A Comprehensive Technical-Economic Cost Analysis of Drill and Blast Operations in a Basalt Quarry

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Abstract

Cost analysis of drilling and blasting operations in open-pit mining is particularly important in hard rock formations such as basalt and in rainy climatic conditions. This study presents a comprehensive cost analysis of drilling and blasting processes based on field data obtained from a 27-hole blast at a basalt quarry in the Eastern Black Sea Region. The blasting design was optimized to reduce environmental risks with a 11.56 m high compression dimension due to its location near the main road and riverbed. The analysis, performed using the phase cost method, examines in detail the cost of explosives as well as depreciation (21.45%), fuel (12.87%), labor, maintenance, repair, and logistics expenses. The results show that energy and depreciation expenses account for more than 90% of the total cost. Performance metrics such as 37.05 kg ANFO usage per hole and 0.74 L/meter fuel efficiency were calculated. The study presents a cost model that can serve as a reference for similar operations, emphasizing the critical role of optimizing depreciation and fuel costs on overall operational efficiency.

Keywords: Drill and Blast, Cost Analysis, Surface Mining, Basalt Quarry, ANFO, Blast Optimization, Operational Efficiency, Phase-Cost Method.

Introduction

Drilling and blasting are among the fundamental operations in mining. These are some of the most crucial processes for the rapid and controlled fragmentation of hard rock. Regardless of whether it's an open-pit or underground operation, the primary goal of blasting in mining is to achieve suitable rock fragmentation. For a blasting operation to be efficient, the drilling and blasting processes must be carried out seamlessly, and the broken rock must be reduced to the desired size for feeding into the plant. The cost of rock fragmentation directly and indirectly impacts the economic viability of a mine (Singh and Singh, 2005). Achieving the desired rock size through blasting reduces crushing costs, as well as drilling, loading, and hauling costs, and also prevents additional expenses associated with ground vibrations and fly rock. A well-designed blast not only reduces costs but also contributes to increased production and safer operations in terms of occupational health and safety (Latham et al., 2006; Monjezi et al., 2009).

The importance of efficient and economical blasting is growing daily in the context of mining. Various studies show that the practices required for efficient blasting vary depending on the site and mine conditions. In a study on Golden Star Resources, an open-pit gold mine in Ghana, current cost trends related to drilling and blasting operations were examined, and cost-effective drilling and blasting geometric parameters were established for the mine. In this surface mining operation, three pits (A, B, and C) were blasted. The post-blast estimated average fragment size was within the mine's desired range (25-65 cm), and the explosive energy was used effectively for the material throughout the blasted area. They observed that the volume of blasted material increased by 14.3% to 50% in ore zones and 12.5% to 50% in waste zones, when compared to the original blast parameters. It was estimated that adopting the proposed blast parameters would result in a total drilling and blasting cost savings of 5.3% to 12.2% for ore zones and 2.9% to 14.8% for waste zones (Afum and Temeng, 2015; Malli and Karakuş, 2019).

Zarghami et al. (2018) stated in their work that determining blasting costs and designing the blast contributed significantly to cost reduction during ore extraction. They also mentioned the existence of additional costs besides the primary ones. In their study, they investigated the effect of hole diameter, which significantly impacts blasting costs, at a copper mine in Iran. They determined and evaluated the blasting costs per cubic meter as a function of hole diameter, bench height, uniaxial compressive strength, joint orientation, drilling cost, and the unit cost of explosives. Through this design, they were able to estimate the blasting cost and determine necessary precautions before the blast. They noted that increasing rock strength and the angle between the bench face and the main joint increases blasting costs, while increasing the hole diameter for each rock uniaxial compressive strength range helps reduce costs. Bahtavar et al. (2021) used a different approach to determine blasting costs. They stated that blasting has an impact on subsequent processes such as loading, hauling, crushing, grinding, and mineral processing. They developed a risk-based probability and mathematical model to minimize the total cost of a blasting operation. They created a model that provided a 23% reduction in total costs and increased efficiency in a limestone mine based on a planned blasting model. This model can be easily updated and applied to different studies to determine the best blasting plan for similar geomechanical conditions.

For open-pit mining operations, planned blasting is a key factor for production continuity and cost control. The total cost and efficiency of a blast are determined after analyzing and examining the sub-operations of the blasting process, such as drilling, explosive loading, advance, transportation, etc. (Zeqiri, 2021; Ahmadı et al., 2024). Blasting is a necessary operation for efficient and economical production in mining. The choice of explosives, number of holes, and blast design are the most important factors to consider to ensure the blast is efficient, safe, and economical (Şensöğüt and Uçkaç, 2018; Uçkan, 2018). In mining, blasting design parameters such as explosive type and properties, hole patterns, delay systems, and explosive loading should be analyzed before the blast, and the design should be based on these analyses (Jahit et al., 2016). Blasting operations inevitably cause environmental problems such as ground vibration, air shock, noise, and dust. The rock fragmentation and distribution created after the blast necessitate the use of modern blasting techniques and technologies, adherence to safety precautions, and compliance with legal regulations (Afum and Temeng, 2014; Fattahi and Ghaedi, 2024; Hilton and Platt, 2020).

