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Article

An Evaluation on the Impact of Ore Fragmented by Blasting on Mining Performance

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Abstract: In open-pit mines, the blast operation should be effectively optimized, leading to minimization of production costs through the application of specific technical specifications. However, there is inadequate information in the literature to link blasting to comminution stages. To this end, the effective parameters for the performance of mining unit operations were scrutinized in this work. In this regard, the rock fragmentation distribution (RFD) caused by blasting was considered the main determinative criterion for providing the optimum conditions for the blasting operation at Sarcheshmeh copper mine. By carrying out a statistical analysis of the experimental data, operational parameters affecting the blasting were optimized. The relationship between parameters was obtained using the technique of regression and in accordance with the evaluation criterion under which correlation coefficient (R^2) was used to determine the best fitting model. A high correlation coefficient of the loading cycle of the machine's bucket (C_l) with the independent variables showed that the C_1 was more affected by the RFD, as well as the dimensions of the blast block. Because of the wide variations in the nature and structure of rock mass in different mines, in each case, sufficient data should be collected, and these relationships should be analyzed statistically for each individual mine showing wide ranges of fractures and cracks. Therefore, due to these wide variations of ore characteristics, with the current data it seems very difficult to quickly find a significant operational relationship between downstream processes such as crushing efficiency and blasting operations. Therefore, the focus of this research was limited to the effective parameters for blast efficiency. According to the analysis of the data obtained from 20 blasts under different operating conditions, the diameter of the hole was 241.3 mm (such as blast number 20), the ratio of length to width of the explosive block was about 6 (average blasts with high fragmentation efficiency), and the best index of mining operations was 0.22 (such as blast number 20).

Keywords: blast operation; fragmentation; production performance; statistical analysis

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1. Introduction

As an integrated system from mine to mill, optimizing drilling patterns and blasting operations is a systematic strategy for mining activities to increase the efficiency of mining and downstream processes by reducing energy consumption. This optimization activity should be performed on the mining site, and each operation should determine which of the variables are tailored to the needs of the same site. The extraction stages of open-pit metal mining ores include drilling, blasting, loading, and haulage. The appropriate implementation of this process has a significant impact on production costs, the quality of the product, and the production rate. Many research studies have investigated the impact of fragmentation caused by blasting operations on production performance in the extraction stage. On one hand, increasing the amount of fragmentation increases drilling costs; on the other hand, it also reduces loading and haulage costs. In some cases, a boulder creates a side stage of secondary blasting in the extraction cycle. Thus, a suitable level of fragmentation increases the performance of the loading–haulage system and improves the quality and uniformity of materials transferred to the processing plant. Controlling the fragmentation caused by the effective blasting pattern and its effectiveness on the productivity of rock fragmentation is a challenging task for the blasting engineers [1]. Optimal fragmentation minimizes any negative impact on the mixing (ore and waste) with the maximum integrity of the wall and the floor of the bench. In spite of this, the output of the blasting directly affects not only the drilling, displacement, and the ore control needed but also the needs and requirements of the crushing and grinding, i.e., mine to mill. There is a range of fragmentation in which the total production costs are the lowest (optimal range of fragmentation). It has also been proven that an optimal blasting operation has had a significant positive impact on the entire economy of mining operations. To achieve this, it first requires precise and systematic execution of blasting operations [2].

Simulation offers a quick and cost-effective way to reach a successful and comprehensive result from the high number of steps, complexity, and excessive interactions in the efficiency of mining operations [3,4]. For example, the effect of ore crushing on the shovels of the Gol-e-Gohar iron ore mine was presented with a mathematical model to determine their production levels. This model was obtained using data that differed from the shovels' production levels in different blasting patterns with different fragmentation results. This model concluded that large pieces of the rock greatly reduced the production power and performance of the shovel. By applying this model, the optimum slope of crushing for the proper performance of the shovel was obtained (20 to 40 cm) [5]. Since the efficiency of each crusher depends on the specific characteristics of its feed in terms of particle size distribution, the time and energy consumed per ton of the product can be used as a crushing index in the evaluation of blasting fragmentation [6].

Effective parameters for the blast cycle for each particular mine should be identified and evaluated. In this regard, the ease of penetration index for the loading machine is introduced as the ratio of the number of loaded buckets to the total number of penetration activities in the fragmented ore, whose primary function is the rigidity and cross section of the mining face. Its strong point is its ability to investigate the diggability index on the crushing of the blasted muck pile and its effect on the mining operation [7]. However, this is only effective if the interaction of other parameters is also investigated. A model is presented to determine the loading capacity as a method of crushing the rock caused by the blasting. In this model, parameters leading to re-operating costs are predicted. However, its main weakness is parameters leading to reduction of operating costs, which are only predicted from a loading point of view [8].

An investigation into the details of several blasting cases shows the relationship between the desired blasting and the efficiency of the crusher. However, only crusher efficiency has been investigated [9]. An investigation into the results of the output parameters for the blast showed the effect of the blasting design on the loading and hauling process. With this data, it is possible to evaluate the cycle time of loading and transporting devices based on the physical characteristics of the fragmented pile of blast [10].

Prediction of plucking performance (penetration and production) is possible by investigating the blasting fragmentation, parameters involved in plucking, and open harvesting of piles. In this way, the efficiency of the loading machine can be predicted by measuring the penetration and production of crushed piles [11]. With emphasis on the parameters involved in loading, investigating the interaction between the rock size distribution (RSD) of the blast pile and the loading equipment, as well as the role of muck-pile profiles in the loading efficiency, showed that the angles of the pile, its geometry, the implementation of the loading in operational conditions, and the type of loader design are the index parameters [12]. Optimization of the drilling process focused on the type and effectiveness of the drilling rig as the basis for evaluation [13].

Optimization of blast operations with the most effective parameters, i.e., crushed rock status, retardation or delay timing, coarse parts, floor and toe conditions of the bench, environmental considerations, and stolen holes, leads to a demand value model being presented. According to this model, output of blast operations is ranked in five situational categories without examining the effect of these parameters in any of the manufacturing down sectors. However, this model did not take into account the RSD of the blast fragmentation [4]. These optimizations can ultimately lead to a decrease in the RSD of the ore resulting from the blasting, a reduction in loading time, and, consequently, a reduction in the costs of this process, in which the mathematical relationships between the parameters of the blasting design can be of considerable help [14]. Table 1 shows the most important studies conducted in optimizing blasting operations. As can be seen, the most attention in technical literature is devoted to the parameters DF, Sc, and Oc.

Table 1. The most important studies performed to evaluate blast operations.

Parameter	Refs
EC	[4,15–26]
OC	[4,15–17,22–38]
El.Cs	[17,18,21,23,24,31,36,39–42]
En.Cs	[17,24,31,39,41–43]
TC	[15,23,24,26]
S_c	[4,16,18–28,30,33–40,42–50]
S_d	[4,20,22–26,33,42,43,45,49–51]
D_L	[4,11,12,16,17,29,33,48,51–53]
Pe	[33]
LP	[4,11,12,17,21,28–30,33,48,50,51,53]
Cr.P	[18,24,28,32,33,36–39,41–43,50,54]
MT	[18,24,34–42,55]
Mu	[4,22,29,33,46–48,52,53]
D_F	[4,11,12,15,16,18–51,54–57]
E.Co	[4,27,33]
SB	[4,22,26,27,32,33]
D_i	[26,33,39]
R_{LW}	[36,58]
D_{BB}	[36,58]

EC: explosive cost, OC: operational (blasting, drilling, or loading) cost, El.Cs: electrical consumption, En.Cs: energy consumption, TC: total costs of mining, S_c: specific charge, S_d: specific drilling, D_L: diggability of loading machines, Pe: expert personnel, LP: loading equipment productivity, Cr.P: crusher productivity and delays at the crusher, MT: mill throughput, Mu: condition of muck pile, D_F: degree of fragmentation and required size distribution of fragmented rocks, E.Co: environmental considerations, SB: secondary blasting, D_i: dilution constraints, R_{LW}: ratio of length (L) to width (W) of blast block, D_{BB}: dimensions of blast block.

