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A REVIEW OF THE STATE-OF-THE-ART OPTIMIZATION ALGORITHMS FOR DIMENSIONAL STONE CUTTING

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Abstract: *In the dimension stone quarrying industry, the presence of fractures and discontinuities within in-situ blocks presents significant challenges, leading to substantial waste production. As a result, the economic viability of ornamental stone quarries relies on the implementation of optimization algorithms to determine ideal cutting directions and block dimensions. These approaches seek to minimize waste generation while maximizing the extraction of non-fractured commercial-sized blocks. This review examines cutting-edge optimization algorithms for dimensional stone cutting through a systematic literature review (SLR) using the PRISMA methodology. The study identified 37 articles from 20 nations, including Italy, Iran, China, Canada, Germany, Croatia, Vietnam, Portugal, Australia, Spain, Austria, USA, Poland, Pakistan, Egypt, Russia, Turkey, Sweden, Japan, and Slovenia, which discussed various optimization algorithms used in the dimensional stone quarry industry. The analysed articles cover a wide range of tools and methods, from ground penetrating radar (GPR) and scanline surveys to photogrammetry and advanced modelling techniques such as 3DEC and Discrete Fracture Networks. Qualitative analysis was conducted using four major databases: Scopus, ScienceDirect, Web of Science, and Springer Nature Link. The findings indicate that all identified optimization algorithms can be categorized into two main groups: those focused on fracture and discontinuity detection and modelling, and those centred on block geometry modelling. In this SLR, GPR technology stands out as a key tool, widely used for its non-destructive nature and effectiveness in identifying fractures and discontinuities within quarry locations. In addition to GPR, stochastic modelling techniques such as discrete fracture networks have also shown effectiveness in simulating fracture networks. Algorithms for block geometry modelling aim to determine the shape, size, and arrangement of quarry blocks. Various algorithms for analyzing block geometry, such as SlabCutOpt, 3D Block Expert, BlockCutOpt, and RANSAC, are commonly combined with fracture modelling tools and algorithms such as DFN and GPR fracture data to improve optimization. This integration is essential for the effective extraction and processing of ornamental stones. The ability to view block boundaries in three dimensions significantly improves decision-making processes, enhances ornamental stone quarry operations, and reduces waste. This SLR offers a comparative framework by examining these different algorithms, allowing for a better understanding of their advantages, constraints, and suitability in diverse ornamental stone-quarrying environments.*

Keywords: *Optimization algorithms; Stone cutting; Dimensional or Ornamental stones; Blocks; Fractures; Discontinuities; PRISMA*

1. Introduction and review

In the mining and construction sectors, optimizing quarries and extracting dimension stones efficiently are of utmost importance [1, 2, 3]. The construction industry heavily relies on dimension stone quarries, as they supply crucial raw materials necessary for the development of infrastructure [4]. Natural rock materials fashioned into standard shapes and sizes for use in construction cladding, paving, monuments, memorials, and various industrial applications are referred to as dimensional stone, ornamental stone, or natural stone.

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These stones are employed in different ways based on their visual characteristics (including colour, grain, and pattern), measurements, and physical-mechanical attributes [5, 6]. Dimension stone is distinguished from crushed and broken stone, which are utilized for purposes such as aggregate, roadstone, fill, or chemical raw materials [7]. Ornamental stones encompass a range of rock types, including igneous, metamorphic, and sedimentary formations. According to ASTM standards, dimension stones are classified into seven primary categories: granite, marble, limestone, sandstone, slate, serpentine, and travertine [5, 8].

However, the process of extracting dimensional stone blocks from quarries often faces difficulties, particularly due to the occurrence of discontinuities, also known as fractures, within rock structures [3, 9]. Fractures not only affect the structural integrity of rocks but can also affect the safety of quarry operations. The orientation and spacing of discontinuities significantly affect the potential shapes and sizes of dimensional stone blocks [2, 10]. Moreover, inefficient identification and management of fractures in dimensional stone quarries can lead to suboptimal productivity and contribute to environmental disturbances [11].