In open-pit ore or quarry operations, blasting operations are highly likely to create additional costs due to the environmental problems they cause. The importance of blasting is even greater for high-strength volcanic rocks like basalt, which are used in various fields such as road construction, concrete aggregate, and fill material (Ashmole and Motluong, 2008; Eleren and Ersoy, 2007). The province of Trabzon in the Eastern Black Sea Region of Turkey has vast basalt aggregate reserves, significantly contributing to the structural needs of the province and the region. The basalt generally has high uniaxial compressive strength, low fracture density, and a homogeneous structure. However, low-strength basalts with voids and fractures, which have been exposed to intense tectonic activity, are also common in the region. A good blast design and proper parameters are essential before conducting any blasting operation (Bilgin et al., 2014; Kahriman, 2004).

In Trabzon, most quarries blasting basalt for aggregate production prefer ANFO-type explosives. The main reasons for choosing ANFO in open-pit mining are its low cost, easy preparation process, and high crushing capability (Başçetin, 2004). While ANFO has advantages, its use in the region also has disadvantages (Tunçdemir, 2007). ANFO's low water resistance, especially in humid regions like Trabzon, can reduce its effectiveness and requires hole waterproofing. Failure to control the sealing and waterproofing inside the holes can lead to poor rock fragmentation and low efficiency. It can also cause environmental problems (Jimeno et al., 1995; Siskind et al., 1980). Therefore, careful attention is needed during hole preparation and ANFO loading, especially due to the high rainfall in the region.

To increase the blasting effectiveness and reduce or prevent negative environmental impacts, the blast design must be well-executed (Mallı and Karakuş, 2019; Rehman et al., 2018). Key design parameters such as hole diameter, burden, spacing, explosive column length, and delay timing must be carefully determined. The improper selection of these parameters can lead to irregular and heterogeneous rock size distribution, increased wear and tear on excavation machinery, inefficiencies in loading and hauling, various other problems, and increased costs (Singh and Narendrula, 2006; Olofsson, 1990).

This study aims to analyze the drilling and blasting activities using ANFO at a basalt quarry in Trabzon, located in the Eastern Black Sea Region. The work consists of an analysis of blasting parameters obtained from the field and the efficiency and cost of the planned blast based on these parameters. Based on post-blast field observations, the study evaluates blasting efficiency, fragment size distribution, environmental impacts, and operational performance. Furthermore, it aims to provide guidance for similar operations by presenting proposals for optimum drilling and blasting desig ns based on the findings.

MethodsMaterials and

2.1. Study Area and Site Characteristics

This study was conducted in a basalt open-pit quarry located in the Trabzon province of the Eastern Black Sea Region, Turkey (Figure 1). The region is characterized by a humid subtropical climate with high annual precipitation, which presents significant challenges for blasting operations, particularly regarding the use of water-sensitive explosives like ANFO. The basalt formation in the area is of volcanic origin, typically exhibiting high uniaxial compressive strength and a homogenous structure with low fracture density. The quarry site is situated in close proximity to critical infrastructure, including a main roadway and a riverbed, necessitating stringent control measures for flyrock, ground vibration, and air overpressure.

