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PRODUCTION OPTIMISATION AND ENVIRONMENTAL PROTECTION IN ORNAMENTAL STONE QUARRIES USING GROUND PENETRATING RADAR TECHNIQUES

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Abstract: *In this study, three grids on the same quarry bench were analysed in the Botticino marble quarry in Northern Italy. This research seeks to enhance quarry productivity by employing the European Union Eco- label scoring based on ore extraction efficiency ratio and optimizing cutting directions and block dimensions to maximize usable volume and minimize waste. Using non-destructive Ground Penetrating Radar (GPR) for fracture detection and SlabCutOpt software for optimal cutting and block analysis, this study recorded recovery ratios of up to 49.1%, 33.3%, and 47.5% for Grids 1, 2, and 3 based on the results of the SlabCutOpt algorithm. Comparisons of cutting tools indicated that diamond wire cutters offer a more sustainable option than chain saw cutters, with significantly reduced dust, water, and energy consumption. Economic analysis showed that marble blocks with larger volumes have a higher Relative Money Value (RMV), with the highest RMV at 21.8 for a 4.5 m³ block. In the case of Lombarda Marmi, all waste materials serve as raw materials for on-site cement production. Consequently, they are evaluated based on a recovery ratio of 100% or 1.0, rather than the computational results from the grid analyses performed in SlabCutOpt. Optimal block dimensions based on volume and waste reduction were identified for each grid. This research underscores the importance of integrating advanced tools, like GPR and optimization algorithms and friendly environmental practices before extracting dimensional stone blocks to improve resource extraction efficiency and sustainability in ornamental stone quarrying.*

Keywords: *Production optimization; Stone cutting; Marble quarry; GPR; Optimal block dimension*

1. Introduction

Quarries are fundamental to the construction industry, providing essential raw materials for infrastructure development [1]. However, the extraction of resources from quarries is often associated with challenges, including the presence of discontinuities alias fractures within the rock formations. Fractures not only affect the structural integrity of the rock but can also have implications for the safety of quarry operations [2]. The potential shapes and volumes of primary blocks are significantly affected by both the orientation and the respective spacing of discontinuities. [3, 4].

Integrating AI into GPR-based fracture detection can enhance the accuracy and speed of analysis [1, 5]. Machine learning algorithms can be trained to recognize patterns indicative of fractures, allowing for real-time identification and classification [6, 7, 8]. The synergy between GPR and optimization algorithms, therefore, holds the potential to revolutionize fracture detection in quarry operations [2, 9]. The goal of this article is to assess the potential benefit of combining GPR and AI or optimization algorithms in detecting fractures within the Botticino Quarries. The objectives of this paper are to:

- Assess the effectiveness of GPR technology in detecting and characterizing fractures within the quarry rock formations at Botticino.
- Employ and optimize machine learning algorithms, SlabCutOpt [8, 10], developed at the University of Bologna, capable of efficiently processing GPR and ParaView data for real- time identification and classification of fractures for the Botticino Quarries.

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- Evaluate the extent to which the integration of GPR contributes to optimizing quarry productivity, considering factors such as the development of block models on a given bench (number of fractured or intercepted and unfractured or non-intercepted blocks).
- Compare the economic, environmental, and operational cost benefits of utilizing advanced fracture detection technologies (GPR) using two distinct cutting tools, the diamond wire cutter and the chain saw cutter widely employed in quarry operations.
- Investigate the role of GPR in reducing environmental anomalies associated with quarry operations analyse the potential environmental benefits of improved fracture detection and compute the European Union (EU) Ecolabel Scoring or certification for the Botticino Quarries.

By achieving these objectives, the research aims to contribute valuable insights to the quarrying industry, offering a practical and technologically advanced approach to fracture detection and management.

2. Materials and methods

2.1. Site description

This study investigates three distinct areas (Grids) within a single quarry bench of the Botticino marble quarries. These open-pit dimensional stone quarries are located in the Botticino, Rezzato, and Mazzano region, to the east of Brescia in the Lombardy Province of Northern Italy (Fig. 1). The marble consists of compact micritic limestones that have been partially dolomitized and feature stylolites. It forms thick beds that range in color from ivory to grey or cream. This stone is classified as a metamorphic rock, resulting from the metamorphism of sedimentary rocks, predominantly limestone [11, 12]. The study area, Lombarda Marmi Srl Quarry, is situated at 45°32′56″ N and 10°19′02″ E at an elevation of about 240 m above Mean Sea Level (MSL).

