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MINIMISATION OF WASTE, WATER AND ENERGY CONSUMPTION AT EXTRACTION OF DIMENSION STONE TO SUPPORT ECO-LABEL CERTIFICATION

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Abstract: *Dimension stone quarrying faces significant environmental challenges related to waste production, water usage, and energy consumption. The extraction process typically yields recovery rates between 3% and 60%, resulting in substantial waste material. Modern optimisation techniques and technologies, particularly diamond wire cutting, have revolutionised extraction efficiency while reducing environmental impact [1]. The EU Eco-label criteria now mandate specific material efficiency thresholds for natural stone extraction, emphasising the importance of sustainable quarrying practices. This paper examines strategies for minimising environmental impact in dimension stone quarrying through advanced algorithms that optimise cutting patterns, reduce waste production, and decrease resource consumption. This paper explores how these optimisation methods align with Eco-Label standards while maintaining economic viability. Special attention is given to the relationship between cutting surfaces and operational efficiency, as these directly influence energy, water, and tool consumption rates.*
Keywords: *dimension stone quarrying, eco-label standards, waste minimization, water consumption, energy efficiency, sustainable extraction*

1. Introduction

Dimension stone quarrying faces significant environmental challenges, primarily related to waste production, water usage, and energy consumption. Modern optimization techniques and technologies have revolutionized extraction efficiency while reducing environmental impact. Particularly, diamond wire cutting has emerged as a game-changing technology in the industry, offering improved precision and reduced waste generation [1]. These advancements are crucial as the dimension stone sector grapples with balancing economic viability with environmental sustainability.

The European Union has recognized the importance of sustainable quarrying practices by incorporating specific material efficiency thresholds for natural stone extraction into its Eco-label criteria. These criteria aim to promote environmentally friendly production methods and encourage continuous improvement in the industry. [2]

This paper examines strategies for minimizing environmental impact in dimension stone quarrying through advanced algorithms that optimize cutting patterns, reduce waste production, and decrease resource consumption. These optimization methods align with Eco-Label standards while maintaining economic viability by focusing on cutting surfaces, block value, and waste generation.

The paper will explore how these approaches can contribute to more sustainable quarrying practices, addressing the industry's environmental challenges while meeting the growing demand for eco-certified natural stone products.

2. Current State of Dimension Stone Quarrying

The dimension stone industry faces significant challenges in resource efficiency and environmental impact. These issues primarily manifest in three key areas: recovery rates and waste production, water usage, and energy consumption.

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2.1. Recovery Rates and Waste Production

Dimension stone quarrying is characterized by notably low recovery rates, typically ranging between 3% and 60%. This inefficiency results in substantial waste generation, which poses significant environmental and economic challenges:

- As of 2021, the global dimension stone industry produced approximately 318 million tons of gross quarrying material;
- Of this total, about 163 million tons (51%) became quarrying waste during the extraction phase;
- In the subsequent processing stage, an additional 63.5 million tons (20% of the total gross quarrying) was converted to waste;
- Ultimately, only 91.5 million tons (29%) of the total extracted material reached the market as processed products, meaning about 71% was lost as waste.

The primary factors contributing to this high waste production are:

- Geological conditions of the deposit, particularly discontinuities and fractures in the rock mass;
- Limitations of current extraction and processing technologies. [3]

2.2. Water Usage in Quarrying Operations

Water is crucial in dimension stone quarrying and is primarily used in cutting and processing operations; however, the industry faces challenges related to water management:

- Cutting operations generate turbid wastewater containing fine stone particles;
- There is an urgent need for more efficient water recycling and treatment technologies, such as filter press systems and decanters;
- Improper wastewater management and marble sludge can lead to pollution of surface water, groundwater, and springs.

2.3. Energy Consumption in the Extraction Processes

Energy consumption is a significant factor in the environmental impact and operational costs of dimension stone quarrying:

- Modern extraction techniques, such as diamond wire cutting, have improved efficiency but still require substantial energy input;
- The number of cutting surfaces required to extract desired blocks from the quarry face directly affects energy consumption;
- Increased waste production leads to higher energy consumption per unit of marketable product, as energy is expended on material that ultimately becomes waste.

These challenges must be adequately addressed. The industry is exploring optimization algorithms considering block production, waste reduction, and parameters like cutting surfaces, which significantly impact energy and water consumption. These efforts aim to improve both the economic viability and environmental sustainability of dimension stone quarrying operations.