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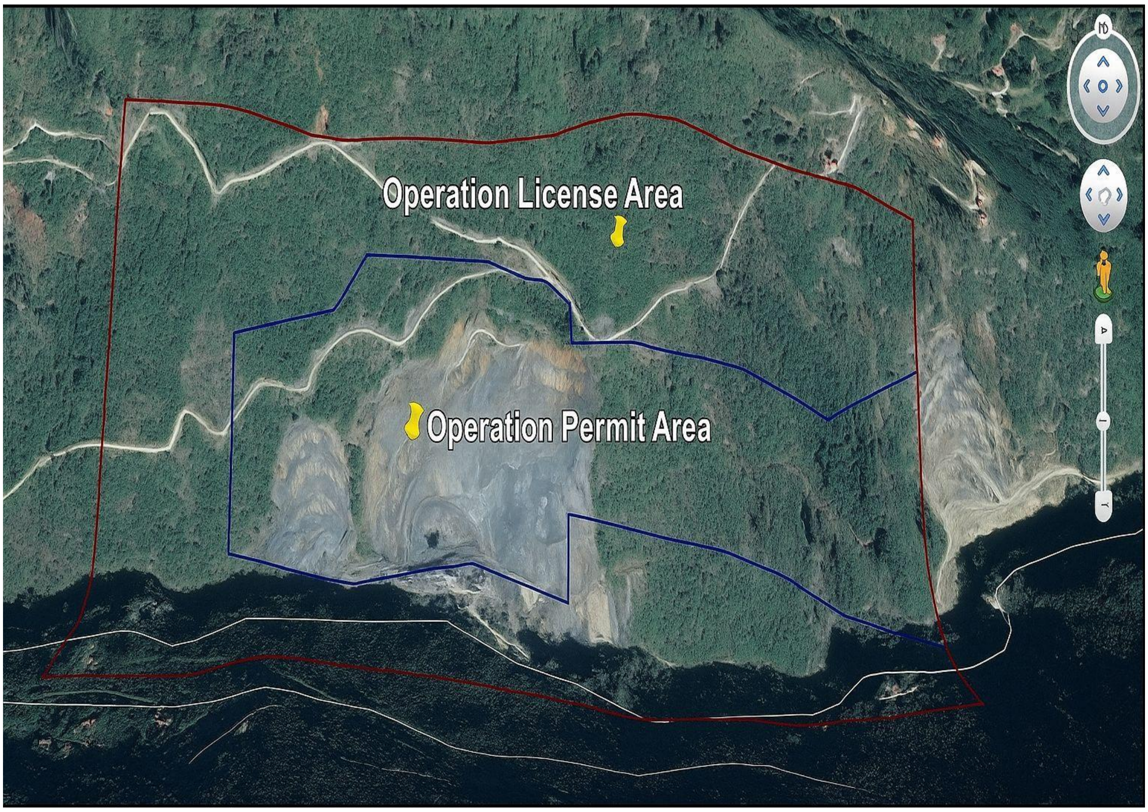

Figure 1. Work area location map

2.2. Parameters Determining Drilling and Blasting Costs

In this study, the determination of costs in the drilling and blasting process consists of materials and supplies that must be directly used, labor expenses of workers involved in blasting operations, and other factors generally affecting production. Each phase influencing the cost of drilling and blasting operations was identified both individually and in total.

1.2.1. Stage Costing Method: The stage costing method was employed in this study because production consists of interrelated and sequential stages, and due to the production of large quantities of one or several similar products. This method is particularly applied in industries such as cement, textiles, chemicals, plastics, flour, and rubber. In the method, cost analysis is carried out under three main headings: direct raw material and supply expenses, direct labor expenses, and general production expenses.

1.2.1.1. Raw Material and Supply Expenses: Raw materials and supplies arise during production and may become invisible when subjected to physical and chemical changes. The raw material and supply expenses used in mining activities are presented in Table 1.

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Table 1. Raw Material and Supply Expenses for Drilling and Blasting

	Drilling		Blasting
Costs of raw materials and supplies	Diesel fuel (used for drilling machinery)		ANFO (explosive placed into boreholes), Detonators (firing devices), Dynamite (explosive used in blasting)

1.2.1.2. Labor Expenses: Labor costs are considered as the wages earned by workers after working at the mining site, and constitute a significant factor directly affecting the production process. For each worker, the tasks performed and the working hours during blasting operations are taken into account (Table 2).

Table 2. Labor expenses for drilling and blasting

	Drilling	Blasting
Labor Costs	Driller	1. Site Supervisor 2. Machine Operator 3. Crushing-Screening Operator 4. Truck Driver 5. Maintenance Personnel 6. Loading Worker 7. General Worker

1.2.1.3. Other Production Expenses: These are items other than raw material, supply, and labor costs that affect the total blasting cost (Table 3).

Table 3. Other expenses for drilling and blasting in aggregate quarrying

	Drilling	Blasting
Raw material and supply-related:	Drill bit, Drill rods	-
Direct labor-related	Share of engineer/technician, Operator wages,	Share of engineer/technician
External services:	Maintenance and repair, Drilling machine fuel, Oils and hydraulic fluids, Transportation and haulage, Other (spare parts, occupational safety, compressor costs)	-
Depreciation costs:	Depreciation (drilling equipment)	-

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Blast Design and Data Acquisition

A single-row blast design was implemented for the controlled fragmentation of the basalt bench. The key design parameters, summarized in Table 4, were as follows: a bench height of 10 m, 27 vertical blast holes (90°) with a diameter of 127 mm, drilled to a depth of 15 m.

Table 4. Blast design parameters and explosive consumption.

Parameter	Value	Unit
Hole Pattern	Single-row	-
Bench Height	10	m
Number of Holes	27	-
Hole Diameter	127	mm
Hole Depth	15	m
Burden	3	m
Stemming Length	11.56	m
ANFO	1000	kg
Dynamite	20	kg
Detonators	30	-

The burden and spacing were set at 3 m. A stemming length of 11.56 m was employed to ensure safety and mitigate environmental impacts. The explosive column consisted of a prime charge of 20 kg of dynamite and a main charge of 1000 kg of ANFO (Ammonium Nitrate Fuel Oil), initiated with 30 electric detonators. Data on drilling performance, including total drilling meters (405 m), operational time (5 hours), and fuel consumption (300 liters), were recorded on-site using equipment manuals and operator logs.

