



DISCRETE FRACTURE NETWORKS AND ENVIRONMENTAL PERFORMANCE IN ORNAMENTAL ROCK QUARRIES

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Abstract: *This contribution investigates the role of fracture networks in controlling both operational efficiency and environmental performance in ornamental rock quarries. The study integrates structural geology, rock mechanics, and environmental assessment within a digital workflow based on high-resolution terrain models derived from aerial and terrestrial point cloud surveys. Multisource 3D datasets are processed to generate detailed Digital Elevation Models that capture the real geometry of quarry benches, highwalls, and extraction platforms. On this geometric framework, an automated procedure is applied to detect and characterise rock mass discontinuities directly on quarry surfaces. The resulting structural information allows the identification of dominant fracture sets, their orientations, spacings, and persistence, and their influence on block-size distribution and rock fabric. The derived fracture parameters are further used to support the construction of discrete fracture network models and to evaluate their implications for extraction strategies, quarry layout optimisation and slope stability. Beyond purely mechanical considerations, the study explores how rock mass structure influences key environmental indicators throughout the quarry life cycle. These include the generation of mining waste, recovery rates of marketable stone, industrial water consumption, energy demand, dust production and the associated carbon footprint per unit of product. Case studies from ornamental stone operations illustrate how integrating structural analysis with digital terrain modelling and environmental monitoring enables the definition of quarry-specific performance metrics. The results demonstrate that fracture-controlled quarry planning can significantly improve resource efficiency, reduce environmental impacts and support more sustainable closure and rehabilitation strategies [1], [2], [3].*

Keywords: *discrete fracture networks, cutting grids, ornamental stone quarry, diamond-wire cutting, block recovery rate, water consumption, CO₂ footprint*

1. Introduction

Ornamental stone commands the highest market value per unit mass in the extractive industry, yet paradoxically exhibits the lowest material-recovery rates. Industry surveys converge on roughly 51% of in-situ material being lost as waste during quarrying, and an additional 41% during transformation, leaving an overall recovery rate of around 29% [4], [5], [6], [7].

The primary culprit is not the cutting technology per se, but its misalignment with the natural in-situ fracture network: any block traversed by a single persistent discontinuity is relegated from premium dimensional stone to mere aggregate or fill.

Consequently, cutting decisions without an explicit fracture model inevitably propagate preventable losses of water, energy, and carbon emissions throughout the entire production chain.

The AI-COSTSQO project (ERA-MIN) was designed around this premise.

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Five partner quarries spanning two lithological families and three countries - Botticino (Italy, marble), Onur Marble Finike (Turkey, marble), Rușchița (Romania, marble), Carpinis (Romania, travertine) and Pietroasa (Romania, andesite), provide the calibration set for a Software-as-a-Service platform that converts in-situ discontinuity measurements into Discrete Fracture Networks (DFNs), proposes alternative cutting grids, and ranks them by environmental performance [4], [7].

This paper formalises the environmental-performance layer of that workflow. The Botticino marble quarry serves as the primary demonstration site because its carbonate "Corna" lithology is extracted using conventional diamond-wire and chainsaw technologies, marble dust is not classified as a pollutant in the Lombardy permit framework, allowing isolation of waste-volume effects from chemical-pollution effects, and ten years of grid-level cutting records are available in machine-readable form.

Ruschita and Carpinis provide benchmarks: structural at the Ruschita marble face, and geophysical at the Carpinis travertine bench. Pietroasa demonstrates the transferability of the DFN engine to silicate rock dust and slurry [4], [5], [8], [9].

The contributions of this paper are threefold.

First, we bridge the gap between microscale in-situ fracture statistics and macroscale cutting-grid performance by linking the three crack-structure scenarios observed at Botticino to practical extraction scales through Crack Structure 1, for which block-recovery rates as a function of block volume are derived directly from project field data.

Second, we recompute across three adjacent grid sections of the same Botticino bench the four core environmental indicators mandated by EU Ecolabel applications, extracted volume, usable volume, waste volume, and recovery rate, together with volume-normalised water consumption and CO₂ footprint under diamond-wire and chainsaw scenarios.

Third, we detail the reweighting protocols required to transfer these indicators to the Romanian benchmark sites Ruschita marble and Carpinis travertine, where differences in dominant cutting technology (diamond wire), lithology, and receptor environments (e.g., headwaters vs. Quaternary deposits) necessitate site-specific adjustments.

