2 can also influence the gases reaction, that is, the oxidation of CO to CO_2 and of NO to NO_2.

Even though the atmosphere inside the mine is different from the NPT atmosphere, is still crucial to have a good air quality for the miner's safety, and so, it is critical to control de quantity of the gases, specially the toxic gases. To understand the gases' presence inside the mine, it is required to know how they are produced.

2.3. Principal Causes of Emissions

The presence of toxic gases in underground mines has several origins, but *"The exposure of workers will mainly occur in active mining and extraction areas due to machinery and explosives used"* (Euromines, 2017). The technical operations related with production and extraction can lead to emissions. It is also possible to perceive that the blasting process fumes are a source of gases. Therefore, the use of explosives and diesel equipment are the main causes of most toxic gases present in this environment, *"The concentration of NO, NO_2 and CO in workplaces in underground mines arises predominately from the use of explosives and from vehicles and mobile machines equipped with diesel engines"* (Euromines, 2017). Depending on the mineral being explored, its extraction or reaction with the oxygen and other gases can lead to fires and, perchance, explosions, as it is the case of pyrite; this event is not a normal occurrence in a mine, however its occurrence can lead to major impacts, including the abrupt increase of toxic gases inside the mine.

On this chapter will be done an analysis of the emissions produced by commercial explosives, diesel vehicles and the mine fires caused by pyrite's decomposition.

2.3.1. Explosives

The use of explosives is a source of toxic gases in the underground environment. *"Toxic fumes production should also be accounted when selecting explosives and primers"* (Harris *et al.*, 2003). The proper explosive selection can have a great influence in the amount of gases released, leading to a safer work environment and have a great economical advantage. *"The mining industry is fully committed – mainly driven by economics factors and workers protection - to optimize the use of explosives"* (Euromines, 2017).

The selection of explosives is made considering the following aspects, as stated by Bernardo (2014), Economical factor (e.g. cost of explosive and cost of drilling), rock mass characteristics (e.g. geomechanically properties, fracturing), explosive's characteristics (e.g. storing necessities), existing conditions (e.g. water presence and temperature of the rock at the drill hole), expected results (e.g. fragmentation intended and volume of rock to blast), and environment's restrictions (e.g. vibrations, sound and atmospheric contaminants – dust and gases).

According to Bernardo (2017), there are three types of explosives more common on the market: dynamite, ammonium nitrate-fuel oil (ANFO) and explosive emulsions. The dynamite is composed by a combination of nitro-glycerine, absorbents and stabilizers. The ANFO is a mixture of approximately *"94,6% AN* (ammonium nitrate) + *5,4% fuel oil (≈ diesel)"* (Hartlieb, 2017). The emulsion is the newest development in explosives, and it is composed by "*saturated AN solution mixed with oil"* (Hartlieb, 2017) and sensitized with micro spheres, that can be made with glass or plastic; this type of explosive can have from 40% to 85% of AN (Joyce, 1992) In table 5 are addressed other characteristics from the explosives mentioned before.

Table 5 - Characteristics of Explosives (Bernardo, 2014)

Type of explosive		Dynamite	ANFO	Emulsion
Resistance to water		Yes	No	Yes
Packaging	Bulk	No	Yes	Yes
	Cartridge	Yes	Yes, but very unusual	Yes
Density (kg/m^3)		1,4 / 1,5	0,85 / 1,0	0,9 / 1,45

The toxic gases produced by explosives will depend on the type of explosive, the quantity of explosives used, the rock mass and the surrounding atmosphere; *"carbon dioxide, water vapor, and nitrogen are always produced. In addition, CO, NO, NO_2, methane (CH_4) and hydrogen (H_2) may from in large or small quantities"* (Harris *et al.*, 2003). The oxygen-balance will also have an influence on the toxic gases produced by the explosives. The explosive reaction's main reagents are the oxidizers and the fuel-sensitizers. According to Dick & Ehrhorn (1973), the oxygen's quantity will depend on the on the ratio between these two reagents:

- Oxygen balance: 94,5% oxidizer and 5,5% of fuel-sensitizers;
- Oxygen deficiency: 92% oxidizer and 8% of fuel-sensitizers;

- Excess Oxygen: 96,6% oxidizer and 3,4% of fuel-sensitizers.

When there is an oxygen deficiency, *"the carbon in the fuel oil is oxidized only to CO"* (Dick & Ehrhorn, 1973). When there is excess oxygen, the nitrogen, from the AN, reacts with the oxygen forming NO, which can, subsequently, react with the oxygen present on the fresh air and produce NO_2 (Dick & Ehrhorn, 1973).

Explosives are one of the main producers of NO_x in the mine, especially because of the presence of AN in their composition. The AN are possible to find after blasting, but also in waste rock disposal, in the mine's water and as a cement product. The introduction of AN in the mining system can be diminished with proper selection of explosives, the water conditions in the mine, the explosives correct handling and the blasting operations efficiency (Forsyth *et al.*, 1995).

According to Joyce (1992), when the AN is in contact with cement or shotcrete, ammonia gas can be generated. The composition of cement can vary but always contains calcium oxide (CaO). When the cement is mixed with water, calcium hydroxide ($Ca(OH)_2$) is produced. When calcium hydroxide enters in contact with water the result will be an alkaline solution. When the AN comes in contact with the alkaline solution it will release ammonia (NH_3).

In accordance with Forsyth *et al.* (1995), the water's conditions in the mine influence directly the volume of water in the blastholes and, consequently, the exposure of water to the explosives. This will influence the nitrogen in the mine's water cycle.

The explosives' correct handling should be done during all stages of its process. Spillage of explosive can lead to a greater quantity of nitrogen in the mining environment, since the explosive's spillage can enter the rock disposals and the water system. Most explosive's spillages occur while filling the equipment, filling the blastholes and when the excess of explosive is discarded. *"Appropriate handling and loading procedures represent the most cost-effective means of reducing nitrate concentrations" (*Forsyth *et al.*, 1995). The type of explosive used on the mine is a crucial factor to educate the miners how to handle the product. For example, explosives that are not water resistant, dissolve in the water, when the loading processes are not conducted properly there is a higher quantity of nitrogen inflowing the water system.

The blasting operations efficiency will influence the misfires. Even with a good boreholes' design and a good execution there will be misfires. The undetonated boreholes will contaminate the muck piles with explosive. *"NO, along with CO, can remain in the expanded rock for a long time and NO only gradually to NO_2 with exposure to oxygen. NO_2 will rapidly dissolve in water and absorb strongly on most surfaces"* (Harris *et al.*, 2003).

The development of explosives is fundamental to mining companies, since *"the further development of economically reasonable explosives to lower the amount of blasting fumes and optimise their components concerning new exposure limits"* (Euromines, 2017).

2.3.2. Diesel Equipment

Energy is a cornerstone to mining *"the mining sector accounts for 7% of the world's energy use"* (Hertwich *et al*., 2010 in Bharathan *et al*., 2017) from which 19% is electric power, 3% renewable energy and 78% fossil fuels (Bharathan *et al*., 2017), without taking into account the smelters.

Diesel equipment are one of the main sources of toxic gases; exhaust emissions from this equipment expose the workers to health-related risks, since it is considered carcinogenic. The diesel exhaust emissions *"contains nitrogen, oxygen, water, and the asphyxiant carbon dioxide, it also contains recognized noxious, toxic and potentially harmful substances."* (Schanakenberg & Bugsrski, 2002). Constituents such as NO, NO_2, CO and diesel particulate matter (DPM) can be extremally toxic and *"represent the most difficult diesel engine emissions to control"* (Euromines, 2017). In figure 1, it is possible to analyse the percentages by weight of diesel emissions.

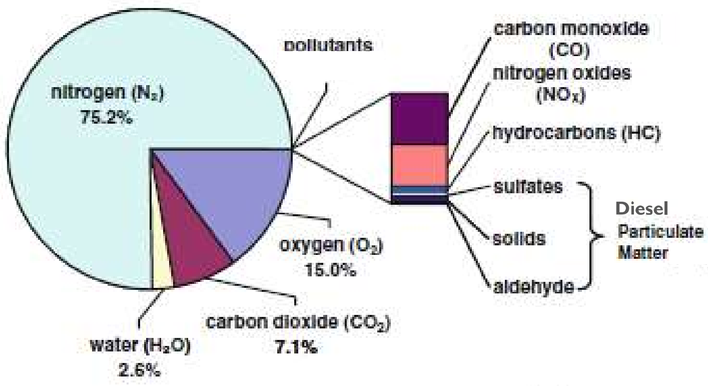


Figure 1 - Diesel engine emissions (Tschoeke, et al., 2010)

As seen in figure 1, the toxic substances of exhaust diesel emissions are a very low percentage, approximately 0,1%; however, they represent serious health problems to which the workers are exposed.

The CO emissions from diesel engines are low and, if the temperature is high enough, when the carbon monoxide is mixed with the air, it oxidizes into carbon dioxide (Tschoeke *et al.*, 2010) that is less toxic than carbon monoxide (Dick & Ehrhorn, 1973).

Although the CO_2 is not as toxic (in comparison with CO, NO and NO_2), when its concentration on the atmosphere is higher than 1% it can become toxic, and if it reaches concentrations greater than 10% can be fatal. According to figure 1, the CO_2 represents 7,1% of the diesel emissions, adding to this percentage the oxidation of the CO, it can turn the atmosphere into a highly toxic one.

The nitrogen oxides of diesel exhaust emissions are composed by NO and NO_2. The thermal formation of NO can occurs through reactions (2), (3) and (4) (Tschoeke *et al.*, 2010):

$$N_2 + O \rightleftharpoons NO + N \quad (2)$$

$$O_2 + N \rightleftharpoons NO + O \quad (3)$$

$$OH + N \rightleftharpoons NO + H \quad (4)$$

The NO_2 represents from 5% to 15% of the NO_X diesel emissions. This gas can be produced by the reaction stated in equation (1) or (5):

$$NO + HO_2 \rightleftharpoons NO_2 + OH \quad (5)$$

Even though the hydrocarbons (HC) and the DPM are explicit in the Commission Directive 2017/164, it was considered important to mention, since these pollutants are dangerous hazards driven from the use of diesel as source of energy.

The HC are *"the major organic pollutants in diesel exhaust"* (Schanakenberg & Bugsrski, 2002) and occur due to low temperatures during combustion (Tschoeke *et al.*, 2010). These emissions can be materialized in gas, condensed liquid or solid; the phase will depend on molecular weight, temperature and concentration (Schanakenberg & Bugsrski, 2002).

The DPM *"is emitted by diesel engines due to incomplete combustion and impurities in the fuel"* (Vergne (2003) in Jacobs *et al*., 2015). According to Ristovski *et al*. (2011), DPM are a mixture of solid and liquid particles suspended in a gas, and its composition will depend on many factors, such as: engine operating conditions, after-treatment devices, maintenance status, type of fuel and lubricants. In figure 2 is described the relation between this particulates' sources. DPM exposure is associated with several health problems, such as, the respiratory system obstruction and can even be a cause for lung cancer. Although DPM appear in a very low percentage when compared to other emissions, they constitute a major hazard and henceforth *"underground miners are exposed to the highest concentration of DPM of all occupations"* (Jacobs *et al*., 2015). Although it is not mentioned on the Directive being studied, the EU imposed limit values for DPM. According to European Environment Angency (2018), the limit value is 50 µg/m^3 and this value should not be exceeded on more than 35 days per year.

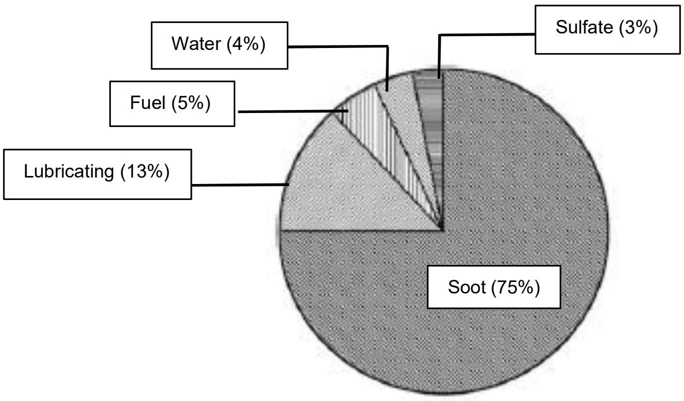


Figure 2 - Typical diesel particulate matter composition with a standard oxidation catalysis (Tschoeke, et al., 2010)

Through the previous analysis allows to comprehend the many hazards compelled by the use of diesel vehicle in the mines. However, the focus of this research will be in the NO_x and CO, since these gases are present in the IOELV in the Directive fourth list.

2.3.3. Mine Fires: Pyrite's Decomposition

The pyrite is the most common sulphide minerals (Chandra & Gerson, 2010). On mines with pyrite, there is an associated danger of fires due to the pyrite's decomposition. The pyrite is classified as an iron sulphide, and its chemical structure is FeS_2. When this mineral is exposed to the fresh air, available on the mine, it starts oxidizing promptly (Chandra & Gerson, 2010). *"Pyritic sulphides will oxidize at normal ambient temperatures"* (Calizaya & Marks, 2011). The oxidation of pyrite will lead to the production of sulphur dioxide (SO_2). The mixture of SO_2 and the fresh air, in a certain ratio, will lead to an explosive atmosphere. If the there is an ignition source, it can induce an explosion, followed by a fire.

The fire on an underground mine are particularly dangerous because of the confined spaces on the mine, the toxic gases and fumes produced and the hardship to rapidly control its dispersion through the mine, and the difficulty of the miner's evacuation (MIAC, nd).

Although the pyrite decomposition can cause one of the greatest hazards on a mine, there are several ways to control it. In Portugal, there are two mines with pyrite (Almina and Somincor) that implement the following control measures:

- The ventilation should be enough for the dissipation of SO_2, creating a lower quantity of this gas and limit the possibility to achieve the explosive ratio;
- The watering should always be done after blasting, to decrease the toxic gases on the atmosphere;
- The explosives should be of lower temperature (such as emulsions);
- The drilling holes after filled, should be buffered, preferably with clay.

These mitigations measures should always be applied on mines with pyrite to decrease the possibility of explosions and mine fires.

2.4. Measurements Methods

On underground mines there is the necessity to measure the temperature, humidity, air velocity, level of gases, dust, DPM, noise, radiation, among other parameters. The measurements of these parameters are done to evaluate and create a quality work environment and to detect any alarming conditions. In the case of gases, it is essential to control the levels, because the presence of these can cause serious health issues and some even can lead to death.

The appropriate gas detectors selection should be made considering the mine's layout, the types of gases, and *"other hazardous substances, is short-term, long-term, or continuous measurement to be used, is it necessary to have warning and alarm functions when limits are exceeded"* (Dräger, 2012). In general, mines have fixed and personal/portable devices. The placement for the fixed devices may change due to the necessity of measurements in different sites, such as workshops, ramps and stopes. Each worker should always carry a device, namely after detonations, therefore, in addition to the fixed devices, there are the personal devices.

Personal detectors can be used in four situations: personal monitoring, area monitoring, confined space entry and leak detection. Personal monitoring allows the workers to measure the gases in the immediate work area, indicating the level of one or several gases and allowing the workers to know when they are in a dangerous environment. The devices for area monitoring should be placed in a central area in the workplace in order to alert the workers in case of dangerous concentrations. When entering a confined space, it is necessary to be extremely careful, since these spaces have little ventilation leading to a thin atmosphere; therefore, the measurement of toxic gases and the concentration of oxygen is mandatory before entering. Gases and liquids that are stored can leak and induce dangerous environments; the detection of these leakages will allow to take the necessary measures to prevent critical situations.

Although the mines do measurements periodically, for legal reasons and for the control of air quality, there are no legislations or directives with a methodology on how to do them and how regularly they should be done. Due to absence of a procedure to gather this data, a methodology must be created to record the values of the mines' gases, and possibly other hazards.

2.5. Ventilation and Dilution of Gases

The ventilation system is crucial for the proper operation of a mine. Throughout the mine ventilation is able to: supply fresh air, cool the work fronts and dilute the toxic and explosives gases (Camacho, 2017). According to Sifferlinger (2017), ventilation can represent 25% up to 40% of the energy cost, and in the case of deep mines, it can reach 50% of the costs.

The ventilation's layout of a mine must consider the intake flow and the return flow. The intake flow brings the fresh air to the mine into the work fronts or places with a high concentration of hazards (e.g. toxic gases, high temperatures). After being exposed to pollutants, fresh air becomes contaminated and it goes through the return airways.

The ventilation system of a mine can be divided in main and secondary ventilation. The main ventilation consists on the system that brings the fresh air inside the mine, through the intake airways, and removes the contaminated air, through the return airways. The secondary ventilation can be divided in auxiliary ventilation and structures. The auxiliary ventilation are the fan and sleeves assembled inside the mine with the purpose of redirecting the airflow to areas where the main ventilation is not enough. The structures can be assembled in several parts of the mines and the main, and general, purpose is to redirect the airflow creating a more balanced system and reducing the ventilation energy costs.

There are two types of ventilation: natural ventilation and forced ventilation. To know which type of ventilation will be used in a mine it is necessary to know the pressure differences, since *"flow occurs because a pressure difference is created between two points in the system"* (Sifferlinger, 2017).

The natural ventilation is dependent from the disparity of temperatures between the interior and the mine's exterior, and the elevation difference between the work fronts and the surface. The natural ventilation will work by the thermodynamics reason, in which heat rises; and so, the ventilation intensity will depend on the natural pressure which is originated by the air columns movement: the column of cooler air, which is heavier, will induce the column of hotter air to move up, since it is lighter; the natural airflow will occur from the cool column side to the hot column side. The flow's direction depends on the temperature gradient between the outside and the inside; if it is hotter outside it has one direction and if it is cooler it has the opposite direction; is it also important to mention that when the temperature difference is small, the change of temperatures during the day will have a great influence on the airflow as well in its direction. The mine's geometry has a great impact on the airflow, as well; greater the depth difference between the columns, greater the flux of air.

The forced ventilation is done by artificial means, such as fans/ventilators. According to Bernardo (1995), this ventilation type is most commonly used on the mines. Therefore, the directions and the intensity of airflow are well defined and can be changed when and how its best suits the mine. This type of ventilation can be done by an exhausting system or a supply system. The exhausting ventilation occurs when the main fan withdraws the contaminated air from inside the mine, forcing fresh air to enter. On supply ventilation system, the main fan forces the entrance of fresh air and, consequently, the contaminated air is compelled to leave the mine. It can also be used a system with both an exhaust and supply ventilation.

The use of natural ventilation allows lower operational costs. However, it is highly influenced by natural factors, impossible to control. When forced ventilation is used, it is necessary to acknowledge the natural flow of air on the mine, so that the ventilation is preserved and enhanced.

The principal equipment in the main ventilation system is the main fan, whereas it will have to last the mine lifetime and it must be capable of producing airflow in a volume and pressure to sustain all the mine. To choose the fan it is necessary to know the volume of air moved by the fan (Q), the load (H), the power (P) and the efficiency (η). In figure 3, is possible to analyse the characterization curves of a fan (where H_t is maximum load and H_v is the fan load).

