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INNOVATIVE CRITERIA FOR ECONOMICAL EXPLOITATION OF ORNAMENTAL DEPOSITS APPLIED THE CUT-OFF GRADE CONCEPT

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An innovative methodology and mathematical model is developed to determine the cut-off grade of ornamental stone exploitation called cut-off quality, based on the balance between the present value and production process cost. These methodology and model is validated with excellent results in nepheline syenite quarry located in complex alkaline Monchique, Portugal.

Ornamental stone, cut-off quality, production, cost, planning

INTRODUCTION

In the ornamental stone deposits, the quarrying process consists liberating, toppling and dividing the primary block, then block squaring, and finally commercial or trade blocks with different stone qualities as $q_1, q_2, q_3 \ldots q_n$, are obtained. The rubble waste material w is resulted after the process (Fig. 1).

The commercial or trade blocks thus produced have their respective prices on the market. And after comparing the total sales values of these products with the total operational costs, profits will be generated concordant with the company business objectives.

But for better and optimum ornamental stone production management, it is extremely important to know the threshold of the quantity production of different qualities of ornamental stones whose total economic value does not produce income, this threshold in terms of metal mining is called cut-off grade. In the present research a mathematical model is developed for quantifying this threshold in ornamental stone production and called cut-off quality, finally this model is validated in nepheline syenite of Monchique quarrying in Portugal.

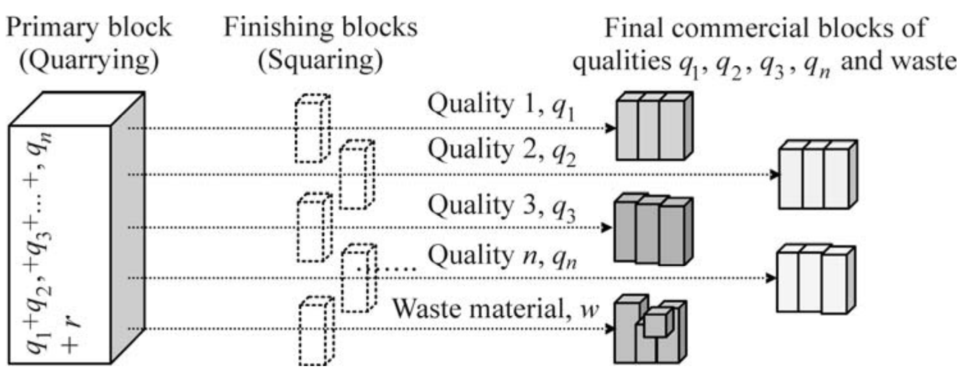

Fig. 1. Schematic of a simplified ornamental rock production process

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Ornamental Stone Quality In Situ Characterization

For the purposes of cut-off quality criteria applied in ornamental stone exploitation, it is necessary to characterize the rock quality distribution in defined reserves or quarrying area using appropriate geological, statistical or computer methodologies, and then to determine the area of interest for operation (Fig. 2). Each zone (1, 2, 3….., *n*) provides a spatial distribution of ornamental stone qualities ($q_1, q_2, q_3 \ldots q_n$), so that the cut-off quality criteria can be applied for a planned and controlled quarrying.

As you know, the quality of natural stone is determined based on the appearance, colour, grains or crystals size, the homogeneity, the alterations and oxidation, the mechanical strength, fracturing, etc. [1, 2].

Development of Mathematical Model

The cut-off quality is defined as the minimum stone quality that balances between production process costs and total product sales market value. That means the cut-off quality does not generate losses or profits in the exploitation process.

The balance between product value, *V*, and total cost production process, *C*, [3] is achieved when:

$$V - C = Q\sum_{i=1}^{i=n} IB_{qi}C_{qi} - C = 0\,, \tag{1}$$

where Q is the production rate (m^3/year, m^3/month, m^3/week), IB_{qi} is block index of ornamental stone quality in situ or quarrying area, q_i, (dimensionless) and C_{qi} is quotation market value of the product with quality q_i. The complete product value equation is expressed as follows:

$$V = Q\sum_{i=1}^{i=n} IB_{qi}.C_{qi} = Q(IB_{q1}C_{q1} + IB_{q2}C_{q2} + IB_{q3}C_{q3} + \ldots\ldots\ldots + IB_{qn}C_{qn})\,. \tag{2}$$

The C_{qi} and therefore V varies in function of the product (blocks) quotation market value, contractual agreements with the buyer company and is still influenced by the fate of product delivery.

