Quantifying the Environmental Sustainability in Underground Mining

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ABSTRACT: Currently in the world is being on increasing importance of sustainable development (SD) of human activities. Underground mining operations must be in balance with the economic, environmental and social aspects and guarantee the advantage for humanity at the moment and in the future.
For real and efficient management of the DS quantification of the Sustainability Indicators is required.
In the Geotechnical Center of IST (Technical University of Lisbon) research works for development the mathematical model for quantification the environmental component of undeground mining and geotechnical works and called *Environmental Sustainability Index* ISA. This model uses five environment indicators: materials, water and energy use; geotechnical and water qualities; atmosphere quality; biodiversity and cultural patrimony; waste and environmental incidents.
The present article includes some inicial research results and is aplied to the Panasqueira Portuguese underground mine.

1 INTRODUCTION

The three main supports of the DS are constituted by the economic performance, the environmental protecção and the social responsibility, that are determinative in the practical application of its basic principles.
In the European Union (EU) exist the European Commission for SD (1) and in the United Nations is the Division for SD (2), implementing strategies of the SD in regional and global level.
The economic dimension of sustaibability (ST) concerns the organization´s impacts on the economic circunstances of its stakeholders and economic systems at the local, national and global level. The environmental dimension of ST concerns the organization´s impacts on living and non-living natural systems, including ecosystems, land/rock, air and water. The social dimension concerns the organization´s impacts on the social systems (stakeholders at the local, national an global levels) with wich it operates.
In the mineral industry the efforts in the operacionalization of the DS carrying through diverse organizations as Mineral Mining ans Sustainable Development - MMSD(3), Global Reporting Initiative - GRI(4), International Council on Mining and Metals ICMM(5), World Busines Council for Sustainable Development(6), etc. but that to the date they only identified the qualitative and not quantitative level.
The ST is resultant of the SD concept and it is the condition to the permanence in the time of any activity and the benefits derived from them. The ST looks to harmony or balance between the economic, environmental and social aspects for improvement the quality of human life, respecting the right to next generations in benefiting et least (Navarro Torres, V., 2005).
For real and efficient management of the SD in underground mining is necessary to quantify the Sustainability Index (IS) on the economic, environmental and social fields. In the present study we present the modelling of the ISA.

2 THE *SD* TO MINERAL SECTOR AND *ISA*

2.1 Role of the mineral sector in the humanity development and the SD

The role of the mineral sector in the humanity development can be explained with the relation of production and consumption of primary minerals and they are characterized for common trends, as the example of copper can evidence.
Global ore copper reserves had a strong icrease in the sevnty decade, having a recently trend for the stabilization, being at present 320 Mt, sufficient to the demand of this metal during 60 years. The global production at 2000 was 14.8 Mt (Chin S., et. al. 2000).
The most consuming are the developed countries (U.S. and E.U.) with GDP 10 kg of Aluminum, Copper and Zinc and 1 kg of Nickel; against the inferior consumptions the 0.5 kg in not developed countries (Africa, Asia, etc.).
At 2050 the world-wide population will increase in 3 billion (7) that imply an addition of the metal consumptions. For example the copper production at 2000 was 14.8 Mt and at 2050 will be necessary to produce 27.1 Mt.
The role of the mineral sector in the SD is the project rentabilized in balance with the environmental protection and the social responsability, with community participation in coordination of the government.
But for real effecttivity is determinative the adoption of the SD politics, as for example Luzenac company member of Rio Tinto (Turner, E., et al. 2003): Quality of relationship with the customer; practical joust in the respect to the job and the communities; responsible management of the environment; efficiency in the use of the mineral deposits; respect to the standards of the environment, health and safety.

2.2 Environmental sustainability in mining industry

The operacionalization of the SD of the mineral sector is a very complex task, but the management based on the ST through IS is a very important way, therefore it would allow to standardized the ST and to manage the great amount of intervening parameters to the long life cycle of mineral industry, being considered the permissible levels of the ST that guarantees the economy (*ISE*), the environment protection (*ISA*) and the social responsibility (*ISS*) in benefit of the current and the future generation.
The *Sustainable Environmental Index ISA*, is part of the three-dimensional mineral sector structure of the ST (Fig. 1), composit for five (5) indicators and each have lots of sub-indicators depending on the type, dimension, localization and other characteristics of the mining operation.
The IS and particulary the ISA can be expressed with reference of 0 and 1 values, being the ST level caracterized by appropriate scale, as indicated in Table 1.