3. Modern Optimization Techniques

Modern optimization techniques have revolutionized dimension stone quarrying, significantly improving extraction efficiency and reducing environmental impact. These techniques focus on three main areas:

- Diamond wire cutting technology;
- 3D modelling and advanced surveying;
- Quarry optimization algorithms.

3.1. Diamond Wire Cutting Technology

Diamond wire cutting has become a game-changing technology in the dimension stone industry. This innovative technique involves pulling a continuous loop of wire fitted with diamond-bonded steel beads through the stone in a plane, offering improved precision and reduced waste generation compared to traditional methods. The process typically consists of five phases: drilling, cutting, block dropping, block slicing, and loading.

Throughout the cutting operation, water is continuously fed to cool the wire, improving efficiency and significantly reducing dust production. This advanced method has revolutionised quarrying operations, enabling more precise extractions while minimising environmental impact.

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Diamond wire cutting has several advantages:

- It allows for more precise cuts, resulting in higher-quality blocks;
- The technique reduces waste production, improving overall material efficiency;
- It consumes less energy compared to traditional cutting methods, contributing to reduced environmental impact. [1]

3.2. 3D Modelling and Advanced Surveying Techniques

Modern quarrying operations now employ sophisticated 3D modelling and surveying techniques, significantly enhancing dimension stone extraction's accuracy and efficiency. These advanced methods allow for precise rock mass mapping, including detailed identification of discontinuities and fractures that can affect quarrying outcomes. Cutting-edge surveying techniques, such as LiDAR (Light Detection and Ranging) and photogrammetry, provide comprehensive and highly detailed information about the quarry face, enabling operators to make more informed decisions. The resulting 3D models are invaluable for planning optimal cutting patterns and predicting block sizes and quality, reducing waste and improving overall quarry productivity. [4]

3.3. Quarry Optimisation Algorithms

Sophisticated algorithms have been developed to optimize dimension stone quarrying, revolutionizing the industry's approach to extraction. These advanced computational tools analyze discontinuities and fractures in the rock mass to determine optimal cutting patterns, considering critical factors such as block size, cutting surfaces, and potential waste production. [5]

The primary objective of these algorithms is to maximize the recovery ratio of dimension stone while simultaneously minimizing cutting costs, thereby enhancing both economic efficiency and environmental sustainability.

One promising approach in this field is the integrated modelling between joint sets and cutting grids. This method generates a comprehensive model of intact and fractured blocks based on the rock mass structure, providing a detailed representation of the quarry face. [6]

By integrating joint set data with cutting grid parameters, the algorithm allows for calculating maximum recovery ratios and minimum cutting rates.

These advanced optimization techniques improve the economic viability of dimension stone quarrying and contribute significantly to reducing waste production and energy consumption, aligning with the industry's growing focus on sustainable practices.

4. EU Eco-label Criteria for Natural Stone

The European Union's Eco-label criteria for natural stone products serve as a benchmark for sustainability in the dimension stone sector. These guidelines aim to enhance resource efficiency, mitigate environmental consequences, and foster responsible stewardship of natural resources. [2]

A cornerstone of these criteria is the establishment of material efficiency thresholds. By mandating minimum standards for resource utilization in block extraction, the EU ensures that quarrying operations optimize their use of raw materials while limiting waste generation.

Another crucial element of the Eco-label framework is the extraction efficiency ratio requirements. These provisions are created to incentivize more sustainable quarrying methods and diminish the ecological footprint of stone extraction. The guidelines advocate for techniques that minimize landscape disruption, striving to balance industry profitability and environmental preservation.

The criteria also emphasize the importance of by-product utilization. The EU promotes a circular economy approach within the industry by encouraging the repurposing and recycling of process residuals. This not only reduces waste but also maximizes the economic value of extracted materials.

Beyond these core aspects, the Eco-label criteria encompass a range of environmental considerations:

- Energy usage - The framework establishes caps on feasible energy consumption and mandates reduction strategies where benchmarks are not applicable;
- Water conservation - The guidelines advocate for water-efficient production methods, stipulating standards for wastewater recycling and consumption limits;
- Emissions regulation - The criteria set specific restrictions on CO_2, SO_x, NO_x, and particulate matter emissions from fuel combustion processes;
- Quarry stewardship - A rehabilitation strategy for the quarry site is required, along with measures to safeguard local ecosystems and wildlife.

