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DETERMINATION OF AN OPTIMAL ARRANGEMENT OF BLOCKS FOR DIMENSION STONE MINING

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Abstract. Over the years, planning in dimension stone mining has been neglected, which has led to the publication of various environmental regulations in localities such as the Tuscany region (Italy) to guarantee the preservation of the natural heritage (as is the case of the Apuan Alps). These regulations establish parameters for the minimum percentage of material recovery in quarries. Therefore, this research aims to recognize which factors are present in a dimension stone mine that affect the material recovery, and at the same time provide an approach to reduce the amount of waste material produced at the moment of the extraction. In order to achieve the objectives, first it is carry out and presents an investigation of all the techniques and methods used in the dimension stone mining, and secondly to propose the application of an approach based on the raster method of the bin packing problems, through the use of the CAD and GIS software, and the Python programming language. Thus, with the combination of these tools, form a procedure to obtain an optimal stone block arrangement that can serve as a guide in the planning and at the moment of performing the cutting operations. Finally this procedure was applied for three different cases giving different block arrangements that optimize the material recovery. However, it is recommended to continue developing this type of approach in order to exploit the potential of the available computational tools and thus achieve better performance in dimension stone exploitation.

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INTRODUCTION

In the mining field exists different types of mining where various methods and techniques are applied to go from the extraction planning of the target material until obtain the final product. One of these types of mining is dimension stone mining, which is performed in a particular way, since the main objective of this is to extract ornamental rock blocks with a specific shape and size to be commercialized in the production chain of construction materials.

The constant efforts to obtaining these blocks and the lack of attention in planning has caused that currently the waste material produced by this type of mining becomes a concern for the authorities responsible for guaranteeing a sustainable mining and the preservation of the natural heritage. As a result, the authorities in different localities have published environmental regulations in order to protect the environment and the landscape, establishing parameters with respect to the minimum material recovery in this type of extraction.

Moreover, it is known that the waste material produced in the extraction of dimension stones could generally be used to produce construction aggregates. However, the relationship between the value of the material in a block form and the value of the same material as a construction aggregate normally leads to ignoring this waste material.

Therefore, rather than looking for possible uses for the waste material, the main objective is to optimize the diverse labors that are performed to extract the blocks in order to reduce this waste material and have a better performance and a greater economic benefit. An important labor involved is the planification of the cutting and subdivision of the rock blocks originated by the discontinuities in the rock mass.

Depending on the shape and size of these rock blocks, it is necessary to organize the desired stone blocks in an arrangement that achieves the highest possible material recovery, i.e. the highest possible quantity of marketable stone blocks.

The following research is an exploration through the methods and techniques applied to dimension stone mining, and the main limitations present at the moment of performing the exploitation. In addition, it is formulated and implemented a procedure that applies the knowledge of bin packaging problems in combination with computational tools such as GIS and CAD software, and the programming language Python, in order to produce an optimal block that serves to improve the material recovery and in the same way reduce the waste material produced. This procedure is applied in three different scenarios, for which their results and respective discussions are presented.

CHAPTER I

PROBLEM STATEMENT

Ornamental stones have been used mainly for construction throughout the history of mankind for their special physical-mechanical characteristics and for their attractiveness, some of them being considered as luxurious material, however, although the mining of these rocks is performed from the most remote antiquity this activity remains a challenge due to the infinity of difficulties that can occur in a deposit.

Generally the main difficulties in the extraction of the ornamental stones are given by First, the geo-structural conditions of the deposit, i.e., the quality of the rock mass, which is directly related to the distribution and arrangement of the discontinuities that may exist within the deposit, such as joints, fractures, folds, cracks, inclusions, veins, etc. (Mosch, 2011). Second, the absence of a decision variable, since, contrary to the deposits of metallic minerals, the deposits of ornamental stones do not have a decision variable as well as the concentration (grade) which allows to discriminate with exactitude between the zones of material that can be extracted with different profitability, and thus perform a selective mining (Mutluturk, 2007). These reasons make planning a complex problem of multiple variables that despite being possible to solve it, it does not have the necessary certainty due to the heterogeneity of the geology, this at the same time has caused that the planning activities be commonly neglected.

These complications presented in the planning affect the profitability and yield of the extraction, because in addition to the intrinsic value of the rock per se, the most important requirements that must be satisfied are that the material must have a specific size and shape as a final product (raw block), which represents a continuous challenge in the extraction labors, due to the difficulty in obtaining blocks (cuboid form) of a marketable size and shape producing the minimum amount of waste material possible.

At international level it is known that in the extraction of ornamental stones (regardless of its origin) the average percentage of waste material produced with respect to the suitable stone blocks for sale is 51%, however this figure could be even higher reaching around 80%, since in some cases the reputation and demand of certain stones in the market make economically feasible the extraction of some deposits, but in these cases the profitability of the deposit must be seriously questionable. For example, in Finland have been identified some granite quarries that operate by performing a stone block extraction with a yield of about 10% of the total volume of exploited rock, this will also depend strongly on the utilization of the waste material which in certain circumstances may be sold as a secondary product (Mosch, 2008).

Considering the amounts and characteristics of waste material produced, these types of extractions nowadays have captured the attention of entities responsible of guaranteeing that mining activities are performed in accordance with sustainable development objectives. For example, in March 2015, the Regional Government Council of the Tuscany Region (Italy) published a series of guidelines to be satisfied by quarries. According to article 13 of this document, it is established the minimum amount of the total extracted volume that must be destined to the transformation in stone blocks, more specifically it is mentioned that it is of strictly mandatory a minimum yield of 25% for the extractions of any quarry of dimension stones (L.r.n35, 2015).

Additionally to the concern about the landscaping and the conditions imposed by the guidelines for quarrying, it is important to highlight that the ornamental stones have an advantage over other types of mining extractions, since there are several options to obtain profit from the material that does not comply with the standards (waste material) as to be considered as a marketable block, between the options could be mentioned those such as: for aggregates in construction, as natural stone for agriculture, or for several manufacturing industries due to its mineral composition (calcium carbonate, quartz, feldspars, etc., depending on the rock) (Jethoo, A. S. Harshwardhan, S.C. Kalla, P. Gautam, K, 2017). Nevertheless, the value of the secondary goods obtained from the waste material is quite inferior in relation to the value of the final product when it is commercialized as stone blocks; therefore it is fundamental to take advantage of the maximum possible volume that can be extracted in the form of blocks.

In the same way, in case of determining the reason of the abrupt difference of prices between both products, it is sufficient to compare the process by which those are obtained, the difficulty in the labors to extract the blocks of ornamental stones gives them a high added value as a final product. Observing the market prices of both it is possible to see why the waste material lost its attractiveness as a secondary product of a quarry, for example, in Italy in 2008 the average value of a cubic meter of raw block was 2686 USD; while for a cubic meter of aggregates it was 15 USD (Balletto, 2013). Due to this phenomenon it is also crucial perform efficiently the labors avoiding the production of waste material.

BACKGROUND

In Madrid, in 1968, the first official meeting of the "Commission for the Standardization of Laboratory and Field Testing of Rocks" was held, during which a questionnaire was circulated to all the members of the "International Society of Rock Mechanics" in order to know the general opinion of the members on the standardization of testing procedures, which at the time was highly received and after subsequent meetings a document was published in 1977 containing the "suggested methods" with the intention of achieving a certain degree of uniformity in the description of the discontinuities into a rock mass considering these methods as a reference framework. Among the procedures proposed in the document were the following: description of orientation, spacing, persistence, roughness, wall strength, opening, filling, separation, and number of sets of joints, block size and drilling core (ISRM, 1977). By this time had already started the interest to find a standard procedure for the description of the potential sizes of blocks formed by the discontinuities within a rock mass. Then in 1996, Palmstrom published his work on the "rock mass index" in which were extended the procedures for the estimation of the block sizes within the rock mass, adding schemes for the estimation of the block shapes (figure 1).

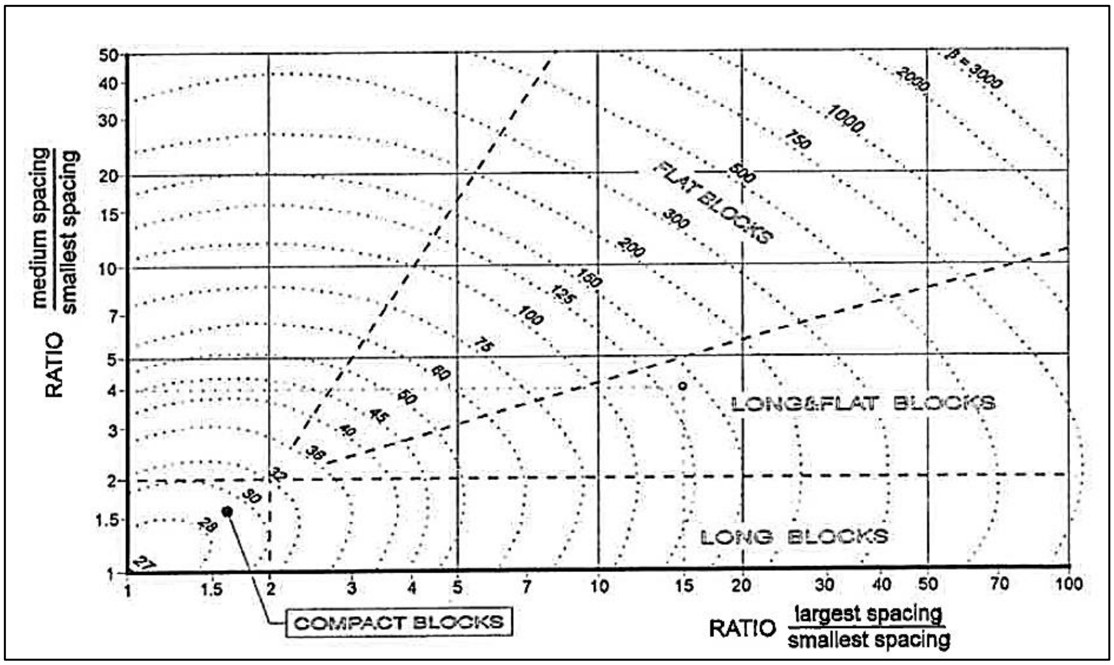

Fig. 1: Block types characterized by the block shape factor, found from the ratio between the longest and shortest side (Palmstrom, 1996. P31).

These works established a frame of reference for the planning of the mining of dimension stones, since clearly the amount of marketable stone blocks that can be extracted from each rock block caused by the discontinuities will depend first of all in the size of this rock block, which in turn is directly related on the distribution of the joints and the number of these in a certain length (Sousa, 2010).

Later, knowing and developing several sampling techniques to evaluate the distribution of the discontinuities, it made possible to define the network of the joints with methods such as: scanline and core sampling, window mapping, image processing, and GPR technique (Bagherpour, Taherian, Sousa & Yaramahdi, 2015). This encouraged progress towards research to determine the amount of blocks that can be extracted from a certain volume, previous to its extraction.

For the year 2007, Mutluturk presents a simple methodology applicable to any dimension stone quarry (figure 2) that allows planning without the uncertainties caused by the empirical practice of the proceedings and reducing the probability of undesired surprises on the exploitation front; even affirming not to be the best possible solution, but nevertheless still preferable to other solutions that estimated the exploitable volume according to decision variables that, despite working for the metallic minerals mining, these were not so optimal for dimension stones. Therefore, the research concludes that the best decision variable for planning in dimension stone mining is the amount of marketable stone blocks.

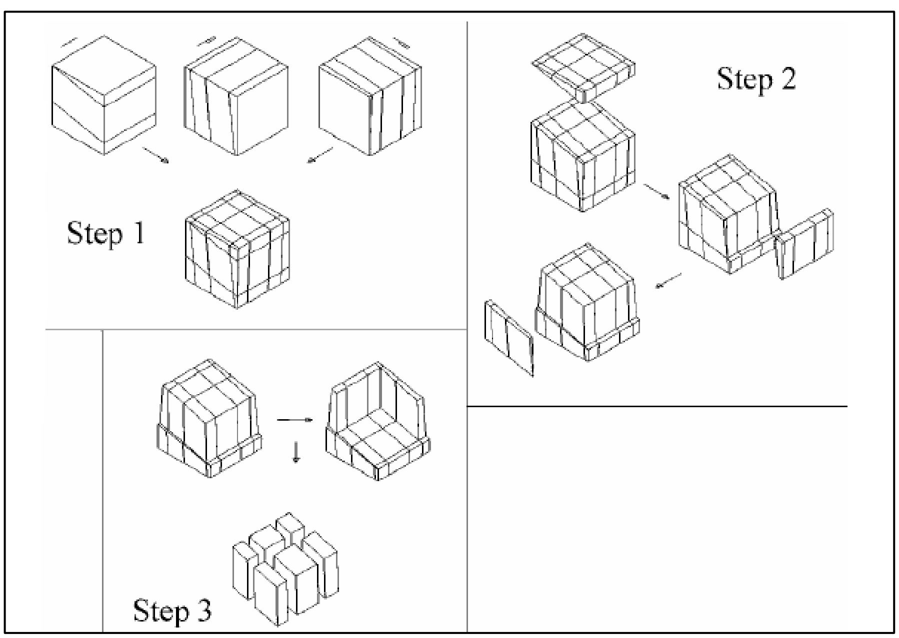

Fig. 2: An example for first three main steps for obtaining extractable blocks (Mutulurk, 2007. P4).

In the same way were established some values in order to classify among the different block sizes that could be obtained from a given deposit, using as reference the values obtained through the formulas postulated by the ISRM for the calculation of the volumetric joint count (Jv), since through this parameter it is possible to have an approximate idea of the dimensions of the rock blocks delimited by natural fractures or joints. Clearly for the mining industry of dimension stones is advantageous to extract blocks of large size but this is not always possible, then in order to determine the average size of the rock blocks and that in turn these comply with possibility to obtain raw blocks with the market requirements, it was defined that the volumetric joint count must be <2.0 in order to affirm the possibility of extracting stone blocks of an appropriate size (Sousa, 2010). The following table shows the relationship between the volumetric density of joints and the possible average volumes of blocks.

Table 1: Relationship between Jv and block size (Souza, 2010)

Description	Jv (joints/m³)	Volume (m³)
Very large blocks	< 1.0	> 25
Large blocks	1 – 3	1 – 25
Medium blocks	3 – 10	0.025 – 1
Small blocks	10 – 30	0.001 – 0.025
Very small blocks	> 30	< 0.001

Diverse subjects related with dimension stones exploitation have emerged researched in the last decade, because it is evident that in some quarries exist arrangements of discontinuities practically ideal for the extraction of dimension stones, as for example the case of the granite "Silvestre Moreno" from the municipality of Tui, Spain, which presents an almost orthogonal joints arrangement (Figure 3) which facilitates to achieve the final shape of the marketable blocks, and furthermore by using these planes of weakness as the cut direction, the cutting work is simpler and less costly (Alejano. Castro-Filgueira. Perez-Rey. Arzua, 2017).

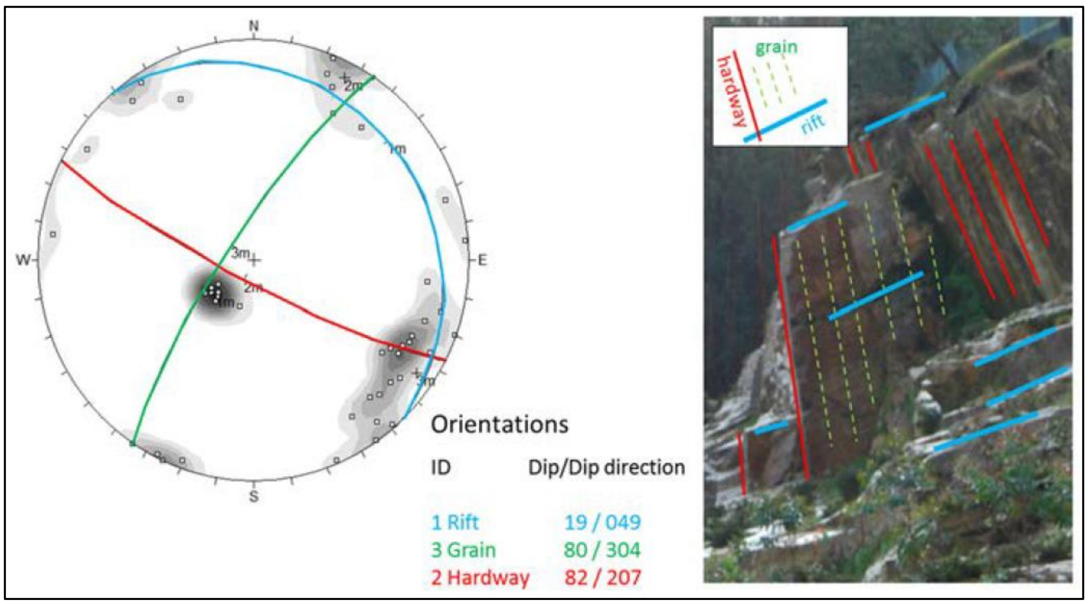

Fig. 3: Stereographic pole representation and distribution of discontinuities measured in and around the quarry (Alejano. Castro-Filgueira. Perez-Rey. Arzua, 2017. P3).

However, this particular case evidently does not cover all existing quarries, because the joint arrangement could have any angle and spacing relationship between them. Depending on these conditions, some planning actions can be implemented in order to extract the material more efficiently. An example of this is recognizing the orientation of the main joints and adjusting the mode of advance of the quarrying front in order to avoid further fragmentation of the material (Mosch, 2011); figure 4 shows an optimal execution of this procedure.

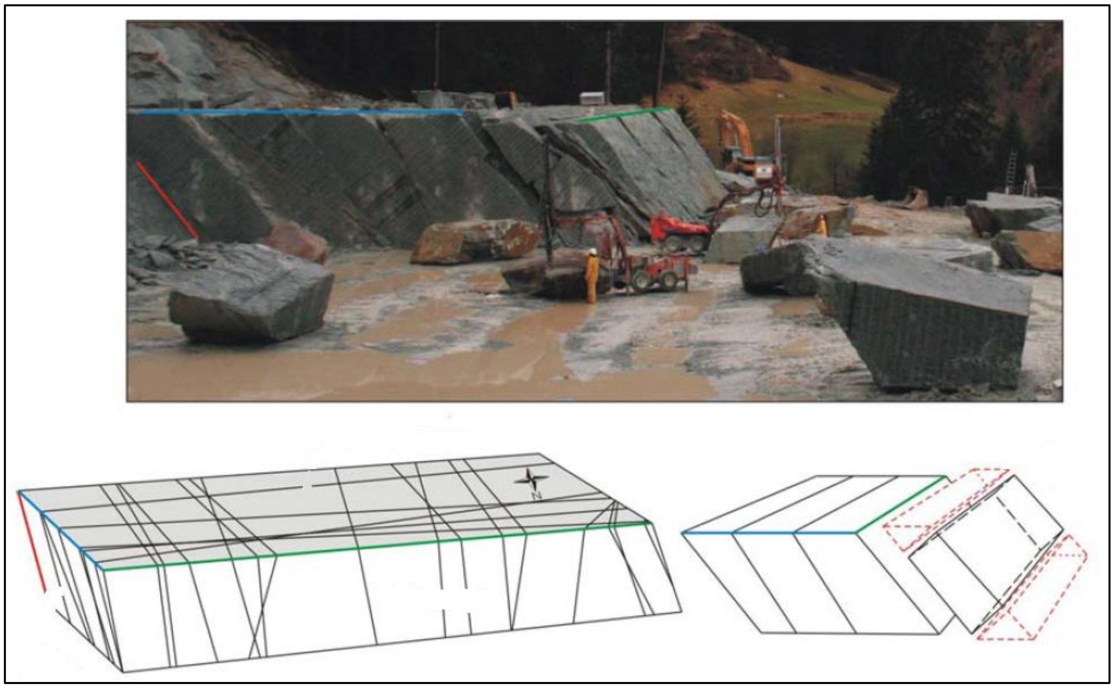

Fig. 4: Example of a favorable exploitation front for non-orthogonal discontinuities (Mosch, 2008. P38).

As a direct consequence of a non-orthogonal arrangement of the discontinuities, polyhedron-shaped rock blocks are generated (figure 5), which will generate a greater amount of waste material when are extracted and formatted, and these rock blocks will require to have a considerable volume in order to be formatted and obtain a marketable stone block.

Certainly depending on the arrangement of discontinuities there will be diverse cases with different degrees of complexity at the moment of performing an optimal mining plan. Although at first glance this may seem a simple geometric problem, the reality is that as the size of the rock blocks increases, there are also other variables in the planning that give rise to the possibility of accomplish the formatting of the raw blocks in different ways, in other words, the possibility of optimizing even more the planning process.