The called block index, IB_{qi}, calculated by Eq. (3), based on the volume of in situ total rock mass or primary block, *v*, and the volume of ornamental stone qualities exploitation v_{qi}.

$$IB_{qi} = \frac{v}{v_{qi}} = \frac{\sum_{i=1}^{i=n} v_{qi} + v_w}{v_{qi}} = \frac{v_{q1} + v_{q2} + v_{q3} + \ldots + v_{qn} + v_w}{v_{qi}}\,, \tag{3}$$

where i = 1, 2, 3, ..., n and w is the volume of waste material.

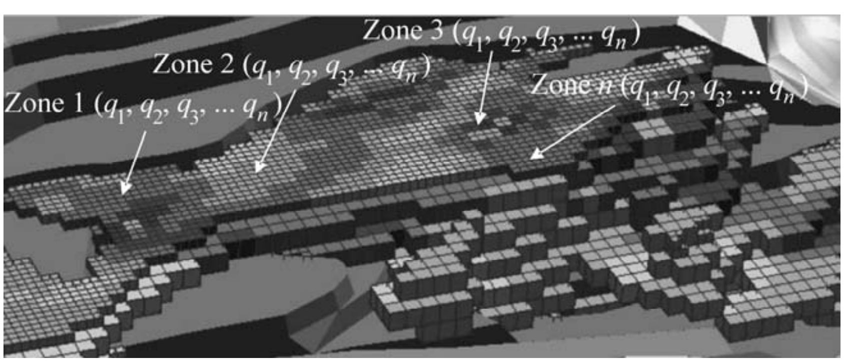

Fig. 2. Characterization of stone quality distribution

TABLE 1. Cost Structure in Ornamental Stone Exploitation [1, 4]

Costs	Cost structure	Details
DC	Equipments	Cost of ownership
		Direct operation cost and maintenance
	Direct human resources	Production and supervision
		Maintenance (production and supervision)
		Other direct labour charges
	Materials	Spare parts and repair materials
		Materials for production process
		Primary materials
		Gasoil, electricity, water, etc.
	Preparation	Initial preparation (Brushwood)
		Benches preparations
IC	Indirect human resources	Administrative
		Service, warehouse and workshops
		Technical assistance, other indirect labour charges
	Deprecation and interest	Liabilities
		Several acquisitions
	Taxes	Insurance, sales tax, income tax, etc.
	Environmental and social aspects	Landscape, land restoration, water control etc.
	Office costs	Miscellaneous equipment, materials, furniture, etc.
	Travel	Diverse purposes, congress, etc.
	Public relations, etc.	Internal and external company system
GC	Marketing	Supervision and sellers
		Market research and marketing
		Travel and other wage charges
	Transport	To quarry of local product destination
		To quarry to shipment port
		Shipment port to destination port
	Management, etc.	General and other management levels
		General and analytical accounting
		Geology, planning and control department
		Financing and legal department

The total production cost, C, should be quantified for the production rate (time) being the cost structure (Table 1) using Eq. (4):

$$C = DC + IC + GC\,, \tag{4}$$

where DC is direct costs, IC is indirect costs, and GC represents general costs.

When there is a considerable ornamental stone quality, a simplified representation can be adopted by called Equivalent Block Index, IB_{qe}, which is referred to a certain representative quality. For example, considering represented the quality q_1 (IB_{q1}), the equivalent block index for other qualities can be calculated with Eqs. (5), (6), (7) and (8):

$$IB_{q1} = \frac{C_{q1}}{C_{q2}} IB_{q2}\,, \tag{5}$$

$$IB_{q1} = \frac{C_{q1}}{C_{q3}} IB_{q3}, \tag{6}$$

$$IB_{q1} = \frac{C_{q1}}{C_{q4}} IB_{q4}, \tag{7}$$

$$IB_{q1} = \frac{C_{q1}}{C_{qn}} IB_{qn}. \tag{8}$$

Based on these equivalent block indexes, using Eqs. (1), (2), (3) and (4), and applying the cut-off quality concept, the equivalent block index referred to q_1 (IB_{q1e}) results:

$$IB_{q1e} = \frac{CD + CI + CG}{\frac{Q}{C_{q1}}(C_{q1}^2 + C_{q2}^2 + C_{q3}^2 + ... + C_{qn}^2)}. \tag{9}$$

The equivalent block index referred to ornamental stone quality q_1, IB_{q1e}, represents the equivalent cut-off quality, as other all qualities are included.

