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in

Mineral Production Systems

Economic and Environmental Optimization of Ornamental Stone Block Cutting with a 3D Algorithm

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Abstract

This thesis focuses on finding the optimum block cutting dimension by using a 3D algorithm for a limestone quarry located on Poggio Imperiale, Foggia, Italy, in terms of the environment and economy.

The environmental concerns of quarrying operations are mainly: energy consumption, material waste and pollution. The main economic concerns are the block recovery, the selling prices and the production costs. Fractures and joints adversely affect the block recovery or the slab production. In case of the availability of a fracture model, the block recovery from a quarry and the slab production from blocks can be optimized. In this research, the waste volume produced by cutting natural stones in order to obtain slabs from blocks was minimised in order to decrease the total waste amount and to increase the recovery ratio together with ensuring economic benefits.

The software SlabCutOpt is a tool developed at DICAM – University of Bologna for block cut optimization, that tries different cutting angles ‘Tetha’, ‘Phi’,’ Csi’ on the x-y-z planes in order to test several possible cutting angle alternatives. It allows to test several block sizes and gives in output the optimal result for each block size. For this research, by using the SlabCutOpt software, ten different block dimensions were analysed and the results indicated the maximum number of non-intersecting blocks for each dimension. Results were then interpreted and the total volume of natural stone that could be obtained by using such block dimensions to cut the bench was calculated. The results indicated that the block named number 1 with the dimensions ‘1m x 1m x1m’ had the highest recovery ratio with a value of 43% and the total Relative Money Value (RMV) with a value of 22829. Dimension number 1, was yet again found as the block dimension with the lowest waste volume, by having a volume of 3953.25 m^3, for the total bench, while the dust emitted through cutting had its lowest value for the diamond wire cutter at the block dimension number 3, with the dimension ‘2m x 2m x 2m’, and with a total dust volume of 24 m^3, for the cutting operation of the total bench volume of 6932.25 m^3. When compared with the Eco-Label standards, the block dimensions having surface area values lower than 15 m^2, were found to fit the natural resource waste criteria of the label, as the threshold required 25% of minimum recovery from quarries [1]. Due to the relativity of production costs, together by considering the Eco-Label threshold, the research suggested the selection of the block dimensions for blocks having surface area values between 6 m^2 and 14 m^2.

Keywords: mining, quarry, limestone, economy, environment, ornamental stone, optimization algorithm

1. INTRODUCTION

Mining is one of the primary economic activities that provides resources for industry today. Ornamental stone extraction in quarries is one of the key sectors of mining activities. Resources such as marble, granite, and limestone are exported to industry around the world from the main producers of such materials in countries such as: India, China, Iran, Turkey and Italy which constitute the leading extractors of natural stone. As the leading country of natural stone quarrying, China holds a $6.8 billion export value according to 2017 reports [1].

Natural stones like marble, granite and limestone are rich in quartz minerals, which are mainly composed of calcium (Ca), and for these stones the price of each slab or block is defined by varying aspects of the extracted material's properties. The durability, grain size, colour, pattern, polishing, dimensions, and aesthetic value are some of the key aspects which determine the price. Italy is one of the main exporters and importers of natural stones, with its high-quality ores lying along the country. It is one of the few countries left in Europe still quarrying together with Spain and Portugal. While China, India, and Turkey hold the top three places with a total of 21.5%, 19.7% and 10.8% of the world's quarry production respectively, Italy holds fifth place with a total of 8.5% of the world’s total natural stone production [2]. According to the 2017 reports of the Italian Marble Association, Italy holds revenues verging on €4.2 billion, with exports close to €3.2 billion which represents 6% of the annual national economy [3].

One of the main factors for any natural stone producer is the pricing of the produced blocks and slabs. The natural stone sector has an increasing price scale for block and slabs which have higher surface areas, thus producers prefer higher production rates with block and slab dimensions that have higher surface areas. However, one of the biggest concerns during the production of such blocks and slabs with big surface areas is the fractures or discontinuities within the stone. According to the geological features of the area that a natural stone ore lays on, the fracture content and layout can differ. It is possible to detect vertical and horizontal fractures in quarries using geophysical methods or by survey the outcrops rocks. These fractures can be related to the tectonic history of the area which result in different geological evolutions. Natural stones are nowadays extracted after high-level research, carried out using a range of different techniques.

This thesis was carried out in order to obtain the optimal block dimension when looking to meet both economic and environmental targets equally. The optimization was based on the fracture model of the limestone quarry located on Poggio Imperiale, Foggia, Italy, which belongs to the basin ‘Apricena’ which is the biggest mining area in the region of ‘Apulia’. The SlabCutOpt software developed by Bondua and Elkarmoty is a software which gives the best solution, in term of cutting design, for fracture model of a certain domain for a block or slab dimension [2]. The software will detect the number of slabs intersected with the fracture model with different angles on the x-y-z plane and displacement [12]. The software computes several cutting scenarios for the in term of ‘Tetha’ ‘Phi’, and ‘Csi’, representing the Eulero’s angles of each plane. As some of the blocks intersect with fractures, the software detects these blocks as unusable and selects the best solution through the angle options where the non-intersecting block number is the largest. It is possible to survey a variety of dimensions in order to compare the solutions with each other and select not only the best cutting angle but also the best block dimension for the bench.

The focus of this paper is to find the optimal block dimension in order to minimise the waste volume and increase the potential economic value of the bench. The recovery ratio is one of the indicators of waste, when the recovery ratio is high the wasted stone volume is low. Therefore, in order to minimise waste block dimension, higher recovery ratios were searched. On the other hand, the selling price of blocks differ according to the surface area, when a block has bigger surface area the price per block increases rapidly. According to the relative selling price of limestone blocks, the waste and total possible earnings by using each dimension was compared. For the 10 dimensions surveyed using the SlabCutOpt software, optimal solutions were found and the comparison of each parameter was done based on the block surface area and volume. The comparisons also include the recovery ratio, dust generation and possible production costs affecting the selection of the dimension. Additionally, the Eco-Label measures were considered in order to suggest the best fit for the bench in terms of environmental standards. Eco-Label is a brand, founded by the European Commission that is created to improve sustainable industries and has become applicable to the stone industry since 2009.

An optimal block dimension was then suggested for the bench by selecting the dimension where the earnings were the highest and the waste generation was the lowest. The bench with the fracture model and the results of the optimal solution from each block dimension was able to be visualised in the SlabCutOpt software.

1.1 Technical Efficiency

The block and slab are produced using different cutting techniques. These techniques can be divided into two main groups: ‘Drilling Techniques’ and ‘Saw/Wire Cutting Techniques’. According to the position of the ore and the physical and chemical properties of the surrounding rock, one method is often preferred to another. However, the usage of Saw and Diamond cutting techniques are highly popular as mostly the extraction of natural stones is done via quarrying (open-pit mining). Each machine used in the quarry consumes electricity and oil, usually in high quantities, and it is important to select the best fitting cutting method to ensure efficiency. The chain saw cutter and the diamond wire cutter are two valid alternatives and companies are nowadays choosing these methods. Through the research conducted in this thesis, the efficiency of both machines was compared and the diamond wire cutter was found to be the more efficient in terms of “time required to cut per m^2” of surface area. Furthermore, the diamond wire cutter was found to use less electricity and consume less oil when compared with the chain saw cutter.

That said, seeing as the diamond wire cutter is a more recent technological development, it is equally important to find workers who are adequately trained in the use of this kind of machinery. It is the industry's responsibility to provide the necessary training through obligatory measures in order to keep their workers updated and ensure the efficiency of their production in terms of time and energy. When lower cutting durations are reached through more efficient cutting techniques, not only can the total energy consumption per surface area be decreased but also the total production rate of a quarry can be increased as less time is spent on each surface area.

Most of the used energy for quarries come from ‘electricity from the grid’ which is a linear approach for energy generation, while circular approaches such as bio-energy is dismissed due to its low popularity in industrial areas. In order to generate bio-energy, a high amount of investment is required therefore it is yet not possible to use such an alternative in the industrial field as high efficiency is a key aspect for industries. By using more efficient production methods, the consumption of electricity and oil can fall and this does not only benefit the industries environmentally but also economically saving high amounts of revenues. On the other hand, the pollution due to chemical agents and greenhouse gas emissions are one of the important factors for environmental pollution. Increasing the efficiency of machinery means decreasing the CO_2 emissions. As CO_2 is one of the greenhouse gases, it is important to select methods that have a lower carbon footprint. As an example, for this research the chain saw cutting machine and the diamond wire cutter were compared in terms of CO_2 emissions. For each surface area to be cut, the diamond wire cutter produced 37% lower carbon emissions than the chain saw cutter.

1.2 Impact of Industrial Activity on the Environment

The impact of industrial activity on the environment is one of the main concerns of today's industries. It is not only important but also obligatory to protect the environment and wildlife. Quarrying operations have a high environmental impact due to their open-pit operations and due to the non-renewable aspects of the extracted material. The main concerns surrounding quarrying operations are energy consumption, environmental pollution and waste production.

As the cutting machines are using water in the cutting operations, another important aspect to consider is the water amount usage per surface. Water is the one of the most important natural sources that every industry is obliged to protect with regards to environment and the responsibility towards the society. Lower water consumption not only lowers the environmental impact but also lowers the cost during quarrying operations. Therefore, the selection of the cutting tools must be done carefully in order to ensure the efficiency and sustainability of industries together with the environmental commitments.

On the other hand, due to water usage and the dust emitted through the cutting operations, a slurry is generated with cutting. This slurry has the possibility to affect the environment in various domains. Due to weathering activities, the slurry can cause clogging in the natural drainage channels which can cause a change in the natural water table. According to the Eco-Label standard for quarries, each industry would need to ensure no interference with any deep-confined waterbed [4]. Therefore, it is the industry's responsibility to direct the drainage correctly in order to protect the natural waterbed. The generated slurry can not only affect the natural drainage but additionally, after the evaporation of water the dust with high percentage of $CaCO3$ can have a direct effect on the vegetation of the area. This not only endangers the vegetation growth but it can also cause a change in the nutritional value of the plants as $CaCO3$ increases the alkalinity of the soil. The wildlife which inhabits the area can also be affected after consuming the alkalinized plants. According to the calculations done in this paper, the total amount of dust generation through cutting the quarry bench with a total volume of 6932 m^3, was up to 893m^3 and 178 m^3, via chainsaw and diamond cutting, respectively. On the other hand, the total water consumption of the chain saw cutter and the diamond wire cutter were 4.71 and 2.02 m^3, respectively. The calculation leads to the created slurry dilutions of 58.33 % and 27.7% respectively [3] [4].

Noise is one of the essential subjects where environmental pollution is concerned. Noise in higher frequencies stated by the environmental law can pose a threat to the natural environment. Animal species and the plants can be affected by noise in high decibels. Animal species are often affected by high and consistent noise in the area and migrate to other areas and so the noise pollution can imbalance the natural habitat. Additionally, the society living near such industrial areas can experience side effects of stress after being exposed to noise in high frequencies. It is the responsibility of the industry to select operation time and intensity by respecting the natural habitat and society sharing the same environment. The noise limits for industrial applications have been stated as; for the first action level85 dB (A) and for the second action level as 90 dB (A) [5]. Additionally, each industry is obliged to respect the mandatory environmental law.

1.3 Waste Management

Furthermore, one of the most important concerns of quarrying operations is 'waste'. Natural stones are a non-renewable resource, therefore waste production in quarrying operations should be minimalised in order to maintain the circularity. According to the European Union Directive 2008/98/EC the following order is suggested to be taken in order to improve the protection of the environment: 1) Prevention of Waste; 2) Preparation for Waste RE-Utilisation; 3) Recycling; 4) Recovery Options; 5) Disposal [5]. As natural stone wastes take up to 25% of the waste generation by economical activities in Europe, it is crucial to take the necessary measures [6].

Quarrying operations produce dust and fractured natural stones as the two main waste types. Although stated as being non-renewable, there are options to use marble waste both in dust and coarser forms. Due to the chemical composition, natural stones such as marble and limestone contain high amounts of $CaCO_3$, and it is possible to reuse the fine particles in construction, soil treatment, paper and tire industry. Research proves that the usage of marble dust not only lowers the cost of cement mixes, but it also enhances the compressive and flexural strength of concrete when mixed in proper quantities [7]. It is, therefore possible to classify marble dust as a suitable additive for cement mixes [8]. On the other hand, the alkaline features of natural stone dust can be used against acidity, this can even be used in order to take immediate measures to stop acid-mine drainage. Additionally, adding marble dust has been proven to increase soil strength and therefore improve soil characteristics. For areas that are prone to landslides due to poor soil characteristics, the situation can be improved by using marble dust as an additive [9]. Moreover, marble dust can be used as 'bio-marble' which applies biological filtering to soil and has beneficial characteristics due to advanced characteristics in terms of: low weight, large surface area, durability, minimal clogging, high BOD5 reduction, low capital, corrosion resistance [10]. Additionally, marble slurry can be used in the paper, tyre and rubber industries as the slurry has low impurities but shows beneficial effects on the characteristics of such products when used in the mixes [11].

Coarse marble particles refused due to fractures and mis-applications during production, do not have any economic value in the stone-market, therefore they are defined as waste. In order or to use such materials, physical and aesthetic aspects can be taken advantage of. Using these materials in gardening or in interior design can create a market for this kind of natural stone waste.

One of the biggest problems of the natural stone industry is the fractures laying inside the quarries. This problem affects industries economically and is one of the main reasons of waste generation. Before high level technology was introduced to the natural stone sector, it was not possible to detect fractures laying inside ores. The assumptions were made according to the tectonic history of such areas and the geological indicators which could signal the potential fracture composition and layout of its direction. In order to find better solutions that enhance efficiency, as an initial step, the fractures are required to be detected and with today’s technology, these fractures can be analysed. Through photogrammetric methods, fracture geometry can be detected and with visual systems that use the Computer Aid Design (CAD) and Computer Numeric Control (CNC) technology the visual layout of the fractures in quarries can be found. Additionally, through Terrestrial Laser Scanning it is possible to gather a 3D model of the quarry in question and create a 3D model detailing the fractures. Furthermore, by using MATLAB, further fracture modelling algorithms can be applied. Consequently, optimizing algorithms can be used to use the data from fracture modelling and find optimal alternatives for production methods. Currently, numerical algorithms through MATLAB and 3D applications can find optimal solutions for prospective quarries. While for this research, the optimization algorithm ‘SlabCutOpt’ software was aimed to be used.

1.4 The Eco-Label

Founded by the EU, the Eco-Label is a brand given to industries that volunteer to improve their sustainability and efficiency level. In 2009, the European Commission decided to define a guideline for natural stone industries, to obtain the label. The brand takes the aim of its criteria by reducing: impacts on habitats and resources, energy consumption, toxic discharges, dangerous substances and ensuring safety and risk absence in industries. According to the criteria, the quarries were decided to be scored through a weighted average on the following topics: waste recycling, quarry impact ratio, natural resource waste, air quality, water quality and noise [4]. By acquiring a minimum of 19 points from the indicated score matrix, companies are able to obtain the brand and earn the ‘Eco-Label’ title.

2. ORNAMENTAL STONES AND PRODUCTION IN ITALY

Ornamental stone extraction is one of the most traditional economic sectors in Italy and the country is known to be a rich in marble and sandstone quarries [6]. In 2014, the total mining and quarrying activities in Italy amounted almost 185.8 million tons, with an overall decrease of 4.8% compared to the past year [7]. In Italy, the main mining and quarrying minerals extracted are: *Clay*, *Limestone, Travertine, Gypsum and Sandstone*, *Sand and gravel*, *Granite, Marble*, *Porphyry*, *Basalt* and other volcanic rocks. In terms of quarrying operations, the most representative aggregate was found as "limestone, travertine, sandstone and gypsum" while for mining minerals "cement marl" was the mineral with the highest representation [7]. It is possible to acknowledge the decrease in mineral extraction both in mining and quarrying activities in Italy over the past years. Nevertheless, the industry in Italy continues to have a competitive role in the natural stone industry world-wide. In Figure 1 is shown the chart containing the top ten quarry stone output by countries, according to the IMM Hatch report., for the year 2009. It can be seen that China, India and Turkey lead the Top-3 while Italy is on the 5th spot.

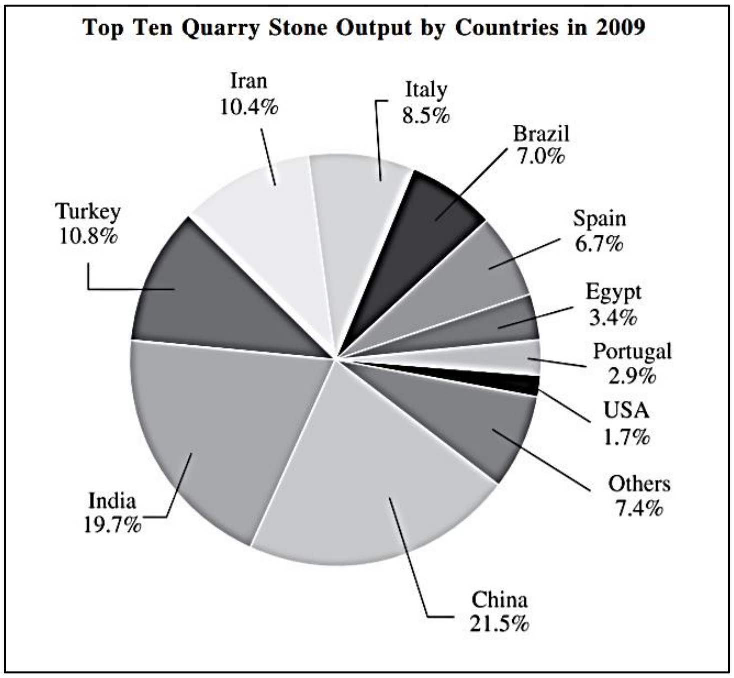

Figure 1 Top Ten Quarry Stone Output by Countries, 2009 [8]

2.1 Marble

Marble is a carbon-based stone which is recrystallized to carbonate minerals, where the metamorphism is influenced by heat and pressure [9]. Italy is one of the main producers of the world marble industry, where the Carrara marble leads the industry with is word-wide fame in terms of quality and aesthetics characteristics. Carrara is the name of an area located on North-West Florence and many quarries lay on the area, producing the marble type ‘Carrara’. Marble is famous for its usage in interior and exterior design while it is an asset for the Italian mining and quarrying industry with its word-wide demand. In Figure 2, Carrara Marble’s marble quarries has been shown.