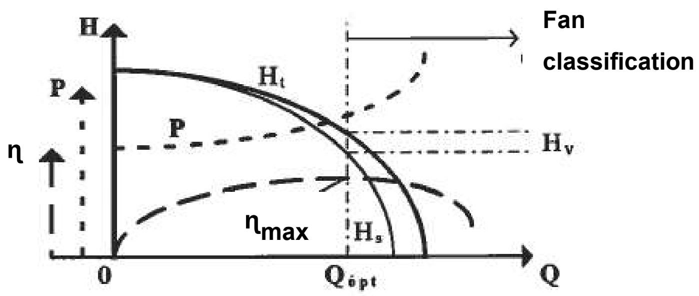


Figure 3 - Characterization curves of a fan (Bernardo, 1995)

Since Q is a value determined by the law of each country, the other parameters should be characterized in function of Q. P and η, can be calculated, as a function of Q, by the equations (6) and (7), respectively:

$$P[W] = \Delta p\ [Pa] * Q[m^3/s] \tag{6}$$

P: $Fan\ power$

Δp: $Pressure\ rise\ inside\ the\ fan$

Q: $Volume\ of\ air\ moved\ by\ the\ fan$

$$\eta = \frac{Q[m^3/s](p_{stat}[Pa] + p_{dynamic}[Pa])}{P_{electric}[W]} \tag{7}$$

η: $Fan\ efficiency$

p_{stat}: $static\ pressure\ at\ the\ fan$

$p_{dynamic}$: $dynamic\ pressure\ at\ the\ fan$

$P_{electric}$: $electric\ power\ installed$

With the development of a mine, it may be necessary to associate fans in order satisfy the new necessities. The association can be done by fans in series or in parallel. On the first case, the airflow goes through one fan at the time, increasing the load [$H_1 + H_2 = H_{1+2} = H_T$] but the volume of airflow is the same [$Q_1 = Q_2 = Q_T$], as it is shown in figure 4.

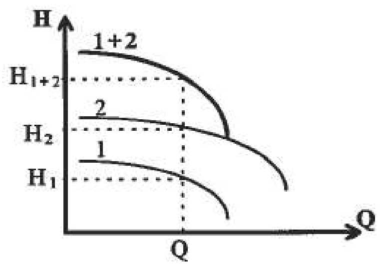


Figure 4 - Characterization curves of two fans in series (Bernardo, 1995)

On the second case, the airflow is divided by both fans, increasing the volume of air [$Q_1 + Q_2 = Q_{1+2} = Q_T$], while the load in the same [$H_1 = H_2 = H_T$], as figure 5 demonstrates

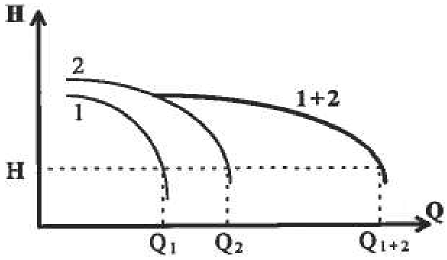


Figure 5 - Characterization curves of two fans in parallel (Bernardo, 1995)

Complementary to the main ventilation system, there is the necessity of auxiliary ventilation in drifts and stopes, because these areas do not have a natural airflow and the main ventilation is generally not enough to remove the contaminated air and supply the area with enough fresh air. The auxiliary ventilation can be done by a forcing system, an exhausting system, or a combination of both systems, that in its turn can be a forcing system with an exhaust overlap or an exhausting systems with a force overlap (Tuck, 2011), as it is shown, respectively, in figure 6. In supply ventilation the fresh air passes through a portable fan and it is blown through flexible ventilation sleeves into the work front and the contaminated airflows naturally to the return airway. In the exhaust ventilation, the contaminated air is removed by a fan through rigid ventilations tubes, and the fresh airflows naturally goes to the work front. In a combination system, both tubes are installed.

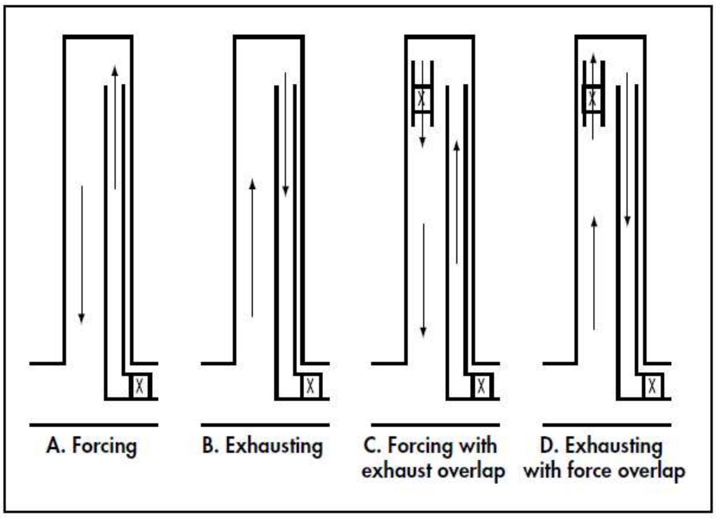


Figure 6 - Auxiliary ventilation, forced, exhaust and combination, respectively (Tuck, 2011)

With the development of a mine, it is also necessary to create structures to regulate and direct the airflow. These structures can be stoppings, seals, doors, regulators and air crossings. The stoppings are built inside a stope still being explored when an access is no longer necessary. In order to stop the flow of air to that area, structures of masonry, concrete, steel or wood are made. The seals are used to isolate an abandoned area that no longer needs ventilation; wood doors are built, and the interior is filled with cement, pastefill or hydraulicfill, leading this structure to be permanent. The doors are built when there is a need to separate the intake and return airway, but it is still necessary to have access between the areas; when this structure is built between the main intake and return airways, it is created an airlock, by setting up two doors, which will prevent short circuits. The regulators can be classified as passives, that are made by creating orifices in doors, and actives, that increase airflow by the means of a booster fan. The air-crossing structures are created when the intake airflow and the return airflow must pass through the same area; it is created a tube, so the airflows do not mix, and the intake air does not become contaminated.

For the implementation of a ventilation system that meets the mine needs, it is compulsory to calculate the minimum airflow required. The required airflow must be able to dilute the toxic gases, cool down the temperature inside the mine, and to supply fresh air to the personal. The amount of fresh air necessary, will differ in each country, but it is always considered, at least, a minimum of fresh air per person and per diesel power engine. In table 6 are shown the values for Portugal, for the quantity of fresh air for people and diesel equipment:

Table 6 – Mandatory fresh air volumes for Portugal

Country	Law	Fresh air per person (m^3/min/person)	Fresh air per diesel power engine (m^3/min/kW)
Portugal	DL 162/90	3	2,8 [7]

As mentioned previously, it is also required to analyse the need of fresh air under special conditions, such as, in a toxic atmosphere (e.g. after detonations). In a toxic atmosphere is mandatory to dilute the gases before the workers enter the area; the TLV of each gas will demand the amount of fresh air necessary for its dilution.

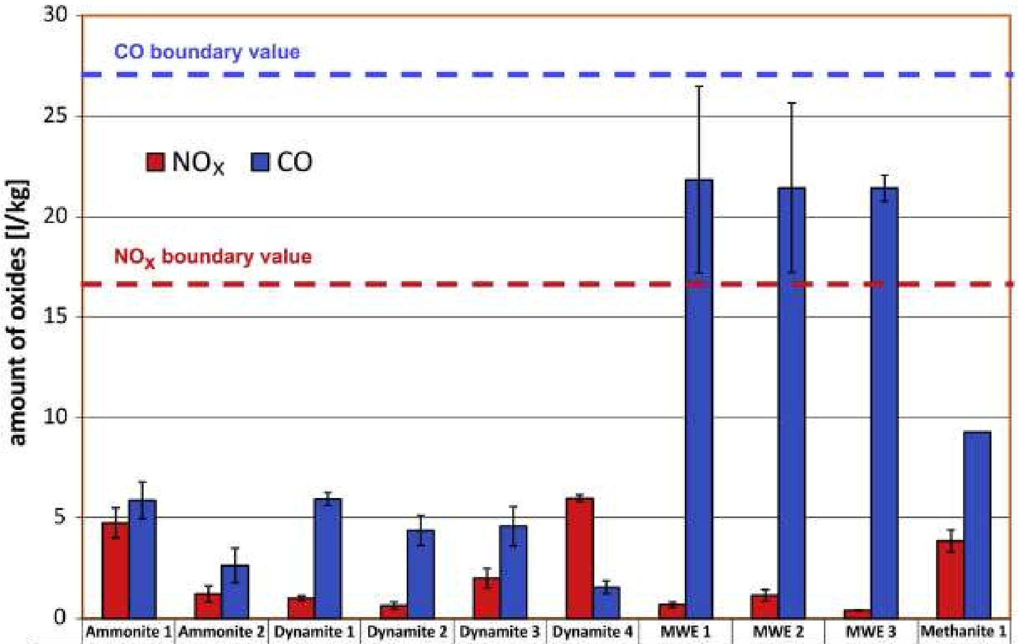
2.6. Explosives Comparison

Nowadays the most used commercial explosives are ANFO and emulsions. Dynamite is very unstable, creating dangerous environments when it is used. For this reason, in this chapter it will be done an assessment focussed on the differences between ANFO and emulsions. As reported by Vestre (2005), these two explosives can be compared considering the following aspects: detonations fumes, visibility, dust, nitrogen run-off, nitrite and ammonia; nevertheless, it will only be compared the difference between detonation fumes, due to the dissertation objective.

As previously described, the explosives' detonation will lead to a release of gases *"detonation products depend both on their* [explosives] *chemical composition and the conditions in which detonation occurs"* (Zawadzka-Malota, 2016). One of the products of detonation are the toxic gases, such as, CO and NO_x, and its quantity will be influenced by: *"the degree of confinement of an explosive charge and the material being blasted"* (Sapko *et al.*, nd).

[7] The equivalence considered was 1 cv=0,7355 kW

Regarding the research, led by Zawadzka-Malota (2016), on which were compared the gases released form the detonation of ten explosives (ANFO: Ammonite 1, Ammonite 2, Methanite 1; Dynamite: Dynamite 1, Dynamite 2, Dynamite 3, Dynamite 4; Emulsion: MWE 1, MWE 2, MWE 3). The results related with the amount of NO_x and CO, are displayed in figure 7. The units regarding the gases' values are in L per Kg of explosive.



	Ammonite 1	Ammonite 2	Dynamite 1	Dynamite 2	Dynamite 3	Dynamite 4	MWE 1	MWE 2	MWE 3	Methanite 1
NOx	4.74	1.22	0.99	0.64	2.00	5.96	0.68	1.15	0.40	3.86
CO	5.87	2.63	5.93	4.37	4.58	1.56	21.85	21.43	21.43	9.29

Figure 7 - Presentation of the mean values of CO and NO_x in explosives blasting gases with regard to the boundary values required in Poland in the year 2015 (Zawadzka-Malota, 2016)

Through the analysis of figure 7, it is possible to theorize the average of toxic gases released by the two explosives in comparison: after the detonation of an emulsion, the CO released is approximately 3 times higher than after an ANFO detonation; however, regarding the NO_x, the emulsion will release values approximately null, unlike ANFO, which the levels of NO_x are considerable higher.

Through the ®*Orica Mining Services* software, ®*IDeX*, it was done a simulation regarding the gases produced during a detonation using ANFO and a detonation using bulk emulsion. This data was provided by ®*Orica Mining Services* Portugal, in order to do a comparison regarding the ANFO and the Emulsion. The results from ANFO's simulation are revealed in figure 8; and from emulsion's simulation in figure 9.

Products produced at the detonation (CJ) State

	Product	Moles/kg	g/100 g, %ww	l/kg @ STP
CH4	methane	0.0000	0.0000	0.000
CO	carbon monoxide	0.2823	0.7907	6.327
CO2	carbon dioxide	3.9158	17.2332	87.767
H2	hydrogen	0.1625	0.0328	3.642
NH3	ammonia	0.0132	0.0224	0.295
H2O	water	27.1123	48.8436	607.691
N2	nitrogen	11.7348	32.8731	263.021
NO	nitric oxide	0.0555	0.1665	1.243
O2	oxygen	0.0129	0.0412	0.288
C(G)	carbon	0.0000	0.000	
C(D)	carbon (diamond)	0.0000	0.000	
Sum		43.2892		970.275

Figure 8 - Products produced at an ANFO detonation[8]

Products produced at the detonation (CJ) State

	Product	Moles/kg	g/100 g, %ww	l/kg @ STP
CH4	methane	0.0094	0.0151	0.210
CO	carbon monoxide	0.3463	0.9701	7.762
CO2	carbon dioxide	5.1250	22.5551	114.871
H2	hydrogen	0.1266	0.0255	2.838
NH3	ammonia	4.0246	6.8541	90.207
H2O	water	26.6718	48.0501	597.817
N2	nitrogen	7.6855	21.5298	172.262
NO	nitric oxide	0.0000	0.0000	0.000
O2	oxygen	0.0000	0.0000	0.000
C(G)	carbon	0.0000	0.000	
C(D)	carbon (diamond)	0.0000	0.000	
Sum		43.9894		985.969

Figure 9 - Products produced at an Emulsion detonation[9]

Considering the results from both simulations (figure 8 and figure 9), was posteriorly calculated the products released percentages from both explosives in analysis (table 7). The detonation of explosives *"produces both toxic and nontoxic products"* (Mainiero *et al.*, nd) as it is possible to analyse.

[8] Data provided by ®*Orica Mining Services* Portugal
[9] Data provided by ®*Orica Mining Services* Portugal

Table 7 - Percentage of products produced for ANFO and Emulsions

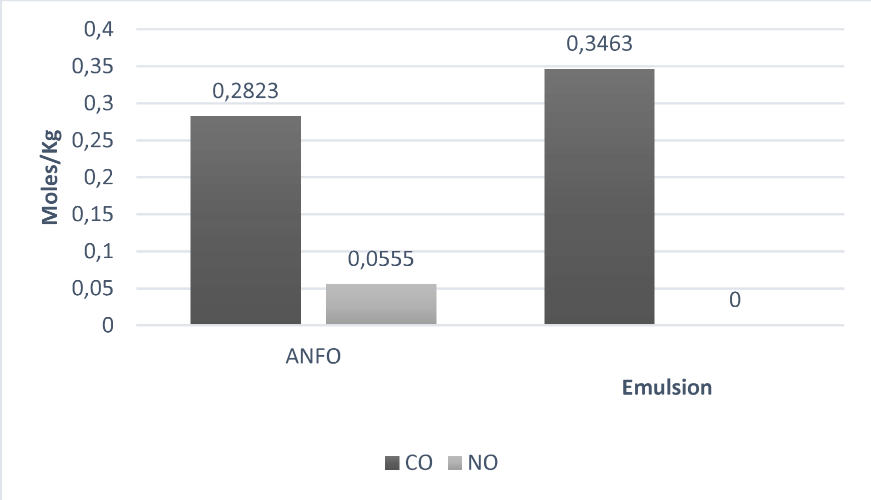
	ANFO	Emulsion
CH_4 (%)	0,00	0,02
CO (%)	**0,65**	**0,79**
CO_2 (%)	9,05	11,65
H_2 (%)	0,38	0,29
NH_3 (%)	0,03	9,15
H_2O (%)	62,63	60,63
N_2 (%)	27,11	17,47
NO (%)	**0,13**	**0,00**
O_2 (%)	0,03	0,00
C(G) (%)	0,00	0,00
C(D) (%)	0,00	0,00
Total (%)	100,00	100,00

Through the analysis of table 7, one can confirm that the principal gases produced are nontoxic: H_2O and N_2. According to Mainiero *et al*. (nd), the main toxic gases produced are CO and NO_x; however, regarding the simulation under analysis, the main toxic gases will differ according to the explosive. The main toxic gases produced by ANFO are CO and NO, but the main toxic gas produced by emulsions is the NH_3 and secondly the CO. Even though, the levels of NO are null, but, during the evolution of a detonation, the levels of NH3, may turn into NO due to its oxidation, as the following equation exemplifies:

$$NH_3 + O_2 \rightarrow NO + H_2O \qquad (8)$$

The production of NO_2 after detonation with ANFO or with emulsion, occurs due to the NO's oxidation, *"As the NO is released from the muck pile following the detonation of the blast pattern, the gas is further oxidized in the air to form the colourful after-blast fumes of NO_2"* (Sapko *et al*., nd), as shown in equation (1). Therefore, the concentration of NO_2 will directly depend on the quantity of NO.

The graphic 1 was done to compare the emissions of CO and NO, for ANFO and for emulsions, in moles/kg (moles of gas released per kg of explosive blasted).



Graphic 1 – Results from IDeX Simulation

From graphic 1 it is possible to conclude that: the ANFO produces lower levels of CO in comparison to the emulsion; the initial levels of NO after blasting with emulsion are null, unlike with ANFO. The simulation results are referring to the initial gases released after blasting with both type of explosives, for that reason and taking into account the reactions between the gases after blasting, more gases may form, such as NO_2, and the quantity of others may differ, for example, the NO can increase and the NH_3 decline (equation (8)).

The study, conducted by Sapko *et al*. (nd), with the objective of examining the factor that influence the NO_x (NO + NO_2) production in blasting, confirmed the previous results: *"the ANFO and 50/50 ANFO/Emulsion blend produced more NO_x than the emulsion"* as shown in figure 10. To justify this conclusion the authors presume that the ANFO has high amounts of AN when it starts to decompose produces NO_x [The AN is composed by ammonium (NH_4^+) and nitrate (NO_3^-) ions. The AN in the emulsion reacts with hydrocarbons producing nitrogen (N) and water, therefore, there is less NO_x on the atmosphere after an emulsion detonation.

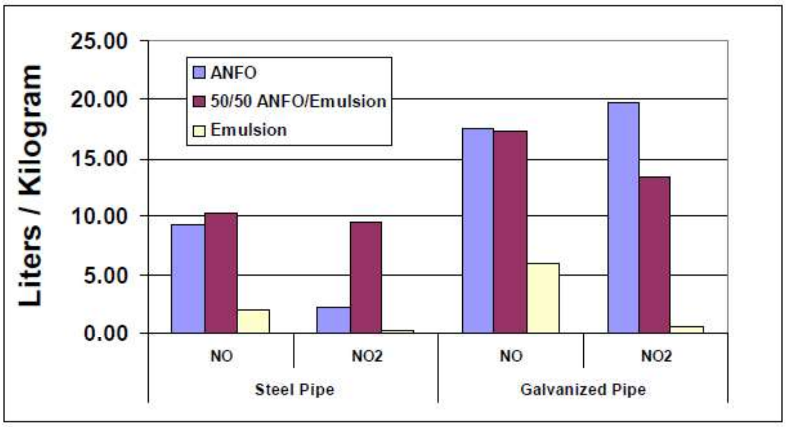


Figure 10 - The effects of relative confinement on the NO and NO_2 production from the detonation of ANFO, Emulsion, and 50/50 blend (Sapko et al., nd)

The atmosphere created after blasting can put the miners in great risk due to the presence of toxic fumes and dust. To create a more work-friendly environment is essential to remove the gases produced by blasting and clearing the air. The time frame when access must be temporarily interdicted is denominated by blast-clearance time or re-entry time. Several factors are considered when calculating the blast clearance time, such as, volume of the blasted area, explosive quantity, type of explosive, efficiency of the fresh air ducts, among others. However, *"re-entry times into development headings are often standardized based on worst case scenarios, resulting in unnecessary delays"* (Stewart, 2014).

According to Stewart (2014) there are three main methods to calculate a theoretical blast-clearance time:

a) A logarithmic decay method incorporating dispersion factors for distance away from the face as De Souza, Katsabanis, Roberts and Heidrich, proposed on 1991 at the paper "Blasting fume prediction and control as a means of reducing ventilation costs";
b) A modified logarithmic constant to improve correlation from Gillies, Wu, and Shires, proposed on 2004 at the paper "Development of an assessment tool to minimize safe after blast re-entry time to improve the mining cycle";
c) A computational fluid dynamic from Agasty, Clausen, Kellner and Langefeld, proposed on 2013 at the paper "After blast re-entry time for a room & pillar operation";
d) Stewart also proposed a method to calculate the clearance time by using a blast throwback approach on the paper "Practical prediction of blast fume clearance and workplace re-entry times on development headings" (2014).

The use of these methods to calculate the blast-clearance time will contribute to an optimization of this re-entry, and, consequently, the works will be stopped for less time, resulting in more production. However, a common time used is 30 minutes (Sirait, Widodo, & Simanjuntak, 2013), or by estimating the gases decay after blasting, or even by the experience acquired at each mine.