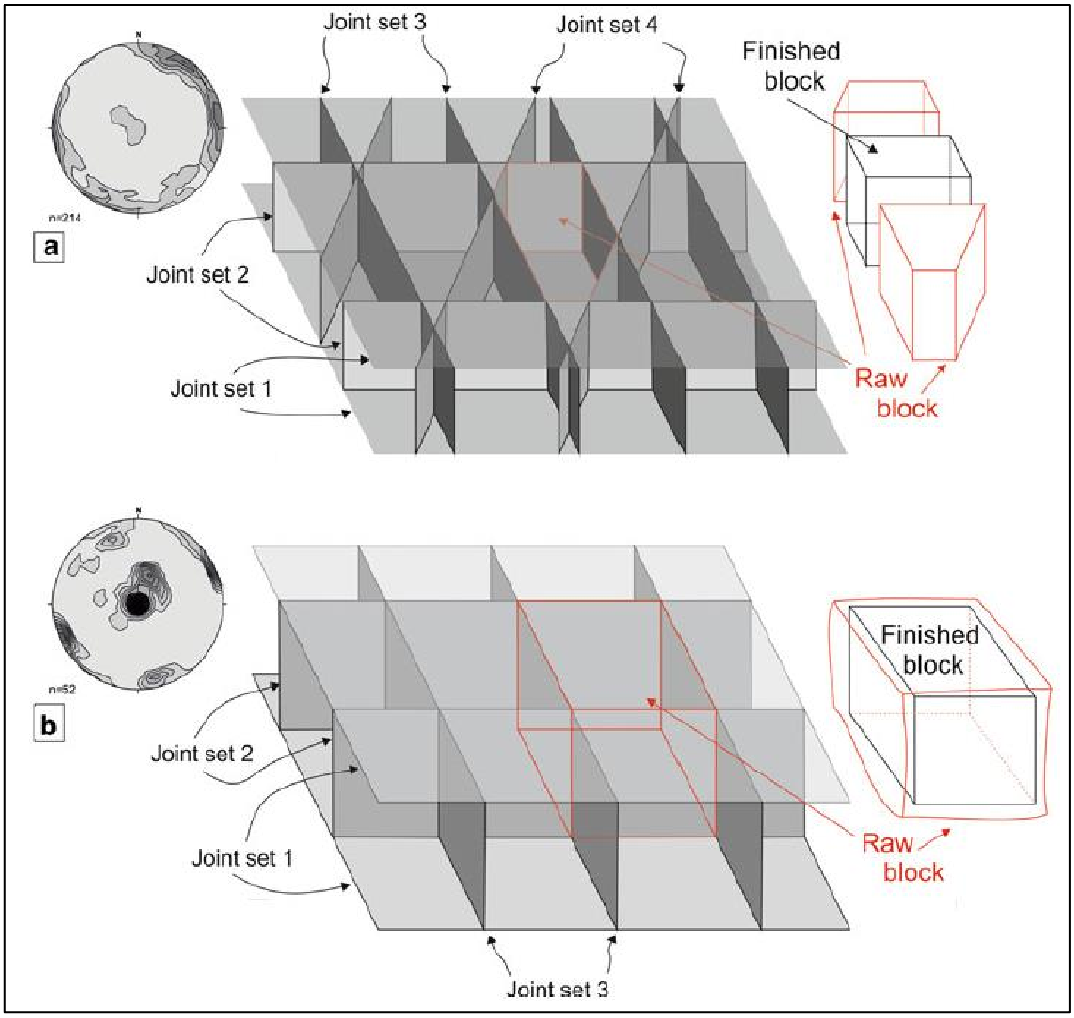

Fig. 5: Comparison of the stone block formatting of two deposits with different joint arrangements (Morales Demarco, 2012. P22).

Keeping this in mind, three scenarios can be studied, the first scenario is in which the arrangement of discontinuities does not allow consider a dimension stone mining, because the rock blocks are not of an appropriate size and shape. The second scenario is when the arrangement of the discontinuities allows the profitable extraction of raw blocks; however these discontinuities are so close to each other that the rock block that is extracted is only cut to give it the cuboid shape that is required (see figure 4). And the third scenario is when the discontinuities generate large rock blocks which can be cut and extracted in various ways with different results.

The second case is clearly a geometric problem which consists of determining the largest stone block that can be obtained by cutting a rock block, and at the same time satisfying the required measures. To solve this problem several authors have proposed algorithms to define the maximum block of stone in each block of rock to be extracted (Ulker & Turanboy, 2009), these solutions vary depending on how the discontinuities are defined. An example of this type of procedure is shown in figure 6.

On the other hand in the third scenario a geometric problem with infinite solutions is presented, since from a rock block a different number of stone blocks can be extracted depending on the arrangement of these, in addition as a consequence each arrangement will have different amounts of waste material produced and different cost-benefit relations (Mosch, 2011). An example of this can be seen in figure 7 where three of all the possible solutions are shown, in this particular case it can be seen how each different arrangement has different relative length in the cuts of the blocks. This relationship between the arrangement, the waste material produced and the work required to carry it out produces an economic factor that can serve to differentiate the possible solutions.

In the case of the third scenario, algorithms and methodologies have been proposed to define the best possible arrangement of blocks through a regular cutting network giving a macroscopic solution. Theoretically it is known that better results can be obtained if the selection of the block arrangement is approached with the possibility of defining an irregular cutting network, however this is generally considered complicated to implement considering the typical cutting techniques used in the extraction of ornamental stones (Elkarmoty. Bondua. Bruno, 2019).

Currently even though there have been quite a bit research advancements related into the dimension stones world, this type of mining does not have a well-defined, stablished and applicable sustainable model which reduces the waste material as much as possible when producing an optimal block size (Morales Demarco, Oyhantcabal. Stein & Siegesmund, 2012).

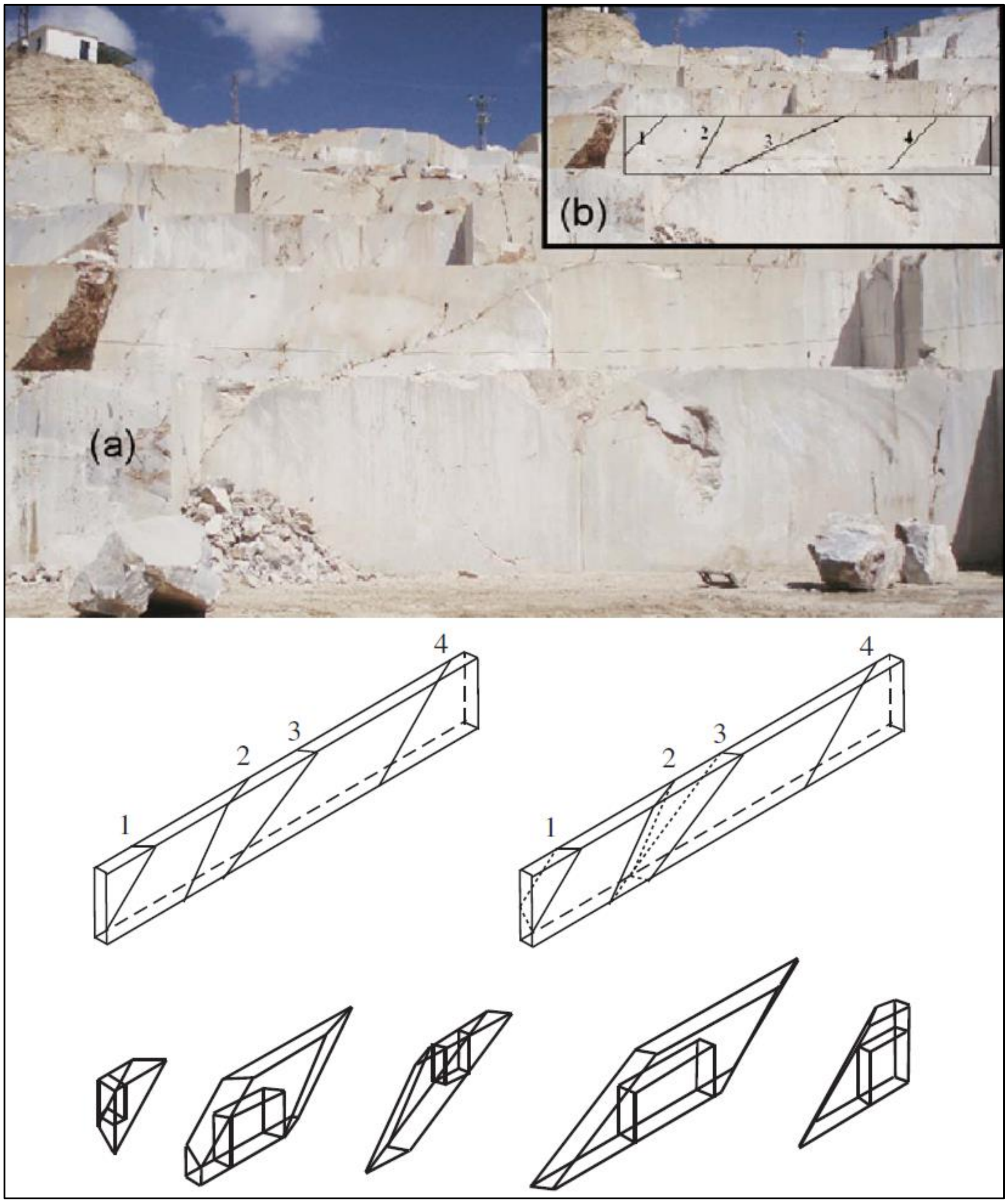

Fig. 6: (a) General view of benches in quarry, (b) modelling boundary as a rectangle with approximate discontinuity traces on modelled bench outcrop, and (c) the final result of the application of the algorithm that calculates the maximum stone block (Ulker & Turanboy, 2009. P4-P9).

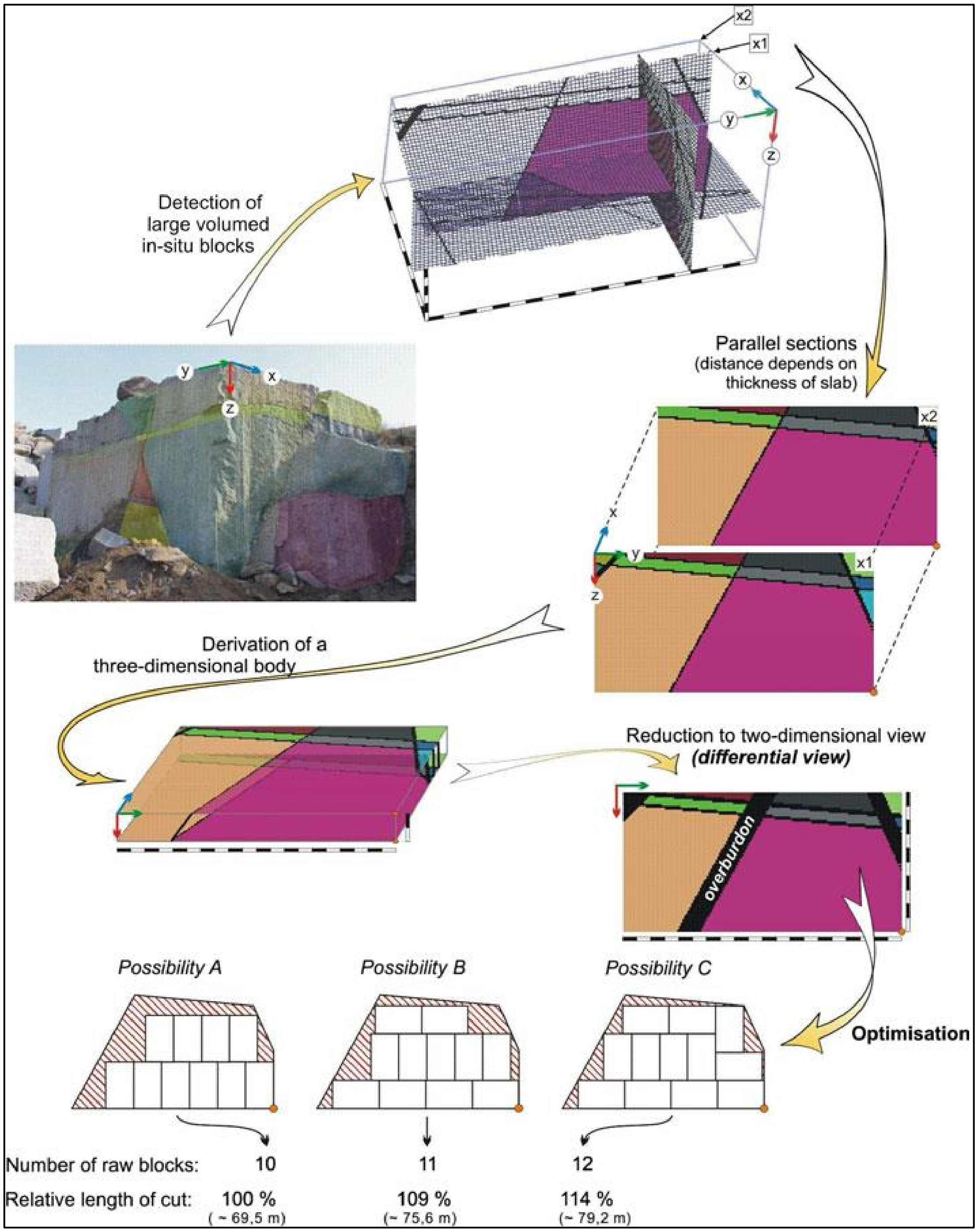

Fig. 7: Optimization of raw block production by mean of optimal surface area utilization in the San Antonio granite, Sardinia (Mosch, 2011. P9).

AIM OF THE THESIS

The objective of this research is determine an optimal arrangement of stone blocks into an extractable rock block in dimension stone mining, that allows to reduce the waste material produced, maintain sufficient practicality of the extraction activities, and by the same way that this theoretical approach may also serve in the future to propose an algorithm to select the most suitable arrangement for obtaining stone blocks with the requirements of the market.

This research aims to differentiate between the different possible ways of extracting the stone blocks and discriminate the least beneficial. In order to accomplish this it is proposed:

- Study the flexibility of the techniques used in the mining of dimension stones regarding the geometry of the blocks and the direction of extraction.
- Identify the general constraints in the extraction of dimension stones using an irregular arrangement of the raw blocks.
- Appraise the difference between a regular and an irregular block arrangement in terms of the amount of waste material produced.
- Evaluate the variation between a regular and an irregular block arrangement in terms of the cutting length required.
- Propose a practical procedure for determining an optimal arrangement through computational tools.
- Determine the optimal stone block arrangement into a rock block.

CHAPTER II

CONCEPTUAL FRAMEWORK

The purpose of this chapter is to compile the conceptual basis that supports the research and at the same time to clarify the ideas expressed throughout the document, therefore following it is shown a compendium of concepts that are considered relevant for the work.

2.1.1 Dimension Stones

According to USGS the dimension stones can be defined as:

"*A natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size (width, length, and thickness) and shape. Color, grain texture and pattern, and surface finish of the stone are normal requirements. Durability (essentially based on mineral composition and hardness and past performance), strength, and the ability of the stone to take a polish are other important selection criteria*".

There are several types of sedimentary, metamorphic and igneous rocks that can be exploited as dimension stones, among which the main types are granite, limestone, marble, sandstone and slate. Also are commonly exploited but on a smaller scale: alabaster (massive gypsum), soapstone (massive talc), and various products fashioned from natural stone.

The following figure shows some examples of common uses attributed to ornamental stones:

Fig. 8: Examples of commercial stones use; a) outdoor façade using dolerite and granite, b) outdoor sculpture using granite, c) outdoor façade using syenite, d) outdoor sculpture using granite, e) different sorts of outdoor flooring slabs, f) outdoor socle and columns using tonalite (Morales Demarco, 2012, P3).

2.1.2 Profitability of dimension stone deposits

As in any type of mining, it is necessary to know if the deposit can be profitably exploited; in the case of dimension stones the goal is obtain stone blocks with sizes from 1.90 x 1.00 x 0.90 meters to 3.30 x 1.50 x 1.20 meters approximately; therefore different types of studies are carried out.

According to Morales Demarco (2012), there are three main geological studies that through each one allow obtaining elements or control variables about the profitability of the deposit in dimension stones, these studies are:

- **An inventory of the joint sets** to determine the frequency of minimum size of extractable stone block and to minimize the waste material produced.
- **An assessment of the mineralogical and structural factors** that affect the formation, stability, and variability of the fabric and color of the material.
- **An analysis of the genesis and alteration factors** of the deposit, which determine if the material is usable (petrophysical properties).

Finally with the knowledge of these control elements it is possible to diagnose the profitability of the deposit, in general it will be preferable for a proper block obtainment that the rock is the least fractured possible and that the intrinsic characteristics of the rock do not vary enough to impact the external appearance and the physical properties of the rock.

2.1.2.1 Block Recovery

Following the appropriate studies to characterize the rock mass and to evaluate the geological factors mentioned above, the profitability of a dimension stone deposit can be assessed.

Contrary to other types of mining which compare the ore volume obtained to the total extracted volume, in dimension stone mining the ratio between the commercial blocks obtained and the total extracted volume is used to evaluate the profitability of the exploitation. According to Oggeri (n.d.), the overall profitability of a mine is directly proportional to the overburden material that must be extracted before exploitation, the deposit volume, and the possible intercalations or portions of waste or sterile or unwanted material within the deposit. This material distribution in the deposit is shown in the following figure.

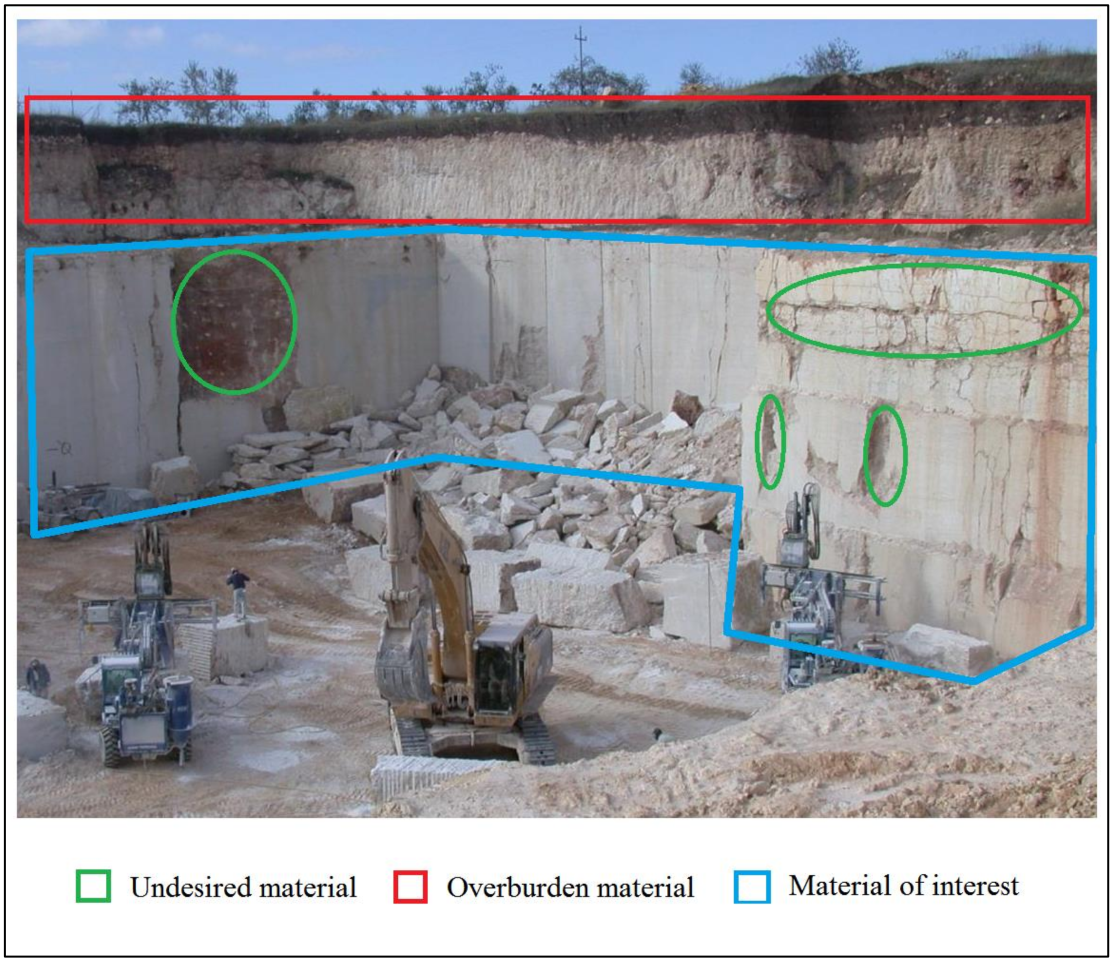

Fig. 9: Example of desired and undesired material distribution in a dimension stone deposit (Oggeri, n.d., P13).

However, the profitability assessment in exploitation is a control parameter or indicator related to economic returns, while block recovery is a parameter considered when assessing the extraction efficiency and the cutting operations in order to obtain the final stone blocks. The corresponding relationship between these parameters can be seen in the following equation:

$$\frac{\text{Extracted volume}}{\text{Total volume}} \times \frac{\text{Commercial blocks volume}}{\text{Extracted volume}} = \frac{\text{Commercial blocks volume}}{\text{Total volume}}$$

Mining recovery < 1; *Block recovery < 1;* *Profitability << 1.*

Furthermore, it is fundamentally important to understand and apply these concepts since a deposit usually cannot be fully mined due to technical reasons such as for example slope stability or the deposit geometry. In other words, as in other types of mining there are dilution losses, on the contrary, in the case of dimension stones there are losses when exists the occurrence of any unwanted material within the deposit or when simply for technical reasons it is not possible to extract the whole material of interest, always considering that it is necessary to perform the extraction in order to obtain blocks with specific dimensions.

An example of the point mentioned previously commonly occurs in underground dimension stone quarries when it is employed the room and pillar method, because the necessity to leave and maintain specific placed pillars to guarantee the roof stability and support (which is a technical requirement that clearly cannot be neglected) reduces the material recovery, and thus the profitability of the quarry.

2.1.3 Methods for discontinuities and rock survey

2.1.3.1 Discontinuities survey

In dimension stones there are often few discontinuities and these are usually placed randomly into the rock mass forming a discontinuity network, which has to be determine in order to identify and calculate the geometry of the rock blocks (Yarahmadi, Bagherpour, Sousa & Taherian, 2015).

Then, to determine the discontinuity network it is required measure specific elements and characterizes the discontinuities, these elements are: dip, dip direction, aperture, location, outcrop, shape, and size. Subsequently, it is obtain the discontinuity density and spacing which determine the network. Most common methods are briefly exposed below (Yarahmadi et al., 2015):

- **Scanline and core sampling**

  It is a very common one-dimensional method, simple, but with a large error. It consists on defining a scan line along a segment of exposed rock (outcrop), and on this segment are take measurements to define the position, orientation and frequency of discontinuities. This method cannot survey discontinuities that do not intersect the scan line and towards the depth of the rock mass can only provide information about the spacing and orientation of the discontinuities, not about the size. The disposition of the perforations would also be carried out along the scan line

- **Window mapping**

  This is a two-dimensional method and was developed to survey discontinuities in a specific region of the rock mass, giving better and more reliable results of discontinuity trace lengths and their densities. It consists in defining a circular or square area in the rock with specific dimensions where all the characteristics of the discontinuities are measured (figure 9).

- **Image processing**

  Image processing is a modern two- and three-dimensional method that provides the advantage of fast sampling of discontinuities in inaccessible places. In this method are taken a series of pictures from different positions and angles, then these images are combined and used to identify the traces and faces of the discontinuities in order to determine the main groups.

- **GPR technique**

  Ground penetrating radar (GPR) is a modern geophysical method in three dimensions that detects the discontinuities in the rock mass by applying electromagnetic waves, and then with the data obtained from different wave paths, the information is combined to establish the model of the discontinuity network in the study area.

