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Selecting the optimal scenario for the simultaneous application of diamond wire cutting and chainsaw machines in dimensional stone mines using SECA multi-criteria decision-making method

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Abstract
Currently, diamond wire cutting is used in most dimensional stone mines to extract stone blocks. Despite the capabilities of diamond wire cutting, stone extraction is associated with limitations or productivity loss in some cases. For this purpose, different scenarios resulting from the combination of diamond wire cutting and chainsaw machines had been investigated by discrete-event simulation in this research with the aim of improving the productivity of mining operations, and the best scenario was selected using the multi-criteria decision-making method of Simultaneous Evaluation of Criteria and Alternatives (SECA). In this research, the Shayan dimensional stone mine was selected as a case study, and based on the information related to mining operations, ten scenarios were defined for cutting the stone blocks. 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 to sixth scenarios, in addition to the diamond wire cutting to cut side faces, a chainsaw machine was added to the mining process to cut the bottom face of the block. Depending on the continuity and intactness of the rock mass, and the need for horizontal drilling, the block dimensions varied across these scenarios. In the seventh to ninth scenarios, in addition to the diamond wire cutting to cut side faces, two chainsaw machines were used to cut both the back and the bottom faces of the block. These scenarios may differ in terms of the stone's intactness, the need for horizontal drilling, and block dimensions. Finally, in the tenth scenario, both the back and bottom faces were cut using two chainsaw machines, while the side faces were cut using two squaring chainsaw machines. In order to find the best scenario to achieve the optimal technical and economic conditions, the SECA decision-making method was used due to the presence of several influential criteria. Based on the available information, four criteria including the production rate, capital cost, operating costs, and productivity were considered to compare the defined scenarios. According to the results, the final weights of the criteria were respectively equal to 0.228, 0.32, 0.239, and 0.213. Based on the criteria weights and the performance of each scenario across the criteria, the final scores of the scenarios were determined, and ultimately, the second scenario with a score of 0.655 emerged as the optimal configuration for the Shayan mine due to its balanced performance across all criteria.

Keywords:
discrete-event simulation, dimensional stone mine, diamond wire cutting, chainsaw machine, SECA method

1. Introduction

Iran, owing to its favorable geological conditions and geographic location, is among the countries with high potential in the field of dimensional stones (**Hayati et al., 2023**). With the expansion of construction, maximizing the efficiency and production of dimensional stones has become essential as a key material in this industry (**Mohammadi et al., 2018; Macedo et al., 2017**).

Currently, diamond wire cutting is used for the extraction of most dimensional stone quarries (**Mikaeil et al., 2018; Korman et al., 2016; Rasti et al., 2021**). However, the use of chainsaw machines alongside diamond wire cutting can significantly increase mine efficiency (**Copur et al., 2007; Copur et al., 2008**). The necessity of the simultaneous application of these two machines becomes apparent when, in addition to increasing the efficiency and profitability of the mine, the application of diamond wire cutting is limited or impossible in some working benches. In this regard, **Copur et al. (2006)** evaluated the performance of mining operations before and after adding a chainsaw machine. The results showed that after adding only one chainsaw machine, the overall performance of the mine will be improved by about 20%. The results of other studies in two travertine mines in Turkey also showed that by adding a chainsaw machine to the extraction operations, mine productivity would be increased from a range of 7 to 14% to about 56 to 80% (**Sariisik and Sariisik, 2010**).

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These findings underscore the potential benefits of integrating these two technologies.

Making a correct decision regarding the use of chainsaw machines in the extraction of dimensional stone quarries, as well as the way employing this machine along with diamond wire cutting, depends on various factors and criteria. The use of Multi-Criteria Decision Making (MCDM) methods is a common approach for selecting the optimal alternative or making an optimal decision based on multiple criteria (**Esmailzadeh et al., 2018**). In this regard, several studies have been conducted to make decisions and select appropriate equipment and machinery in dimensional stone quarries. **Esmaeili and Safari (2014)** proposed a combined method of chainsaw machine and diamond wire cutting for the extraction of dimensional stone quarries using the Analytic Hierarchy Process (AHP). **Javanshir Giv et al. (2022)** suggested diamond wire cutting for a granite quarry mine based on the Elimination Et Choice Translating Reality (ELECTRE) method. **Esmailzadeh et al. (2018)** introduced diamond wire cutting as the best alternative among extraction methods of dimensional stone quarries through weighting the criteria by the Fuzzy Delphi Analytic Hierarchy Process (FDAHP), and ranking them using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

In order to identify the most suitable scenario for the concurrent application of diamond wire cutting and chainsaws, this research utilized the Simultaneous Evaluation of Criteria and Alternatives (SECA) decision-making methodology. Unlike many MCDM methods that are only used to rank alternatives or calculate the weight of criteria, this method can solve an MCDM problem by simultaneously evaluating criteria and alternatives (**Keshavarz-Ghorabaee et al., 2018**). The SECA method has been favored by researchers due to its practical capabilities and relatively new approach (**Das et al., 2023; Assadi et al., 2022; Zhang et al., 2024; Namin and Amou, 2024**). Unlike previous studies examining the simultaneous use of diamond wire cutting and chainsaw machines, this research investigates various scenarios of their combined application, considering four criteria: production rate, capital cost, operating cost, and efficiency. Also the SECA method was firstly employed for this analysis in our research.

2. SECA Decision-Making Method

The primary objective of the SECA method is to simultaneously determine the scores of alternatives and the criteria weights by defining a nonlinear multi-objective mathematical model. Two reference points for weighting criteria were considered to formulate the mathematical model. The first type is based on information about intra-criteria (within-criteria) variations, defined by standard deviation. The second type relates to information about inter-criteria (between-criteria) variations, determined based on the correlation coefficient. In essence, in the nonlinear multi-objective mathematical model a weighted sum model is used as one objective to maximize the performance score of each alternative. Moreover, the sum of the squares of deviations of criteria weights is used as the other objective to minimize the deviation from the reference points. By optimizing the developed mathematical model, the overall performance scores of the alternatives and the weights of the criteria can simultaneously be determined (**Keshavarz-Ghorabaee et al., 2018**).