The studies previously addressed, and the dada provided reach the same conclusion, regarding the gases formed thereupon a detonation:

- The CO values are higher after an emulsion blasting in comparison with ANFO;
- The NO values are low, almost null, after emulsion blasting unlike ANFO blasting;
- The NO_2 values are low with the use of both explosives, however, with the oxidizing process of NO, the nitrogen dioxide values start to increase.

Considering that the toxicity of the NO_2 when comparing with the NO and the CO (Harris *et al.*, 2003), the use of emulsion can lead to a safer work environment.

2.7. Equipment Alternatives

Nowadays, on underground mines, most equipment runs on diesel. Even though some equipment can perform with electric energy (e.g. jumbos), the movement between the work sites is done with the use of diesel. Recently, there has been developments regarding the use of electric energy as a power source, with the motivation of decreasing the energy costs regarding the diesel consumption and the ventilations and to improve the air quality (Paraszczak *et al*., 2014).

The haulage system "*involves transportation of mined-out material from the faces (draw points) to the loading areas, and them to the mine surface"* (Salama *et al*., 2014). Considering the operations on the haulage system, is possible to analyse that most costs on this phase will depend on *"fuel costs, haul road conditions, idling time, over/under loading, maintenance, operator competency"* (Bharathan *et al*., 2017). Most of the energy consumed on the underground mine, being *"Diesel fuel, the principal power source for haulage in underground mines"* (Bharathan *et al*., 2017). Consequently, the machines used on loading and haulage operations are the bigger consumers of energy, *"Loaders and trucks consume about 80% of the diesel fuel shipped underground"* (Svedlund, 2018); therefore, presenting the biggest challenge to reduce the diesel emissions. The loading equipment extracts the ore or waste from the face into the haulage equipment or ore pass and can be done by shovels. The haulage equipment will transport the ore from the face to the dumping area (such as ore passes, conveyor belt, the surface or crushers); this process is usually done by haulage trucks. Another equipment that is important to mention is the load-haul-dump (LHD), that is a combination of a loading and haulage equipment, since it can extract the ore from the face and transport it to the dumping area without the need of any other equipment. This thesis will mainly focus on the following equipment, since they present the main demand for energy regarding diesel:

- **Loading Shovels**

The loading shovels can be distinguished into two main types: excavators and wheel loaders. The main differences consist on the loading times and time of dislocation between faces. The excavators allow a lower loading time, since the manoeuvres, at the face, are done on the same axis, allowing faster movements; however, the dislocation between faces is slower. The wheel loaders, have the opposite characteristics, having higher loading times and lower dislocation times.

- **Haulage Trucks**

There are two types of haulage trucks: rigid and articulated. The choice between them will depend on the mine conditions, hauled material, production rates and loading equipment. The rigid trucks are prepared to transport higher quantities of material, and can handle great impacts in the loading process, nonetheless the roads need to be well maintained, for the trucks be able to circulate. On the other hand, articulated trucks are built for adverse road conditions, because they allow an easier manoeuvre; they are also prepared for narrow dumping areas and are more flexible to the loading operation, however, the quantity of material transported is less than the rigid trucks.

- **LHD**

The use of a LHD on a mine will dismiss the use of loaders and trucks. LHDs are typically used in mines with narrow areas and haul the material for small distances. The capacity of this machines will depend on the bucket size, that can go from $3m^3$ to $11.6m^3$.

On this chapter are approach solutions, on the market, to reduce or annulate the emissions produced by the diesel vehicles used inside underground mines.

2.7.1. Diesel Equipment

As mentioned before, diesel equipment is used in most mines of the world. These equipment presents some clear advantages:

- High mobility and versality, allowing to machine to dislocate inside and outside the mine without restrictions (Jacobs, 2013);
- No need for specific infrastructures on the mine, except fuel stations;
- Diesel can be *"easily transported and refilled into a tank in matter of minutes"* (Kukkonem, 2017) meaning that they can operate with barely any stop time for energy.

Although it is the most commonly used equipment, the disadvantages are in agreement with the governments' pressure to increase air quality on mines; in other words, the main drawback of diesel equipment is the emission of toxic gases (CO, NO_x, HC and CO_2) and DPM. These emissions contribute to the degradation of work environment and, although there are some mitigation's processes: *"Filtering, water spraying and ventilating"* (Bharathan *et al*., 2017), the costs associated are very high; so, decreasing the emissions of contaminates is fundamental to improve the work environment and to reduce costs. Other disadvantages related with diesel equipment are the intensification of temperature, high levels of noise (Salama *et al*., 2014), reduced energetic efficiency, poor overload capacity, vibrations, a great need of maintenance, the flotation of costs related with petrol price (Paraszczak *et al.,* 2014) and the operating costs related with fuel consumption and ventilation requirements (Kukkonem, 2017).

The fuel consumption allows the calculation of the costs associated with its use, and it is given by equation (9) (Hays, 1990 in Bharathan *et al.,* 2017). In equation (9) is clear that the fuel consumption will depend on the equipment specifications, the load it transports and the fuel specificities.

$$C_F = \frac{\beta P \rho}{\gamma} \quad (9)$$

$C_F: Fuel\ consumption\ (L/h)$

$\beta: Energy\ specific\ fuel\ consumption\ \ (kg/kWh)$

$P: Equipment\ power\ (kW)$

$\rho: Load\ factor\ (\%)$

$\gamma: Fuel\ density\ (kg/L)$

Adding to costs related with the fuel consumption, the ventilation also presents a large cost, from 40% (Jacobs, 2013) to 70% (Fiscor, 2018) of the electricity consumed. The new restriction of pollutants in the air, oblige an increase of ventilation, translating in more costs.

Considering the pros and cons, there are enhancements, to improve the equipment's endurance and its components and to enable the possibility of diesel use, even with the Directive's new values. Following are specified the improvements on the diesel emissions with the use of catalysts and with the use of biodiesel.

Catalyst Technologies

The catalyst aims to convert the toxic gases, produced by equipment that uses fuel, into less toxic substances to the environment. In the case of mobile equipment, usually, this device is located on the exhaust system, before the exhaust pipe. There are several types of catalysts on the market and new technology is being developed to improve this anti-pollution system. In general, the catalysts are made with noble and rare metals (typically platinum, palladium and rhodium) and need a minimum temperature to work, at least 350ºC (Imporfase, 2019); meaning that, when the vehicles are cold, this system does not work, expelling the toxic gases to the atmosphere.

There are different categories of catalyst accordingly to the type of fuel used by the vehicle and the gases it processes. Considering that most mines only use diesel vehicles, this chapter will be focused on the catalysts used on diesel engines. On the current market, there are four main types of diesel catalyst technologies (Majewski, 2016): diesel oxidation catalyst, selective catalyst reduction, lean NO_x Catalyst and NO_x Absorber catalyst.

The diesel oxidation catalyst (DOC) was he first device introduced on the market *"in 1970s for underground mining applications"* (Majewski, 2016). This catalyst functions by an oxidation reaction *"promotes oxidation of exhausts gas components by oxygen"* (Majewski, 2018A). This device has three main target emissions: CO, HC and DPM. It oxidizes the CO into CO_2 and the HC into CO_2 and H_2O. It is also important to mention, that the oxidation of HC will also decrease the diesel odour. The DOC will also oxidize the NO, turning it into NO_2, which is a more dangerous gas, increasing the NO_2/NO ratio; this reaction obliges the use of another catalyst in combination with DOC.

The selective catalyst reduction (SCR) aims to reduce the NO_x emissions. It is also important to mention that the "*improvement of the fuel use is associated with larger NO_x emissions"* (Shär *et al.,* 2006), that is, an engine's higher efficiency causes a higher production of NO_x.

The target toxic gases reduction, by this type of catalyst, can be done by the use of an reduction agent, commonly, ammonia or urea, accordingly to the type of machine; typically stationary machines use ammonia and mobile machines use urea (which is an ammonia precursor) (Majewski, 2005A). The urea-SCR system is composed by a SCR catalyst an auxiliary oxidation Catalyst (regularly a DOC) and a urea injection system (AdBlue – aqueous solution of urea) (Majewski, 2005B). The components released to the atmosphere after the use of this type of catalyst are N_2 and H_2O.

The Lean NO_x Catalyst (LNC) is a recent technology and its use is very limited in the current market (Majewski, 2016). This device reduces NO_x with HC, in contrasts to the SCR that used O_2 (Majewski, 2004). The reduction by hydrocarbons will release N_2, CO_2 and H_2O to the atmosphere.

The NO_x Absorber catalyst is commercialized on gasoline engines and light-duty diesel engines. Although this does not apply to the diesel heavy-duty machinery used on underground mines, it can be applied to the vehicles used to transport the miners. This device "traps" the NO_x with an acid-based washcoat chemistry *"involves the storage o NO_x on the catalyst washcoat during lean exhaust and realised during rich operation and/or increase of temperature"* (Majewski, 2018B). There are two types of NO_x Absorber catalysts: active (stores the NO_x and periodically releases it) and passive (absorbs the NO_x when the engine is cold and releases when the temperature increases. This type of catalyst must be used with a SCR, in order for the second one to oxidize the NO_x that is released.

Biodiesel

Biodiesel is an alternative fuel considered a renewable source of energy. Although this fuel is very similar to the traditional diesel fuel, biodiesel is a fatty-acid mono-esters, that is, it is made with triglyceride (such as vegetable oil and/or animal fat) and esters (Acevedo & Mantilla, 2011). The biodiesel can be used by itself or can be blended with diesel fuel; the representation of the proportion of x% biodiesel with diesel is represented by *Bx* (Pollitt *et al*., 2019).

This fuel presents some advantages and disadvantages when in comparison with diesel. The advantages include: it does not contain sulphur (less corrosion of the machine), it has a high oxygen content (reducing the emission of elemental carbon) (Acevedo & Mantilla, 2011), cleaner burning, nontoxic and biodegradable (NREL, 2009). Concerning the disadvantages, this fuel has a lower density (the same quantity of fuel will provide less power *"biodiesel has 7% less energy per gallon"* (NREL, 2009)) and lower oxidative stability (the time of storage has to be lower) (Acevedo & Mantilla, 2011).

Regarding the emissions, the biodiesel has some potential for the improvement of air quality. The impact on the decrease of emissions will depend on the *"source of the biodiesel and the type of diesel fuel to which the biodiesel was added"* (Pollitt *et al*., 2019). There is a reduction of DPM related with the Bx use, higher percentage of biodiesel on the mixture leads to lower emissions of DPM (NREL, 2009), this is related with the elemental carbon lower concentration and the non-volatile polycyclic aromatic hydrocarbon (Pollitt *et al.,* 2019). There is also a decrease of emissions of CO (Acevedo & Mantilla, 2011), related with the fuel's high oxidation. However, the NO_x emissions have been reported to increase, due to the unsaturated fatty-acid chains form the vegetables oils (Pollitt *et al.,* 2019). According to Acevedo & Mantilla (2011), the NO_x emissions can rise or decrease depending on the vehicle in question.

The use of catalysts and biodiesel can decrease the emissions produced by diesel vehicles. However, the use of these two technologies and alternatives, probably, does not guaranty a sufficient reduction for the Directive's fulfilment. Therefore, it is necessary to study these alternatives for each mine.

2.7.2. Electric Equipment

Electric equipment "*have been employed in the mining industry for over 100 years, actually longer than diesel engines*" (Paraszczak *et al.,* 2014). However, with the development of diesel equipment the electric use to power the mining machinery has declined. With the nowadays challenges, the electric energy supply has benefits and are a possible solution for the diesel equipment disadvantages.

According to Paraszczak *et al*. (2014), electric equipment can be divided by the different ways the energy is supplied to the machine engine. Therefore, it will be considered the following types of equipment: battery-powered, cable-powered and trolley-powered.

Although each type of equipment has its own advantages and disavantages, there are several advantages common to all, such as: no toxic gases' emissions, high energy efficiency, low heat emissions, more stable and lower prices of the energy used (electricity), less need of maintenace, low noise and vibration (Paraszczak *et al.,* 2014), a lower necessity of ventilation, inferior cost of operations, and lower risk associated with fuel storage (Salama *et al.,* 2014).

In table 8 are approached the current alternative energy sources for the vehicle, on the market, their advantages and disadvantages.

Table 8 - Electric equipment advantages and disadvantages

	Battery-Powered	Cable-Powered	Trolley-Powered
Advantages	-High versatility and mobility -Good power efficiency -Good overload capacity -Low need of maintenance	-Autonomy	-Higher overload capacity -Autonomy
Disadvantages	-Autonomy -Specific energy	-Mobility -Limited operating range -Cable damage	-Mobility -Infrastructure costs

Battery-Powered

The battery-powered equipment is one of the electrical alternatives most studied to become a substitute to diesel equipment; and the development of this market has made this technology "*technical and commercial viable*" (Liimatainen *et al.,* 2019). This equipment operates with an electric engine that is charged by batteries, which can be recharged; this energy source present a high versatility and mobility, good power efficiency influencing the reduction of energy by 80% (Fiscor, 2018), good overload capacity, and a low need of maintenance (Paraszczak *et al*., 2014).

The main drawbacks of these vehicles are the autonomy and the specific energy, characteristics driven by the type and batteries capacity *"battery-powered equipment can beat diesel in every aspect of performance except run time"* (Fiscor, 2018). The batteries' development is a market in great expansion with new alternatives and improvements taking place daily. The battery mining machinery's autonomy will depend on the manufacture, load capacity, vehicle dimensions, the operator and the battery's capacity of storing energy; for example *"battery-powered loaders have 4-hours run time on average in heavy operations"* (Fiscor, 2018). As an example of specific energy comparison between diesel and lithium-ion batteries, a diesel equipment is *"20 times the energy per mass ratio compared to lithium-ion batteries"* (Weiss *et al*., 2018).

Cable-Powered

Cable-powered equipment is another electrical supply possibility, in which the electrical engine is powered through a cable. However, this solution can only be applied in certain circumstances, since the vehicle mobility is determined by the cable length. Considering this characteristic, and the route lengths travelled by LHDs and trucks, this solution could only be applied to LHDs.

The cable powered vehicles main advantage is the autonomy, since there is no need to refuel or change the battery, and, consequently, it is possible to increase the production. The logistics demanded behind this energy source, can present some challenges. To supply the electrical power, the cable must have an electric infrastructure prepared in the working areas, and when these areas change the infrastructure needs to be reinstalled. Another aspect regarding the logistics is the mobility between work sites. For this type of equipment, the operating range is very limited, which leads to a low flexibility for manoeuvring, this can lead to cable damage, and consequently, to its replacement; the estimated price of cable is 60 €/m (Paraszczak *et al*., 2014), so the its replacement represents very high costs. The mobility of the machine until the new face also presents challenges, since it does not move when it is not connected.

Trolley-Powered

Trolley-powered equipment works by powering the electric engine with energy provided through an overhead catenary (Mazumdar, 2011) allowing for the vehicle to be always charged and ready to work. At the moment, this technology has only been applied to trucks.

This type of solution functions with a higher overload capacity at a great speed, even instep ramps *"On a 14% ramp the speed for the electric truck running up is almost double when compared to a similar diesel unit"* (Paraszczak *et al.,* 2014); this will contribute for a higher production rate, since the cycles are completed in less time. The shortcoming of this vehicles is the flexibility of mobility and the infrastructure costs. The movement of trolley-powered machines are only possible when these are connected to the catenary, so if it is necessary to take a different route, a new structure is in order to be allow the equipment's mobility. The catenary's infrastructure has high costs, about 75% of the equipment price (Paraszczak *et al*., 2014); although it is necessary less ventilation, the infrastructure requires more space for its installation, so it compounds more costs to the development.

2.7.3. Hybrids

Hybrid vehicles uses an electric engine, moved by batteries, and an internal combustion engine as a power source. This type of vehicle aims to overcome the drawbacks of fuel-powered equipment (such as mileage before re-fuelling and emissions) and electric equipment (as autonomy). The hybrid system has three configurations: the parallel configuration, in which the mechanical and the electrical have separated engines, meaning, the paths can work individually or in collaboration; the series configuration, the engine power can be provided by the battery or a generator that transforms the fuel power into electrical power; and the power-split, that combines both configurations (Liu & Peng, 2008).

Even though this type of vehicle is not 100% electric, and still use fuel energy, they present some of the electric benefits when compared with only-diesel machines: less waste of energy, (mainly at low speeds or idling time, because it uses the electric motor, which will, subsequently, reduce the noise and vibrations during this periods), the machine autonomy rises (as a result of the regenerative braking system, that recharges the battery using the energy generated in the brakes) and the necessity of ventilation in underground mines is reduced (due to the diesel engine decrease) (Paraszczak *et al.*, 2014).

Regarding the cabled-powered and trolley-powered alternatives approached previously, these can also be adapted to a hybrid solution, settling their main disadvantage: mobility without constrains; the cable-powered equipment can have a diesel motor that can be turned on when it is necessary to change areas similarly to how jumbos operate; concerning the trolley system *"where there is no access to an overhead trolley rail (…) the truck disengages itself from the trolley and automatically activates a small, onboard diesel engine"* (E&MJ, 2013).

2.7.4. Automation

Mines with automatic equipment are spoken to be the industry's future. The use of automatic machinery eliminates safety hazards of the miners, does not expose the miners to toxic gases and other threats, presents higher productivity rates due to higher reliability and equipment availability, a reduction of operational costs and less expenses with personnel (Gustafson *et al.*, 2017).

Although this technology might create safer mines, more productive and with less costs, the technology is still very recent and *"many technical and operational problems remain"* (Paraszczak *et al.*, 2015) and it is necessary to invest in order for it to progress. In Europe, a research project regarding robots for mining, *ROBOMINERS®*, has been initiated and prototype robots are expected by 2030 (Robominers, 2019).

3. Gases Evaluation Methodology

The Commission Directive 2017/164 implements new IOELV for CO, NO and NO_2, specifically new TWA and STEL limits (table 1). Throughout the interpretation of the Directive, it was considered that the new values must be implemented in all areas of the mine, all operations and situations where the workers can be, since the Directive main intention is to protect the workers from the dangers associated with these gases. Nor the Directive, nor the legislations, or national laws present an indication regarding the method of measurement to acquire the toxic gases values. There is no indication, from a governmental institution, on where to do the measurements, in which situations, for how long, and how many times a year. In this thesis is proposed a gas evaluation methodology (GEM) aims to help the mines create a structure plan for the data acquisition, and for the governmental authorities to have a cohesive structure on how the evaluation results.

Every mine has its own challenges, and so, GEM was developed aiming to be adaptable to the majority of the underground mines, making it possible to adapt to most mining methods or most ore's explored. Firstly, a preliminary qualitative approach is done, by characterizing the mine, followed by a quantitative approach, data gathering and analysis, where is possible to identify patterns and understand where adjustments should be applied to fulfil the Directive. Initially, it is necessary to do a theoretical approach, with the objective of contextualizing the circumstances and gain in-depth insight of the mine under analysis. Posterior to this analysis, it will be possible to know where the new IOELV for toxic gases are not fulfilled and which are the contaminants' producers.

3.1. Mine's Characterization

The most used mining methods on the world are cut and fill, room & pillar, block caving, sublevel caving and sublevel stoping. The mining method choice will depend on many factors (e.g. deposit's geometry, depth below surface, strength of strata) and it is directly related with the operations conducted on the mine. However, there are some operations common to all methods: mine's development, mineral excavation, waste/ore transportation and maintenance.

Having a deep knowledge of the mine being studied is fundamental for reaching the ideal solution. In most mining methods, the operations expose the workers to toxic gases. For this qualitative mine's characterization is fundamental to define the:

- Mining method;
- Operations performed at the mine;
- Ventilation system;
- Equipment used;
- Prospecting plan.

The information described is essential, since it is necessary to create a strategy regarding the needed measurements, by establishing a gas measurement plan for each mine.

3.2. Data Gathering

The locations identification and operations that mostly contribute with toxic gases is fundamental to create a solution to achieve a non-toxic work environment. This identification cannot be done only with a theoretical approach, since the circumstances are different on every mine and the conditions that the workers are exposed to can differ even inside the same mine.