According to data published by Montani in the World Stone Report in 2021, of the total 318 million tons of gross extraction from dimension stone quarries during the extraction phase, around 163 million tons, or in other words, around 51% of the total gross extraction, became quarrying waste [12, 13]. The main factors affecting waste production during quarrying are the deposit's geological features, particularly the rock mass's discontinuities and fractures, which primarily generate waste materials like irregular blocks and debris [6, 14]. [13] reports that in the continuous production process, approximately 49% of the remaining raw materials, amounting to roughly 155 million tonnes, are sent to dimension stone processing facilities. Of this, about 63.5 million tonnes or 41% (approximately 20% of the total gross quarrying) becomes waste during processing, mainly comprising crushed slabs, sludge, and sawdust [13, 15]. These figures suggest that out of the total gross quarrying in the dimension stone production cycle, only 91.5 million tonnes or 29% were sold as processed products, while about 71% was lost as waste during production [12]. Since quarry products provide potential aesthetics and economic incentives, further attention is needed to guarantee a cost-effective and environmentally efficient system for waste management in various production stages [16].

To improve the production efficiency of dimension stones, it is important to minimize the amount of waste and resource loss using optimization methods and technologies [12]. The optimization process is vital for minimizing waste, reducing costs, and improving efficiency. Various optimization algorithms have been developed and applied to address the complexities of dimensional stone cutting. Stone quarry optimization algorithms are divided into two broad categories. Algorithms that focus on modelling fractures using either deterministic [1, 4, 17, 18] or stochastic approaches [19, 20, 21], that is the exploration and identification of discontinuities in the rock mass through various detection methods, where the discontinuity planes are modelled based on their properties — such as dip, dip direction, and average joint spacing — and intersected within a 3D space. The next category of algorithms focuses on modelling block geometry, which typically involves assessing the block yield potential of dimensional quarries by calculating the geometry of in-situ blocks using various algorithms. Several quarry optimization algorithms based on block geometry modeling have been developed. These algorithms mainly focus on the production volume of economic blocks [22, 9, 6, 12, 23, 24, 25, 26]. Production optimization algorithms initially emerged as 2D [9, 27] and well-developed methodologies that possess the capability to model complete and incomplete discontinuities, determine the geometry of blocks, perform 3D modeling, and conduct grading of blocks [28, 29].

This systematic literature review (SLR) seeks to explore state-of-the-art optimization algorithms used in fracture detection, computational analysis, and optimization of block geometry in ornamental stone quarries. It explores the techniques and algorithms utilized in the field of quarry optimization. This research examines the tools, strategies, methods, and limitations involved in assessing rock mass properties and improving block extraction processes. The goal is to provide a comparative assessment that highlights their practical applications and identifies areas that require further research and development.

2. Methodology

This SLR aims to consolidate existing research on optimization algorithms for dimensional stone cutting. The study follows the PRISMA methodology, ensuring a structured and reproducible review process. The methodology consists of four primary stages: identification, screening, eligibility assessment, and data extraction.

2.1. Identification and search strategy

The search process was conducted in October 2024 across four major databases: ScienceDirect, Scopus, Web of Science, and Springer Nature Link (Fig. 1). These databases were selected for their comprehensive

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indexing of peer-reviewed journals. The search terms included: ("optimized extraction" OR "quarrying optimization" OR "fracture" OR "discontinuity" OR "stone cutting algorithm" OR "optimum cutting") AND ("dimension stone" OR "ornamental stone" OR "in situ block"). This search yielded 1,580 articles.