The selection and application of these methods is conditioned by the outcrops of the discontinuities, the access to the study area and the density of discontinuities. Depending on the importance of the project, more than one method can be used, combining them to obtain more reliable results.

In the case of dimension stone quarries it is considered advantageous to implement the methods of "window mapping" and "image processing" if the exploitation front is already specified and the mining work is already in progress, on the other hand for those quarries that have not been excavated it is considered more effective a combination of "core drilling" and "GPR".

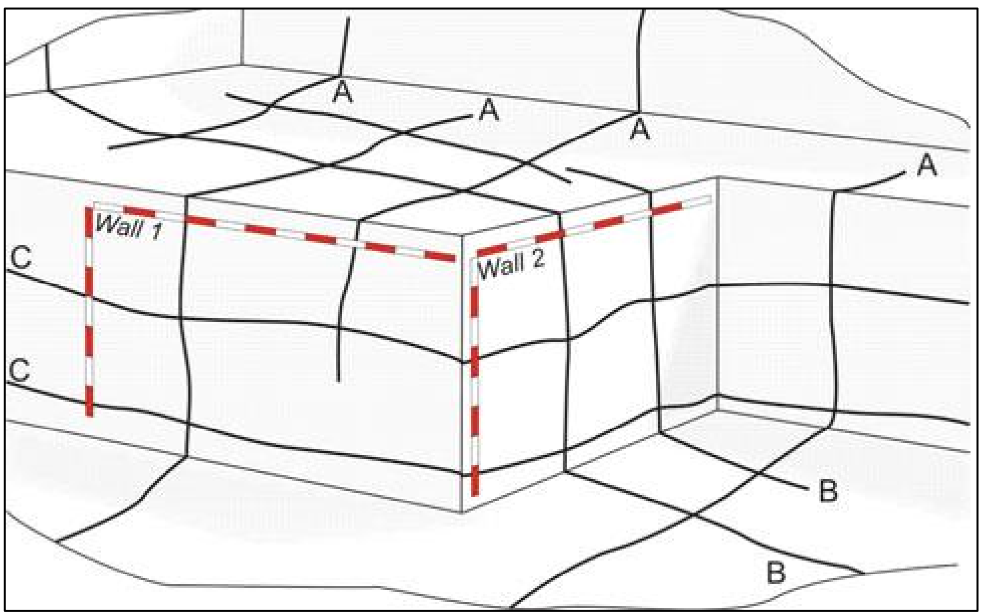

Fig. 10: Example of window mapping surveying of the three different joint orientations in an active quarry (Mosch, 2012, P2).

After sampling a discontinuity network must be defined for the rock mass, in some cases it is impossible to sample all the discontinuities due to the amount of data that would have to be collected, therefore in those cases statistical approximations are applied by means of techniques such as Monte Carlo simulation (Yarahmadi et al., 2015).

2.1.3.2 Rock block surveying

According to Yarahmadi et al. the most important point at the moment of studying the rock blocks is to obtain the best possible approximation of the block geometry, i.e. to reduce to the most the error obtained in the determination of the size and the average expected shape. Nowadays to calculate the block geometry there are several methods known as general methods, and also there are the modeling and simulation methods.

- **Index methods**

  The general methods or index methods use geometric parameters to define an average block size, which serves as a representative value for the set. The most important parameter to determine the average size is the discontinuity spacing. These methods are fast and low cost compared to modeling methods, and are used when a general interpretation of the rock mass is required. These methods are basically quite useful for preliminary studies, but are not recommended for reserve evaluation.

  Various authors have contributed to the development of the index methods, for example one of the most important "Palmstrom" introducing the concepts as the volumetric joint count (Jv) and shape factor. On the other hand, for the case of dimension stones, Elci and Turk proposed to use block quality designation (BQD) to measure the size of the rock blocks in the quarries.

  In general, the index methods consider the discontinuities as infinite planes and then define a main set of discontinuities with relatively constant arrangements in order to advance in the design of the cutting plane pattern. Below in table 2 are shown various parameters used to calculate the average block volume.

Table 2: Some indices to determine the block volume (Yarahmadi et al., 2015)

Measurements	Determination of V_b or J_v
Joint set spacing's (Si)	$V_b = S_1 \times S_2 \times S_3 * (\mathrm{Sin}_{\gamma 1} \times \mathrm{Sin}_{\gamma 2} \times \mathrm{Sin}_{\gamma 3})$
Joints dip (γi)	$V_b \approx 5S_1^2 \times S_2$
Number of random joints (Nr)	$V_b \approx 50S_1^3$
Shape factor (β)	$J_v = \frac{1}{S_1} + \frac{1}{S_2} + \frac{1}{S_3} + \ldots + \frac{Nr}{5}$
Block quality designation (BQD)	$V_b = \beta \times J_v^{-3} \times (\mathrm{Sin}_{\gamma 1} \times \mathrm{Sin}_{\gamma 2} \times \mathrm{Sin}_{\gamma 3})^{-1}$
	$V_b = \beta \times J_v^{-3}$
	$V_b = 1.88 \times \beta \times \mathrm{BQD}^6 \times 10^{-12}$
Joints density in an area (Na)	$J_v \approx$ Ka*Na
Weighted jointing density in an area (wJd)	$J_v \approx$ wJd
Joint density along a drill core or scanline (Nl)	$J_v \approx$ Kl*Nl
Rock quality designation (RQD)	$J_v \approx 35 - \mathrm{RQD}/3.3$
Weighted jointing density along a line (wJd)	$J_v \approx$ wJd

Ka is the correlation factor, which varies mainly between 1 and 2.5 with an average value of Ka = 1.5. The highest value is where the observation plane is parallel to the main joint set. Kl is the correlation factor, which varies between 1.25 and 6, with an average value Kl = 2.

- **Modeling approaches**

  In this type of method, the determination of the size and shape of the blocks is achieved through mathematical techniques and algorithms, some developed in two dimensions and others in three dimensions. First, the discontinuities of the rock mass are simulated and modeled in order to calculate the geometry of the blocks for each set separately (Yarahmadi et al., 2015).

  The algorithms in two dimensions consider the discontinuities as straight lines and from there the shape of the block is calculated (possibly a polyhedron) that is generated by those lines; these algorithms are based on graphical theories, matrices, directed graphs, vectors and numerical methods.

  On the other hand, the three-dimensional algorithms assume the discontinuities as planes in space, which when intersecting each other generate the blocks. The advantage of these is that it is possible to assign a length value to the planes to achieve a better approximation, an example of this is the algorithm proposed by Heliot in 1988 which consider finite planes.

For cases in which simulation has to be applied due to the large number of discontinuities, it is required to previously obtain the probability distribution function for the spacing, aperture, direction and slope parameters. In addition, statistical methods can be applied to mitigate the error of the simulation linked to the irregularity of the arrangement of the discontinuities.

In the case of dimension stone mining, it is beneficial to use simulations to determine the rock blocks in unexcavated areas, but for active quarries it is not considered necessary to use simulation since most of the discontinuities can be sampled from the mining front.

The main disadvantage and problem that the methods described above present when they are applied to the dimension stones is that the fractures that do not form the contour of the blocks go unnoticed; these are known as isolated and dangling discontinuities that are found within some rock blocks (figure 11) and generate small blocks in the extraction process.

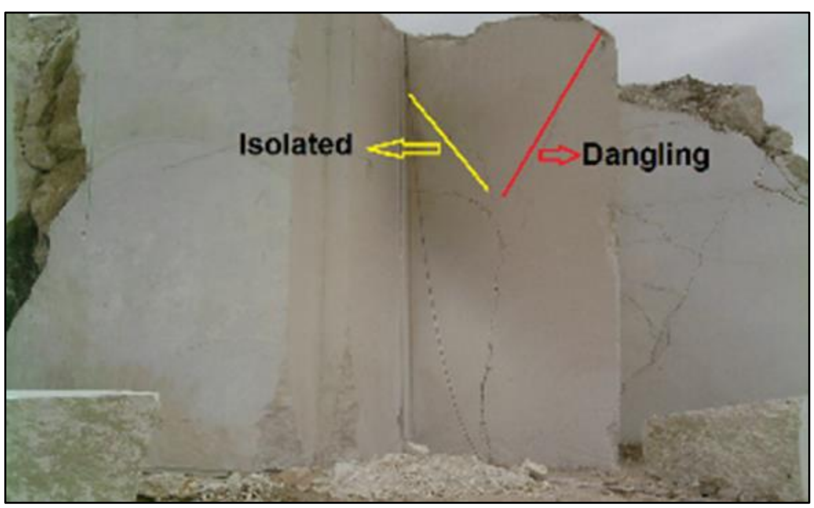

Fig. 11: Dangling and isolated discontinuities, Joshaqan quarry (Yarahmadi et al., 2015, P8).

2.1.4 Exploitation methods applied in dimension stones mining

After having studied the deposit and having noted the possibility of performing a profitable exploitation project, work proceeds to the design of the exploitation and therefore to the selection of the exploitation method. Normally in any quarry of dimension stones it is pretended to initially separate the rock mass in a large block with a parallelepiped shape, and then cut this in smaller blocks until obtaining the required dimensions. The name of the method applied will change depending on the size of the primary rock block, so commonly the exploitation of dimension stones is carried out by the following methods (Herrera, 2007):

- **Vertical slice method:**

  Consists of cutting a large block of rock with a height similar to the area that is being exploited, this is overturned on sterile material to cushion the fall and then cut it into smaller blocks successively.

- **High bench method:**

  The material is extracted by means of benches that are cut into slices with heights from 3 to 15 meters, with the height of the bench as the maximum achievable height. This type of approach allows less preparation labors to extract and cut the rock blocks (figure 12).

- **Low bench method:**

  This method uses low height benches, where the height is the requested height of the blocks, i.e. the stone blocks are extracted directly with the required measurements. The advantage of this method is that it is more flexible since the blocks can be mined in whichever direction at any stage of exploitation (figure 13).

Fig. 12: High bench method being performs (Herrera, 2007, P14).

Fig. 13: Low bench method application (Martina, 2009, P55).

2.1.5 Types of dimension stone quarries

According to Herrera (2007), there are different types of quarries depending on diverse factors such as: the location of the deposit, the topography, the amount of overburden material, etc. These types are briefly mentioned below:

- **Pit quarries and crane extraction:**

  These quarries are developed vertically, descending in a systematic way, and are completely confined by sideways slopes that at the same time are the limits of the deposit. The main complication in this type of quarries is to guarantee the drainage of the mine.

  No ramp access is built because the design of the mine aims to perform the extraction of the blocks by means of cranes, as any addition of machinery or equipment. And by other hand, the entrance of the personnel is through stairs added to the rock slopes.

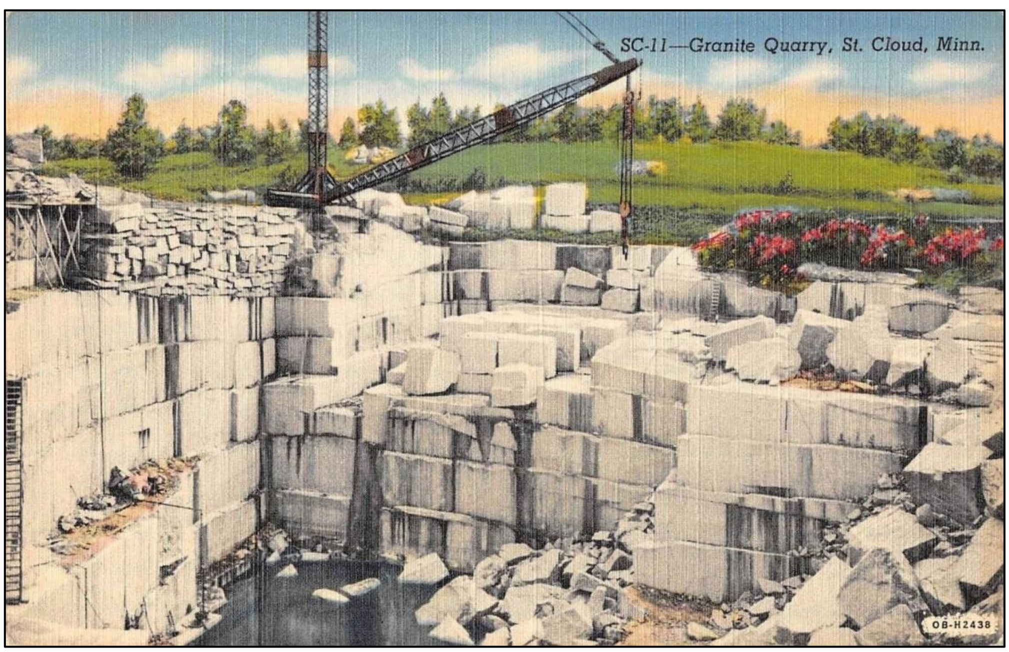

Fig. 14: Pit granite quarry, St. Cloud, Minnesota (Herrera, 2007, P10).

- **Pit quarries with ramps:**

  This design arises from the interest of introducing mobile machines in the quarries (loaders, trucks and excavators), due to the inconvenience or impossibility of using cranes.

  The ramps are built with optimal slopes for the machines and using waste material produced from the same extraction (defective blocks) and sterile materials properly compacted.

Fig. 15: Example of a common access ramp in a pit quarry (Martina, 2009, P113).

- **Hillside quarries:**

  As its name indicates, the hillside quarries are those where the target rock is located in areas of abrupt topography. These are generally exploited in an ascending way but can also be worked in a descending way, and the main challenge is the development phase of the mine because the most complex element in this type of quarry is the construction of the roads.

Fig. 16: Usual appearances of a quarry in exploitation phase (Herrera, 2007, P12).

- **Leveling quarries in mountainous terrain:**

  The leveling quarries are those located at the top of a hill (natural promontory) and have a mine design that aims to exploit the whole area downwards, performing a final leveling of the land with waste and sterile material.

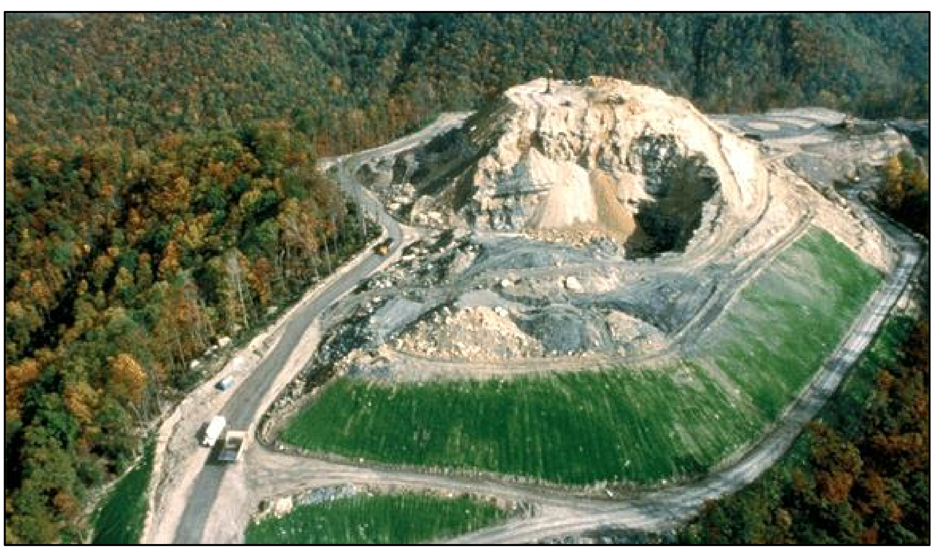

Fig. 17: Location example of leveling quarries (Wang, 2011, P22).

- **Underground quarries:**

  These types of quarries are becoming more and more accepted and commonly are applied with the objective of reducing the visual impact of traditional quarries. Normally an access gallery is created directly to the rock of interest and then a scheme of rooms and pillars is developed.

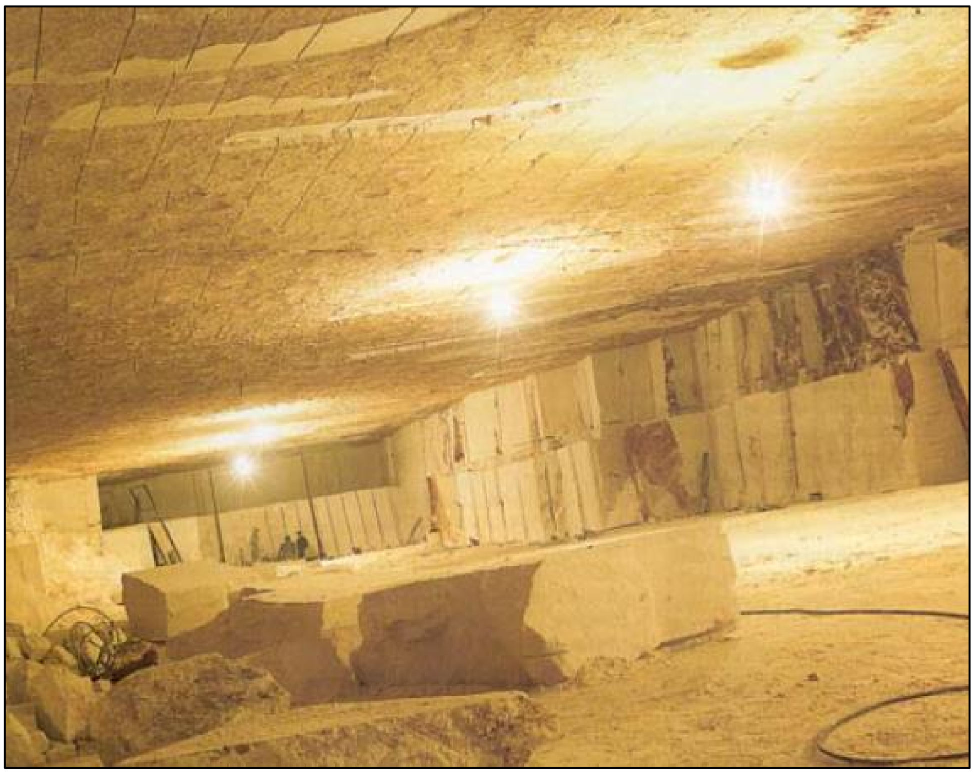

Fig. 18: Underground quarrying by room and pillar scheme (Herrera, 2007, P11).

In fact, as deposits that can be mined by open pit mining run out, the proposal to use underground mining methods to reach other deposits that were previously inaccessible is gaining strength.

According to Oggeri & Oreste (2015), it would be preferable perform an underground dimension stone mining when: the deposit is located in mountain zones, the external surface is regular but the overburden material is excessive, the land costs and reclamation taxes are highly expensive, the ore body is confined and its limits are well-defined, and the safety requirements and stability features are no longer suited to open pit methods.

Along with the points before mentioned, also there are five key elements that must be considered when an underground quarry proposal plan is assess, these are: favorable rock mass structural conditions (this is generally satisfy due to the properties of the ornamental stones), the possibility and flexibility to use cutting techniques to separate the blocks from the surrounding mass (normally mechanical cutting techniques), the homogeneity of the rock mass in terms of physical properties (for example the color and grain size), the economic profitability of the project in contrast with open pit proposals taking into account issues such as the lower block recovery and/or the savings on overburden removal, and finally the safety and environmental reclamation.

2.1.6 Cutting techniques

In dimension stone quarries the local geology has a crucial role, since to extract the rock this must be as less fractured as possible and be strong enough to be used in the construction industry, but at the same time it is important that the rock not be too strong in order to cut it in blocks.

The overburden that covers the deposit is removed by conventional methods, but on the other hand the extraction block systems are particular to this type of mining, these are combined with each other and their use depends on the exploitation method applied to the quarry and the rock's mechanical properties, since each cutting technique uses different mining equipment which is selected depending on each case (SME, 2011). These cutting techniques for obtaining the stone blocks are briefly described below.

- **Slow-burn explosives in small-diameter holes**

  Also known as Finnish method, this technique consists of drilling a series of parallel holes of small diameter outlining the blocks to be extracted, and then the separation of the blocks is accomplished by filling the holes with explosive (Herrera, 2007). Normally this technique is used for hard rocks as granite, an example of its application is shown in the following figure.

Fig. 19: Detonating cord insertion (Martina, 2009, P56).

- **Diamond-toothed saws**

  This type of technique was first used for coal and potassium salt mining, but with technological advances it could be improved for application in dimension stones. Normally this technique is used for rocks of medium and low hardness such as some marbles or sandstones (Herrera, 2007).

The equipment used is a mechanical saw with an arm of approximately 3 meters in length that has small diamond pieces that cut the rock and can be replaced after its lifetime (figure 20).

On the other hand there are also circular saws but these do not have the range that is achieved by using an arm saw, so its use is very scarce and practically limited to subsequent processes in the production chain.

Fig. 20: Operator verifying the cut perpendicularity of an arm saw. (Martina, 2009, P115).

- **Ultra-high-pressure water cutters**

The equipment mainly consists of a hydraulic plant driven by an electric motor and connected to a high pressure hydraulic pump, with the addition of pipes and hoses, the transfer system, the control panel, the water clarification plant and other auxiliary elements.

With this equipment the cut is accomplished with a high speed water jet at a few centimeters of distance. The cutting performance will depend on the porosity, the size of the mineral grains, the mineralogical composition, the degree of weathering, and the elastic behavior of the rock (Herrera, 2007).

Fig. 21: Water jet machine outlining stone blocks (Martina, 2009, P93).

- **Wedge and feather system**

This technique consists in making a series of parallel perforations, forming the plane of cut that is desired to obtain. Once the holes have been drilled, wedges are introduced progressively into the holes, generating a force perpendicular to the plane of cut, and thus producing the fracture along the block. Alternatively, this technique can be performed with hydraulic equipment or filling the drills with expansive mortar, instead of using traditional wedges.

Fig. 22: Application of traditional wedge and feather system (Martina, 2009, P89).

- **Wire ropes (impregnated with sand or industrial diamonds)**

  This technique was developed and implemented for the first time in the 70's to extract the Carrara marble (Herrera, 2007). In order to perform this technique it is necessary to first carry out drillings in the direction of the edges of the rock block, then is introduced the wire which is looped through drilled holes and cut the rock as this travel at high speed against the rock (figure 23).

- **Fame jet**

  The flame jet is a technique that aims to cut the rock by means of the capacity that has this to fracture in presence of a heat source, this happens due to the difference of thermal conductivity of the different grains that constitute the rock (Herrera, 2007).