2.3. Cost Analysis Framework: Phase-Cost Method

A detailed technical-economic analysis was performed using the phase-cost method, which is ideal for continuous production processes with sequential stages. This method allows for the precise allocation of all direct and indirect costs to specific operational phases. The total cost was categorized and analyzed under the following headings:

1. *Direct Material and Explosives Costs:* This included the cost of ANFO, dynamite, detonators, and fuse.

2. *Direct Labor Costs:* Costs for all personnel involved in the drill and blast cycle, including the site manager, drill-blast operator, machine operator, and general laborers. Daily wages were calculated based on fully burdened costs, including gross salary, employer social security contributions, transportation, and food allowances.
3. *General Production Overheads:* This extensive category included:
    - *Equipment and Consumables:* Drill bits, drill rods (tij), lubricants, and hydraulic fluids.
    - *Maintenance:* Scheduled and unscheduled maintenance costs for the drilling rig.
    - *Fuel:* Diesel consumption for the drill rig, calculated based on actual consumption (L) and the market price.
    - *Amortization:* The daily amortization cost of the drilling rig, calculated based on its purchase price and expected service life.
    - *Transportation and Logistics:* Costs associated with moving equipment to the blast site.
    - *Other:* Costs for safety equipment (gloves, ear protection) and compressor usage.

Unit prices for all cost items were based on market values from January 2025 to ensure accuracy and relevance. The total operational cost for the drilling phase was calculated to be 50,000 TL for the analyzed blast.

2.4. Performance and Efficiency Calculations

Key performance indicators (KPIs) were calculated to assess the efficiency of the operations:

- *Fuel Efficiency*: Calculated as the ratio of total fuel consumed to total meters drilled (L/m).
- *Drilling Rate:* Determined as the total meters drilled divided by the total operational time (m/hour).
- *Explosive Concentration*: The volume of each blast hole was calculated using the formula for the volume of a cylinder ($V = \pi r^2 h$). The volume filled with explosive was calculated by subtracting the stemming length from the total hole depth. The theoretical ANFO requirement was then derived using a standard density of 850 kg/m³.

All analyses were conducted to establish a transparent and replicable cost model for drill and blast operations in hard rock quarries.

Findings and Results

3.1. Comprehensive Cost Breakdown and Distribution

The phase-cost analysis revealed a total operational expenditure of 50,000 TL for the drilling phase of the blast. A detailed itemization, presented in Table 5, demonstrates the significant contribution of capital and energy-intensive factors to the overall cost structure.

Amortization of the drilling rig constituted the largest share at 21.45% (10,723 TL), underscoring the capital-intensive nature of drilling operations. Fuel consumption for the drill rig was the second largest cost component at 12.87% (6,434 TL), followed by drill bit (8.58%) and maintenance (10.72%) costs. Direct labor costs for the personnel involved in the drilling phase accounted for a combined 25.94% of the total cost

Table 5. Detailed breakdown of drilling operation costs.

Cost Category	Sub-Category	Cost (TL)	Share (%)
Operational Expenses	Amortization (Drill Rig)	10,723	21.45
	Drill Rig Fuel	6,434	12.87
	Drill Bits (Consumables)	4,289	8.58
	Drill Rods (Tij)	3,217	6.43
Labor Costs	Site Manager (Engineer)	4,000	8.00
	Drill-Blast Operator	3,334	6.67
	Machine Operator	3,000	6.00
	General Laborer	2,134	4.27
Maintenance & Other	Maintenance & Repair	5,362	10.72
	Lubricants & Hydraulic Fluids	2,145	4.29
	Other (Safety, Compressor, etc.)	2,145	4.29
	Transportation & Logistics	3,217	6.43
	TOTAL	**50,000**	**100.00**

3.2. Drilling Performance and Efficiency Metrics

The operational data yielded critical Key Performance Indicators (KPIs) for the drilling operation. The drill rig achieved a total of 405 drilling meters (27 holes × 15 m depth) over an active operational time of 5 hours. This resulted in a drilling rate of 81 meters per hour and a

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rate of 5.4 holes per hour. Fuel consumption was recorded at 300 liters for the entire operation, translating to a fuel efficiency of 0.74 liters per meter drilled. The cost of fuel per drilled hole was calculated to be approximately 444.44 TL/hole.