Figure 2 Carrara Marble Quarry [10]

Marble can be found in a variety of colour series, including white, yellow, red, black and green [8]. Marble resources are mainly located in Italy, China, Turkey, Philippines, France, Brazil, USA, India, Morocco, Austria, Russia, Japan, Portugal and Greece where Italy has high quality marble resources [8].

2.2Limestone

Limestone is an important mineral not only for its aesthetic properties but also for its chemical properties, as a sedimentary rock that covers 10% of the sedimentary rock scene word-wide [11]. Italy is one of the main limestone producers internationally, with quarries located in: Trani, Vicenza, Verona, Provi, Sicily, Solento, Puglia which are spread over the country. Many researches are been conducted in order to improve the usage of limestone over different possible industries due to its low cost and high efficiency for what the chemical properties of the product promises. Below at Figure 3, an image from a limestone quarry in Trani, Italy can be found.

Figure 3 Limestone Quarry in Trani [12]

2.3 Granite

Granite is an igneous rock, that consists quartz which can vary in percentage from 20-60% and is also rich in feldspar [13]. It is possible to fins granite rocks in different colours according to their mineralogical composition, granite types containing high quartz values tend to have lighter colours. Due to the coarse composition, the minerals that compose granite can even be recognised easily [14]. In Italy is possible to fins granite quarries in locations such as: Sardinia, Crodo, Olbia, Torino, Montofano. Granite is one of the most common rocks of the earth's crust and is in fact still one of the major quarrying stones internationally. Granite can be used for interior and exterior decoration, especially for interior designs for kitchen wares. , A picture of granite blocks in a quarry in Bergama, Turkey is shown in Figure 4.

Figure 4 Granite Blocks Bergama, Turkey

According to 2015 statistics, India, Brazil and Norway are the top exporters of Granite where Italy is takes the 6th place with and annual export of 45,313,000$ for the year 2015 [15].

2.4Fiorenzuola (Serena) Stone

The Fiorenzuola stone is a grey-coloured sandstone extracted in Italy and used especially in historic buildings in Tuscany, but nowadays it is possible to find applications in construction and restoration works [16]. It can be understood that the name 'Fiorenzuola' comes from the area it is produced. The main producers of the sandstone locally named as "Pietra Serena or Fiorenzuola" are companies such as: Berti Sisto & C. Industrial Pietra Serena SRL, Calamini Urbano. The current production of the stone is done in the "Fiorenzuola" area with a yearly production rate of 50,000 m^3 [16]. In Figure 5, a picture of the Pietra di Fiorenzuola being processed for decoration can be found. Throughout history, the stone 'Fiorenzuola (Serena)' was used both in architecture and sculpture and still continues to be one of the traditionally extracted and used stone types in Italy.

Figure 5 Pietra (Stone) di Fiorenzuola [17]

3. CONTINIOUS CUTTING METHODS IN QUARRY

For stone cutting in quarry, it is possible to use different types of machinery. Depending on the mechanical and chemical futures of the prospective stone, the proper type of machine can be selected. In terms of stone cutting in quarry, many different methods have been developed depending on the different physical and chemical characteristics of quarries and the developing technology by time. In Table 1, a resume of the methods of cutting together with the used technology is presented.

Table 1 Marble Cutting Techniques in Quarry [18]

Techniques	***Method***	***Technology***
With Drilling Techniques	Drilling & Wedge	Pulsed Drillers + Wedges
	Direct Drilling	Pulsed/rotatory drillers and blasting agents
	Drilling & Blasting	Pulsed/rotatory drillers
With Saw/Wire Cutting Techniques	Wire Cutting	Diamond wire cutters, steel rope cutters & drilling machines
	Disc Saw	Disc Saw Cutters
	Chain-Saw Cutting	Chain-Saw Cutting Machine
	Fire-jet cutting	Fire-jet equipment and tools
	Water-jet Cutting	Water-jet equipment and tools

From Table 1,is clear that several methods can be applied to extract/cut marble blocks in different quarry. Conventionally, the drilling and blasting techniques are applied in quarried by using drill-bits and proper injection of blasting agents. However, due to thick drilling widths the recovery of blocks with this method can be low. In addition, the blasting operation poses threat on blocks as it can create fractures due to stress and strain equilibrium and brittleness of the marble stone. Additionally, the environmental effects of drilling and blasting, especially for open-pit stone extraction can be higher, relatively to the other techniques [18].

Water-jet and Fire-jet technologies can also be applied in order to cut marble blocks. The system works with the generation of high pressure and the acceleration of the water due to this high pressure. When the water reaches the desired high-speed, it is forced on the material and the high speed/pressure causes abrasive properties and the erosion of the material [19].

Nowadays, efficiency comes out as the key word when it comes to material extraction. In terms of cutting techniques, due to their high efficiency and suitability on field, two types of machinery can be the focus, which are ‘Chain Saw Cutting’ and ‘Diamond Wire Cutting’ machines. In quarry, these two machines can be used separately or combined in application in order to increase the ease of the operation [20]. For this research project, due to their technological ease and wide-spread use in various marble quarries, the two cutting techniques, ‘Chain Saw Cutting’ and ‘Diamond Wire Cutting’, will be the analysed in detail.

3.1 Chain Saw Cutting

Chain saw cutting machines are widely used for stone cutting in quarry. The machine has a vertical and horizontal cutting direction. The machine appears as a big-scale saw with a mobile arm that carries the chain and can be used either dry or with water [21]. The simplified figure of the chain saw cutting machine in quarry can be seen in Figure 6. A typical bench height of 5 m was chosen as typical height used in quarry. The approximate length of the industrial chain saw’s arm is approximately 5-6 m. The bench height and the bench angle are often designed according to the mechanical properties of the stone to extract.

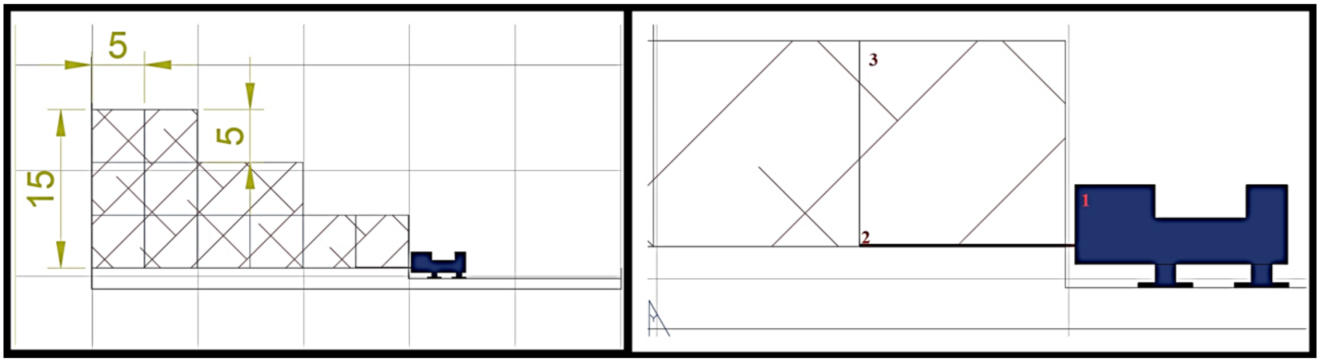

*Figure 6 Simplified Chain-Saw Cutting Machine in Quarry *1: Machine Body, *2: Chain Saw, 3*: Marble Quarry*

In order to have a better understanding on the Chain Saw Cutting machine's, the catalogue of one of the producers used in the industry is shown in Figure 7, the chain saw machine ***QS6000D of Dazzini Machines***.. The machine works with two motors, where the first motor belongs to the cutting action and is 75HP and the second motor is for the blade's rotation, machine feed and level positioning and has variable motor power [3]

Figure 7 Dazzini QS600D Chain-Saw Marble Cutting Machine [3]

3.2 Dimond Wire Cutting

Dimond Wire Cutting, is one of the widely used cutting method in quarry due to its efficient cutting technology. The machine cuts the stone in quarry, with simply diamond beats that are attached to the wire. The system use water to remove the cutting fragments and the heat produced during the cut. , It is important to avoid stone-burn which might be a result of friction caused by the cutting action.

The machine works with the rotation of the wire with diamond-beats through the pulley wheel. The cutting proceeds as the machine moves towards the prospective block, by the installed rails though the route of the machine. The movement of the machine allows to maintain the wire's tension. [20]. To start the cutting operations with the diamond-wire, three holes should be drilled to the prospective block in quarry, the layout of cutting operation in quarry with the holes can be seen on Figure 8.

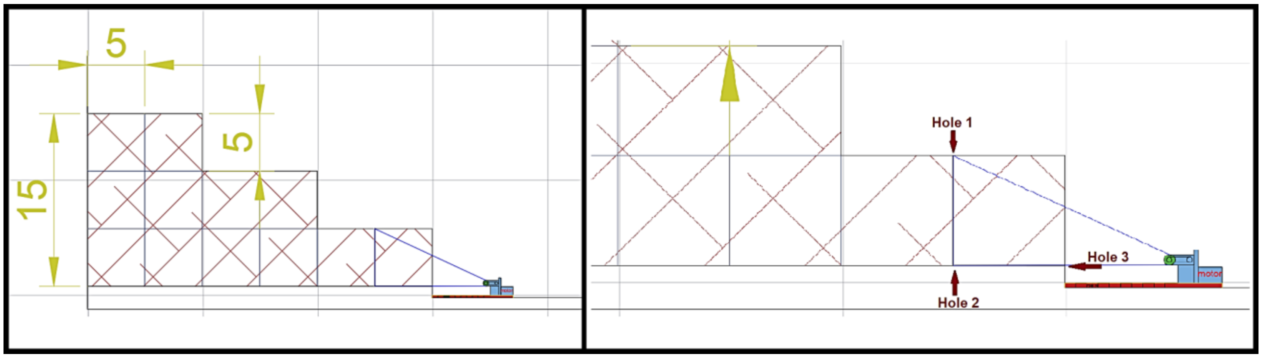

Figure 8 Diamond Wire Cutting Machine Layout

The length of the rail is usually 6m and the cutting procedure of the prospective block in quarry proceeds as followed:

1. Drilling the holes to install the diamond wire
2. Cutting the main mass with the diamond wire
3. Tilting the main mass that was cut
4. Dimensioning the main block
5. Transporting the obtained block
   [22]

The diamond wire cutting machine has two motors, one for the rotational movement of the wire and one for the movement through the rails. The motor regarding the rotational movement through the pulley wheels, is the major action which uses the majority of the power that the machine uses in total. On the other hand, an average 500-600 L/hr of water is spent for hydraulic purposes of the cutting machine and the spent energy is 56-76 kW/HP [4]. Below at Figure 9, a picture of Dazzini Machine's Diamond Wire Cutting Machine S800A can be seen.

Figure 9 Dazzini Diamond Wire Marble Cutting Machine

3.3 Blocks Commercial Dimensions

Blocks commercial dimensions are one of the main aspects that determines the selling price of an ornamental stone block. Fractures in blocks lower the value of blocks and therefore are not able to be sold commercially by industries. Many different block dimensions can be used in industries varying in surface area and volume.

Blocks with higher surface areas can be sold with higher value, therefore one of the aims of stone industries is to produce blocks and slabs that have high surface areas. According to the fracture layout in a bench, different commercial dimensions can be preferred. It is important to decide on these dimensions considering the selling price, total number of producible blocks/slabs with the selected dimensions and the demand of the clients for the selected block/slab’s dimension.

According to the application that the blocks or slabs will serve, it is possible to define different dimensions for such products. As natural stones are non-renewable materials it takes high importance to define dimension for production that would ensure the profitability of the production, according to the corresponding selling price [23]. Additionally, according to the machinery and application available in quarries the choice of commercial dimensions may change, it is important to define the most efficient size which can ensure the highest profitability.

3.4 Environmental Aspects

Environmental problems are one of the biggest concerns of today’s world and in order to increase sustainability, crucial importance has started to be given to minimize the environmental impacts of industries. Quarrying and processing of natural stones raise important issues that relate not only to process efficiency but also to some environmental concerns, which are mainly: energy consumption, material waste management and environmental pollution [24]. Each waste type has its own effect on the environment. From radioactive to inert waste it is possible to manage and consider sustainability to a higher degree. According to the European Directive 20008/98/EC, better protection of the environment is achievable through approach industry practices in the following order when dealing with by-products: 1)Prevention of Waste; 2) Preparation for Waste RE-Utilisation; 3) Recycling; 4) Recovery Options; 5) Disposal [25].

3.4.1 Environmental Concerns

3.4.1.1 Waste Production

As every active-industry of today, environmental issues related to waste production is one of the biggest concerns of natural stone quarrying too. For the natural stone industry, it is estimated that 175 million tonnes of quarrying waste are produced each year [26]. In addition, mining and quarry activities cover 25% of the total waste generated by economic activities in Europe., According to the Eurostat, the European Commission's Statistics Directory [27], the contribution of mining and quarry activities to total waste production from to industrial activities is shown in Figure 10.

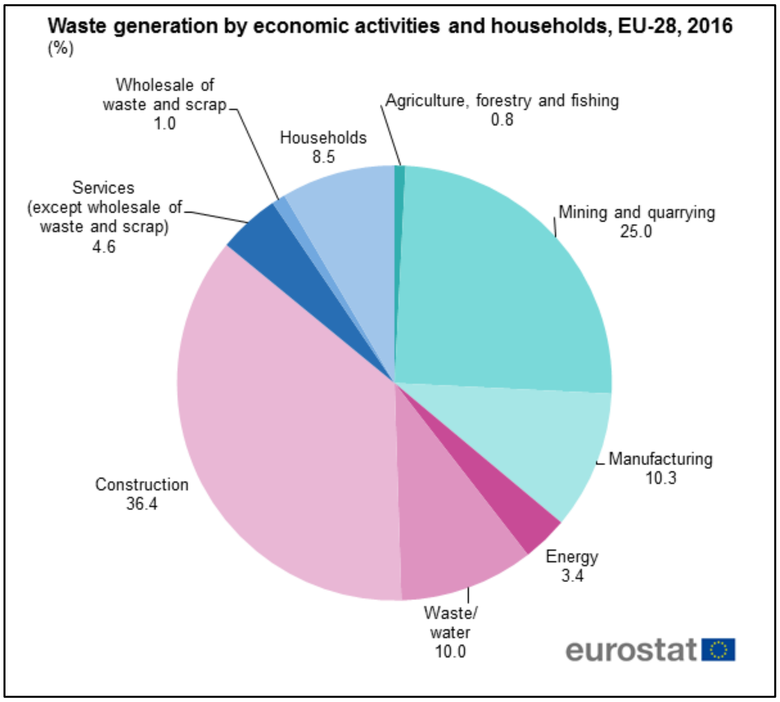

Figure 10 Waste Generation by Economic Activities and Households-EU 2016 [27]

The identification of the amount, type, source and location of the waste raises the question of 'how can we deal with this problem?'. For cutting operations in quarries, two main sources of waste were discerned. These include: the **stone-dust** produced as the cutting operation is done with machinery like diamond wire & chain-saw cutters and the **damaged and/or irregularly shaped stone pieces** due to fractures and/or poor cutting practices [28]. Particularly, the amount of quarry waste can vary from 50 to 95 % of the total volume of extracted marble blocks, which is a very high percentage [21]. Therefore, it is important to understand the properties of a marble quarry and focus on methods to develop efficient extraction procedures.

3.4.1.2 Water Consumption & Slurry production

Water consumption is one of the critical aspects for quarrying activities in terms of natural resources as the entering clean water is contaminated by the dust during the cutting activities and a slurry is generated. According to the used cutting technique, the amount of dust emitted differs, most of the cutting applications in marble quarries use water in order to prevent the dust emissions the surrounding areas and affect the health of the workers. As much as this method protects workers from exposure to fine particles in air, the used water is often not renewable due to the thick slurry generated which have properties similar to clay paste. This slurry can pose thread to the environment, specifically the natural drainage and the flora-fauna habitat in the area.

A quick calculation regarding the amount of dust produced and water used via ‘diamond-wire’ cutters for a 5m x 5m x 5m marble block by cutting 0.25m x 5m x 5m slices can be found below at Table 2, according to the max-cutting speed implemented for the ‘KAPTANLAR ETK-80’ Diamond Wire-Cutting Machine [20].

Table 2 Diamond Wire Cutting- Slurry Generation

Diamond Wire Cutting		
Block Volume	6.25	m3
Typical Cutting Speed	15	m2/s
Surface to Cut	55	m2
Wire Thickness	0.01	M
Total Dust from 1 slice	0.55	m3
Water Consumption	0.55	m3/h
Cutting Duration	3.66	H
Total Water Consumption for 1 slice	2.02	m3
Slurry Dilution	27.27	% (by volume)
Total Duration for Entire Block	69.66	H
Total Water Consumption for Entire Block	38.31	m3

On the other hand, the same calculation can be done for the chain saw cutting machine. The calculations which were made according to the features of the catalogue of Dazzini Chain Saw cutting machine can be seen below from Figure 11.

Table 3 Chain-Saw Cutting Machine

Chain Saw Cutting		
Block Volume	6.25	m3
Typical Cutting Speed	9.8	m/h
Length to Cut	84	M
Saw Thickness	0.05	M
Total Dust from 1 slice	2.75	m3
Water Consumption	0.55	m3/h
Cutting Duration	8.57	H
Total Water Consumption for 1 slice	4.71	m3
Slurry Dilution	58.33	% (by volume)
Total Duration for Entire Block	162.86	H
Total Water Consumption of Block	89.57	m3

Two machine types can be compared according to the calculations above. It can be seen that the chainsaw cutting machine has much higher cutting durations, which points also to ‘higher energy consumption’. The dilution of the slurry produced was found as 28 % and 58% for diamond-wire and chain-saw cutting machine, respectively.