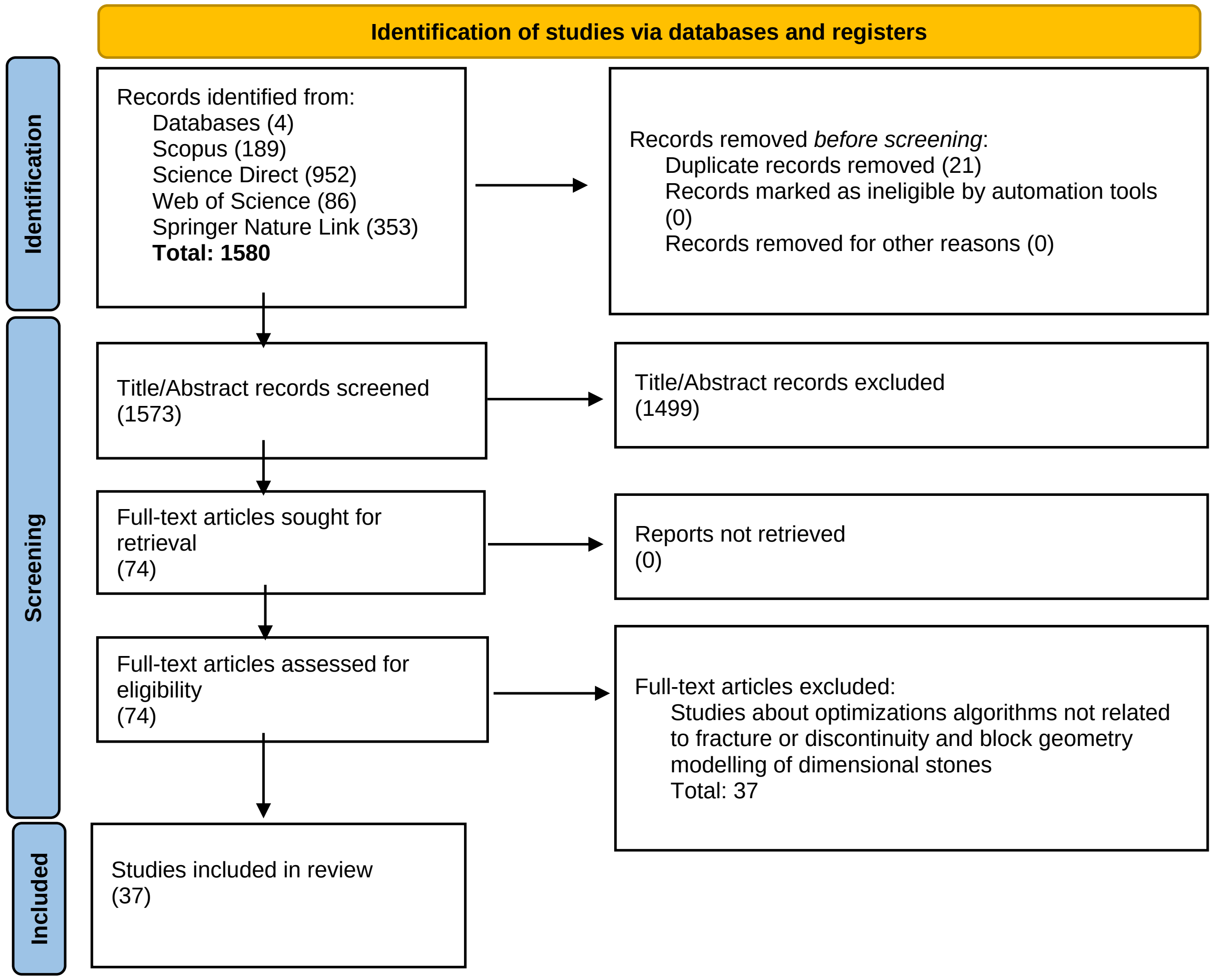

Fig.1. The steps of PRISMA for SLR of the studies

2.2. Screening and Eligibility

After removing duplicates, 1,580 articles were screened based on relevance to stone quarrying optimization. Exclusion criteria included studies unrelated to fracture modelling or block geometry optimization (Table 1). The final selection consisted of 37 articles that closely aligned with the research objectives.