  This technique can only be used for igneous rocks with high silica content and for the opening of initiating trenches. Currently it is not widely used due to its economic disadvantage compared to other techniques and its environmental impact (figure 24).

Fig. 23: Diamond wire cutting machine (Martina, 2009, P77).

In some quarries after having separated the rock blocks, they are turned over with different equipment that works by performing force on the cutting planes, an example of this equipment can be excavators with a special bucket or inflatable cushions (figure 25).

Afterwards, the stone blocks that are extracted from the quarry front generally are transported by means of loaders, cranes, and/or trucks to a specialized plant that processes the stone blocks, cutting and polishing them for the manufacture of slabs that can then be destined to different uses such as for example paving slabs or walling stones (SME, 2011). Other part of stone blocks is sold to sculptors to create luxurious art pieces or monuments.

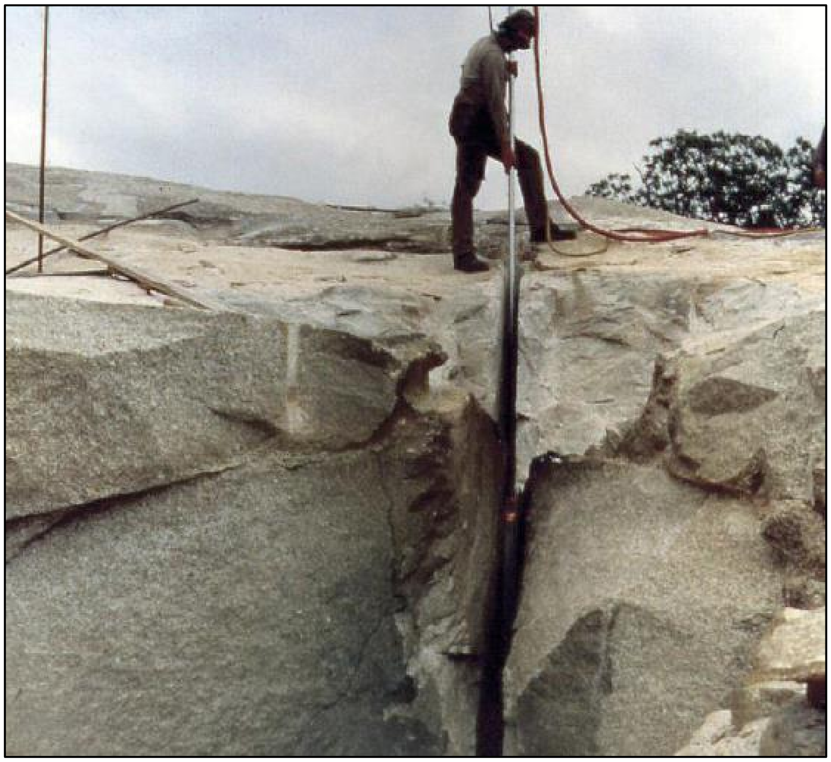

Fig. 24: Example of flame jet cutting technique (Martina, 2009, P91).

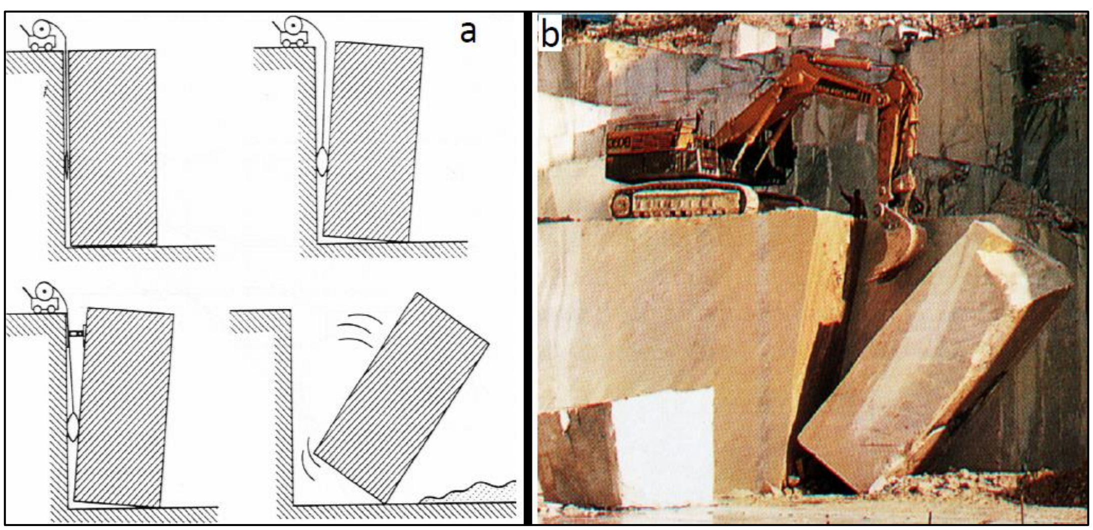

Fig. 25: a) Example of stone block overturning by mean of special inflatable cushion; b) Overturning of stone block by hydraulic excavator (Cardu, 2018, P100).

2.1.7 Interaction between the geostructural conditions and the exploitation methods

Geostructural conditions are a key factor in dimension stone mining, according to Del Greco, Formaro & Oggeri (1992) these determine both the quarrying design and the mining method employed, thus guaranteeing the bench stability and the proper quarry evolution. The ornamental stone exploitation is planned and performed with respect to the discontinuity surfaces. For this purpose, first of all, the overburden material that covers the deposit is removed, and panels subdivided in benches of appropriate heights are defined, so that finally, it is possible to obtain movable blocks.

Depending on the distribution of the discontinuities in the rock mass (orientation of the main sets, persistence, spacing, etc.) it is possible to differentiate between the following three cases.

2.1.7.1 Sub-vertical main joints set

For this type of configuration, the operations normally initiate from the top of the deposit, and then progressively turn over vertical rock panels of thickness equal to the spacing of the vertical discontinuities. In order to accomplish this, it is necessary to apply a force to the rock panel that is sufficient to push the panel; normally this is achieved with blasting charges. For those cases where no lateral discontinuities exist, lateral cuts are prepared in advance.

The extraction planning is determined on the basis of the geo-structural data and also on the force required to push and overturn the rock panels. An example of this type of configuration is shown in figure 26.

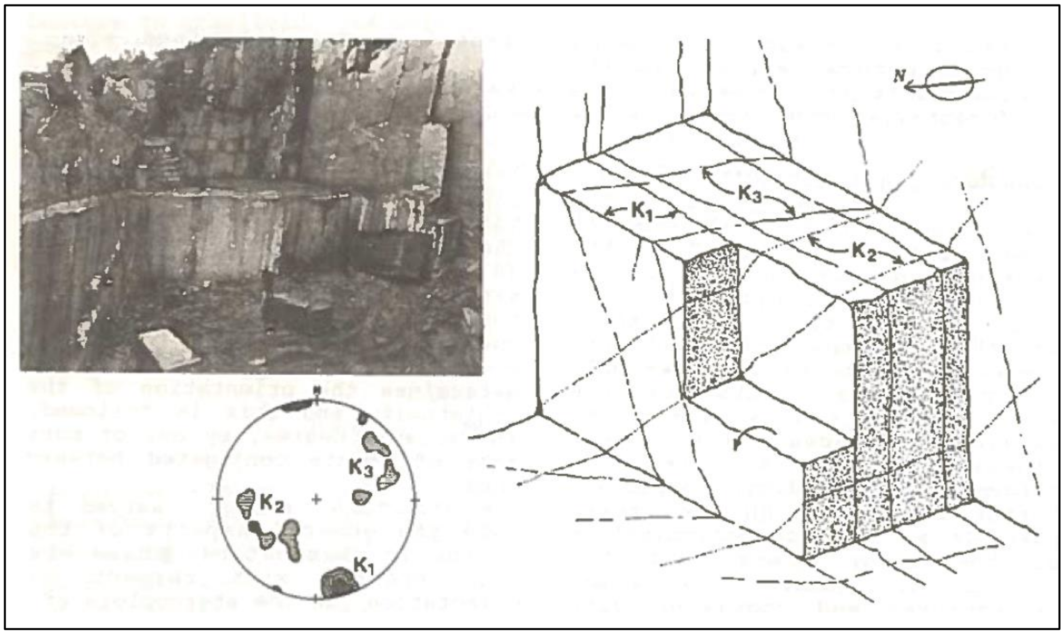

Fig. 26: Scheme of sub-vertical main joints set (Del Greco, Formaro & Oggeri, 1992, P7).

2.1.7.2 Main joints set with an average dip

The rock blocks are obtained by controlled sliding along the main discontinuity set, these blocks are separated laterally from the rock mass using blast holes or diamond wire saw, and are separated from the bottom and top (if necessary) by pre-splitting, making parallel holes spaced at 5 to 10 times the diameter, and filled with black powder to drive the rock.

The key point of this type of extraction is to assess the stability of the blocks by verifying that the blocks cannot slide spontaneously at any moment, if this is not possible then the exploitation is conducted from top to bottom by means of horizontal benches.

Furthermore, for the blasting design that separates the blocks, it is crucial to know the values of the shear strength between the blocks and the sliding surface, as well as the tensile strength of the rock.

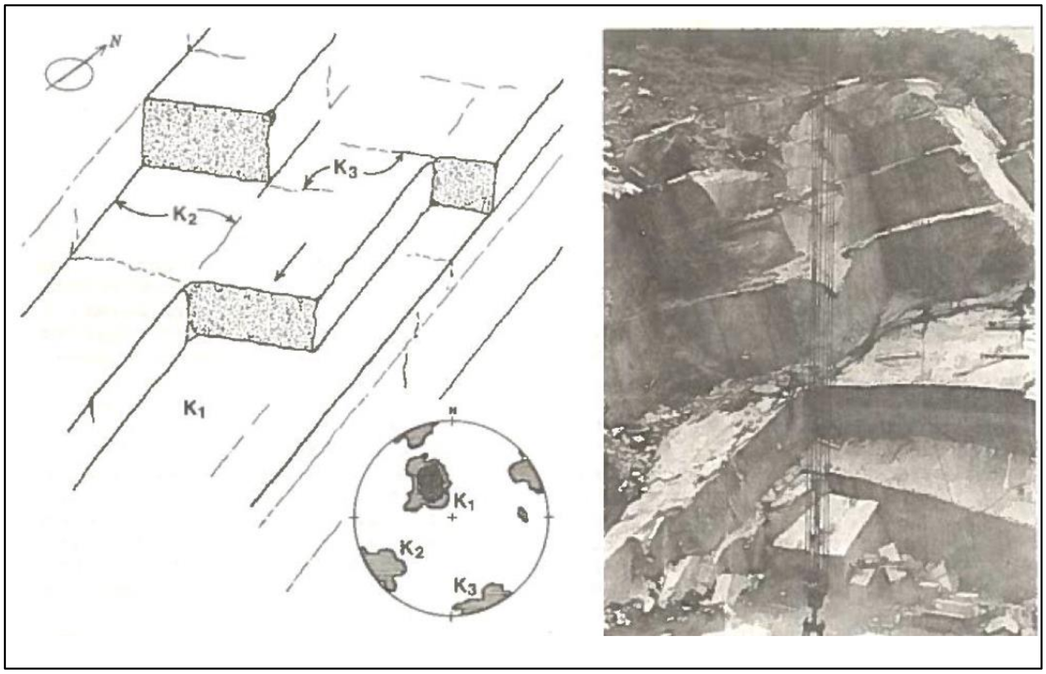

Fig. 27: Scheme of main joints set with an average dip (Del Greco, Formaro & Oggeri, 1992, P9).

2.1.7.3 Sub-horizontal main joints set

This configuration, generally present in granites, besides clearly being the safest in terms of stability, also allows a certain degree of mechanization in the phases of separating the rock blocks from the rock mass. First of all, a trench is created along the layer to be extracted, and then the blocks are separated by making two orthogonal vertical cuts, one at the back of the block and the other at the side in order to separate it completely. These cuts can be made by dynamic splitting or diamond wire cutting.

The exploitation is conducted from top to bottom along horizontal slices, and the crucial factor to take into account in the design of the benches is the possible occurrence of wedge faults due to the other joint sets.

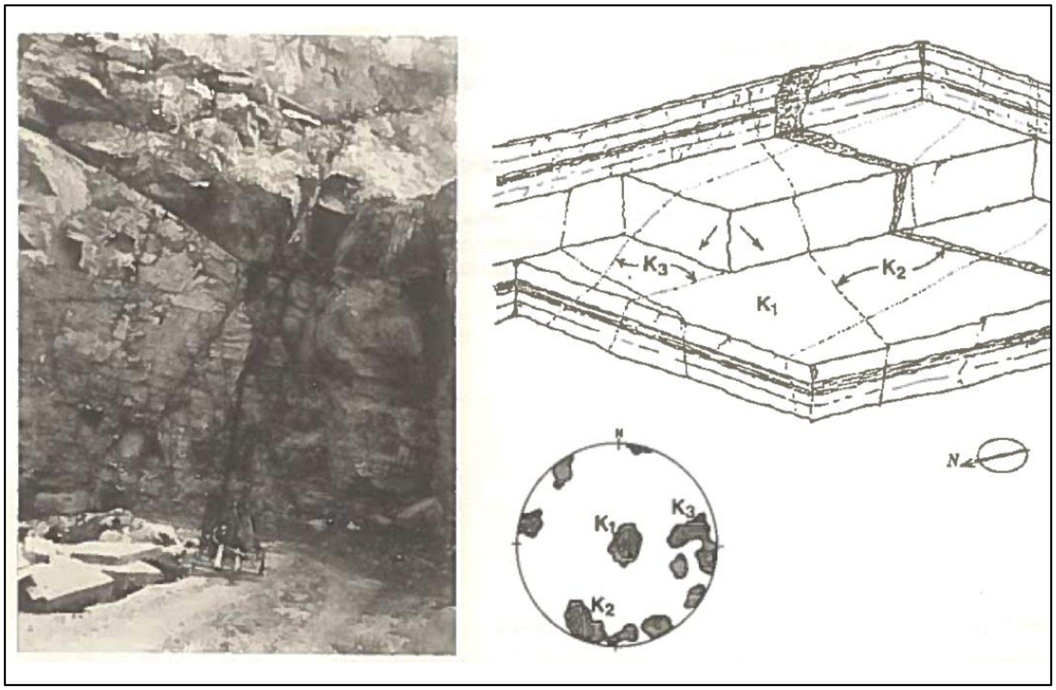

Fig. 28: Scheme of sub-horizontal main joints set (Del Greco, Formaro & Oggeri, 1992, P10).

The geo-mechanical criteria are a fundamental element that allows the assessment of the mining site and the correct elaboration of the mining design in the case of dimension stones, as well as providing the basis for the beginning of any mining improvement strategy guaranteeing safe working conditions.

Furthermore, these criteria contribute towards mining operations that, as these advances form a stable rock slope that respects the safety regulations for mine reclamation plans, in such a way that after the end of the deposit, landscaping works can be organized to guarantee a healthy environment.

2.1.8 Packing problems and their relation with dimension stones

Packaging problems (also known as cutting problems) often occur in various life scenarios, some basic examples of these are when people want to order and put different things in a backpack to go on a trip, or when a tailor wants to cut different parts of a piece of fabric to make a suit, in this last case the raw piece of fabric would be called an "object" and the pieces you want to get from it are called "items" (Figure 29).

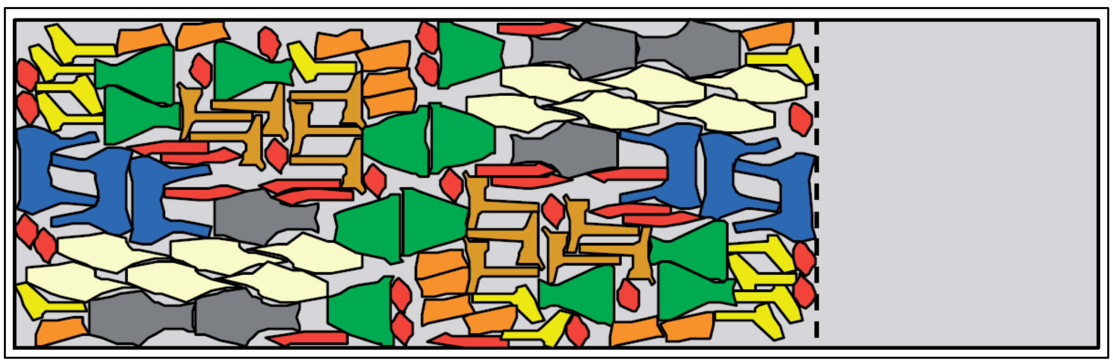

Fig. 29: An example layout from garment manufacturing (Bennell & Oliveira, 2006, P398).

Generally, packing problems consist on finding an arrangement of pieces (items) inside one or various objects such that the number of objects required to contain all pieces is minimum or the number of items that can be fit into the object is the maximum possible (Camacho, Ochoa, Terashima, & Burke, 2013). Then this means that every packing problem consists of two sets of input data: objects and items, and the items should always be placed inside the objects (Abeysooriya, 2017).

In the same way, manufacturing industries use cutting and packing approaches to make efficient use of material, either aiming at minimizing the material waste or maximizing the value of cut pieces as much as possible under essential constraints such as overlapping and containment of pieces (Abeysooriya, 2017).

Packing problems are classified depending on the various criteria applied to the scenario. On the one hand, packaging problems can be classified into one, two or three dimensional problems, whether you have a linear, surface or space problem. Also depending on the shape and size of the items, these problems can be classified in the following cases: identical items, weakly heterogeneous assortment and strongly heterogeneous assortment. As it may also be classified depending on the shape of the container, being this so called regular or irregular bin packaging problem.

In dimension stones, a packing problem can occur when cutting stone blocks from a raw rock block defined by the rock mass natural fractures, since the rock block can be seen as the container (object) and the stone blocks to be cut as the items. This scenario can be seen as a three-dimensional problem, however it can also be worked as a two-dimensional problem (figure 7) due to the fact that the items being organized are "prismatic blocks" means that there is an affinity (due to the geometries) to organize the stone blocks by making one of their sides coincide in a parallel way with one of the sides of the container, and thus obtaining a compact arrangement.

Depending on the geometry of the rock blocks there will be a set of possible solutions, which may be infinite in some cases. These solutions are considered "sub-optimal" if evaluated only by the ratio given by the amount of material and the amount of material recovered.

Therefore, the final solution, besides guaranteeing the maximum benefit of the material, must also consider the technical aspects involved in the cutting process and the exploitation methods used. These aspects as well as the circumstances present in the context of the quarry are the criteria that allow the proposal of an optimal solution, discriminating between the possible arrangements or between the distributions of items of the arrangement.

2.1.9 Common approaches for solving packing problems

According to Bennell and Oliveira (2006), there are different methods for addressing packaging problems, each with different idiosyncrasies, and selecting a method to utilize depends not only on how well the method performs, but also on the complexity involved in using the method or the robustness of it. Therefore the choice of method will also have an impact on the time required to implement it and on the preparation of the data. Below are presented the most common methods for working with packaging problems.

- **Pixel/raster method**

  Raster methods are approaches that divide the space where items are placed into discrete areas, i. e. the area of the "object" is divided into grids or pixels. Different authors have used different ways of coding, however commonly the grids are represented by a matrix, which will have different values for the occupied and empty spaces, a clear example is shown below.

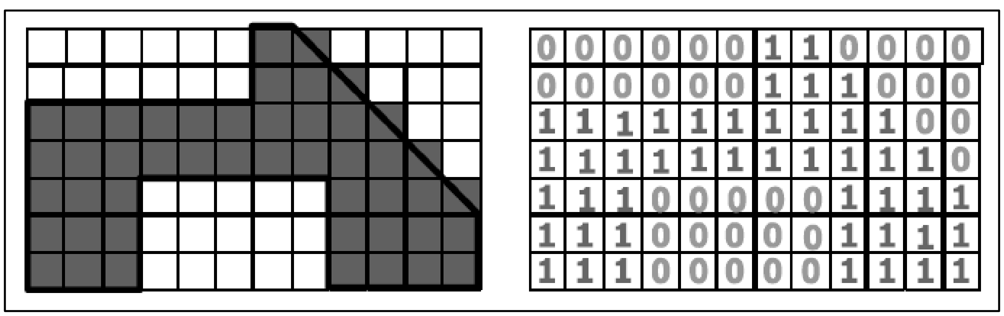

Fig. 30: Raster representation for irregular pieces (Bennell & Oliveira, 2006, P4).

- **Direct trigonometry and the "D" function**

  This method consists of directly representing and employing the polygons, and evaluating their position by means of line intersection and point inclusion tests. For this method, polygons are considered as shapes or pieces enclosed in a rectangle given by the limits of the polygon (its sides and/or its vertices). An example of this can be seen in figure 31.

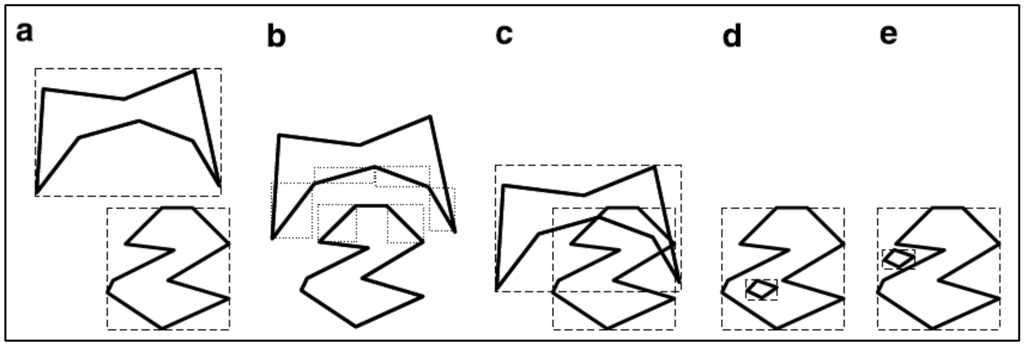

Fig. 31: Examples of relative position in direct trigonometry method (Bennell & Oliveira, 2006, P6).

- **The "nofit" polygon (NFP)**

  The nofit polygon method (NFP) is a complex and robust approach which employs the components of the polygons and their position vectors to determine whether these overlap, touch or are separated from each other, through a test that consists of calculating the position vectors while the items are being moved to generate an arrangement between them.