As specified in Table 1, the degree of fragmentation (D_F) as a blasting rate index has attracted the most attention. The particular charging index (S_c) and mining operation costs (OC) have also been widely evaluated. However, less attention has been paid to the dilution index (D_i), environmental evaluations (EE), and Blast Safety Index (BS). Other interesting aspects of blasting using the technique of modeling and optimizing the process from technological and economical points of view can be found in many works. The issues of millisecond delays as well vibration structure are discussed in [59–65].

This research aimed to evaluate the production performance regarding the outputs of blasting operations. Because of the wide variations in the nature and structure of rock mass in different mines, it seemed difficult to quickly find a significant operational relationship between downstream processes such as crushing efficiency and blasting operations. For example, the effect of the efficiency of the crushing in the mining operations index was statistically analyzed before creating the prediction model for the crushing stage. However, due to significant changes in rock mass in the mine, there was no suitable correlation coefficient between independent parameters and the efficiency of the crushing. Therefore, it is emphasized again that, although the properties of rock mass have a significant effect on both blast stages and downstream processes such as crushing, due to these vast changes in the properties of rock mass in metallic open-pit mines, the extracted benches have a wide variety of rock units. Even in an extracted bench, there are rock units with different compressive strengths and characteristics. Therefore, despite their high level of reliability, these models cannot be used to predict the correlation between blasting operation and the efficiency of the downstream processes. Therefore, as mentioned above, the focus of this research was limited to effective parameters for the blast operation efficiency.

This work aimed at determining key parameters affecting the different units of extractive operations at the Sarcheshmeh open-pit mine. In this way, the recognition and ranking of practical components in the distribution of fragmented rock dimensions due to blasting may be obtained. In addition, effective indicators for mining operations were introduced, and the parameters affecting this index were ranked. For this purpose, the parameters of the ratio (R) of length (L) to width (W) of the explosive block (R_{LW}) and the operating parameters (O_l), failure (F_l), readiness (R_l), and displacement of loading machines (M_l) as well as a special crushing parameter (S_{cr}) were measured.

2. Materials and Methods

2.1. Mining Performance

Recording and extracting operational indicators for each production unit of mining operations make it possible to monitor the optimization process. Therefore, it is necessary to prepare a database of mining production operations. Suitable rock fragmentation distribution (RFD) in each blasting cycle directly contributes to reduced costs, improved performance, and an increase in the efficiency of the post-blasting stages, i.e., loading and hauling equipment.

The knowledge of the performance status and the output of the blast operation according to various fragmentation conditions (the RFD) and an accurate analysis of the information obtained using image analysis may result in a proportional and optimal blasting pattern design and implementation.

First, a database including extraction operations and the primary crushing of 20 blast blocks at Sarcheshmeh Copper Mine was prepared, as shown in the flowsheet in Figure 1.

2.2. Structure of the Database

The database was composed of the four nodes listed below.

(1) Drilling included the length, angle, and diameter of each hole; drilling time per meter and drilling time per hole; total drilled length and number of the hole; type of drilling machine; movement time, failure, and performance; and total drilling time in any blast block or rock type of blast block.

(2) Blasting included the burden, spacing, height of the bench, specific drilling, specific charge (d_{50} and d_{80}) in each blast block, explosive type, fragmentation efficiency index, percentage of over-fragment rock, percentage of boulder, and length to width of blast block.

(3) The loading unit included a loading cycle for the machine's bucket, cycle of filling a truck, performance, failure, ready and movement loading machine, type, fuel of specific loading, and haulage machine. Specific loading, with the symbol (S_L), is the specific loading of j^{th} blast blocks (hour per cubic meter) obtained by dividing the total available time of the loading machinery of the j^{th} blast block (in an hour) by the total volume of the j^{th} blast block (in cubic meters) [4].

(4) Mine crusher included input rock tonnage to the crusher, the performance and failure of the crusher in blasting, and specific crushing of each blasting. Specific crushing, with the symbol (S_{cr}), is the specific crushing of the j^{th} blast block (kW per cubic meter) obtained by dividing the total consumption energy of the j^{th} blast block (in kW) by the total tonnage of input rock into the crusher of the j^{th} blast block (in cubic meter) [66]. The

specific fixed gravity as well as the specific gravity of fragmented rock resulting from the blasting operation were 2.57 and 1.8 t/cm^3, respectively.