2.1. Decision Matrix Formation

To develop the decision matrix, all alternatives to be compared and all criteria that are important in ranking the alternatives are first determined. Then, considering the two-dimensional nature of the decision problem, two vertical and horizontal axes are considered; such that the vertical axis represents the alternatives and the horizontal axis represents the criteria. If the problem has *n* alternatives and *m* criteria, and the weight of each criterion (w_j, $j \in \{1, 2, \ldots, m\}$) is unknown, the decision matrix will be formed as:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1j} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2j} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1} & x_{i2} & \cdots & x_{ij} & \cdots & x_{im} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nj} & \cdots & x_{nm} \end{bmatrix} \quad (1)$$

where x_{ij} denotes the performance value of the i[th] ($i \in \{1, 2, \ldots, n\}$) alternative on the j[th] criterion, and $x_{ij} > 0$. Considering the scores that each alternative has obtained in each criterion based on the opinion of the expert(s), the entries of x_{ij} are completed. Scoring is done for each alternative based on each criterion; in other words, the decision matrix is completed column by column and vertically.

2.2. Decision Matrix Normalization

Criteria may differ in dimension (unit of measurement) and positive and negative aspects. Normalization of criteria enables their correct comparison. In the SECA method, **Equation 2** is used for normalizing the decision matrix (**Baradari et al., 2021**).

$$x_{ij}^{N} = \begin{cases} \dfrac{x_{ij}}{\max_k x_{kj}} & if\ j \in BC \\ \dfrac{\min_k x_{kj}}{x_{ij}} & if\ j \in NC \end{cases} \quad (2)$$

where *BC* represents a positive criterion and *NC* represents a negative criterion. Thus, the normalized matrix is rewritten according to **Equation 3**.

$$x^N = \begin{bmatrix} x_{11}^N & x_{12}^N & \dots & x_{1j}^N & \dots & x_{1m}^N \\ x_{21}^N & x_{22}^N & \dots & x_{2j}^N & \dots & x_{2m}^N \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{i1}^N & x_{i2}^N & \dots & x_{ij}^N & \dots & x_{im}^N \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ x_{n1}^N & x_{n2}^N & \dots & x_{nj}^N & \dots & x_{nm}^N \end{bmatrix} \quad (3)$$

2.3. Determining reference points

In the SECA method, the standard deviation of the elements of each vector (σ_j) is used to get the within-criterion variation information. Besides, to capture the between-criterion variation information from the decision matrix, it is necessary to calculate the correlation between each pair of criteria vectors. Therefore, if r_{jl} represents the correlation between the j[th] and l[th] vectors (j and $l \in \{1,2,...,m\}$), the inconsistency degree (π_j) can reflect the degree of conflict between the j[th] criterion and the other criteria as:

$$\Pi_j = \sum_{l=1}^{m} (1 - r_{jl}) \quad (4)$$

An increase in the variation within the vector of a criterion (σ_j) and also an increase in the degree of conflict between a criterion and the other criteria (π_j) intensifies the objective importance of that criterion. Based on this, the normalized values of σ_j and π_j are defined as the reference points for the weights of criteria:

$$\sigma_j^N = \frac{\sigma_j}{\sum_{l=1}^{m} \sigma_l} \quad (5)$$

$$\pi_j^N = \frac{\pi_j}{\sum_{l=1}^{m} \pi_l} \quad (6)$$

2.4. Weighting and Ranking Mathematical Model

Ultimately, a multi-objective nonlinear programming model is defined as (**Das and Chakraborty, 2022**):

$$\begin{aligned} &\max S_i = \sum_{j=1}^{m} w_j x_{ij}^N, \forall i \in \{1,2,\cdots,n\} \\ &\min \lambda_b = \sum_{j=1}^{m} (w_j - \sigma_j^N)^2 \\ &\min \lambda_c = \sum_{j=1}^{m} (w_j - \pi_j^N)^2 \\ &s.t. \\ &\sum_{j=1}^{m} w_j = 1 \\ &w_j \le 1, \forall j \in \{1,2,\cdots,m\} \\ &w_j \ge \varepsilon, \forall j \in \{1,2,\cdots,m\} \end{aligned} \quad (7)$$

where, simultaneously, the overall performance of each alternative is maximized and the deviation of criteria weights from the reference points is minimized. Obviously, the sum of weights is equal to 1. Also, the values of criteria weights are set in the range $[\varepsilon, 1]$. It is worth mentioning that ε is a small positive parameter that is considered as a lower bound for the weights of criteria. In this study, this parameter is considered to be equal to 10^{-3}.

In order to optimize the mathematical model of **Equation 7**, multi-objective optimization techniques have been used, and the resulting model is rewritten as:

$$\begin{aligned} &\max Z = \lambda_a - \beta(\lambda_b + \lambda_c) \\ &s.t. \\ &\lambda_a \le S_i, \forall i \in \{1,2,\cdots,n\} \\ &S_i = \sum_{j=1}^{m} w_j x_{ij}^N, \forall i \in \{1,2,\cdots,n\} \\ &\lambda_b = \sum_{j=1}^{m} (w_j - \sigma_j^N)^2 \\ &\lambda_c = \sum_{j=1}^{m} (w_j - \Pi_j^N)^2 \\ &\sum_{j=1}^{m} w_j = 1 \\ &w_j \le 1, \forall j \in \{1,2,\cdots,m\} \\ &w_j \ge \varepsilon, \forall j \in \{1,2,\cdots,m\} \end{aligned} \quad (8)$$

Therefore, the minimum of the overall performance score of alternatives is at least λ_a, which will be maximized in the objective function. Since the deviation from the reference points (λ_b and λ_c) must be minimized, these values are subtracted from the objective function with a coefficient β. This coefficient changes the importance of the difference between the reference points and the criteria weights in the objective function. The coefficient β will increase until the performance score of each alternative (S_i) and the target weight of each criterion (w_j) becomes constant.