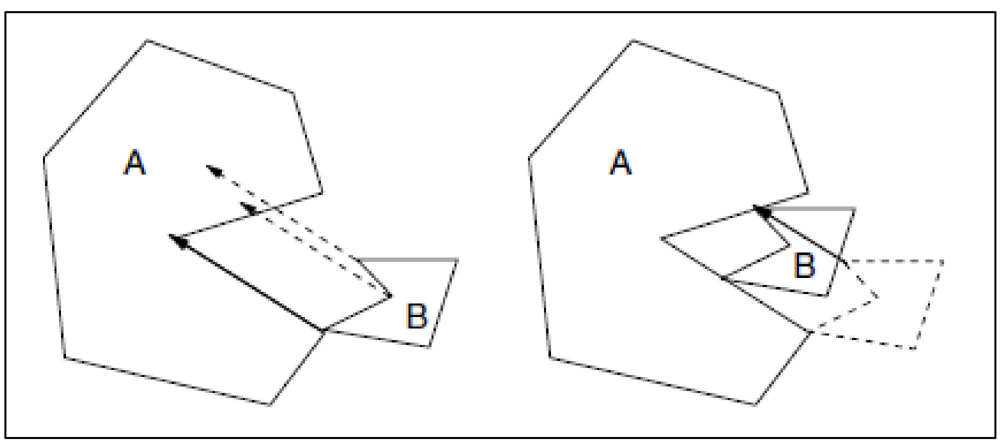

Fig. 32: Example of the nofit polygon method (Bennell & Oliveira, 2006, P10).

- **Phi function**

This recent approach consists on generate a mathematical expression that represents the mutual position of two objects, this kind of functions are known as "Phi functions". Once the Phi function is obtained for two arbitrary objects, this is evaluated and returns values greater than zero, less than zero or equal to zero that indicate respectively whether the objects are separated, overlap, or only touching their boundaries.

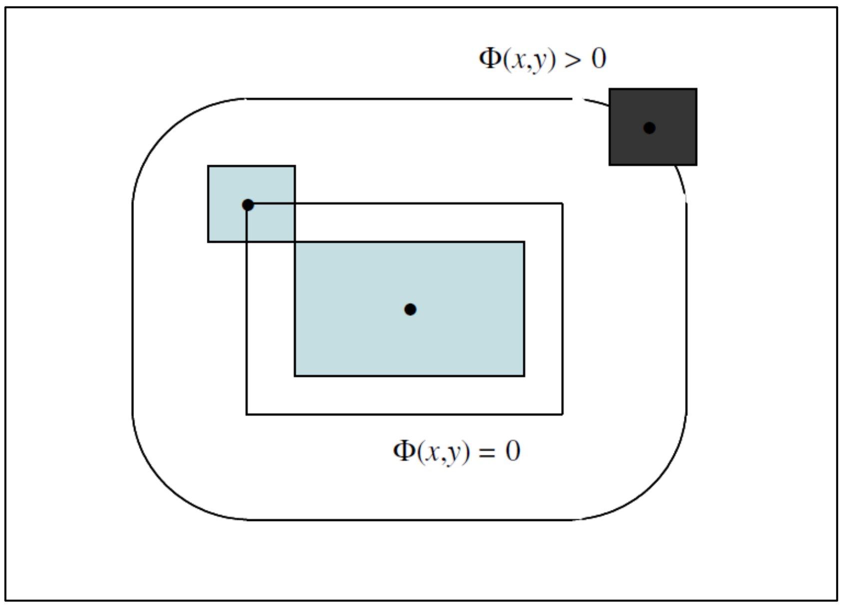

Fig. 33: Two different instances of the Phi function (Bennell & Oliveira, 2006, P18).

CHAPTER III

METHODOLOGICAL APPROACH

In this chapter are presented the methodological aspects that have been selected to perform the research project, whose main objective is to determine an optimal arrangement of the stone blocks to be extracted from a given rock block, in the context of dimension stone mining.

In order to achieve the established objective, an applied research of exploratory-descriptive level is proposed, which pretends to apply to mining the strategies used in the solution of the packing problems, and at the same time to generate knowledge that could be implemented in the productive sector, in order to impulse a positive impact in the extraction of ornamental rocks.

3.1.1 Research design

For the purpose of this study, the research design applied is experimental and semi-quantitative, in which an existing study object (sample) is selected and the problem variables are consciously modified. Furthermore, the data used does not depend on the time in which the study is performed.

3.1.2 Data and sample

The necessary data for the study have been acquired through bibliographic resources. This information allows us to describe the universe of the study, which are ornamental rock deposits that are described by the disposition or arrangement of their natural fractures. Moreover, the samples selected are different rock blocks of all those formed by the discontinuities in three different quarries.

In order to perform the research, the rock block faces must be considered as polygons and then the coordinates of the vertices that form each of the block faces must be defined. Later, one side of the block is selected to apply the method, taking into account the orientation of the discontinuities, i.e. it is selected the side with the greatest amplitude that has a relative width equal to or greater than the width of the blocks to be cut.

This is crucial since as a three-dimensional problem is being addressed with a two-dimensional approach, it is possible to obtain solutions with blocks that intercept with the discontinuities in space, and this at the same time is not visible by working on only one face of the block. If it is not possible to clearly define a face to work on, the geometry of the block can be modified to eliminate areas that form oblique angles or wedges.

In figure 34 the steps in the planning and adaptation of the data and the sample for the correct application of the method being used are illustrated. Initially, once the existence of the rock block is confirmed, within this are defined two cross sections separated each other by a width equal to one of the sides of the stone block desired, which normally enclose the cutting volume for extracting the blocks. These two cross-sections can overlap in such a way that it is possible to recognize whether there is a very pronounced wedge-shaped area. If this is the case, the smaller cross-section can be used to cut or delimit the larger section, in order to eliminate wedging and obtain a block with orthogonal angles between its faces as in this example. It is also important to appreciate that as the obliquity of the block is greater, there will be a greater amount of overburden material that must be cut to obtain the desired rock block, so this sample preparation procedure must be carried out carefully, in order to select the rock block face that allows the highest recovery after its preparation.

For this research were employed cross sections separated from each other by a width of 2 meters, to obtain an arrangement that produces stone blocks of 3 x 1.8 x 2 meters for the first case and stone blocks of 2 x 1.5 x 3 for the other cases respectively.

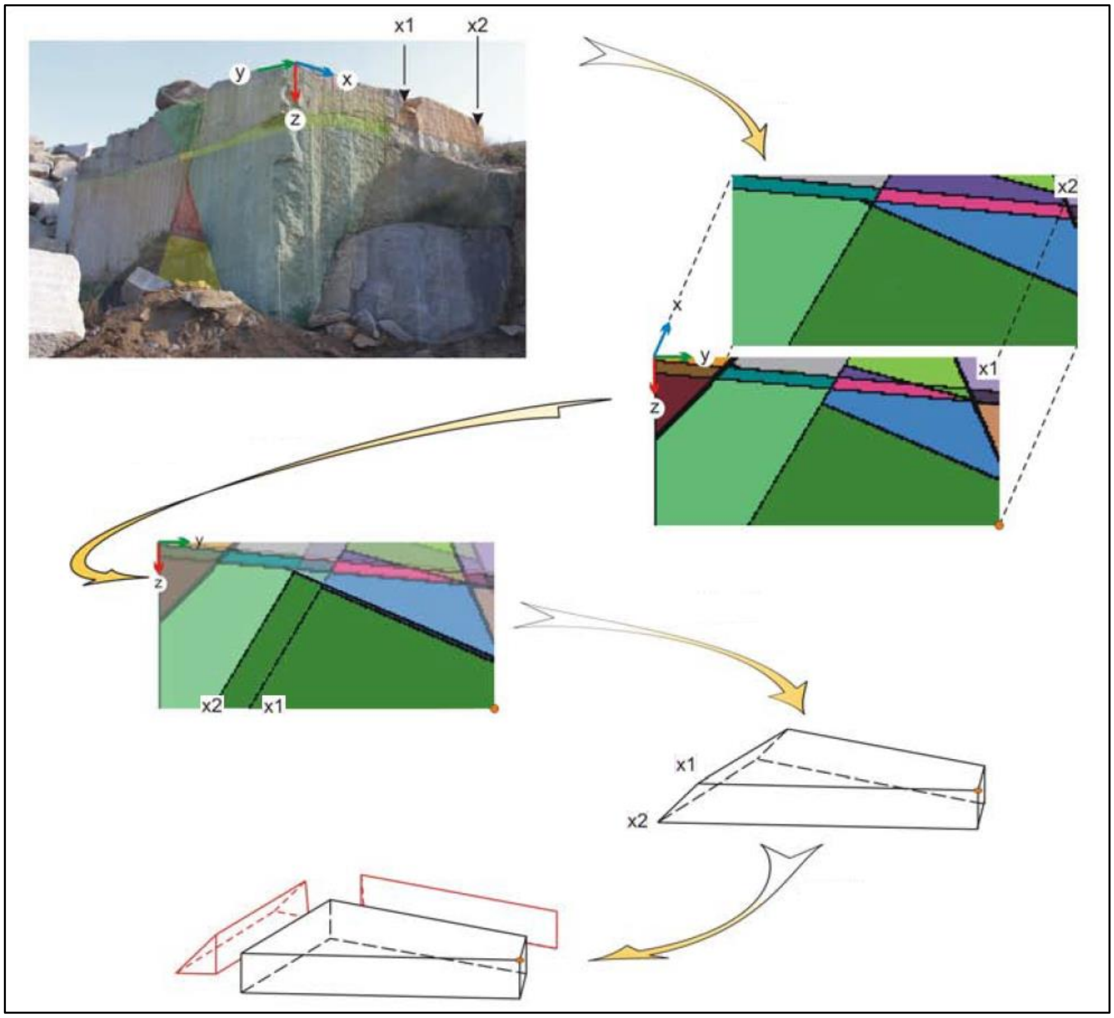

Fig. 34: Scheme of geometry modification of the rock block for the correct use in the research (Mosch, 2008, P36).

3.1.3 Method and software implemented

To solve this problem, a method was devised that integrated the use of geographical tools with the automation provided by the creation and execution of scripts.

The method consists of placing a mesh with grids of specific width and height dimensions over a polygonal surface to count the number of grids that fit inside the polygon. Later, the spaces not occupied by grids are individually intervened to determine if by rotating or moving the grid, it can be fitted within these areas.

Finally, a count of the grids that fit within the polygon is carried out, and then the same script is repeated to move and rotate the main mesh to discover if there are other grid arrangements that can fit more grids, and thus occupy more area of the polygon's surface. The final result of the script is a layer of polygonal feature with an irregular arrangement of grids that fits completely inside the polygon representing the face of the rock block.

In order to implement this method exactly as it was applied in this research, it is necessary to have the following tools available on a computer: ArcGIS desktop software, any source-code editor or an integrated development environment (IDE) for Python, and have installed the Python programming language. This software was selected for the research due to the tools it has, the convenient Python API and the possibility that it offers to create user scripted tools that can use different modules from its libraries.

Certainly the method can be replicated with any software that contains a programming interface (API) and that also has the tools to execute the script to create, move, rotate and intersect the mesh with the polygonal surface. It is also important to mention that because the software and/or the programming language used have their own tools and libraries, recreating the code can be a time-consuming task.

3.1.4 Experimental procedure

When the data has been prepared, the experimental procedure can proceed. This procedure takes place entirely within the ArcGIS software work environment (Figure 35), and was completed step by step as described below.

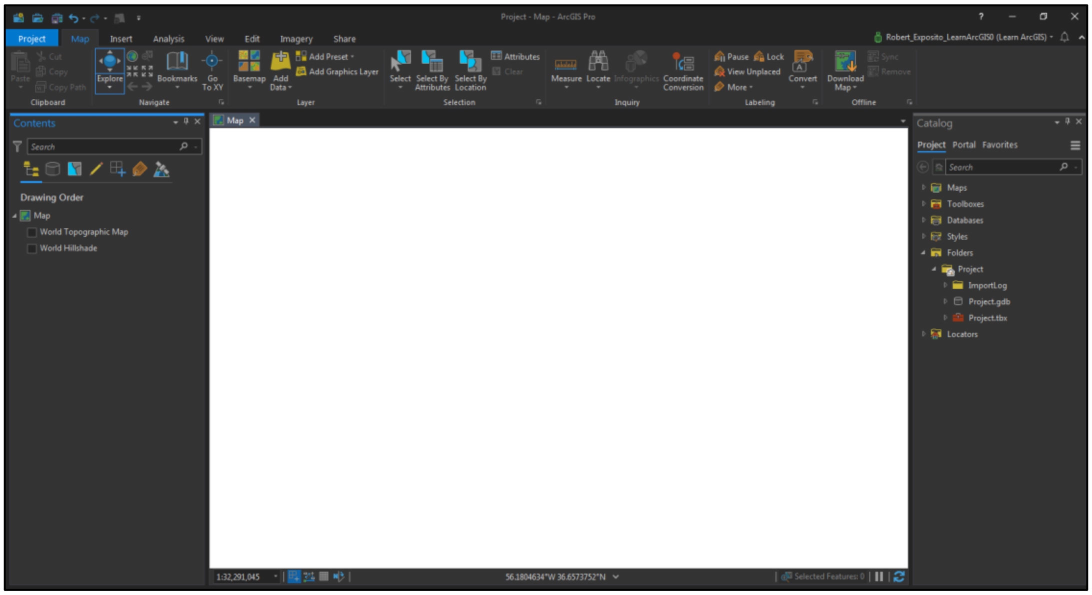

Fig. 35: ArcGIS software work environment.

At the working environment, the first thing that needs to be created is the element that will act as the study object, i.e. the drawing object that represents the selected face of the rock block to be cut. For this, firstly a type "feature class" geodatabase file must be created into the project folder in the catalog panel, to this file must be assigned the type of “polygonal feature class” (figure 36).

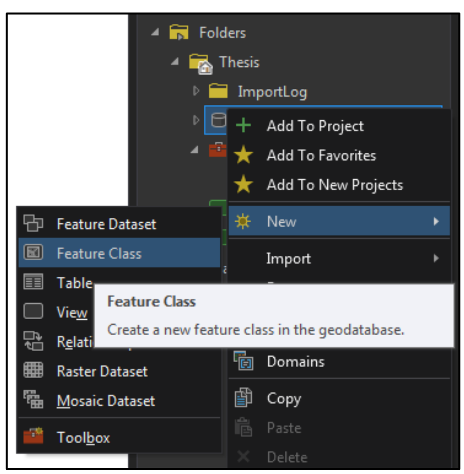

Fig. 36: Creation of polygonal feature class geodatabase.

Then a file to store our drawing object or polygonal feature was created. For this, the user goes directly to the project folder and creates a new “shapefile”. It is important that this layer file is configured to store polygonal features (Geometry type), and also that it works with the measuring units and the desired coordinate system as is shown in the figure 37. In the case of this research the layer was configured with metric units in the "x-y" axis, and a Mercator WGS 1984 auxiliary coordinate system.

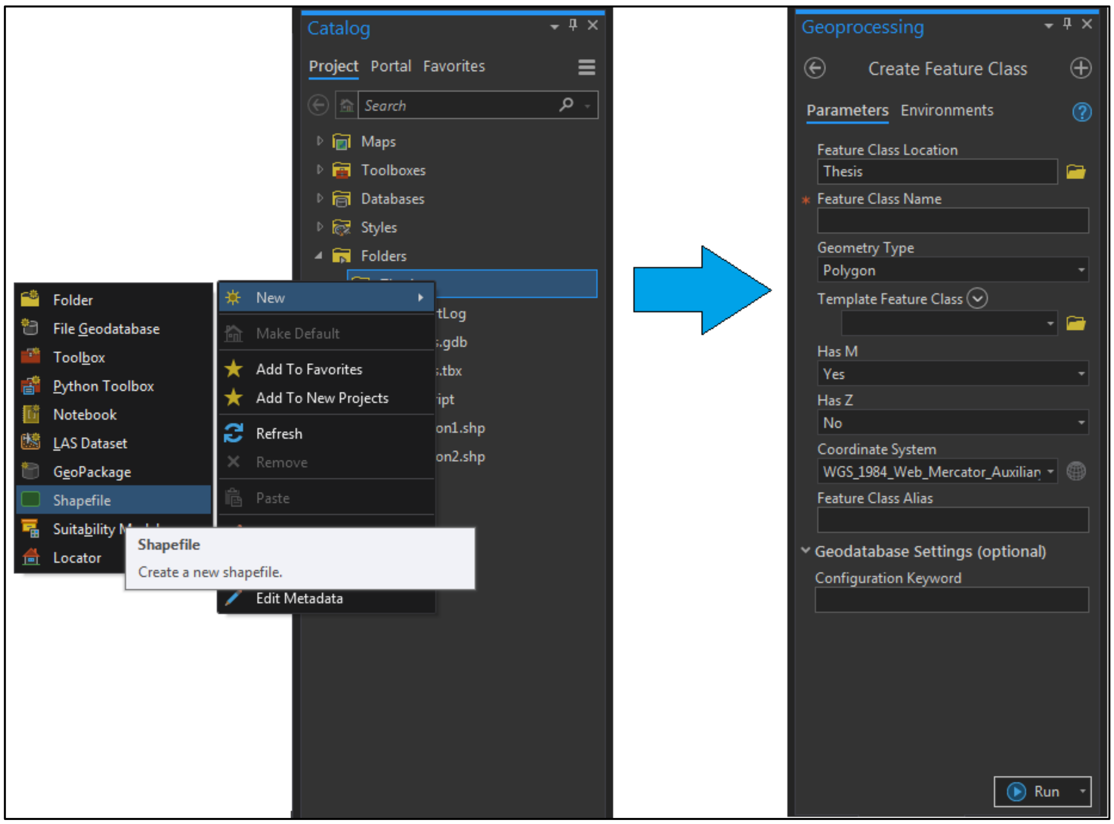

Fig. 37: Creation and configuration of the work layer.

For creating the polygonal surface the previously created shapefile was added to the project and edited to draw the polygonal surface by directly adding the x-y coordinates of each vertex as shown in figure 38. At this point the procedure was completed with the ArcGIS work objects needed for the implementation of the script.

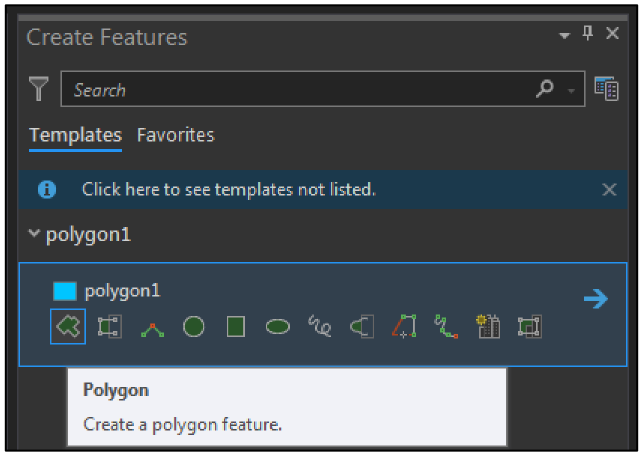

Fig. 38: Creation of the polygonal surface.

In order to implement the command sequence within the software, a script was created within the project folder and its toolbox. This new script is seen as an empty tool for the software until it is given the path to the text file containing the Python code, this script was imported from a ".py text file" as shown in the following figures.

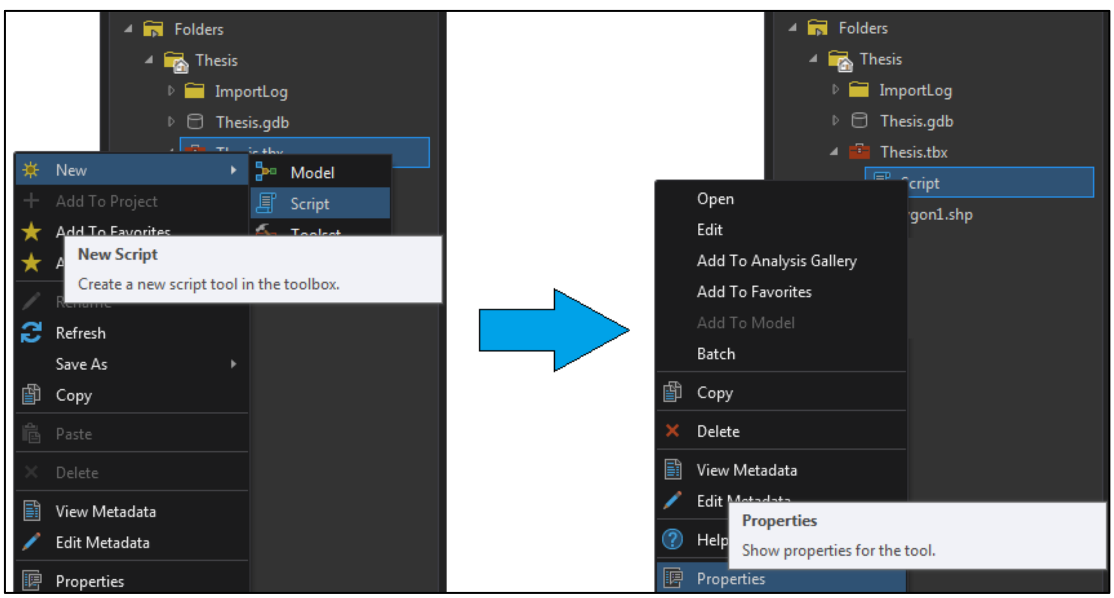

Fig. 39: Creation of a new script tool in ArcGIS.

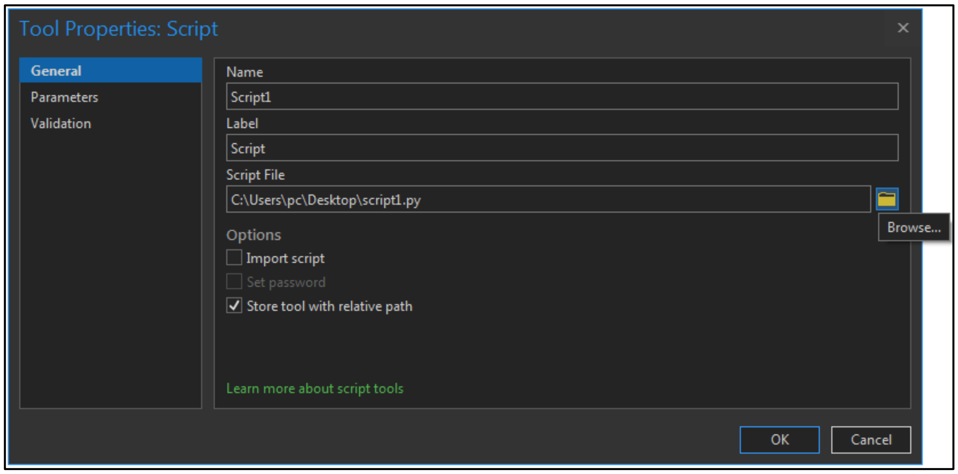

Fig. 40: Properties pop-up window for importing the script.