In Eq. (9), the equivalent block index referred to q_1, IB_{q1e} and production rate, *Q*, are variables and their graphical representation is shown in Fig. 3.

In particular situation where quarrying four ornamental stone qualities and constant trend of q_3 and q_4 qualities is observed, q_1 and q_2 qualities results variables, in this case, Eq. (9) becomes the simple equation:

$$IB_{q1}C_{q1} + IB_{q2}C_{q2} = \frac{CD + CI + CG}{Q} - q_c, \tag{10}$$

where $q_c = IB_{q3}C_{q3} + IB_{q4}C_{q4}$.

The behaviour of ornamental stone block index of quality q_1 and q_2 in function of production rate, *Q*, is shown in Fig. 4.

Moreover, it is possible modelling the cut-off quality only considering the direct costs *DC*, and this is so called exploitations cut-off quality, as is presented in Eq. (11):

$$IB_{q1e} = \frac{CD}{\frac{Q}{C_{q1}}(C_{q1}^2 + C_{q2}^2 + C_{q3}^2 + ... + C_{qn}^2)} \quad \text{or} \quad IB_{q1}C_{q1} + IB_{q2}C_{q2} = \frac{CD + CI + CG}{Q} - q_c. \tag{11}$$

In this situation the direct cost, *DC*, is composed of: initial preparation (Brushwood), benches preparing, drilling and cutting (diamond wire, etc.), toppling and dividing this primary block, loading, hauling, dumping, squaring and commercial blocks depositing in block pads.

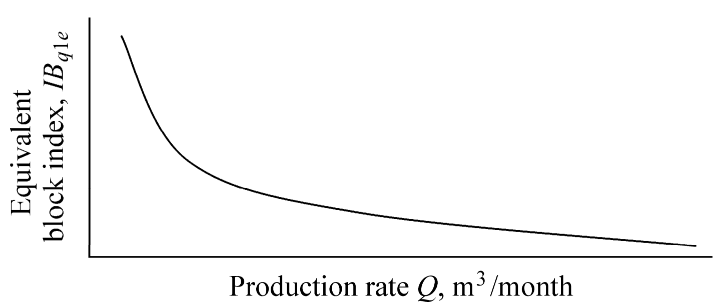

Fig. 3. Cut-off quality equivalent based on equivalent block index and gross production rate

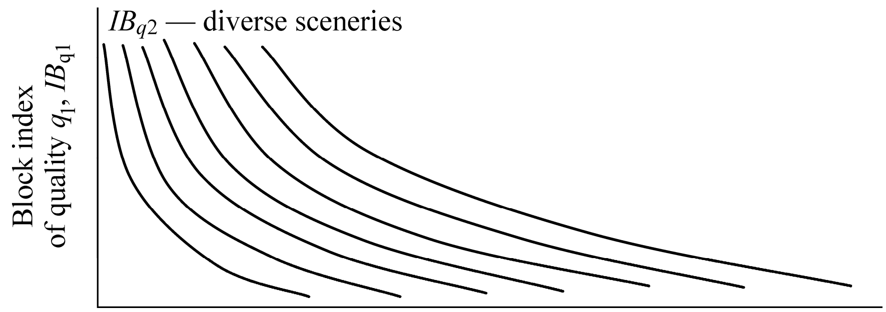

Fig. 4. Behaviour of variable two qualities in function of production rate

VALIDATION IN ORNAMENTAL NEPHELINE SYENITE MONCHIQUE´S QUARRY, PORTUGAL

Quarry Location and Accessibility

The practical validation is in nepheline syenite quarry of Carlos Vida Larga Lda. company, located in Monchique village and Faro district (Fig. 5), it is 2.5 km in south Monchique village and 20 km away from Portimão city. It is accessible by taking highway A2, national roads IC1 and N266 from Lisbon, totally 260 km.

The alternative accessibility to the quarry is taking flight at Lisbon airport to Faro airport and then taking highway A22 and national road N266.