2. Study Sites and Datasets

2.1 Botticino marble quarry (Lombardy, Italy) - primary site

The Botticino quarry complex spans the municipalities of Botticino, Nuvolento, Nuvolera, Serle, and Paitone. The exploited lithology is the karstic "Corna" carbonate unit, marketed as Botticino Classico and Semiclassico marble. Geologically, the Corna unit is a Mesozoic carbonate limestone that is commercially classified and marketed as Botticino "marble".

The bench geometry analysed herein corresponds to a single working face from the AI-COSTSQO field campaign - a subvertical wall subjected to scanline mapping and to the co-registration of a structure-from-motion photogrammetric point cloud with a terrestrial laser-scanning point cloud.

A 3D digital surface model of the face was derived from these point clouds and segmented to retain the bare rock surface for discontinuity-set extraction solely.

The face was further processed to robustly extract three discontinuity systems using two independent algorithmic chains for enhanced reliability: K-D Tree and Fast Marching surface-normal classification within CloudCompare, and Discontinuity Set Extractor, which combines a Kernel Density Estimation step on stereographic poles with a DBSCAN family-clustering step.

These methods produced consistent results across chains and were independently validated against structural benchmarks from the Ruschita marble quarry.

The three resulting crack structures are the basis for the cutting-grid scenarios analysed in section 4.1. The Botticino TLS and SfM point clouds are publicly browsable via the project's point cloud server, enabling third-party verification and reproducibility [10], [11], [12].

2.2 Ruschita marble quarry (Caras-Severin, Romania) - structural benchmark

Ruschita quarry extracts metamorphic marble from the Poiana Rusca massif, located in the headwaters of Racului Creek. The operating area spans 0.286 km².

Primary block detachment employs diamond-wire cutting. Within the AI-COSTSQO project, Ruschita provides the structural benchmark - scanline mapping across multiple bench levels, augmented by optical televiewer logs from two boreholes drilled behind the working face.

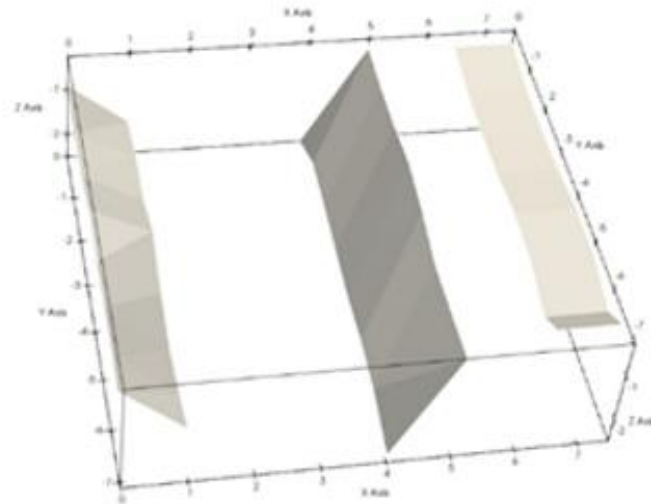


Fig. 1. Vertical wall at Botticino quarry for scanline mapping and TLS/ SfM point cloud segmentation

These datasets calibrate the distributions of orientation, spacing, and persistence that input the DFN engine and furnish independent validation of the photogrammetric discontinuity extraction at Botticino.

Long-term records indicate approximately 72,700 m³ of bench-scale waste generated annually [7], [9], [11].

2.3 Carpinis travertine quarry (Hunedoara, Romania) - geophysical benchmark

Carpinis quarry exploits a Quaternary travertine sequence in Hunedoara County, Romania. Unlike marbles, this deposit is markedly more porous and less mechanically uniform, causing surface fracture measurements alone to substantially underestimate persistence at depth.

Carpinis thus supplies the critical geophysical benchmark for the workflow: ground-penetrating radar profiles, multi-electrode electrical resistivity tomography, and seismic refraction lines acquired across the bench surface, both perpendicular and parallel to the dominant strike reveal fracture corridors and karst voids undetectable by scanline methods alone.

This multi-method integration validates DFN extrapolations into heterogeneous subsurface regimes. Recorded annual waste averages 2,160 m³, over an order of magnitude below Ruschita's 72,700 m³, yet includes a disproportionately high slurry fraction from carbonate dust, underscoring the need for lithology-specific waste accounting in environmental indicators [4].