Table 1. Eligibility, inclusion and exclusion creteria

Eligibility criteria	Inclusion	Exclusion
Publication time frame	January 1994 – December 2023	December 1994 and before
Type of document	Journal (research and review articles)	Journal (systematic literature review), review paper, conference papers, book chapters, books, and book series
Subject matter	Stone cutting algorithms use in dimensional stone quarry	Exclude algorithms employed in other industries other than mining
Language	English	Languages other than English
Coverage	Every country in the world	
Access	Open access and subscribed journal via university credential	Non open access and subscribed journal

2.3. Data abstraction and analysis

The selected studies were analytical summarized in Microsoft Excel to categorize optimization approaches. The review focused on fracture detection, computational analysis, and block geometry modelling. The findings are presented in the Results section.

3. Results

The quarrying industry faces challenges due to fractures and discontinuities within rock masses, leading to high waste production. Optimization algorithms are employed to improve extraction efficiency and minimize losses. The reviewed literature categorizes these algorithms into two groups: fracture detection and modeling techniques and block geometry optimization.

3.1. Fracture Detection and Modeling

Ground Penetrating Radar (GPR) is a widely used non-destructive method for identifying fractures in quarry locations. Studies by [30] and [18] highlight its capability to generate three-dimensional models for fracture analysis. Discrete Fracture Networks (DFN) have also proven effective for simulating fracture behavior, as demonstrated in research by [31, 32].

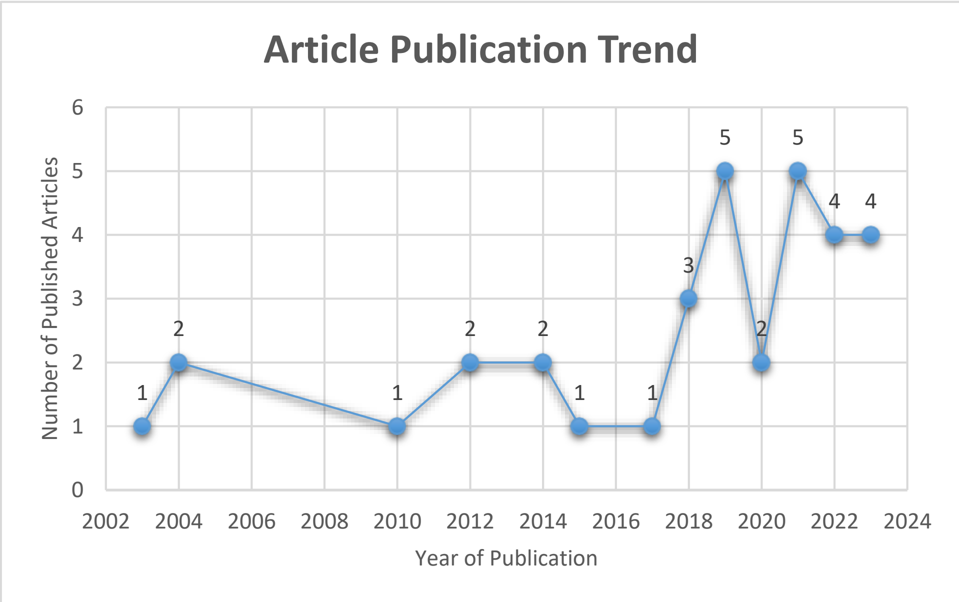

Fig. 2. Article publication trend

3.2. Block Geometry Optimization

Algorithms focusing on block geometry modelling determine the shape, size, and orientation of extractable blocks. Several studies integrate DFN with RANSAC, 3D BlockExpert, and SlabCutOpt for enhanced block yield estimation. [9] combined GPR data with optimization software to improve extraction efficiency. The ability to visualize block boundaries in 3D contributes to reducing waste and optimizing quarry operations.

Although significant advancements have been made, further research is required to develop computational models that incorporate dynamic material properties and digital elevation models. A comparative analysis of existing algorithms provides insights into their advantages, limitations, and applicability in diverse quarrying environments.

4. Discussion

This SLR explores the role of advanced algorithms in optimizing ornamental stone quarrying. The findings indicate that fracture detection and block geometry modelling are crucial for improving efficiency and minimizing waste. GPR remains a leading tool for non-invasive fracture detection, while DFN models offer reliable simulation frameworks for understanding fracture behaviour.