Monchique Alkaline Complex

The Monchique alkaline complex is located in the south-western margin of Iberia and belongs to the Late Cretaceous Iberian Igneous Province.

The nepheline syenite ornamental stone of the Carlos Vida Larga Lda. quarry has an age of approximately 72 m.y. [5, 6] and it is a part of Monchique alkaline complex (63 km^2) that belongs to an important igneous province of the Iberian Peninsula that it relates with the opening of the North Atlantic and particularly the opening of the Bay one of Biscay (Fig. 6). The Monchique mass consists of 95 % of nepheline syenite composed by "foyaites" type (20 – 30 % nepheline) and "pulasquites" type (< 10 % of nepheline), 4.5 % of igneous breach and 0.5 % small bodies of basics rocks.

The nepheline syenite of Carlos Vida Larga Lda. quarry is composed of potassic feldspar (orthoclase) 61.8 %, nepheline 23.4 % and others 14.8 %. The chemical composition of potassic feldspar is $KAlSi_3O_8$, nepheline $2NaAlSiO_4(NaAlSi_3O_8) + H_2O$ and the plagioclase (albite) $NaAlSi_3O_8$ [7].

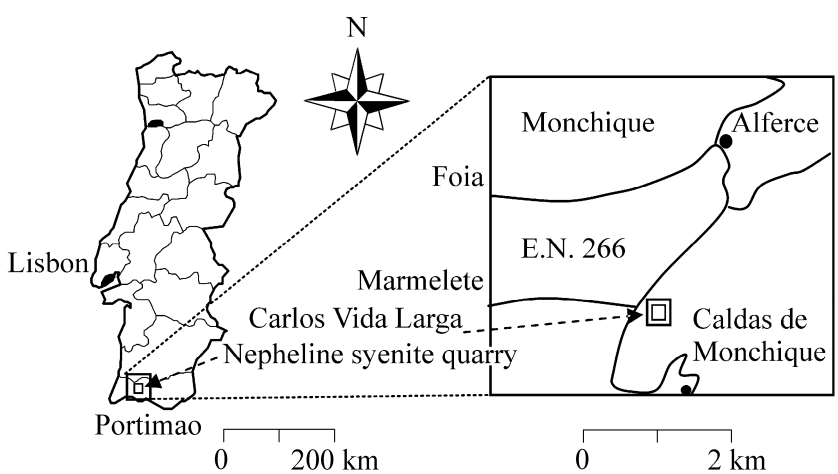

Fig. 5. Location of nepheline syenite of Carlos Vida Larga Lda. quarry

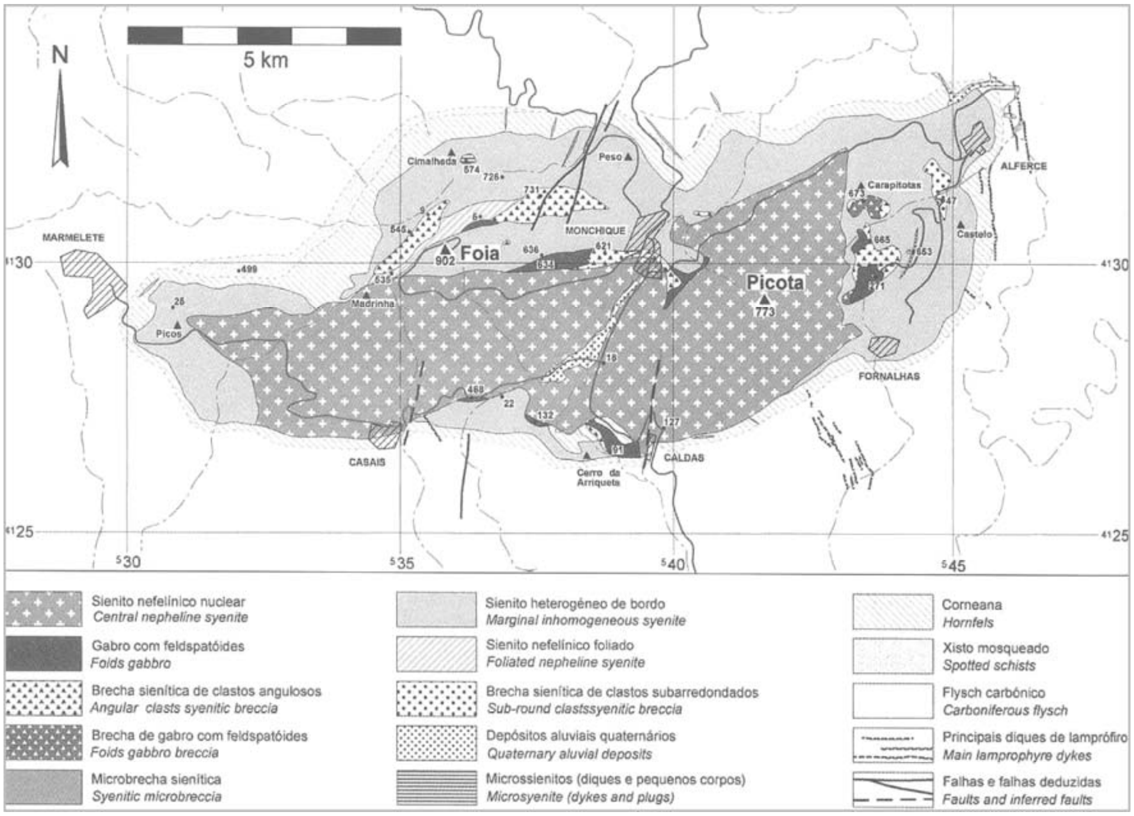

Fig. 6. Geology of Monchique,s alkaline complex [8]

Ornamental Nepheline Syenite Stone Qualities