2.4 Pietroasa andesite quarry (Hunedoara, Romania) - silicate transferability site

Pietroasa quarry exploits an andesite intrusive complex over an area of 854436 m². Annual waste from 2000 to 2022 averaged 1,443 m³. Pietroasa is included in this paper not as a primary case but as a silicate-lithology transferability test: marble dust is treated as inert by Lombardy environmental regulators, whereas silicate dust contributes free crystalline silica and must be modelled separately in the air-quality module of the workflow [4], [13].

2.5 Project context and additional partner site

Onur Marble Finike, the fifth AI-COSTSQUO partner quarry, contributes a Mediterranean-marble field dataset that broadens the project's lithological and geographical scope beyond Central and Eastern European sites.

Although not analysed in detail here, its bench geometry and dust regime provide a critical external validation case for the workflow's transferability within the project's SaaS platform.

Key deliverables include the AI-COSTSQUO web portal and a public point-cloud server hosting the Botticino, Ruschita, and Carpinis datasets, ensuring reproducibility and third-party access [4], [7], [8], [12].

3. From Field Measurements to Environmental Indicators

3.1 Discontinuity extraction

Three independent data sources are integrated at each site. Scanline mapping along the bench foot provides a one-dimensional sample of orientation and spacing with minimal directional bias.

Photogrammetric (structure-from-motion) and terrestrial laser-scanning point clouds, processed in Agisoft Metashape (for SfM) and CloudCompare (for classification), provide two-dimensional samples after vegetation removal and surface normal computation (e.g., Hough Normals) [12].

Where available, optical televiewer logs from boreholes and geophysical profiles (ERT/ seismic refraction) contribute a subsurface dimension.

At Botticino, the dominant input is the bare-rock segmented point cloud derived from co-registered TLS and SfM data of the bench wall, classified via K-D Tree and Fast Marching surface-normal methods in CloudCompare and complemented by the Discontinuity Set Extractor pipeline [4], [6], [12].

Three principal discontinuity sets are retained; persistence and spacing for each are characterised by fitted probability distributions.

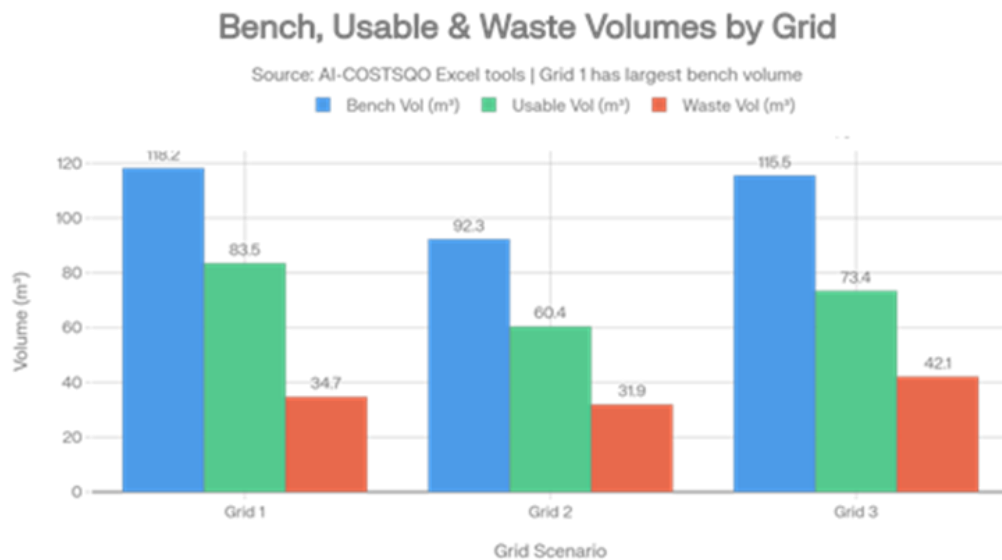


Fig. 2. Botticino, Joint Structure 1: bench, usable, and waste volumes for Grids 1–3. Grid 1 has the largest bench volume; Grid 2, the lowest waste-to-bench ratio but the smallest absolute recovery

3.2 DFN generation and validation

The fitted statistical distributions drive a stochastic Discrete Fracture Network generator, which iteratively places fractures within the bench volume until the simulated trace-length, orientation, spacing, and persistence statistics match the field-measured statistics within a specified tolerance.