3.3. Explosives Calculation and Charge Efficiency

The volume of a single blast hole was calculated to be 0.190 m³. Given the high stemming length of 11.56 m, designed for environmental control, the effective height of the explosive column was 3.44 m. This resulted in an effective explosive volume (V_pat) of 0.0436 m³ per hole. Using the standard density of ANFO (850 kg/m³), the calculated explosive charge per hole was 37.05 kg.

For the 27-hole blast pattern, the total theoretical ANFO requirement was therefore 1,000.35 kg, which aligned exactly with the actual amount used (1,000 kg). This design choice resulted in a notably low charge concentration but was imperative for mitigating flyrock and ground vibration risks in a sensitive operating environment. The ratio of stemming length to hole depth (77%) was a primary factor in the reduced explosive consumption per hole.

3.4. Production Output and Overall Efficiency

The blast was designed to achieve a theoretical production volume of 75,000 m³. Based on the designed fragmentation volume per typical single-row shot (6,840 m³), it was calculated that approximately 11 blasts would be required to meet this total production target. Post-blast field observations and initial fragmentation assessment indicated a blast efficiency in the range of 60-65%, suggesting potential for optimization in future blast designs to improve yield and reduce cost per ton of fragmented material. The findings confirm that while environmental safety was successfully prioritized, a trade-off was made in terms of maximum fragmentation efficiency.

3.5. Labor cost analysis

In the study, the distribution of wages of the personnel working in the aggregate quarry according to their positions is presented in Table 6. The calculations were made by considering various parameters, and numerical data were obtained. These data include gross salary + employer's social security contributions (SGK) + meal allowance (1500 TL) + transportation service (1000 TL) + severance pay provision (~4%). The calculations are based on a 30-day working month and 8 working hours per day.

Table 6. Cost analysis of labor expenses

	Employee Definition	Monthly Wage (TL)	Daily Wage (TL)	Hourly Wage (TL)
1.	Site Chief (Engineer)	60000	2.000	250
2.	Driller–Blaster	50000	1.667	208.3
3.	Machine Operator	45000	1.500	187.5
4.	Crushing–Screening Operator	42000	1.400	175
5.	Truck Driver	40000	1.333	166.6
6.	Maintenance Personnel	38000	1.267	158.3
7.	Loading Worker	34000	1.133	141.6

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8.	General Worker (Helper)	32000	1.067	133.3
	Total Daily Labor Cost (8 personnel):		11.367	1.420.7
	Total Weekly Labor Cost (6 working days)	11367x6	68.202	
	Total Monthly Labor Cost (26 working days)	11367x26	295.542	

Discussion

Figure 2 visually demonstrates the significant share of capital-intensive costs in drilling operations. Amortization (21.45%) and fuel (12.87%) together constitute more than one-third of total costs, highlighting the capital-intensive nature of drilling operations. Labor costs represent 25.94% of total expenses, while maintenance and other operational costs account for the remaining 40.74%. This distribution underscores the importance of focusing optimization efforts on equipment efficiency and fuel consumption rather than solely on explosive costs, which are typically the focus of blast optimization studies.

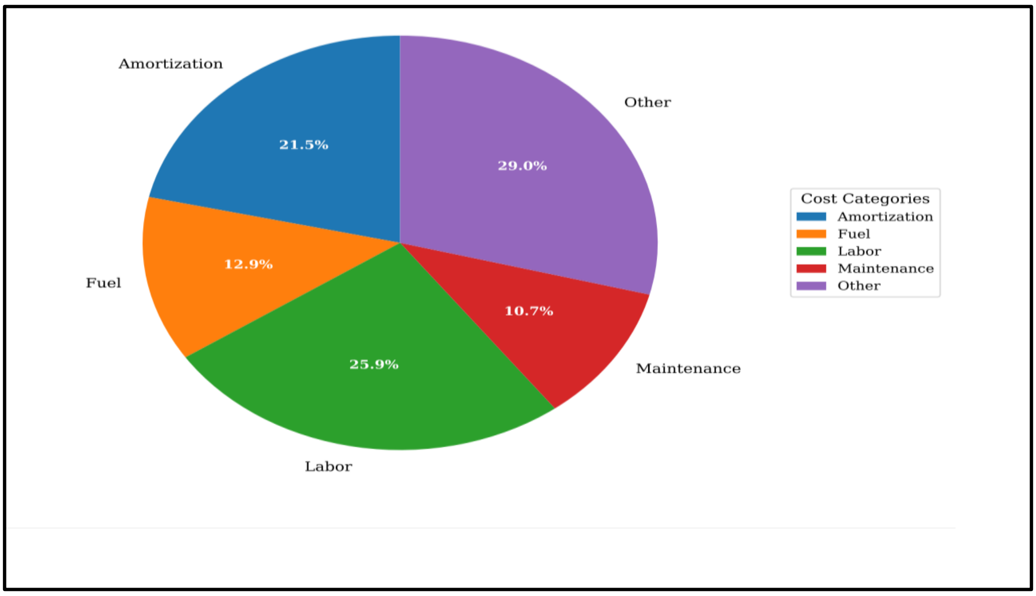

Figure 2. Cost distribution of drilling operations in the basalt quarry.