3. Shayan Quarry mine

The Shayan quarry mine is located in Fars Province, 230 km northeast of Shiraz. The active mining area is situated between longitudes 53° 31' 56.09" and 53° 32' 27.93" and latitudes 30° 21' 59.98" and 30° 22' 20" (**SMTO, 2022**).

The first six benches of the quarry were extracted using diamond wire cutting. These six benches were completely weathered and tectonized, and were transferred to the waste dump. From the seventh bench onwards, a chainsaw machine initially performs the primary cutting throughout the whole length of the bench, which is called the cutting cycle. The distance of the machine from the edge of the bench is 6 m, and the useful length of the blade is also 6 m (**Masoudi, 2021**). Then, dia-

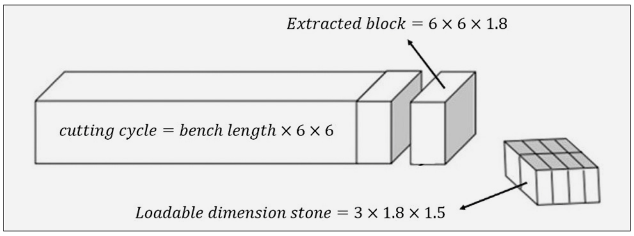

Figure 1. Cutting stages of dimensional stone in Shayan Mine

mond wire cutting is used to cut the blocks into dimensions of 1.8 $m \times 6\ m \times 6\ m$ (block height or bench height is 6 m, block length is 6 m, and its width is 1.8 m), with an approximate weight of 162 tonnes (specific gravity of 2.5 tonnes per cubic meter) (see **Figure 1**).

4. Simulation of Simultaneous Application of Diamond Wire Cutting and Chainsaw Machine

In this research, a discrete-event simulation approach is used to compare different scenarios of the simultaneous application of diamond wire cutting and chainsaw machines. In this approach, the system's operations in each scenario are represented as a time sequence of extraction operations (the occurrence of each event at a specific moment in time). If the simultaneous use of chainsaws machines and diamond wire cutting is not managed correctly, it can lead to a loss of time and costs (**Rasti et al., 2021**). Therefore, simulation not only depicts how the system works, but also the best scenario can be identified by running different scenarios without physical execution, improving the performance of extraction operations (**Liu et al., 2017**). On the other hand, to select the optimal scenario, a set of criteria must be considered (**Cardu et al., 2014**). Given the simultaneous impact of multiple criteria, the use of MCDM methods is a suitable approach for selecting the optimal scenario.

Considering the type of use and application of each machine for cutting each face of the stone block, ten scenarios have been defined for extracting blocks, each one having its own advantages and disadvantages. In our simulations, it is assumed that there is only one bench face for all ten scenarios, and the machines cannot move between two or more bench faces. Also, the duration of all simulations is considered to be 300 working days.

I. Scenario 1 (S1): Diamond wire cutting is used for all three faces of the block, with the cutting dimensions assumed to be 6×6×1.8 m^3 (see **Figure 2**).

II. Scenario 2 (S2): The back face is cut using a chainsaw machine, while the other faces are cut with diamond wire cutting. Considering the 6-meter blade length of the chainsaw machine, the cutting dimensions are assumed to be 6×6×1.8 m^3 (see **Figure 3**).

III. Scenario 3 (S3): The bottom face is cut using a chainsaw machine, while the other faces are cut with a diamond wire cutter. In this scenario, it is assumed that the stone has many fractures and cracks, requiring the

