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Research article

Modeling the Effect of Simultaneous Usage of Chainsaw Machine and Diamond Wire Cutting on the Productivity of Dimensional Stone Mines Using Discrete Event Simulation Approach

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English Extended Abstract

Summary

Dimensional stones industry has a significant position in most countries for supplying materials required for civil and industrial projects. The most important issue for the optimal exploitation of dimensional stone mines is the effective management of the extraction process and production planning with the aim of enhancing production and productivity. Diamond wire cutting and chainsaw machine are usually utilized for the extraction of dimensional stone mines. Therefore, the management process for simultaneously application of them have a significant effect on the production and productivity of the mining operations. In this research, according to the performance of each machine in the mining operations, four scenarios were defined for cutting the stone blocks by employing the discrete event simulation approach. In this way, firstly, the time-related data of cutting rate of chainsaw machine, drilling length, and cutting surface of the diamond wire cutting in each shift for both vertical and horizontal orientations were recorded in Shayan mine, and a suitable probability density function was then fitted for each data series. Thereafter, four scenarios of different mining modes using diamond wire cutting and chainsaw machines had subsequently been simulated, assuming a single active bench face. In the first scenario, a diamond wire cutting was alone used to cut all three sides of the block. In the second scenario, in addition to the diamond wire cutting, a chainsaw machine was added to the mining process to cut the back face of the block. In the third scenario, in addition to the diamond wire cutting, a chainsaw machine was also added to the mining process to cut the bottom face of the block. In the fourth scenario, two chainsaw machines were used to cut both the back and the bottom of the block. Based on the results, the production rate for the first to fourth scenarios were 36, 95, 56.5 and 50 thousand tons in 300 working days, respectively. Therefore, the second scenario with the highest production rate and maximum productivity has been proposed as the best scenario for Shayan mine.

Introduction

Currently, most of the dimensional stone mines employ the diamond wire cutting and chainsaw machines in order to ectract the stone blocks. It was appeared that higher production rates and greater efficiency can be achieved when diamond wire cutting and chainsaw machines are simultaneously used. In general, the simultaneous usage of chainsaw machines alongside diamond wire cutters significantly reduces the number of drill holes required for block extraction, which in turn decreases operational time and labor requirements [1]. In 2008, Copur et al. demonstrated that the simultaneous usage of chainsaw machines and diamond wire cutting in the travertine quarry mines may be improved overall mine performance by approximately 20% [2]. Sariisik and Sariisik have investigated the effect of adding a chainsaw machine to dimensional stone mines in Turkey, and observed that after adding the chainsaw machine, the efficiency has increased from 7-

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Vol. 15, No. 44, Fall 2025, Pages 27-36

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

14% to 65-80% [3]. Previous studies have primarily compared the outcomes before and after adding the chainsaw machines. However, no research has investigated the method of integrating chainsaw machines with diamond wire cutting. If the addition of a chainsaw machine does not yield positive results or is not employed correctly, it may lead to lost costs and time. Therefore, this study employs a discrete event simulation approach to examine the effect of incorporating a chainsaw machine on the productivity of mining operations by comparing various scenarios involving the simultaneous use of diamond wire cutting and chainsaw machines.

Simulation of Extraction Operations

Simulation refers to the process of creating models of existing real-world systems or future hypothetical systems and executing these models to explain system behavior, improve system performance, or design new systems [9]. It serves as a method for planning and optimizing complex systems, assisting in decision-making and design. Simulation also enables the evaluation of risks, costs, and operational challenges within a system [4]. Assessing systems through simulation is safer, more cost-effective, and faster. Not only does simulation provide insights into system performance, but it also allows for the identification of the optimal scenario by testing various alternatives without physical implementation [5]. Simulation is categorized into various types, including physical simulation, interactive simulation, continuous simulation, discrete event simulation, etc. Discrete event simulation is a technique that models the operation of a system as a sequence of discrete events occurring at specific points in time. In this approach, each event occurs at a particular moment, triggering a change in the system's state. Between successive events, no changes are assumed, and the simulation advances instantly from one event to the next [6]. In general, random events in simulation occur in two ways: I) the timing of an event may be random, and II) the state transition of an event may be random [7]. The probabilistic characteristics of random variables are defined by their distribution functions. In probability theory, the Probability Density Function (PDF) of a random variable is a function that specifies the relative likelihood of a specific outcome in the sample space [7]. In this study, time-related data, including the advancement rate of the chainsaw machine, the drilling length of the drill, and the cutting surface of the diamond wire in both vertical and horizontal orientations were collected from the Shayan mine during each work shift. The most appropriate PDF for each data series was determined using EasyFit software. Subsequently, four possible scenarios for stone extraction operations using diamond wire cutting and chainsaw machines were simulated based on these distributions in Arena software as seen in Fig. 1. In this study, diamond wire cutting, chainsaw machine, and drill were defined as resources that perform various operations on entities (stone blocks). The simulation assumed a single active working face for all four scenarios, with no equipment movement between multiple faces. Additionally, the total simulation time for all scenarios was set to 300 working days.