The nepheline syenite of Carlos Vida Larga Lda. quarry produces four ornamental stone block qualities characterized by geometric dimensions (Table 2) and the physical appearance (Figs. 7, 8). The physico-mechanical parameters are compatible with the standard qualities required by the market and they are as follows: 2.6 t/m^3 of apparent density, 103 MPa of compressive strength, 17 MPa of flexural strength, 0.25 % of water absorption, 0.65 % of porosity and 0.5 mm of slake durability [7, 9].

The historical output of nepheline syenite ornamental stone blocks produced in Carlos Vida Larga Lda. quarry (Fig. 9) illustrates the approximately constant trend of first small block quality (IB_{q3}) and second block quality (IB_{q4}). However the first great quality (IB_{q1}) and called commercial quality (IB_{q2}) are varies considerably.

The economic parameters needed for the application of developed mathematical model are shown in Table 3.

TABLE 2. Geometrical Characteristics of Nepheline Syenite Stone Blocks Produced in Carlos Vida Larga Quarry [10]

Quality	Symbol		Geometrical size, m	
	Quarry	Study	Minimum	Maximum
First quality and big size	BL1G	q_1	1.80×1.20×0.80	3.40×1.70×1.70
Commercial quality	BLCO	q_2	1.80×1.20×0.80	3.40×1.70×1.70
First quality and small size	BL1P	q_3	1.80×1.20×0.80	1.80×1.20×0.80
Second quality	BLO2	q_4	1.80×1.20×0.80	3.40×1.70×1.70