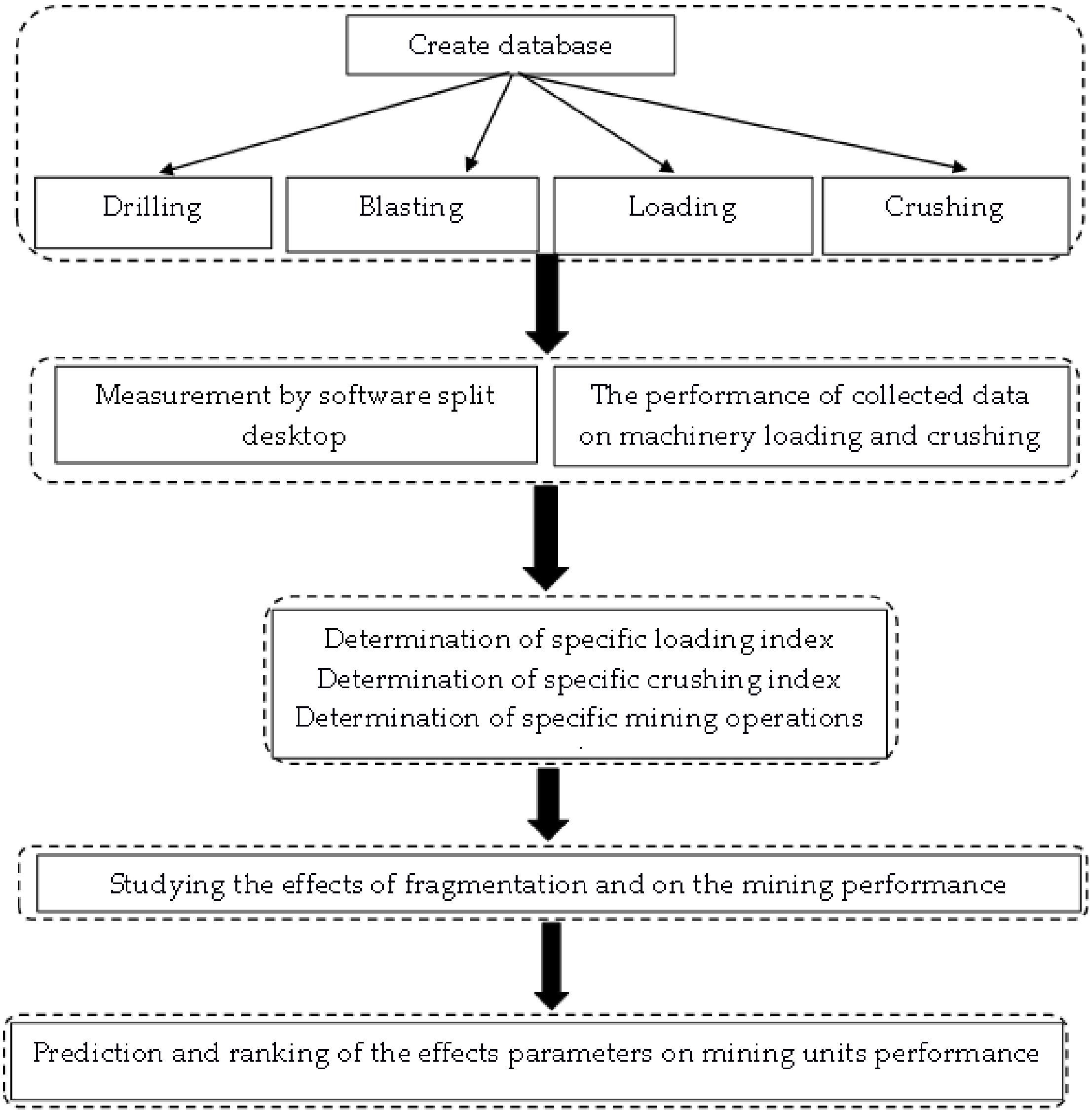

Figure 1. The algorithm used to evaluate the impacts of the RFD on mining performance.

2.3. *Specific Unit Operation Index*

The specific unit operation index (S_{u0j}) represents mining operations in blast block in $\frac{kg \cdot h \cdot kW}{m^{11}}$ and is obtained using Equation (1) [4].

$$S_{uO_j} = 10^5 \times S_{cj} \times S_{dj} \times S_{lj} \times S_{crj} j = 1, \ldots, m. \quad (1)$$

where S_d is the specific drilling of the jth blast block (m/m^3), S_c is the specific charge of the jth blast block (kg/m^3), S_l is the specific loading of the jth blast block (m^3), and S_{cr} is the specific crushing of the jth blast block (kW/m^3).

2.4. *Sarcheshmeh Copper Mine*

Sarcheshmeh Copper Mine (Kerman, Iran) contains about 1.7 billion tons of copper with a cutoff grade of 0.25% and an average grade of 0.60% [66]. Annual extraction is determined by 25 million tons of ores and 35 million tons of wastes. The height of the benches used is 12.5 m, and the width is 8.75 m. A wide bench with a width of 23.75 m is periodically placed for each of the four benches. The final slope of the wall of the mine is currently equal to 34 to 36°. Additionally, the width of the mine roads is estimated at 30 m and the slope is estimated at 8% [67].

2.5. Database from Unit Operation

Table 2 shows the descriptive parameters for the database. To evaluate the impact of rock fragmentation by blasting on mining performance at the Sarcheshmeh copper mine, drilling unit database, blast, loading, and crusher units were created (Tables 3–8).

Table 2. Description of collected parameters to create the database.

Parameter (Unit)	Symbol	Explanation	Average	Std. Deviation
Diameter (inch)	D	Hole diameter of blast blocks	8	1.8
Burden (m)	B	Row spacing of blast blocks	26	0.9
Spacing (m)	S	Hole spacing in a row of blocks	7.3	1.3
Uniaxial compressive strength (MPa)	UCS	Mechanical properties of rocks	28	11
Ratio of length to width of blast block	R_{LW}	Division of length of blast block by width of blast block	6.05	2.75
Volume of blast block (m^3)	V_b	Non situ volume of blast blocks	17,798.36	23,609.78
Specific drilling (m/m^3)	S_d	Division of area of blast block on non situ volume	0.029	0.011
Specific charge (m/kg^3)	S_c	Division of consumption charge of blast block on non situ volume	0.198	0.07
50% Input dimensions (cm)	d_{50}	50% Input dimensions of rock caused by blasting operation	3.26	2.11
80% Input dimensions (cm)	d_{80}	80% Input dimensions of rock caused by blasting operation	9.41	6.36
Fragmentation efficiency index	FE	-	36.3	18.1
over-fragment rock	F	-	70.7	5.26
A loading cycle of machine's bucket(s)	C_l	Including a round cycle of bucket of loading machine	58.34	9.507
Operation of machine (min/m^3)	O_l	Operation of loading machine for loading 1 cubic meter	17.623	0.002
Failure of machine (min/m^3)	F_l	When loading machine is in loading blast block is out of order	0.027	0.102

Table 2. *Cont.*

Parameter (Unit)	Symbol	Explanation	Average	Std. Deviation
Ready machine (min/m^3)	R_l	When the loading machine is ready for loading operation of blast block	0.067	0.058
Movement machine (min/m^3)	M_l	Length and width handling time of loading machine in block	0.045	0.004
Tonnage of loading per hour (ton/h)	T_l	Division of total tonnage of blast block on the hour of operation	1058.02	574.202
Specific loading (h/m^3)	S_L	Division of total available time of loading machineries' blast block according to hour to total volume	0.005	0.002
Operation of crusher (h)	O_{cr}	Operation of crusher for grading in blast block	12.102	15.132
Operation of crusher (h)	F_{cr}	Failure of crusher for grading in blast block	12.687	0.853
Production of crusher (m^3/h)	P_{cr}	Production of crusher in blast block	1245.158	143.99
Specific crushing (kW/m^3)	S_{cr}	Division of total consumption energy of blast block according to KW on total tonnage of input rock	0.135	0.006
Specific mine unit operation index (kg.h.kW/m^2)	S_{uo}	Multiplication of specific drilling, specific charge, specific loading, and specific crushing	0.439	0.549

Table 3. Evaluation of fragmentation due to blasting on the production levels of loading machines and mining operations.

Fragmentation Efficiency	Boulder (%)	Loading Efficiency in Muck Pile [24]	Digging Conditions in Muck Pile [24]	Overall Blast Result		Capacity		T_l (ton/h)
				j	Condition	Shovel (m^3)	Truck (ton)	
Very good	0	Moderate	Difficult	47	Good	16.5	100	476.34
Good	0	Relatively good	Easy	61	Moderate	4.5	136	556.31
Good	0	Relatively good	Easy	30	Good	16.5	100	533.59

Table 3. *Cont.*

Fragmentation Efficiency	Boulder (%)	Loading Efficiency in Muck Pile [24]	Digging Conditions in Muck Pile [24]	Overall Blast Result		Capacity		T_l (ton/h)
				j	Condition	Shovel (m^3)	Truck (ton)	
Good	0	Very good	Very good	40	Good	12	100	1552.35
Good	0	Excellent	Excellent	41	Good	12	136	2179.15
Moderate	0	Excellent	Excellent	34	Good	4.5	136	602.79
Good	0	Excellent	Excellent	42	Good	18	136	1663.86
Good	0	Excellent	Excellent	44	Good	2.15	100	471.18
Good	0	Excellent	Very good	35	Good	12	136	1480.15
Good	0	Good	Excellent	55	Good	12	136	1197.88
Good	0	Excellent	Very good	55	Good	12	136	1563.58
Very good	0	Excellent	Difficult	36	Good	15	100	565.98
Good	0	Relatively good	Easy	33	Good	12	136	1185.02
Good	0	Relatively good	Difficult	32	Good	12	136	703.56
Very good	0	Moderate	Moderate	37	Good	11	136	451.71
Good	11	Low	Difficult	30	Good	18	100	394.71
Good	0	Excellent	Excellent	30	Good	12	136	1744.71
Very good	0	Relatively good	Relatively difficult	33	Good	16.5	100	653.33
Very good	0	Relatively good	Relatively difficult	35	Good	16.5	100	620.26
Good	0	Excellent	Excellent	25	Good	12	136	1982.29

Table 4. Classification of blast ratings ($_j$) and their analyses [4].