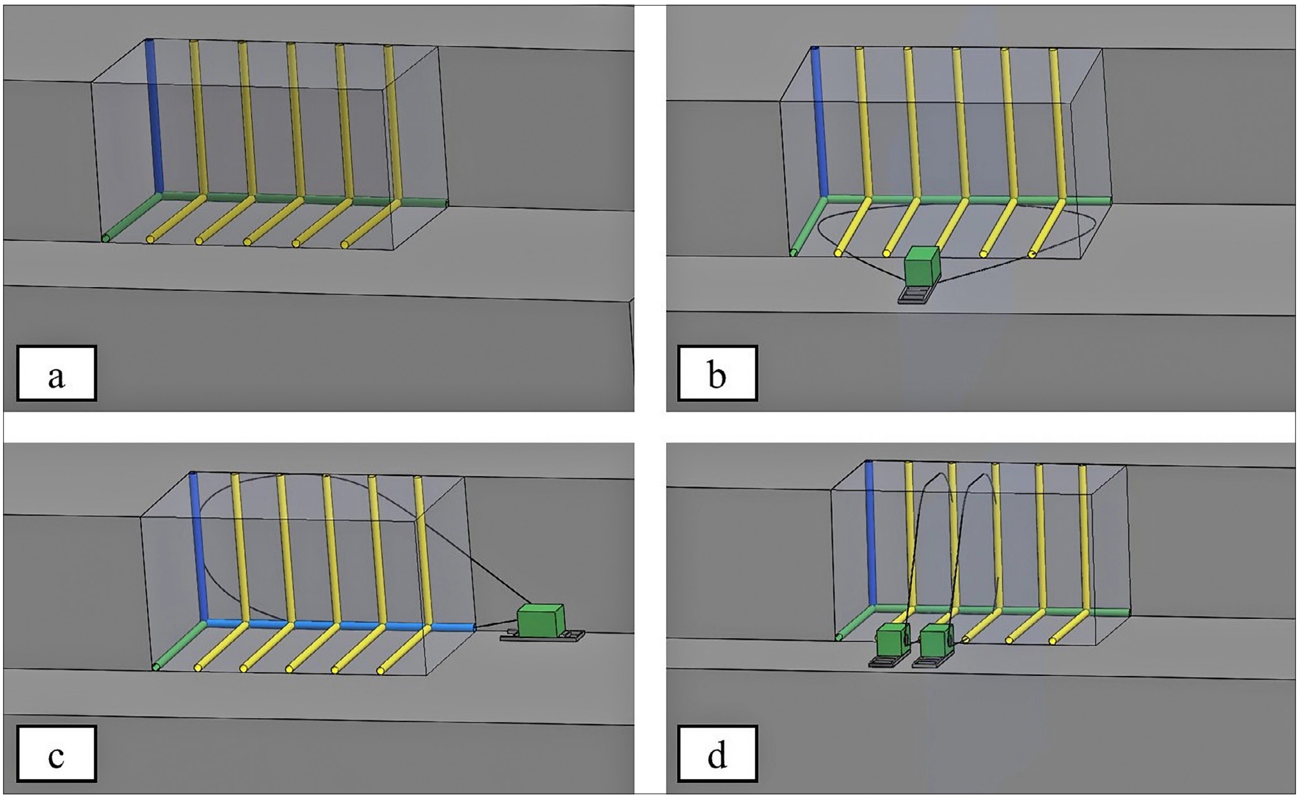

Figure 2. Diamond wire cutting method (Scenario 1)

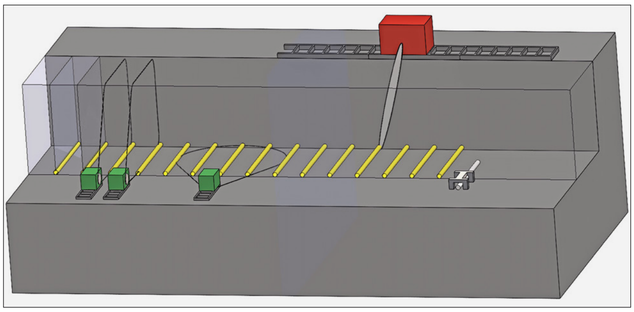

Figure 3. Diamond wire cutting along with chainsaw machine for back face cutting (Scenario 2)

horizontal borehole even after cutting with the chainsaw. Additionally, due to the risk of blade jamming or stone breakage, the blade length is limited to 3 m. Thus, the cutting dimensions are assumed to be 3×6×1.8 m^3 (see **Figure 4**).

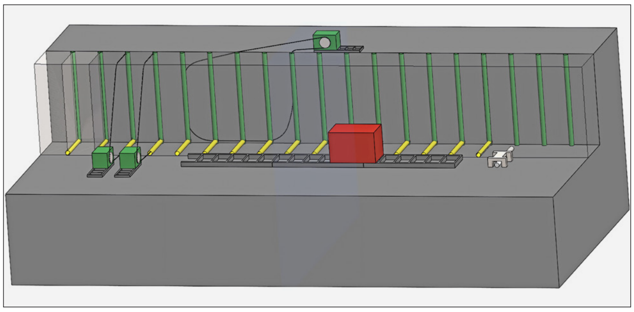

Figure 4. Diamond wire cutting along with chainsaw machine for bottom face cutting (Scenario 3)

IV. Scenario 4 (S4): This scenario is similar to Scenario 3, except that the rock mass is assumed to be intact. Therefore, after cutting the bottom face, there is sufficient space for the diamond wire to pass through, without requiring a borehole (see **Figure 5**).

V. Scenario 5 (S5): This scenario is similar to Scenario 4, except that the geological conditions may allow the use of a 6-meter blade for cutting the bottom face. Therefore, the cutting dimensions are 6×6×1.8 m^3 (see **Figure 5**).

VI. Scenario 6 (S6): To examine the impact of cutting height on production, this scenario assumes a cut-

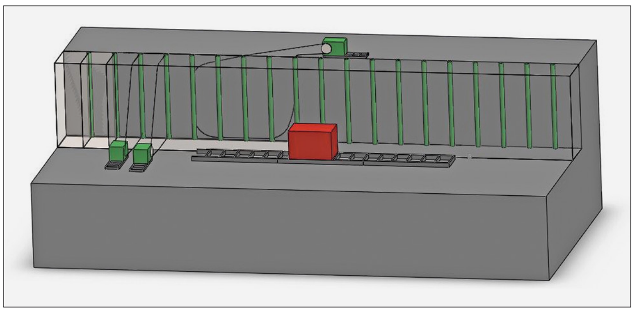

Figure 5. Chainsaw machine for bottom face cutting (intact stone), and diamond wire cutting for other faces (Scenarios 4, 5, and 6)

ting height of 10 meters, while the other dimensions and the machinery are similar to Scenario 5 (see **Figure 5**).

VII. Scenario 7 (S7): Two chainsaw machines are used to cut the back and bottom faces of the block, while diamond wire cutting is used for the side faces. In this scenario, it is assumed that the fractures and cracks are propagated through the rock mass. After cutting the bottom face with the chainsaw machine, a horizontal borehole is still needed. Additionally, due to the risk of blade jamming or stone breakage, a 3-meter blade is used for the bottom cut. Thus, the cutting dimensions are 3×6×1.8 m^3 (see **Figure 6**).

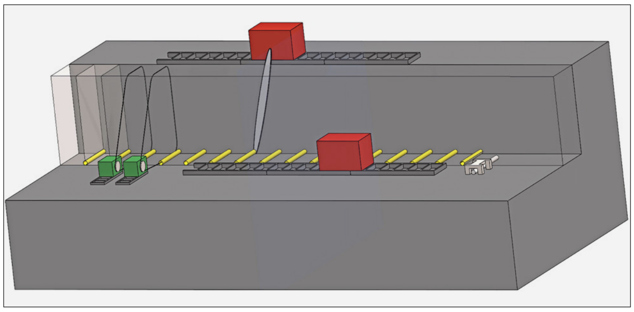

Figure 6. Diamond wire cutting along with two chainsaw machines for both back and bottom faces (Scenario 7)

VIII. Scenario 8 (S8): The cutting dimensions and the machinery are similar to Scenario 7, except that the rock mass is assumed to be intact, eliminating the need for a horizontal borehole for the diamond wire to pass through (see **Figure 7**).