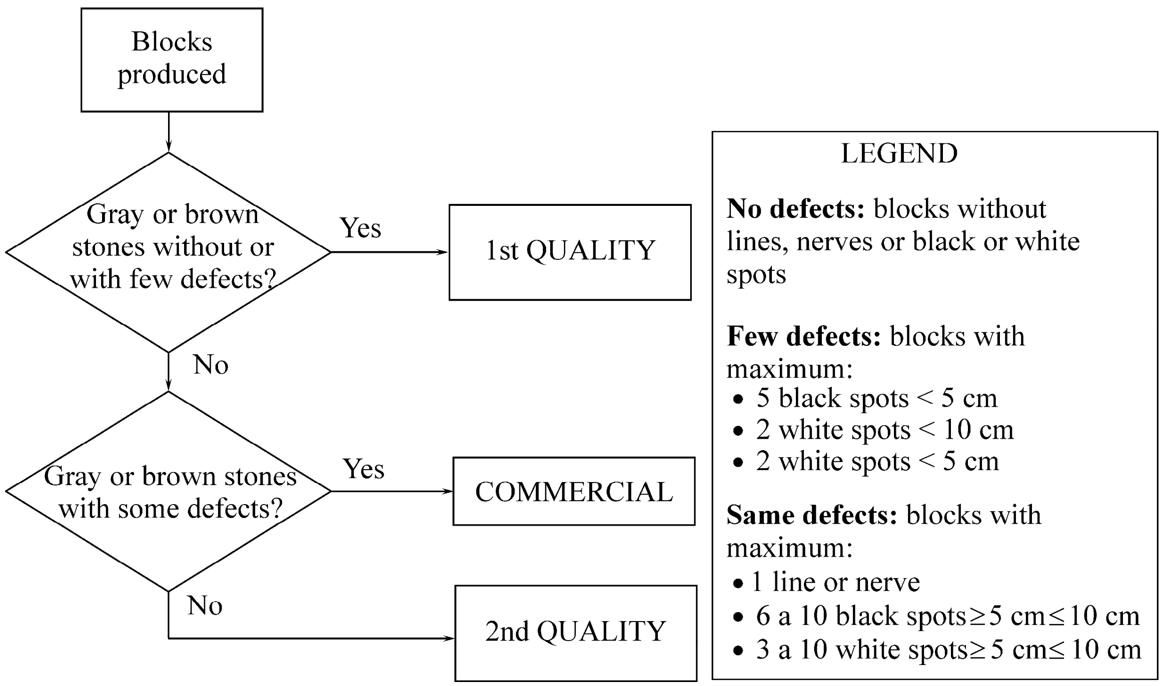

Fig. 7. Block qualities definition [10, 11]

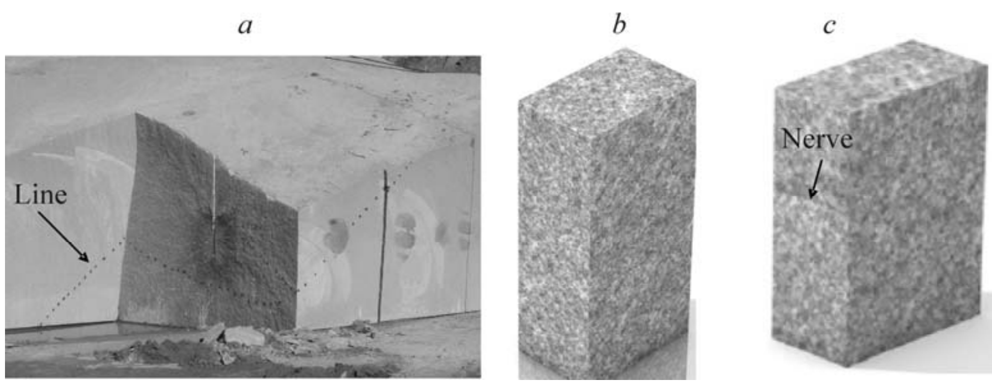

Fig. 8. Defects of nepheline syenite: (*a*) lines in quarry; (*b*) no defects block; (*c*) one nerve in block

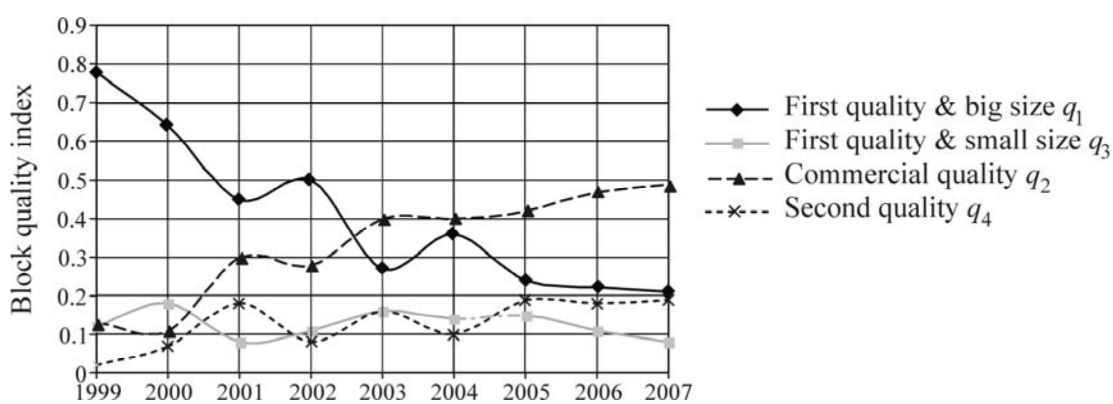

Fig. 9. Historical output of stone blocks of the past nine years in Carlos Vida Larga Lda. quarry