The produced slurry has impacts on the environment in various domains. Usually the slurry contains $CaCO_3$. The $CaCO_3$ has the potential to move underground due to weather activities like rain, and this might cause the clogging of soil which might lead to problems on the natural drainage kinematics and eventually cause an increase in the soil alkalinity [29]. This directly affects the plantation in the area as it decreases the fertility and could even lead to a decrease in the nutritional value of the surrounding vegetation. The downstream process affects both the agricultural sites and the drinking water sources as the generated slurry drains through the natural drainage channels by gravity and weathering [30]. As a chain-effect, the animal species in the affected plant’s habitat can be harmed due to the lack of natural nutrition needs. Additionally, after the evaporation of the water in the slurry, the remaining $CaCO_3$ poses environmental threats as a visual pollutant.

Therefore, it is important to establish a formal process for the management of potential environmental hazards. Even though with the use of new technologies like saw chain and diamond-wire cutters it is possible to minimise the waste percentage, due to fractures in marble blocks it is yet not possible to generate a high recovery rate.

3.4.2 Energy Consumption

Energy that is used by machinery in quarries is either sourced by electricity or fuel oil. According to a study done in 2006, for the 'Garrone 340 Chainsaw Cutter (electric)', the total time spent cutting 12832.6 m^2 of stone surface in the quarry, was 1506.7 hours [31]. The total energy spent was calculated to be 75335 kWh, for the total surface area-according to the machine specifications taken from the Garrone Catalogue [32]. The average energy spent per m^2 was calculated as 5.87 kWh/m^2. The average CO_2 emissions per kWh of electricity from the grid was worked out to be 0.441 kg in order to calculate the average CO_2 emission per m^2 of surface cut done by the chain saw [33]. It was calculated that; **2.59 kg CO_2** was emitted **per m^2** of stone cut in the quarry by the Garrone 340 Chainsaw Cutter.

On the other hand, the diamond wire cutting machines have different cutting speeds and consumption values. The production value of such machines is usually around 15 m^2/h [20]. In order to calculate the approximate CO_2 emission of the diamond wire cutting application, the machine features of 'PELLEGRINI TELEDIAM 80' was used through its catalogue [34]. According to the catalogue, the motor of the machine was 56 kW. As the total duration for a m^2 of stone to be cut is 0.06 hours, the total energy for each m^2 of stone cutting was calculated as 3.73 kWh. Accordingly, the total CO_2 emissions **per m^2** of stone cutting with the diamond wire machine is **1.64 kg CO_2**.The calculation was done without the consideration of bench preparation for the cutting activities.

According to the two calculations done for the two different cutting methods, the Diamond-Wire cutter's CO_2 emission per m^2 of natural stone was found to be 37 % lower than the Chain Saw Cutter. As a conclusion, due to lower cutting durations and lower CO_2 emissions, the Diamond-Wire Cutter was suggested as a better alternative when compared to the Chain Saw Cutter.

3.4.3 Noise

Due to the heavy machinery use in the quarry cutting process, noise is one of the aspects that pose a threat to health and safety. Exposure to noise at high decibels can affect human health from even lowering the life quality to permanent or temporary loss of hearing. It is important for the workers to take the required precautions by using the correct gear whilst operating the machinery.

There are decibel limits determined for workers in order to ensure their safety, the limits given in dB are given as; 85 dB (A) for first action level and 90 dB(A) for the second action level [5]. Operations like blasting, drilling, or excavation are the main applications related to cutting operations in the quarries which are sources of noise. Fixed abrasive diamond wire cutting was found quieter than many other machines and the usage could help reduce the overall noise level in plants [35]

3.4.4 Environmental Solutions and Waste Re-Use

Natural Stone wastes, unfortunately, lead to serious environmental problems. Consequently, it is crucial to find solutions for the industry that decrease the waste production and increase the use of wastes in order to maintain the circularity together with minimising the necessary energy consumption and creation of pollutants. Waste is defined by the European Union under the directives ***2006/21/EC, 2008/98/EC and 1999/31/EC*** , that focus on the management of waste from extractive industries, waste and the landfill of waste, respectively [36] [37]. The marble slurry which contains high percentages of marble dust together with irregular-shaped marble chunks are the main waste types produced in quarry. Wastes from a quarry can be categorized as: fine particles/dust, aggregates, larger stone pieces and fractured blocks/slabs. The present re-use/recycling applications of each waste type can be found in the following chapters.

3.4.4.1 Fine Marble Particles-Dust

The re-use of waste can depend on physical and/or chemical aspects of the material. In terms of chemical composition, marble/natural stone dust is mostly composed of $CaCO_3$ and for most of the cases the re-use of the waste is related to the suitability of this chemical compound. On the other hand, aspects like: hardness, colour, density can be taken in account when it comes to physical suitability.

Usage in the Construction Industry

The usage of marble dust created by cutting activities in quarries were investigated through research carried out by *Ulubeyli (2015).* The aim of the research was to discover the usage of marble dust in concrete mixes. The properties of concrete like compressive, flexural tensile strength, elastic modulus, ultrasonic pulse velocity, and Schmidt surface hardness on hardened concrete were examined [38]. The results of the research confirmed the suitability of marble dust in concrete mixes. Additionally, according to research done in 2010 by *Demirel,* the effect of using marble dust as fine sand in concrete was examined. The research showed that replacing marble dust for materials finer than 0.25 mm in the proper ratio, had an enhancing effect on the compressive strength [39]. Similarly, the research of *Sakalkale, Dhawale and Kedar* have showed that the addition of marble dust up to 50% by weight to concrete increased the compressive and flexural strength by 10.72 % and 13.13 % respectively [40].

Moreover, the usage of marble dust in the mix of road embankments was discussed in a paper written by *Khanam et.al* and results were promising in terms of the geophysical properties of the mixture [41]. Therefore, it is possible to classify marble dust as an additive in such mixes used in construction applications due to its suitability and positive effect on the geothermal properties of mixtures.

Usage in Soil Treatment

It is possible to use marble dust through several applications to soil. Firstly, due to the strong anti-acidic characteristics of $CaCO_3$, marble dust can be used to treat acidic soils. Calcium carbonate is the active ingredient in agricultural lime and is commonly used medicinally as a calcium supplement or as an antacid [42]

Secondly, it is possible to use marble dust in soil to improve the stability. The characteristics of expansive soil types result in problems during construction applications and according to a study done by *Yılmaz* in 2017, marble dust has a high potential to improve the soil characteristics in such cases [43]. The research focuses on evaluating geotechnical properties of mixtures including marble dust, and the results indicate that the addition of marble dust enriches the unconfined compressive strength of the mixture.

On the other hand, marble dust can be used as ‘bio-marble’ in the biological filtering of soil. In fact, the usage of marble dust is highly beneficial due to its properties including: low weight, large surface area, durability, minimal clogging, high BOD5 reduction, low capital, corrosion resistance [44]. Due to geographical and biological aspects of areas, drainage patters do not always occur ideally. Bio-filtering is often used in stormwater management as drainage patters are not always ideal and as stormwater occurs with high intensity. Biofilters are used in order to manipulate these patterns and reduce the mobility of biologically influenced media [45].

Additionally, marble dust can be used to improve geotechnical properties of some soil types. According to a study done in 2014 by Akinwumi and Booth, the usage of marble dust in order to improve geotechnical properties of lateritic soil was researched and the results showed that improvements included: specific gravity, Atterberg limits, compaction, strength and permeability characteristics [46].

Paper, Tire and Rubber Industry

Moreover, an extensive study was carried out by G. Marras on the further usage of marble slurry in the paper, tyre, and rubber industries. The research confirmed the inert behaviour of marble slurry and its suitability to the given industries with very minor or no further processing [37]. The re-use has economic advantages as $CaCO_3$ has a certain value in the market. As the marble slurry has impurities in low percentages, its replacement in the industry has direct advantages, both economically and environmentally.

3.4.4.2 Aggregates and Larger Stone Pieces

Coarse and irregularly shaped marble-pieces do not have economic values in the marble stone-market. As a result, marble-pieces that do not comply with the industrial requirements are inevitably defined as waste. For example, the use of these wastes as aggregates might help meet the increasing demands and slow down any detrimental effects on the environment [47].

On the other hand, it is possible to take advantage of the enchanting physical aspects of marble itself. Utilization of waste marble pieces is often found in garden decorations and/or interior designs. In Figure 11, the usage of these pieces can be seen.

Figure 11 Marble Chips used in gardening [48]

3.4.5 ECO-LABEL for the Stone Industry

The European Eco-Label is a brand which is given to companies across many different fields who practice high efficiency processes in their industry and comply with sustainability standards [28]. In order to increase the sustainability and circularity of the stone industry, the European Commission has found the “Eco-Label” brand applicable for the stone industry. In accordance with the act, in July 2009 the Official Journal of the European Union published a commission decision under the code 2009/607/EC entitled “Establishing the ecological criteria for the award of the Community eco-label to hard coverings”. This decision included the description of: *what the “Eco-Label” brand is*, *which industries can volunteer to obtain the label* and *what are the criteria for the label to be earned by natural stone producers*. The aim of the act was to encourage industries to increase their sustainability and efficiency, in order to decrease the environmental impacts of the stone industry.

The framework of the 2009/607/EC involved the description of the criteria:

- Reduction of impacts on habitats and associated resources;
- Reduction of energy consumption;
- Reduction of discharges of toxic or otherwise polluting substances into the environment;
- Reduction of use of dangerous substances in the materials and the finished products;
- Safety and absence of risk to health in the living environment;
- Information that will enable the consumer to use the product in an efficient way which minimises the whole environmental impact [1].

After setting such aims for the criteria, the methodology of the “Eco-Label” brand to be given to the contributors of the stone industry involved ‘scoring’ the industries with six main indicators [1]. The total score was decided to be calculated according to the sums of individual scores given for each indicator, that would be multiplied by corrective weighting [1]. The quarries were decided to be eligible for the brand after earning 19 points out of the total weighted score, where each index had to be higher than the decided minimum or maximum threshold [28].

3.4.5.1 Eco-Label Criteria for Quarries

The quarries which volunteered to earn the Eco-Label were obliged to obtain a minimum of 19 points out of the total weighted average defined. In addition to the weighted average, each company was to comply with the conditions given below:

- There shall be no interference with any deep confined waterbed;
- There shall be no interference with surface water-bodies with civil catching or springs, or if the water body is included in the Register of protected areas established by Directive 2000/60/EC of the European Parliament and of the Council, or the watercourse's average flow is $> 15m^3/s$;
- There shall be a waste-water recovery system avoiding sawing waste dispersion to the environment and to feed the recycling loop. Water shall be contained in the close proximity to the place where it is used in quarrying operations [1].

The Euro-Label scoring was based on the following points:

- Water recycling ratio;
- Quarry Impact Ratio;
- Natural Resource Waste;
- Air Quality;
- Water Quality;
- Noise.

In addition, the matrix for calculating the scoring of each industry can be found in APPENDIX 1. The matrix scoring sets a threshold and excellence level for each subject as given below at Table 4.9

Table 4 Eco-Label Threshold and Excellence References for Quarries [1]

Indicator	***Notes***	***Threshold***	***Excellence Level***
Water Recycling Ratio	Waste Water Recycled/ Total Water Leaving the Process [%]	< 65	> 80
Quarry Impact Ratio	m^2 of affected area/m^2 authorized rea [%]	> 50	< 15
Natural Resource Waste	m^3 usable material/m^3 extracted material [%]	< 25	> 50
Air Quality	Yearly Limit Value Measured [μg/Nm^3]-EN 12341	> 150	< 20
Water Quality	Suspended solids [mg/l]-ISO 5667-17	> 40	< 15
Noise	Measured along the border of quality area [dB(A)]-ISO 1996-1	> 60	< 30

4. A REVIEW ON OPTIMISATION METHODS AND ALGORHYTIMS

One of the biggest conflicts in ornamental stone cutting is the discontinuities/fractures inside the prospective block. Microcracks, partings, cracks, fissures, bedding planes, joints, shear zones, and faults constitute the important discontinuities which can be found in the rock mass [49]. It is important to determine the existing discontinuities inside the blocks, model the fractures and generate optimization methods in order to obtain the optimum economic outcome from the prospective stone. Fractured stones, unfortunately, don’t have the same commercial value with the unfractured and correctly sized stones. Therefore, the value of a fractured stone is much lower and often it goes to waste.

It is important to find technologies that solve such problems in ornamental stone cutting, in order to increase the economic value of the existing stone, decrease the waste production and lower the environmental impact caused by the waste. Some of the existing systems are as followed:

4.1 Fracture Detection

a) **Photogrammetric Techniques of Measurement:** The method uses the technique of photogrammetry in order to determine the in-situ slab geometry. It puts out an analytical understanding to improve the resolution of the images taken by a simple digital camera, and obtain information about the crack/fracture(s) [50]

b) **Marble Cutting Through a Visual System:** It is a visual system that equips a CNC machine tool for cutting marble and similar stones, which allow a semi-automatic detection of surface defects and then computes an optimal distribution of the workpieces to cut by avoiding the defective parts of the slab [51]. The system works by taking a picture of the slab and afterwards importing the image to a CAD/CAM environment. After this operation is done, a qualified CAD/CAM worker defines the toolpath for the CNC machine. The slab is moved to the CNC counter, some differences may take place with the pre-defined CAD/CAM toolpath due to the change of location etc. In this case, the close cooperation of the CNC worker and the CAD/CAM professional takes high importance. With deficiencies like: finding highly skilled CAD/CAM specialist and CNC operator, the visual system suggests a new approach to stone slab cutting

4.2 Fracture Modelling

a) **Discontinuity Modelling and Rock Block Geometry Identification:** It is an algorithm developed in order to increase the efficiency of in-situ stone cutting. The algorithm has been developed in the MATLAB environment to determine the geometry of the blocks and optimize the extraction for random discontinuities in a 3D environment [49].

b) **Terrestrial 3D Laser ScanningTeh two indicators of fractures** are ‘faces’ and ‘traces’ and the paper focus on the orientations of the facets. The research focuses on detecting the fractures by using 3D Terrestrial scanning, which has advantages due to easy application and flexible measurement distances. The method provides a 3D layout of quarries in terms of fracture layouts and consistency of the stone.

4.3 Optimization Algorithms

a) **Computational Algorithm for rock cutting optimisation from primary blocks:** The algorithm uses data from the prospective deposit and has a calculation sequence resulting the direction to cut processes in quarry, it also gives the maximum number of blocks to obtain with the chosen direction [52]. It is a modelling technique that puts-out the results for prospective cutting directions and formulate an optimisation for the extraction process. One of eh crucial parts of the technique is the calculation of the maximum number of blocks to extract with any prospective direction.

b) **Modell-based prediction of unfractured rock masses:** Nikolayev et al. [53] defined model-based prediction of unfractured rock masses using numerical analysis to determine the distribution of individual shapes, and volumes of in-situ blocks [54]. The method provides an analytical solution that is effective through numerical analysis. After determining the fractures and shapes, the paper puts an understanding on block dimensions.

c) **Discontinuity Modelling and Rock Block Geometry Identification:** The research focuses on the modelling of the fractures to create a fracture network and focuses on different cutting patterns which result in smaller blocks. The method uses a generated MATLAB-based software called '*3D-Quarry Optimiser'* and therefore determines the most ideal cutting geometry. [55]. The software focuses on different cutting directions and determines the best fit for the geometrically defined stone quarry. The method had six different steps which are: continuities, discontinuity intersections and edge formation, edge/face regularization, face tracing on each discontinuity plan, formation of matrices required, and block tracing [56].

d) **Characterisation and Quality Assessment with Horizontal Sheet Joints:** The research paper which was published in 2017 characterises granitic building stone deposits. The paper suggests the usage of horizontal sheet joints during the exploitation process and calculates the maximum available block number, although hesitations of over-estimating the deposit remain [57]. The paper initially determines the physical characteristics of the prospective rocks and daws the discontinuity network with the use of the developed 3D software.

e) **Numerical Algorithm on Extraction Optimisation:** It is an algorithm based numerical solution in order to find the optimised dimension of the prospective blocks. The optimisation was carried on by the *3D-Block Expert*, software. The paper also focuses on the alternative use of the waste stone that is the refuse from the cutting operations. [58]

5. OPTIMISATION USING THE ‘SLABCUTOPT’ SOFTWARE

One of the main problems of the marble and stone cutting industry is the factures inside quarry blocks. As fractured marble blocks no longer have their actual commercial value, avoiding the extraction of fractured blocks has become one of the main objectives of the industry. Nevertheless, it is not possible to completely avoid extracting blocks with fractures. As mentioned in the previous parts, different methods have been developed.

In this paper, the software **SlabCutOpt** developed by Bonduà and Elkarmoty, has been used as an optimization method. The details regarding the program and the application process has been given in the next sections.

5.1 SlabCutOpt Software

The SlabCutOpt Software is a software written in C++ and works with a defined domain. Which, in this case is the quarry boundaries and the fractures. The program generates a hypothetical 3D cutting grid in the specified domain. The 3D cutting grid is then rotated and translated (in the 3 Cartesian Directions) several times. The method mainly tests if any of the grids intersect with the defined fractures. This application is performed by using a segment/triangle intersection algorithm [59]. The algorithm defines the fractures in triangles and the program checks the blocks intersecting with the triangles. The representation of the fractures in triangles not just allows the approximation of using planes for representing the fractures, but also the possibility of representing the fracture as discrete surfaces, additional to represent with holes and complicated shapes. In the end, the software identifies the optimum cutting angle of each block/slab dimension and gives the number of blocks that were intersecting and not intersecting to the fractures. By testing several blocks dimension, it is possible to determine the best fit for the bench.