It is also necessary to establish the data type, their direction and name of the parameters that the script requires to run, in other words, a data input and output path is assigned for feature layers, with the names of the variables defined in the Python code, as it is shown in figure 41.

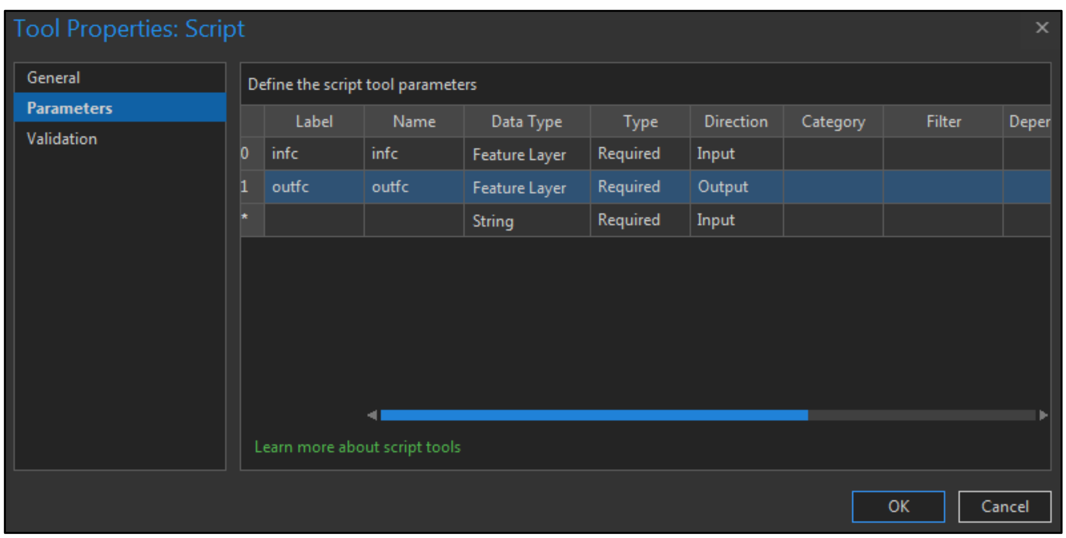

Fig. 41: Input and output parameter assignation required by the script.

Finally, the script tool was executed (figure 42) obtaining as a result the feature layer that contains the possible block arrangement. In this research the script was used twice to generate arrangement results based on the required stone block size, and in a grid of width and height equal to a multiple of the width and height values of the desired stone block. For accomplish this change, only the width and height values were edited directly in the text file with the script as it is shown in figure 43.

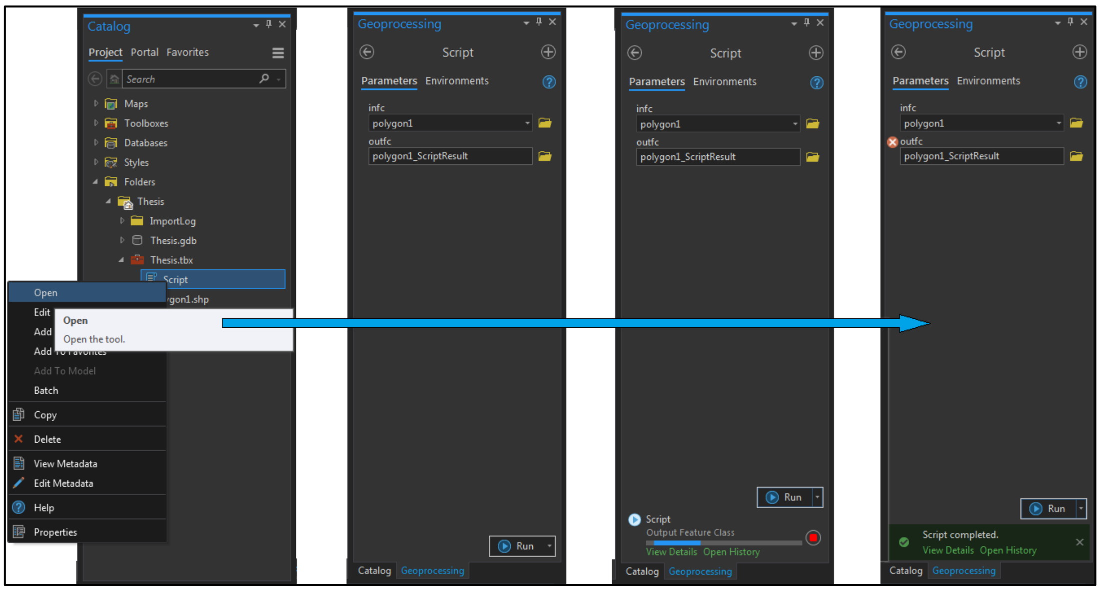

Fig. 42: Execution of the script tool to obtain the entity layers.

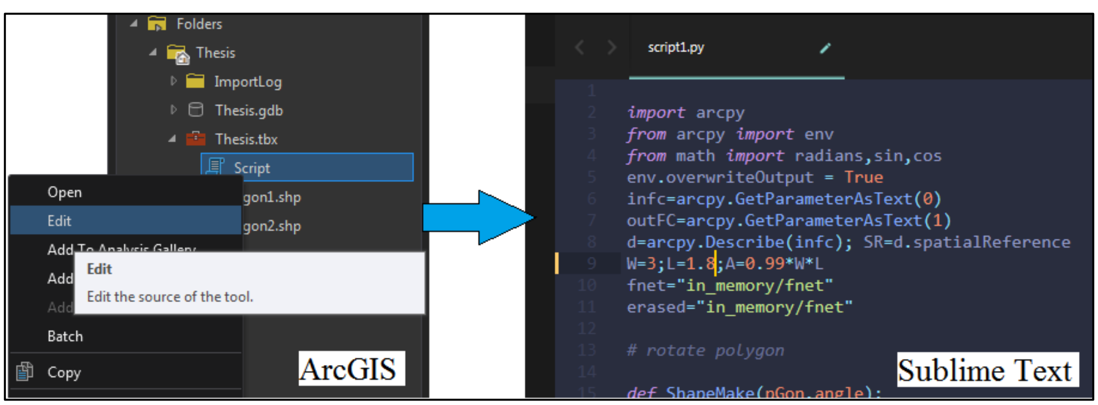

Fig. 43: Modification of the variables in the tool's Python code.

3.1.5 Research limitations

This research provides a solution for a very complex problem for which there is currently no applicable algorithm for any case that may be faced. Therefore, it is not still possible to completely automate the process of selecting the three-dimensional arrangement by ensuring that it is the best possible in terms of material utilization.

However, the fact that the problem can be approached from a two-dimensional perspective allows optimizing the planning process, although it cannot be guaranteed that by addressing the problem from a three-dimensional point of view better results may be obtained.

An additional limitation of the research is that there are scarce bibliographical resources related to the knowledge of packaging problems applied to mining, therefore proposing an optimal algorithm for the resolution of this type of problem may be a complex challenge.

CHAPTER IV

RESULTS AND DISCUSSION

The following chapter is intended to present and discuss the results obtained during the research, which were acquired by means of the bibliographic review and by the experimental determination of the block arrangement using programming tools in combination with the tools provided by GIS software. Besides discussing the aspects related to the applicability of this procedure considering the current environment that can be present in a dimension stones quarry.

4.1.1 Suitable planification of cutting patterns in dimension stones

As shown in the previous chapters, in dimension stone mining there is a set of prospecting and extraction methods and techniques that are combined and used in the quarrying stages to maintain a systematic and constant advancement. The utilization of certain methods and techniques will depend on diverse factors which occur in the deposit such as: topography, local geology, physical, mechanical and chemical rock properties, etc., as well as other factors which do not depend on the deposit but rather on technical or economic factors such as the availability of certain machinery or equipment, its scale, or the preference for the application of a certain method.

In order to provide an effective planification, it is crucial to have a broad description of the deposit of interest, since as more information is available; it is possible to formulate a proper planification that produces a more efficient performance. Therefore it is essential to prepare the deposit or exploitation front for the previous application of the study methods (image processing, ground penetrating radar, window mapping, scanline, core sample, etc.) of the existing discontinuities, and thus be able to establish criteria for recognizing and extracting the different blocks produced by the discontinuities. In addition, the accuracy and precision in the identification of the discontinuities allows a more effective selection of the exploitation method and the cutting techniques to adopt.

4.1.2 The role of exploitation methods and cutting techniques

The exploitation methods and cutting techniques for dimension stone quarrying are selected depending on the conditions and characteristics of the concerned deposit. These are also associated with whether the material is exploited in a massive or selective way, an example of this are the methods of exploitation of high bench and low bench, where it can be appreciated that for each one commonly different cutting techniques are applied (figure 12 and 13) which provide specific advantages in certain cases.

On the other hand, regarding to the flexibility of extracting stone blocks by means of a cutting pattern with an irregular block arrangement, there is no factor that shows that this type of approach is not possible. However, the methods and techniques applied for a selective extraction have the advantage of changing more simply the orientation of the blocks that are being extracted, since it extracts the stone block directly with the required dimensions, and make this more convenient for the implementation of an irregular arrangement.

4.1.3 Potential constraints respect to irregular block arrangements

In order to consider an irregular block arrangement it is necessary that certain factors are present in the deposit, clearly in any dimension stone quarry where the discontinuities are practically orthogonal to each other, the application of an irregular arrangement will not take place, since it is not required to maximize the use of the material by mean of an irregular cutting pattern. The same occurs when the deposit presents a reduced spacing between discontinuities which does not allow the obtaining of more than one stone block by cutting a rock block.

In the same way there are certain factors that may cause that the application of an irregular arrangement is not feasible, such as: the difficulty of the cuts that are planned, the precision that may be required to carry out these cuts, and the total cutting length that is required to perform the extraction.

Firstly, it is important to know the precision of the cutting techniques that are applied, as for example, when working with diamond wire, the execution of each cut will be much more precise than working with a system of wedges and feathers, this last complicates carrying out an irregular arrangement because it may cause damage to the blocks that are extracted. Basically, it is necessary to be aware of the error associated to the cutting technique employed in order to correctly establish the measurements of the stone block cutting pattern.

Furthermore, after determining that it is technically feasible to implement an irregular arrangement, it is important to compare the possible solutions (the different arrangements) with respect to the cutting length required by each of them, and the amount of material these can extract, since depending on the economic value of each stone block to extract, the economic cost of the cutting operations may or may not be assumed. Therefore it is important to take into account the economic value of each block to be extracted and the total cost of each cutting pattern in order to correctly choose the appropriate one, because due to this it may occur that the arrangement that exploit more material (higher recovery) may be not the best economically.

4.1.4 Procedure verification for stone block arrangement obtainment

This results section describes the steps sequence for obtaining an optimal stone block arrangement, taking the case of San Antonio granite (Sardinia, Italy) as example, in order to present the reasoning behind the formal procedure and to apply it to other cases that will be discussed afterwards.

4.1.4.1 Feature class layers obtained

Through the procedure described in chapter 3 were obtained two results, first was generated a layer that contains an optimal and regular block pattern, and then was obtained a second layer that divides the polygon into smaller grids that demarcate the spaces where the blocks could be located, it is important to mention that this second layer determines the maximum number of grids that can be introduced in the polygon.

The polygonal features that were created in the obtained layers are shown below in figure 44. The first block arrangement is shown in blue, and the squares that represent the possible spaces that a block can occupy for a feasible arrangement are shown in yellow.

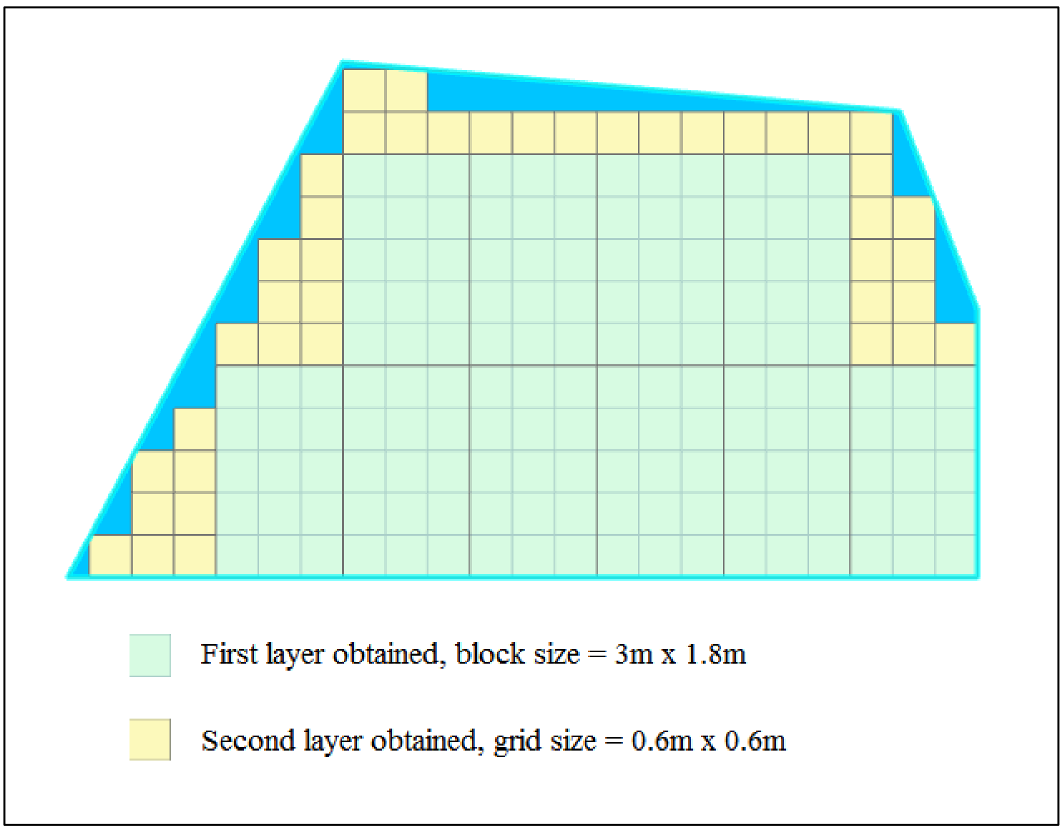

Fig. 44: Layers generated automatically through the application of the script.

As shown in the figure, the result of the first layer was a regular block arrangement even though this was not the expected outcome, this occurred because of the algorithm involved in the script code. The command sequence cuts the polygon into grids by means of a mesh, so the script first gets the best regular block arrangement and then tries to fit blocks in any orientation into the still unoccupied spaces. This algorithm has the advantage that it produces a solution that does not need the performance of a complex cutting pattern, but also does not prioritize the amount of blocks over the cutting pattern.

On the other hand, the result of the second layer shows the maximum number of grids that fit inside the polygon, with a multiple width and height of the sides of the blocks that are expected as a result. This second layer first shows the spaces not occupied by the regular arrangement, which being delimited by these grids can be counted easily. Counting these grids permits to know in a certain way if the unoccupied space along the whole polygon is sufficiently large to consider the possibility of an irregular arrangement that allows fitting more blocks inside the same polygon.

As can be seen in figure 44 it was obtained a regular arrangement of 10 blocks, and an empty space divided into 42 grids with an area of 0.36 m^2 each. Taking into account the fact that each stone block within the arrangement occupies a space equal to 15 grids; it can be presumed that there are other block arrangements that can accommodate more blocks within the polygon, since the area not occupied is almost the necessary for 3 additional blocks, although this kind of assumptions cannot be guaranteed for any case.

4.1.4.2 Stone block arrangement obtainment

After comparing the area covered by the regular arrangement with the number of grids in the remaining spaces, a reorganization of the stone blocks can be proposed to obtain the arrangement with which the greatest number of blocks can be extracted, in other words the arrangement with the best performance in terms of the use of the material.

This reorganization of the blocks can be easily carried out by using the layer of the grids as a guide template. It is clear that having compared the block size which corresponded to 15 squares, with the area not covered which resulted in a total of 42 empty grids; it can only be expected to achieve an irregular arrangement that can introduce a maximum of two more blocks (figure 45).

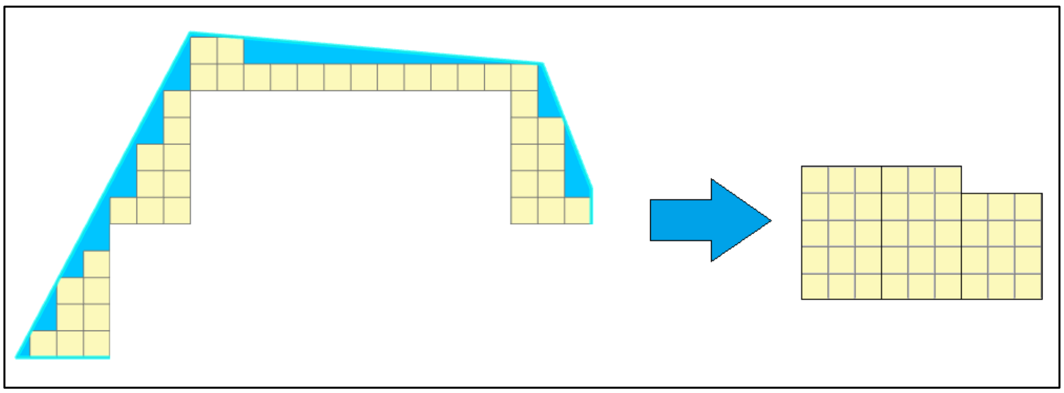

Fig. 45: Representation of the total number of uncovered grids.

Performing these reorganizations leads to different results that can fit the same number of blocks with different arrangements. However, the variations of the arrangements are limited and the advantage that an arrangement has over another is the simplicity with which the cuts can be performed to separate each stone block, which can be recognized when the boundaries of the blocks are parallel and continuous.

In figure 46 and 47 are shown the results obtained from the reorganization of the stone blocks by means of the use of the grid layer. For this particular polygon, it should be noted that there are many block arrangements that can fit 10 blocks, but for arrangements of 11 and 12 blocks there are few variations given the area available.

Taking into account the arrangements that fit 11 blocks in figure 46, it is observed that two different solutions can generate the same result in terms of the number of blocks; however each arrangement of blocks will require a different cutting length due to how each block is positioned with respect to the others. For example, for these two cases, a cutting length of 57.60 meters is required to perform the arrangement "a", while 56.40 meters are required to carry out the arrangement "b" (considering that the edges of the polygon are the natural fractures of the rock mass and it is not necessary to cut these faces).

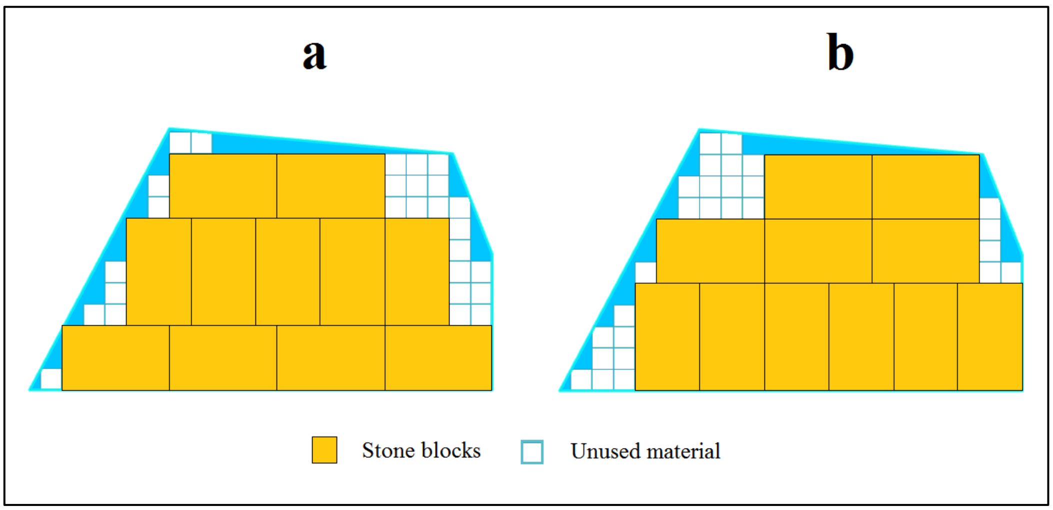

Fig. 46: Different arrangements for quarrying 11 stone blocks.

For this particular case between the options “a” and “b” there is a difference of 1.20 meters in the cutting length required, this comparison might be taken into account to determine which is the most favorable arrangement along with other factors. This difference in cutting length between arrangements that produce the same amount of blocks could be neglected depending on the economic value of the material and the cost of quarrying personnel and equipment required to perform the arrangement cuts, but nevertheless whether this scenario occurs several times on different rock blocks throughout the quarry, it will produce a difference which can result in significant cost savings.

To have a clear idea of the importance of this comparison, the difference in percentage of the required cutting length between the two arrangements in figure 46 can be evaluated. As a result, it was observed that for arrangement "a" a 2.13% greater cutting length is required than for arrangement "b", this excluding the labor and time needed to perform that difference in the cutting length, which could result in a greater difference in terms of feasibility.