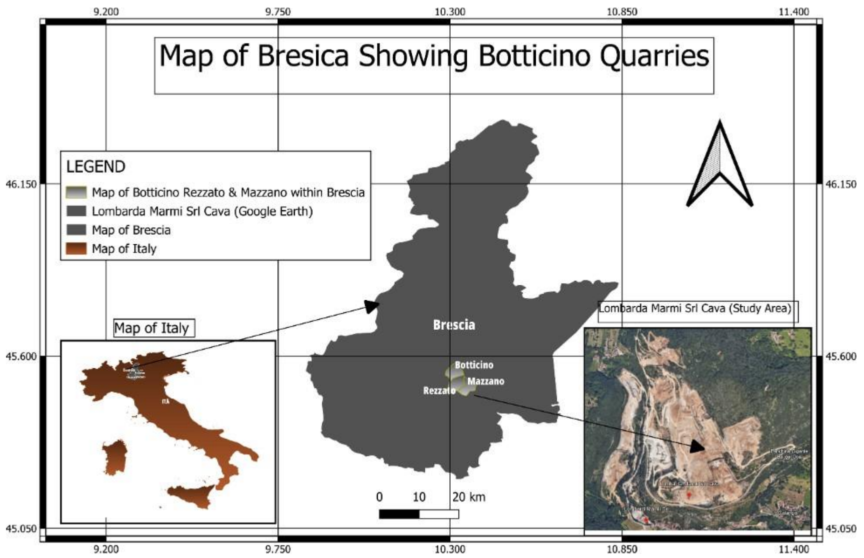

Fig. 1. Map of study area showing the Lombarda Marmi Srl. Quarry in Brescia

Italy's geological landscape boasts a diverse range of rock types, which has served as a valuable resource for building materials throughout history. The country ranks among the top producers of dimension stones globally and excels in developing advanced techniques for quarrying, cutting and finishing these materials [13]. Approximately 4,900 quarries are currently operational in Italy, with a significant concentration of these sites located in just two regions. Lombardy and Veneto collectively host over 1,000 licensed quarries, accounting for about 25% of the country's total active quarrying operations [14]. The European Commission (EC) reports that Europe accounts for roughly 35% of global natural stone production, with Italy, Greece, Spain, and Portugal collectively responsible for more than 80% of this European output [12]. Italy accounts for 3.80% of the global production of dimension stones [15]. According to [16] the mining and quarrying industry provided jobs for 22,000 individuals in 2019, representing approximately 0.4% of the nation's workforce.

2.2. Field data acquisition

Data acquisition of the Botticino Quarry topography and fractures and/or discontinuities mapping began with a geophysical Survey – using a non-destructive geophysical survey technique, the GPR, Total Station, and Light Detection and Ranging (LiDAR) instrument to map out the study area. The GPR instrument used in the Botticino quarry was the Multi-frequency Georadar Opera Duo, 200-900 MHz, from IDS Georadar.

To achieve the ultimate objective of acquiring a geo-reference for both the 2D and 3D models, Lidar technology was employed as part of Slam modelling **(**Fig. 2).

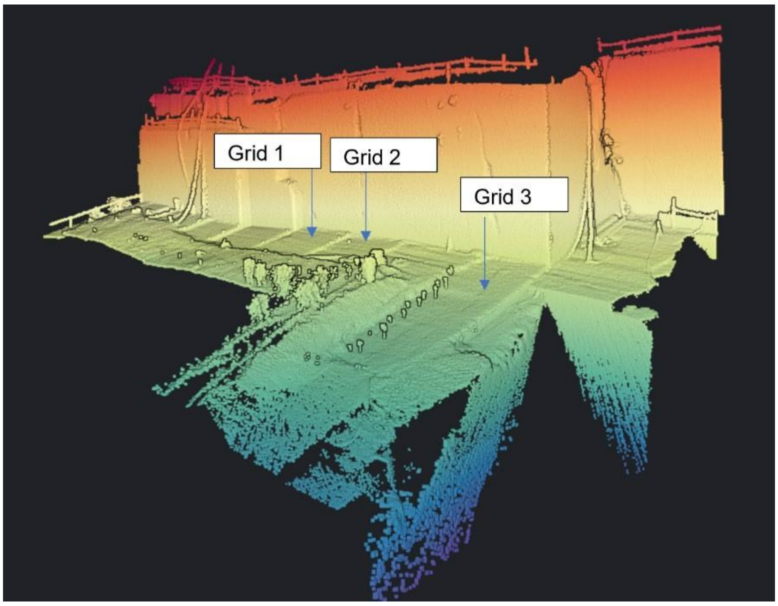

Fig. 2. A 3D representation of the quarry bench obtained with LIDAR survey

The purpose of the GPR and LiDAR technological application is to identify discontinuities within the rock mass, test the ability to follow the discontinuity up to its maximum depth and, depending on the geometry and analysable limit size of the discontinuity, and understand the extension of the discontinuity. Horizontal delamination or vertical cracks were also sought in the calcareous block in situ, lying in the quarry as a structural part subjected to extraction.