5.2 Input Files

The software runs by inserting the main input file'***SlabCutOpt.par'*** which has the '.par' extension. The file is an ASCII file and contains parameters like: geometrical parameter of the domain for the investigated area, block dimensions, the orientation and translation step parameters and options about the operating mode and the output mode.

Additionally, the .par file refers to some data which are also inserted as inputs. These inputs were ASCII files with '.dat' extensions. One of the .dat files is named as '***PLY_FileList.dat'*** and contains the ply file list of the fracture set that belongs to the investigated area. The '.ply' files of the listed fracture sets are also inserted as inputs in order to use the fracture model and run the program successfully. As the last input file type, the ASCII file named as 'borders.dat' is inserted, but this function can be used optionally.

5.2.1 Output Files

The software generates two type of output files. Firstly, the '***Results.log'*** file which each line contains: the orientation of the cutting grid, the translation used, the number of blocks inside the domain, the number of blocks with non-intersection (recoverable blocks).

Secondly, 'vtu' files for each generated cutting grid, a vtu file is generated to allow 3D visualization. A colour for each rock type is assigned to each block to allow easy identification of blocks inside the domain, intersected blocks and no-intersected blocks. This way, as much as the numerical data of the intersected grids, it becomes possible to visualise the intersected and non-intersected grids on the ParaView software. Information regarding the ParaView software can be found at the next section.

5.3 ParaView Software

Paraview is an open source software that converts raw data in to images in order to put a better understanding to the calculated data. In our case, the Paraview software was used to initially visualise the bench and its fractures, and secondly to visualise the block fitting after the related optimisation was done with the "SlabCutOpt" software. The software Paraview depends on a "Visualisation Toolkit (VTK)" which is a system based on data-flow paradigm, where at this paradigm data flows through the system being transformed at each step by modules known as algorithms [60]. The VTK system is a software system consisting in 3D computer graphics, modelling image processing, volume rendering, scientific visualisation, and information visualisation. It is written with the C++ language. The system works as transferring the C++ coded data to a Python [60].

In our case, the initial data source from “SlabCutOpt” was used as the input to the Paraview system as both of the software’s were written with the C++ programming language. The initial input of the factures located on the referred bench that the research is focusing on can be seen at Figure 12. The tool also allows to filter images with chosen threshold values in order to visualise the data with specific purposes, in this way it is possible to filter the non-intersecting blocks that are related to the optimised block dimension and only visualise the blocks that do not intersect with any discontinuity, a sample image can be found at Figure 16.

6. CASE STUDY

6.1 Case Study

The case study of this research focuses on finding an optimal block dimension in terms of economic value and the environment, precisely waste, for the studied quarry. One of the biggest problems of the natural stone industry is the fractures hidden inside quarries. Thanks to new technologies it is possible to identify these fractures with several methods, as given in the previous sections. This paper’s application will be focusing on finding the best cutting angle and block dimensions for the quarry with defined dimensions and the fractures. The research puts a further perspective to the previously done research by *Bonduà and Elkarmoty* as it aims to define the environmentally optimum cutting dimensions together with economic aspects.

The bench in interest has dimensions of 27.00 m x 65.00 m x 3.95 m and belongs to a limestone quarry in Italy. After the detection of the fractures with the 3D GPRS system which had transmission speeds of 250 and 750 MHz for its dual frequency, the analyse with the previously introduced SlabCutOpt software began. In order to visualise the initial data gathered with the GPRS, the ‘. ply’ files containing the graphical data of the fractures were put into the Paraview program in order to have a better primary understanding. The layout of the factures inside the bench can be seen below from Figure 12.

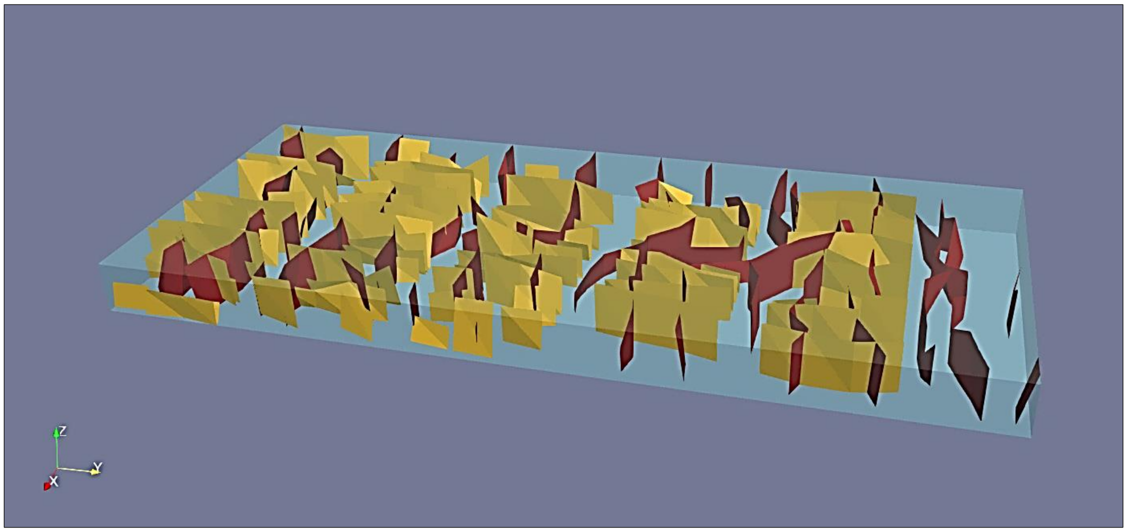

Figure 12 Initial Visualization of the Bench with Paraview

The case study determines the optimum block dimensions, according to the initial 10 different block dimensions tested through the SlabCutOpt program. The program mainly investigates the optimum angle of each plane(x-y-z) for the block sizes inserted, while testing several block dimensions it is possible to create a balance between the economically optimum and environmentally optimum block dimensions with the determine angles on the x-y-z planes.

6.1.1 Site Location

The area of interest for the application of the optimisation model was a limestone quarry located in Poggio Imperiale, Foggia, Italy, which belongs to the basin ‘Apricena’ which is the biggest mining area in its own region ‘Apulia’ with an aerial coverage of 24.1 km^2. The characteristics of the bench are related to its limestone formation, which consists ultra-fine-grained beige-white micritic limestone which belongs to the “Fiorito Succession” [61]. The quarry itself consists the applications of several mining methods which capture drilling/blasting and diamond wire cutting. This can be related to the complicated formation of the quarry involving the site geography to the fracture characteristics as much as the layout of the limestone ore in the area. The location of the quarry can be seen on the map below at Figure 13.

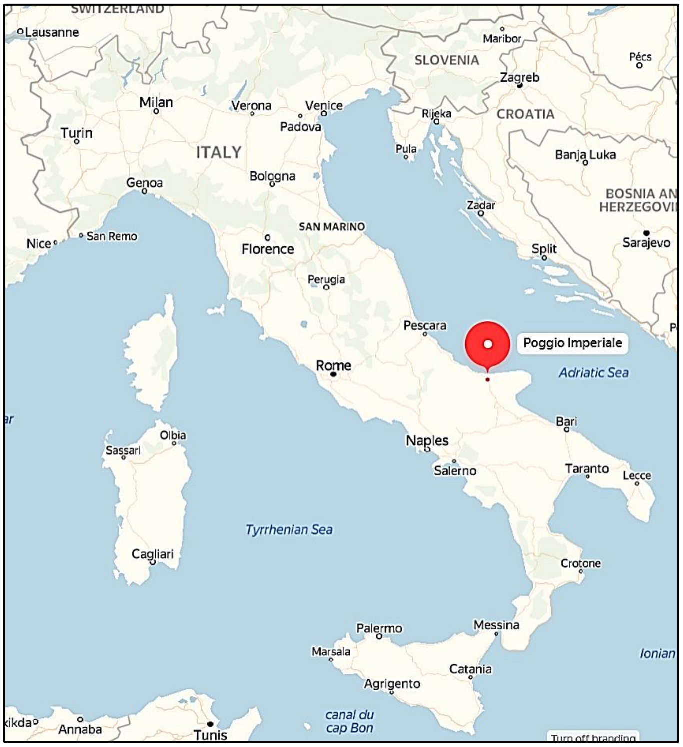

Figure 13 Site Location-Poggio Imperiale (Yandex Maps)

The bench in focus was characterised by two sets of fractures which were named as Set-1 and Set-2, which were two sub-vertical fractures [23]. Below at Figure 14 Case Study Bench-Italy, the bench in focus for the case study can be found together with the fracture sets in the area.

Figure 14 Case Study Bench-Italy [23]

6.1.2 Blocks value estimation

For the ornamental stone industry, one of the core aspects is the economic value of the blocks/slabs produced. The slab/block prices have an increasing trend with the increasing surface area as it is hard to produce blocks with larger surface areas without intersecting any fractures. Therefore, the aim of the industries is to produce blocks/slabs with higher surface areas by ensuring the feasibility of the extraction.

According to the research paper of Bonduà and Elkarmoty in 2018 [23], the *Relative Money Value* (RMV) of slab dimensions with certain surface areas (m^2) were plotted and according to the data, a linear trend was generated which can be found at Figure 15. In this study the RMV of each block dimension will be determined according to the formula given Figure 15.

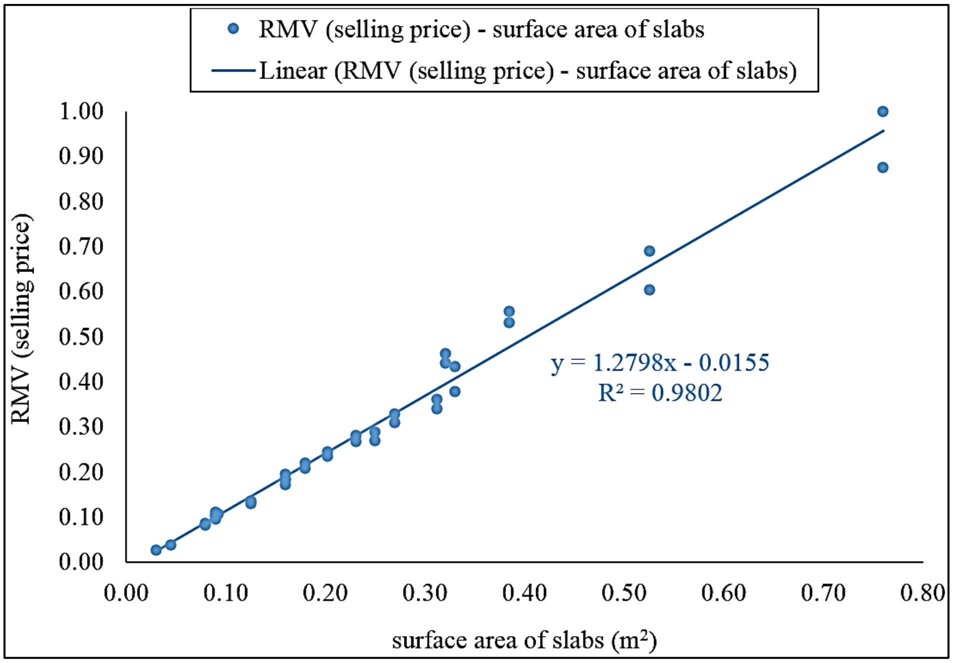

Figure 15 Slab's Selling Price vs Surface Area [23]

6.1.3 Application with the 'SlabCutOpt' and 'ParaView' Data

The two programs SlabCutOpt and ParaView were used to search the optimum block dimension from the limestone bench in question. Initially 10 different block dimensions were selected to be used, the selected dimensions and the maximum surface area obtained with such dimensions have been given at Table 5.

Table 5 Block Dimensions to Test

Dimension # No	***x_dim [m]***	***y_dim [m]***	***z_dim [M]***	***Surface Area [m2]***
0	2.00	2.00	1.00	16.00
1	1.00	1.00	1.00	6.00
2	1.00	1.50	1.50	10.50
3	2.00	2.00	2.00	24.00
4	2.00	1.50	1.00	13.00
5	1.25	1.25	1.25	9.38
6	1.25	1.50	1.25	10.63
7	2.00	1.25	1.25	13.13
8	2.00	1.50	1.25	14.8
9	1.5.0	1.50	1.50	13.50

The selected hypothetical block dimension values were then inserted to the “SlabCutOpt” software as the block dimensions, together with the fracture/discontinuity data which were the “ply” files gathered from the Ground Penetrating Radar (GPR), data from the previous researches. The SlabCutOpt program generates a results file where the steps of its iterations can be seen. This file contains a summary with the best fitting solution of each block dimension concerning the angles of the x-y-z plane together with the number of non-intersecting block numbers for each best fit.

6.1.4 Results and Discussion of the SlabCutOpt Application and Paraview

The SlabCutOpt software was ran for the initial 10 block dimensions and a results report was extracted as one of the main outputs of the algorithm that the software is based on. The results report indicated the best fit of each block dimension based on the angle of cutting on each x-y-z plane. For the 10 different block dimensions the results were scripted on the report as given at the exam below.

“Optimum solution for slab [0] is solution [30], no_intersected_block=358”

For each of the block dimensions inserted as input data, the optimum solutions were found as given below at Table 6. Additionally, the results report can be found in APPENDIX-1

Table 6 Optimum Solutions for Each Block Dimension

Dimension # No	***x_dim [m]***	***y_dim [m]***	***z_dim [m]***	***Tetha***	***Phi***	***Csi***	***Volume [m3]***	***Non-Intersecting Block Number***
0	2.000	2.000	1.000	0.500	0.500	-0.500	4.000	358
1	1.000	1.000	1.000	-0.500	-0.500	-0.500	1.000	2979
2	1.000	1.500	1.500	-0.500	-0.750	0.250	2.250	1049
3	2.000	2.000	2.000	0.500	0.500	-0.500	8.000	104
4	2.000	1.500	1.000	0.000	-0.750	-0.500	3.000	504
5	1.250	1.250	1.250	-0.625	0.375	-0.625	1.953	1314
6	1.250	1.500	1.250	-0.625	-0.750	-0.625	2.344	1013
7	2.000	1.250	1.250	0.500	0.375	-0.625	3.125	626
8	2.000	1.500	1.250	0.000	-0.750	-0.625	3.750	511
9	1.500	1.500	1.500	-0.250	-0.750	0.250	3.375	487

After the results were gathered through the output files of the SlabCutOpt software, the Paraview software was used to visualise the block fitting of each dimension. As the SlabCutOpt program generated 'vtu' files for each optimum solution according to its algorithm, the files were then inserted to the ParaView software in order to visualize the final optimum solution from each block number. At Figure 16, the resulting ParaView visual which displays the bench, the fractures and the fitted block dimensions for the block dimension No#1 can be found. At Figure 16, the factures have been represented with the 'red' colour while the fitted blocks can have been represented with as the blue blocks with black frames , inside the bench which has been represented with yellow.

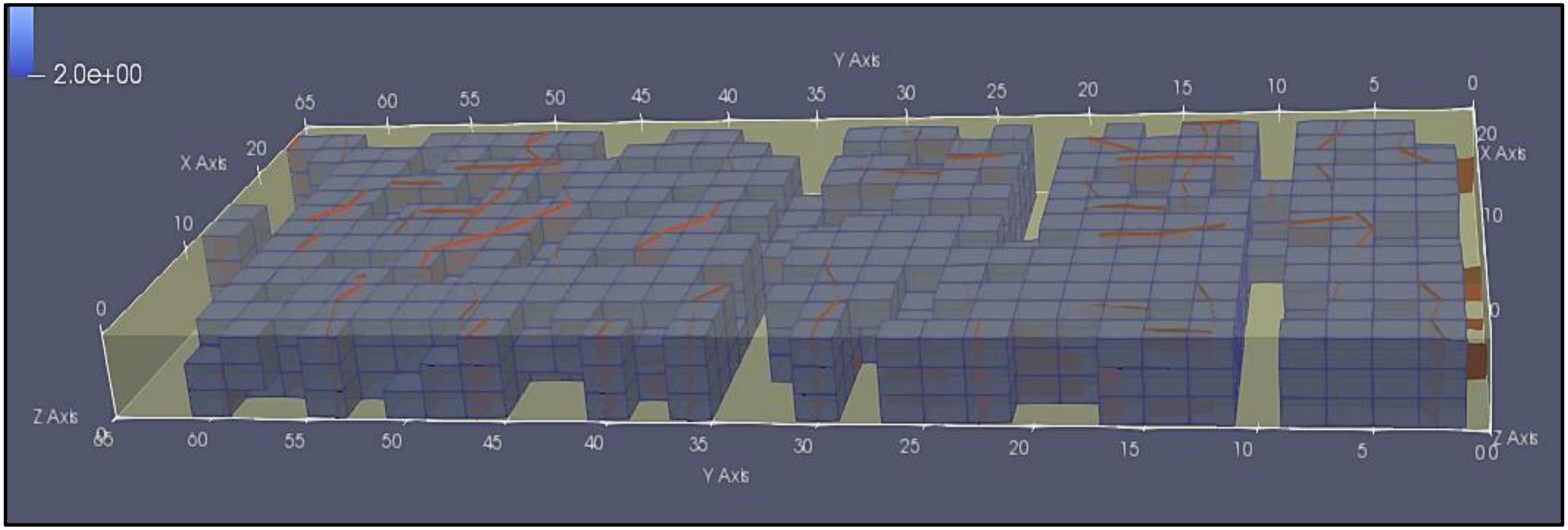

Figure 16 Visualizing the Optimum Solution for Dimension No#1 in ParaView

On the Figure 16it is possible to visualize the blocks that intersect with the fractures together with the blocks that do not intersect.

6.1.4.1 Recovery Ratio

After the results of the optimum solutions for each block dimension was gathered, the calculations regarding the total usable block volume and the total waste volume was done. The equations regarding the calculations have been given at Equation 1 and Equation 2.