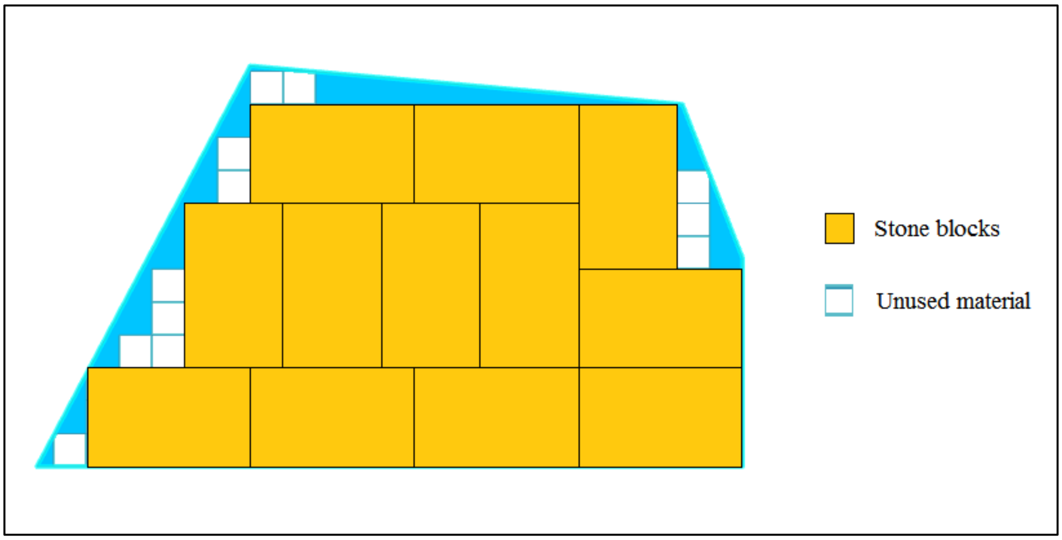

Fig. 47: Optimal irregular arrangement for maximum material utilization.

On the other hand, in order to implement the arrangement that produces 12 stone blocks (figure 47); a cutting length of 60.60 meters is required, resulting in a difference of 4.20 meters with respect to arrangement "b" in figure 46, which represents an increment of 7.45%.

Therefore, to determine whether it is preferable to apply one option or another, it is necessary to know the specific economic value of the block of stone to be extracted and thus evaluate the economic feasibility of carrying out more cutting labors to obtain an extra stone block, since in some cases the economic value of the stone block is not high enough to achieve a greater benefit than with other arrangements, regardless of the fact that more blocks may be produced.

In terms of material utilization and for this particular case, the irregular arrangement presented in figure 47 is the most efficient option, because this allows the insertion of 2 more blocks in comparison to a regular arrangement (each block with dimensions of 3 x 1.8 x 2 meters), which results in a benefit of 21.60 cubic meters of material in stone blocks with the dimensions required by the market.

4.1.4.3 General procedure

The following section presents the general procedure for obtaining a scheme of stone blocks arranged in such a way as to achieve the most efficient material recovery possible for a particular rock block, through the application of Python tools in GIS software.

- **Define the configuration of discontinuities in the rock mass**

  Subsequent to the respective field surveys (those described on point 2.1.3), the values of dip, dip direction and spacing for each main set of discontinuities are used to recognize the rock blocks formed by these in the rock mass.

- **Define the rock block to extract**

  By selecting the block to quarry, and having the discontinuities data, it is possible to define a model of the rock block to extract (this may be created in a software CAD). This model represents the rock block that will be quarried and divided into the final stone blocks.

  The final rock block shape may vary in practice depending on the mining method adopted, giving additional sides to the final rock block.

- **Assess each side and determine the most suitable rock block face**

  Due to the fact that this method requires transforming a three-dimensional problem into a two-dimensional one, the block face to be treated must be selected, since depending on the rock block face chosen, a greater amount of waste material could be produced at the moment of performing the preliminary preparation of the block.

- **Perform preliminary preparation of the rock block model**

  On the selected face, a preliminary preparation is performed by cutting the oblique edges of the block to produce a block with sides which are orthogonal to the plane of the selected face, as shown in figure 34. The cross-sectional distance or block thickness is adjusted with respect to the desired final block size and the total thickness of the rock block, in such a way that the maximum material amount is recovered.

- **Create the 2D block model as a polygon in ArcGIS**

  Once the rock block has been prepared, the face to work on is plot by its coordinates, and a polygonal entity layer with these points is generated within the ArcGIS. This layer will be overwritten automatically by means of the Python tool, generating other polygonal entity layers.

- **Select the stone block disposition to outline**

  Considering the desired stone block size and the rock block thickness, the layout of the final stone blocks is selected, i.e. which face of the final stone blocks will be parallel to the face of the rock block that is treated (2D block model). Then the values for the height and width of the final stone blocks are entered into the Python tool code.

- **Select the grid size for the creation of the grid layer**

  The grid layer is an auxiliary layer that serves to assess the material recovery of different block arrangements, and for the rearrangement of the stone blocks within the polygon. This layer is created with a specific grid height and width value, which is the minimum value multiple of the height and width of the stone blocks, an example of this is shown in figure 44.

- **Execute and collect the Python script results**

  For this, in the Python tool created, the polygonal entity layer containing the polygon representing the rock block is entered (input), and an output path is typed for producing the script's final result.

- **Assess the remaining space inside the polygon**

  At this point two entity layers were obtained, a layer with a regular block arrangement generated automatically by the script, and a grid layer. With these two layers it is possible to assess the material recovery that can be achieved by using the generated regular arrangement; this can be evaluated by counting the number of unoccupied grids as it is shown in figure 42.

  Depending on the number of grids that conform a stone block and the number of unoccupied grids, it may be presumed that an irregular block arrangement exists which allows introducing more stone blocks in the polygon, as shown in figures 44, 45, 46, and 47.

- **Rearrange the stone blocks within the polygon**

  In case the grid count results in a number of unoccupied grids greater than the number of grids needed to form at least one stone block, the blocks are rearranged in such a way as to produce a place to fit a greater number of blocks.

- **Compare the different alternatives**

  In case that exist different arrangements that can be used to obtain the same number of stone blocks, the options can be compared with respect to the cutting length required to perform each arrangement, and thus discriminate those options that require a greater cutting length and therefore entail a higher cost.

- **Select the final arrangement**

A flowchart of the procedure is presented in the following figure.

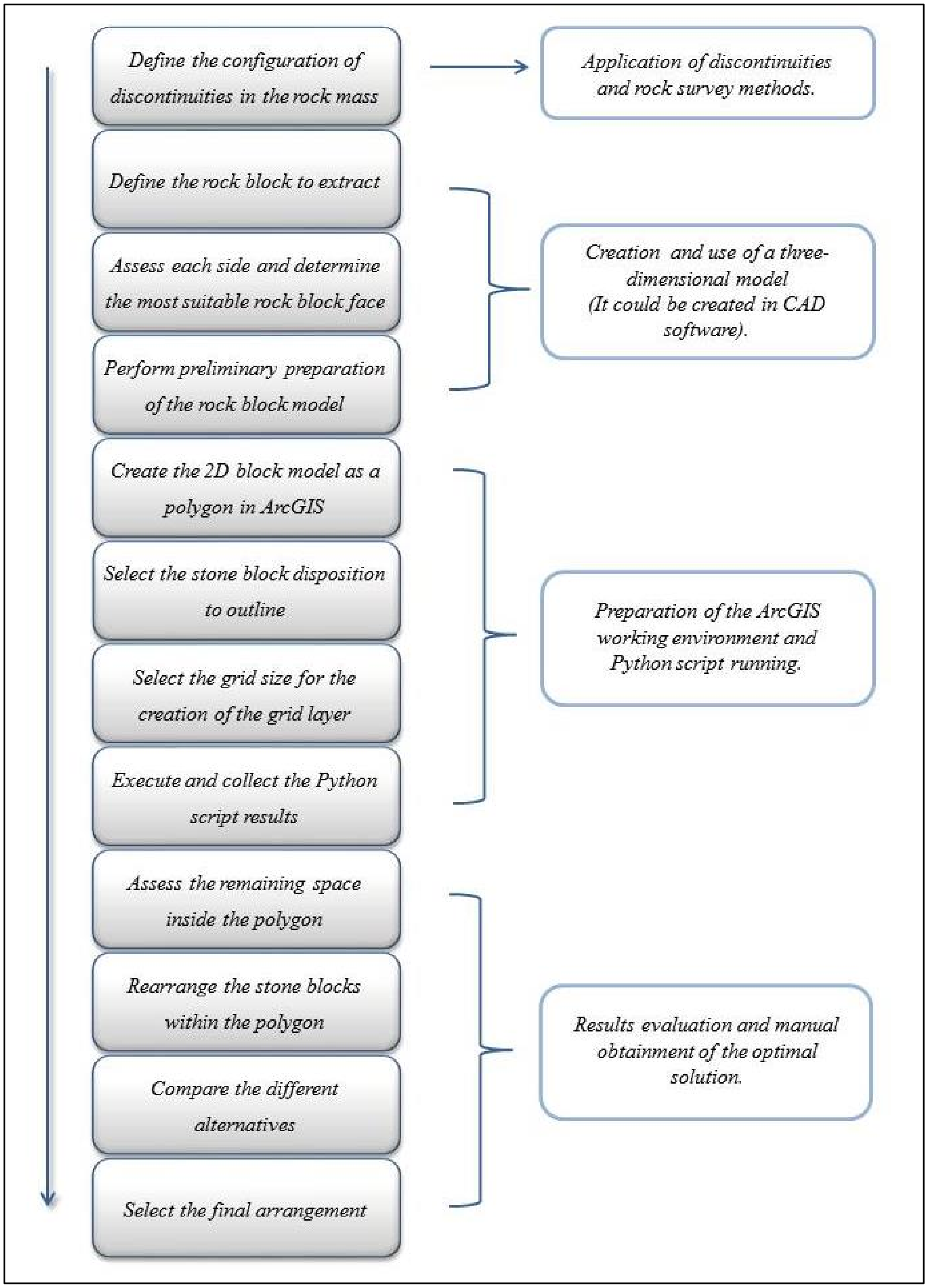

Fig. 48: Procedure flowchart for the optimal block arrangement obtainment.

4.1.5 Study case: Serizzo Gneiss

This case study involves the determination of an optimal block arrangement for the exploitation of Serizzo Gneiss through the extraction of large blocks, i.e. through the high-bench method.

Fig. 49: Serizzo Gneiss extraction in large blocks (Domo Graniti, 2020).

4.1.5.1 Geological description – Serizzo Gneiss

According to Del Greco, Fornaro & Oggeri (1992), *"this is an orthogneiss with a granodioritic composition, characterized by a very marked schistosity and by* *medium-large sized crystalline elements. Depending upon the level of metamorphism, in some places the gneiss still has a granitic facies, in other zones the facies is porphyritic and in some others is foliated".*

4.1.5.2 Block arrangement determination – Serizzo Gneiss

The distribution of the main discontinuities (K1, K2, and K3) present in the rock mass produces a sub orthogonal system, where the discontinuity K2 is taken as a guide to conduct the extraction of the large blocks parallel to this discontinuity in order to obtain a proper recovery, as shown in figure 49 and 50. The necessary data that describe the orientation of these discontinuities is shown in the table 3.

Fig. 50: Main discontinuities in Serizzo Gneiss (Oggeri, 2020).

Table 3: Discontinuities orientation data – Serizzo Gneiss

Joint	Dip	Dip Direction	Avg. Spacing
K1	55° – 60°	150°	2 – 6 m
K2	85°	65°	3 – 5 m
K3	70°	330°	2 – 8 m

A three dimensional model was created using the discontinuities data in order to simulate the rock blocks that may be found into Serizzo Gneiss rock mass, as shown in figure 51. Furthermore, adding and employing the maximum spacing value of each joint, a large rock block model (prismatic block) was obtained, which is produced with the main set of discontinuities; this is shown in figure 52. This rock block was utilized to determine the block face that allows the maximum material recovery by means of the GIS script application.

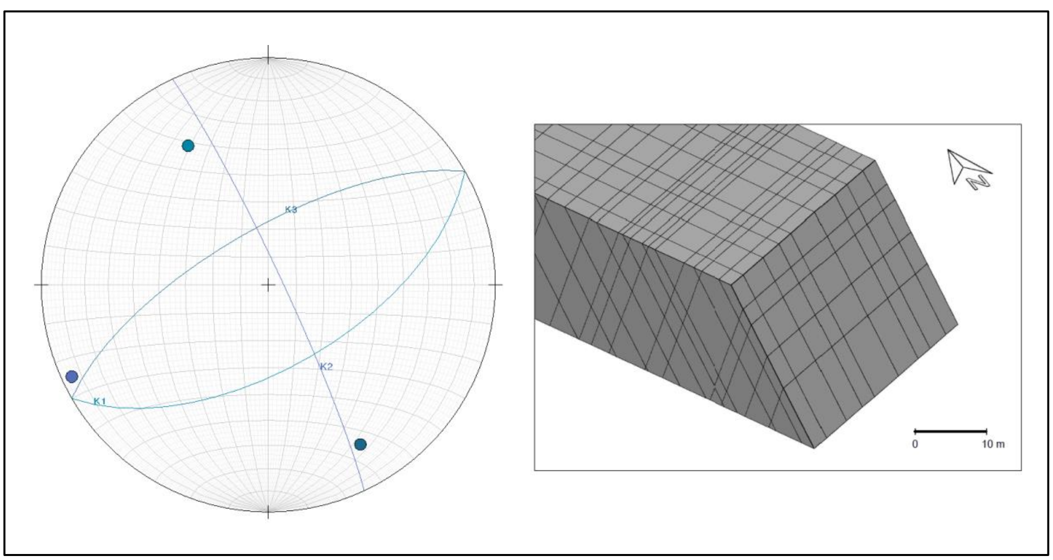

Fig. 51: Modelling of Serizzo Gneiss rock mass.

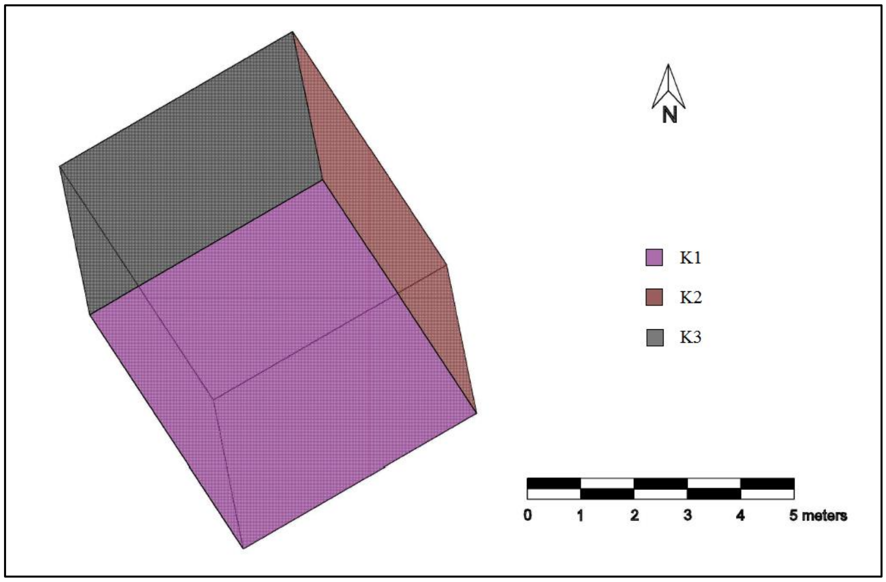

Fig. 52: Large rock block model from Serizzo Gneiss.

Once it was selected the block side to be used for the preliminary preparation, the block model with its respective coordinates were obtained, as shown in the figure 53. Furthermore, in this image may also be appreciated that the selected side is precisely the side that generates least waste material when the block is cut; this occurs on the face defined by the dip and dip direction of the discontinuity K2.

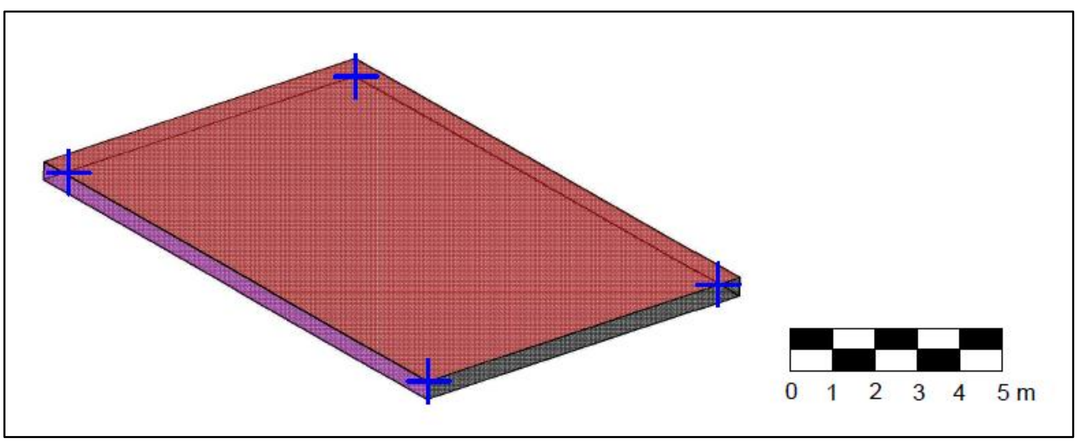

Fig. 53: Preliminary preparation of a large Serizzo Gneiss block.

Certainly for this case was adopted a huge prismatic block defined by discontinuities, however the shape of this rock block could vary depending on the way in which it is extracted. For example, in this quarry, the rock blocks are first separated by dynamic splitting and then the resulting block is divided into the final commercial stone blocks. For technical reasons, it is not always possible to obtain the rock block as defined by the discontinuities; nevertheless the procedure can still be applied.

Figure 54 shows the block arrangement obtained by the procedure and the application of the Python script. This arrangement shows the maximum amount of stone blocks that can be obtained from the previous rock block (figure 53), since even though this arrangement does not cover an amount of grids equivalent to the required amount for two more stone blocks, the geometry of the block does not allow the use of these spaces.

Moreover, it is true that there are other cutting patterns that manage to introduce the same number of blocks; however the usefulness of these other options is limited due to the factor of the required cutting length.

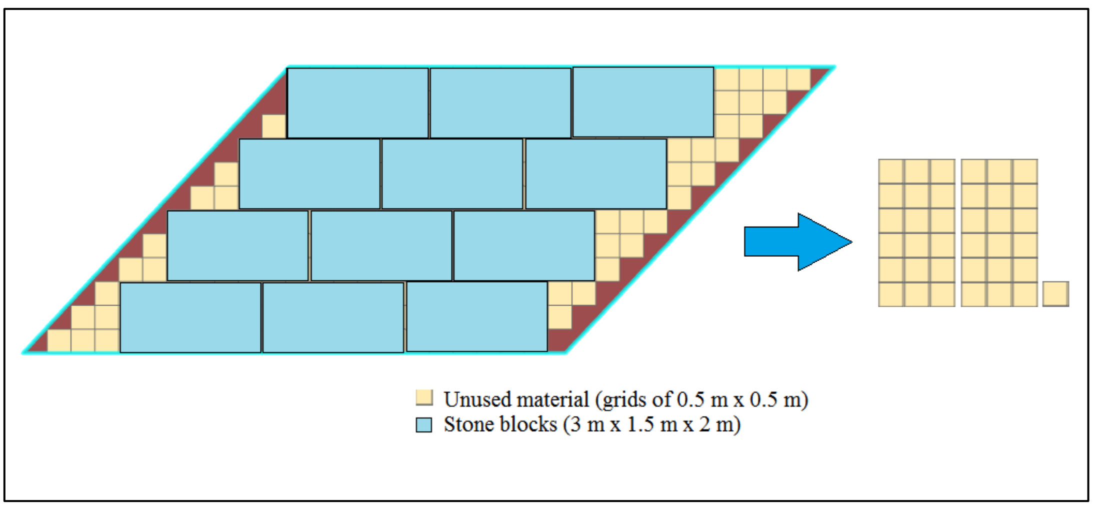

Fig. 54: Optimal arrangement for a large Serizzo Gneiss block.

4.1.6 Study case: Luserna Stone

In the case of dimension stone mining at the Luserna Stone quarry, the extraction of the material is performed through the low-bench method, since due to the discontinuities spacing it is not possible to obtain large blocks as in the case of Serizzo Gneiss described previously.

4.1.6.1 Geological description – Luserna Stone

According to Del Greco, Fornaro & Oggeri (1992), *“this stone is a gneiss with some little clear eyes of feldspar; it also contains quartz and green micas which give the stone its typical light grey-green color. It has marked laminated and cleaved structure so that it is easy to divide into tabular elements”*.

4.1.6.2 Block arrangement determination – Luserna Stone

Fig. 55: Luserna Stone extraction in rectangular blocks (Oggeri, 2020).

In figure 55 it is observed rock fragments placed around the site, these fragments are the waste material resulting after having performed the cutting and having obtained the marketable stone blocks. This waste material is caused by the disposition of the main discontinuities in the rock mass, which are defined by the following data:

Table 4: Discontinuities orientation data – Luserna Stone

Joint	Dip	Dip Direction	Avg. Spacing
K1	10° – 15°	270°	1.5 – 3 m
K2	30°	20°	5 m
K3	50° - 80°	290°	3 – 4 m

Figure 56 shows the distribution of the discontinuities in the deposit from a lateral perspective, and it is also appreciated how this distribution allows the direct extraction of rectangular blocks by means of the low-bench method in an efficient way. Then, considering the disposition of the discontinuities and employing the data presented on the table 4, it was obtained a three-dimensional model of the discontinuities, which is shown in figure 57 from two different perspectives.

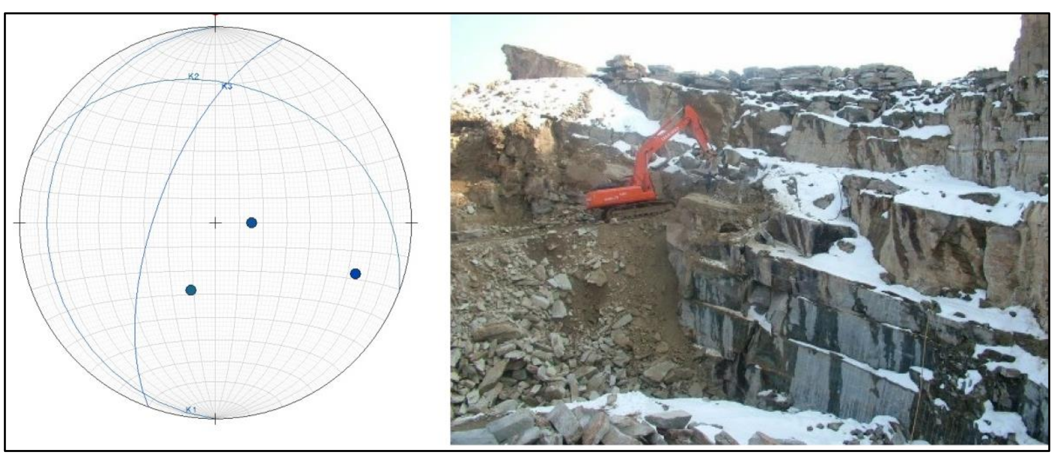

Fig. 56: Disposition of the discontinuities in Luserna Stone.