In block geometry optimization, integrating 3D modelling techniques with fracture detection tools enhances extraction precision. Research shows that algorithms such as SlabCutOpt and 3D BlockExpert significantly improve block yield and reduce processing costs. Moreover, studies integrating UAV-based photogrammetry and GIS mapping offer promising improvements in quarry assessment and planning.

Table 2. SLR results based on year, country, number of published articles, title of journal

Year	Country	Number of published articles	Title of Journal
2023	Iran	1	Scientific Reports
	Vietnam	1	Inzynieria Mineralna
	China	1	Acta Geotechnica
2022	Canada	1	Environmental Earth Sciences
	Iran	1	Applied Sciences MDPI
	Germany	2	Environmental Earth Sciences
	Spain	1	Engineering Geology
2021	Austria	1	Applied Sciences MDPI
	China	1	Remote Sensing MDPI
	Croatia	1	Applied Sciences MDPI
2020	USA	1	Mining, Geology, Petroleum Engineering Bulletin (MGPB)
	Croatia	1	Geosciences MDPI
	Italy	1	Resource Policy
2019	Poland	1	Archives of Mining Science
	Vietnam	1	Inzynieria Mineralna
	Slovenia	1	Archives of Mining Sciences
	Paskistan	1	Journal of Mining Science
2018	Iran	1	Bulletin of Engineering Geology and the Environment
	Egypt	1	Geosciences MDPI
	Canada	1	Journal of Rock Mechanics and Geotechnical Engineering
	Portugal	1	Environmental Earth Sciences
2017	Italy	3	Mining, Geology, Petroleum Engineering Bulletin (MGPB), Procedia Engineering (2)
2015	Russia	1	Journal of Mining Science
2014	Turkey	1	The Scientific World Journal
	Australia	1	Rock Mechanics and Rock Engineering
2012	Iran	1	Journal of the Geological Society of India
	Australia	1	Rock Mechanics and Rock Engineering
2010	Portugal	1	Quarterly Journal of Engineering Geology and Hydrogeology
2007	Italy	1	Rock Mechanics and Rock Engineering
2004	Turkey	1	Experiments in Fluids
	Sweden	1	Rock Mechanics and Rock Engineering
2003	Japan	1	Rock Mechanics and Rock Engineering

Despite notable progress, gaps remain in incorporating dynamic geological parameters and real-time adaptability in optimization models. Future research should focus on refining algorithms that can account for material heterogeneity and operational variability, thereby further optimizing the extraction process.

Overall, this review highlights the importance of multidisciplinary approaches in quarry optimization, combining geophysical surveys, computational modelling, and automation techniques to enhance sustainability and efficiency.

5. Conclusion

This paper presents a SLR of optimization algorithms used in the dimensional stone quarrying sector, covering the years from 1994 to 2023 (Table 2). Thirty-seven selected articles were systematically reviewed from highly reported databases: ScienceDirect, Scopus, Web of Science, and Springer Nature Link, using the PRISMA approach. The study identified two broad categories of algorithms used in ornamental stone optimization processes: tools and algorithms used for fracture and discontinuity detection modelling and algorithms employed for block geometry modelling. GPR technology has emerged as a prominent tool, utilized extensively for non-destructive operation and effectiveness in detecting fractures. Algorithms for block geometry analysis, including SlabCutOpt, 3D Block Expert, MAKEBLOCK, and RANSAC, are frequently integrated with fracture modelling tools and algorithms, such as GPR, DFN, scanline survey, and photogrammetry fracture data, to enhance optimization. These algorithms and tools emphasize the significance of specialized approaches in addressing specific challenges within quarry operations. While fracture and discontinuity modelling ensure structural integrity and safety, block geometry modelling focuses on optimizing operational efficiency and resource recovery. By utilizing these complementary methodologies, the industry can achieve a more sustainable and optimized approach to ornamental stone quarry productivity and management.

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