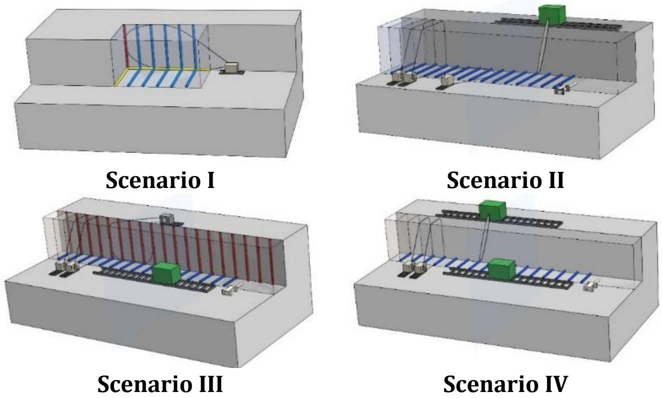

Fig. 1. Simulation possible scenarios for stone extraction using diamond wire cutting and chainsaw machines

Scenario I; in which diamond wire cutting was employed to cut all three faces of the stone block. Due to the greater deviation of vertical drill holes compared to horizontal ones, vertical holes were drilled first, followed

Vol. 15, No. 44, Fall 2025, Pages 27-36

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

by a horizontal hole on the back face of the block parallel to the working face, and finally, horizontal holes perpendicular to the working face. Next, the bottom face of the block was cut, followed by the back face, using diamond wire cutting. Lastly, slotting cuts (regularly spaced cuts to achieve the desired final dimensions) were performed. After completing the cuts, the overturned blocks were transported, preparing the working face for the next round of cutting.

Scenario II; in which the chainsaw machine was used to cut the back face of the block, while diamond wire cutting was utilized for cutting the botton and performing the slotting operation. The process began by drilling horizontal holes, spaced evenly across the bench width. The chainsaw machine was then positioned on the upper bench to start vertical cutting, ensuring the blade intersected the ends of the drill holes. Once the chainsaw advanced equivalent to cutting through five horizontal holes, horizontal diamond wire cutting was initiated for the bottom face of the block, followed by vertical diamond wire cutting for slotting. Finally, the blocks were moved and transported.

Scenario III; in which the chainsaw machine was used for cutting the bottom face of the block, while diamond wire cutting was employed for cutting the back face and slotting. The process began with drilling vertical holes, followed by horizontal drilling. The chainsaw machine then initiated cutting the bottom face of the block, and once it completed the cut for five consecutive blocks' width, the back face cutting commenced, followed by vertical slotting with diamond wire cutting. Finally, the blocks were moved and transported.

Scenario IV; in which the chainsaw machine was employed for cutting both bottom and back faces of the block, while diamond wire cutting was used for slotting. Initially, horizontal holes were drilled, after which the chainsaw performed horizontal cutting for the block base, followed by vertical cutting for the back face. Slotting was then carried out using diamond wire cutting. Finally, the extracted blocks were overturned and transported.

Results and Conclusions

Since four bench faces in the Shayan mine are operated under conditions similar to those of Scenario II, this scenario was used to validate the simulation results. The total annual extraction from these four benches are 380,000 tons, which corresponds to an average of approximately 95,000 tons per each bench face. According to the simulation results, the exact extracted tonnage for Scenario II was 94,770 tons. The difference between the actual extracted tonnage and the simulation result for one year of operation was only 230 tons. This minimal error confirms the reliability of the simulation results for other scenarios.

Based on the simulation results, the number of extracted blocks (with dimensions of 1.8×6×6 meters) was 224 in Scenario I, and 585 blocks in Scenario II. In addition, 698 and 617 blocks (with dimensions of 1.8×3×6 meters) were respectively extracted in Scenarios III and IV. Because the blade length in horizontal cutting is shorter, the cutting dimensions for Scenarios III and IV have changed. Considering the average specific weight of the Shayan mine's stone, which is 2.5 tons per cubic meter, the extracted tonnage for Scenarios I to IV was approximately 36, 95, 56.5, and 50 thousand tons, respectively.

The diamond wire cutting (Scenario I) requires drilling holes at the back face of the block, which cannot proceed until the blocks from the previous cuts have been removed. This limitation reduces production rate and efficiency. On the other hand, the cutting area achieved by the diamond wire cutters is approximately three times larger than that of the chainsaw machine in the same period. However, the primary factor contributing to increased production after adding the chainsaw machine is the reduced amount of drilling required. This reduction is due to the optimal cutting thickness of the chainsaw (5 to 7 cm), which provides sufficient space for the diamond wire to pass through. In Scenarios III and IV, after cutting the bottom and back faces of the block, the block tends to settle, necessitating additional horizontal drilling for wire passage. Consequently, the lower the specific drilling requirements and the cutting area required by the chainsaw, the higher the production rate. Table 1 presents the specific drilling lengths (drilling per cubic meter of extraction) and the cutting area by the chainsaw machine relative to the total cutting area required for block extraction in Scenarios II to IV.