Table 1. Sustainability level of undergorund mining

ISA ≤0.35	0.35<ISA ≤0.70	0.70<ISA≤1.0	ISA≥1
Very low	Low	Moderate	Good

The *ISA* considering five main indicators of the SD environmental performance in the mineral sector and can be express by the equation (1) in function of the IS of materials, water and energy consumption (ISA_{mae}), of the Geotechnical and Groundwater IS (ISA_{gw}), of the air quality IS (ISA_a), of the Biodiversity IS (ISA_b) and of the waste and incidents IS (ISA_r).

$$ISA = \frac{1}{5}\sum_{i=0}^{i=5} ISA_i = \frac{1}{5}\left(ISA_{mae} + ISA_{gw} + ISA_a + ISA_b + ISA_r\right) \quad (1)$$

An underground mine will be environmentaly sustainable when the environment system is kept in steady conditions, healthful levels and improvement instead of deterioration, using measured of technical protection and economical viability.

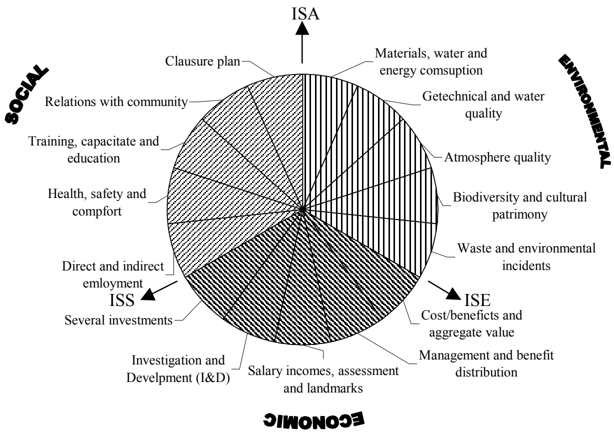

Figure 1. Sustainability Indicator in mineral sector

3 MATHEMATICAL MODEL FOR DETERMINATION OF *ISA* IN UNDERGROUND MINING

3.1 Geotechnical Sustainability Index (ISA_g)

The ISA_g is composed with two sub-indicators: underground opening stability *ISGr* and dynamic properties of rock mass ISG_v. The mathematical model proposed is express by the equation (2) in function of local quantity *l*.

$$ISA_g = \frac{1}{2l}\left(\sum_{i=1}^{l} ISG_{r(i)} + \sum_{i=1}^{l} ISG_{v(i)}\right) \tag{2}$$

Applying the geotechnical environmental impact criterion of Navarro Torres et al. (2005), the sustainability of unsupported underground opening that will remain steady to the long time (ISG_r) will be:

$$\mathrm{ISG_r} = 1 - \frac{\mathrm{A}}{2.282.\mathrm{ESR.Q}^{0.3898}} \quad \text{(unsupported span)} \tag{3}$$

Where *A* is the opening span (m), *ESR* is Excavation Support Ratio and *Q* is the Tunnelling Quality Index (Barton N., et al., 2000).
Applying the rock mass failure and deformation around of underground openings, that occurs when the support pressure p_i is inferior to the critical support pressure P_{cr}, in this condition, the geotechnical sustainability ISG_r will be:

$$ISG_r = \frac{(1+K)p_i}{2P_o - \sigma_{cm}} \quad \text{(underground openings with support)} \tag{4}$$

where *K* factor is calculated by equation 5 in function of the friction angle of rock mass ϕ, P_o is the principal stress, σ_{cm} is the simple compressive strength of the rock mass, calculated in function of cohesion *c* and the friction angle by equation 6.

$$\mathrm{K} = \frac{1+\mathrm{sen}\,\phi}{1-\mathrm{sen}\,\phi} \quad (5), \qquad \sigma_{cm} = \frac{2c\cos\phi}{1+sen\phi} \quad (6)$$