The acquired GPR data were further subjected to the application of filters and analysis. The analysis was conducted by applying digital filters of the type: Band Pass in the time domain with extremes between 200 MHz and 900 MHz, followed by soil sampling, then background removal to better define the data and a signal gain of equalizer, with a 1.00 m step application.

After obtaining GPR data and digitally filtering and processing the images (Swaths), the subsequent phase involved characterizing, extracting, and modelling fractures using AutoCAD 2023.

2.3. ParaView input data and files

The input files for ParaView are both the generated ***'vtu'*** files from the SlabCutOpt software for each cutting grid and the triangular fracture sets (Fig. 4) earlier converted to ***'.ply'*** developed and visualized in ParaView.

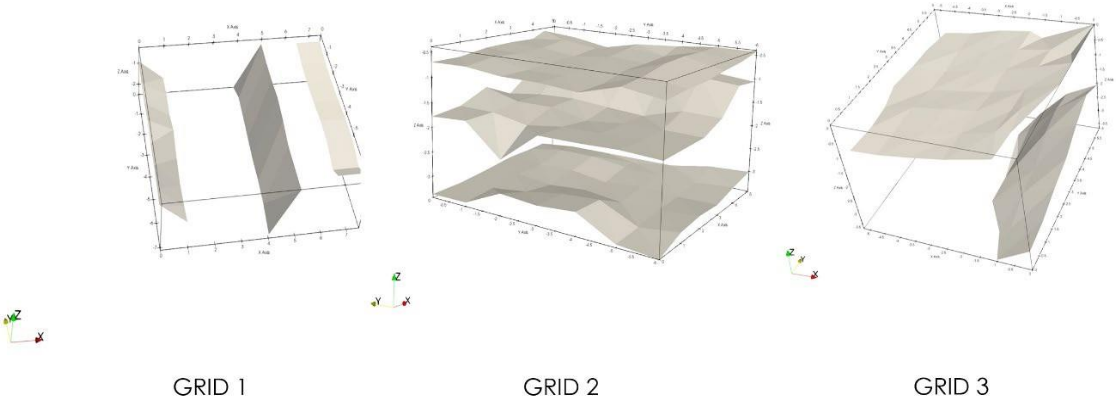

Fig. 3. Triangular fracture sets for the three grids examined in ParaView 5.10.

2.4. Optimization algorithms

The *SlabCutOpt* software developed by [17] at the University of Bologna, is used as optimization tool. The SlabCutOpt Software, written in C++ programming language, operates within a predefined domain, specifically the quarry boundaries and fractures.

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The SlabCutOpt software generates two types of output files. First, the *'Results.log'* file, where each line provides information such as the orientation of the cutting grid, the applied translation, the count of blocks within the domain, and the total number of blocks with or without intersected fractures. The software generates *'.vtu'* files for each cutting grid produced as second output file. These *'.vtu'* files are created to facilitate 3D visualization. Each block in the generated cutting grid is assigned a color corresponding to its rock type, aiding in the straightforward identification of blocks within the domain, intersected blocks, and non-intersected blocks. The output of the ParaView software is the 3D visualization of the combined intersecting blocks and non-intersecting blocks with the triangular fracture model (Fig. 4).

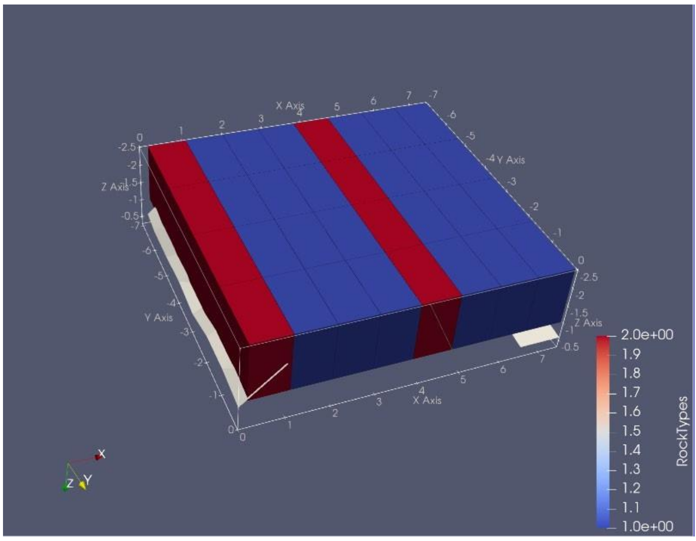

Fig. 4. 3D visualization of the quarry bench showing fracture surfaces (colored in grey), fractured blocks (colored in red), and unfractured blocks (colored in blue)