The gas' measurements should be done on a normal performance of the mine; so, it is necessary to conciliate the measurements plan with the mine's prospecting plan. With resource to the data gathered beforehand, is proposed to select:

- Two development areas[10];
- Two stopes[11];
- Other areas where the workers stay for more than 15 minutes (e.g. workshops).

Posterior to the location's choice, it should be determined which operations are performed at the sites, to each are necessary the workers presence.

The gas detector equipment necessary to collect the data, must measure, at least the CO, the NO and the NO_2, register the time period and have a range that cover, at least, the STEL limit values. Preferentially, all the measurements should be done with the same gas detector, that needs to be always calibrated, to guarantee a coherence of results and secure their veracity. It should be possible to transfer the data to the computer for the posterior data analysis.

The measurements should conciliate the locations with the operations performed at the site. To have a complete analysis, the data must be collected for, at least, the time of one cycle of each operation. During the acquisition of data, it should always be indicated:

- Which are the machines working at the time and the its source of energy;
- If the auxiliary ventilation is on;
- If there are any other contributors of toxic gases at the site;
- Period of measurements (day, time it starts and time it stops).

In table 9 are shown the general locations and situations of measurements needed to be done in order to have conclusions related with the gas emissions along the mines; however, it is firmly proposed to adapt the table to the mining method used.

[10] Should be measured two development areas so it is possible to compare both.
[11] Should be measured two stopes so it is possible to compare both.

Table 9 – General table for data gathering

Localization	Operation	Time (date + star&stop)	Machinery	CO	NO	NO_2
Stope/Development	Drilling					
	Explosives loading					
	Watering					
	Loading/hauling					
Resting areas						
Workshops	Equipment maintenance					
Ore Pass	Dumping					
Primary Crushing						
Ventilation Chimney	Geological and Geotechnical Surveys					

It is also important to have the gases' values on the atmosphere at the locations chosen when there are no operations occurring. For this data acquisition, the measuring equipment should be placed when no operations are occurring, and it has been well ventilated. These values will be important hereafter for the data analysis, in order to compare both values and validate the results.

3.3. Data Analysis

The data analysis aims to define how the data should be examined in order to identify the situations where the new limits are not fulfilled. The analysis method can be done by using a spreadsheet program, since it is based on number evaluation and interpretation, employing statistical methods and graphics. This data analysis will be divided in three main phases: organization of data, classification of values, statistical analysis.

Data Organization

Firstly, it is necessary to organize the data in order to create a homogeneous data base for further comparison. The data should be prearranged following the structure provided in table 8. As mentioned before, it is important to identify the location, the operations, the machinery being used and the time. To simplify the analysis, the data should be separated, firstly by location and after by operation.

Classification of Values

After the data organization, it is necessary to understand when the new limits are not respected. For an easier interpretation, the data can be identified by the colour scheme displayed in table 10. The data can be identified as:

- Green: fulfilment of the TWA limit

If the values are classified as green, the location/operation are not a preoccupation to the mine, since the TWA limits are followed, therefore it follows the Directive.

- Yellow: unfulfillment of the TWA limit

If the values are classified as yellow, it is necessary to identify for how long. If the time the values are above the TWA limit does not surpass the 15 minutes, then the location/operation is in accordance with the Directive. Otherwise, it should be a concern for the mine, since the workers are exposed to a dangerous atmosphere for a large period (>15 minutes), and so, the mine needs to do adjustments, regarding the location itself or the operation.

- Red: unfulfillment of STEL limit

If the values are classified as red, the location/operation do not comply with the STEL limit on the Directive, and so, the mine needs to do adjustments, regarding the location itself or the operation.

Table 10 - Identification of data range

CO (ppm)	**NO_2** (ppm)	**NO** (ppm)
$[0, 20]$	$[0, 0{,}5]$	$[0, 2]$
$]20, 100]$	$]0{,}5, 1]$	> 2
> 100	> 1	

Statistical Analysis

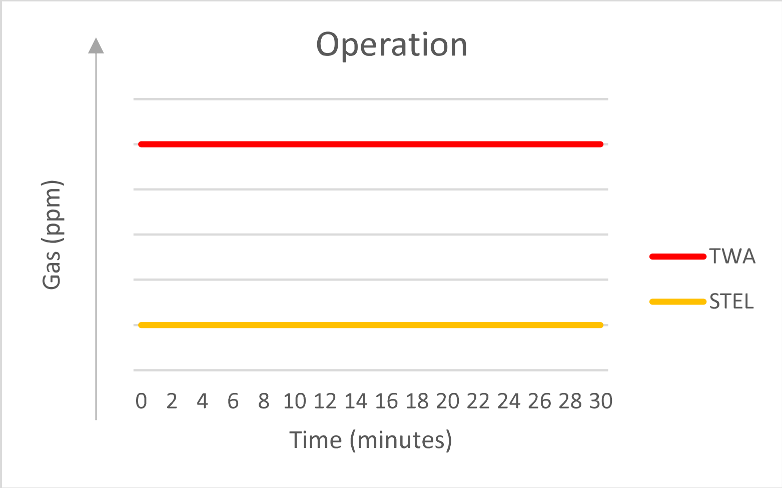
To do the statistical analysis it is fundamental to choose a representative period, in order to compare all the situations through the same amount of time, creating a more cohesive statistical analysis. The representative period should be decided taking into consideration the operation that takes less time to finish. When chosen the period, all operations should include all the situations that occur the operation under analysis (e.g. during drilling should be selected a period that includes the movement of the jumbo (use of the diesel engine) and the drilling (use of the electric engine)) .

For each situation should be done the maximum, minimum, average, standard deviation and coefficient of variance. If the maximum and/or the minimum are too distinct from the average, this will allow the identification of abnormal situations, that need to be identified. The standard deviation will allow understanding if the values spread out from the average, that is, if the average is the usual values the workers breathe in. The coefficient of variance will enable the detection of abnormal values.

Additionally to the statistical analysis, the production of graphics will assist the data interpretation; this will improve the study and allow a more accurate conclusion. The graphics should be done with the representative period chosen previously. Following are exemplified the types of graphics:

a) Gas concentration (ppm) vs Time

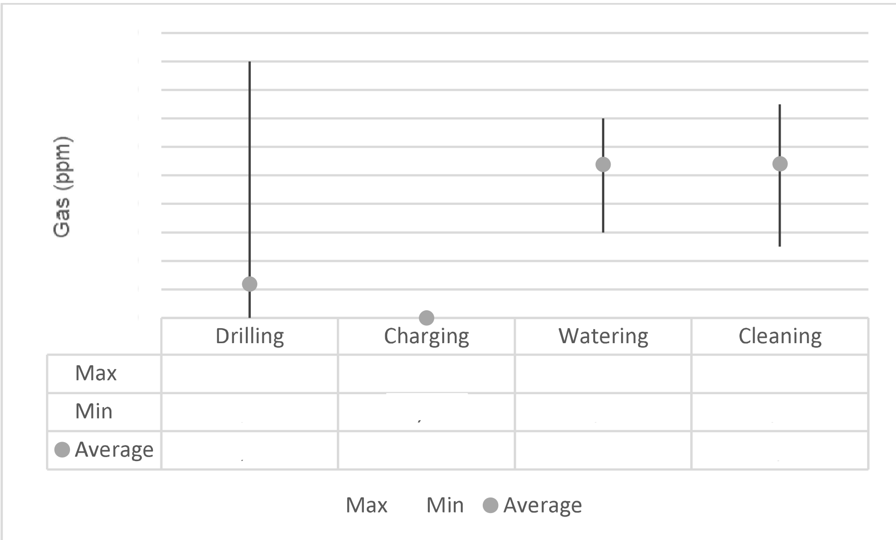
In this graphic it is studied each operation and each gas at a time, this is, the graphic will show a curve that represents the gas (CO, NO_2 or NO) concentration expressed in ppm's for the operation under analysis, within the representative period. The graphic should also show a representation of the STEL limit and the TWA limit. It is represented in graphic 2 a generic example.



Graphic 2 - Example Gas concentration (ppm) vs Time (minutes)

b) Gas concentration (ppm) vs Operation

Especially in stopes and development areas, there are more than one operation taking place; usually in these areas the operations are related with the mining cycle. In the interest of comparing all the operations and understand how, in the same place, the atmosphere can change accordingly to the operation occurring, this graphic will simplify this analysis. It should be done by gathering the data previously calculated (average, maximum and minimum) for the same representative period. is demonstrated in graphic 3 an example.



Graphic 3 - Example Gas concentration (ppm) vs Operation

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4. Case Studies

After the GEM development for the analysis of the current situation on the mines, was important to put in practice by applying it to a mine. It was possible to put it in practice in two case studies. On the first case study was possible to do direct measurements during the months of July and August 2019; on the second case the data was provided by the mine, for further analysis. The two mines represent very different scenarios (such as the mined mineral, the mining method and their dimensions) making them unfeasible to compare. However, it is possible to find some common issues, regarding the Commission Directive 2017/164 fulfilment.

The GEM was adapted to the mine approached on the case study 1. This case study allowed the understanding of the current situation during all operations and in all types of locations on the mine, by processing and analysing of the data collected, throughout a time period of two months. It was possible to identify which are the critical areas/operations and where changes should take place in order to fulfil the new limit values.

It was also possible to study another mine, addressed on the case study 2. On this case study the GEM was only partially implemented, since the data obtained was only from the cleaning cycle. The case study 2 allowed the atmosphere characterization during the cleaning operations and evaluate which were the problems associated with this process.

4.1. Case study 1

The case study 1 is a mine situated in Europe. The company's main product is tungsten (from wolframite), and as secondary materials, it is also able to produce tin (from cassiterite) and copper (from chalcopyrite). To obtain these materials, the company mines it and takes part on the minerals processing. Last year (2018), the mine produced 1203 tons of wolframite concentrate, 142 tons of cassiterite concentrate and 411 tons of chalcopyrite concentrate. There are around 270 workers that work 5 days per week, in three shifts of 8 hours.

4.1.1. Mine's Characterization – Case Study 1

Room & Pillar is the mining method used at the mine allowing for a controlled exploration and an ore deposit recovery of approximately 84%. In figure 11 is shown the mine's deposit.

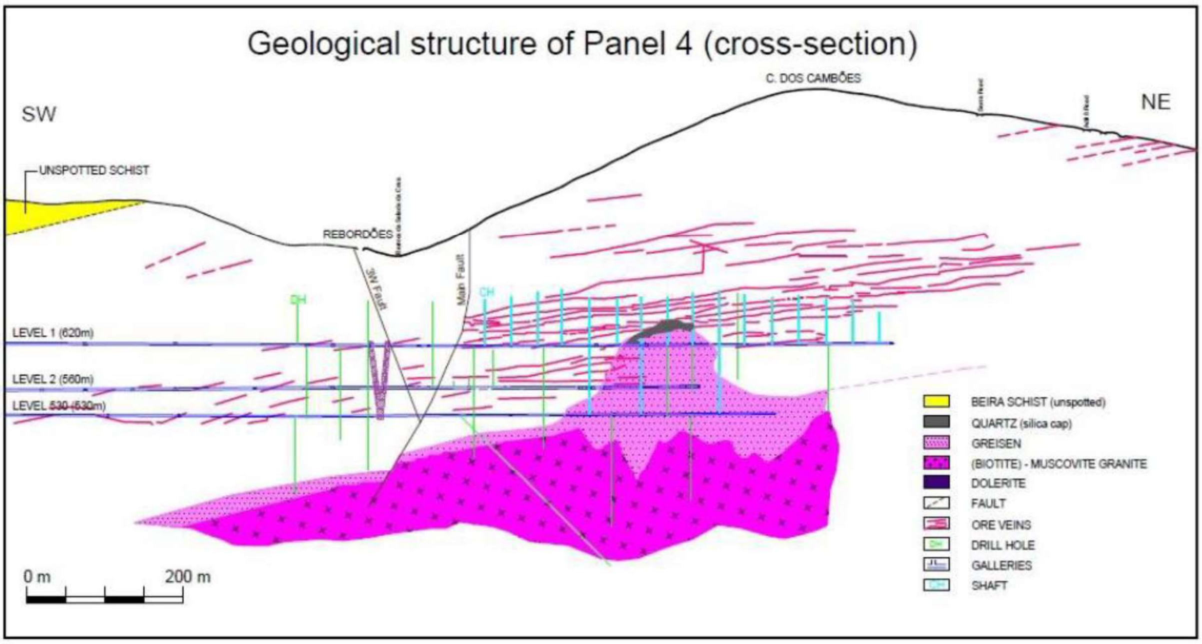


Figure 11 - Deposit from case study 1 (Beralt, 2019)

The room & pillar method is considered an unsupported stoping method, that is to say, the stopes are left without ground support (e.g. mesh, shotcrete) or backfill (Moser & Wimmer, 2017). On this mine, the method is divided in the following five stages:

1st Stage: Opening of the inclines

The galleries are opened in the intersections between the principal levels of exploration (L0, L1, L2 and L3) and the ramps that lead to the veins between levels. The galleries can be 100x100 meters or 100x50 meters with 2,2 meters height and are divided by the inclines, with a 4,5 to 5 meters of width. After opening the galleries, it is possible to have a greater knowledge of the vein's grade development and evaluate its potential for exploitation (if the grade is higher than the cut off, the 2nd stage may begin).

2nd Stage: 11x11 pillars

On this stage the galleries are excavated with a section of 4,5 to 5 meters of width and 2,2 meters of height, creating pillars of 11x11 meters, as shown in figure 12 A. The vein's grade continues to be evaluated and, in order to potentialize to a maximum the mine's production, the pillars that will continue to be mined are set. It is necessary to be aware of the pillar location, since it should be superimposed to the pillars above and underneath. In case the pillars are poorly positioned, it can increase the pillar's stress, since the rock mass's stress is defectively distributed.

3rd Stage: 3x11 pillars

The rock from the previous stage is loaded and hauled and new pillars are defined. Considering the grades attributed to each pillar beforehand, the 11x11 meters pillars are mined into 3x11 meters pillars, as illustrated in figure 12 B.

4th Stage: 3x3 pillars

Once more, the rock from the previous stage is loaded and hauled. The 3x11 meters are mined creating 3x3 metres pillars, as shown in figure 12 C; these are the final pillars and will provide support for the ceiling for the final operations.

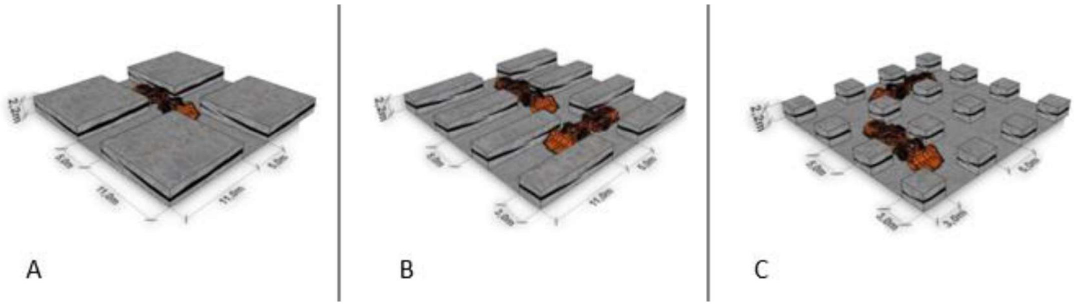


Figure 12 - Room and Pillar at case study 1 (Beralt, 2019)

5th Stage: Cleaning

Ultimately, the gallery is cleaned, in order to recover the highest amount of ore possible. Since wolfram is extremely dense (ρ=7,3 kg/m^3), smaller materials tend to be left on the floor on the previous stages.

The ore produced on the previous stages are loaded and hauled by diesel-powered LHDs to chimneys and forwarded to the extraction area. Afterwards, with the use of diesel-powered locomotives, the ore goes to the crushing area.

The opening of such large stopes has a great influence on its ventilation. When the pillars get smaller and the open space gets bigger, it is necessary to increase the ventilation to dilute the gases, decrease the temperature and bring fresh air to the miners.

The mining method imposes some technical characteristics necessary to understand in order to do a proper analysis of the ongoing situation at the mine. The excavation, the cleaning process structure and the ventilation system, correspond to the most important mine's exploration characteristics, since these will define the air quality on the underground environment.

Excavation

The excavation method used for the development, for the opening of inclines and stopes, is drilling and blasting. Excavation with the use of explosive has a superior behaviour on harder rocks; the main rock on the mine is shale, allowing for the blasting excavation's positive performance. Excavation by blasting can be defined, for each mine, by the cut design, the type of explosive used and the initiation system.

The cut design will differ regarding if it is a development gallery or a production stope. On a development gallery is used a V-cut, as illustrated in figure 13 (front view), figure 14 (side view) and figure 15 (top view), in a section of 3,8 by 2,8 meters.

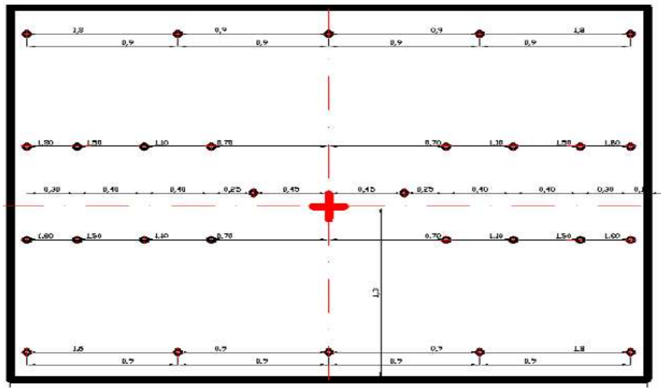


Figure 13 - V-cut front view (Beralt, 2019)

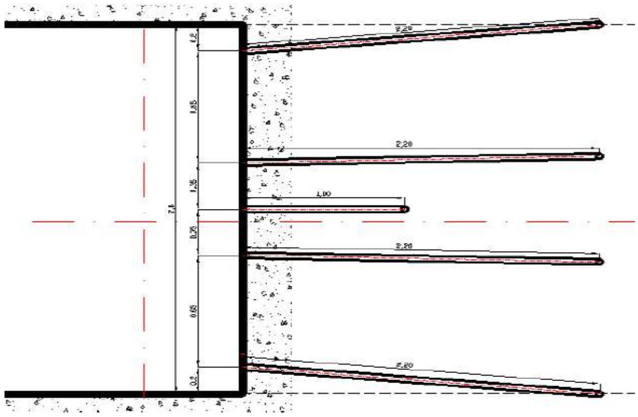


Figure 14 - V-cut side view (Beralt, 2019)

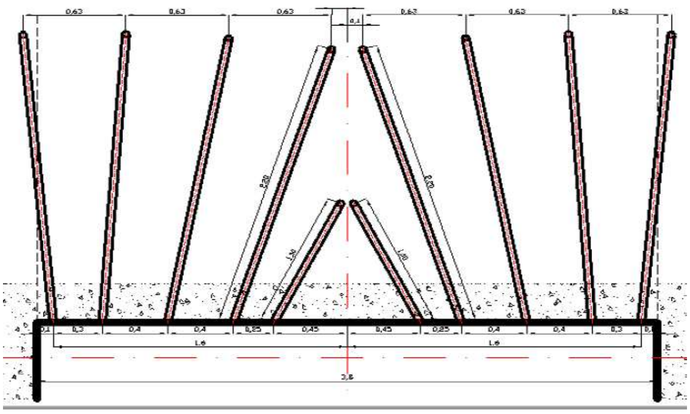


Figure 15 - V-cut top view (Beralt, 2019)

On a production stope is applied a fan-cut, as exemplified in figure 16 (side view) and figure 17 (top view), in a section of 4,5 by 1,8 meters. In general, each blasting contains 26 drill holes, that are divided in four types of length (1,0 m; 1,5 m; 2,0 m; 2,5 m) allowing the fan-cut profile represented in figure 17.