V	IV	III	II	I	Class
>100	75–100	50–75	25–50	<25	ξ_j
Very weak	Weak	Moderate	Good	Very good	Condition

Table 5. Reasons for low production levels of loading machine in contrast to good crushing caused by blasting operations.

Blasting No.	Possible Reasons for Low Production Levels of Loading Machine
1	(1) Blast used to create new horizon on the floor of the mine and lack of suitable design of pattern for blast to create new benches. (2) Insufficient efficiency of loading device in muck pile due to lack of free surface of the blast and lack of displacement of the block after blasting. (3) Penetration and carving of crushed piles caused by blasting operation and by loading machine with more time. (4) Disproportionate capacity of loading bucket with the hauling machine. (5) Wear and depreciation of the hauling devices.
2	(1) Inappropriate efficiency of loading device in muck pile due to lack of free surface of the blast and lack of displacement of the block after blasting. (2) Too much time wasted penetrating and digging out the muck piles by loading machine. (3) Disproportionate capacity of loading bucket to the hauling machine. (4) Wear and depreciation of the hauling devices.
3	(1) Disproportionate capacity of loading bucket with the hauling machine. (2) Wear and depreciation of the hauling devices.

Table 5. *Cont.*

Blasting No.	Possible Reasons for Low Production Levels of Loading Machine
6	(1) Disproportionate capacity of loading bucket to the hauling machine. (2) Depreciation of the hauling devices.
8	(1) Disproportionate capacity of loading bucket to the hauling machine.
12	(1) Inappropriate efficiency of loading device in muck pile due to lack of free surface of the blast and lack of displacement of the block after blasting. (2) Too much time wasted penetrating and digging out the muck piles by loading machine. (3) Disproportionate capacity of the loading bucket to the hauling machine. (4) Wear and depreciation of the loading devices.
14	(1) Disproportionate capacity of loading bucket to the hauling machine. (2) Depreciation of the loading devices.
15	(1) Inappropriate efficiency of loading device in muck pile due to lack of free surface for the blast and lack of displacement of the block after blasting. (2) Too much time wasted penetrating and digging out the muck piles by loading machine. (3) Wear and depreciation of the loading devices.
16	(1) Inappropriate efficiency of loading device in muck pile due to lack of free surface for the blast and lack of displacement of the block after blasting. (2) Disproportionate capacity of loading bucket to the hauling machine. (3) Wear and depreciation of the loading devices.
18	(1) Inappropriate efficiency of loading device in muck pile due to lack of free surface for the blast and lack of displacement of the block after blasting. (2) Too much time wasted penetrating and digging out the muck piles by loading machine. (3) Disproportionate capacity of loading bucket with the hauling machine. (4) Wear and depreciation of the loading devices.
19	(1) Inappropriate efficiency of loading device in muck pile due to lack of free surface of the blast and lack of displacement of the block after blasting. (2) Too much time wasted penetrating and digging out the muck piles by loading machine. (3) Disproportionate capacity of loading bucket with the hauling machine. (4) Wear and depreciation of the loading devices.

Table 6. The relation of regression and the results of the obtained variance analysis d_{50} and d_{80} with production performance.

	Predict Model					
1	$d_{50} = 29.544 + 17.161\log D + 4.235\log R_{LW} - 9.135\log V_b$					
2	$d_{80} = 44.805 + 43.026\log D + 7.531\log R_{LW} - 21.822\log V_b + 19.766\log H$					
Model No.	Analysis of variance (ANOVA)					
	R	R^2	Adj. R^2	Std. error	F change	*p* Value
1	0.803	0.646	0.579	1.872	9.714	0.001
2	0.762	0.581	0.469	4.759	5.19	0.003

R: correlation index; R^2: determination index; Adj. R^2: adjusted determination index; Std. error: standard error; F change: change of F-test value; *p* Value: significance level (if it is lower than 0.05, then the model can be accepted as statistically significant).

Table 7. The relation of regression and the results of variance analysis C_l obtained, with production performance.

Predict Model						
3	$C_l = 1.843 + 2.750D + 1.112R_{LW} + 0.543d_{80}$					
4	$C_l = -30.092 + 50.498\log D + 8.936\log R_{LW} + 14.\log d_{80}$					
5	$C_l = -25.107 + 51.265\log D + 8.425\log R_{LW} + 13.705\log d_{50}$					
6	$C_l = -25.107 + 51.265\log D + 8.425\log R_{LW} + 13.705\log d_{50}$					
7	$C_l = 2.756 + e^{1.363\times10^{-5}R_{LW}} + 3.053D + 0.613d_{80}$					
Model No.	Analysis of variance (ANOVA)					
	R	R^2	Adj. R^2	Std. error	F change	*p* Value
3	0.853	0.727	0.676	5.549	14.235	0.001
4	0.845	0.715	0.661	5.676	13.365	0.001
5	0.831	0.69	0.632	5.917	11.876	0.004
6	0.893	0.797	0.759	4.791	20.917	0.001
7	0.836	0.699	0.642	5.832	12.382	0.007

Table 8. The relation of regression and the results of variance analysis S_l obtained, and S_{uo} with production performance.

Predict Model						
8	$S_l = 0.017 + 0.005\log R_l + 0.003\log M_l$					
9	$S_{uo} = 3.444 - 0.005D^2 - 0.011H^2 - 2.444 \times 10^{-5}{R_{LW}}^2 + 0.001{d_{80}}^2$					
10	$S_{uo} = 0.053 - e^{1.61\times10^{-5}D} + e^{5.578\times10^{-6}d_{50}}$					
Model No.	Analysis of variance (ANOVA)					
	R	R^2	Adj. R^2	Std. error	F change	*p* Value
8	0.895	0.8	0.777	0.001	34.04	0.001
9	0.811	0.658	0.567	0.371	7.215	0.002
10	0.801	0.642	0.600	0.356	15.229	0.008

In this study, the selection of variables was based on the experts' opinions and the operational experience of the reasoned relationship between model variables and dependent parameters. Additionally, based on the design of drilling and blasting patterns, the mechanism of blasting operations, and the interaction of the parameters on the production performance, a suitable model was proposed. In addition, software capability in the proposed models was based on independent variables of one to four parameters. In selecting the models, the coefficient of variance was used so that the variables in the model did not correlate if their variance coefficient was less than 10. This meant that there was no correlation between the input of independent variables calculated for each model. It is worth noting that in some mines, due to the imposition of operational conditions, the blasting circuit changes so that B and S may be moved in relation to the free surface of the blasting face.