This study provides a granular, phase-cost analysis of drill and blast operations in a basalt quarry, revealing a cost structure dominated by capital and energy inputs rather than explosive materials themselves. The finding that amortization and fuel collectively constitute over 34% of the total drilling cost (Table 5) aligns with the capital-intensive nature of surface mining (Afum and Temeng, 2015) but offers a level of detail often absent in literature. This underscores a critical managerial insight: investments in newer, more fuel-efficient drilling equipment, while capital-intensive upfront, could yield significant long-term savings through reduced fuel consumption and lower maintenance costs, directly addressing the two largest cost drivers identified.

The deliberate design choice of an extensive stemming length (11.56 m, 77% of hole depth) directly resulted in a reduced explosive charge density of 37.05 kg/hole. This trade-off, which prioritized environmental safety and regulatory compliance over maximum fragmentation

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power, is a central finding of this research. While this successfully mitigated risks of flyrock and ground vibration—a non-negotiable requirement given the quarry's proximity to infrastructure—it also resulted in a suboptimal blast efficiency estimated at 60-65%. This efficiency rate is lower than the 70-80% often targeted in optimally designed blasts (Jimeno et al., 1995), highlighting a tangible cost of operating in environmentally sensitive areas. This finding directly complements the work of Siskind et al. (1980), quantifying the economic impact of stringent environmental controls.

The calculated fuel efficiency of 0.74 L/m and a drilling rate of 81 m/hr provide valuable benchmarks for basalt quarries in similar geological settings. However, these metrics also indicate a potential area for improvement. Advanced drilling techniques and real-time monitoring systems could optimize these rates, thereby decreasing the time-based costs (labor, machine hours) associated with the drilling phase.

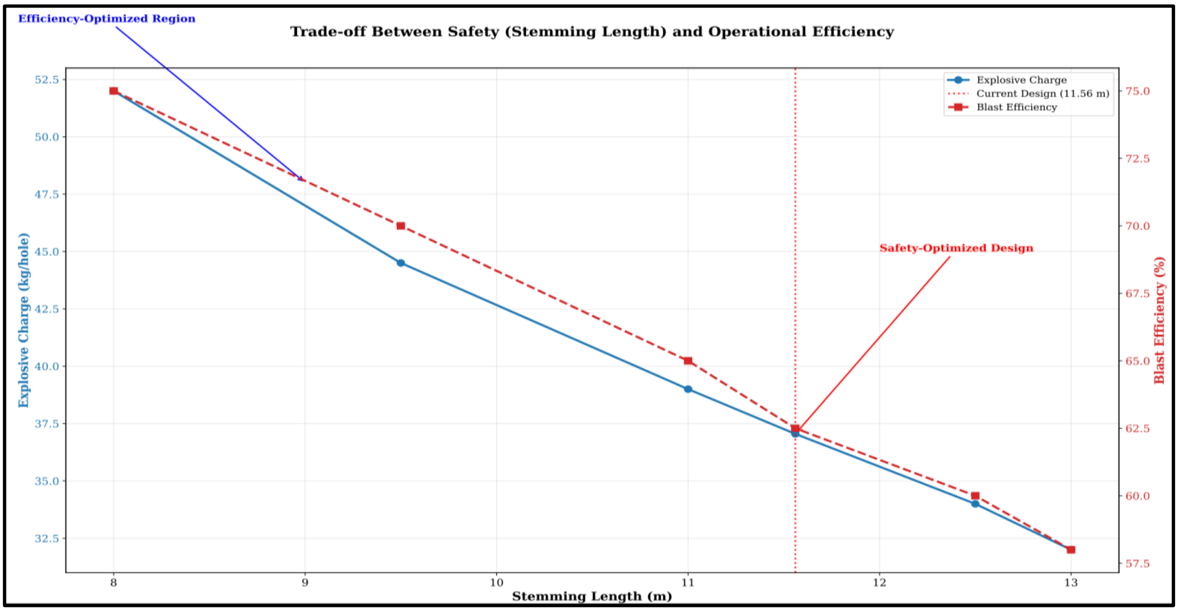

Figure 3. Trade-off relationship between stemming length and explosive efficiency.

A pivotal discussion point is the reliance on ANFO in a high-precipitation climate. While its low cost is economically justified (Başçetin, 2004), its known susceptibility to water (Tunçdemir, 2007) likely contributed to the reduced blast efficiency. This suggests that the apparent savings in explosive material cost might be partially offset by lower fragmentation efficiency, which increases downstream costs in loading, hauling, and crushing. Future cost-benefit analyses should explore the potential of water-resistant explosives or improved hole lining techniques, which could enhance energy delivery to the rock mass and improve overall system efficiency, even at a higher upfront cost.