This comprehensive approach ensures that EU Eco-label-certified stone products represent the apex of environmental performance in the market, driving sustainable practices across the entire dimension stone industry. A summary of the Eco-label criteria and requirements is presented in Table 1.

Table 1. Requirements and scoring system for ECO-LABEL for dimension stones' quarries

Criteria where points can be awarded	**Intermediate blocks or slabs of dimension stone (Points)**	**Final transformed natural stone hard covering products (Points)**
Environmental Management System of the quarry (optional)	0.3 or 5	N/A
Environmental Management System of the transformation plant (optional)	N/A	0.3 or 5
Energy consumption at the quarry	Up to 20	Up to 20
Material efficiency at the quarry	Up to 25	Up to 25
Quarry landscape impact ratios (optional)	Up to 10	Up to 10
Energy consumption at the transformation plant	N/A	Up to 20
Water and wastewater management at the transformation plant	N/A	Up to 5
Reuse of process waste from the transformation plant	N/A	Up to 10
Regionally integrated production at the transformation plant (optional)	N/A	Up to 5
Total maximum points	**60**	**100**
Minimum points required for EU Eco-label	**30**	**50**

5. Strategies for Minimizing Environmental Impact

The dimension stone industry has developed several strategies to minimize its environmental impact, focusing on waste reduction, water management, and energy efficiency.

Waste reduction techniques have become increasingly important in quarrying operations. In-situ cutting equipment for block adjustments has emerged as a valuable tool for reducing waste at the source. This technology allows for precise cutting and shaping of blocks directly at the quarry face, minimizing the amount of material that becomes waste. Additionally, mobile crushing plants for aggregate production have been implemented in many quarries. These plants process waste material on-site, converting it into usable aggregates for construction and other purposes, thereby reducing the overall waste output and creating a valuable by-product. [7, 8]

Water management has become a critical aspect of sustainable quarrying practices. Stormwater collection and recirculation systems have been implemented to reduce freshwater consumption and minimize runoff. These systems capture rainwater and surface water, which can be used in cutting operations. [2]

Wastewater treatment and reuse technologies have also been developed to address the issue of turbid wastewater containing fine stone particles. Advanced filter press systems and decanters are now being used to treat and recycle water, significantly reducing overall water consumption and preventing pollution of surface and groundwater.

Energy efficiency measures have been implemented to reduce the environmental impact and operational costs of dimension stone quarrying. Optimizing cutting surfaces has emerged as a key strategy to reduce energy consumption. By carefully planning cutting patterns and minimizing the number of cuts required, quarries can significantly reduce their energy usage. This approach decreases energy consumption and reduces wear on cutting tools, improving efficiency. The integration of renewable energy in quarry operations has gained traction in recent years. Some quarries have begun to install solar panels or wind turbines to power their operations, reducing reliance on fossil fuels and decreasing their carbon footprint. This shift towards renewable energy sources aligns with broader industry efforts to improve sustainability and meet increasingly stringent environmental regulations. [9]

These strategies collectively contribute to more sustainable quarrying practices, addressing the industry's primary environmental challenges while maintaining economic viability. As technology advances, more efficient and environmentally friendly techniques will likely be developed, further reducing the environmental impact of dimension stone quarrying.

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6. Case study

An important component in determining the environmental impact of activities in ornamental rock quarries is energy, water consumption, and the quantity of waste generated – through the Recovery Rate Index.

This case study examines the Botticino Marble Quarry (Fig. 1), a notable example from the Italian dimension stone industry that serves as a model of sustainable extraction.