The DFN module has been re-implemented as a back-end service within the AI-COSTSQO SaaS portal. Validation employs trace-line resampling: virtual scanlines are simulated across the synthetic DFN, with the resulting distributions of orientation, spacing, and persistence compared against those from field scanlines. In this implementation, fracture persistence for each set is represented by a lognormal distribution calibrated to field-measured trace lengths on the Botticino bench.

At Botticino, the simulated spacings for the three principal discontinuity sets reproduce the field-measured spacings with relative errors below 10% [9] [13].

3.3 Cutting grids and recovery

Once a DFN is generated, a candidate cutting grid is superimposed on the bench volume. Resulting blocks are classified as massive (NONI - no fractures intersecting) or fractured.

Only NONI blocks contribute to the usable volume; fractured blocks are classified as waste. The recovery rate for a grid is thus defined as the ratio of usable volume to total bench volume. Per the project convention, "Joint Structure 1" denotes the principal discontinuity scenario at Botticino used in the demonstration below; Structures 2 and 3 represent alternative interpretations retained for sensitivity analysis [5], [11].

3.4 Environmental indicators per grid

Four key environmental indicators are computed for each candidate cutting grid as follows:

- Bench volume - geometric volume of the analysed bench cell, measured in situ (m^3);
- Usable volume - sum of volumes of NONI blocks (m^3);
- Water consumption - cutting-fluid volume required to extract the usable blocks (m^3), estimated as the product of required cutting time and tool-specific flow rate. Project measurement-campaign reference values are 2.02 m^3 of water per cubic metre of block for diamond-wire sawing and $4.71 \text{ m}^3/\text{m}^3$ for chainsaw cutting, which correspond to bench-scale totals of 38.31 m^3 and 89.57 m^3 of water per 6.25 m^3 block, respectively;
- Carbon footprint: total CO_2 emissions from electricity and fuel (kg), computed from installed power ratings and operating times. Per project convention, electricity is charged at the Romanian national grid emission factor of 0.441 kg CO_2 per kWh. The emission factor of 0.441 kg CO_2 per kWh corresponds to the Romanian national average used in the AI-COSTSQO baseline and is retained here for consistency with project-wide reporting [4], [8], [12].

4. Results - Botticino Grids 1 - 3

4.1 Discontinuity Structure Scenarios: Empirical Selection and Validation

Three joint structures were retained for the Botticino bench from the discontinuity extraction in section 3.1.

- Joint Structure 1 comprises two near-orthogonal subvertical sets and one shallow-dipping bedding-parallel set;
- Joint Structure 2 additionally emphasises a third oblique set;
- Joint Structure 3 consolidates the two subvertical sets into a single dispersed family.

Joint Structure 1 serves as the base-case scenario demonstrated here, as its simulated trace lengths best match those measured on the bench face. For Joint Structure 1, the recovery curve versus block volume computed block-by-block from the fitted DFN overlaid on the segmented point-cloud face is shown in Fig. 3 [9].

4.2 Grids 1, 2 and 3 - environmental indicators

Three adjacent grid sections (Grids 1 - 3) on the same Botticino bench level, each exhibiting distinct orientations relative to the principal discontinuity sets under the baseline Joint Structure 1 scenario, were rigorously evaluated to demonstrate DFN-guided grid optimisation.

As visualised in Fig. 2 and detailed in Table 1, their bench-scale volumes, DFN-derived usable and waste fractions, and corresponding water consumption and CO_2 emissions for diamond-wire sawing (the operational technology at Botticino) reveal substantial variability attributable to discontinuity alignment, with chainsaw values provided alongside for comparative benchmarking only [4].