Drilling: The holes produced were drilled with diameters of 15.24, 22.86, 24.13, and 25.4 cm. Paying attention to ore and waste of the drilling, patterns of 5 × 6, 5 × 6.5, 6 × 7, 7 × 8, 7 × 8.5, 7 × 9, 7.5 × 9, 7 × 9.5, 7.5 × 10 m^2 were designed and implemented. Sub-drilling was estimated at 2.5 m and the mean length of holes was 14.5–15 m. [68].

Blasting: A Nonel and Detonating Cord were applied for the initiation system, and Pentolite booster and Emuline (depending on hole diameter) were used as a booster. In dry mining conditions, ANFO or a combination of ANFO with Emuline (Emulan) in wet conditions was used as the main charge [61]. The largest and smallest volumes of blasting blocks were taken as 105,525.29 and 7875.02 m^3, respectively. Moreover, the average volume of the blasting block was equal to 47,132.87 m^3. An image analysis method was employed to obtain the passing distribution curve of blasting patterns, and Split Desktop software (Version 4.0) was used to measure fragmentation at the Sarcheshmeh copper mine.

Loading: In the loading and haulage operations, loading by electric rope shovel and hydraulic excavator (Hydraulic) with bucket volumes of 18, 16.5, 15, 12, 4.5, and 2.15 m^3 was used. The average volume of the bucket of the shovel was about 12 m^3. Additionally, haulage was performed using 218-, 136-, 100-, 60-, and 35-ton trucks [67].

Specific loading with the symbol (S_{Lj}): Specific loading of the j^{th} blasting block (h/m^3) was calculated by dividing the total time available for the loading machineries of the j^{th} blasting block (per hour) to the total volume of the j^{th} blasting block (per m^3) [4].

Crushing: Rock fragmentation in the first stage was calculated based on the feed for the primary gyratory crusher, with d_{80} range of the feed equal to 1524–2260 mm [67]. There are multiple methods used to determine the dimensions of over-fragment rock and boulder. The most common methods calculate the suitable size by considering the dimensions of the feed to the primary crusher. In this way, boulders are estimated at 80% entrance of primary crusher, and the size of over-fragment rock is estimated at one-sixteenth of boulder dimensions. Since the shovel machine is not capable of loading boulders greater than around 100 cm, in a practical operating project, this size range (about 100 cm) applies to boulder rock used in the machine [58]. The specific energy level S_{cr} of the j^{th} blasting block used in the crusher (kW/m^3) is calculated by dividing the total energy consumption of the j^{th} blasting block (per kW) to the total tonnage of rock fed into the crusher at the j^{th} blasting block (per m^3) [66]. The specific fixed gravity and specific gravity of fragmented rock resulting from the blasting operation were 2.57 and 1.8 tons per cubic meter, respectively.

2.6. Measurement of Blast Fragmentation

2.6.1. Stages of Image Analysis

In image analysis, to achieve the RFD, three steps should be performed: sampling, imaging, and image analysis. Split-Desktop software (Version 4.0) is a tool for analyzing the digital images to measure the RFD resulting from the blast. In order to analyze each image with this software, five steps must be taken: (1) image scaling, (2) automatic or manual bordering of the fragmented rock parts in the image, (3) estimating the amounts of fines in the image, (4) evaluating the result of the work, and (5) reporting the output of the image analysis result in Excel as the RFD curve.

With the help of this software, images can be bordered in two manual and automatic ways. In the first, the boundary between the pieces of the fragmented rock is determined by the user, while in the second, the software itself performs finding the boundaries according to the contrast in the image. The speed of work in the second is higher, while the accuracy of the first one is higher.

What distinguishes this software from other similar software is the existence of features that make it easier for the user to work with and significantly reduce the amount of some errors. The features include working with various and common image extensions such as .bmp, .jpg, and .tiff, changing the resolution of the image by the software itself, using up to three scales in one image, having the ability to extremely zoom in on the image, drawing automatically the crushed materials, determining the range of the fines as well as the ranges that do not need to be analyzed, and combining the various RFD curves related to each image in a blast pattern. Additionally, presenting the result of the RFD curves for that pattern and also the possibility of presenting the final results in the form of an Excel file with the help of a shortcut key are the other great features of the software.

2.6.2. Working Algorithm of This Project

In this project, due to time and safety limitations, a random sampling method was used to select the sampling location. In this regard, in different times, if the conditions were favorable, the crushed rock pile was photographed. In general, the image was obtained from three sections of the top, the middle, and end of the crushed rock pile. The images were mostly produced between 9:00 a.m. and 12:00 a.m. and the hours of the day when the weather was cloudy, due to which the environment was in full shade. Attempts were made to reduce the numbers of errors in imaging by using different methods such as using two balls, not taking images under direct sunlight, and so on. In order to investigate and determine the RFD analysis after the blast operation, a total of 30 blast blocks was considered for the study, 10 blocks of which were specific to tailings' investigation and the rest to the ore blocks. For the purpose of the software calibration, the number of analyzed images was 755, with an average of about 25 for each blast pattern. Then, all images were analyzed manually using Split-Desktop image analysis software, and the RFD curve of each pattern was obtained separately.

As mentioned earlier, the determination of the rock fragmentation distribution (RFD) of blasted block is the main criterion by which the fragmentation of the different blasts can be compared. Because the process of obtaining the RFD curve is costly and time consuming, indirect methods, including qualitative observational analysis, visual analysis, photogrammetry method, and high-speed photography, were used to evaluate the RFD. Finally, this RFD can serve as a basis for studying the efficiency of the loading machines, secondary blast, failure, fragmentation efficiency index, over-breaking percentage, and burden.

Split-Desktop software was used as an image analysis tool for analyzing the digital images needed to find the RFD caused by blasting. To analyze each image, five steps were undertaken: (1) scaling the image, (2) automatically or manually limiting the fragments of the rock, (3) estimating the fines, (4) evaluating the results, and (5) exporting the image analysis result to Excel and plotting the curve. Figure 2 shows the analysis of the RFD using this software package. The RFD analyses showed that 80% (d_{80}) and 50% (d_{50}) of the passing sizes were about 13.06 cm and 6.48 cm at the current conditions of blasting design. Table 5 shows the distribution of d_{50} and d_{80} given for 20 studied blast blocks.

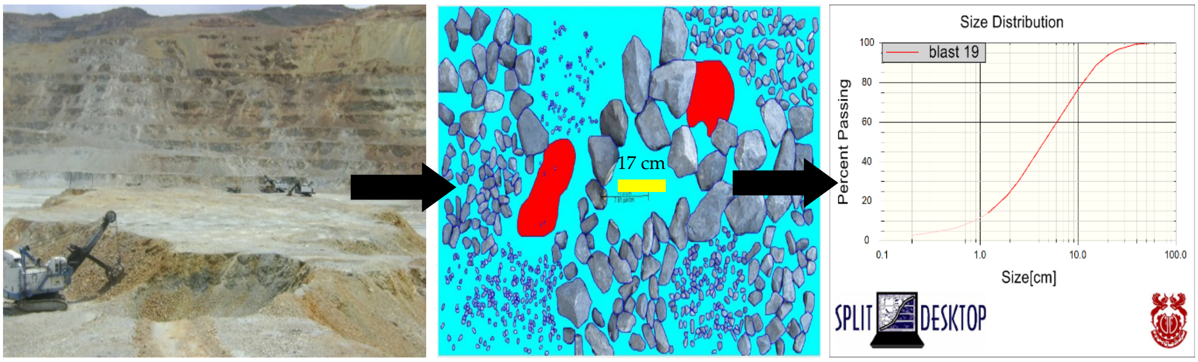

Figure 2. Process of image analysis in Split-Desktop software.