IX. Scenario 9 (S9): This scenario is similar to Scenario 8, except that the geological conditions may allow the use of a 6-meter blade for cutting the bottom face. Therefore, the cutting dimensions are 6×6×1.8 m^3 (see **Figure 7**).

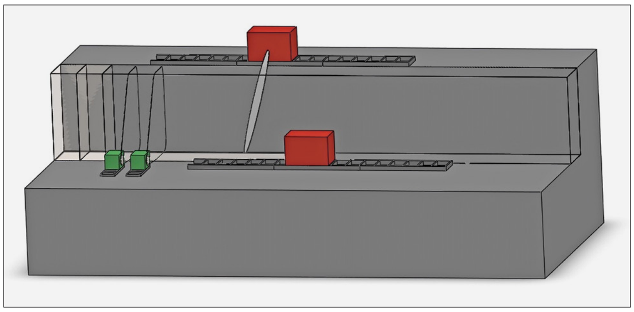

Figure 7. Two chainsaw machines for back and bottom faces (intact stone), and diamond wire cutting for other faces (Scenarios 8 and 9)

X. Scenario 10 (S10): Two chainsaw machines are used for cutting the bottom and back faces of the block, while two squaring chainsaw machines are used for cutting the side faces. In this scenario, all four machines are equipped with 6-meter blades, resulting in cutting dimensions of 6×6×1.8 m^3 (see **Figure 8**).

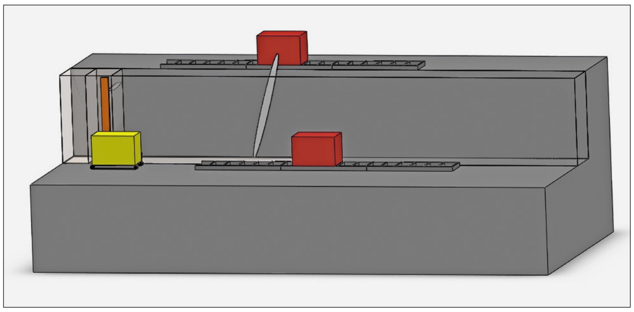

Figure 8. Two chainsaw machines for back and bottom faces, and two squaring chainsaw machines for side faces (Scenario 10)

4.1. Comparison of Simulation Scenarios

To compare different scenarios, four criteria were considered including: production rate (C1), capital cost (C2), operational cost (C3), and machines utilization (C4).

4.1.1. Production Rate (C1)

In each of the ten simulated scenarios for the simultaneous application of diamond wire cutting and chainsaw machine, data recorded from the Shayan mine, including drilling speed, chainsaw machine cutting rate, and diamond wire cutting rate, were utilized. The production rates for each scenario over a 300-day working period are presented in **Table 1**.

4.1.2. Capital Cost (C2)

The optimal number of machines was calculated considering their capital costs, and the results were summarized for each scenario in **Table 2**. Based on the simulation results, increasing the number of machines beyond this number did not have a significant impact on the extraction rate, but reducing the numbers below these values would significantly decrease the production rate. In this research, the price of each chainsaw machine was assumed to be 180,000 USD, each diamond wire cutter 4,500 USD, and each drill 1,500 USD.

4.1.3. Operating Cost (C3)

According to the Shayan mine report, each segment of the chainsaw machine cuts approximately 10.5 square meters of stone on average, while each meter of diamond wire cuts 58 square meters. Another critical consumable during chainsaw cutting is grease, used to lubricate the chain's movement on the blade. In the Shayan mine, recycled oil is employed as a substitute for grease, with an average consumption of 2.97 litres per square meter of stone cut. **Table 3** summarizes the consumption of chainsaw segments, diamond wire, and oil along with the total operating costs for each scenario per cubic meter of extracted stone block. These calculations assume the following costs: 3.75 USD per chainsaw segment, 24.75 USD per meter of diamond wire, and 0.34 USD per litre of recycled oil.

Table 1. Production rates for the ten simulated scenarios over a 300-day working period

Scenario	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Production rate (thousand tonnes)	36	95	56.5	60	92	118	50	50	97	49

Table 2. Number of machines and capital costs for each scenario

Scenario	Diamond wire cutter	Chainsaw machine	Drill	Capital cost (USD)
S1	2	0	2	12000
S2	3	1	1	195000
S3	3	1	2	196500
S4	3	1	2	196500
S5	3	1	1	195000
S6	4	1	2	201000
S7	2	2	1	370500
S8	2	2	0	369000
S9	2	2	0	396000
S10	0	2+2	0	820000

4.1.4. Machinery Utilization (C4)

In the simulation of each scenario, the overall utilization of machinery (R_i) is calculated based on the active time of each machine according to **Equation 9**:

Table 3. Operational costs for each scenario

Parameter	Unit	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Block volume	m³	64.8	64.8	32.4	32.4	64.8	108	32.4	32.4	64.8	64.8
Cutting area with diamond wire	m²	57.6	46.8	28.8	28.8	46.8	78	18	18	36	-
Cutting area with chainsaw	m²	-	10.8	5.4	5.4	10.8	10.8	16.2	16.2	21.6	57.6
Diamond wire consumption	m/m³	0.015	0.012	0.015	0.015	0.012	0.012	0.009	0.009	0.009	-
Chainsaw segment consumption	n/m³	-	0.016	0.016	0.016	0.016	0.016	0.047	0.047	0.031	0.085
Oil consumption	Lit/m³	-	0.056	0.056	0.056	0.056	0.056	0.017	0.017	0.99	2.64
Total operating costs	USD/m³	0.37	0.38	0.46	0.46	0.38	0.38	0.47	0.47	0.68	1.22