3.2 Undeground Atmosphere Sustainability Index (ISA_a)

The environmental impacts in underground atmosphere are related to the air flow, air velocity, dust, gases and noise pollution. Therefore, the mathematical model for the ISA_a, considers these sub-indicators (Equation 7):

$$ISA_a = \frac{1}{j.l}\left(\sum_{i=1}^{l} ISQ_i + \sum_{i=1}^{l} ISV_i + \sum_{i=1}^{l} ISP_i + \sum_{i=1}^{l} ISg_i + \sum_{i=1}^{l} ISR_i\right) \quad (7)$$

where *j* is total sub-indicators, *ISQ* is air flow IS, *ISV* is air velocity IS, *ISP* is dust IS , IS_g is gases IS and the *ISR* is noise IS.
Based on mathematical models developed by Navarro Torres V. et al, (2005), the Sustainability Index *ISQ, ISV, ISP, ISg* and *ISR* can be calculated by equations 8, 9, 10, 11 and 12, respectively:

$$\mathrm{ISQ} = \frac{\mathrm{Q_a}}{0.05\mathrm{N} + 0.035\mathrm{hp}} \quad (8)$$

where Q_a is the air flow in underground atmosphere (m^3/s), *N* is the maximum human beings in the local, *hp* is the total power of diesel equipments (HP) and the coefficients are sustainable air quality defined by Portuguese Law D.L. N.º 169/90 (0.05 m^3/s.people and 0.035 m^3/s.HP).

$$\mathrm{ISV} = 6.6\mathrm{V_a} - 0.33 \text{ for } V_{is}=0.2 \text{ m/s}, \quad \mathrm{ISV} = 2.143 - 0.143\mathrm{V_a} \text{ for } V_{is}=8 \text{ m/s} \quad (9)$$

Where V_a is the air velocity (m/s), V_{is} is sustainable air velocity (m/s) and the coefficients ar defined by Portuguese Law D.L. N. º 169/90 ($0.2m/s<V_{is}<8m/s$).

$$\mathrm{ISP} = \frac{1}{\mathrm{n}}\left(\mathrm{n} - 0.0025\mathrm{P_d} - 0.33\mathrm{P_r}\right) \quad (10)$$

where *n* is number of environmental variable, P_d is dust concentration of diesel emissions (mg/m^3), P_r is rock dust concentration (mg/m^3) and the coeficients are the resultants aplied by MSHA (MSHA, 2001) satandards and the D.L. N.º 169/90 (400 mg/m^3 of diesel emission and 3 mg/m^3 dust with < 6% for free SiO_2).

$$\mathrm{ISg} = \frac{1}{\mathrm{n}}\left(\mathrm{n} + 0.048\mathrm{O_2} - 0.02\mathrm{CO} - 0.0002\mathrm{CO_2} - 0.04\mathrm{NO} - 0.2\mathrm{NO_2} - 0.2\mathrm{SO_2}\right) \quad (11)$$

where O_2(%), CO, CO_2, NO, NO_2, SO_2 are express in ppm, for being the most common gases in the underground atmosphere and *n* is the number of identify environment pollutants. The coefficients are defined by the MSHA standard (O_2 20.95%, CO 50ppm, CO_2 5000ppm, NO 25ppm, NO_2 5ppm and SO_2 5ppm).

$$\mathrm{ISR} = 1 - 0.011\mathrm{r} \quad (12)$$

where *r* is the continuos noise equivalent measured in the local (dB) and the coefficient results aplied Portuguese standard defined by D.R. n.º 09/92 (90 dB maximum).

3.3 Groundwater Sustainability Index (ISA_w)

The ISA_w can be quantified considering physicist-chemistries properties ISA_{fq}, toxic elements ISA_{st} and other components ISA_o (Equation 13).

$$ISA_w = \frac{1}{n.l}\left(\sum_{i=1}^{l} ISa_{fq(i)} + \sum_{i=1}^{l} ISa_{st(i)} + \sum_{i=1}^{l} ISa_{o(i)}\right) \quad (13)$$

Based on World Bank standards and developed groundwater quality model (Navarro Torres,V., et al., 2005) ISA_w quantify by equation 14:

$$ISAw = \frac{1}{n}\left((n-1) - 0.036T + 0.16pH - 0.05BOD - 0.05OG - 0.02S^* - As - 10Cd - 0.5Fe^* - Cr^* - 1.67Pb - 500Hg - 2Ni - Zn - 3.3Cu\right) \quad (14)$$

where T the water temperature(ºC), pH is a water acidity, BOD biochemical oxigen demand, OG the oil and fatness and S solids in suspension. These variables and metals are express in mg/l or ppm and * indicates the total concentration.

4 CASE STUDY IN PORTUGUESE PANASQUEIRA MINE

The Panasqueira mine (Beralt Tin & Wolfram – Portugal S.A.) producing of wolfram average 320000 t of raw ore or 1330 t of WO_3 per year. It is located in the south of Serra da Estrela mountain at altitude around 700 m and 250 km NW of Lisbon (Fig. 2). The explotaition mehtod used in this mine is room and pillars (Fig. 3).