2.7. Evaluation of Fragmentation

To evaluate the fragmentation results for the registered blasting operation, the fragmentation efficiency (FE) index was used. This index for the ore used in the investigation was calculated according to Equation (2) [58].

$$FE = 100 - (B + F) \quad (2)$$

where FE denotes the fragmentation efficiency index (%), F is the percentage of over-fragmented rock, and B represents the percentage of boulder. Based on this index, fragmentation was divided into six categories, whose quality of fragmentation for each blasting block can be obtained with the help of tables presented in Appendix A (Tables A1–A6).

2.8. Data Analysis

To optimize mining operations, effective parameters and the range of their impact on fragmentation should be identified so that they can be used in the design phase of the blast pattern. Linear or nonlinear regression analyses were used to study the relationships between variables to ascertain, above all, how one variable depends on the others. This analysis, performed using the Statistical Package for the Social Sciences (SPSS) software (IBM SPSS Statistics, 2016), showed precision, accuracy, and trend of changes in theories used to predict the effects of the RFD on production performance.

3. Results and Discussion

3.1. Blasting and Mining Performance

Drilling and blasting parameters have a direct impact on mine production levels. Accordingly, one of the parameters that should be optimized is the diameter of the hole (D), whose suitable range for a 12.5-m-high bench used in open-pit mines is at least 200 mm (8 inches) [9]. The blast data for the Sarcheshmeh mine in Table 3 show that the D is not optimal for the benches in some blasts. The best diameter in the blasts was 200 mm fitted with the benches. Accordingly, the drilling pattern should be also modified (the diameter of the hole in blast nos. 3, 4, 5, 6, 7, 8, and 10 (Table A1) was changed from 152 mm to 200 mm because, by increasing the diameter of the hole proportional to the height of the benches, the mining costs may decrease from economic viewpoints). Thus, it should be modified according to the diameter of the 200-mm drilling hole.

The amount of special drilling in blast no. 1 was higher than others because, with the first blast, the crushed rock suffered from severe muck-pile locking and, therefore, did not reach the desired height for the loaded code. For this reason, to create a new surface on the bottom of the bench, drilling operations and block reblasting were conducted mainly due to a lack of the continuity in the rock, according to the appropriate drilling pattern. Additionally, reblasting may resolve the problem of holes falling out of the bottom due to the highly moisturized blast block, as well as a lack of free surface in the primary blast. Fragmentation efficiency in blast no. 1 was 92.50%, which was due to a higher amount of powdering and fine production for reblasting the block. The efficiency of machinery in mining operations is directly related to blast fragmentation; so, the loading rate is adversely affected by the coarseness of the rock fragments, but directly depends on the swelling of the muck pile. As such, the presence of boulders, as well as low swelling in poor bench toe conditions, directly affects the efficiency of the loading machines.

Although the RFD and the FE resulting from the blast were classified as perfect, in some cases, the production level of the loading machine per hour was low compared to the RFD. To ascertain the causes of this, in addition to the RFD, the effective results of explosion operations in the production levels of the loading machine and specifications of the loading and hauling machines were investigated (Table 3).

The overall result of the blast rating (ξ_j) was based on output figures for various blasting blocks. Considering seven main outcomes of the blast, including fragmentation (ξ_{FR}), muck pile position (ξ_{MU}), overbreak status (ξ_{OV}), conditions of toe and bench floor (ξ_{FL}), boulder (ξ_{BO}) and environmental considerations (ξ_{EN}), the status of the misfired hole (ξ_{MI}), and the points corresponding to each parameter, the overall score was calculated with Equation (3) [4]. Accordingly, the results were divided into five categories (Table 4).

$$\xi_j = \xi_{FR} + \xi_{MU} + \xi_{OV} + \xi_{FL} + \xi_{BO} + \xi_{EN} + \xi_{MI} \tag{3}$$

To evaluate the low production of the loading machine against the good FEs, the overall results of the blasts were calculated using Equation (3). Then, in addition to the RFD, other factors involved in the production per hour of the loading machine, including the efficiency of the loading device in the muck pile and penetration conditions in the muck pile, were investigated. According to the results of the RFD and efficiency of the loading machine in conditions where crushing was good, the cable shovel showed a higher level of efficiency than other loading machines in proportion to the capacity of the loading machine.

By studying the production subsystem, including drilling, blasting, loading, hauling and crushing, it is possible to know which part needs to be optimized. For example, in blast no. 1, the main drawbacks were drilling and reblasting, undesirable blast outputs, and disproportionate capacity of the loading and hauling machines. Additionally, in blast nos.

6 and 8, despite the appropriate RFD, due to the disproportionate capacity of the loading and hauling machines, they were ultimately not desirable (Table 5).

3.2. Statistical Analysis

Tables 6–8 summarize the multi-parametric linear fitting on the data. This fitting may determine the most effective parameters. In this analysis, parameters including d_{50} and d_{80}, a loading cycle, loading bucket, specific loading, specific crushing, and specific mine unit operation were the indexes regarded as the main dependent and/or independent parameters. Variations between the dependent and independent parameters can be deduced from the relationship between each other. Thus, different linear models were tested to select the best model with the highest coefficient of determination (R^2) and the simplest mode.

Comparing statistical models, the F-distribution model is the most commonly used statistical test under the hypotheses applicable to a data set, in order to identify the suitability of the model to the population from which the data were sampled. Since F-test > F-tab = 4.38 and the significance of F-test was smaller than p-value = 0.05 at 95% confidence level, the zero hypothesis was rejected. Therefore, it can be inferred that the proposed model was statistically significant. This compared the new model with the proposed model (Table 6).

3.2.1. Relation of d_{50} and d_{80} with Production Performance

Both d_{50} and d_{80} may be functions of the B, S, D, hole length, R_{LW}, and V_b. Based on the statistical analysis, the prediction model of d_{50} and d_{80} and an analysis of variance were conducted by using multiple linear and nonlinear analysis (prediction models 1 and 2, shown in Table 7).

The yield of fragment and the percentage of over-fragmentation of harvested blast blocks were 81.98 and 51.23%, which showed high potential for fine particles in the mine, i.e., 58.23% of ore caused by blasting operations into the crusher was less than 203 mm in size. This is why the required feed of the condensation factor was 203 mm. In an analysis of fragment data with production performance, d_{50} in comparison with d_{80} showed better significant relations with the independent variables. In Figure 3, the comparison of frequency d_{50} and d_{80} is as shown in blast blocks.