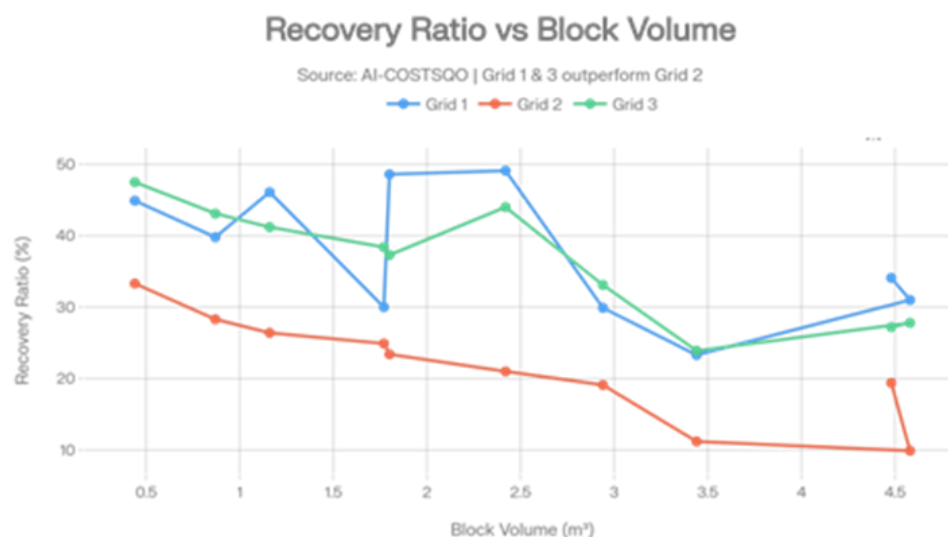


Fig. 3. Botticino, Joint Structure 1: recovery ratio vs. block volume. Block-by-block values from the segmented point-cloud face and fitted DFN decline monotonically from ~49% (smallest blocks) to ~31% (blocks $>4.5 \text{ m}^3$)

Three observations emerge from Table 1.

First, Grids 1 and 3 exhibit nearly identical recovery rates (36.4 and 35.7, respectively), demonstrating that grid orientation relative to the principal discontinuity sets dominates over absolute bench volume.

Second, Grid 2 achieves only 21.7% recovery, about 40% lower than Grids 1 and 3, because the high-persistence subvertical set bisects the cell, an outcome undetectable via purely geometric grid optimisation lacking DFN inputs.

Third, CO₂ emissions per m³ of usable volume range from 29 kg/m³ to 49 kg/m³, varying by nearly a factor of two; this reflects reduced cutting times when more slices align with pre-existing discontinuities.

Table 1. Botticino, Joint Structure 1: per-grid environmental indicators (diamond-wire sawing). Grids 1 and 3 have similar recovery rates; Grid 2 performs worst, bisected by the high-persistence subvertical set (4.1)

Grid	Bench V (m ³)	Usable V (m ³)	Waste V (m ³)	Recovery (%)	Water – DW (m ³)	CO ₂ – DW (kg)
Grid 1	118.2	83.5	34.7	36.4	122	3 793
Grid 2	92.3	60.4	31.9	21.7	89	1 769
Grid 3	115.5	73.4	42.1	35.7	108	3 610

4.3 Water and CO₂ budget per grid

Volume-normalised water consumption and CO₂ emissions for the three Botticino grids are summarised in Fig. 4 and Fig. 5.

Diamond-wire cutting consumes around 35% less process water than the chainsaw alternative on every grid, with the absolute saving largest on Grid 2 (49 m³ saved at the bench scale) because the high-persistence subvertical set pre-cuts much of the cell and reduces the number of full slices required [4], [9], [12].

The CO₂ panel is dominated by cutting time rather than by haulage; the chainsaw scenario emits roughly 25% more CO₂ per cell.

Grid 2 has the lowest absolute footprint in both panels, but the highest CO₂ per cubic metre of usable rock because of its low recovery rate.

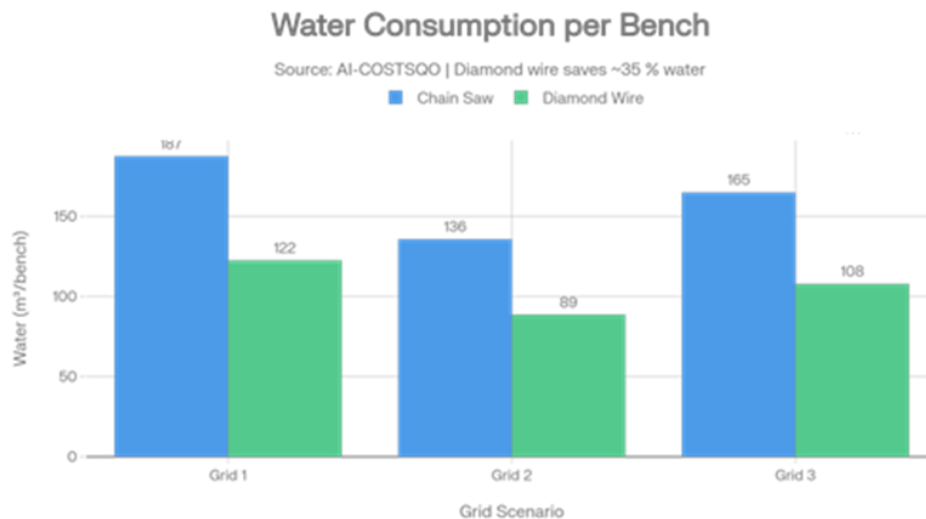


Fig. 4. Botticino, Joint Structure 1: per-bench water consumption for chainsaw vs. diamond-wire cutting across Grids 1 - 3. Diamond-wire saves ~35% process water at the bench scale; savings are largest on Grid 2, where the high-persistence subvertical set pre-cuts much of the bench