3. Results and discussion

3.1. Block analysis

Standard dimensions of a commercial block size range between 2.00 m x 1.00 m x 0.50 m and 3.00 m x 2.00 m x 1.00 m [18]. Based on industrial standards in the dimension stone industry, ten (10) hypothetical block dimensions (No.0 – No.9) were adopted for analysis in this paper. Table 1 presents the hypothetical dimensions of the blocks including block surface area and block volume computed for the three grids. The area and volume were calculated using equations (1) and (2) according to [8, 17].

$$A = 2ab + 2bc + 2ac \quad (m^2) \tag{1}$$

$$V = a * b * c \quad (m^3) \tag{2}$$

where A = Surface Area (m²), V = Volume (m³), and a, b, c = Dimensions of the block (m) which corresponds to X, Y, and Z dimensions.

Table 1. Hypothetical block dimensions adopted for the Lombarda Marmi case study

Block ID	**X-Dim (m)**	**Y-Dim (m)**	**Z-Dim (m)**	**Surface Area (m²)**	**Volume (m³)**
0	2.01	2.01	1.11	17.00	4.48
1	2.01	1.51	1.51	16.70	4.58
2	1.51	1.51	1.51	13.68	3.44
3	2.01	1.21	1.21	12.66	2.94
4	1.76	1.51	0.91	11.27	2.42
5	1.76	0.81	1.26	9.33	1.80
6	1.21	1.21	1.21	8.78	1.77
7	1.51	1.01	0.76	6.88	1.16
8	1.51	0.76	0.76	5.75	0.87
9	0.76	0.76	0.76	3.47	0.44

3.2. Recovery ratio vs block volume

Recovery ratio (also termed as extraction efficiency ratio according to the EU ecolabel criteria) is the quantity of marble blocks produced to the waste rock (i.e., overburden and dust) removed to produce a refined unit of a marble block. The recovery ratio is an important metric for understanding mine wastes and environmental burdens [18].

The extraction efficiency ratio shall be at least 0.50 or 50% to meet the EU eco-label criteria and certification [19]. The ore recovery ratio can be expressed using equations (3 - 5) according to [8, 20]:

$$V_{usable} = No_{Non-Intersect} * V_{block} \quad (m^3) \tag{3}$$

$$V_{Waste} = V_{bench} - V_{usable} \quad (m^3) \tag{4}$$

$$R = \frac{V_{usable}}{V_{bench}} * 100 \quad (\%) \tag{5}$$

where:

V_{usable} = Total Usable Block Volume (m³)
V_{bench} = Total Bench Volume (m³)
V_{block} = Volume per block (m³)
No*Non-intersect* = Number of unfractured blocks
V_{waste} = Total Waste Volume (m³)
R = Recovery Ratio (%)

3.3. Grids

For each Grid (1-3), based on the above Eq. *(4)*, the total usable volume and the total waste volume were first computed to be able to calculate the Ore Recovery Ratio. The assumption is that each block would be extracted and utilized with an optimum solution from the bench. The results of the total usable volume and the total waste volume and recovery ratio for Grid 1 are presented in Table 2.

Table 2. Usable block volume, waste volume, and recovery ratio calculations for Grid 1

Block ID	Volume (m³)	Total no. of Blocks	No. of Unfractured Blocks	Total Usable Volume (m³)	Total Bench Volume (m³)	Waste Volume (m³)	Recovery Ratio (%)
0	4.48	18.00	9.00	40.36		77.86	34.14
1	4.58	12.00	8.00	36.66		81.56	31.01
2	3.44	16.00	8.00	27.54		90.68	23.30
3	2.94	15.00	12.00	35.31		82.91	29.87
4	2.42	32.00	24.00	58.04	118.22	60.18	49.10
5	1.80	40.00	32.00	57.48		60.74	48.62
6	1.77	25.00	20.00	35.43		82.79	29.97
7	1.16	72.00	47.00	54.48		63.74	46.08
8	0.87	72.00	54.00	47.10		71.12	39.84
9	0.44	162.00	121.00	53.12		65.10	44.93

According to the results obtained for Grid 1, the block dimension with the best recovery ratio was block dimension No. 4 with a recovery ratio of 49.10% and a corresponding block volume of 2.42 m^3 followed by block dimensions No. 5 and No. 7 with recovery ratios of 48.62% and 46.08% corresponding to 1.80 m^3 and 1.16 m^3 of volume for each block, respectively. Fig. 5 a & b shows the graphical representation of the recovery ratio against block volume. The trendline shows slightly decreasing recovery ratios with increasing block volumes.

3.4. Environmental analysis

The environmental analysis covered key environmental issues in ornamental stone quarrying operations such as dust generation, water consumption energy consumption, and / or carbon emission or footprint.