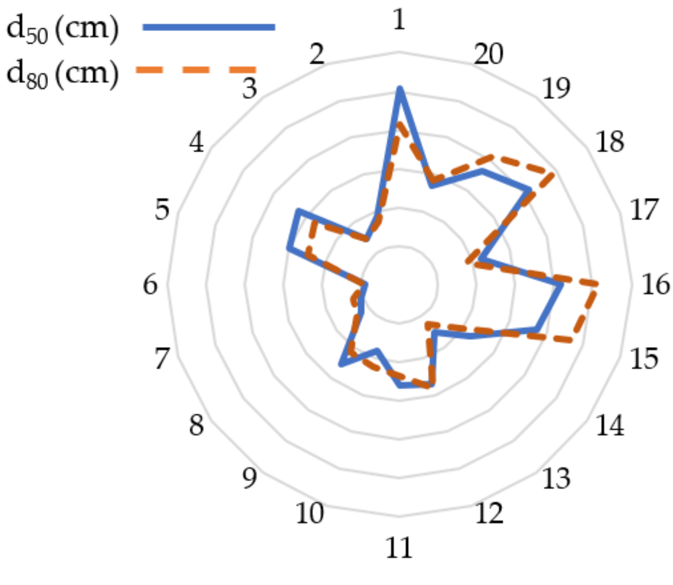

Figure 3. Radar chart of d_{50} and d_{80} in 20 blast blocks of Sarcheshmeh Copper Mine.

3.2.2. Loading and Production Performance

For multiple logarithmic linear and nonlinear regression analysis, an exponential was used. Hole diameter, the ratio of length to width of blast block, and d_{80} were regarded as independent variables and C_l as a dependent variable. The results of this analysis and variance analysis with the aforementioned methods are shown in Table 7 (prediction models 3, 4, 5, 6, and 7). In the proposed models, the correlation coefficient value was high, which indicates a significant relation between independent variables with a loading cycle and C_l. Additionally, based on the F test, the obtained models were acceptable to such an extent that the variable of a loading cycle, C_l, was more affected by fragmentation caused by blasting and the dimensions of the blast block. The best and worst of a loading cycle, loading bucket, at the Sarcheshmeh Copper Mine were 14.38 and 51.15, respectively, in which d_{50} was 3.02 and 10.39 cm, respectively, and d_{80} was 6.69 and 24.49 cm. Figure 4 shows the relation between C_l measured and predicted for each of the models.

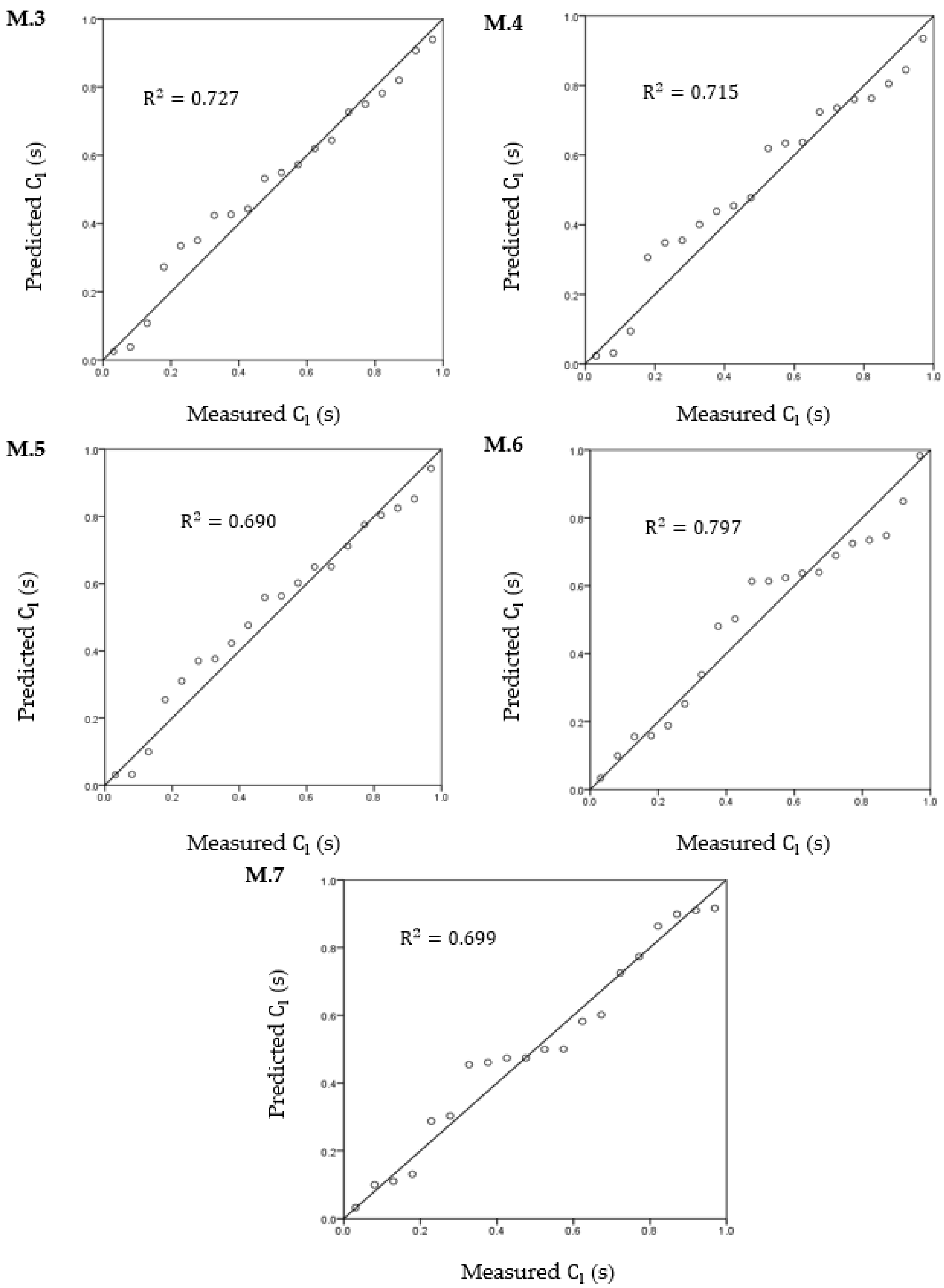

Figure 4. Comparison relation between C_l measured and predicted for models (3, 4, 5, 6, and 7).

3.2.3. Specific Loading and Specific Mine Unit Operation Index

To predict the relation of specific loading (S_L), dependent variable and independent variables including sleep and handling the loading device were performed using the logarithmic regression method. Accordingly, a correlation coefficient of 0.8 was obtained for specific loading (S_L) in all blast blocks. Correlation and determination coefficients are shown in Table 8. Two models, 9 and 10, showed the relation of index-specific mining operations with independent parameters (Table 9). The correlation coefficient of models 9 and 10 was equal to 0.658 and 0.642, respectively, showing the great influence of the desired independent variables on index-specific mining operations (S_{uo}). The ratio of length to width of the blast block (R_{LW}) was one of the important parameters closely associated with the various mining units and should be prioritized in the optimization. Hole diameter, as in previous studies, also showed that blasting is another very important parameter in improving the conditions of fragmentation, which results from hole diameter leading to an increase or decrease in the cost per ton of crushed rock.

3.2.4. Ranking the Most Effective Parameters for Mining Performance

By analyzing the output of the drilling and blasting process and identifying the most effective parameters, the effect of extractive parameters in different parts of production was ranked. Moreover, interaction between blasting and mining operations was achieved by evaluating each unit of mining from a theoretical point of view, under continuous control until the end of each process, and also from operational experience. Finally, with this knowledge base, the results of different theoretical and experimental results were determined as a coherent and comprehensive method for optimal operation. A standardized coefficient column test was used to rank these effective parameters based on the models predicted. The test may evaluate the parameters based on their positive or negative effect through the standardized coefficients of applied regression. Accordingly, the effective parameters on d_{50} were D and R_{LW}, while in d_{80}, the main positive parameter was only R_{LW}. Therefore, the positive impact of d_{50} on the specific mine operations' index was more than that of d_{80}. The most effective components in the loading machine cycle were R_{LW}, D, and d_{80}. Additionally, a strong relationship was revealed between the readiness and the special loading parameters of the loading device.