$V_{usable} = Total\ Usable\ Block\ Volume\ [m^3]$

$No_{NonIntersect} = Number\ of\ NonIntersecting\ Blocks$

$V_{waste} = Total\ Waste\ Volume\ [m^3]$

$V_{block} = Volume\ per\ block\ [m^3]$

$V_{bench} = Total\ Volume\ of\ the\ bench\ [m^3]$

$R = Recovery\ Ratio\ [\%]$

Equation 1 Total Usable Block Volume

$$V_{usable}\ [m^3] = No_{NonIntersect} x\ V_{block}\ [m^3]$$

Equation 2 Total Waste Volume

$$V_{Waste}\ [m^3] = V_{bench} - V_{usable} [m^3]$$

Equation 3 Recovery Ratio

$$R = \frac{V_{usable}}{V_{bench}} * 100\ [\%]$$

According to the given equations, the total waste volume and total usable block volume was calculated, assuming that each block would be used with its optimum solution for the bench, below at Table 7 Usable Block and Waste Volume Calculations the results can be found.

Table 7 Usable Block and Waste Volume Calculations

Dimension # No	Volume [m3]	Non-Intersect	Total Usable Block Volume [m^3]	Waste Volume [m^3]	Recovery Ratio %
0	4.00	358	1432.000	5500.25	20.65
1	1.00	2979	2979.000	3953.25	42.97
2	2.25	1049	2360.250	4572	34.05
3	8.00	104	832.000	6100.25	12.02
4	3.00	504	1512.000	5420.25	21.81
5	1.95	1314	2566.410	4365.84	37.02
6	2.34	1013	2374.220	4558.03	34.25
7	3.12	626	1956.250	4976	28.22
8	3.75	511	1916.250	5016	27.64
9	3.37	487	1643.625	5288.62	23.71

According to the results the block dimensions with the best recovery ratios were found as Dimension No#1, No#5 and No#6, which had 1 m^3, 1.95 m^3 and 2.34 m^3 of volume for each block, respectively. The block dimension No#1 was found to have the best recovery ratio with 42.97 %. Below at Figure 17, the graph regarding the recovery ratio's according to changing block volumes can be found.

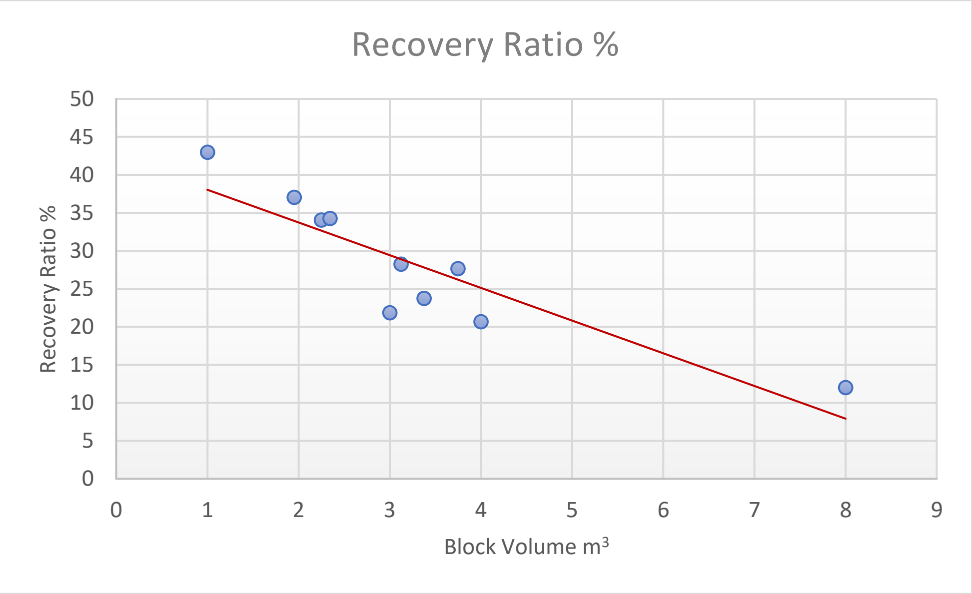

Figure 17 Recovery Ratio of the Optimal Solutions

The recovery ratio was found to have a decreasing trend with the increasing block volume. This was associated with the limited rotation that bigger blocks can do compared to smaller blocks. As the fractions of the bench had both vertical and horizontal alignment, the bigger blocks were not able to fit in spaces that smaller volume blocks did.

6.1.4.2 Total Dust Amount

The total dust amount for cutting each block dimension was calculated according to the thickness of each cutting method used. As each block with different dimensions have differing surface areas, it is important to draw a conclusion between the surface area and the total dust created, due to environmental concerns and the workers safe and health. According to the total surface area intersecting with the cutting tool, the dust volume emitted to cut each block was calculated and later was multiplied with the total number of blocks that do not intersect with any fractures.

The method was applied to the cutting tools “Chain Saw Cutter” and “Diamond-Wire” cutter. The blade thickness of the chain saw was taken as 5cm where the diamond wire cutters thickness was taken as 1cm as given in the tables: Table 2 and Table 3. The total dust volume was then compared to the total bench volume in order to put a better understanding to the total amount of dust generated through the operations, according to the changing block dimension and, accordingly, the changing available block number.

The detailed calculation regarding the dust volume can be found in APPENDIX 1, while at Figure 18 the dust percentages in total bench volume and in total waste volume can be seen for both the Chain Saw and the Diamond Wire cutting tool. As it can be observed, the Diamond Wire cutting tool produces much less dust than the Chain Saw cutter as the thickness of the Chain Saw cutter is five times more than the Diamond Wire cutting tool. As the surface area increases the total dust amount decreases due to the lower production rates that suit the blocks with larger surface area. The increase in the surface area of produced blocks cause the waste amount. As the Chain Saw cutter was observed to cause up to 12.76% of the actual bench volume to be wasted in the dust form, the Diamond Wire cutting tool was suggested due to its lower dust emission due to cutting which scores 2.52% at its highest rate. Since the total number of producible blocks are higher for blocks with lower surface area values, the increase in the total dust value, on the left-hand side of each graph was found natural and further researches can be suggested to be done according to the air pollution regulations stated by the European Union and the Italian Law.

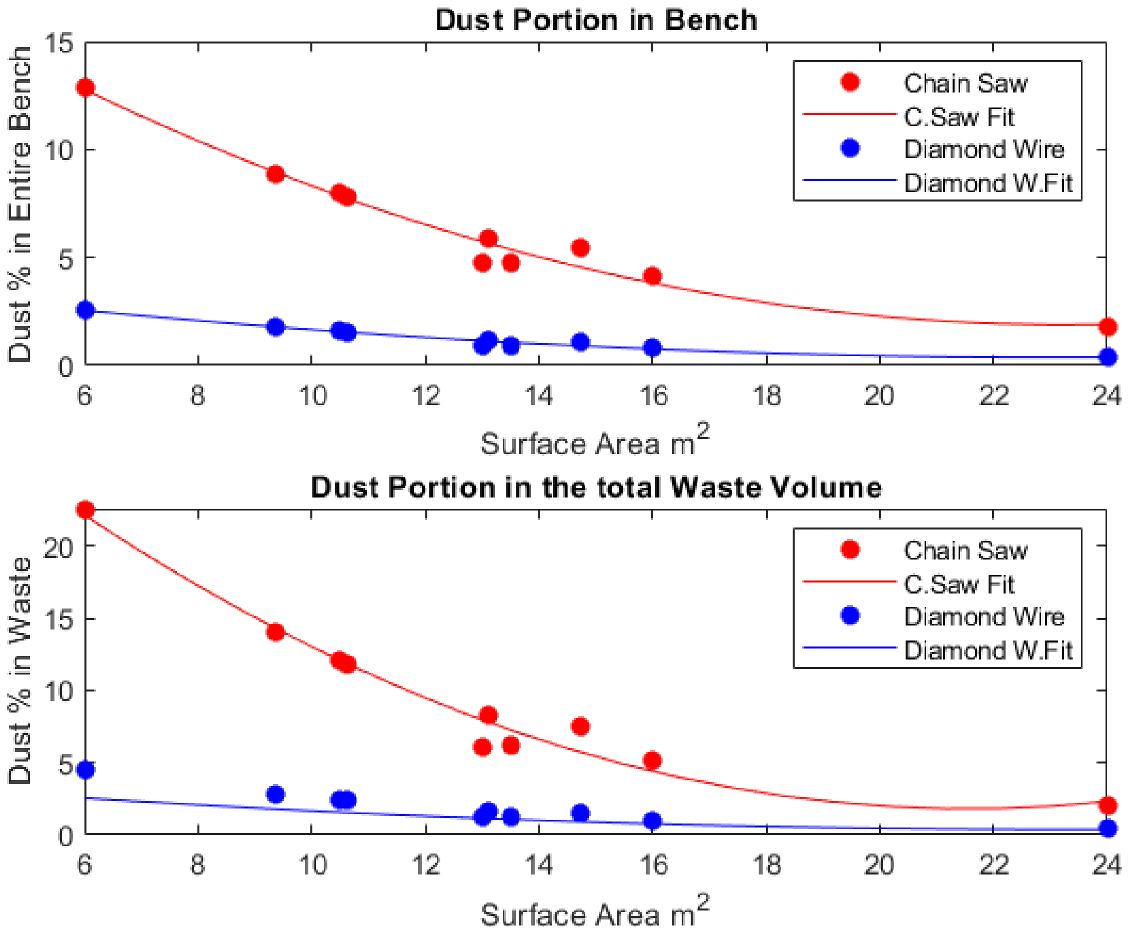

Figure 18 Plots of the Dust portion in Bench and in Total Waste Volume

6.1.4.3 Usable Block Volume and Waste Volume

As one of the aims of this study, an optimal point was searched between the waste block volume and usable block volume for each optimal solution. In order to do so, according to the initial data from each optimal solution the waste block volume [m^3] and usable block volume was calculated according to the given equations Equation 1 and Equation 2, the results can be seen on Table 7. After the data was calculated, by using MATLAB the linear regression curve of the usable block volume and waste volume was generated, the code can be found at APPENDIX 3. By superimposing the two graphs together on a logarithmic scale the trend of both values was able to be observed, the graph can be found below at Figure 19. As it can be seen from the figure, the waste and usable block volumes had opposite trends. Therefore, an optimum point was searched the point where two graphs cross-sect was selected as the optimal point and this corresponded to the block with the volume of 16.75 m^2. The optimal point chosen had a waste block volume of 5426.325m^3, while the usable block volume had a value of 1505.924 m^3.

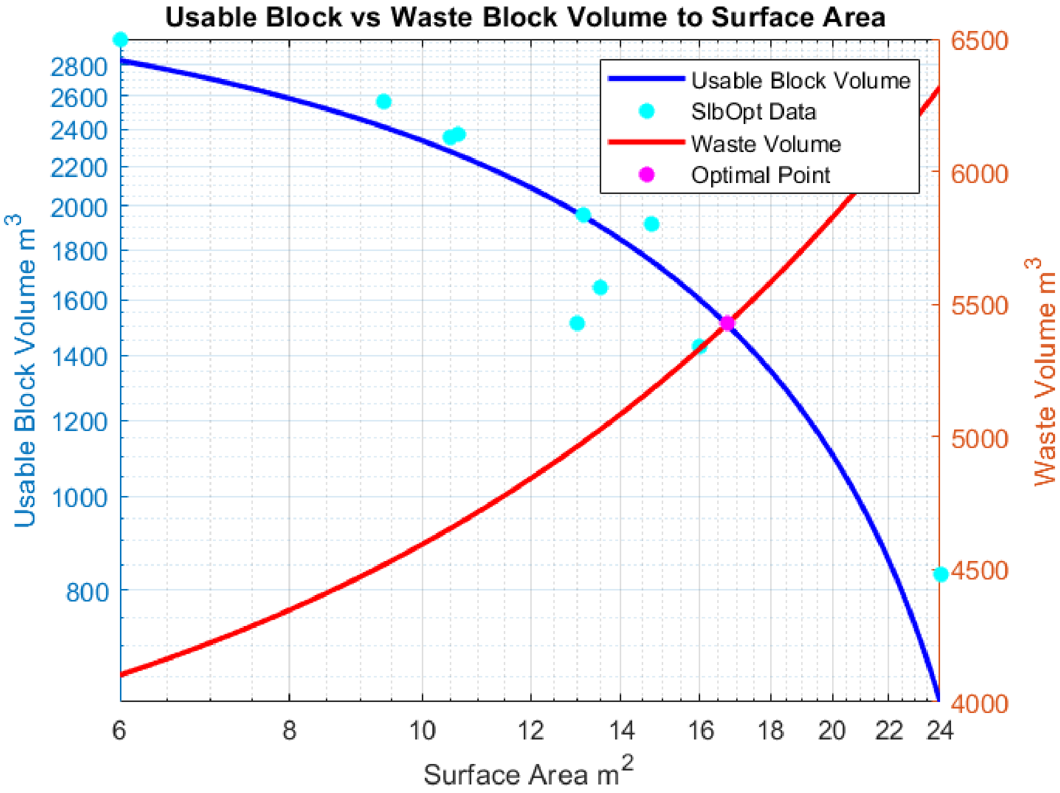

Figure 19 Usable Block vs Waste Volume

6.1.4.4 Total RMV/ Selling Price Calculations

After the calculations were done on the usable block volume and the total waste volume by using the data gathered via SlabCutOpt software's output file and the further interpretation done via MATLAB by using linear regression, the RMV values for each block size and the total possible RMV that can be obtained from each block dimension was calculated. By using the RMV formula given in Figure 15 Slab's Selling Price vs Surface Area the RMV value of each block size was calculated and according to the total block number that does not intersect with any block , the total RMV value that can be obtained by using each block size was calculated. The calculations can be found below at Table 8.

Table 8 Economical Evaluation of Optimal Solutions of the Block Dimensions

Dimension # No	*Volume [m3]*	*Surface Area [m2]*	*RMV per Block*	*Block Number*	*Total RMV/Selling from Dimension*
0	4.00	16.00	20.46	358.00	7325.15
1	1.00	6.00	7.66	2979.00	22828.97
2	2.25	10.50	13.42	1049.00	14080.10
3	8.00	24.00	30.70	104.00	3192.77
4	3.00	13.00	16.62	504.00	8377.44
5	1.95	9.38	11.98	1314.00	15745.17
6	2.34	10.63	13.58	1013.00	13758.95
7	3.13	13.13	16.78	626.00	10505.45
8	3.75	14.75	18.86	511.00	9638.25
9	3.38	13.50	17.26	487.00	8406.50

According to the calculations, block dimension No#1 was found as the optimal solution with the highest total RMV value "22828.97" among each optimal solution for the dimension tested. In order to put a better understanding to the total RMV values, the data points were interpreted as polynomial of the 1st degree which implements linear regression. The interpretation was done for the block surface area range that was from 6 to 24 m^2 After interpreting the data in such a way the total RMV values and total usable block volume data was, together, superimposed on a log scaled graph. The resulting graph can be seen below from Figure 20.

As much as the log-scaled graph indicates a parallel behaviour of the two parameters, the sudden decrease in the RMV values on the left-hand side indicate low number of producible block numbers for blocks with higher surface areas. As the initial aim of any industry, it is important to decide on a point of production where the income has the highest value. Therefore, for this case study, based on the total RMV values, selecting block sizes with lower surface areas but higher total RMV values can be suggested. Considering the total labour work and energy consumption that additional production may cost, the optimum point of production for this case can be argued.

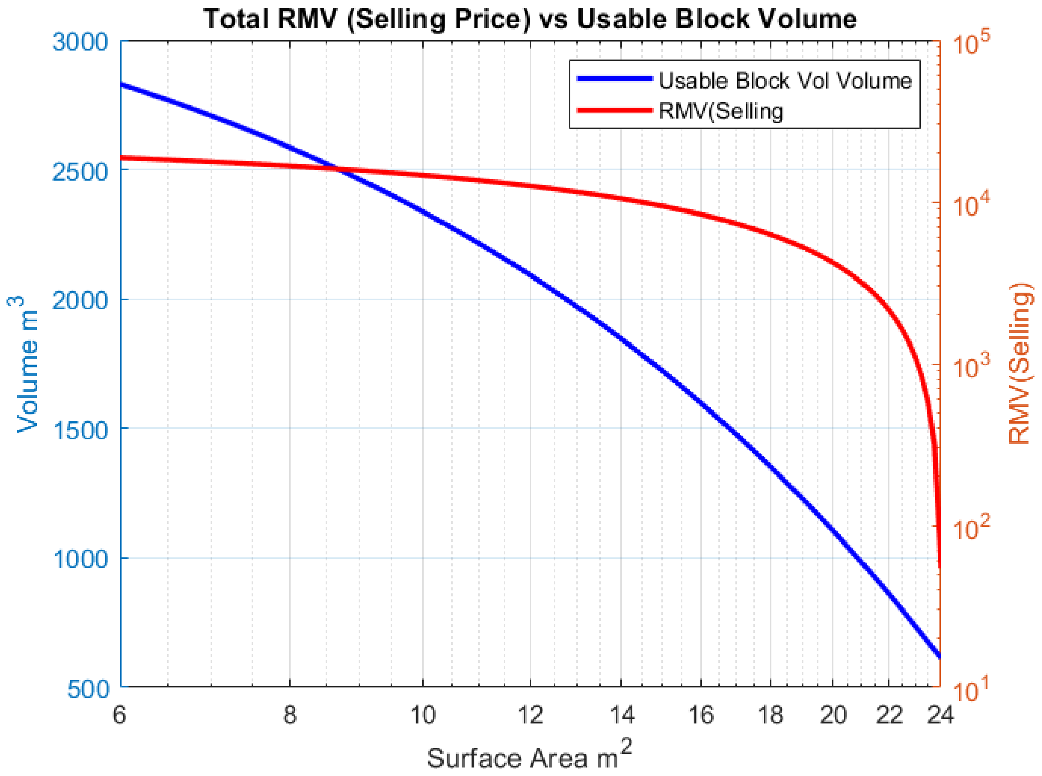

Figure 20 Total Selling Price vs Usable Block Volume

After the comparison with the total selling price (RMV) and the usable block volume was done, the total RMV values were compared with the total waste volume from each block dimension's optimal solution. In order to do so, resulting linear regression curves of both variables were superimposed on the graph, where it can be seen below at Figure 21.