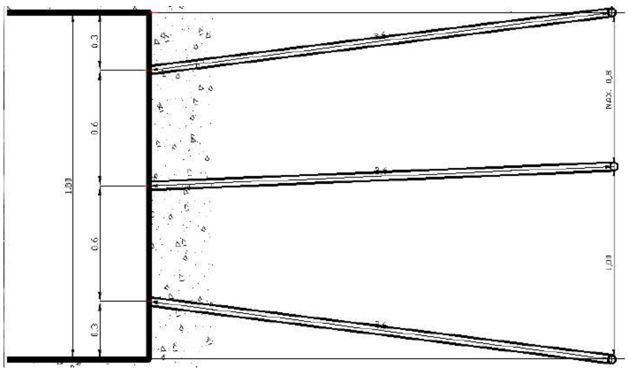


Figure 16 - Fan-cut side view (Beralt, 2019)

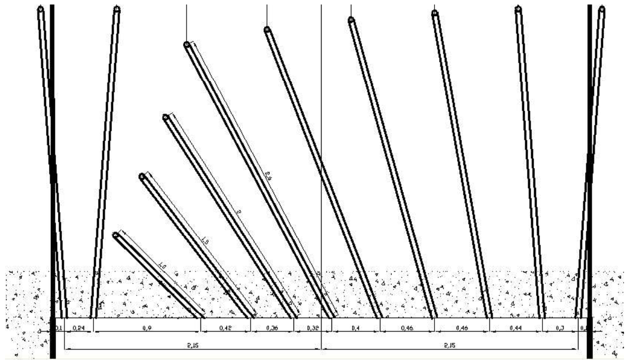
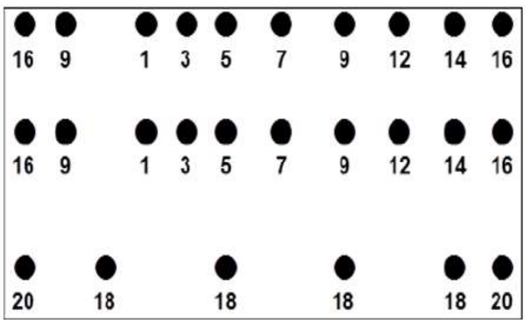


Figure 17 - Fan-cut top view (Beralt, 2019)

There are two types of explosives used on a drill hole: the bottom charges and the column charges. The explosive that is applied as bottom charge, in all stopes, is a nitro-glycerine (Riodin®). The principal explosive used as column charge is ANFO (Amonoleo®), however, the use of this explosive is directly related with the drill holes water content, since, if it has water, it cannot be used. In those cases, it is used a hydrogel (Riogel Troner Por®).

The initiation system allows the introduction of delays between the blast of each drill hole, in order to offer a proper response regarding the environmental impacts and the blasted rock quality control. Since 2016, the initiation system has been the non-electric system (Rionel MS®). This system allows 20 milliseconds delays, without any limitations per stope; in figure 18 is represented the delay time layout from each drill hole. This system is initiated by a mechanical impact, reducing the errors of delays (in comparison to the electric initiation system).



1	25 ms
3	75 ms
5	125 ms
7	175 ms
9	225 ms
12	300 ms
14	350 ms
16	400 ms
18	1800 ms
20	2000 ms

Figure 18 - Non-electric delays (Oliveira, 2018)

The detonations are conducted at the end of the 2nd shift, when only the workers from the blasting team are present on the mine. The blast clearance time is 7 hours (from 12 pm to 7 am); however, during the night shift there are some workers inside the mine.

Loading and Hauling

The blasted material transportation inside the mine is done by means of ore passes, LHDs, and locomotives. In figure 19 is displayed a schematic representation of the ore transportation on the mine.

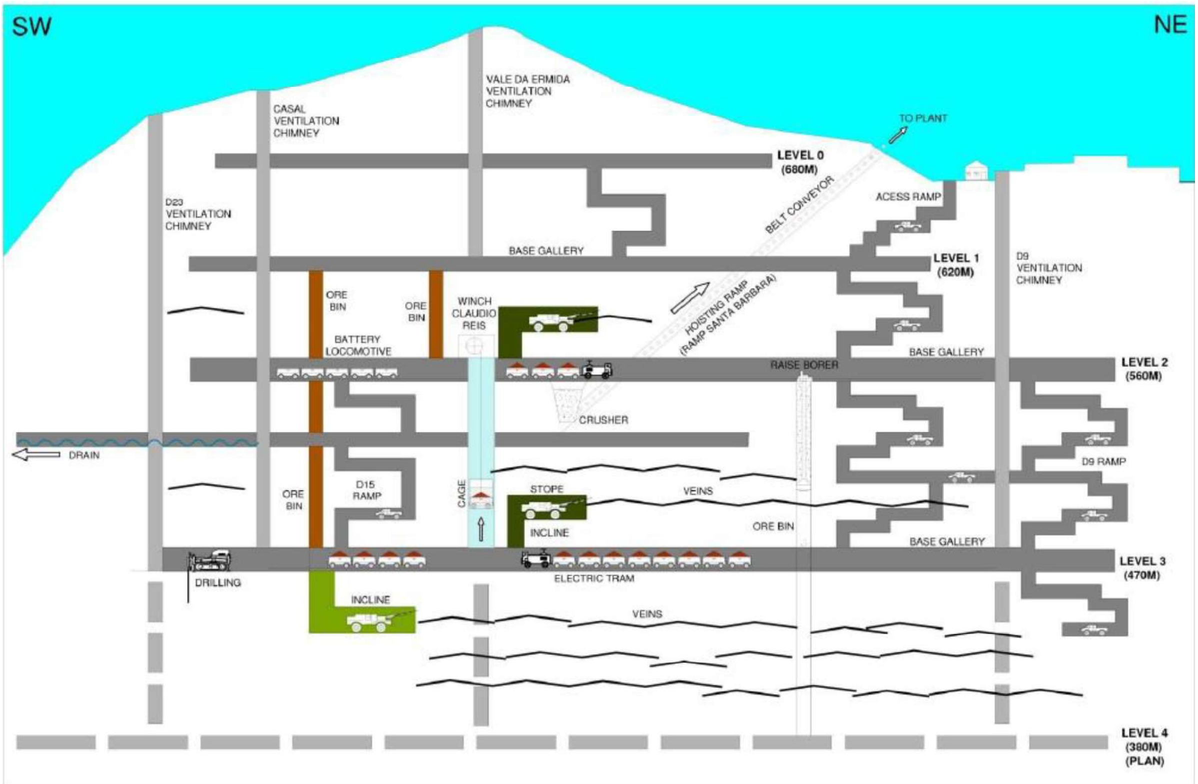


Figure 19 - Blasted material transportation (Beralt, 2019)

As mentioned previously, the LHDs have the capacity to load the blasted material, from the face, and haul it to the dumping area. In this mine, the LHDs dump the ore on the chimney closer to the working area. The LHDs models used on the mine are: *Atlas Copco Scooptram ST7LP, Atlas Copco Scooptram ST600LP, GHH LF-4.4, Sandvik LH208L, Atlas Copco Wagner ST3.5*. The LHDs used have a maximum height of 2,250 meters; this specification is extremely important, since the mine never presents a height superior to 2,5 meters to eliminate the vein content dilution, so it is extremely important for the equipment to be low profile.

The locomotives are also a part of the ore's process of transportation. The wagons are filled on the chimneys and the locomotives pull the full wagons to the crushing area top, where the ore is placed to be crushed. The locomotives models used on the mine are: BEV WR8, GIA D12, and GIA DHS90; these models work by diesel. The locomotive model BEV WR8 is electric, works with a lead acid cells battery, however, it is not often used. On the mine it is also used a trolley locomotive, the Clayton 5 Ton.

Ventilation

The mine's main ventilation is natural, in other words, the mine's main air flow is dependent on the pressure difference and the temperature discrepancy between the interior and the exterior of the mine. Adding to the natural ventilation, the mine also has a main fan that outtakes the contaminated air, reinforcing the main ventilation system. The main ventilation system moves around 4000 m^3/minute.

Additionally, to the main ventilation system, on the stopes are used secondary fans with sleeves allowing the air to move inside the stope.

4.1.2. Data Gathering – Case Study 1

The acquisition of data, on this case study, had into account the GEM and the measurement method developed. Considering the method, described on chapter 3.2, the table 8 was adapted to this mine; each one of the areas and the operations performed on them are described on chapter 4.2.1.

The measurements were done throughout the months of July and August of 2019, mostly during the first shift (from 7 am to 3 pm); nonetheless, others were done during the second shift (from 3 pm to 11 pm). It was possible to acquire data from 20 situations. The measurements were done by taking a measurement equipment (described on chapter 4.2.2) into the mine and overseeing the different operations. The measurements were made by accompanying the miners through the different areas and operations. The measurement equipment was calibrated outside the mine and after taken inside where it was positioned, always near the workers, in order to have better comprehension and the real levels to which the workers are exposed to, for at least one cycle of each operation. The cleaning operation was an exception, regarding the measurement process, since the measuring equipment was transported by the LHD driver; this allowed to have the complete data of a cleaning cycle.

On the following chapters is done a description of where the data was gathered and the respective operations, followed by a description of the measuring equipment and the data processing and respective analysis.

4.1.2.1. Data Measurements – Case Study 1

Taking into considerations the mine's prospecting plan and the short time available to do the measurements, it was not possible to measure all the areas planned on GEM, described on chapter 3.2. Nevertheless, it was possible to measure 2 stopes, 1 incline, 1 development area, 2 workshops, the main ore pass ("viradouro") and the primary crushing unit.

On the stopes, inclines and development areas, the operations of a mining cycle are drilling, charging the explosive, blasting, watering the face, scaling and cleaning with an LHD. The drilling operation is done with the aid of a jumbo; this equipment moves with diesel energy, however, when it is drilling, it is connected with the cable, using only the electric motor. The loading of explosives is done by hand; the only machine used is a tractor to help the miners carry the explosive to the faces. The face's watering is conducted on the shift after the blasting, usually 7 hours later; this operation aims to reduce the gases on the air and identify where it is necessary to scale. The scaling is done by hand and seeks to create a safer environment by removing the loose rocks on the ceiling and walls. Finally, the last phase of the mining cycle is the cleaning operation; this operation is divided in three phases (loading, hauling and dumping) and on this mine it is done using an LHD, moved by diesel.

On the mechanical workshop, the first part of the shift consists on the LHD's check-up and filling the diesel tanks. Following the check-ups, the workshop does complex repairs. On the electrical workshop there are only performed machinery repairs; small repairs are done at the damage location.

At main ore pass, designated by *viradouro*, the ore from all the mine is dumped using locomotives (running on diesel) and wagons. The ore dumped here goes to the primary crushing area, where it is crushed; from here it is transported to the plant by a conveyor belt. On the primary crushing area there are no vehicles used, and all the machinery is electric.

Present in table 11 are the areas and operations where the measurements were done, on this case study. As a result of the mining prospecting plan, it was only possible to do one incline and one development area. All the operations analysed were measured for, at least, 30 minutes.

Table 11 - Data collected from case study 1

Location	Designation	Operations
Stope	L1D09R5BAAW16	Drilling | Charging | Watering | Cleaning
	L2MDWR5AW21	Drilling | Charging | Watering | Cleaning
Incline	L2D25R13I1	Drilling | Charging | Watering | Cleaning
Development	L2P6D7-D1	Drilling | Charging | Watering | Cleaning
Mechanical workshop	L1D13	Machinery check-up + Machinery repairing
Electrical workshop	L1D13	Machinery repairing
Ore pass	"Viradouro"	Transportation of ore (wagons) + Dumping
Primary crushing Unit	L530	Crushing

4.1.2.2. Measurement Equipment – Case Study 1

On this case study was used the gas detector equipment *MSA ALTAIR 5X.* The detector is property of the mine, and it was calibrated on May 2019.This detector measures 5 gases: O_2 (%), CO (ppm), CO_2 (%), NO (ppm) and NO_2 (ppm). Regarding its functions:

- Measures and presents the immediate gases levels' results;
- Registers and saves the gases levels every minute;
- Is equipped with two alarms (the values for the alarms are defined by the manufacture and are available on the attachment A.1.).

Although the gas detector can measure O_2 and CO_2, for the thesis purpose, that data was not used, since the focus is the CO, NO_2 and NO. In table 12 is displayed the range of values that the equipment measures for the target gases.

Table 12 - MSA ALTAIR 5X measuring range for the target gases

	CO (ppm)	NO (ppm)	NO_2 (ppm)
Minimum	0	0	0
Maximum	2000	100	50

4.1.3. Results and Data Analysis – Case Study 1

After the measurements previously described were finished, the data gathered was organized according to table 13. The values of CO, NO_2 and NO were classified based on the information displayed in table 10.

Table 13 - Organization of data from case study 1

Time (Day+hour)	Location	Operation	Equipment	Observations	CO (ppm)	NO_2 (ppm)	NO (ppm)

Posteriorly to the previous organization, a representative period of 30 minutes was selected for every operation at each location. This period was selected considering the shortest operation. However, the longest operations were acknowledged in order to validate the representativeness of the 30 minutes timeframe. In table 14 and table 15 (confidential attachment (CA): table 35 and table 36) are shown the values for 30 minutes and for 1 hour and 30 minutes from the drilling operation at the same site. When comparing both tables is possible to conclude that there are no significative differences and so, the selected period is representative.

Table 14 – Results of 30 minutes measures during drilling

	CO	NO_2	NO
Average			
Max			
Min			
Coef. variance (%)	1,14	1,74	2,64

Table 15 - Results of 1 hour 30 minutes measures during drilling

	CO	NO_2	NO
Average			
Max			
Min			
Coef. variance (%)	0,65	2,62	3,27

Once the representative period was selected all the data was processed according to chapter 3.3. Below are shown the results and their analysis, followed by a brief data explanation [12].

Stope L1D09R5BAAW16

The results from the stope L1D09R5BAAW16 are represented in table 16 (CA: table 37).

Table 16 - Stope L1D09R5BAAW16 statistical analysis

	CO				NO_2				NO			
	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean
Average												
Max												
Min												
Coef. variance (%)	56	10	6	43	161	17	13	48	251	74	6	30

While drilling:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average and minimum are classified as green, and the maximum is classified as red. The coefficient of variance is high (>100%), meaning that there are abnormal values. The abnormal values happen when the jumbo turns on the diesel engine.
- NO values: average and minimum are classified as green, and the maximum is classified as yellow. The coefficient of variance is high (>100%), meaning that there are abnormal values. The abnormal values happen when the jumbo turns on the diesel engine.

While charging the explosives:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO values: the minimum is classified as green; however, the average and maximum are classified as yellow. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution. There higher values appear when the tractor is near the equipment.

[12] The original tables are displayed on the confidential attachment. The tables displayed on the text do not have the average, maximum and minimum values, and the standard deviation.

While watering the face:

- CO values: the average, maximum and minimum are classified as red. The values were not found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as red. The values were not found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as yellow. The values were not found compatible with the Directive.

The coefficient of variance low values show that during watering the values have a low dispersion, that is, most values are close to the average which is not fulfilling the Directive.

While cleaning the face with the LHD:

- CO values: the average and maximum are classified as red and the minimum as yellow (values that happen when the LHD goes to the gallery). The values were not found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as red. The values were not found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as yellow. The values were not found compatible with the Directive.

Stope L2MDWR5AW21

The results from the stope L2MDWR5AW21 are described in table 17 (CA: table 38).

Table 17 - Stope L2MDWR5AW21 statistical analysis

	CO				NO_2				NO			
	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean
Average												
Max												
Min												
Coef. variance (%)	80	5	16	30	273	16	41	35	207	0	18	26

While drilling:

- CO values: the average and minimum are classified as green and the maximum as yellow. The coefficient of variance indicates that there is some values distribution. The higher values happen when the jumbo turns on the diesel engine.
- NO_2 values: the average and minimum are classified as green and the maximum as red. The coefficient of variance is high (>100%), indicating that there are abnormal values. The abnormal values happen when the jumbo turns on the diesel engine.

- NO values: average and maximum are classified as yellow, and the minimum is classified as green. It is also possible to analyse the very coefficient of variance high values (>100%), meaning that there are abnormal values during the drilling operations; these abnormal values occur when the jumbo turns on the diesel engine.

While charging the explosives:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

While watering the face:

- CO values: the average, maximum and minimum are classified as red. The values were not found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as red. The values were not found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as yellow. The values were not found compatible with the Directive.

The coefficient of variance low values show that during watering the values have a low dispersion, that is, most values are close to the average which is not fulfilling the Directive.

While cleaning the face with the LHD:

- CO values: the average and minimum are classified as green, and the maximum as yellow (values that happen when the LHD loads the material).
- NO_2 values: the average, maximum and minimum are classified as red. The values were not found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as yellow. The values were not found compatible with the Directive.

Incline L2D25R13I1

The results from the incline L2D25R13I1 are described in table 18 (CA: table 39).

Table 18 - Incline L2D25R13I1 statistical analysis

	CO				NO_2				NO			
	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean
Average												
Max												
Min												
Coef. variance (%)	59	21	90	55	0	190	0	97	0	180	0	62

While drilling:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

While charging the explosives:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO values: the average and minimum are classified as green; however, the maximum is classified as yellow. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution. There higher values appear when the tractor is near the equipment.

While watering the face (It is important to mention that in the incline, under analysis, was used hydrogel):

- CO values: the average and maximum are classified as yellow, and the minimum is classified as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

While cleaning the face with the LHD:

- CO values: the average and minimum are classified as green. Although the maximum is classified as yellow, the values are respecting the IOEVL.
- NO_2 values: the minimum is classified as green, the average as yellow and the maximum as red. Although these three statistical parameters have several classifications, through the coefficient of variance analysis, it is possible to conclude that most values are close to the average.
- NO values: the average and the maximum are classified as red, and the minimum as yellow. The coefficient of variance shows a values dispersion.

Development Area L2P6D7-D1

The results from the development area L2P6D7-D1 are described in table 19 (CA: table 40).

Table 19 - Development area L2P6D7-D1 statistical analysis

	CO				NO_2				NO			
	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean	Drill	Charge	Water	Clean
Average												
Max												
Min												
Coef. variance (%)	39	25	103	18	51	22	81	22	47	0	0	18

While drilling:

- CO values: the average and maximum are classified as yellow, and the minimum as green. The coefficient of variance show that most values have values near the average but can still achieve values under the TWA limit.
- NO_2 values: the average and maximum are classified as red, and the minimum as yellow. The coefficient of variance show that most values have values near the average but can still achieve values under the STEL limit.
- NO values: the average and maximum are classified as yellow, and the minimum as green. The coefficient of variance shows that most values are near the average but can still achieve values under the TWA limit.

While charging the explosives:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

- NO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

While watering the face (It is important to mention that in the incline, under analysis, was used hydrogel):

- CO values: the average and maximum are classified as yellow, and the minimum is classified as red. It is also possible to examine that since the coefficient of variance value is high (>100%) there is some values distribution.
- NO_2 values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

While cleaning the face with the LHD:

- CO values: the average and minimum are classified as green. Although the maximum is classified as yellow, the values are respecting the IOEVL.
- NO_2 values: the minimum is classified as green, the average and the maximum as yellow. Through the coefficient of variance analysis, is possible to conclude that most values are close to the average.
- NO values: the average, the maximum and the minimum are classified as red; the confident of variance low values show that during cleaning operation the NO values are not fulfilling the Directive.

Mechanical Workshop L1D13

The results from the mechanical workshop L1D13 measurements are shown in table 20 (CA: table 41).

Table 20 - Mechanical Workshop L1D13 statistical analysis

	CO	NO_2	NO
Average			
Max			
Min			
Coef. variance (%)	18	22	18

At the mechanical workshop, the acquisition of data was done during the LHD's check-up, at the beginning of the second shift. The LHD have to run on the diesel engine during this operation.

- The CO's average and minimum are classified as green, and the maximum as yellow. Considering the coefficient of variance is low, most of the time the mechanics are not exposed to high levels of CO, and when the values are higher than the TWA limit, the exposure is lower than 15 minutes.