Table 4. Decision matrix

Alternative \ Criteria	C1	C2	C3	C4
S1	36	12000	0.213	0.375
S2	95	195000	0.380	0.924
S3	56.5	196500	0.370	0.636
S4	60	196500	0.460	0.640
S5	92	195000	0.380	0.890
S6	118	201000	0.380	0.700
S7	50	370500	0.185	0.738
S8	50	369000	0.470	0.740
S9	97	396000	0.680	0.890
S10	49	800000	1.220	0.640

$$R_t = \frac{\sum C_i R_i}{\sum C_i} \quad (9)$$

where C_i is the price and R_i is the utilization percentage of machine i. According to this equation, the scenario with the highest continuity and maximum utilization of machinery will receive a higher score. It should be noted that the extraction of dimensional stones is a multi-stage series operation. This means that the next operation cannot start until a previous activity is completed. For example, in the simulation of the first scenario, drilling holes in the back face of the block is not possible until the blocks from the first cut are transported.

5. Discussion and results

To determine the performance of different scenarios, production rate and machinery utilization were considered for each scenario based on the simulation results considering the capital and operating costs in each scenario, i.e. the total cost of machinery and the costs of tools and consumables used by each machine.

5.1. Comparison of Scenarios in the Decision Matrix

After calculating the performance of each scenario, the final decision matrix was formed as shown in **Table 4**. To normalize this decision matrix, **Equation 2** was used, and the results are summarized in **Table 5**. In solving the model, the criteria of utilization and production were positive; as they increase, the desirability of the alternative increases. However, the capital and operating costs were negative; as they decrease, the alternative will have greater desirability.

5.2. Calculation of Reference Points

To calculate the inconsistency among criteria, the correlation coefficients between each pair of criteria were first determined. Then, using **Equation 4**, the inconsistency rate of each criterion was calculated as presented in **Table 6**.

Table 5. Normalized decision matrix

Alternative \ Criteria	C1	C2	C3	C4
S1	0.305	1.000	1.000	0.406
S2	0.805	0.062	0.974	1.000
S3	0.479	0.061	0.804	0.688
S4	0.508	0.061	0.804	0.693
S5	0.780	0.062	0.974	0.963
S6	1.000	0.060	0.974	0.758
S7	0.424	0.032	0.787	0.799
S8	0.424	0.033	0.787	0.801
S9	0.822	0.030	0.544	0.963
S10	0.415	0.015	0.303	0.693

Table 6. Correlation matrix and inconsistency index for each criterion

Alternative \ Criteria	C1	C2	C3	C4
C1	1.000	-0.414	0.248	0.670
C2	-0.414	1.000	0.370	-0.731
C3	0.248	0.3701	1.000	-0.039
C4	0.670	-0.731	-0.039	1.000
Inconsistency	2.495	3.774	2.420	3.100

Table 7. Normalized standard deviation and inconsistency (reference points)

Alternative \ Criteria	C1	C2	C3	C4
σ_j^N	0.250	0.324	0.238	0.189
Π_j^N	0.212	0.320	0.205	0.263

To obtain the reference points, the standard deviation and inconsistency rate for each index were normalized based on **Equations 5** and **6** (see **Table 7**).

5.3. Solving the Final Model

To solve the final programming model using the SECA method, the weights of the criteria and the score of each scenario were determined for different values of β. **Figure 9** shows the changes in the weights of the criteria, and **Figure 10** illustrates the changes in the scores and rankings of the alternative. As seen, for values of β greater than 60, the weights of the criteria and the alternative scores did not change significantly (less than 10^{-3}) and continued in parallel.

The SECA method, as a compensatory MCDM approach, was instrumental in evaluating the ten defined scenarios based on four key criteria: production rate, capital cost, operating cost, and machinery utilization. This method allowed trade-offs among the criteria,