TABLE 3. Operational and Economical Parameters [11]

Component	Symbol	Quantity
Total average cost production process, €/month	CD	95875.76
Product value, €/m^3	C_{q1}	469.82
	C_{q2}	221.72
	C_{q3}	262.84
	C_{q4}	92.45
Block index	IB_{q3}	0.03
	IB_{q4}	0.08

Economical Parameters and Cut-Off Quality

Using these operational and economical parameters in formations and applying Eq. (9), the behaviour of equivalent cut-off quality of nepheline syenite quality q_1 is obtained in function of the production rate (Fig. 10). This illustration shows that the equivalent cut-off quality of ornamental stone nepheline syenite decreases with the increase of the production rate.

For example, for a 1150 m^3/month gross production, 0.12 equivalent cut-off quality is needed expressed in function q_1 (first quality and big size), that means in order to generate profits for the expected production rate, IBq_{1e} should be greater than 0.12.

Similarly, apply Eq. (11) to get the cut-off quality of q_1 (first quality and big size), cut-off quality of q_2 (commercial quality) and gross production rate behaviour (Fig. 11). For this simulation, the block quality index for the quality q_3 (first quality and small size) and q_4 (second quality) is considered approximately constant according to the statistical results (Fig. 6).

The simulation results (Fig. 12) show that the lower the cut-off ornamental nepheline syenite quality q_1 and q_2 is, the greater the gross production is, and vice versa. Moreover, for a particular production rate, when the cut-off ornamental nepheline syenite quality of q_1 decreases, it is needed to increase the cut-off ornamental nepheline syenite quality of q_2.

For example, for 1150 m^3/month gross production rate, for 0.05 cut-off quality of nepheline syenite q_2 (commercial quality), the cut-of quality of nepheline syenite q_1 (first quality and big size) is corresponded to 0.13. These results mean that for 1150 m^3/month gross production rate, the minimal proportion of ornamental nepheline syenite of quality q_1 in rock mass should be 13 % and the quality q_2 should be 5 % (Fig. 9). That is, when the q_1 and q_2 stone qualities are lower than the cut-off grades, respectively, the quarrying or exploitation will have economic losses, so some profitable operation with higher q_1 and q_2 qualities is needed to exploit mineral mass in relation to their cut-off quality.