Dust generation

Dust generation for all three Grids was plotted against block volumes based on the ten hypothetical block dimensions adopted for this case study. The total dust generated, expressed in percent from the total bench volume was computed considering the thickness of the cutting tool or method used and a comparison was drawn between the use of the Dazzini QS4000D Chain-saw Cutter and the Kaptanlar ETK-80S Diamond Wire Cutter.

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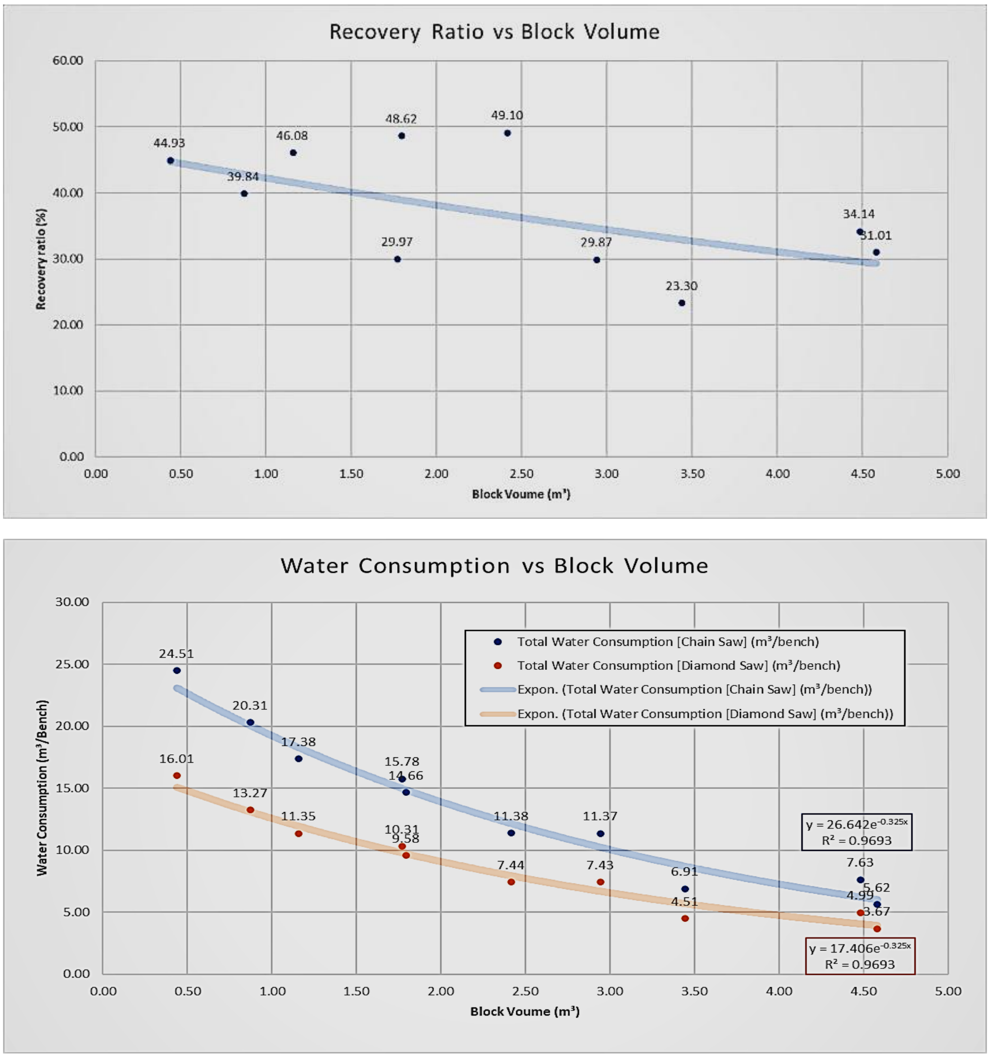

Fig. 5. Recovery ratio versus block volumes for Grid 1 (a); water consumption (b)

Water consumption

Water usage for all three Grids was plotted against block volumes based on the ten hypothetical block dimensions adopted for this case study. The quantity of water consumed, expressed in m³/ bench was computed considering the cutting speed and water consumption rate as key parameters of the cutting tool or method used and a comparison was drawn between the use of the Dazzini QS4000D Chain-saw Cutter and the Kaptanlar ETK-80S Diamond Wire Cutter. The graphs as shown in Fig. 6 depict that the diamond wire-cutting tools the diamond wire cutter consume less water per bench compared to the chain saw.