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Vol. 15, No. 44, Fall 2025, Pages 27-36

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

Table 1. Specific drilling length and cutting area ratio in chainsaw

Scenario	Specific drilling (m/m3)	Cutting area ratio in chainsaw (%)
2	0.037	18.75
3	0.111	15.79
4	0.037	47.37

The simultaneous usage of machinery across different scenarios led to variations in waiting times for prerequisite operations. For instance, in Scenario I, horizontal cutting could not commence until all required holes were drilled. This emphasizes the influence of operation sequencing on machinery utilization. Furthermore, simulations involving adjustments to the number of machines identified the optimal number of machines for each scenario. Fig. 2 illustrates the optimal number of machines and their utilization rates for each scenario. It was observed that adding machines beyond the optimal number yielded negligible production gains, while a shortage of machines significantly decreased production. If R_T is defined as a measure for the capital productivity of machinery, the utilization index for each scenario can be calculated using Equation 1:

$$R_T = \frac{\sum C_i R_i}{\sum C_i} \qquad (1)$$

Where C_i is the cost, and R_i is the utilization percentage of machine i.

Considering the relatively high costs of the chainsaw (120 billion rials), the diamond wire cutter (8 billion rials), and the drill (1 billion rials), the capital productivity for Scenarios I to IV was calculated as 37.5%, 92.4%, 63.6%, and 73.8%, respectively.

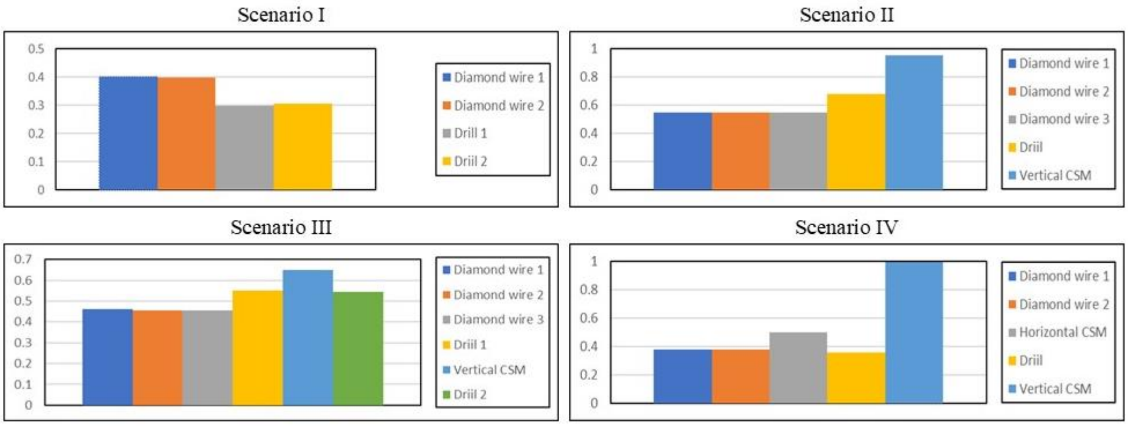

Fig. 2. Optimal number of machines and their utilization for Scenarios I to IV

According to studies conducted in Turkish travertine mines [3], productivity increased from 7-14% to 65-80% after adding a chainsaw machine. Similarly, in this study, the capital productivity index in Scenario I was 37%, where only diamond wire cutting is used; while in Scenarios II to IV productivity will be increased to 67-92% by adding the chainsaw machine.

In general, the production rate of cutting machinery in dimension stone quarries plays a critical role in the efficiency of extraction operations, particularly when considering the final extraction costs of a block. Therefore, taking appropriate measures to enhance the efficiency and productivity of machinery in the dimension stone industry is of significant importance. According to the simulation results, the most influential factor in production rates is the drilling length. Additionally, drilling the hole behind the block has the greatest influence on the production continuity, as this drilling cannot proceed until the blocks from the previous cutting operation have been transported. Overall, the cutting rate of the chainsaw machine is lower than that of the diamond wire cutting; however, incorporating the chainsaw machines into the extraction process reduces drilling length and improves production continuity. Consequently, the simultaneous usage

Vol. 15, No. 44, Fall 2025, Pages 27-36

Journal of Analytical and Numerical Methods in Mining Engineering

Journal home page: http://anm.yazd.ac.ir/

of both diamond wire cutting and chainsaw machines should be optimized to minimize drilling length and the cutting surface of the chainsaw while ensuring block extraction.

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