- The NO_2's minimum is classified as green, and the average and maximum as yellow. Considering the coefficient of variance, it is possible to note that the values are near the average and the mechanics might be exposed to values higher than the TWA limit for more than 15 minutes.
- The NO's minimum is classified as green, and the average and maximum as red. Considering the low coefficient of variance, is possible to examine that the values are near the average and the mechanics might be exposed to values higher than the STEL limit, and so, this work space does not fulfil the Directive.

Electrical Workshop L1D13

The results from the electrical workshop L1D13 measurements are shown in table 21 (CA: table 42).

Table 21 - Electrical Workshop L1D13 statistical analysis

	CO	NO_2	NO
Average			
Max			
Min			
Coef. variance (%)	76	25	137

- The CO's average, the maximum and minimum are classified as green. Considering the coefficient of variance's value is possible to understand that the values may vary, but never surpass the Directives' IOVEL.
- The NO_2's average, the maximum and minimum are classified as green. Considering the low the coefficient of variance, it is possible to examine that the values are near the average and the space fulfils the Directive.
- The NO's average and minimum are classified as green, and the maximum as red. Considering the high coefficient of variance values, is possible to examine that most values are near the average but there are some abnormal values. The abnormal values happened when a diesel machine passed through the workshop.

Ore Pass "Viradouro"

The results from the main ore pass measurements are shown in table 22 (CA: table 43).

Table 22 - Ore pass "viradouro" statistical analysis

	CO	NO_2	NO
Average			
Max			
Min			
Coef. variance (%)	548	0	0

- The CO's average, the maximum and minimum are classified as green. Considering the high value for the coefficient of variance it is possible to understand that there are some abnormal values, even though the values never surpass the Directives' limits. The abnormal values occurred when the locomotives had to stop at the ore pass.
- The NO_2's average, the maximum and minimum are classified as green.
- The NO's average, the maximum and minimum are classified as green.

Primary Crushing Area

The results from the primary crushing area measurements are shown in table 23 (CA: table 44).

Table 23 - Primary crushing area statistical analysis

	CO	NO_2	NO
Average			
Max			
Min			
Coef. variance (%)	0	0	0

- The CO's average, the maximum and minimum are classified as green.
- The NO_2's average, the maximum and minimum are classified as green.
- The NO's average, the maximum and minimum are classified as green.

4.1.4. Discussion of Results – Case Study 1

Previously, there were shown the results and a brief explanation of the data obtained on the measures conducted on the mine from case study 1. In the tables 16 to 23 (CA: 37 to 44) are displayed the summarize from 20 situations that relate to different working areas and different operations. On this chapter it is done a discussion of the results from each table and posteriorly, an identification of the most critical situations.

Throughout the analysis of table 16 (CA: table 37) and the observations taken during the data gathering, at the stope L1D09R5BAAW16, is possible to observe:

- The high values of NO_2 and NO during drilling are due to the jumbo relocating on the faces, using the diesel motor;
- The high concentration of NO during the loading of explosives occurs when the tractor moves near the faces;
- The watering and cleaning are the operations on which the workers are exposed to highest gas' concentration;
- Watering improves significatively the air quality;
- During the cleaning, the three gases values have a high discrepancy: during loading the values are the highest because the LHD is on maximum effort and the atmosphere is contaminated with the explosive's toxic gases; during the dumping, the values are lower, since the LDH is on a well ventilated area.

Through the study of table 17 (CA: table 38) and the annotations recorded during data gathering, at the stope L2MDWR5AW21, is possible to observe:

- The high values of gases, principally NO, during drilling, occur when the jumbo is moving, using the diesel motor; the environment can reach high values when the jumbo remained immobile while the helper was rearranging the cables;
- This stope is very vast, creating difficulties on the ventilation. The watering operation is the most affected;
- The area cleaning is done with two LHDs (due to the stope size): the first LHD carries the ore from the face to a pile, the second LHD carries the ore from the pile to the ore pass. The measurements of gases during this operation was done on the cycle of the second LHD, consequently, the values of gases are lower, since this machine works on a well-ventilated area in comparison the first LHD.

The incline L2D25R13I1 was blasted using the hydrogel, since the faces were extremely wet. It is also important to mention that the area was very well ventilated, as represented in figure 20.

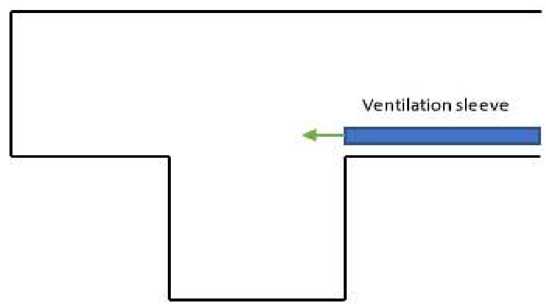


Figure 20 - Secondary ventilation L2D25R13I1

As a result of the study of table 18 (CA: table 39) and the remarks noted during data gathering, at the incline L2D25R13I1, is possible to observe:

- The NO_2 and NO present high values when the equipment on the stope runs on diesel, such as, during charging (tractor) and cleaning (LHD);
- During watering the values of NO_2 and NO are null due to the use of hydrogel. Although the CO presents high values, these never exceed TWA limit for more than 15 min and at any time surpasses the STEL limit, therefore this operation accomplishes the Directive.

The development area L2P6D7-D1, was blasted with hydrogel, due to the presence of water at the face. This area is equipped with a ventilation sleeve that directs air from the main gallery to the face, creating a well-ventilated environment. As a result of the analysis of table 19 (CA: table 40) and the observations noted during data gathering, at the development area L2P6D7-D1, is possible to observe:

- During drilling and cleaning is possible to understand the influence of the diesel machinery on the atmosphere, since the values, principally of NO, surpass the STEL limit values;
- During watering the values of NO are null and the values of NO_2 are within the TWA limit; The CO presents higher values, but these never exceed TWA limit for a period longer than 15 min and at any time outdo the STEL limit.

As a result of the examination of table 20 (CA: table 41) and the observations noted during data gathering, at the mechanical workshop L1D13, is possible to observe that during the LHDs check-ups, the atmosphere becomes toxic; posterior to this work the atmosphere continues to have substantial values of NO and NO_2, since the area does not have a secondary ventilation system and has to rely exclusive on the primary ventilation to clean the air.

As a result of the analysis of table 21 (CA: table 42) and the observations noted during data gathering, at the electrical workshop L1D13, is possible to observe that the gases values only reach higher values when a vehicle passes nearby; on the normal workshop functioning, the gases never go above the TWA limits.

As a result of the analysis of table 22 (CA: table 43) and the observations noted during data gathering, at the ore pass, is possible to conclude the area is extremely well ventilated. The ore pass is situated on a main gallery, so all the possible gases released from the locomotives are well diluted. So, this area is not problematic regarding the values of the toxic gases in consideration. As a result of the analysis of the table 23 (CA: table 44) and the observations noted during data gathering, at the primary ore crushing unit L530, is possible to conclude that the primary crushing does not represent a problem related with the fulfilment of the Commission Directive 2017/164, since all the values from the CO, NO_2 and NO are always zero.

Considering the results from each area where the data was gathered, it is possible to understand the existence of some common points regarding the toxic gases sources, the dispersion measures and sources of abnormal values.

The stopes are the areas with the greatest difficulties in ventilation, since their expansion can reach great distances from the main galleries. These areas have secondary ventilation, but, usually, the fan is placed in the middle of the stope and it does not bring fresh air into the faces, it only makes the contaminated air move.

The main ore pass is located in a main galley with a high airflow; this will directly contribute to a good air quality, as it is shown in table 22: even though the locomotive works with a diesel engine, the levels of toxic gases present on this area are always bellow the TWA limit.

The primary crushing unit is free from toxic gases; it is important to note that on this area there are no diesel machinery or use of explosives.

During drilling, the only contribution with toxic gases are when the jumbo's diesel motor is on. Generally, these periods are very short (no longer than 15 minutes). However, if the jumbo is only repositioning in the face, it can create a dangerous atmosphere. Another dangerous situation related to the jumbo, is when the helper is arranging the cable, since the worker becomes directly exposed to the exhaust pipe fumes.

During charging, the main contribution with toxic gases to the atmosphere are the tractors. The loading of ANFO and/or hydrogel does not promote the atmosphere toxicity.

Watering the faces after blasting does, in fact, contribute to the levels of toxic gases decay. However, the miner responsible for this job is exposed to high levels of toxic gases for a period longer than 15 minutes.

Cleaning presents a high coefficient of variance. The moment with higher levels of toxic gases is during loading, since the LHD's operator is working on a contaminated atmosphere and the machine is being put to its highest power. During dumping the LHD is, usually, on a well-ventilated area, decreasing the values of toxic gases, but the machine is still contributing with toxic gases, since it is necessary to elevate the power to dump the material. This oscillation of values is possible to analyse in table 24 (CA: table 45) (the values of this table were measured when the gas detector was with the LHD operator).

Table 24 - Toxic gases during cleaning at L2MDWR5AW21

Situation	CO (ppm)	NO_2 (ppm)	NO (ppm)
Loading			
Hauling - Full			
Dumping			
Hauling - Empty			
Hauling - Empty			
Loading			
Hauling - Full			
Dumping			
Hauling - Empty			
Loading			
Hauling - Full			
Dumping			

At the ore pass (usually located on a main gallery) after the LHD dumps the material, the atmosphere stays contaminated with toxic gases, to which the helper is exposed to. It is possible to analyse in table 25 (CA: table 46) the atmosphere created by the LHD during dumping at the ore pass (the data of the table was collected by placing the measuring equipment near the helper while he was cleaning the ore pass).

Table 25 - Toxic gases during cleaning on the ore pass near the stope L2MDWR5AW21

Situation	CO (ppm)	NO_2 (ppm)	NO (ppm)
Dumping			
Cleaning chimney			
Cleaning chimney			
Cleaning chimney			
Dumping			
Cleaning chimney			
Cleaning chimney			
Cleaning chimney			
Dumping			
Cleaning chimney			
Cleaning chimney			
Cleaning chimney			
Dumping			

Considering all the results analysis above, it is possible to conclude that in areas where there are diesel engines working, the values of NO are high, even after the machinery left the area and despite secondary ventilation is on.

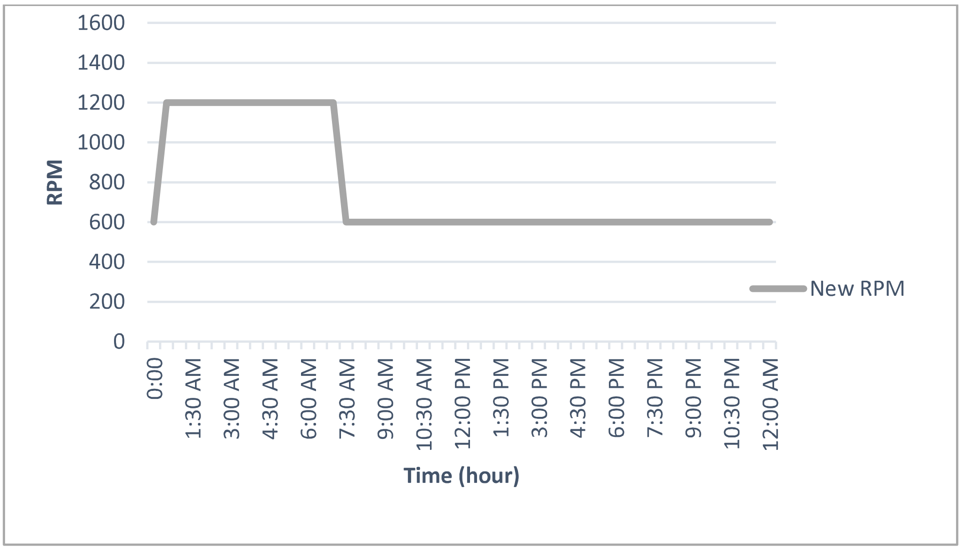
Regarding the explosives use, there is a great difference on the morning shift concerning the presence of toxic gases: when hydrogel is used, the values of NO_2 and NO in the morning (7 am) are very low or null and the CO does not reach values higher than the STEL limit, unlike ANFO on which all three gases surpass the STEL limit.

4.1.5. Other Measurements and Results

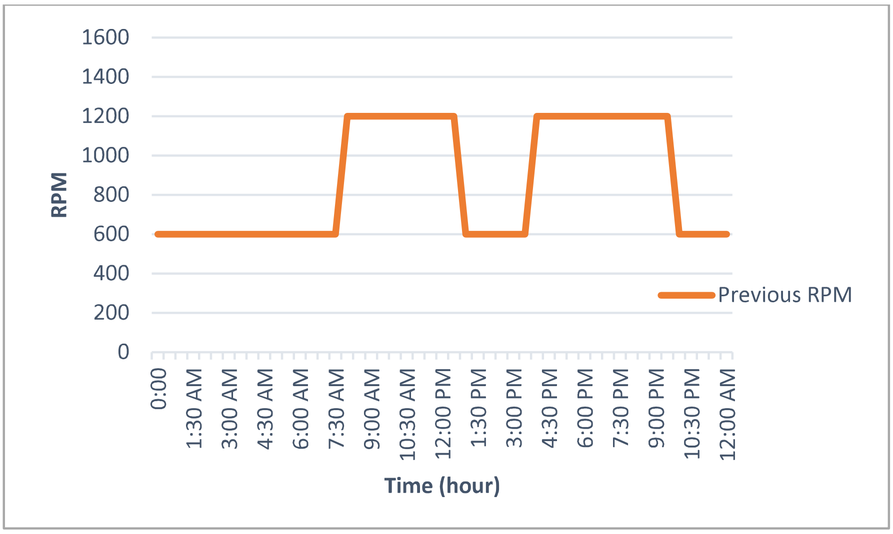
Posteriorly to the data analysis, it was important to do a deeper study regarding the ventilation and the explosives in order to have an improved approach for possible changes to be made at the mine.

Ventilation

The main fan was enhanced during the blast clearance time and decreased during the shifts, has shown in graphic 4. In graphic 5 is possible to analyse the previous model of rotation per minute (RPM) from the main fan. After this improvement the gases' levels were measured at the L2MDWR5AW21 stope during the watering of the faces. This measurement allowed to study the influence of the primary ventilation at the faces, by comparing the previous results with the values after the change in the ventilation.



Graphic 4 – Alteration on the main fan rpm from case study 1



Graphic 5 - Previous rpm from the main fan case study 1

In table 26 it is possible to analyse the CO and NO_2 values before the change of the primary ventilation and after the change. It was not possible to compare the levels of NO, because the gas detector had a problem regarding the pump of this gas and was not possible to measure it after the ventilation enhancement.

In table 26 (CA: table 47) is possible to analyse the decrease of the gases' levels when the primary ventilation is altered.

Table 26 - Difference of gases levels, at L2MDWR5AW21, before and after the change of the primary ventilation

	CO	NO_2	NO
	Reduction (%)	Reduction (%)	Reduction (%)
Average	56,05	46,25	*(13)

Although there was a CO and NO_2 reduction, it was not enough to follow the Directive. It was not possible to comprehend the impact of the main ventilation on the levels of NO. Consequently, the primary ventilation improvement consists on a possible procedure but needs to be support by other solutions.

Explosives

As previously mentioned, the main type of explosives used at the mine is ANFO; however, when the face is wet it is used a hydrogel. To understand the difference of gases released by these two types of explosives, was measured, at the same face (incline L3I6) the decay of CO, NO and NO_2 after blasting.

[13] No data due to the gas detector malfunction.

The incline where the measurements were made, did not have the secondary ventilation turned on. It is also important to note that the main ventilation had already been increased when these tests were made.

This data was collected by placing the measuring equipment at the face (on the same location both times), the nearest possible spot in order to detect the gases but without out suffering damages. The equipment was placed before the detonation (at 11pm) and left at the face during the night. Due to the battery's equipment autonomy, it was able to measure the gas decay until 5 am. It is important to note that the maximum levels regarding the measuring range from the equipment (specified in table 12) have an influence on the higher value of gas read by the detector. On the measurements during hydrogel blasting, was not possible to measure the NO due to the problem regarding the pump of this gas on the gas detector and was not possible to solve it.

In table 27 are shown the maximum and the minimum values from the gases being studied, generated by ANFO and Hydrogel. Due to the mishap mentioned before, it is only possible to compare the levels of CO and NO_2 after the detonation of both types of explosives.

Table 27 - Difference gas levels released between the ANFO and Hydrogel

	CO		NO_2		NO	
	ANFO	Hydrogel	ANFO	Hydrogel	ANFO	Hydrogel
Max (ppm)	2000,00(14)	2000,00(14)	50,00(14)	36,30	200,00(14)	*(13)
Min (ppm)	1,00	150,00	1,40	0,00	6,00	*(13)

By analysing the data collected of the CO, it is possible to observe:

- With the use of both types of explosives it is reached the maximum equipment's range;
- Following the ANFO detonation, the CO decays quite fast initially, taking around 2h30min to reach the STEL limit; after it takes longer to dwindle, around 4h to reach the TWA limit (CA: Graphic 6).
- After the hydrogel detonation, the CO levels have three moments: it starts by oscillating for around 20 minutes; after it starts decaying with a linear tendency (following the equation $y = -3,5743x + 1647$) for around 4h30min; lastly, it wanes very fast, decreasing 600 ppm in 10 minutes. Although it is not possible to analyse when the CO reaches zero, considering table 18 and table 19 and how fast the CO starts to decay by the end, it is possible to predict that, around 7 am, the CO is lower than the TWA limit (CA: Graphic 7).

[13] No data due to the gas detector malfunction.
[14] Gas detector maximum range.

By analysing the data collected of the NO_2, it is possible to observe:

- After the ANFO detonation, the values of NO_2 reach the maximum capacity of the measuring equipment for 2h 20min. Posteriorly, it starts to decrease at a fast pace; however, during the time the equipment was measuring, the NO_2 is always higher than the STEL limit. In the morning shift (7 am) there is an intense smell of this gas (CA: Graphic 8).
- Following the hydrogel detonation, the values of NO_2 remain zero for 10 minutes. When the levels stars to increase, it takes 15 minutes to peak (36,30 ppm), and right after the levels start to decay very rapidly. It takes around 4 hours for the levels to be lower than the TWA limit. It is also important to notice that in the morning (7 am) the smell of NO_2 is very subtle, almost non-existent (CA: Graphic 9).

4.2. Case Study 2

The case study 2 is another mine located in Europe. The mine extracts magnesite and dolomite. The mine's production is around 420000 t/year of concentrate; there are around 40 workers, divided in 20 per shift in the mine.

4.2.1. Mine's Characterization – Case Study 2

On the mine in study, the magnesite mineral is explored in open-pit and underground operations, as seen in figure 21. Considering the objective of this thesis, only the underground mine site will be taken into consideration. The mine is explored by two mining methods, depending how deep the deposit is: post pillar (on the mine's shallow levels) and sublevel open stopping (on the mine's deepest areas) (Wagner et al., 2015).