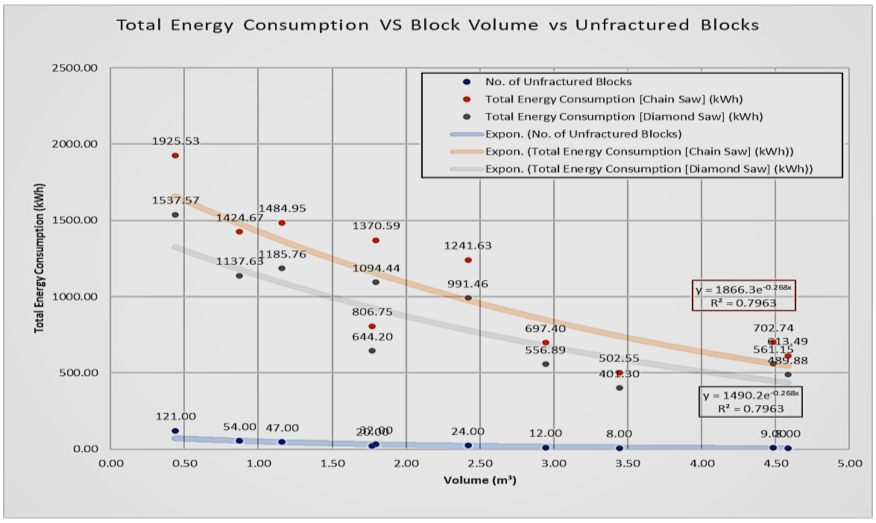

Fig. 6. Comparison of diamond wire cutter versus chain saw cutter for total energy consumed against block volume

Energy consumption and carbon dioxide emissions

Energy consumption for all three Grids was plotted against block volumes based on the ten hypothetical block dimensions adopted for this case study. The total energy consumed, expressed in kWh was computed based on the cutting speed and average motor power as key parameters of the cutting tool or method used the diamond wire cutter, the highest total energy consumption was obtained with the block dimension No.9 with a total energy consumption of 1537.57 kWh corresponding to a total CO_2 emission of 678.07 kg CO_2 (Fig. 6).

3.5. Economic analysis

The economic assessment of the Botticino marble quarry is determined by calculating the Relative Monetary Value (RMV), which combines the selling price and total revenue, along with the production cost associated with each block size adopted. To evaluate the quarry's profitability, the researchers utilized the results from the SlabCutOpt software, which identifies the maximum number of intact blocks achievable for various dimensions. This data was then analysed in conjunction with the overall earnings and production costs to draw conclusions about the quarry's economic viability.

For all three Grids (1-3), the computation depicts a higher RMV per block or slab with higher surface area and/or volume. The exponential fit (trendline) shows an increasing RMV per block with increasing block volumes. The Highest RMV per block, 21.75, was for block dimension No.0 (dimension 2.01 m x 2.01 m x 1.11 m) with a surface area of 17.00 m^2 and volume of 4.48 m^3.

The total RMV for all three Grids is plotted against the block surface area based on the ten hypothetical block dimensions adopted for this case study. The total RMV was computed as the product of the number of unfractured or non-intercepted blocks for the various dimensions adopted and the RMV per block previously calculated. For all three Grids, the quantity of unfractured blocked significantly influenced the total RMV calculated and/or projected.

For Grid 1 (Fig. 7), block dimension No.9 was found to have the highest total RMV value of 534.79.

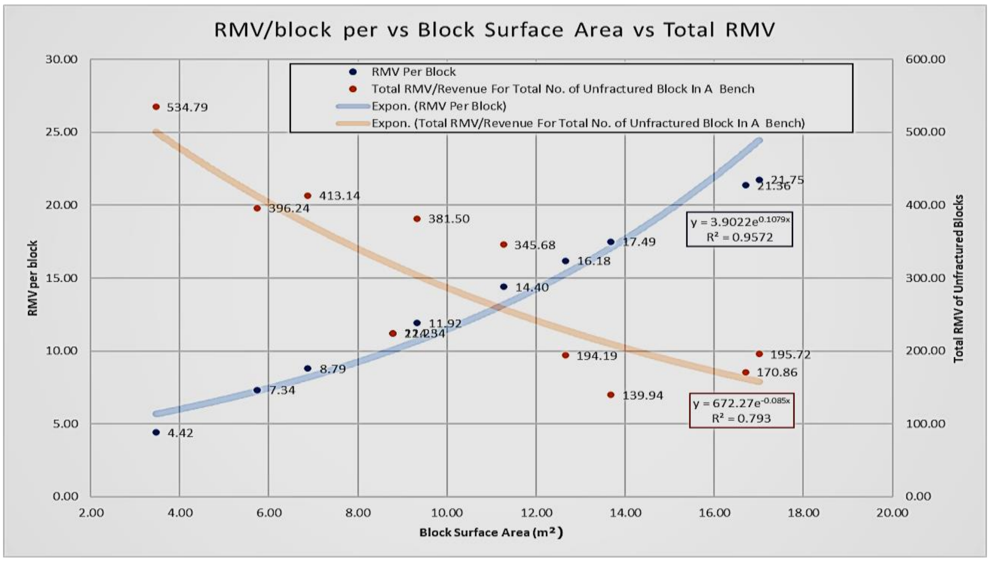

Fig. 7. Relative Money Value per block vs total RMV vs block surface area (Grid 1)

3.6. Total production cost vs block volume

The expense associated with extracting a marble block from a quarry is referred to as the production cost. It is crucial to determine the ideal point where production expenses, waste, and total RMV converge [8].