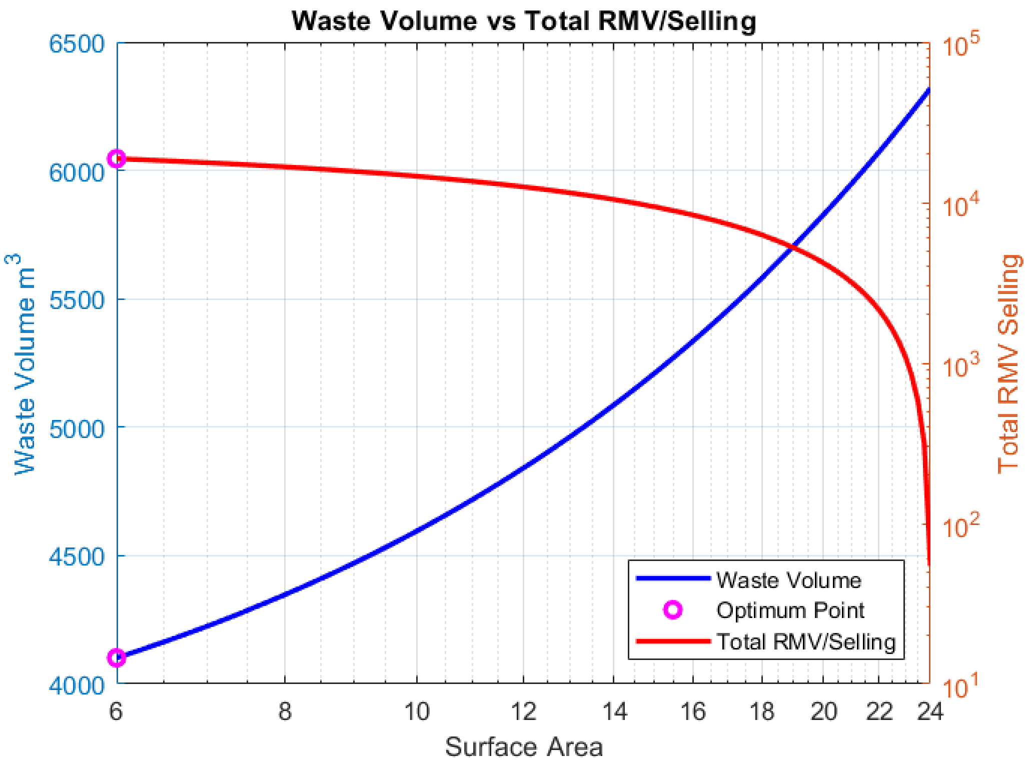

Figure 21 Waste Volume vs Total RMV Values

The left-hand side of the graph, where the waste value is minimum and the total RMV is maximum, was considered as the optimal point when the RMV and waste volume was compared. This corresponded to the surface area volume of 6 m^2, while according to Figure 19 a different result for the optimal solution was observed. According to Figure 19, the optimal solution corresponded to the block dimensions with the surface area of 16.75 m^2, while for Figure 21 the optimal solution corresponded to the surface area of 6 m^2.The reason of the difference was found as the differing block RMV values and related production rates. As the main objective of the project was to optimize the block dimension according to the economic and environmental aspects, the optimal solution through the linear regression was taken as 6m^2.

On the other hand, the actual block dimensions tested through the SlabCutOpt software were compared with each other to understand the block dimensions with the highest total RMV values. Below at Figure 22, the comparison between each block dimension can be found according to the total RMV values calculated. The graph indicated the Dimension No#1 to have the highest total RMV value, with a total RMV of 22,828.97, which had a surface area of 6 m^2 with the dimensions “1m x 1m x 1m”.

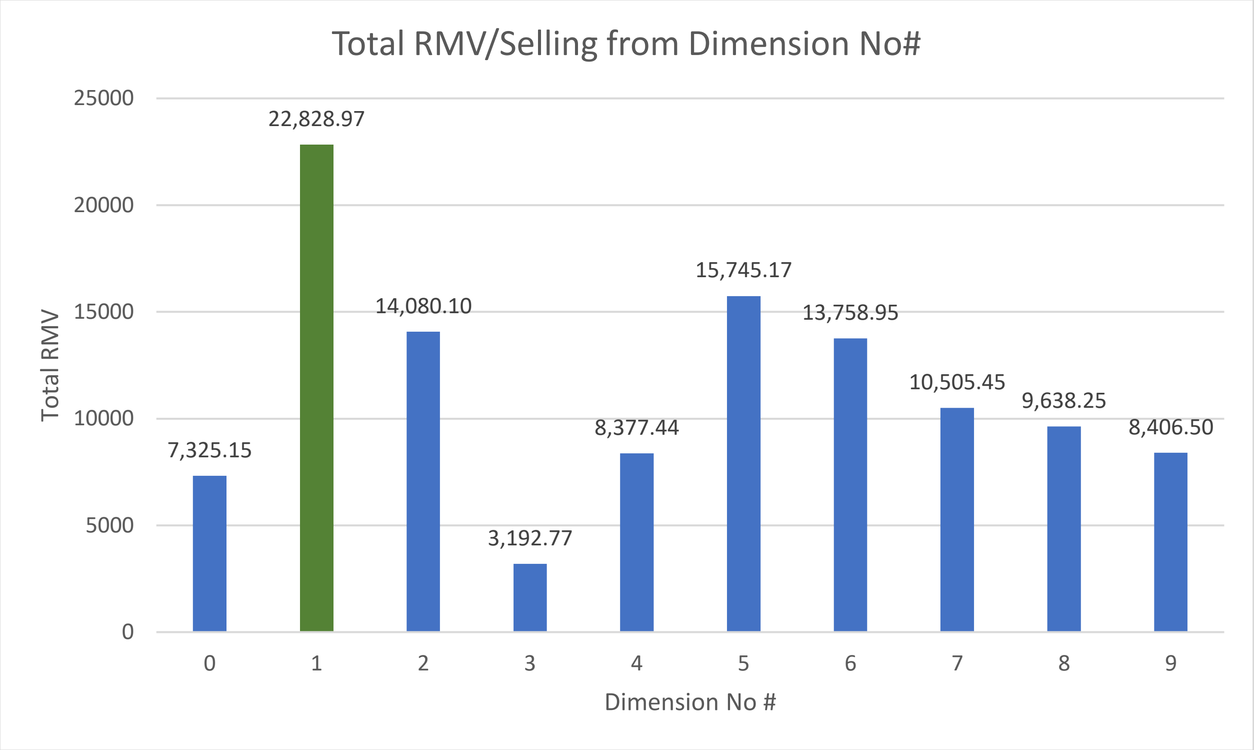

Figure 22 Total RMV Comparison for the tested Block Dimensions

6.1.4.5 Production Cost Calculations

There is a cost to produce each block in a quarry, it is important to find the optimal point where the cost of production, the waste and the total RMV intersects. By focusing on such a subject, it is possible to advice the best practice for the case study. As the trendline of the Total RMV values show near to constant behaviour between the surface areas 5-10 m^2, the case can have arguable values when compared with production costs. According to the research done in 2008, the average cost of marble production cost per m^2 was stated as 6.48$ for unpolished marble [62].

In order to draw a comparison between the production cost and usable block volume, the specific production cost will be approximated as 6.5 $ per m^2 of limestone produced. Below at Table 9, the calculation of the production costs can be found.

Table 9 Production Costs of Each Block Size

Dimension # No	Surface Area [m2]	RMV per Block	Block Number	Production Cost per Block ($)	Total Production Cost ($)
0	16.00	20.46	358.00	104.00	37232.00
1	6.00	7.66	2979.00	39.00	116181.00
2	10.50	13.42	1049.00	68.25	71594.25
3	24.00	30.70	104.00	156.00	16224.00
4	13.00	16.62	504.00	84.50	42588.00
5	9.38	11.98	1314.00	60.94	80071.88
6	10.63	13.58	1013.00	69.06	69960.31
7	13.13	16.78	626.00	85.31	53405.63
8	14.75	18.86	511.00	95.88	48992.13
9	13.50	17.26	487.00	87.75	42734.25

Within the aim of, interpreting the data better and evaluate together with the Total RMV values, the data from Table 9 was interpolated to a 1st degree polynomial and the total cost was interpreted to surface areas values between 5-25 m^2. The “Total RMV” and “Total Production Cost” graphs were superimposed and plotted by using a log scale via MATLAB, the code used can be found at APPENDIX 5. The resulting graph can be found below at Figure 23 Total Production Costs vs Total RMV From the figure it can be observed that, the total production cost has its highest value for where the total RMV values are the highest. This can be related with higher production costs due to higher number of blocks when blocks with lower surface areas are chosen. The block dimension number #1 was found as the block with the highest production cost, 45% higher than the block dimension with the second highest production cost. This was related to the high number of producible blocks that the blocks with lower surface areas have.

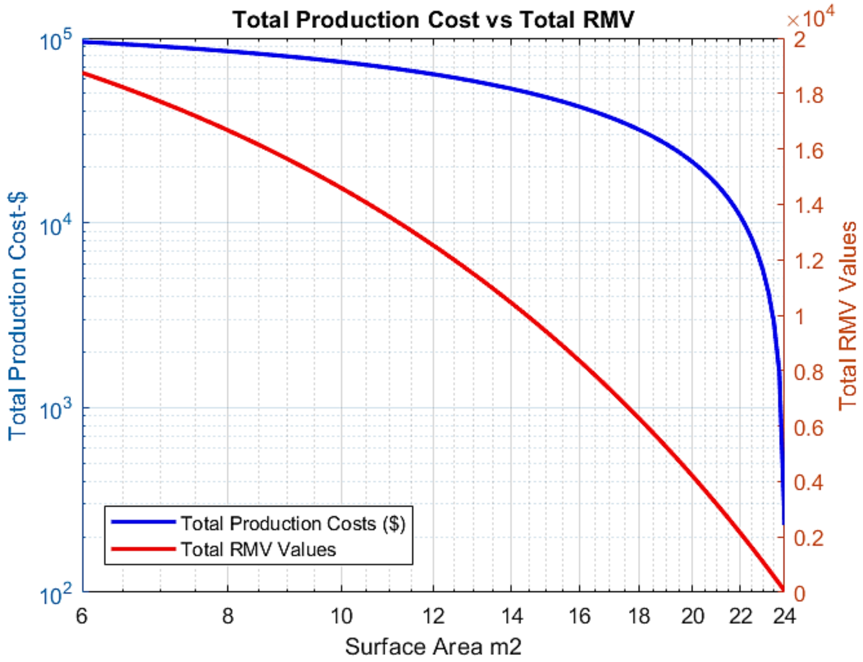

Figure 23 Total Production Costs vs Total RMV

To address the initial aim of the case study, waste reduction, the total production cost was then compared to the total waste production. The two graphs were superimposed on the same x-plane (Surface Area), and the resulting graph can be seen below from Figure 24.

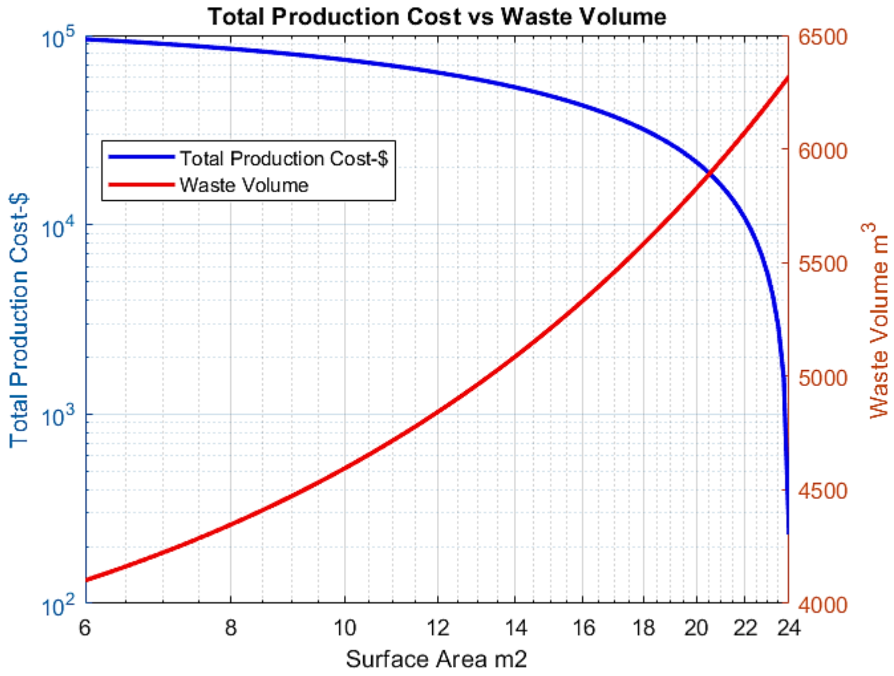

Figure 24 Total Production Cost vs Waste Volume

6.1.4.6 Applying the Eco-Label Criteria for the Quarry

For this project, in order to increase the prospective environmental measures for the quarry in question, the Eco-Label brand was considered to be applied in order to determine the environmental and economical optimum point. For this point, in order to determine the best fitting block dimension in the environmental sense the minimum threshold of the Eco-Label criteria was aimed to be applied for the 3rd criteria given in APPENDIX 1, under the title "Natural Resource Waste". The criteria indicate "> 25%" of threshold for quarries in order to meet the criteria of the brand while the excellence level was set as ">50 %". In this paper, the production results for each tested block dimension was compared to the threshold and excellence level of the Eco-Label brand according to the 2009/607/EC decision. In order to do so, the recovery ratio found for each block dimension's results given in Table 7 were used to interpret the data with a 1st degree polynomial. The inserted threshold and excellence levels were superimposed to the graph in order to determine the sustainability level of the quarry, the resulting graph can be found below at Figure 25 and the code used to generate the interpolant can be found in APPENDIX 6.

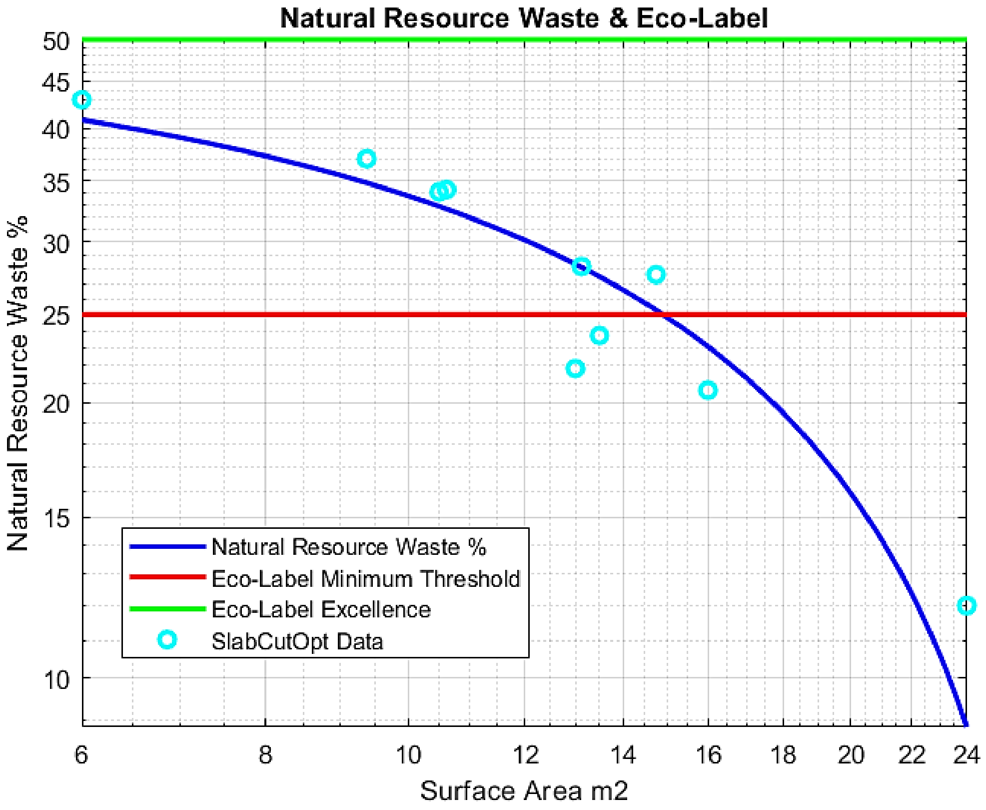

Figure 25Natural Resource Waste compared to the Eco-Label Criteria

According to Figure 25, none of the bock dimensions in the range of 6-24 m^2 surface area were found to pass the Eco-Label Excellence limit. On the other hand, most dimensions with lower surface areas than 15 m^2 were found to pass the threshold limit of 25% natural resource waste percentage. In order to comply with the Eco-Label Threshold Limits, block dimensions higher surface areas than 15 m^2 were not suggested to be used for production, and block dimension with surface areas lower than 15 m^2 were suggested for this case study in terms of corresponding to the Eco-Label brand's criteria defined by the European Commission. The block dimension corresponding to the highest recovery ratio was found as the one with the surface area value of 6 m^2, which corresponds to the Dimension Number #1.

7. DISCUSSION

The presented case study focusing on the optimizing solutions was done for the bench with the dimensions 27.00m x 65.00 m x 3.95 m in the limestone quarry located in located in Poggio Imperiale, Foggia, Italy, which belongs to the basin 'Apricena'. For the natural stone industry, some of the key factors in terms of the natural stone market are the; total block number and natural stone volume available to extract and the price range of the produced blocks according to the dimensions. On the other hand, for environmental aspects the major concerns are the; energy consumption, pollution and waste production. It can be observed that the economic and environmental concerns intersect where the available block volume and generated waste, expressed with the recovery ratio, are in discussion.

For ornamental stone producers, it is important to determine the dimensions of the blocks in order to plan and organise the selling price and the expected revenues from the quarry. The selling price of block dimensions increase rapidly with the increasing surface area of blocks. Producing blocks with big surface areas can be an advantage, but the availability of the bench geometry is an important aspect to consider, fractures can be the factor determining the most suitable block dimension for a quarry.