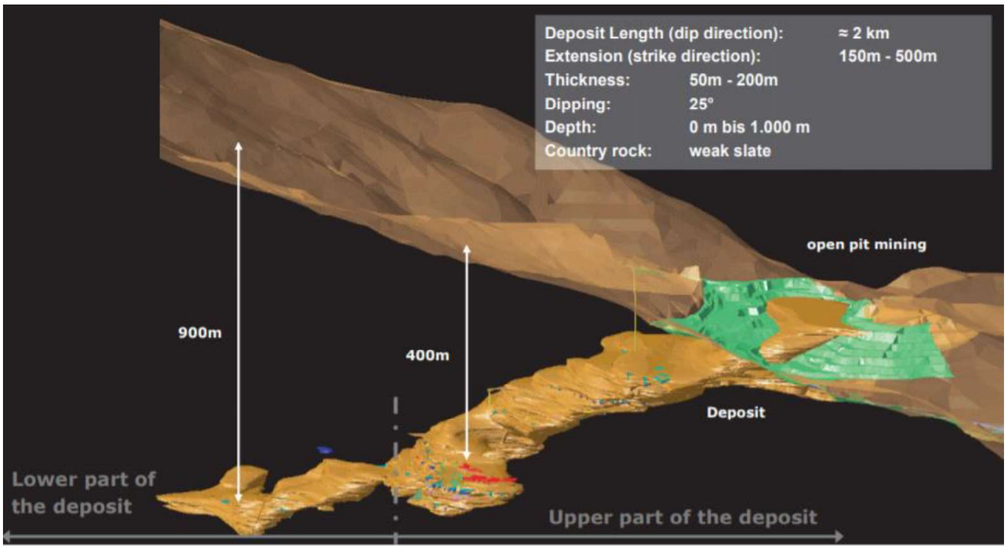


Figure 21 - Deposit from case study 2 (Wagner et al., 2015)

According to (Hustrulid & Bullock, 2001) the mining method used on the upper area of the mine, the post pillar mining method, is a combination of room-and-pillar and, in the case of this mine, overhand cut-and-fill stoping, assigning the advantages of both methods to the exploration: the spacious work sites from room-and-pillar and the smooth floors from cut-and-fill. The ore recovery is done in horizontal slices, starting from the bottom and moving upwards. Inside the panels are lefts pillars, and when each stope is mined-out, it is backfilled. On the case study 2 mine, the sections defined by pillars with 4 m of width, 15 m of length and around 80 m of height are created. Inside each section, the ore is explored by overhand cut & fill method; on this method, the ore exploration begins on the bottom of the panel and moves upwards while the bottom slice is filled, allowing a safe work by always working with a stable celling and a smooth floors. On the mine, the process starts by cutting a 7 m height slice; posteriorly it is backfilled 3,5 m and another slice of 3,5 m is mined, always maintaining a space 7 m high to work on (Wagner et al., 2015) (as shown in figure 22 and figure 23).

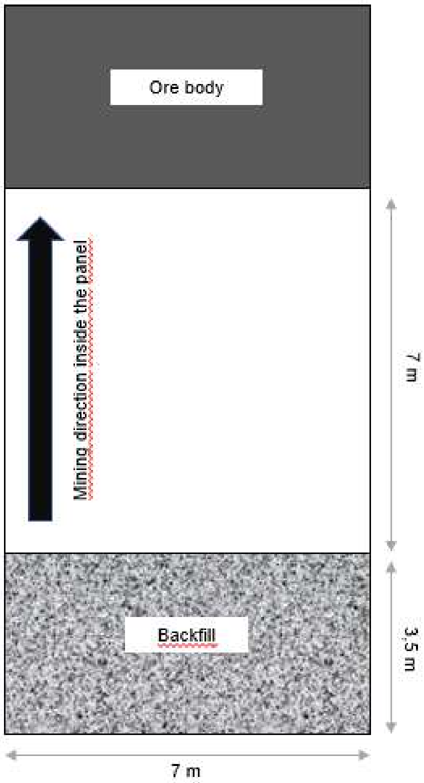


Figure 22 - Overhand cut and fill from case study 2

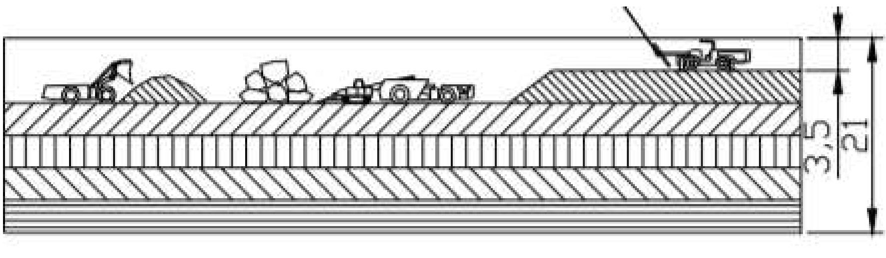


Figure 23 - Stope development in the upper part of the deposit (Wagner et al., 2015)

On the deepest part of the mine is used sublevel stoping in order to mine the ore. This method consists on creating primary and secondary pillars; the primary pillars are mined first and, after backfilling them, the secondary pillars are mined. On the mine, stopes of 7 by 7 m are created (width of the stope 7 m and width of the pillar 7 m); the primary pillars are mined leaving a stope between them (figure 24 A); afterwards the middle stope is explored creating a stope with 21 m of height (figure 24 B) and, posteriorly, the whole stope is backfilled (figure 24 C); after the primary pillars are mined, the same process is repeated to the secondary pillars (figure 24 D) (Wagner et al., 2015).

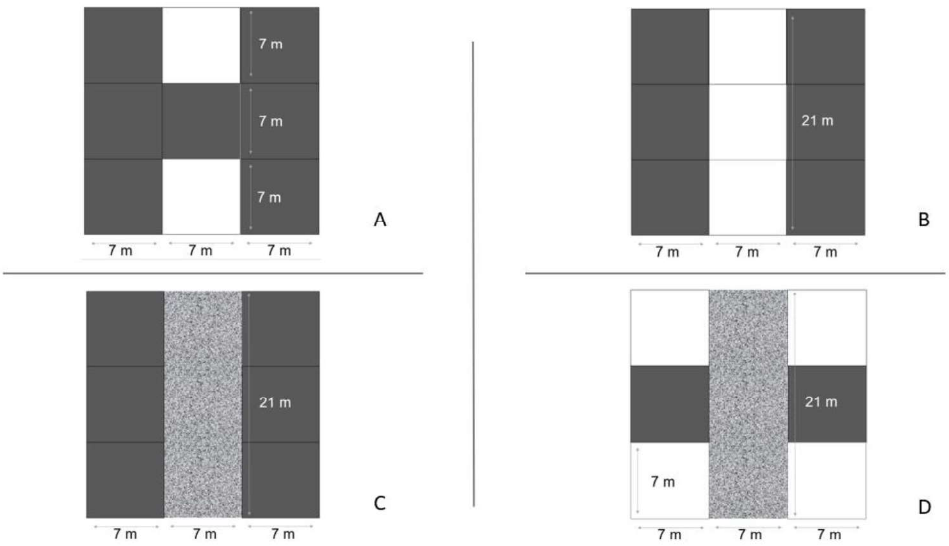


Figure 24 - Sublevel Stoping from case study 2

The ore excavation and the loading & hauling are sources of toxic gases, therefore, on this chapter will be done their analysis. Another important technical characterization to understand is the ventilation, since this is a proactive factor regarding the air quality.

Excavation

On the mine, the ore is excavated by drilling and blasting. As stated before, blasting can be defined by drill-holes layout, type of explosive and initiation system; the combination of these parameters will allow the rock to break with the desirable dimensions, allowing its handling.

On this mine, the blasting is normally done once a day at the end of the second shift. The explosive used is an emulsion, Hydrox U® and, in average, are used 275 kg of explosive per face. This explosive presents great water resistance, and, consequently, it can be used in all conditions of the mine. The initiation system used is non-electric. After blasting, the re-entry time is minimum 8 hours.

Loading and Hauling

The handling of the blasted material is carried out by loaders and dumpers. The loaders withdraw the ore from the blasted face and places it on the dumper; there are two kinds of loaders used on this mine: CAT R1700G, with a loading capacity of 6,7 m^3 and a power of 235 KW, and Altas Copco ST14, with a loading capacity of 7,6 m^3 and a power of 250 KW. The dumpers carry the material from the face to the ore pass and, therefore, are required to do great effort for long distances; the mine presents two types of dumpers: CAT AD30, with a capacity of 30 t and a power of 305 KW, and the Atlas Copco MT42, with the capability to transport 35 t and a power of 398 KW. All the equipment mentioned run on diesel. Typically, per shift are used one loader and three transporters.

Ventilation

The main ventilation system from the mine is forced ventilation in order to provide fresh air. There are four ventilators in the outgoing air way that move around 6000 m^3/min of fresh air. Regarding the auxiliary ventilation, fans are places in mining areas which are away from the main ventilation streams.

4.2.2. Data Gathering – Case Study 2

The data was gathered by the mine's team during the month of April and May of 2019. The data acquisition of this case study did not go entirely accordingly to the GEM described on chapter 3, and it was collected only during the loading, hauling and dumping operations. The description of the measurements and the equipment used are described on this chapter.

4.2.2.1. Data Measurements – Case Study 2

The data was measured during the operations involving the cleaning process: loading, hauling and dumping. The measurements were made during the first and second shift, and most of them included information for the entire 8-hour shift. The data was collected on several areas of the mine, in a total of 11 situations specified on table 28.

Table 28 - Data collected from case study 2

Location	Designation	Operations	Depth (m)
Stope	Area II North	Loading | Hauling | Dumping	650
	Area III South North	Loading | Hauling | Dumping	595
	Area IV Central	Loading | Hauling | Dumping	480
	Area VI	Loading | Hauling	260

During the loading operation, the gas detector (featured below) was placed inside the cabin (closed and equipped with air-conditioning) of the loader; the gases were only measured when the loader was at the face, not during its movement between faces. Throughout the hauling of the blasted ore, the measurements were taken inside the dumper's cabin, when it was moving from the face to the silo-shaft (at the underground breaking station) and the path back to the face. It was placed another gas detector at the extraction point during the whole shift.

4.2.2.2. Measurement Equipment – Case Study 2

The equipment is calibrated every four months and the last calibration, before the gathering of the data, was on the 3rd of April 2019. The gas detectors were equipped with different sensors regarding its placement, as shown in table 29; at the loader's cabin were measured the NO_2 and the NO, at the dumper's cabin were measured the NO_2 and CO and at the extraction point were measured the NO_2, CO and NO. The measuring equipment registered and saved the gases' levels every minute.

Table 29 - Sensors used on Dräger x-am 5600

Placement	Sensor
Loader cabin	Dräger Sensor XXS NO (6811545) and XXS NO_2-LC (6812600)
Transporter cabin	Dräger Sensor XXS NO_2 (6810884) and XXS H_2S/CO (6811410)
Ore pass	Dräger Sensor XXS NO_2 (6810884), XXS O_2/CO-LC (6813275) and XXS NO (6811545)

Due to the sensors used, during the loading operation it was not possible to measure the NO and during the hauling operation was not possible to measure the NO_2.

4.2.3. Results and Data Analysis – Case Study 2

The data gathered was organized according to table 30, and the values of CO, NO_2 and NO were identified based on the information present in table 10.

Table 30 - Organization of data from case study 2

Time (Day+hour)	Location	Operation	Equipment	CO (ppm)	NO_2 (ppm)	NO (ppm)

Considering the data was only collected during the cleaning process, the analysis will be focused on the cycle of this process. As mentioned previously, the data was measured for an entire shift, therefore, it was used the whole time period for the statistical purposes. In table 31, table 32, table 33 and table 34 (on the CD respectively table 48, table 49, table 50 and table 51) are displayed the values for the different areas during the loading and hauling operations and at the extraction point.

Area II North

Table 31 - Area II North statistical analysis

	CO			NO_2			NO		
	Load	Haul	Extraction point	Load	Haul	Extraction point	Load	Haul	Extraction point
Average (ppm)	-[15]							-[15]	
Max (ppm)	-[15]							-[15]	
Min (ppm)	-[15]							-[15]	
Coef. variance (%)	-[15]	0	234,3	81,38	95,5	80,88	47,67	-[15]	52,13

[15] Not measured.

While loading:

- NO_2 values: the average is classified as yellow, the maximum as red and minimum as green. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.
- NO values: the average and minimum are classified as green, and the maximum as yellow.

While hauling:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average is classified as yellow, the maximum as red and minimum as green. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.

At the extraction point:

- CO values: the average, maximum and minimum are classified as green. It is also possible to examine that the coefficient of variance value is higher than 100%, meaning that there is a high values distribution.
- NO_2 values: the average and the minimum are classified as green, and the maximum as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.
- NO values: the average and minimum are classified as green, and the maximum as yellow.

Area III South North

Table 32 - Area III South North statistical analysis

	CO			NO_2			NO		
	Load	Haul	Extraction point	Load	Haul	Extraction point	Load	Haul	Extraction point
Average (ppm)	-[15]							-[15]	
Max (ppm)	-[15]							-[15]	
Min (ppm)	-[15]							-[15]	
Coef. variance (%)	-[15]	659,12	101,37	77,35	84,83	65,51	49,77	-[15]	70,48

While loading:

- NO_2 values: the average and minimum are classified as green, the maximum as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.
- NO values: the average and minimum are classified as green, and the maximum as yellow.

[15] Not measured.

While hauling:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average is classified as yellow, the maximum as red and minimum as green. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.

At the extraction point:

- CO values: the average, maximum and minimum are classified as green. It is also possible to examine that the coefficient of variance value is higher than 100%, meaning that there is a high values distribution.
- NO_2 values: the average and the minimum are classified as green, and the maximum as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.
- NO values: the average and minimum are classified as green, and the maximum as yellow.

Area IV Central

Table 33 - Area IV Central statistical analysis

	CO			NO_2			NO		
	Load	Haul	Extraction point	Load	Haul	Extraction point	Load	Haul	Extraction point
Average (ppm)	-[15]							-[15]	
Max (ppm)	-[15]							-[15]	
Min (ppm)	-[15]							-[15]	
Coef. variance (%)	-[15]	0	84,99	82,15	67,43	99,23	44,68	-[15]	67,41

While loading:

- NO_2 values: the average and minimum are classified as green, the maximum as red. It is also possible to examine that the value coefficient of variance is higher than 50% and lower than 100%, meaning that there is some values distribution.
- NO values: the average and maximum are classified as yellow, and the minimum as green.

While hauling:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.

[15] Not measured.

- NO_2 values: the average and minimum are classified as green, and the maximum as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is some values distribution.

At the extraction point:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average is classified as yellow, the minimum as green, and the maximum as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is values dispersion.
- NO values: the average and minimum are classified as green, and the maximum as yellow.

Area VI

Table 34 - Area VI statistical analysis

	CO			NO_2			NO		
	Load	Haul	Extraction point	Load	Haul	Extraction point	Load	Haul	Extraction point
Average (ppm)	-[15]		-[15]			-[15]		-[15]	-[15]
Max (ppm)	-[15]		-[15]			-[15]		-[15]	-[15]
Min (ppm)	-[15]		-[15]			-[15]		-[15]	-[15]
Coef. variance (%)	-[15]	277,98	-[15]	74,43	104,40	-[15]	37,17	-[15]	-[15]

While loading:

- NO_2 values: the average and minimum are classified as green, the maximum as red. It is also possible to examine that the coefficient of variance value is higher than 50% and lower than 100%, meaning that there is value dispersion.
- NO values: the average and maximum are classified as yellow, and the minimum as green.

While hauling:

- CO values: the average, maximum and minimum are classified as green. The values were found compatible with the Directive.
- NO_2 values: the average and minimum are classified as green, and the maximum as yellow. It is also possible to examine that the coefficient of variance value is higher than 100%, meaning that there is value dispersion.

[15] Not measured.

4.2.4. Discussion of Results – Case Study 2

During the loading and the hauling operations the gas detector measured the gases inside the cabin; the values obtained represent the gases to which the driver of the vehicle, with a cabin, was exposed to, not the atmosphere at the faces. On the extraction point, the measurement equipment stayed at the same place the whole shift, being exposed to the mine's atmosphere at that location. With this information and through the analysis of the previous tables, it is possible to attain the following conclusions:

- The levels of CO never surpass the limit levels (TWA and STEL) imposed by the Commission Directive 164/2017, in any of the situations; therefore, the air inside the cabins and at the extraction point do not represent problems regarding the CO.
- At the extraction point the values of the different gases (CO, NO_2 and NO) present an oscillation of values with peaks when the dumper reached the silo-shaft. By norm, the values of the average and the maximum, are higher at the extraction point, comparing to the dumper; this can be explained by the protection of the cabin. The extraction points are located on an area with good airflow, creating an atmosphere (even without the protection of the cabins) with an average of toxic gases values that fulfils the Directive, since the high values never surpass the 15 min time limit. However, some of the peaks are higher than the maximum limit (for the NO_2 and the NO); this condition represents an issue.
- While loading and hauling the worker should be protected by the cabin. However, it is still possible to point values that surpass the Directive, even inside the cabin.
- During the loading operation, the loader does not leave the face that is being cleaned; this will contribute to a concentration of gases and, consequently, a continuous exposure to them. The values of the gases (predominantly NO) increase, even more, when the machine is put on maximum power (when material is being collected the and when is depositing it on the dumper). Although the vehicle is equipped with a cabin, the worker that drives it is not fully protected.
- Throughout the hauling operation, the dumper spends most of the cycle on a well-ventilated area (main galleries). When the vehicle is being filled, with the blasted ore, the exposure reaches a peak; since the dumper does not remain at the face for a long period, the values of NO_2 do not increase significantly.

4.3. Global Discussion of Results

The main objective of this investigation was to have a deeper knowledge of the mines' current situation. To attain this knowledge, it is fundamental to understand which are the main producers of toxic gases on underground mines, how the ventilation influences the dilution of the gases, how the type of explosives used will affect the air quality and how adjustments in the machinery can decrease the toxic gases produced. Through the study conducted in both mines, was possible to answer some parts of the research question.

The research demonstrates a correlation between some situations and reach the following conclusion: The most critical situations are watering and cleaning. The concentration of gases during watering are mainly influenced by the type of location, the type of explosive and the blast clearance time. Regarding the cleaning operation, the highest gas' concentration will also depend on the location, the machine used, the effectiveness of the watering operation, and consequently on the type of explosive.

The stopes are the areas where the accumulation of gases is the greatest. The main ventilation and the auxiliary ventilation have an influence on the concentration of gases at these areas. However, the expansion of stopes can reach great distances from the main galleries, creating a difficulty for their ventilation.

The type of explosive is directly related with the gases produced. When emulsion/hydrogel is used, the quantity of NO_x on the air posteriorly to the detonation, is much lower, especially when comparing with the emissions from ANFO.

The blast-clearance time is important to clear most of the toxic gases after blasting. However, if the auxiliary ventilation is not turned on or if it is not well placed, the blast-clearance time (independently of the time used) will not clear the air.

Considering the use of diesel equipment, it is possible to understand that in areas where there are diesel engines working, the values of NO increase, even after the machinery left the area and despite secondary ventilation is on. Even though the cleaning was the operation where this situation most critical, on other operations, such as, drilling and use of auxiliary vehicles, the increase of NO_x, especially NO, is notable.

The ventilation will have a great influence on the dilution of the gases. An increase or adjustment on the main ventilation will contribute to a higher effective dilution of toxic gases. However, this decrease of gases may not be enough.

The data, from case study 2, suggests the implications of cabins, in the vehicles, on the decrease of the miner's exposure to toxic gases. Although this protection measure does not protect the workers fully, it does help to lower the contamination level. Considering the Directive, it is not clear if the toxic gases levels inside the cabins are valid.

The studies validate the hypothesis regarding the main producers of the toxic gases under analysis, being the explosives and the diesel equipment. On the case study 1 was possible to understand the difference between ANFO and emulsion. Although it was possible to show, on both studies, the contribution of the diesel equipment with toxic gases to the mine's atmosphere, due to the lack of available data, the results cannot confirm the moments where the diesel equipment produced the highest values of toxic gases and how adjustments on these equipment can decrease the toxic gases production.

5. Suggested Adjustments

From the analysis of the case studies, it is possible to conclude that on some situations at the mines the Directive is not fulfilled, at the moment. Therefore, it is suggested to do adjustments on the mines until the end of the transitional period (21 August 2023). The economic value of the adjustments can vary deeply, depending on the alterations made, and so, in this chapter will be addressed several possible solutions to decrease the toxic gases levels. The solutions are approach on an increasing level of complexity and investment, but it is not certain that the simplest solutions will be enough to meet the values of the Directive. The suggestions were made without detailed evaluation studies, and so, the proposal is to adjust the solutions and control the results, moving to larger solutions if the results are not enough. Therefore, there are presented three types of solutions: adjustments of immediate mitigation that are connected with low investments and low costs; general adjustments that have already been tested at the case study; and adjustments that include the new advances of technology but have considerable high investments. It is important to consider the mine's characteristics, since these are directly related with the effectiveness of the adjustments.

a) Adjustments for Immediate Mitigation (low costs)

The adjustments for immediate mitigations, aim to describe low cost solutions especially dedicated to the critical situations, identified on the case studies.