For all three Grids (Fig. 8), the results show a higher cost of production per marble block with a larger surface area and vice-versa. When blocks with smaller surface areas are selected, this results in an increase in production costs because there are more blocks to be extracted.

3.7. Optimal block volume based on environmental and economic feasibility

This research aimed to find a balance between increasing quarry productivity and at the same time reducing waste produced during ornamental stone production. Based on the above results and computations, the best optimal solutions for each grid of the examined quarry bench in Botticino are tabulated in terms of the optimal dimension of usable volume and the optimal dimension of waste volume.

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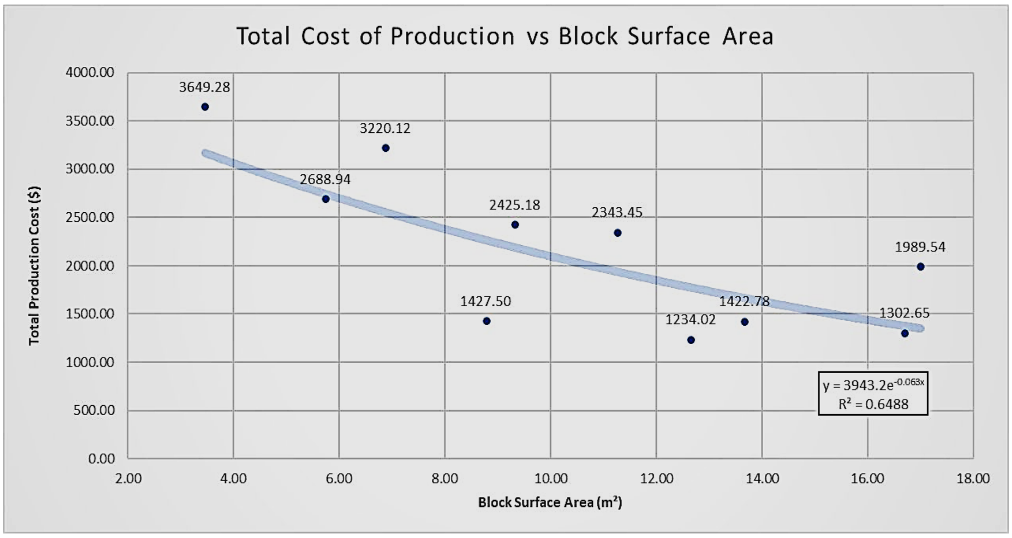

Fig. 8. Production cost vs block surface area

3.8. European Union (EU) ecolabel score for Botticino Quarry

The guidelines for stone quarrying under the Ecolabel Standards are governed by Commission Decision (EU) 2021/476, issued on March 16, 2021. As the European Union's official mark of environmental distinction, the EU Ecolabel is granted to products that demonstrate sustainable design, repairability, and resource conservation. These products also foster innovation and contribute to the EU's circular economy initiative and its aim to achieve climate neutrality by 2050. Products certified with the EU Ecolabel adhere to rigorous standards that minimize their environmental impact throughout various phases of their lifecycle, including raw material extraction, production, usage, and disposal. Table 3 outlines the criteria necessary for obtaining the Eco Label certification [19]. The EU Ecolabel criteria for hard covering products is divided into two sections. The first section covers only extraction of blocks. The scoring is on a 60-point scale and certification is awarded at a minimum of 30 points. The second section covers extraction and transformation into final products. The scoring is on a 100-point scale and certification is awarded at a minimum of 50 points.