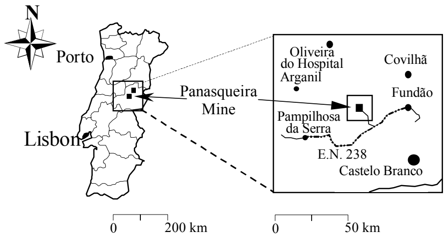

Figure 2. Localization of Panasqueira Mine

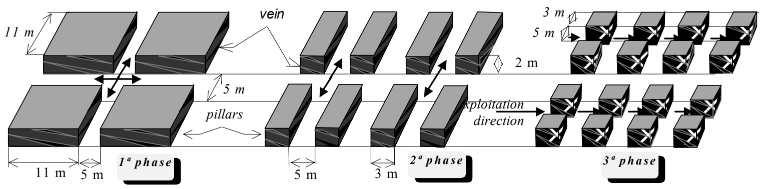

Figure 3. Room and pillar mehtod in Panasqueira Mine (Navarro Torres, V., 2003)

The results of the ISA calculation of the Panasqueira Mine was based measurements on December 2000. The Geotechnical IS (ISA_g) result 0.98 (Moderate), the underground atmosphere IS (ISA_a) 0.54 (Low) and the groundwater IS (ISAw) 0.27 (Very low) (Table 2 and Fig. 4).

Table 2. Environmental parameters and ISA resoults

Sub-indicator	Parameters	Equations	*ISA*	
GT	Level 3 stopes, rock xist (v_P=5100 m/s, Q=39.8) rooms of 5 m and ESR=3.5	3	ISA_g	0.98
UA	Level 3 stopes, N=30 peoples, 2 LHD Wagner with 364hp, air velocity of 0.05 to 0.18 m/s.	7 8	*ISQ* *ISV*	0.98 0.44*
UA	Level 3 stopes, O_2=19.2ª 20%, CO=0 a 500ppm, CO_2=0 a 3000ppm, NO=0 a 4ppm e NO_2=0.8 a 12.4ppm	10	*ISg*	0.21
UA	Level 3 stopes, continuos equivalent noise level of 89 to 120 dB	11	*ISR*	0.39*
MW	Descharge mine water for Salgueira gallery with pH=4, Cu=2.01 ppm, Zn=12.6 ppm, Fe=4.09 ppm, Mn=8.6 ppm e As=0.026 ppm	13	ISA_w	0.27

UA: Underground atmosphere, GT: Teotechnical, MW: Mine water

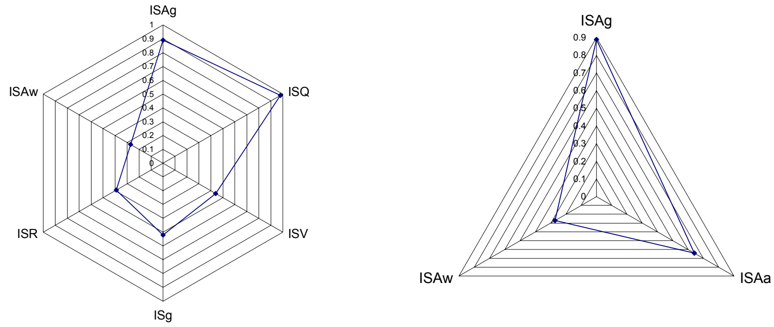

Figure 4. Environmental Sustainability Index in Panasqueira Mine

Simulations for inferior and superior values to the rock quality and the room size practised in stope of level 3, indicates that bigger ST corresponds to the best quality of the rock mass and lesser width of the room (Fig. 5.a)