SlabCutOpt is a software developed by Bonduà and Elkarmoty, which is written in C++ and works with a defined domain [23]. The domain consists the boundaries such as the dimensions of the bench and the fractures inside this boundary. By generating a hypothetical cutting grid according to inserted block/slab dimension(s), the software rotates the grid several times by the angles 'Tetha', 'Phi' and 'Csi', and detects the number of blocks intersecting and non-intersecting with the fractures for each rotation. According to the results of each rotation, the software selects the optimal solution, which is the block dimension used for the grid with the highest number of non-intersections with fractures. In this project, by using the SlabCutOpt algorithm, 10 block dimensions were tested. According to the optimum solution of each block dimension, the comparison between each block dimension was done and further analysis was done by interpreting the data with linear regression.

Firstly, the results of the analysis included the recovery ratio calculation obtained by each block dimension. By calculating the total volume of non-intersecting blocks, the total producible block volume and the total waste volume was calculated. The block dimension with the optimum solution was found as Block Dimension number #1, having the dimensions '1m x 1m x 1m' and the surface area of 6 m^2. The total waste amount for dimension number #1 was calculated as 3953.25 m^3, with a recovery ratio of 43%. Afterwards the total dust emitted by each block dimension scenario was calculated. According to the total producible block number the total block emissions were found to be decreasing with the increasing block surface area. This was related to the low recovery ratio of the blocks with higher surface areas.

Secondly, the waste volume and usable block volume was compared according to the surface areas of each block dimension. The usable block volume had a decreasing trend with the increasing surface area while the waste volume increased with the increasing surface area. An optimum point between the total waste and producible block volume was searched by generating linear regression lines for surface area values between 6-24 m^2. The optimum point was found as 16.75 m^2.

On the other hand, the probable dust emissions resulting from each block dimension was calculated and analysed. According to the total surface area intersecting with the cutting tool, the dust volume emitted to cut each block was calculated and later was multiplied with the total number of blocks that do not intersect with any fractures. The method was applied to both the 'Chain Saw 'and 'Diamond Wire' cutter. The results showed that the diamond wire cutter had much lower dust emissions while the chain saw cutter had much higher dust emissions. When the block dimensions were compared, the total dust emitted had a decreasing trend with the increasing block surface area. This was connected with the lower production rates for blocks with bigger surface areas. The highest dust emission was observed for the chain saw cutter, for block dimension number #1, as the 12.76 % of the bench was calculated to be emitted via dust while this value was 2.52 % for the diamond wire cutter, which shows more optimum results.

In order to extend the study and compare the total earnings in terms of RMV, the total available block volume was compared with the total RMV available to be earned, by applying a linear regression to the known data points, and by interpreting further results between the surface area values between 6-24 m^2. After the two graphs were superimposed on the same plot according to their surface area values, it was observed that while the total available block volume had a linear decrease, the total RMV from blocks showed a rather constant behaviour between the surface area values between 6-10 m^2. This was related with the decreasing block availability but with the increasing block price as the surface area increased for the blocks. In order to extend the analysis, the total waste volume according to changing surface areas were compared with the total RMV available according to the changing surface area values, once again with a linear regression curve. According to this comparison done by superimposing two data plots, the lowest waste volume was found at the point where the highest total RMV was possible, which was the surface area 6 m^2. The surface area value for the optimum point belonged to the dimension number #1, for which the dimensions and further aspects can be found at Table 5, Table 7 and Table 8. The dimension showed a total earning value of 22,829.00 (RMV) by having 45% more earnings than dimension number # 5, which was the second block dimension having the highest total RMV.

As the third point, the production cost was compared with the production rates and earnings for the block dimensions in question. The average marble production cost was taken as 6.48 \$/ m^2 and further analysis was done for each prospective block dimension [62]. According to the calculation, block dimension number#1 had the highest production cost, this was related to the high number of block availability. As the production cost is one of the main aspects affecting the decision of the block dimension, the total production cost was compared with the total RMV available from each block volume according to the surface area values of each block dimension. As the two data were interpreted through a linear regression curve, the production cost and the total RMV available showed similar aspects. On the other hand, as the RMV value was taken as an index without indicating the actual price of the blocks, the estimated net earnings per block were not able to be done. However, the production cost and total waste volume were compared thorough the linear regression curves interpreted. The superimposed graphs of the two parameters indicated a slower decrease in the production costs between the surface areas 6-14 m^2, which indicated an arguable interval for the optimum block dimension.

Finally, the Eco-Label standards were applied for the bench in question. This was done in order to visualize the fitting of the actual data for an environmental standard that indicated high prestige for industries. According to the European Commission's 2009 decision coded as 2009/607/EC, one of the key aspects while determining the sufficiency of quarries were the recovery ratio, indicating the balance between the extracted natural stone and the total usable material. For industries eager to obtain the label, Eco-Label sets a minimum 25% threshold for the recovery ratio, while the brand awards industries with the excellence level for values over 50%. The recovery ratio of each block dimension and the linear regression curve was compared with the threshold and the excellence level. The results indicated that using block dimension higher that 15 m^2 did not comply with the threshold value- of 25%. Nonetheless, none of the block dimension's recovery ratio was found to comply with the Eco-Label excellence level. The highest value came from block dimension number #1, with the value of 42% recovery. According to the Eco-Label guideline, the value of 43% indicates a 'good' level. The analysis suggested the usage of block dimensions having surface areas between 6-15 m^2, while the lower surface area values showed a better fit and are suggested in terms of environmental standards.

Ultimately, the block dimension number #1 was found as the best fitting dimension when economic and environmental parameters were considered. On the other hand, as the production cost is one of the most important parameters for industries, the block dimensions in the 6-14 m^2 surface area range were found considerable as the interval was found arguable due to production costs. Additionally, the interval was found complying with the economic and environmental parameters. The "Diamond Wire Cutter" was found as the optimum cutting tool when compared to the "Chain Saw Cutter", when dust emissions and the energy consumption is considered.

8. CONCLUSION

This research consists a comprehensive analysis on ornamental stone cutting, ornamental stone types, continuous cutting methods in quarry, environmental aspects of quarrying operations, reviewing optimization algorithms and methods. A case study was related to a quarry located on the Apricena basin in Italy was presented according to the environmental and economic aspects of a limestone quarry.

Natural stone exportation and importation activities are one of the important contributors to the world's economy. The countries with the highest quarry stone output are: China, India, Turkey, Iran and Italy. Clay, Limestone, Travertine, Gypsum and Sandstone, Sand and gravel, Granite, Marble, Porphyry, Basalt and the Fiorenzuola stone can be some of the examples for ornamental stones. According to many aspects such as: durability, grain size, colour, pattern, polishing, dimensions, aesthetic value the price of such stones can be determined. Pricing of the stones is one of the key aspects when production rates and methods are determined. Fractures in quarries can limit the production of slabs/blocks with big surface areas.

Environmental concerns are one of the problems of the natural stone industry, as for any active industry producing, using or associating with any natural resource. For quarrying operations these environmental factors are; energy consumption, environmental pollution and waste production. In order to decrease the energy consumption, industrial applications with relatively high efficiency should be preferred. For this research the 'Diamond Wire Cutter' was found to have lower electricity and water consumption and lower carbon emission when compared with the 'Chain Saw Cutter'. Additionally, the research showed that the diamond wire cutter had a maximum of 2.52% of dust emission while this number was 12.76% for the chain saw cutter.

The waste production is a factor affecting the quarries both environmentally and economically, as it produces 25% of the world's waste coming from economic activities. Due to fractures in the quarries, it is not possible to produce all the available natural stone volume. Slabs and blocks with fractures lose their economic value in the natural stone market. By increasing the producible block volume in quarries with the selection of the right slab and block dimensions, industries can comply with environmental standards such as Eco-Label.

In order to increase the production and find the best fitting block/slab size many different technologies such as; optimization algorithms and fracture determination systems have been introduced to the industry. One of these algorithms is the 'SlabCutOpt' developed by Bonduà and Elkarmoty. For a bench that the fracture geometry was modelled, the software uses different gridding angles to analyse blocks intersecting and not intersecting with the fractures. By using the program, ten different block dimensions were tested for the bench in the quarry located in Apricena and the best fitting dimension was searched.

The determination of the best fitting bench was done according to parameters such as: total producible block volume, total waste volume, recovery ratio, total dust amount, total earnable RMV, production costs and the application of the Eco-Label standards to the prospective production of the bench, all according to the surface area of the blocks. Each parameter's results were interpreted with a linear regression curve in order to apply future analysis to the data.

The results indicated that the highest available block volume, lowest waste volume and the highest total RMV value was resulting for the block dimension number #1, with the dimensions '1m x 1m x 1m'. For this block dimension the recovery ratio was 43%, the total dust volume-via diamond wire cutter- was 178 m^3, the total earnable RMV value was 22829 RMV. On the other hand, this was found as the block with the highest production cost with a value of 116181$, 45% higher than the dimension with the second highest production cost. After contrasting the results with the production costs, a wider interval was considered as the production costs con be arguable for industries. The blocks with surface areas between 6-14 m^2 were considered as prospective optimum solutions.

Additionally, the Eco-Label standards were introduced in to the analysis. Eco-Label is a brand that the European union has introduced for the industries, it is a label that any industry volunteering to obtain the label, having fulfilled the requirements, can earn the Eco-Label brand. For this research, the third criteria of the Eco-Label brand, the recovery ratio, was selected to be applied. The block dimensions having surface area values lower than 15 m^2 were found to be above the threshold value that Eco-Label determines for the recovery ratio of quarries, while the block dimension number #1 was found to have eh best with the highest recovery ratio value with 43%.

When all parameters are considered, the block dimensions with the surface areas values between 6-14 m^2 were found in the optimum range while the dimension number #1 was the best fit for many aspects. The optimum solution is suggested between the 6-14 m^2 range, as production costs can vary for quarrying operations. As a conclusion, this research indicates that it is possible to find optimal applications for quarrying activities that can combine economic and environmental priorities. By using new technologies, our ability to create new solutions for the natural stone industry can improve. Industries can benefit from optimal solutions economically, while circularity can be preserved for the environment and its habitants.

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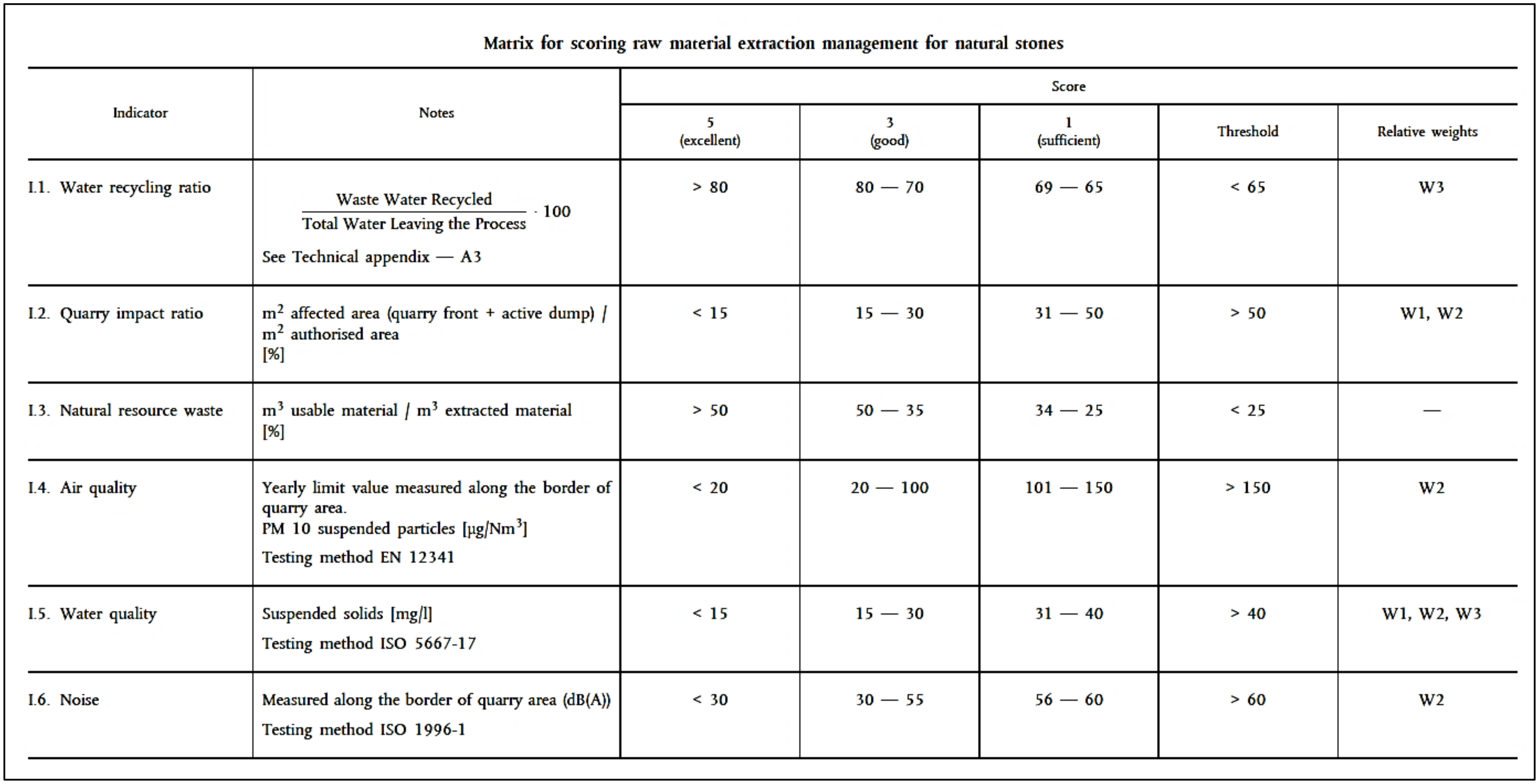
10. APPENDICES

APPENDIX 1 ECO-LABEL Matrix for Scoring Raw Material Extraction Management for Natural Stones [1]



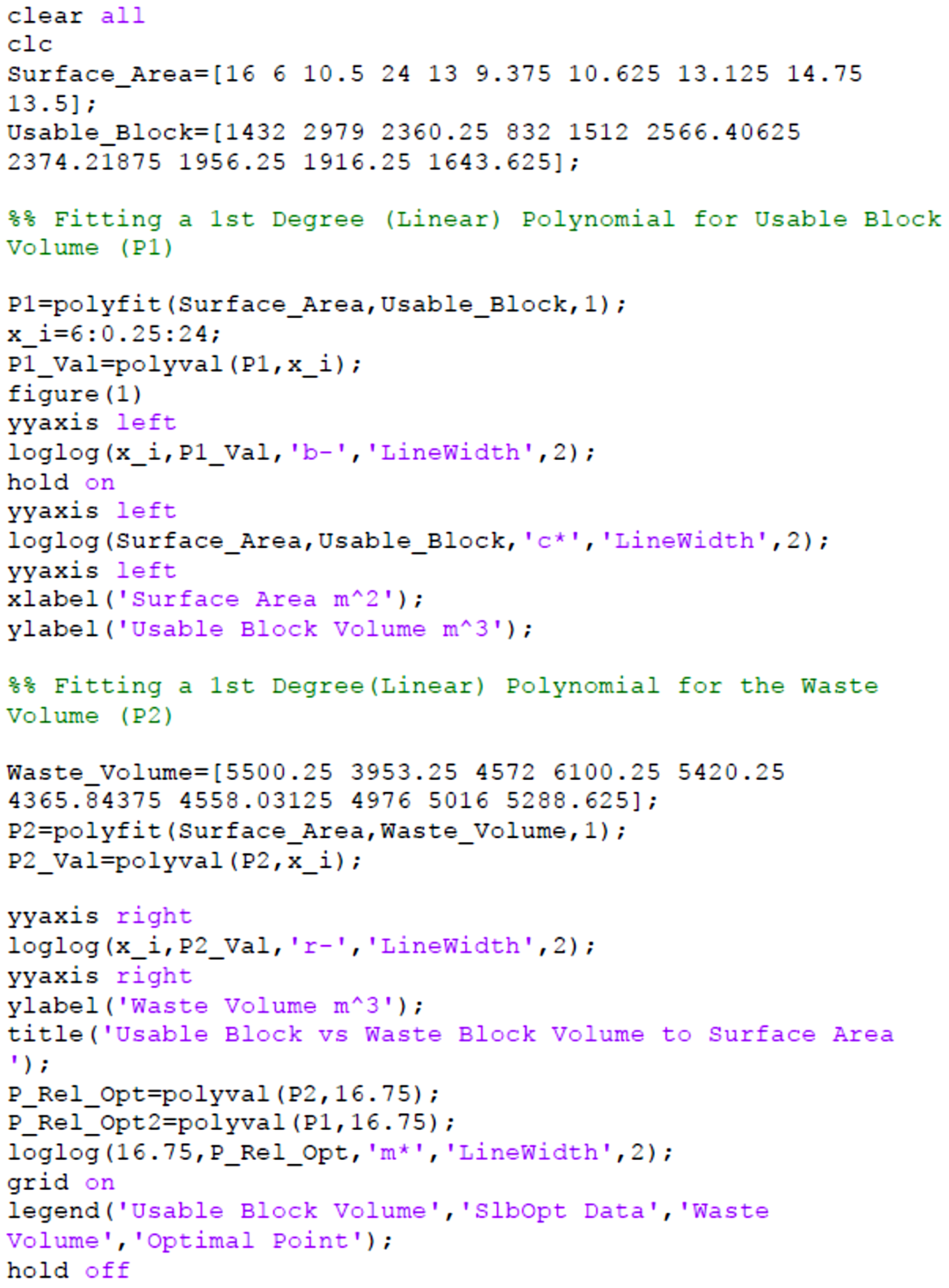
Matrix for scoring raw material extraction management for natural stones