Table 3. Criterion as established by the EU Ecolabel standard

Criteria where points can be awarded	**Intermediate blocks or slabs of dimension stone (Points)**	**Final transformed natural stone hard covering products (Points)**
1.7. Environmental Management System of the quarry (optional)	0 or 3 or 5	N/A
1.7. Environmental Management System of the transformation plant (optional)	N/A	0 or 3 or 5
2.1. Energy consumption at the quarry	Up to 20	Up to 20
2.2. Material efficiency at the quarry	Up to 25	Up to 25
2.6. Quarry landscape impact ratios (optional)	Up to 10	Up to 10
2.7. Energy consumption at the transformation plant	N/A	Up to 20
2.8. Water and wastewater management at the transformation plant	N/A	Up to 5
2.10. Reuse of process waste from the transformation plant	N/A	Up to 10
2.11. Regionally integrated production at the transformation plant (optional)	N/A	Up to 5
Total maximum points	**60**	**100**
Minimum points required for EU Ecolabel	**30**	**50**

There are currently 98,977 products awarded with the EU Ecolabel Certifications and 2,983 licences issued to companies, but only 16 of these products come from the quarrying and dimensional stone sectors [19]. This highlights a significant underrepresentation of sustainability efforts within this industry. Spain leads with 14 certified companies, while Germany has 2. However, countries like Italy, Turkey, and Romania—which are prominent in quarrying and dimensional stone operations, have none. This gap underscores the urgent need to encourage quarry operators in these countries to pursue eco-label certification, given their extensive and dominant roles in the sector.

To assess the EU Ecolabel criterion for the Lombarda Marmi Quarry in Botticino, a streamlined Excel worksheet (Table 4) has been created. The extraction efficiency, also known as the recovery ratio, is considered the most crucial indicator for ornamental or dimension stone quarries [19]. It's important to note that the quarry's extraction efficiency ratio, as calculated by the SlabCutOpt software, is not the sole parameter used in the simplified scoring sheet. According to the criterion, a maximum of 25 points can be awarded based on how much the applicant demonstrates a higher extraction efficiency ratio, up to the environmental excellence threshold of 1.00. This threshold indicates that all waste materials are utilized as primary materials by other industrial partners. In the case of Lombarda Marmi, all waste materials serve as raw materials for on-site cement production. Consequently, they are evaluated based on a recovery ratio of 1.00, rather than the computational results from the grid analyses performed in SlabCutOpt.

The article's focus is restricted to quarry operations, excluding the transformation of slabs and blocks into finished products. Consequently, the Simplified Eco-label certification criteria will only apply to quarry sites, disregarding activities at transformation facilities. To comply with EU Ecolabel standards, applicants must submit a series of declarations when seeking licensure or eco-label certification.

Table 4. Eco-label Criteria Evaluation for Botticino

Eco-label Criteria Evaluation for Bottincino			**Eco-label (Points)**	**Botticino (Points)**
ID	**Description**	**Criterion**		
1.7	Environmental Management System of the quarry (optional)	Valid ISO 14001 certificate	3	3
		EMAS registration and accreditation	5	0
		0% Renewable Energy Sources	0	0
		100% Renewable Energy Sources	0	0
		Private energy service agreements for on- site or near-site renewables	5	0
		Corporate power purchase agreements for on-site or near-site renewables	5	0
		Long term corporate power purchase agreements for grid-connected or remote grid renewables	4	0
2.1	Energy consumption at the quarry	Green electricity certifications	3	0
		Green tariff from utility supplier	2	0
		Carbon footprint analysis in accordance with ISO 14067	3 5	0 0
		Product Environmental Footprint method's elements related to greenhouse gas emissions		
2.2	Material efficiency at the quarry	Extraction efficiency ratio = 1.00	25	25
2.6	Quarry landscape impact ratios (optional)	Quarry footprint ratio = 0.20	5	3.6
		Beneficial land use ratio = 0.40	5	0
Total Maximum Points			60	**31.6**
Minimum Points for EU Eco-label Certification			30	< **31.6**

4. Conclusion

This study provides an additional perspective on production optimization in dimensional stone quarries by examining three sections (Grids) of the same quarry bench, developing a simplified Eco-label scoring based primarily on ore recovery ratio, and predicting environmentally optimal cutting dimensions in terms of maximum usable volume and minimum waste volume coupled with the most suitable cutting tool selection for a Botticino marble quarry owned and operated by Lombarda Marmi Srl, located east of Brescia, Province of Lombardy, Northern Italy. This research offers a comparative analysis of economic, environmental, and operational cost benefits associated with the implementation of a highly recommended and advanced non-destructive fracture detection technology, Ground Penetrating Radar, in quarry optimization. A comparison was conducted using two widely employed cutting tools in quarry operations: The Dazzini QS4000D Chain-saw Cutter and the Kaptanlar ETK-80S Diamond Wire Cutter, which is environmentally favorable than its

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counterparts. The use of non-destructive measurements like GPR allows fracture detection in the bench. The production optimization can be improved by recursive algorithms that can find an optimal solution to maximize the production, reduce the waste generation and, in general, reduce the environmental impact of the quarry by reducing water consumption, dust generation, noise and other related environmental problems usually associated by a quarry. This work shows that the software SlabCutOpt, developed at the University of Bologna, can efficiently be used to evaluate an optimal quarry cut design, able to improve the efficiency of the quarry.

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