4.4 Block-size optimisation and dust budget

The grid analysis above fixes the block size and compares cells; the inverse exercise, fixing the cell and comparing block sizes, was conducted on the same Botticino bench using ten hypothetical block sizes between 0.40 x 0.40 x 0.40 m and 1.20 x 1.20 x 1.20 m. The ten modelled sizes form a regular progression from 0.064 m³ to 1.728 m³, with size No. 9 corresponding to a volume of approximately 0.76 m³, which is representative of sub-commercial pre-cut blocks rather than final marketed Botticino block dimensions. The relative monetary value per block and the total bench RMV were tracked as a function of block surface area, using a reference cost of \$6.50/m² for rough Botticino marble. Across all three grids, the highest count of unfractured blocks and the highest total RMV were obtained for size No. 9, which simultaneously incurred the highest

cutting cost, a classic Pareto trade-off between revenue and operating expense. On the air-quality side, PM₁₀ sampling at the perimeter of the Romanian benchmark site produced a reference value of 21.17 µg m⁻³ against a 50-µg m⁻³ regulatory limit. For Botticino, AERMOD was driven by site-representative meteorological data and calibrated against the Romanian perimeter PM₁₀ reference as a conservative check on overall model behaviour rather than as a strict site-specific validation. At Botticino, the dust budget was computed at source using AERMOD with point sources and line sources; for Joint Structure 1, total dust mass per cell varies between 4% and 11% of the bench volume, depending on the saw type and falls monotonically with increasing block size [4], [7], [12].

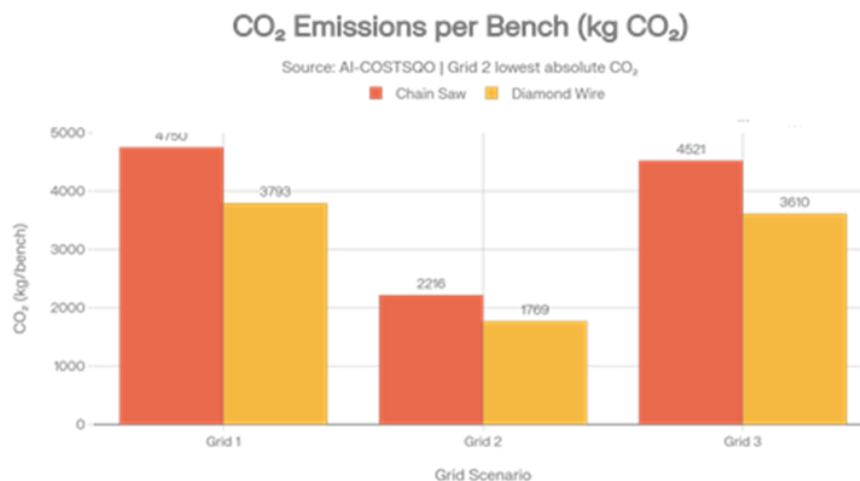


Fig. 5. Botticino, Joint Structure 1: per-bench CO₂ emissions for chainsaw vs. diamond-wire cutting across Grids 1 - 3. Grid 2 has the lowest absolute emissions; Grids 1 and 3 are comparable, dominated by cutting time rather than haulage

5. Discussion

5.1 Value of DFN inputs: evidence from the three grids

A grid that respects the dominant discontinuity orientation (Grids 1 and 3) loses about one-third of the bench; a grid that ignores it (Grid 2) loses more than half.

The cost of being wrong, at the cell scale, is therefore roughly 15 percentage points of recovery, 25 % of operating cost and a factor of two in CO₂ per cubic metre of marketable rock.