The most critical areas are the stopes and development areas, since they are classified as "bag end", that is, the air does not move enough to decrease the contaminants. The implementation of secondary ventilation can improve the air quality at these areas. The use of regulation structures (mentioned on chapter 2.5.) will help to redirect the airflow to areas where it is necessary fresh air (e.g. areas where there are no operations occurring, or where the mine was abandoned, can be sealed, in order to redirect the air to the areas where is necessary, and decrease the ventilation where is not necessary).

Regarding the drilling operations, there are only toxic gases when the jumbo's diesel engine is on, and so, the gases produced by the jumbo are minor (when analysing the whole operation). However, the jumbo's helper is exposed to high levels of toxic gases when is organizing the cables. To decrease the exposure to toxic gases produced by the jumbo, the equipment should always be turned off when someone is connecting the cables and/or needs to be in the back of the vehicle. Another possibility is to change the direction of the exhaust pipe to the side or the bottom of the equipment, decreasing the direct exposure of the miners when connecting the cables.

One of the most critical situations is during the watering of the faces. The high values of toxic gases after blasting, will lead to a toxic atmosphere that should be cleaned before any worker enters those areas. The blast-clearance times should be used to clear the air, through a methodologic implementation of auxiliary ventilation. The auxiliary fan should be installed on the main gallery, where the air is fresh and free from contaminants, so the air moved to the face is always clean. The sleeve attached to the secondary fan should be positioned to move the air inside the stopes and be adapted according to the enlargement of the faces, assuring that it is installed as close as possible without being damaged by the blasting. Immediately after blasting, the auxiliary ventilation should be turned on.

The blast-clearance time should be enough to reduce the gases to values lower than the TWA limit. In the cases where it is not possible, the workers should not be exposed for more than 15 minutes and should have a personal gas' detector to confirm that the levels are never higher than the STEL limits. If necessary, it should be implemented a rotation system of the workers to restrict the exposure of each worker.

Concerning the toxic gases related with use of diesel equipment, it should be done a regular maintenance and a tight control over the emissions. The use of catalysts filters on the machines can filter the CO and the NO_x. Usually it is used a sequence of catalysts, with several functions to create a device that decreases several toxic gases. For the proper work of the catalysts, it is necessary for them to be in good conditions, if damaged or old, the toxic gases might not be filtered. The vehicle maintenance should be done regularly, since change of oil and a good lubrification can extend the catalyst's life. Collisions can also influence the catalyst's functioning, so a carefully maneuverer of the vehicle is necessary. The catalyst must be changed when the vehicle completes the expiration kilometrage or working hours of the device (the manufacturer should indicate this value). The biodiesel will help to reduce the emissions of CO, but the emissions of NO_x are not reduced and can even increase. As mentioned previously, throughout the case studies was possible to conclude that the NO was the most difficult gas to eliminate during the use of diesel machines; so, this cannot be used as a solution.

b) General Adjustments (already tested)

The general adjustments focus on solutions that have been tested on the case studies and have been proven to decrease the exposure of the workers to toxic gases.

The increasement of the main ventilation will raise the quantity of fresh air inside the mine. If the main ventilation works by insufflating air, the fan will directly insufflate fresh air to the mine, forcing the contaminated air to move to outside the mine. If the main ventilation works by exhausting the air, the air in the mine will be obligated to move and, consequently, removes the contaminated air and forces the fresh air to go inside the mine. The power given to the main fan will directly influence the amount of air moved into the mine. On the case study 1, it was possible to compare the same work area after an increase of the main ventilation after the detonations. This study showed that after the increasement of the main ventilation, the toxic gases at the area had a very significant reduction (Table 26 (CA: Table 47)).

The use of explosives has a great impact on the toxic gases released on the mine. There are several components related with blasting that can influence the levels of toxic gases released and the exposure of the miners to them. The layout of the drilling, the type of explosive, the amount of explosive and the detonation system will impact directly the emitted gases during blasting. Through the knowledge acquired on the theorical framework and in the case study 1, is possible to conclude that emulsions are the explosive (currently on the market) with less NO_x emissions. In table 27 is possible to compare the emissions of ANFO and hydrogel at the same face. When the face was blasted with hydrogel the face had less NO_x, and therefore, the emissions of toxic gases from the use of explosive were lower.

The use of vehicles with cabins can be discussed whether it can be used to achieve the Directive or not. However, on case study 2, was possible to analyse the exposure of the workers during the cleaning operation when they are working inside a machine with a cabin. The cabin permits the worker to have a more controlled environment, since the air-condition allows a control of the temperature and a decrease the exposure to toxic gases. Nevertheless, were still found some peaks of exposure even inside the cabin.

c) New Technology Adjustments

The new technology adjustments aim to address solutions related with the new technologies, development solutions that have been put recently on the market and ideas of solutions that can be done hereafter.

As mentioned before, watering is one of the operations the miners are exposed to the higher values of gases. To eliminate the miner's exposure can be used a remote-control watering device. This operations by remote control could be done shortly after the blasting, without the need to wait for the ventilation to clean the air. The miner controlling it would be on a well-ventilated area and not exposed to any toxic gases and free of the danger of falling rocks. Although there are no equipment available on the market for this operation to be remote controlled, the technology is already available to create this robot: the robot should be equipped with a camera, allowing the miners to control it, to see where the machine is at all times and a tank of water with sufficient dimensions to water at least the face (with the tank it is not necessary to be connected to a hose and it is able to move without restrictions); the wheels should be a continuous track, so it can move easily on a fresh blasted face; the robot should water resistant and able to resist the impact from rock falling.

The cleaning operation can be done, principally, in two ways: with an LHD or with a Loader & Dumper. The use of electric vehicles is an option that will eliminate the emissions of gases resultant from the diesel burning. As mention on chapter 2.9.2., there are three types of electric-powered alternatives: batteries, cable and trolley.

The battery-powered vehicles can be applied to all type of mining methods and to all vehicles (LHD, loaders, dumpers). The autonomy of the battery may vary according to the manufacturer, vehicle size, vehicle load and effort that it is put to. The battery's technology is being widely developed with improvements that increase the batteries' autonomy and/or an easy battery swap technology. Several manufactures are investing in the development of battery's technology, as it is an example the following vehicles currently available on the market:

- Epiroc® Minetruck MT42 (Figure 25): an articulated dumper with a capacity of 42 t. Concerning its measures, it has an overall length of 10,945 m and high of 2,575 m. It has a high energy density battery made from lithium-ion and an energy regeneration system to enhance the autonomy (Epiroc, 2019A).

Figure 25 - Epiroc® Minetruck MT42 (Epiroc, 2019A)

- Artisan Vehicles® Z50 (Figure 26): An articulated dumper with a capacity of 50 t. Regarding its dimensions, it as an overall length of 10,754 m and a width of 3,327 m. It is equipped with a lithium-iron-phosphate battery that powers 4 electric motors generating 480 kW of continuous power. (Artisan Vehicles, Battery electric 50 tonne haul truck, nd a)

Figure 26 - Artisan Vehicles® Z50 (Artisan Vehicles, Battery electric 50 tonne haul truck, nd a)

- Komatsu® Elektro Dumper (Figure 27): A rigid dumper with a capacity of 65 t. As for its measurements, it has a length of 15,240 m, a height and a width of 10,363 m. It has a lithium battery that weights 8 t and produces 600 kWh. It also has an energy conversion system, allowing the battery to be recharged when the dumper is braking, as it is explained on figure 28. This vehicle is currently operating on a quarry in Biel, Switzerland. (Manthey, 2018)

Figure 27 - Komatsu® Elektro Dumper (Manthey, 2018)

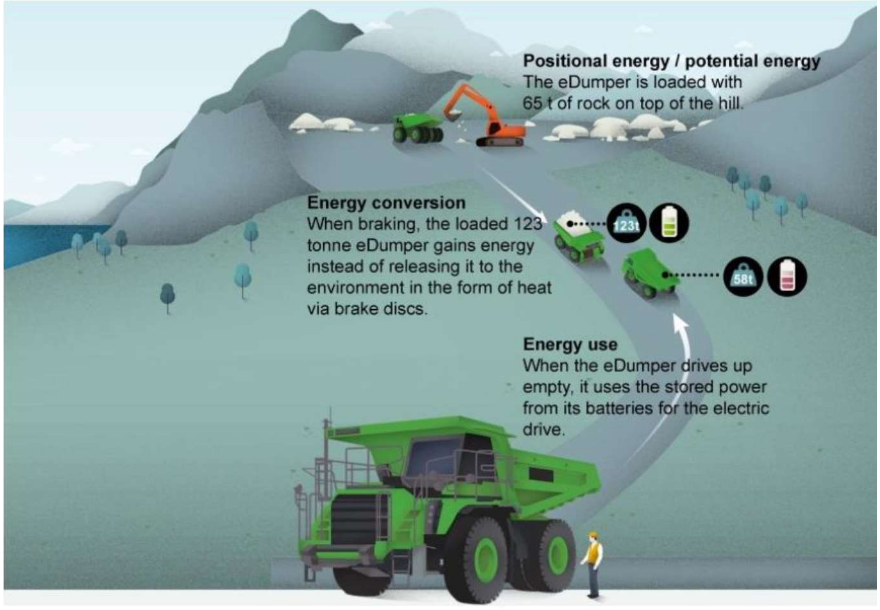


Figure 28 - Regenerative braking system (Manthey, 2018)

- Artisan Vehicles® A4 (Figure 29): An LHD with a capacity of 4 t. The vehicle has an overall length of 6,2 m, a width of 1,68 m and a height of 1,65 m, agreeing with low profile mines. It is equipped with a lithium-iron-phosphate battery that generates 88 kWh. It has also a regenerative braking system, in order to recharge the battery during braking system. (Artisan Vehicles, ndB)

Figure 29 - Artisan Vehicles® A4 (Artisan Vehicles, ndB)

- Artisan Vehicles® A10 (Figure 30): An LHD with a capacity of 10 t. Regarding its measurements, the vehicle has an overall length of 9,9 m, a width of 2,2 m and a height of 2,149 m. It is equipped with a lithium-iron-phosphate battery that generates 265 kWh. Additionally, it has a regenerative braking system, that allows the battery to be charged during braking. (Artisan Vehicles, ndC)

Figure 30 - Artisan Vehicles® A10 (Artisan Vehicles, ndC)

- Epiroc® Scooptram ST14 (Figure 31): An LHD with a capacity of 14t. It has an overall length of 10,865 m and a height of 2,601m. It has a high energy density battery made from lithium-ion that generate 200 kW and an energy regeneration system. (Epiroc, 2019B)

Figure 31 - Epiroc® Scooptram ST14 (Epiroc, 2019B)

The manufactures Epiroc® and Artisan Vehicles®, have also developed in easy battery swapping technology, on which the worker does not have to leave the vehicle. In figure 32 is shown the Epiroc's alternative: *The Battery Sawp Scooptram S14Battery*; and in figure 33, is the Artisan Vehicles's technology: *The PitStop Battery Auto Sawp.*

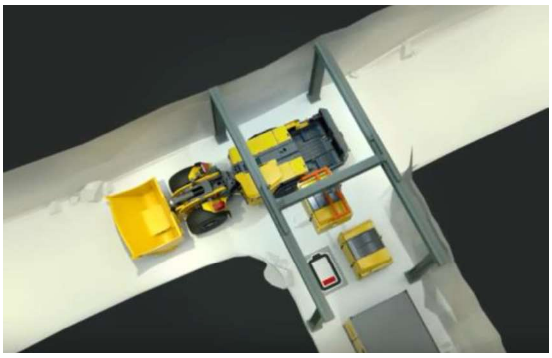


Figure 32 - The Battery Sawp Scooptram S14 Battery (Epiroc, 2019C)

Figure 33 - PitStop Battery Auto Sawp (Artisan Vehicles, 2019)

The cable-powered vehicles can only be used in some types of mines and in some vehicles. The size of the mine will influence largely its possible use; on small mines, the use of cable equipment is easier. The easiest mining methods for the use of this technology are room & pillar and caving, since, usually, the vehicles do the same short-distance trajectory using LHDs. The loader can also be cable-powered, if is towed to the other faces or has a diesel motor to move to the next face. The dumpers cannot use this technology, since this vehicle do long distances and the cable would not allow a great movement. Following is shown a cable-powered vehicle, already on the market:

- Epiroc® Scooptram EST1030 (Figure 34): An LHD with a capacity of 10 t. Regarding its measurements, the vehicle has an overall length of 10,509 m and a height of 2,352 m. It can be adapted with 3 types of cables: cable 1 has 300 m of length, a voltage of 1000 V and a frequency of 50Hz; cable 2 has 300 m of length, a voltage of 1000 V and a frequency of 60 Hz; and cable 3 has 200 m of length, a voltage of 660 V and a frequency of 50 Hz. It is also equipped with a reel control system, that prevents tensile forces on the cable and, consequently preventing its damage. (Epiroc, 2019D)

Figure 34 - Epiroc® Scooptram EST1030 (Epiroc, 2019D)

The trolley-powered vehicles can only be used in caving, since the structure necessary for this technology is very hard to install; since in caving the entire extraction structure is prepared from the beginning, the catenary can be installed right away. On other mining methods, the use of trolley-vehicles can be used has a hybrid, that is, in the main galleries the catenaries are installed and, in the stopes, and development areas the vehicles use diesel or a battery. This technology can be used in LHDs and dumpers, since these are the machines that move. Following, it is shown an example of a trolley-dumper working on an open pit mine:

- Komatsu® 860E-1K (Figure 35): A dumper with a capacity of 254 t. Concerning the measurements, it has an overall length of 14,93 m, a width of 9,39 m and a height of 7,30 m. Although this vehicle works on diesel, it has the option to be adapted to a trolley-assisted system allowing a faster drive up and with less diesel consume. (Komatsu, 2016)

Figure 35 - Komatsu® 860E-1K (Komatsu, 2016)

Although the vehicles related with cleaning are the most pollutant, personal vehicles, such as, tractors or pick-up vans, can also be adapted or replaced. As seen on the case study 1, the tractor was the main contribute for toxic gases during the charging of the explosives, and so, changes on this machine could decrease the exposure of the miners to the gases.

The increasingly stricter requirements from the governmental institutions and the concern with the miner's health and safety will result in stricter regulations. The advance in the technologies and, the adaptation of the mines to them, seems to be an inevitable path.

6. Conclusion

This research aimed to understand the current situation at European mines and the measures necessary to be taken to fulfil the Commission Directive 2017/164 Article 6. Based on the theorical and practical analysis was possible to answer which are the main producers of toxic gases on underground mines, how the ventilation will influence the gases dilution and how the type of explosives used will affect the air quality. The study results to conclude that the main producers of toxic gases on underground mines are the explosives and the diesel equipment. The results also indicate that the type of explosive influences the quantity of gases released during blasting, usually the emulsion releases less $NO_{x.}$ It was also possible to understand that the main and secondary ventilation are directly correlated with the dilution of the contaminated air; an increase on the main ventilation will affect directly the dilution, even inside the stopes, and an adjusted auxiliary ventilation can be enough for a complete dilution after blasting. Nonetheless, on the study was possible to identify the diesel burning as a substantial contributor of toxic gases, but it was not possible to understand how each vehicle components contribute to the emissions and how to adjust the diesel equipment to decrease the emissions.

On the Directive there is no indication regarding the method of measurement or analysis of the toxic gases. Consequently, it was relevant to develop a methodology of measurement and analysis to answer the research question. There are many factors that contribute to the presence of toxic gases on a mine's atmosphere, and the GEM aimed to create a method that allows to compare, not only the locations, but also the different operations that are performed in the locations. The GEM permits to analyse how different operations and how different locations contribute to the levels of the toxic gases under analysis, and the main factors that change. To validate the GEM, it was applied in two mines to evaluate their current situation. On case study 1 the GEM was fully applied, and so, it was possible to measure and analyse all the locations and operations at the mine. On case study 2, it was only partially applied, and it was only possible to analyse the cleaning cycle. This thesis contributes with a methodology, the GEM, that when is applied at the mines, allows to have a coherent way to analyse the data and identify the critical situation, regarding the toxic gases.

The thesis also proposed to suggest adjustments on underground mining sites, to achieve the Commission Directive 2017/164 IOELV. Through the knowledge acquired on the theoretical framework and results of the case studies and was possible to explore solutions to achieve the Directive limit values. The suggested adjustments submitted can have an increasing level of complexity and investment, from changes on the ventilation system to investment on new technologies on the market. However, it is important to consider that every mine has different condition, and so, the less complex adjustments might not be enough to some mines, requiring further studies.

The initially methodology proposed, to achieve the objectives, was revealed effective in answer the research questions. The theoretical framework allowed the knowledge to understand the importance of the Directive and to gain a detailed information of the published information that already exists on the thesis topic. The development of the evaluation plan, the GEM, was fundamental to have a detailed plan on how to evaluate the mine's current situation. The GEM's validation was through its implementation on two mines was essential to understand how the GEM can be adapted and the improvements possible to incorporate on it. Lastly, the analysis of possible adjustments was only possible due to the information gathered on the theoretical framework and the case studies. Therefore, the proposed methodology was revealed has effective on achieving the answers most to the main objectives. Throughout the thesis were encountered some limitations that did not allow to answer some questions. On the case study 1, the gas detector being used had a malfunction during some measures, preventing the NO analysis on the main ventilation study and on the explosive comparison study. Another drawback encountered was the analysis of the diesel machinery components to the toxic gases; due to time insufficiency and proper equipment (an opacimeter and an exhaust pipe gas detector) was not possible to do a detailed analysis to the diesel machinery.

Based on these conclusions, the GEM implementation in more mines, with different mining methods and ores, would allow to understand its full adaptability and do possible adjustments to improve it. Further research is needed to determine the relationship between the diesel machinery components and the emission of toxic gases and how additional adjustments could decrease the emissions. Additionally, to better understand the implications of the adjustments addressed, a study might be required to institute the solutions proposed on a mine and analyse their effectiveness; the study should implement the gradually the adjustments to understand to each extended the solutions can be affective.

This study allowed the implementation of the measurement and analysis methodology, the GEM, that will enable the comprehension of the current situation at the mines and that can be implemented posteriorly to the adjustments to confirm their effectiveness and the fulfilment of the Directive.

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Attachments

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A.1. MSA Altair 5X

Tipo de sensor		Verificación			Ajustes de alarma			
		Gas patrón	Resultado	N.º lote botella	Baja	Alta	STEL	TWA
Sensor de combustible	C5H12 0-100 %LEL	58 %LEL	✓	1031693-60	10 %LEL	20 %LEL		
Sensor de oxígeno	O2 0-30 Vol.%	15,0 Vol.%	✓	1031693-60	19,5 Vol.%	23 Vol.%		
Sensor de tóxicos 1	CO 0-2000 ppm	60 ppm	✓	1031693-60	25 ppm	100 ppm	100 ppm	25 ppm
Sensor de tóxicos 2	NO2 0-50 ppm	10 ppm	✓	1083040-5	3 ppm	5 ppm	5 ppm	3 ppm
Sensor de tóxicos 3	NO 0-100 ppm	50 ppm	✓	917715-3	25 ppm	75 ppm	25 ppm	25 ppm
Sensor IR	CO2 0-10 Vol.%	2,5 Vol.%	✓	1031693-60	0,5 Vol.%	1,5 Vol.%	0,5 Vol.%	1,5 Vol.%
Sensor PID	-							

Figure 36 - Alarms from the gas detector MSA Altair 5X

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