This dual-axis visualization demonstrates the critical engineering trade-off between safety and efficiency in blast design. The figure 3 shows:

1. *Strong Negative Correlation:* As stemming length increases (improving safety), both explosive charge capacity and blast efficiency decrease significantly.
2. *Current Design Point:* The red dotted line marks your specific design choice (11.56 m stemming length), which prioritizes environmental safety and regulatory compliance given the quarry's sensitive location near infrastructure.

3. *Quantifiable Trade-off:* The current safety-optimized design operates at approximately 62.5% efficiency, compared to potential 75% efficiency with shorter stemming lengths that would be unacceptable for this location.
4. *Engineering Decision Framework:* This figure provides a visual tool for operators to make informed decisions based on their specific environmental constraints and efficiency requirements.

Finally, the phase-cost method proved exceptionally effective in unveiling the "hidden" costs of drilling, such as consumables (drill bits, rods) and maintenance, which are often aggregated in broader analyses. This methodological approach provides quarry managers with a transparent template for identifying specific cost centers for targeted optimization, moving beyond generic cost-per-ton models.

4.1. Limitations and Future Research

This study is limited to a specific geological and climatic context. The findings are most directly applicable to hard rock quarries in similar settings. The blast efficiency was estimated based on field observations; future research should incorporate quantitative fragmentation analysis (e.g., image analysis of particle size distribution) to precisely correlate charge design with fragmentation results and downstream comminution costs. Furthermore, a comparative study analyzing the total cost of ownership (TCO) of newer, more efficient drill rigs against the high amortization costs identified here would provide a robust framework for investment decisions. Finally, research into the economic viability of alternative explosive products in humid climates is warranted to fully assess the trade-offs between material cost and blast performance.

Conclusion

This study presents a comprehensive and granular technical-economic analysis of drill and blast operations in a basalt quarry, utilizing a detailed phase-cost methodology to dissect the complete cost structure. The findings clearly demonstrate that the operational economics are overwhelmingly dominated by capital and energy expenditures, not consumables like explosives. Specifically, equipment amortization (21.45%) and fuel consumption (12.87%) collectively account for over one-third of the total drilling costs, highlighting the capital-intensive nature of these operations and pinpointing the primary levers for financial optimization.

A critical finding and central trade-off of this research is the quantifiable impact of environmental and safety constraints on blast efficiency. The implementation of a high stemming length (11.56 m) was a necessary design choice to mitigate flyrock and vibration risks, given the quarry's sensitive location. However, this directly resulted in a reduced explosive charge density of 37.05 kg/hole and an estimated blast efficiency of 60-65%. This underscores a fundamental operational balance: prioritizing safety and regulatory compliance incurs a measurable cost in terms of fragmentation yield.

The study provides robust benchmarks for performance in hard rock mining, with a drilling rate of 81 m/hour and a fuel efficiency of 0.74 L/m. While the use of ANFO proved economically advantageous in terms of direct material cost, its application in a high-humidity environment likely contributed to the suboptimal fragmentation efficiency, suggesting that potential savings may be offset by increased downstream costs in comminution.

In conclusion, for quarry operators seeking to enhance profitability, this study provides two key actionable insights:

1. *Strategic Investment Focus:* Cost-reduction strategies must prioritize high-value targets, specifically investments in fuel-efficient machinery and predictive maintenance programs to mitigate the high costs of amortization and energy.
2. *Holistic Blast Optimization:* Future efforts should focus on integrated blast design that balances environmental safety with fragmentation quality. This could involve testing water-resistant explosives or alternative decking charges to improve energy utilization within the constraints of high stemming requirements, thereby reducing the total cost per ton of fragmented rock.

This research offers a transparent and replicable cost model that serves as a valuable decision-support tool for mine planners and managers operating under similar geological and environmental constraints.

References

Afum, B. O. and Temeng, V. A. (2014). Reducing drill and blast cost through blast optimisation – A case study. *3rd UMaT Biennial International Mining and Mineral Conference*, 137–145. https://www.scribd.com/document/556877456/DOC

Afum, B. O., and Temeng, V. A. (2015). Reducing drill and blast cost through blast optimisation – A case study. *Ghana Mining Journal, 15*(2).

Ahmadi, M. T., Varol, M. K., & Demirdağ, S. (2024). Comparison of splitting/loosening methods used in natural stonen quarries with ahp. *Journal of Technical Science, Volume 14, No. 1, pp. 1-8,*

Ashmole, I., and Motluong, M. (2008). Dimension stone: The latest trends in exploration and production technology. *The Southern African Institute of Mining and Metallurgy*, 3570.