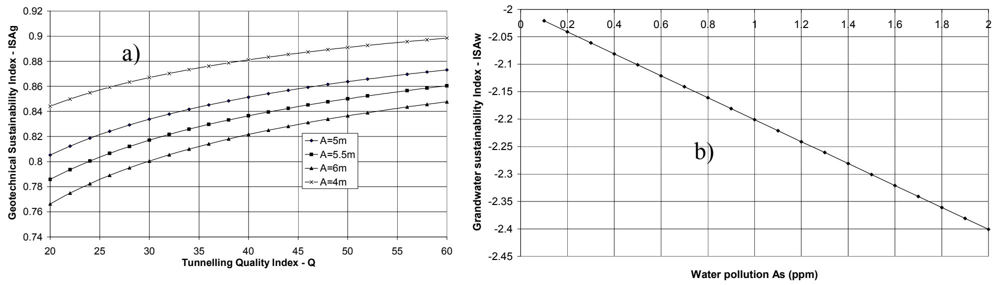

Figure 5. Geotechnical and Groundwater Sustainability Index in Panasqueira Mine

Simulations based on mine water condtitions (Table 2) descharge of Salgueira Gallery for Arsenic influence, the ISA_w is negative (Fig. 5.b) or either extreme low. Relatively to the diesel emission and the gases pollution, simulated based on values presented in Table 2, the results that bigger IS obtained with bigger air flow and smaller power diesel equipment (LHD) (Fig. 6.a).

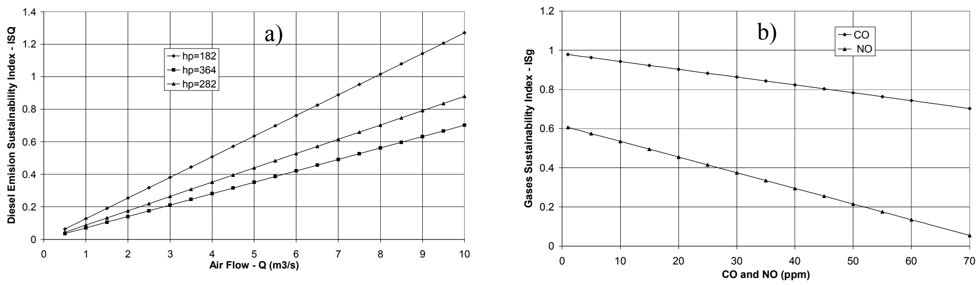

Figure 6. Diesel emission and gases Sustainability Index in Panasqueira Mine

Finally, with the gases concentrations presented in Table 2, evidences greater sustainability corresponding to lesser concentration of gases. It is interesting to observe as each gas influences the ST of diferent form (Fig. 6.b).

5 CONCLUSIONS

The underground mining is very important activity and of greate importance for the human development, but the projects must be economically viable with environmental protection and social responsibility.
The Sustainable Development of the underground mining can be quantified through the Sustainability Index.
This mathematical model opens the way for an evaluation, analysis, operacionalization and contribute to real Sustainable Development of the mineral sector.

6 REFERENCES

Barton N. E. Grimstad, E. (2000). El Sistema Q para la selección del sostenimiento en el método Noruego de excavación de túneles. Capitulo 1, Ingeo Túneles Libro 3, Madrid.

Chin, S.K., et al. 2000. The mineral industries of Europe and Central Eurasia.

Christmann, P. et al. 2003. Sustainability ibdicators for the mining industry: Issues and challenges. Milos, Greece.

Mine Safety and Health Administration MSHA, (2001). Rules and Regulations U.S., Federal Register/Vol.66, No.13/Friday, January 19.

Navarro Torres, V., et al (2005). Engenharia Ambiental Subterrânea e Aplicações. CETEM/CNPq/CYTED-XIII, 550 p., ISBN 85-7227-210-0, Rio de Janeiro.

Navarro Torres, V., et al (2005). A Sustentabilidade das Obras Geotécnicas. 10º Congresso Nacional de Geotecnia. Lisboa.

Navarro Torres, V.(2003). Underground Environmental Engeneering and Aplications in Portuguese and Peruavian Mines. PhD. Thesis, IST Lisboa.

Turner, E., et al. 2003. Achieving sustainability: tracking progress in the European minerals industry using SDI. Milos, Greece.

WBSITES

(1) European Comission Sustainable Development
http://europa.eu.int/comm/sustainable/pages/idea_en.htm

(2) Division for Sustainable Development
http://www.un.org/esa/sustdev/csd/cycle1.htm

(3) The Mining, Minerals and Sustainable Development Porject
http://www.iied.org/mmsd/

(4) Global Reporting Initiative. Integrated with the Mining and Metals sector Supplement.
http://www.globalreproting.org/guidelines/sectors/mining_update.asp

(5) International Council on Mining and Metals
http://www.icmm.com/

(6) World Busines Council for Sustainable Development
http://www.wbcsd.org/templates/TemplateWBCSD5/layout.asp?MenuID=1

(7) United Nations, Populations Division Statistics website
http://www.un.org/esa/population/