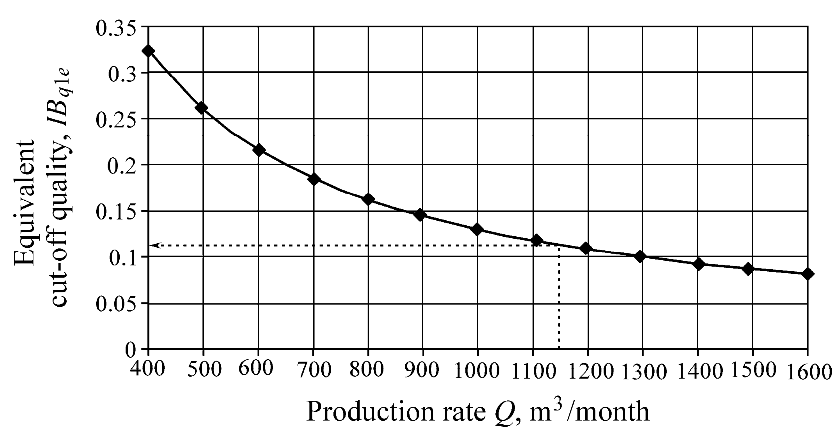

Fig. 10. Equivalent cut-off quality versus total quarry production rate

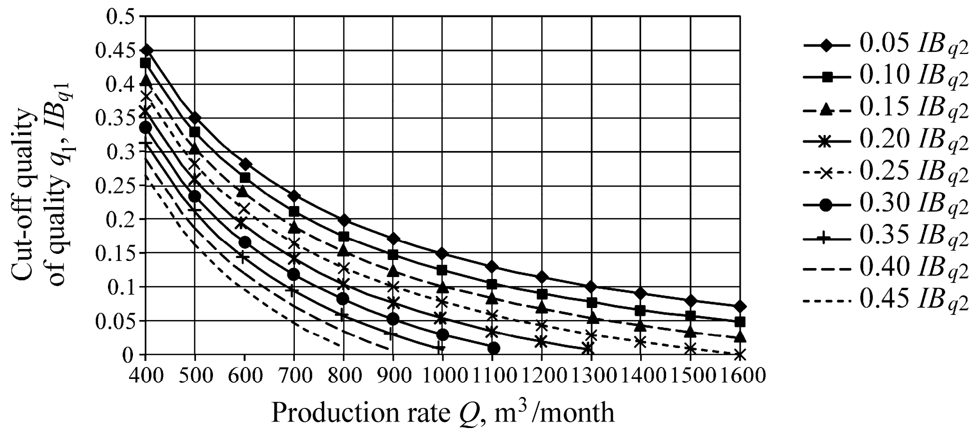

Fig. 11. Cut-off quality of q_1 and q_2 according to the gross production rate

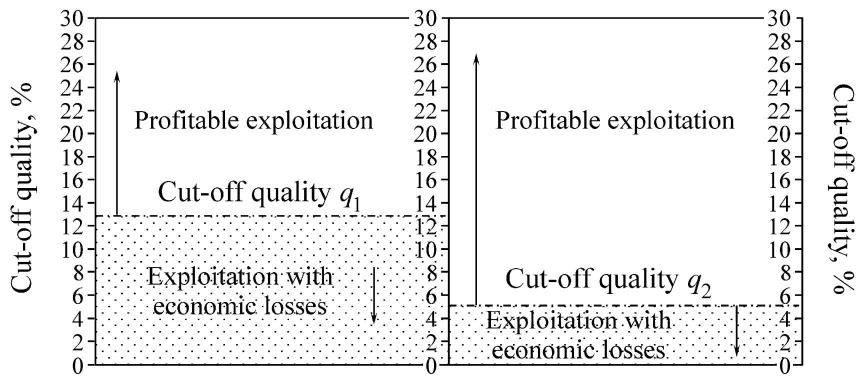

Fig. 12. Cut-off qualities of nepheline syenite q_1 and q_2 for 1150 m^3/month gross production

The great utility of mathematical modeling to cut-off quality of ornamental stone quarrying is to apply the engineering procedures for ornamental stone exploitation, such as strategic planning and control in the short, medium and long term to contribute for a sustainable quarrying of the ornamental stones.

DISCUSSION

At present there is no knowledge about the application of methodology and procedures to determine the cut-off quality in ornamental stone quarrying, except using empirical procedures.

It is known that in ornamental exploitation we have different product qualities ($q_1, q_2, q_3 \ldots q_n$) obtained from in situ mineral mass, therefore, it is possible to apply the procedures in the poly-metallic mining field for this purpose.

The application of the cut-off grade and equivalent cut-off ore grade to the ornamental stone exploitation, called cut-off quality and equivalent cut-off quality, has developed a corresponding mathematical model to calculate the minimum ornamental stone qualities and it is very useful for determining the minimum qualities for profitable exploitation.

To develop the mathematical model, we use the block index (IB_{q1}, IB_{q2}, IB_{q3} ... IB_{qn}) and the economic aspect is considered, such as the product value (C_{q1}, C_{q2}, C_{q3} ... C_{qn}) and the total production process costs.

The difficulties in implementing the mathematical model developed lie in not knowing well the stone ornamental distribution in situ rock mass, but with an organized and systematic follow-up work during the exploration it is possible to know the horizontally and vertically stone quality in situ distribution.

One more thing deserves to be emphasized is that the excellent results are achieved in a case study of nepheline syenite quarry in Portugal, but it is also quite applicable in the operation of any ornamental stone, such as marble [2], granite, etc.

CONCLUSIONS

1. The methodology and mathematical model developed to determine the ornamental stone cut-off quality constitutes a very important tool for natural stone engineering.

2. The validity of this methodology and model developed is demonstrated with excellent results by applications in nepheline syenite quarry in current operation.

3. This methodology and procedure developed is an important innovation in the ornamental stone exploration field.

4. The result of this innovative method open important future researches in this field, such as optimizing the cut-off ornamental stone qualities for the optimum and economical quarrying.

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