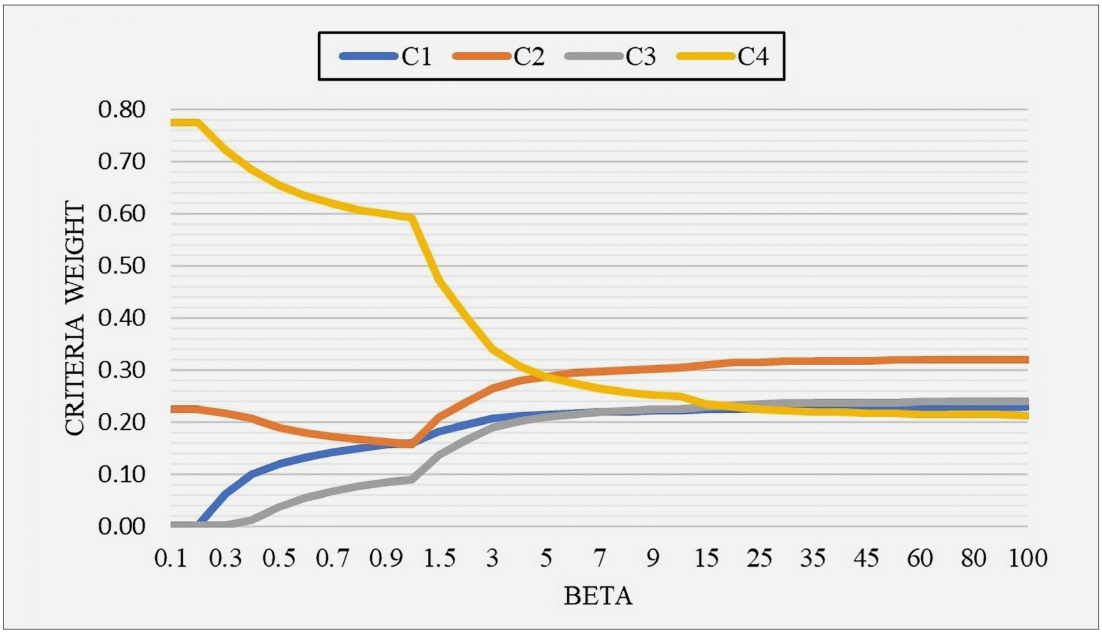

Figure 9. Variation of criteria weights for different values of β

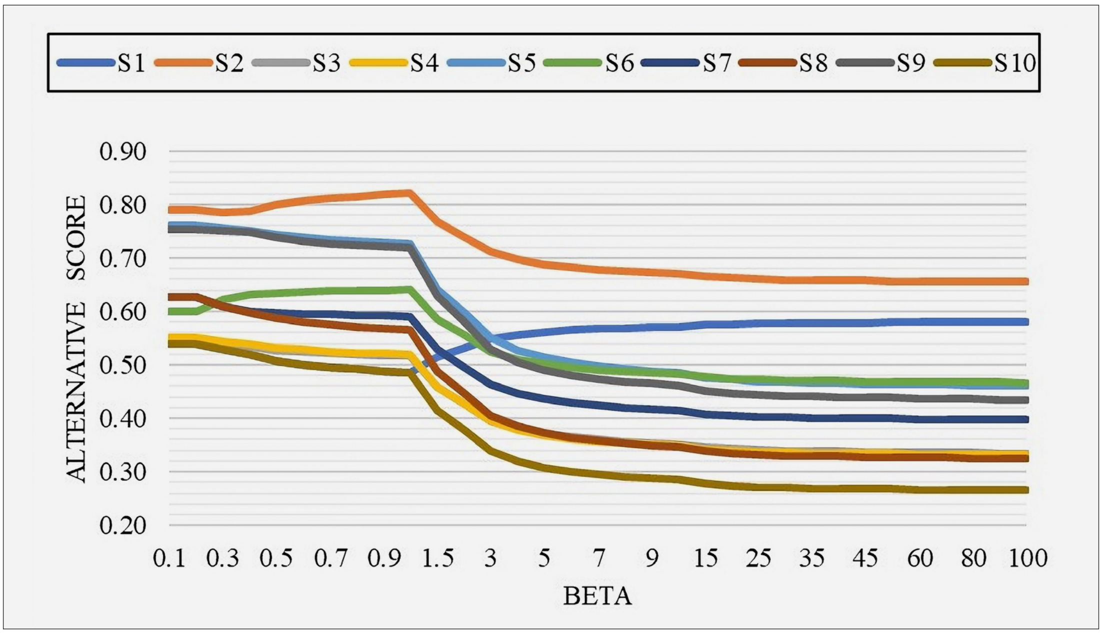

Figure 10. Variation of alternative scores for different values of β

where weak performance in one area could be offset by strengths in another, enabling a holistic evaluation of each scenario. The final results of the ranking of alternatives and the criteria weights are summarized in **Tables 8** and **9**.

Scenario 2 appeared as the optimal configuration due to its balanced performance across all criteria. By using a chainsaw machine for back-face cutting and diamond wire cutting for other faces, Scenario 2 achieved high machinery utilization and a production rate of 95,000 tonnes. The moderate capital cost of $195,000 and efficient operating cost management further solidified its position as the most desirable scenario.

Table 8. Final weights of the criteria

Criteria	C1	C2	C3	C4
Weight	0.2281	0.3199	0.2391	0.2128

Scenario 1, despite its lower production rate (36,000 tonnes), ranked second due to its simplicity and low capital cost, making it a practical choice for cost-sensitive conditions or limited bench lengths. However, its dependence on back drilling significantly reduced machinery utilization and production continuity, as drilling the back hole could not proceed until the blocks from the previous cut were removed, leading to operational de-

Table 9. Final score of the scenarios

Scenarios	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Score	0.580	0.655	0.335	0.331	0.461	0.467	0.397	0.325	0.335	0.265

lays. The results also demonstrated a significant improvement in capital productivity after the addition of chainsaw machines. According to studies conducted by Sariisik and Sariisik in travertine mines (**Sariisik and Sariisik, 2010**), productivity increased from 7-14% to 65-80% by employing a chainsaw machine. Similarly, in this research, the capital productivity index in Scenario 1, which only used diamond wire cutting, was 37%. However, in the 2nd through 9th Scenarios, the addition of chainsaw machines may increase the capital productivity by a range of 63-92%.

Scenario 6 achieved the highest production rate (118,000 tonnes) due to its larger block dimensions (10-meter height). However, this scenario has not ranked the best, because of the multi-stage nature of block cutting in dimensional stone mines, which led to increased machine idling and significantly reduced machinery utilization. This demonstrates that maximizing production does not necessarily equate to optimal performance, as excessive idle times and operational inefficiencies can diminish overall effectiveness.

The results also highlighted the limited impact of horizontal drilling on production rates when high drilling speeds are present. For example, the production rates in Scenario 3 (56,500 tonnes) and Scenario 4 (60,000 tonnes) were similar, even though Scenario 3 required horizontal drilling for diamond wire passage. In contrast, Scenario 4 eliminated this requirement due to intact rock mass and geological conditions. Similarly, Scenario 7 (50,000 tonnes) and Scenario 8 (50,000 tonnes) showed no significant differences in production. These findings emphasize that even with drilling, other cutting operations can proceed without delays, as high-speed drilling ensures that it does not become a bottleneck in the workflow.

Safety and environmental considerations further reinforced the selection of Scenario 2. Employing chainsaw machines minimized diamond wire breakages, a common hazard in dimensional stone mining, and improved the regularity of bench dimensions, reducing waste and environmental impact. In scenarios involving bottom cutting, such as Scenario 7, precautions like limiting blade length were essential to reduce the risk of blade jamming. This approach mitigated potential disruptions but did not entirely eliminate operational risks, especially in fractured stones.