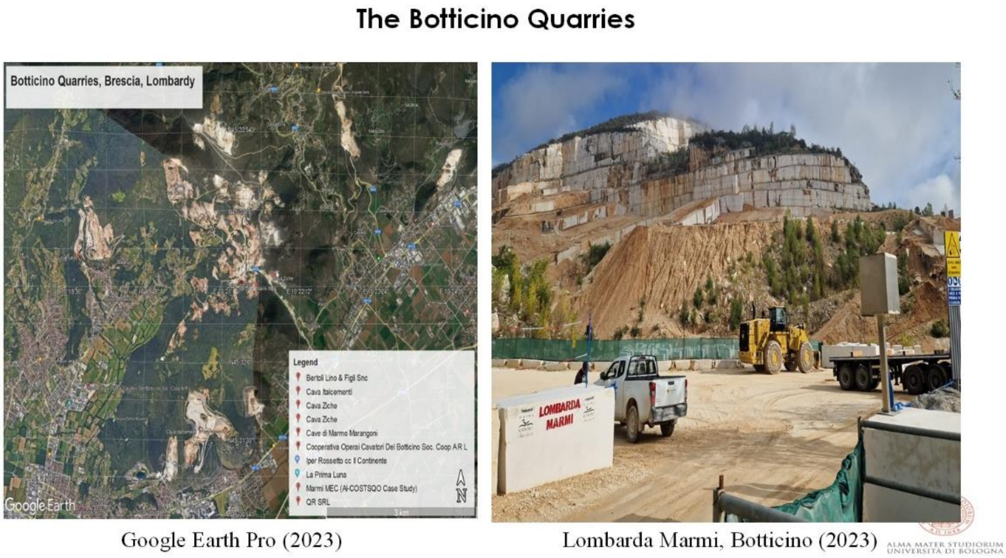

Fig.1. Botticino Marble Quarry

Located in the Lombardy region of northern Italy, the Botticino Marble Quarry is an exemplary case of modern, sustainable dimension stone extraction. This quarry, renowned for producing the prized Botticino marble, has implemented various innovative practices that address the industry's key environmental and efficiency concerns.

The Botticino operation showcases how traditional quarrying methods can be enhanced with cutting-edge technologies and sustainable approaches. Analyzing this quarry's strategies and outcomes provides valuable insights into the practical application of the principles discussed throughout this paper.

The economic viability and/ or profitability of the dimensional stone quarry operations based on adopted block dimensions were examined.

This assessment links the technical optimization from the 'SlabCutOpt' software with some economic variables to gauge the Relative Monetary Value (RMV), recovery ratios, production costs, and potential earnings for each block dimension.

The RMV for blocks was calculated based on block dimensions and surface area. The RMV tends to increase with a larger, un-fractured number of blocks and vice-versa. [10]

The following process flow was used to derive the RMV and Recovery Rate:

- Data acquisition:
  - Geophysical surveys – Ground Penetrating Radar;
  - Topographical surveys – Total station.
- Data processing:
  - DEM and Radiogram generation;
  - Fracture discretization from Radiogram in CAD-2D;
  - Fracture modelling and characterization in ParaView;
  - Parametric block estimation and analysis in SlabCutOpt.
- Data interpretation and findings:
  - Economic analysis;
  - Environmental analysis;
  - Prediction of optimal block dimension;
  - EU ECO-LABEL scoring.

For this quarry, three types of discontinuity / fracturing systems have been identified, which generate different patterns of block volumes - as shown in Fig.2.

Structure 1 was considered, which is shown in Fig. 3 and for which the Recovery Rate is plotted in Fig.4. and its RMV in Fig. 5.

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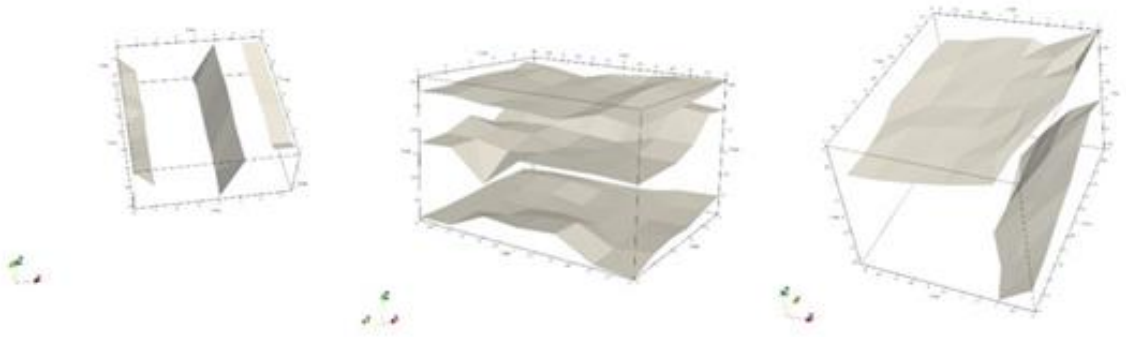

Fig.2. The three types of discontinuities identified in the Botticino Quarry - Italy