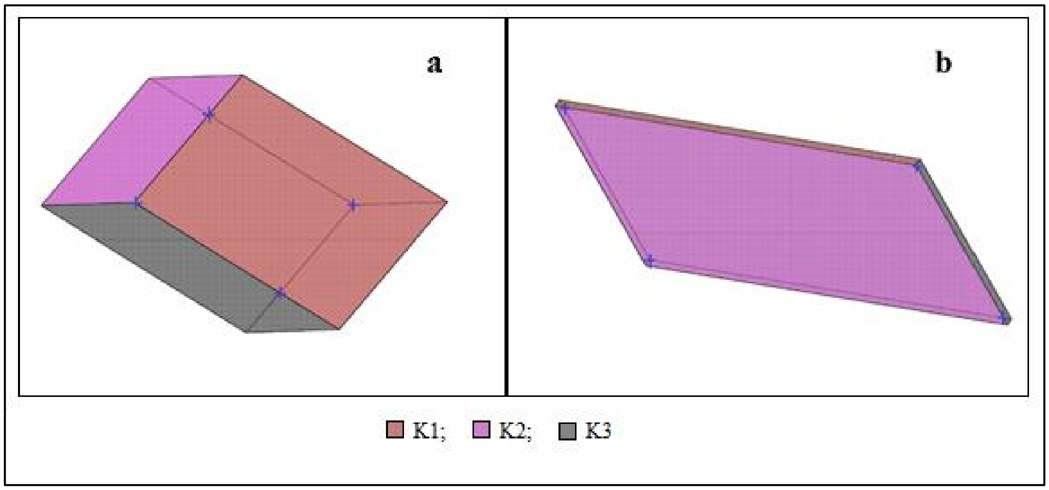

Fig. 57: Example of two different preliminary preparations for the same rock block model.

The discontinuity distribution for this case generates a sub-orthogonal rock block, however the orientation data does not allow to recognize at first sight which block's face must be selected to perform the procedure, therefore for the selection of the face and the preliminary preparation of the block it was required to make the comparison between the material recovery product of the choice of each side.

In figure 57 it can be seen how in option "a" there would be a material loss compared to option "b", which is the recommended option in terms of material recovery, i.e. this figure shows how incorrect selection of the block face for preliminary preparation can considerably increase the amount of waste material.

Then, the Python code tool was applied to determine the optimal block arrangement, which is shown in figure 58. The result obtained shows how the maximum amount of material is exploited leaving an area of unused material lower than that required for an additional block.

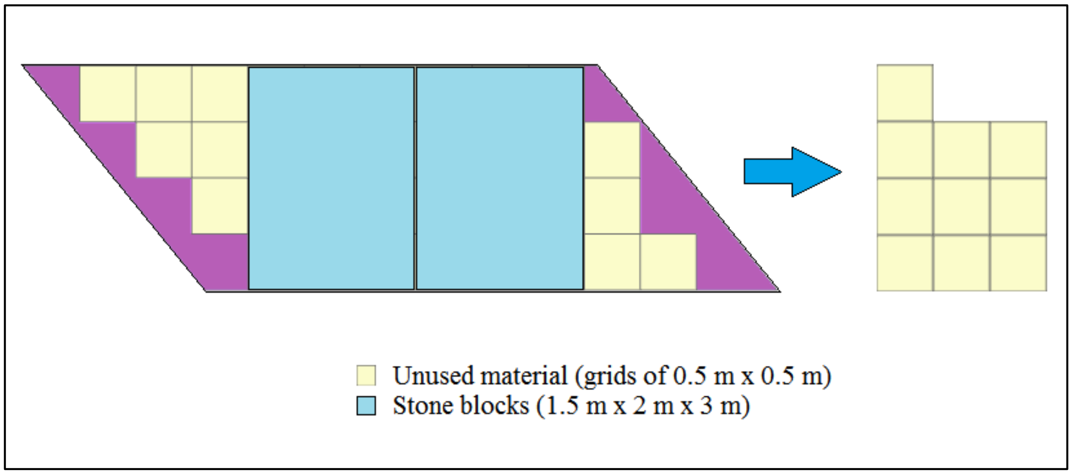

Fig. 58: Optimal arrangement for a Luserna Stone block.

Given the result obtained (figure 58), it can be seen that the procedure for obtaining the final arrangement through the application of the Python code tool and the GIS and CAD software employed, allows the comparison of the waste material produced by each cutting pattern depending on the block face that is selected. This is quite useful for those deposits where the discontinuities do not generate large rock blocks, since the material loss will be lower depending on the block face used for the implementation of this approach.

4.1.7 Study case: Joshaqan white marble

The deposit is located at the edge of the Joshaqan village, approximately 110 kilometers from the province of Isfahan (Iran). The rock blocks are extracted through the high-bench method, and are divided applying diamond wire as the cutting technique on the 3 existing exploitation fronts.

4.1.7.1 Geological description – Joshaqan white marble

According to Yarahmadi, Bagherpour, Sousa & Taherian (2015), this marble was formed by metamorphism of limestone during the Oligocene and Miocene periods, and subsequent tectonic activity in the area had minor influence on the rock body formed, producing just few joints and faults, such that large rock blocks can be found in the deposit. The marble is uniformly white in colour, with a compressive strength of 50 to 80 MPa and possesses a low fossil density.

4.1.7.2 Block arrangement determination – Joshaqan white marble

In order to determine an optimal block arrangement for this quarry, the data that define the discontinuities that outcrop at the first exploitation front were used; the disposition of these discontinuities is shown in the following figure.

Fig. 59: Discontinuities disposition on the exploitation front in Joshaqan white marble (Yarahmadi, Bagherpour, Sousa & Taherian, 2015, P10).

For this case, the three-dimensional model of the discontinuity disposition (figure 60) was recovered from bibliographic resources, and it was performed by use the data shown in table 5.

In this model it may be seen how the discontinuities form different rock blocks in the bench, for this case it was decided to select the block enclosed by discontinuities 1 and 2. In addition, a three-dimensional model was created for this rock block and the preliminary preparation was performed in order to work with the Python tool in the ArcGIS software, as shown in figure (61).

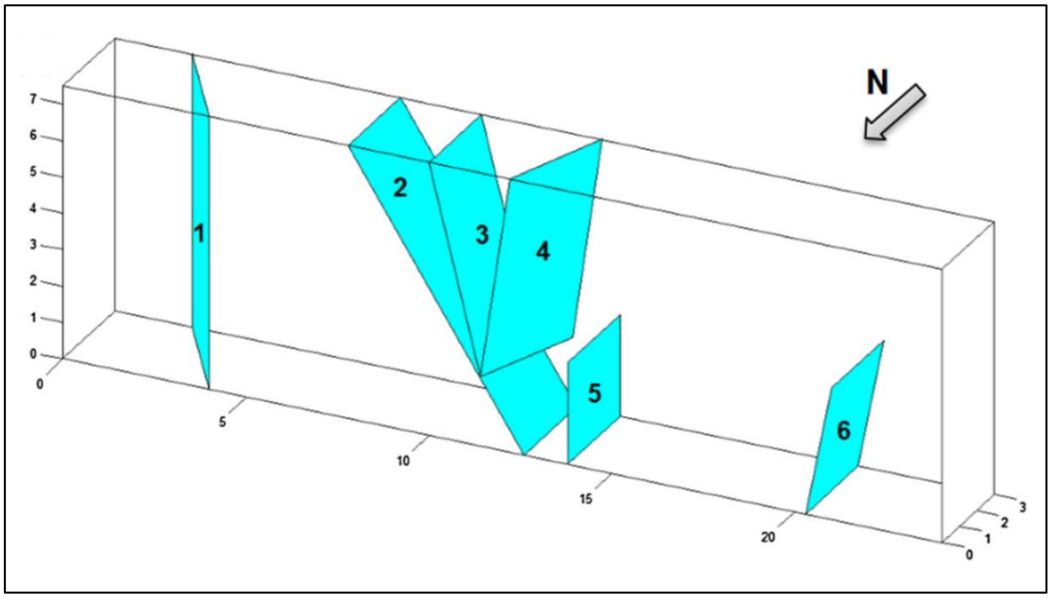

Fig. 60: Discontinuities model of an exploitation front in Joshaqan white marble (Yarahmadi, Bagherpour, Sousa & Taherian, 2015, P11).

Table 5: Discontinuities orientation data – Joshaqan white marble

Joint	Dip	Dip Direction	Length (m)
1	90°	302°	7.50
2	63°	270°	8.91
Bench planes	0°	0°	3.83 & 8.63

Then through the Python tool, the block arrangement shown in figure 62 was obtained, which achieves obtaining 12 stone blocks and produces a waste material equivalent to 32 grids (24 m³), i.e. this arrangement produces an amount of waste material of approximately the necessary volume to produce 2.5 additional stone blocks.

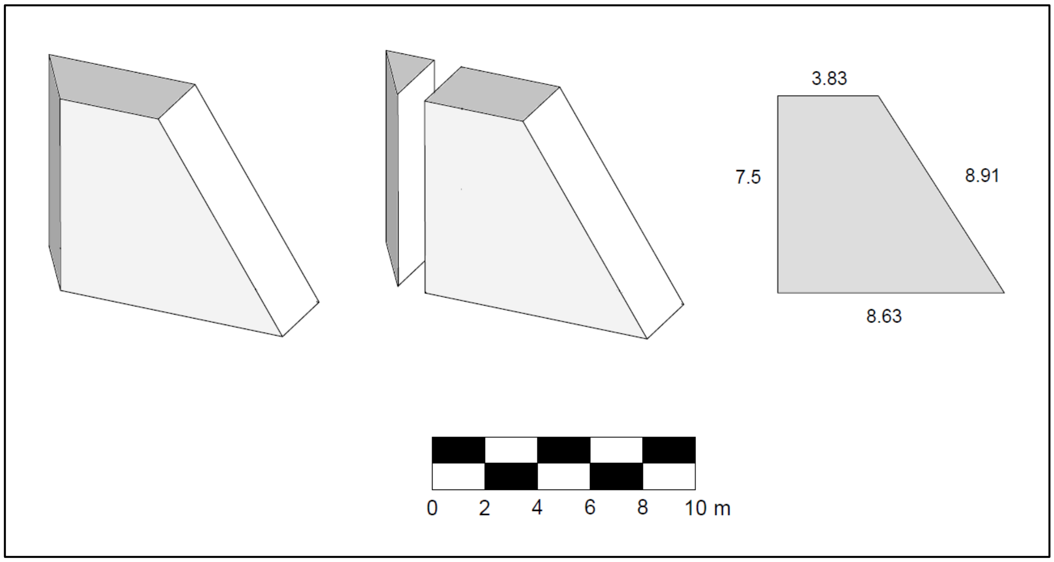

Fig. 61: Rock block model preparation – Joshaqan white marble.

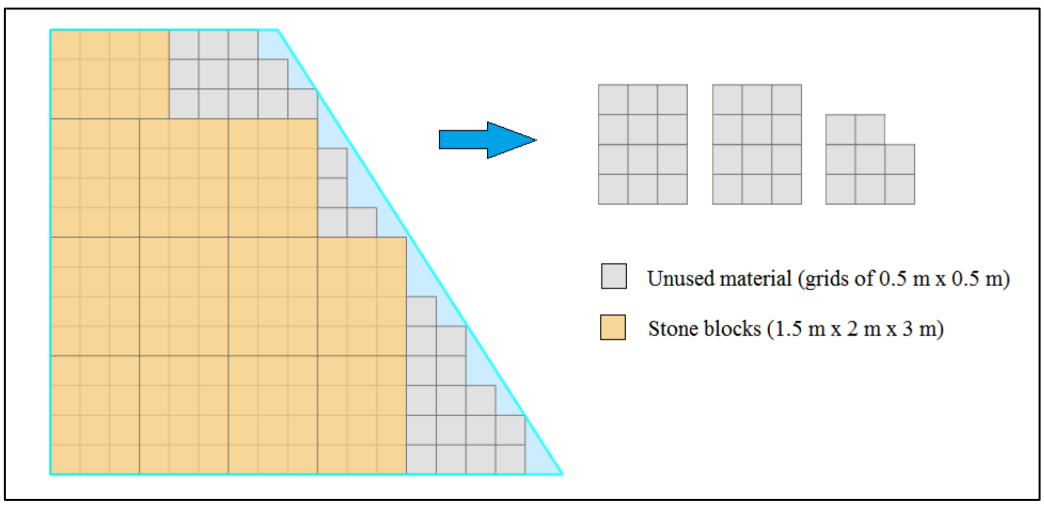

Fig. 62: Stone block arrangement obtained through the ArcGIS script tool – Joshaqan white marble.

Subsequently, and recognizing the possibility of achieving a more efficient arrangement, the stone blocks were rearranged through the use of the grids entity layer, giving as a result the final stone block arrangement shown in the following figure.

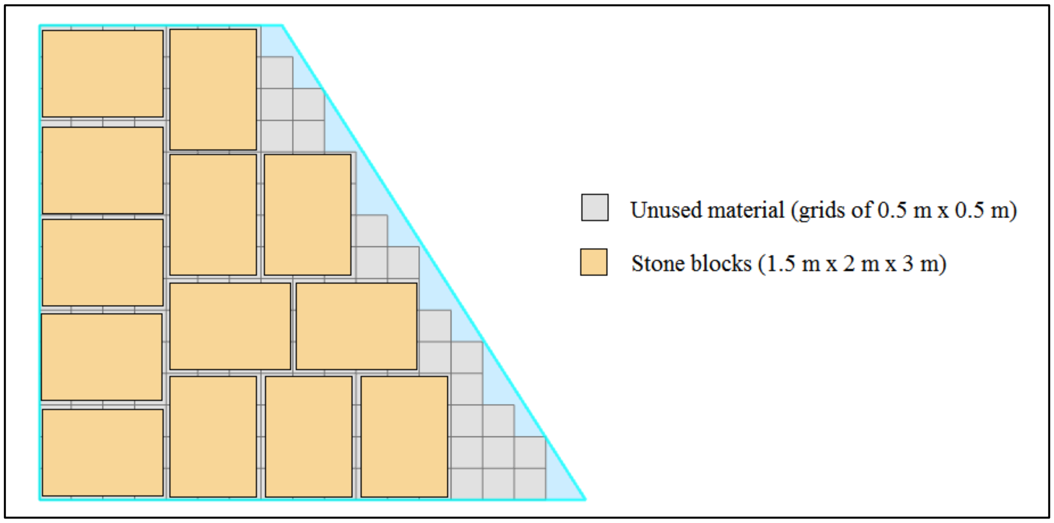

Fig. 63: Final stone block arrangement obtained – Joshaqan white marble.

Finally, it was obtained a stone block arrangement with which it is possible to produce an extra stone block (9 m³), improving the material recovery, and in the same way reducing the waste material produced in the final extraction stage. Furthermore, although the waste material produced in this arrangement is greater than that needed to produce an additional stone block, it was not possible to obtain a better arrangement.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

A lack of planning in mining results directly in low material recovery, which is currently a problem for landscaping and the environment. It is therefore important to describe the deposit and the whole context of the quarry in order to improve material recovery and thus reduce the environmental impact and satisfy the legal environmental requirements. For dimension stone mining the environmental impact is largely caused by the waste material generated when trying to obtain the stone blocks of commercial shape and size, therefore improved planning and procedures for obtaining these blocks presumes an important improvement in terms of material recovery.

In order to efficiently perform the exploitation of dimension stones it must be considered that essentially the material recovery is the result of a combination of inherent factors in the quarry context, which are the deposit type (sedimentary, metamorphic or igneous), the structural geology of the deposit to establish the main sets of discontinuities (joint network), the mineralogical composition of the rock and its inclusions, the mechanical properties of the rock, the location of the quarry and its topographic situation, the mining method used to extract the material, the technique applied to cut the stone blocks, and the geotechnical evaluation to maintain stability and security during the mining operations.

Contrary to other types of mining where there are indicators such as mineral concentration, the dimension stone mining does not possess an index capable of establishing perfectly the economic value of the material, so its demand in the market is linked to the external appearance of the material and its inclusions (if any). This appearance may change depending on the inclusions of the rock and how the final blocks are cut, projecting different forms and designs. Therefore deciding the stone blocks orientation in relation to the rock ornaments (if possible) is of vital importance to maintain profitability and avoid losses.

Due to the fact that the main purpose in dimension stone mining is to obtain a final product with a certain shape and size, attempting to achieve the best-possible performance in spite of the discontinuities in the material, the determination of a stone block arrangement within a large rock block can be considered as a packing problem. Therefore in this kind of scenario it is possible to apply approaches and methods used to the known packing problems in order to optimize the activities of planning and obtaining such blocks.

Regarding the material recovery through different types of stone block arrangements, it was observed that theoretically for oblique and large sized rock blocks, there will always be more efficient results in terms of material utilization when applying irregular arrangements designed specifically for each rock block. However, when these planning tasks are not performed by means of automated tools, these may become quite time-consuming.

The utilization of programming languages in combination with other software with application to mining such as CAD (computer-aided design and drafting) or GIS (Geographical Information System) software provides a great advantage in planning, since by means of the API (application programming interface) it is possible to automate laborious tasks that are normally performed manually or are neglected due to the same reason. Furthermore, the implementation of both knowledges in mining industry allows the possibility of applying new approaches to optimize daily tasks by creating scripts that make effective use of the tools currently available that provides the different software.

The raster method applied for solving the packing problems provides a simple and useful approach applicable to dimension stone mining for the improvement of material recovery and optimization of planning tasks; however it is a two-dimensional approach, so it requires previous preparation of the data to be properly employed. Nevertheless, it is possible to develop a command sequence to automate the preparation of the input data if it is available the appropriate information.

The packing problems and the approaches and methods applied to them are topics that are currently under development, but even though there is a strong description and explanation of approaches that are applicable to two-dimensional cases, clearly a three-dimensional approach (nesting) that could generate irregular arrangements within the rock blocks would probably be more effective. However, as the computing field continues to develop, a number of innovative and improved tools will be available to optimize diverse tasks in the mining industry.

The procedure adopted in this research to determine a block arrangement is an interesting tool to improve material recovery by means of cutting pattern planning, however it does not apply to any scenario. This procedure provides a great advantage when it is applied on large and oblique rock blocks, since in these cases the difference in material recovery between a regular and an irregular arrangement is quite relevant. Therefore this procedure is considered a useful tool that could be improved and tested in order to apply it to those scenarios that comply with these characteristics and thus obtain improvements in the material recovery.

On the other hand, this approach also serves to avoid the material loss for those cases where the studied rock block does not have such characteristics, performing the comparison of the material recovery that can be obtained through different cutting patterns.

CHAPTER VI

CLOSING REMARKS

The advantages provided by the tools available and the advances in technology, equipment and software applicable to the mining sector make it essential to implement them in order to perform any successful project. In a certain way, different software and computer tools have been used separately to complete all the different daily activities required in a mining exploitation.

However, as the computational field develops, the combined utilization of diverse software through the same application programming interface could be considered, which would facilitate the planning of mining projects. It is therefore essential to adopt and develop the applications of this knowledge in the mining industry.

Furthermore, better performance will be obtained as the computational tools are improved and as the fundamental theoretical knowledge to perform dimension stone exploitation is integrated into these tools.

ANNEXES

Python script for automated entity layer generation:

```
import arcpy
from arcpy import env
from math import radians,sin,cos
env.overwriteOutput = True
infc=arcpy.GetParameterAsText(0)
outFC=arcpy.GetParameterAsText(1)
d=arcpy.Describe(infc);SR=d.spatialReference
W=50; L=15; A=0.99*W*L
fnet="in_memory/fnet"
erased="in_memory/fnet"

# rotate polygon

def ShapeMake(pGon,angle):
    a=radians(angle)
    ARR=arcpy.Array()
    cX=cPoint.X;cY=cPoint.Y
    for part in pGon.boundary():
        ar=arcpy.Array()
        for p in part:
            x,y=p.X-cX,p.Y-cY
            xN=cos(a)*x+sin(a)*y
            yN=-sin(a)*x+cos(a)*y
            pN=arcpy.Point(xN+cX,yN+cY)
            ar.add(pN)
        ARR.add(ar)
    pgonRotated=arcpy.Polygon(ARR,SR)
    return pgonRotated

# create fishnet and count complete polygons

def fnetMake():
    FNET=[]
    ext=rotated.extent
    oc='%s %s' %(ext.XMin,ext.YMin)
    ya='%s %s' %(ext.XMin,ext.YMax)
    cc='%s %s' %(ext.XMax,ext.YMax)
    arcpy.CreateFishnet_management(fnet, oc,ya, W, L,"","",
```

```
                                   "","NO_LABELS",
                                   rotated,"POLYGON")
    rects=arcpy.Clip_analysis(fnet, rotated, g)
    for chop in rects:
        if chop.area<A:continue
        FNET.append(chop)
    return FNET

g=arcpy.Geometry()
PGON=arcpy.CopyFeatures_management(infc,g)[0]
theList=[PGON];bigList=[]

nBefore=0
while True:
    for toCut in theList:

        ## FIND rotation to maximise complete rectangles

        nMax=0
        cPoint=toCut.centroid

        for i in range(36):
            angle=5*i
            rotated=ShapeMake(toCut,angle)
            squares=fnetMake()
            N=len(squares)
            if N<=nMax:continue
            nMax=N
            keepers=squares[:]
            bestAngle=angle

        if nMax==0:continue
        arcpy.AddMessage("%s cell(s) found so far" %nMax)

        for item in keepers:
            rotated=ShapeMake(item,-bestAngle)
            bigList.append(rotated)

    if nBefore==len(bigList):break
    nBefore=len(bigList)
    arcpy.Erase_analysis(PGON, bigList, erased)
    theList=arcpy.MultipartToSinglepart_management(erased, g)
arcpy.CopyFeatures_management(bigList,outFC)
```

Taken from: <https://gis.stackexchange.com/questions/296725/fitting-known-size-polygons-into-irregular-polygons-using-arcgis-desktop>

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