Although horizontal diamond wire breakages pose higher risks to personnel due to the radius of wire movement, they typically result in smaller downtimes for operations. In contrast, blade jamming during chainsaw cutting, especially when the stone fractures have the potential to fall upon the chainsaw blade, leads to significantly longer operational disruptions and higher financial losses due to extended equipment downtime and repair costs. These considerations highlight the trade-offs between operational risks and economic impacts in selecting the appropriate cutting configurations.

It is also worth noting that this research considered only a single active bench face, and the movement of machines between two or more bench faces was not simulated. Future research can extend these simulations to evaluate the impact of multiple bench faces on production rates, machinery utilization, and overall operational efficiency.

6. Conclusions

Given the significant role of machinery in production rates, the necessary actions to increase the efficiency and productivity of machinery in the dimensional stone industry are of great importance. In this research, ten scenarios of the simultaneous application of diamond wire cutting and chainsaw machines were simulated by discrete-event simulation, and then compared and ranked using the SECA decision-making method. Four criteria of production rate, capital cost, operating cost, and machinery utilization were considered for ranking the scenarios, and the final weight of each criterion, calculated using the SECA method, was 0.230, 0.320, 0.221, and 0.229, respectively. Scenario 2 was identified as the most effective configuration, offering a production rate of 95,000 tonnes and high machinery utilization while maintaining reasonable costs. Employing a chainsaw machine for back-face cutting in conjunction with diamond wire cutting for the rest faces allowed for continuous operations, reduced idle times, and efficient resource usage. This configuration balanced the additional capital cost of the chainsaw machine with significant productivity improvements. Scenario 1, which relied solely on diamond wire cutting, demonstrated the lowest production rate but offered the advantage of minimal capital investment, making it suitable for projects constrained by budget or space. However, the necessity of back drilling in this scenario caused delays and reduced operational continuity, highlighting the limitations of single-machine setups in maintaining efficiency. While Scenario 6 achieved the highest production rate (118,000 tonnes), it faced challenges with machinery idling due to the multi-stage cutting process required for larger block dimensions. This underscores the importance of operational balance, where maximizing output must align with minimizing downtime and maintaining cost-effectiveness. The study also revealed the limited impact of drilling on overall production in scenarios with high drilling speeds. This was evident in the comparable production rates between scenarios either requiring horizontal drilling or not. Additionally, the results highlighted safety and economic trade-offs; horizontal diamond wire breakages posed more significant risks to personnel but resulted in shorter downtimes, whereas blade jamming during chainsaw cutting caused prolonged operational delays and higher financial costs.

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SAŽETAK

Odabir optimalnoga scenarija za istovremenu primjenu dijamantne žične pile i lančane sjekačice u kamenolomu arhitektonsko-građevnoga kamena korištenjem metode višekriterijskoga odlučivanja SECA

Rezanje dijamantnom žicom danas se koristi u većini kamenoloma arhitektonsko-građevnoga kamena za eksploataciju kamenih blokova. Unatoč većem kapacitetu rezanja dijamantnom žicom eksploatacija kamena u nekim se slučajevima suočava s ograničenjima ili padom produktivnosti. Zbog toga su u ovome istraživanju proučavani različiti scenariji kombinacije rezanja dijamantnom žičnom pilom i lančanom sjekačicom u svrhu poboljšanja produktivnosti rudarskih radova, a najbolji scenarij odabran je korištenjem višekriterijske metode donošenja odluka (*simultaneous evaluation of criteria and alternatives*, SECA). Za studiju slučaja odabran je kamenolom arhitektonsko-građevnoga kamena Shayan, a na temelju informacija vezanih uz rudarske radove definirano je deset scenarija rezanja kamenih blokova. U prvome scenariju dijamantna žična pila korištena je za rezanje svih triju strana bloka. U drugome scenariju, uz rezanje dijamantne žične pile, uključena je lančana sjekačica za rezanje stražnje strane bloka. Od trećega do šestoga scenarija, uz korištenje dijamantne žične pile za rezanje bočnih strana, lančana sjekačica dodana je u procesu rezanja donje strane bloka. U tim scenarijima dimenzije bloka varirale su ovisno o kontinuitetu i cjelovitosti stijenske mase i potrebi za horizontalnim bušenjem. Od sedmoga do devetoga scenarija, uz korištenje dijamantne žične pile za rezanje bočnih strana, dvije lančane sjekačice korištene su za rezanje stražnje i donje strane bloka. Ti se scenariji mogu razlikovati u pogledu cjelovitosti kamena, potrebe za horizontalnim bušenjem i dimenzija bloka. U desetome scenariju stražnja i donja strana izrezane su pomoću dviju lančanih sjekačica, dok su bočne strane izrezane pomoću lančane sjekačice za oblikovanje blokova. Kako bi se pronašao najbolji scenarij za postizanje optimalnih tehničkih i ekonomskih efekata, korištena je SECA metoda odlučivanja koja ima nekoliko ključnih kriterija. Na temelju dostupnih informacija za usporedbu definiranih scenarija u obzir su uzeta četiri kriterija: stopa proizvodnje, trošak kapitala, operativni troškovi i produktivnost. Na temelju rezultata, konačne težine kriterija iznosile su redom 0,228, 0,32, 0,239 i 0,213. Na temelju pondera kriterija i izvedbe svakoga scenarija po kriterijima određeno je konačno rangiranje scenarija pa se na kraju drugi scenarij s ocjenom 0,655 pokazao kao optimalna konfiguracija za kamenolom Shayan zbog svoje uravnotežene izvedbe po svim kriterijima.

Ključne riječi:
diskretna simulacija, kamenolom arhitektonsko-građevnoga kamena, rezanje dijamantnom žicom, lančana sjekačica, SECA metoda

Author's contribution

Abbas Amou (MSc) provided the initial analyses and modeled different scenarios. **Majid Ataee-pour** (Associate Professor) contributed with gathering raw data and analysis. **Satar Mahdevari** (Assistant Professor) provided the required information, analyses, and interpretations of the results.
All authors have read and agreed to the published version of the manuscript.