Indicator	Notes	Score 5 (excellent)	 3 (good)	 1 (sufficient)	Threshold	Relative weights
I.1. Water recycling ratio	$\frac{\text{Waste Water Recycled}}{\text{Total Water Leaving the Process}} \cdot 100$ See Technical appendix — A3	> 80	80 — 70	69 — 65	< 65	W3
I.2. Quarry impact ratio	m^2 affected area (quarry front + active dump) / m^2 authorised area [%]	< 15	15 — 30	31 — 50	> 50	W1, W2
I.3. Natural resource waste	m^3 usable material / m^3 extracted material [%]	> 50	50 — 35	34 — 25	< 25	—
I.4. Air quality	Yearly limit value measured along the border of quarry area. PM 10 suspended particles [µg/Nm^3] Testing method EN 12341	< 20	20 — 100	101 — 150	> 150	W2
I.5. Water quality	Suspended solids [mg/l] Testing method ISO 5667-17	< 15	15 — 30	31 — 40	> 40	W1, W2, W3
I.6. Noise	Measured along the border of quarry area (dB(A)) Testing method ISO 1996-1	< 30	30 — 55	56 — 60	> 60	W2

APPENDIX 2 SlabCutOpt Results Report

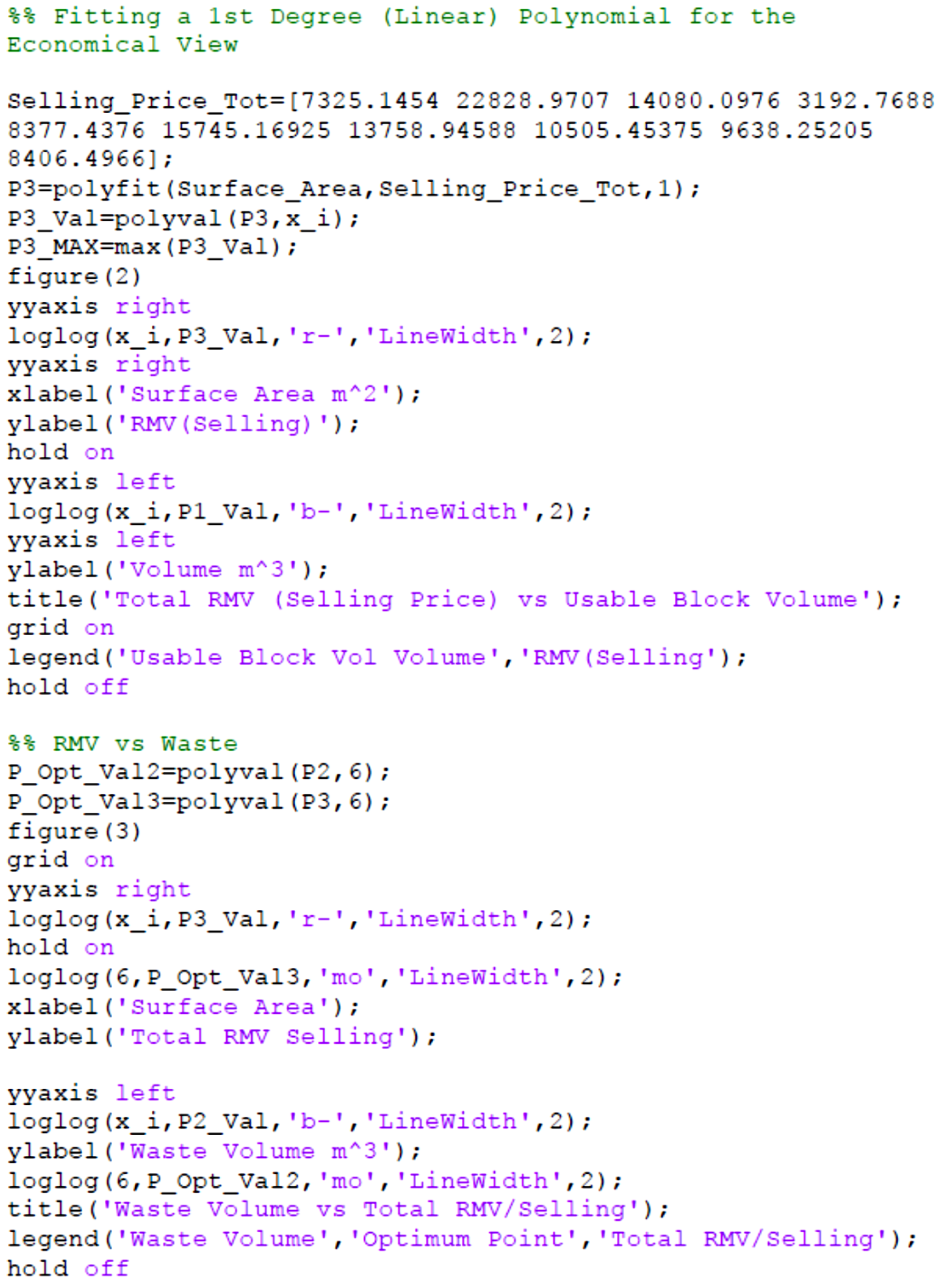
```
*************************************************
*Authors: Stefano Bondua, Mohamed Elkarmoty *
*************************************************
*For any information please contact: *
* stefano.bondua@unibo.it *
*************************************************
*Parameters used *
*************************************************
x_max=27.000000
x_min=0.000000
y_max=65.000000
y_min=0.000000
z_max=3.950000
z_min=0.000000
tetha_step=90.000000
tetha_max=0.100000
phi_max=90.100000
phi_step=30.000000
csi_max=0.100000
csi_step=30.000000
n_x_division=1
n_y_division=1
n_z_division=1
dx_step=0.500000
dy_step=0.500000
dz_step=0.500000
dx_max=0.100000
dy_max=0.100000
dz_max=0.100000
dim_block_x=0.410000
dim_block_y=0.210000
dim_block_z=0.040000
read_block_dimension=1
read_bound=0
BiDimensional=0
write_vtu=2
read_PLY_FileList=1
n_x_division=1
n_y_division=1
n_z_division=1
rotation_method=1
cut_saw_thickness=0.010000
angle_type=1
bound_tolerance=0.00100000000000000
end=end


Optimum solution for slab_[0] is solution[30], no_intersected_block=358
Optimum solution for slab_[1] is solution[128], no_intersected_block=2979
Optimum solution for slab_[2] is solution[162], no_intersected_block=1049
Optimum solution for slab_[3] is solution[293], no_intersected_block=104
Optimum solution for slab_[4] is solution[572], no_intersected_block=504
Optimum solution for slab_[5] is solution[590], no_intersected_block=1314
Optimum solution for slab_[6] is solution[692], no_intersected_block=1013
Optimum solution for slab_[7] is solution[833], no_intersected_block=626
Optimum solution for slab_[8] is solution[1070], no_intersected_block=511
Optimum solution for slab_[9] is solution[1099], no_intersected_block=487
Optimum solution for slab_[10] is solution[1241], no_intersected_block=361
Elapsed time 695747 (ms)
```

APPENDIX 3 MATLAB Code for Data Fitting



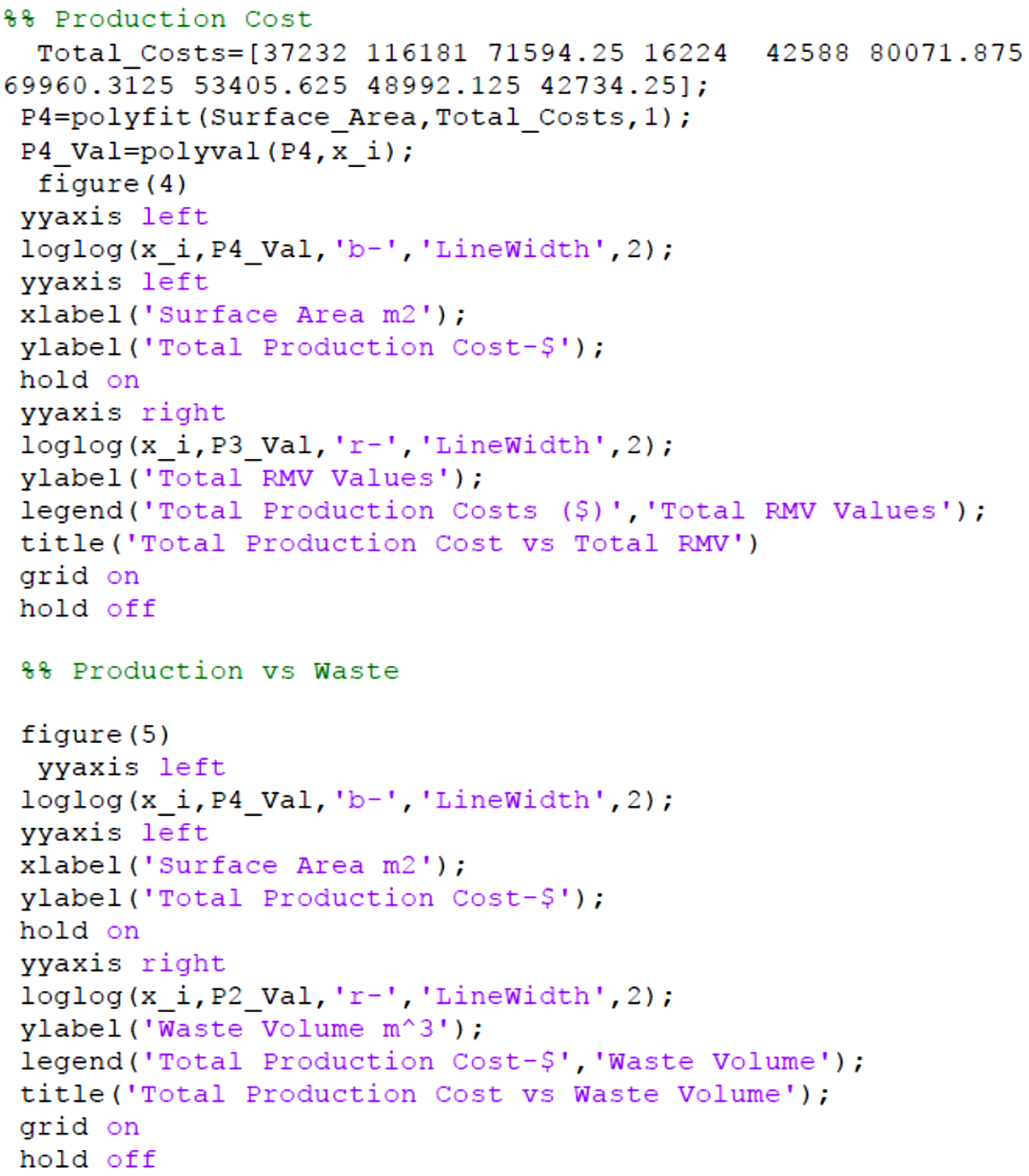
```
clear all
clc
Surface_Area=[16 6 10.5 24 13 9.375 10.625 13.125 14.75
13.5];
Usable_Block=[1432 2979 2360.25 832 1512 2566.40625
2374.21875 1956.25 1916.25 1643.625];

%% Fitting a 1st Degree (Linear) Polynomial for Usable Block
Volume (P1)

P1=polyfit(Surface_Area,Usable_Block,1);
x_i=6:0.25:24;
P1_Val=polyval(P1,x_i);
figure(1)
yyaxis left
loglog(x_i,P1_Val,'b-','LineWidth',2);
hold on
yyaxis left
loglog(Surface_Area,Usable_Block,'c*','LineWidth',2);
yyaxis left
xlabel('Surface Area m^2');
ylabel('Usable Block Volume m^3');

%% Fitting a 1st Degree(Linear) Polynomial for the Waste
Volume (P2)

Waste_Volume=[5500.25 3953.25 4572 6100.25 5420.25
4365.84375 4558.03125 4976 5016 5288.625];
P2=polyfit(Surface_Area,Waste_Volume,1);
P2_Val=polyval(P2,x_i);

yyaxis right
loglog(x_i,P2_Val,'r-','LineWidth',2);
yyaxis right
ylabel('Waste Volume m^3');
title('Usable Block vs Waste Block Volume to Surface Area
');
P_Rel_Opt=polyval(P2,16.75);
P_Rel_Opt2=polyval(P1,16.75);
loglog(16.75,P_Rel_Opt,'m*','LineWidth',2);
grid on
legend('Usable Block Volume','SlbOpt Data','Waste
Volume','Optimal Point');
hold off
```

APPENDIX 4 MATLAB Code for Data Fitting-2



```
%% Fitting a 1st Degree (Linear) Polynomial for the
Economical View

Selling_Price_Tot=[7325.1454 22828.9707 14080.0976 3192.7688
8377.4376 15745.16925 13758.94588 10505.45375 9638.25205
8406.4966];
P3=polyfit(Surface_Area,Selling_Price_Tot,1);
P3_Val=polyval(P3,x_i);
P3_MAX=max(P3_Val);
figure(2)
yyaxis right
loglog(x_i,P3_Val,'r-','LineWidth',2);
yyaxis right
xlabel('Surface Area m^2');
ylabel('RMV(Selling)');
hold on
yyaxis left
loglog(x_i,P1_Val,'b-','LineWidth',2);
yyaxis left
ylabel('Volume m^3');
title('Total RMV (Selling Price) vs Usable Block Volume');
grid on
legend('Usable Block Vol Volume','RMV(Selling');
hold off

%% RMV vs Waste
P_Opt_Val2=polyval(P2,6);
P_Opt_Val3=polyval(P3,6);
figure(3)
grid on
yyaxis right
loglog(x_i,P3_Val,'r-','LineWidth',2);
hold on
loglog(6,P_Opt_Val3,'mo','LineWidth',2);
xlabel('Surface Area');
ylabel('Total RMV Selling');

yyaxis left
loglog(x_i,P2_Val,'b-','LineWidth',2);
ylabel('Waste Volume m^3');
loglog(6,P_Opt_Val2,'mo','LineWidth',2);
title('Waste Volume vs Total RMV/Selling');
legend('Waste Volume','Optimum Point','Total RMV/Selling');
hold off
```

APPENDIX 5 MATLAB Code for Production Cost



```
%% Production Cost
  Total_Costs=[37232 116181 71594.25 16224  42588 80071.875
69960.3125 53405.625 48992.125 42734.25];
 P4=polyfit(Surface_Area,Total_Costs,1);
 P4_Val=polyval(P4,x_i);
  figure(4)
 yyaxis left
 loglog(x_i,P4_Val,'b-','LineWidth',2);
 yyaxis left
 xlabel('Surface Area m2');
 ylabel('Total Production Cost-$');
 hold on
 yyaxis right
 loglog(x_i,P3_Val,'r-','LineWidth',2);
 ylabel('Total RMV Values');
 legend('Total Production Costs ($)','Total RMV Values');
 title('Total Production Cost vs Total RMV')
 grid on
 hold off

 %% Production vs Waste

 figure(5)
  yyaxis left
 loglog(x_i,P4_Val,'b-','LineWidth',2);
 yyaxis left
 xlabel('Surface Area m2');
 ylabel('Total Production Cost-$');
 hold on
 yyaxis right
 loglog(x_i,P2_Val,'r-','LineWidth',2);
 ylabel('Waste Volume m^3');
 legend('Total Production Cost-$','Waste Volume');
 title('Total Production Cost vs Waste Volume');
 grid on
 hold off
```

```
%% Recovery Ratio & Thresholds

Rec_Ratio=[20.65707382 42.97306069  34.04738721 12.00187529
21.81110029 37.02125933 34.24889105 28.21955354 27.6425403
23.70983447];

%Fitting a 1-st degree Polynomial
    P5=polyfit(Surface_Area,Rec_Ratio,1);
    P5_Val=polyval(P5,x_i);
    y=25*ones(1,73);
    y2=50*ones(1,73);

figure(6)
    loglog(x_i,P5_Val,'b-','LineWidth',2);
    xlabel('Surface Area m2');
    ylabel('Natural Resource Waste %');
    hold on
    loglog(x_i,y,'r-','LineWidth',2);
    loglog(x_i,y2,'g-','LineWidth',2);
    loglog(Surface_Area,Rec_Ratio,'co','lineWidth',2);
    title('Natural Resource Waste & Eco-Label');
    legend('Natural Resource Waste %','Eco-Label Minimum
Threshold','Eco-Label Excellence','SlabCutOpt Data');
    grid on
    hold off
```

APPENDIX 7 Total Dust Emitted via Block Cutting

Dimension # No	Surface Area per Block [m2]	Non-Intersecting Block No	Dust Volume per Block via Chain Saw [m3]	Dust Volume per Block via Diamond [m3]	Total Dust Volume via Chain Saw [m3]	Total Dust Volume via Diamond Wire [m3]	Waste Volume [m3]	Portion of the Dust in Bench Chain Saw %	Portion of the Dust in Bench -Diamond Wire %	Portion of the Dust in Waste-Chain Saw %	Portion of the Dust in Waste -Diamond Wire %
0	16.00	358.00	0.80	0.16	286.40	57.28	5500.25	4.13	0.83	5.21	1.04
1	6.00	2979.00	0.30	0.06	893.70	178.74	3953.25	12.89	2.58	22.61	4.52
2	10.50	1049.00	0.53	0.11	550.73	110.15	4572.00	7.94	1.59	12.05	2.41
3	24.00	104.00	1.20	0.24	124.80	24.96	6100.25	1.80	0.36	2.05	0.41
4	13.00	504.00	0.65	0.13	327.60	65.52	5420.25	4.73	0.95	6.04	1.21
5	9.38	1314.00	0.47	0.09	615.94	123.19	4365.84	8.89	1.78	14.11	2.82
6	10.63	1013.00	0.53	0.11	538.16	107.63	4558.03	7.76	1.55	11.81	2.36
7	13.13	626.00	0.66	0.13	410.81	82.16	4976.00	5.93	1.19	8.26	1.65
8	14.75	511.00	0.74	0.15	376.86	75.37	5016.00	5.44	1.09	7.51	1.50
9	13.50	487.00	0.68	0.14	328.73	65.75	5288.63	4.74	0.95	6.22	1.24