Bakhtavar, E., Sadiq, R., and Hewage, K. (2021). Optimization of blasting-associated costs in surface mines using risk-based probabilistic integer programming and firefly algorithm. *Natural Resources Research, 30*(6), 2021. https://doi.org/10.1007/s11053-021-09935-0

Başçetin, A. (2004). Technical note: An application of the analytic hierarchy process in equipment selection at Orhaneli open pit coal mine. *Mining Technology, 113*(3), 192–199.

Bilgin, N., Çopur, H., and Balcı, C. (2014). *Mechanical excavation in mining and civil industries* (pp. 318–322). CRC Press.

Eleren, A., and Ersoy, M. (2007). Evaluation of Marble Extraction Methods By Using Fuzzy Topsis Method. *Scientific Mining Journal, Vol.46, No.3, pp 9-22,*

Fattahi, H., and Ghaedi, H. (2024). Optimizing mining economics: Predicting blasting costs in limestone mines using the RES-based method. *International Journal of Mining and Geo-Engineering, 58*(2), 181–190. https://doi.org/10.22059/IJMGE.2024.363654.595091

Hilton, R. W., and Platt, D. E. (2020). Managerial accounting: Creating value in a dynamic business environment. McGraw-Hill Education.

Jahit, G., Vasil, J., Izet, Z., and Rafet, Z. (2016). Concept paper on exploited area ore body S-150 of Horizon XI in "Trepca" Stanterg Mine. *Journal of International Environmental Application and Science, 11*, 366–370.

Jimeno, C. L., Jimeno, E. L., and Curceda, R. J. A. (1995). *Drilling and blasting of rocks*. A.A. Balkema.

 https://doi.org/10.5281/zenodo.17183365

Kahriman, A. (2004). Analysis of parameters of ground vibration produced from bench blasting at a limestone quarry. *Soil Dynamics and Earthquake Engineering, 7*, 887–892.

Latham, J.-P., Van Meulen, J., and Dupray, S. (2006). Prediction of fragmentation and yield curves with reference to armourstone production. *Engineering Geology, 87*(1–2), 60–74.

Malli, T., and Karakuş, D. (2019). Cost evaluatıon for excavatıon capacıty hyraulıc braker and drıllıng-blasting. *Proceedings of 7th International Congress of Mining Machinery and Technologies*, İzmir, 24–25 October.

Monjezi, M., Rezaei, M., and Varjani, A. Y. (2009). Prediction of rock fragmentation due to blasting in Gol-E-Gohar iron mine using fuzzy logic. *International Journal of Rock Mechanics and Mining Sciences, 46*(8), 1273–1280.

Olofsson, S. O. (1990). *Applied explosives technology for construction and mining* (2nd ed.). Applex.

Rehman, Z. U., Hussain, S., Noor Mohammad, Salim Raza, S. S., Mujahid Khan, M. T., & Murtaza Khan. (2018). Comparative analysis of different techniques used for dimension stone mining. *Journal of Himalayan Earth Sciences, 51*(1), 23–33.

Şensöğüt, C., and Uçkaç, E. G. (2018). Drıllıng and blastıng cost analysıs of a magnesıte open-pıt mıne. *Soma Vocational School Journal of Technical Sciences, 1*(25), 24–32.

Singh, S. P., and Narendrula, R. (2006). Factors affecting the productivity of loaders in surface mines. *International Journal of Mining, Reclamation and Environment, 20*(1), 20–32.

Singh, T., and Singh, V. (2005). An intelligent approach to prediction and control of ground vibration in mines. *Geotechnical and Geological Engineering, 23*(3), 249–262.

Siskind, D. E., Stagg, M. S., Kopp, J. W., and Dowding, C. H. (1980). *Structure response and damage produced by ground vibration from surface mine blasting* (Report of Investigations 8507). U.S. Bureau of Mines.

Tunçdemir, H. (2007). Performance Prediction and Selection Criteria of Hydraulic Breakers. Symposium on Underground Excavations in Transportation, Istanbul, November 15–17, pp. 215–226.

Uçkaç, E. G. (2018). Blastıng cost analysıs of a magnesıte open-pıt mıne. Dumlupınar University, Master's Degree in Mining Engineering, Graduate School of Natural and Applied Sciences, 108pp.

Zarghami, A. G., Shahriar, K., Goshtasbi, K., and Akbari, A. (2018). A model to calculate blasting costs using hole diameter, uniaxial compressive strength, and joint set orientation. *Journal of the Southern African Institute of Mining and Metallurgy, 118*. https://doi.org/10.17159/2411-9717/2018/v118n8a10

Zeqiri, R. (2021). Applyıng massıve blastıng durıng ore exploıtatıon ın underground mınes. *Scientific Mining Journal, 60*(1), 63–70.

 https://doi.org/10.5281/zenodo.17183365