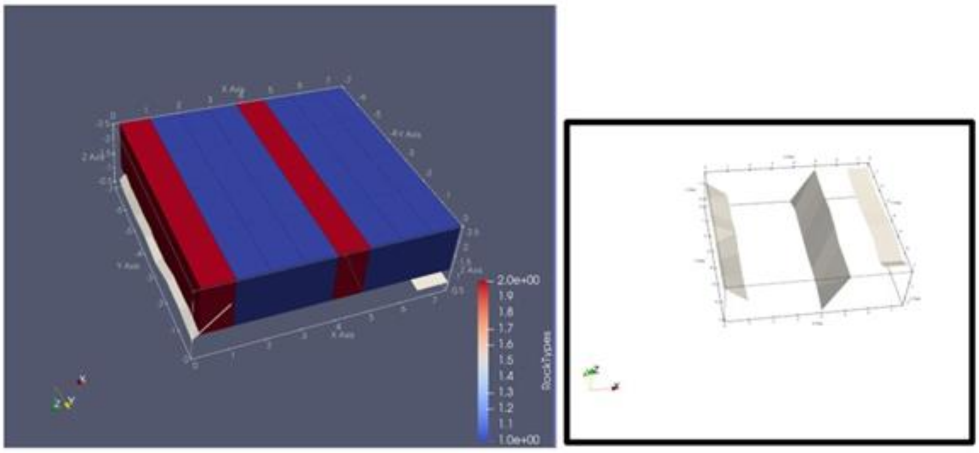

Fig.3. Discontinuity Structure 1 and resulting blocks in the Botticino Quarry – Italy

For the Botticino Marble Quarry, 10 different hypothetical block dimensions were tested across three grid sections of the same quarry bench to assess the RMV and production costs.

The highest RMV was observed for Dimension No. 9 (0.76 m X 0.76 m X 0.76 m) in all three grids, which would produce the highest number of un-fractured blocks, indicating a higher return on investment.

Regarding the production cost, an estimated cost of £6.50 per square meter for unpolished marble was used as the basis.

The cost increased for smaller blocks due to the greater number of extractions needed. For Dimension Block No. 9, the point of maximum RMV coincided with the highest production cost, indicating a trade-off between high profitability and increased production expenditure.

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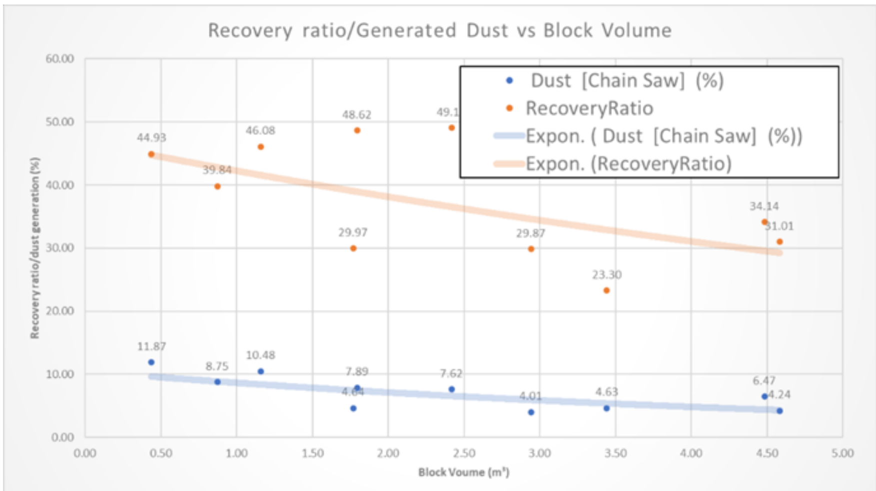

Fig.4. Recovery rate of blocks and dust in Structure 1 discontinuity in the Botticino Quarry – Italy