Independent studies on the same Botticino bench using GPR-supported cutting-grid optimisation have reported somewhat higher recovery ratios, highlighting that DFN-based results should be interpreted as conservative within the range of plausible fracture-network realisations. Since a DFN inversion can be produced from a single afternoon of scanline work plus a TLS scan, the return on the geotechnical investment is the largest single lever available to a marble operator before any change of cutting technology is considered [14].

5.2 Transfer to Ruschita, Carpinis and Pietroasa

The Botticino numbers are not directly portable to the Romanian sites, for three reasons:

- Cutting technology: Ruşchiţa also employs diamond-wire sawing, but operates in a substantially colder hydrologic regime, yielding higher water-reuse efficiency and a corresponding ~20 % drop in the water indicator;
- Lithology: Carpinis travertine exhibits bulk porosity an order of magnitude above Botticino marble, making the geophysical campaign not optional but a prerequisite, as surface scanlines underestimate persistence at depth;
- Receptor environment: Pietroasa andesite generates silica-bearing dust regulated under a stricter exposure framework than carbonate dust, requiring the dust-indicator threshold of the workflow to be tightened accordingly.

The workflow itself, however, transfers seamlessly across sites. Demonstrated at all four sites, three Romanian sites (Ruschita, Carpinis, Pietroasa) and one Italian site, the DFN engine ingests a uniform probabilistic discontinuity description derived from scanlines, TLS, televiwer, or geophysics, while the cutting-grid optimiser outputs a consistent four-indicator panel (recovery, water, CO₂, dust).

Site-specific adaptations are limited to cutting-technology coefficients and the local CO₂ Intensity of electricity, both configurable per project within the AI-COSTSQO portal [4].

5.3 Implications for EU Ecolabel and LCA reporting

The EU Ecolabel worksheet for ornamental rocks awards up to 60 points for extraction-only operations, requiring a minimum of 30 points for certification.

Quarry energy consumption and material efficiency jointly contribute over 70 % of the score, precisely the metrics optimised by the DFN-driven cutting-grid workflow.

On the Botticino bench, adopting a DFN-informed grid (Grids 1 and 3) instead of the misaligned Grid 2 substantially improves material efficiency and strengthens the evidential basis for EU Ecolabel applications, without altering landscape-impact, water or wastewater scores.

Quarry landscape impact ratios, water consumption, and wastewater management remain unaffected by grid orientation and must be addressed independently [6], [9].

5.4 Limitations

Three key limitations merit discussion.

First, although recovery curves are computed on a single Botticino bench where bench-to-bench variability remains unquantified and could exceed the reported 14 - 15 percentage-point inter-grid differences, this focused analysis nonetheless demonstrates substantial grid-orientation sensitivity, with misaligned layouts incurring up to 1.7× higher CO₂ per usable m³.

Second, the DFN is treated deterministically after statistical fitting, whereas stochastic ensembles are required (and planned) to bracket 95% confidence intervals on cell recovery rates. For the present bench-scale demonstration, the three reported recovery values for Grids 1 - 3 should therefore be read as deterministic best estimates rather than statistically bounded confidence intervals.

Third, the Botticino dust indicator employs AERMOD validated against Romanian perimeter samples 21.17 µg m⁻³, well below the 50-µg m⁻³ limit, conservatively omitting population exposure downwind.

The present material-efficiency budget focuses on fracture-driven waste and does not explicitly separate kerf losses from saw cuts, which in practice contribute an additional few percent of bench-volume loss and will be incorporated in future workflow iterations.

6. Conclusions

A DFN-driven cutting-grid optimiser, calibrated on a Botticino marble quarry bench and validated against Romanian benchmarks at Ruschita and Carpinis, converts hidden discontinuity geometry into quantifiable environmental and economic gains.

Across three adjacent grids, recovery rates spanned 21.7% (misaligned Grid 2) to 36.4% (aligned Grid 1), with CO₂ emissions per m³ usable volume ranging 29 - 49 kg/m³ (factor of ~1.7) and ~25% higher emissions for chainsaw versus diamond-wire cutting.

Block-size optimisation across all grids identifies size No. 9 (0.76/m³) as the economic Pareto optimum, maximising unfractured blocks and relative monetary value despite elevated cutting costs.

Operationalised via the AI-COSTSQO SaaS portal, the workflow delivers a transparent four-indicator panel (recovery, CO₂, dust, and economics) that directly supports EU Ecolabel certification and LCA reporting. Planned extensions include stochastic DFN ensembles for confidence intervals and bench-to-bench upscaling for quarry-wide assessment.

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