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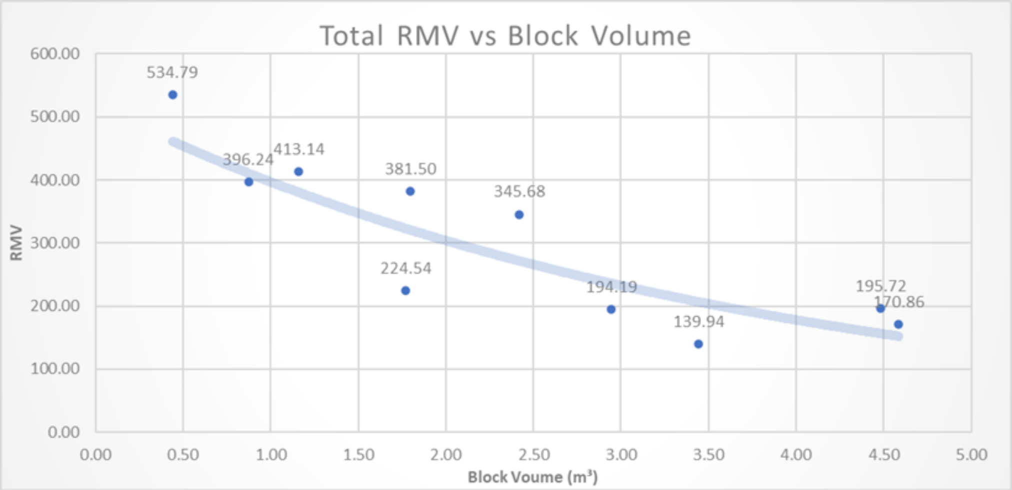

Fig.5. Relative Monetary Value vs. blocks in Structure 1 discontinuity in the Botticino Quarry - Italy

7. Alignment with Eco-Label Standards

Meeting and exceeding EU Eco-label criteria has become a key focus for the dimension stone industry as it strives to improve its environmental performance. The EU Eco-label criteria for natural stone products emphasize material efficiency, waste reduction, and responsible resource management throughout the quarrying and processing stages.

To achieve certification, quarry operators must meet specific thresholds for material efficiency in block extraction, implement water management systems, and develop quarry rehabilitation plans.

Environmental management systems (EMS) are crucial in aligning quarrying operations with eco-label standards. Many companies are adopting ISO 14001 certification to demonstrate their commitment to environmental stewardship.

An ISO 14001-certified EMS provides a systematic framework for managing environmental aspects, setting objectives, and improving performance. This approach helps quarries meet eco-label criteria and enhances their overall sustainability profile. Continuous improvement and innovation in sustainable practices are essential for aligning with evolving eco-label standards. The Natural Stone Sustainability Standard (ANSI/NSC 373) exemplifies this approach, requiring updates every five years to stay relevant in the changing sustainability landscape.

Quarry operators increasingly focus on energy efficiency, implement renewable energy solutions, and optimize water usage to reduce their environmental footprint. Advanced technologies are being employed to maximize resource utilization and minimize waste generation.

By aligning with and exceeding eco-label standards, dimension stone quarries improve their environmental performance and gain a competitive edge in the market. This commitment to sustainability helps meet the growing demand for responsibly sourced materials in the construction industry while ensuring long-term viability for quarrying operations. [2]

8. Conclusion

The dimension stone industry has made significant strides in minimizing its environmental impact by adopting innovative technologies and sustainable practices. Key strategies for reducing environmental footprint include implementing advanced cutting techniques such as diamond wire technology, significantly improving precision and reducing waste generation.

Integrating 3D modelling and sophisticated quarry optimization algorithms has revolutionized extraction planning, allowing for more efficient use of resources and minimizing waste production.

Water management systems, including closed-loop recycling and treatment facilities, have drastically reduced water consumption and prevented pollution of local water sources. Balancing efficiency, sustainability, and economic viability remains a critical challenge for the dimension stone industry. Adopting eco-label standards and environmental management systems has demonstrated that sustainable practices can coexist and enhance economic performance.

By optimizing extraction processes, reducing waste, and improving resource utilization, quarries can simultaneously lower operational costs and minimize environmental impact. The growing demand for sustainably sourced materials further underscores the economic benefits of adopting environmentally friendly practices. There is an urgent need for industry-wide adoption of sustainable quarrying practices.

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As global environmental concerns intensify and regulations become more stringent, the dimension stone sector must proactively embrace sustainability to ensure long-term viability. This call to action extends beyond individual quarry operators to include industry associations, regulatory bodies, and stakeholders across the supply chain. Collaborative efforts are required to develop and implement best practices, share knowledge, and drive continuous innovation in sustainable quarrying techniques. The future of the dimension stone industry lies in its ability to harmonize extraction efficiency with environmental stewardship.

By committing to sustainable practices, investing in advanced technologies, and aligning with eco-label standards, the industry can secure its position as a responsible supplier of high-quality, environmentally friendly building materials. As the sector moves forward, it must continue to innovate, adapt, and prioritize sustainability to meet the evolving demands of a more environmentally conscious market and contribute positively to global sustainability goals.

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