One of the factors affecting the performance was the explosive loading diameter. Therefore, in the results obtained (Table 9), D was a key parameter affecting the blasting. However, according to the results of the ranking, the most influential component in the different parts of the production was the R_{LW}. This could be because, as a general rule, the dimensions of the blast block in the open-pit extraction should be considered as large as possible. In this condition, the number of rows of blast holes may be generally affected by the W of the benches and the effective burden. In this way, productivity could increase due to the reduced movement time, as well as the total increase in hauling units used. In addition, drilling and loading machines may require more time for operations to be performed in a working bench. The cost of the holes could also be more efficient, which shortens the blast cycle and consequently reduces the time needed to change the position of the equipment. With an increase in volume in the blast block, the level of safety increases due to integrated production operations and more effective process management, meaning a reduced number of misfired holes as well as human errors.

These optimal results were used in the Sarcheshmeh mine. In SP + Dike stones, a 241.3-mm hole diameter was used. For this type of stone, R_{LW} was observed at about 6. Currently, with the aim of continuous RFD analysis, fixed and quadcopter cameras are active in the mine and constantly report high-quality images to downstream units for online image analysis. Additionally, the monthly statistics of this image analysis (the RFDs) are dictated as feedback to the operational conditions of the blasting to be used based on the parameters specified to change them to achieve the desired fragmentation efficiency (FE).

Table 9. Multivariate nonlinear regression coefficients and statistical parameters of coefficients for models 1 and 10.

Model No.	Independent Variables	Unstandardized Coefficients		Standardized Coefficients	*t* Values	95% Confidence Interval for B		Collinearity Statistics	
		B	Std. Error	Beta		Lower Bound	Upper Bound	Tolerance	VIF
1	Constant	29.544	6.326		4.670	16.132	42.955		
	D	17.161	5.243	0.625	3.273	6.047	28.275	0.608	1.645
	R_{LW}	4.235	1.692	0.412	2.503	0.648	7.823	0.817	1.223
	V_b	−9.135	1.785	−0.993	–5.117	−12.919	−5.350	0.588	1.7
2	Constant	44.508	26.4		1.697	−11.465	101.075		
	D	43.026	13.352	0.692	3.222	14.566	71.486	0.606	1.651
	H	19.726	28.591	0.15	0.690	–41.215	80.666	0.593	1.687
	R_{LW}	7.531	4.744	0.324	1.587	–2.644	17.706	0.664	1.506
	V_b	–21.822	5.553	–1.048	–3.930	–33.658	–9.986	0.393	2.545
3	Constant	1.843	5.687		0.324	−10.213	13.9		
	D	2.75	0.755	0.524	3.644	1.15	4.35	0.823	1.215
	R_{LW}	1.112	0.488	0.322	2.281	0.079	2.146	0.855	1.175
	d_{80}	0.543	0.199	0.364	2.73	0.121	0.965	0.96	1.042
4	Constant	–30.092	11.795		2.551	−55.096	−5.088		
	D	50.498	13.528	0.544	3.733	21.819	79.176	0.84	1.191
	R_{LW}	8.936	5.075	0.257	1.761	−1.821	19.693	0.836	1.196
	d_{80}	14.921	6.293	0.334	2.371	1.58	28.262	0.899	1.112
5	Constant	−25.107	11.786		–2.130	−50.091	–0.123		
	D	51.265	14.101	0.552	3.636	21.373	81.158	0.84	1.191
	R_{LW}	8.425	5.383	0.242	1.565	−2.986	19.837	0.807	1.239
	d_{50}	13.705	6.941	0.297	1.975	−1.008	28.419	0.857	1.167
6	Constant	16.462	2.776		5.93	10.577	22.347		
	D	0.291	0.044	0.871	6.59	0.198	0.385	0.728	1.374
	R_{LW}	0.296	0.062	1.219	4.762	0.164	0.428	0.194	5.161
	V_b	-4.445×10^{-9}	0	−1.172	−4.263	0	0	0.168	5.957
7	Constant	2.756	6.008		0.459	–9.980	15.492		
	R_{LW}	1.363×10^{-5}	0	0.257	1.788	0	0	0.91	1.099
	D	3.053	0.76	0.582	4.019	1.442	4.663	0.897	1.115
	d_{80}	0.613	0.214	0.41	2.864	0.159	1.067	0.917	1.091
8	Constant	0.017	0.002		8.604	0.013	0.021		
	R_l	0.005	0.001	0.622	4.221	0.003	0.008	0.541	1.848
	M_l	0.003	0.001	0.347	2.355	0	0.005	0.541	1.848
9	Constant	3.444	0.634		5.433	2.093	4.795		
	D	−0.005	0.003	−0.278	−1.628	−0.012	0.002	0.784	1.275
	H	0.011-	0.003	−0.636	−3.887	−0.017	−0.005	0.851	1.175
	R_{LW}	2.242×10^{-5}	0.002	−0.002	−0.010	−0.005	0.005	0.862	1.161
	d_{80}	0.001	0	0.212	1.312	0	0.002	0.874	1.144
10	Constant	0.811	0.118		6.862	0	0.562		
	D	-1.61×10^{-5}	0	−0.241	−1.626	0.122	0	0.955	1.046
	d_{50}	5.578×10^{-6}	0	0.715	4.814	0	0	0.956	1.046

4. Conclusions

The present work comprehensively investigated the interaction and effectiveness of extractive units and parameters in the process of mining operations. Additionally, by combining the data from different units and monitoring them, the main and key parameters were identified, measured, and introduced so that they can finally be used for optimization. Identifying and ranking the effective components in the distribution of fragmented rock dimensions due to blasting were conducted. In addition, effective indicators in mining operations were introduced and the parameters affecting these indexes were ranked. The relation between the most effective parameters for the performance of rock fragmentation distribution caused by blasting operations was investigated. The ratio of length to width of the blast block and loading parameters such as operation, failure, readiness, movement loading machine, and specific crushing were studied. The parameter R_{LW} of the blast block proved significant for the proposed models. Some models were proposed for different aspects of production performance at the Sarcheshmeh Copper Mine to such an extent that, in d_{50} and d_{80}, the highest correlation coefficients were 0.658 and 0.581, respectively, meaning a superior result for of d_{50} because of the high potential production of fine parts in the process of blasting. Additionally, there was a high correlation coefficient for the loading cycle of the bucket (0.727). A correlation coefficient of 0.8 for specific loading in all blast blocks showed a strong influence on specific loading of the RFD of the blasting. The positive effect of the hole diameter parameter was more than that of the blast block length-to-width ratio on d_{50}. However, at d_{80} the positive effect of the parameter of the blast block length-to-width ratio was more than that of the hole diameter. In the loading cycle, the ratio length to width of the blast block was the most effective parameter. The correlation coefficient of prediction models for the specific mine unit operations index equaled 0.658 and 0.642, showing the critical role of the desired independent variables in the specific mine unit operations' index. The effective parameters in the performance of mining operations were ranked using SPSS software. Experiment methods such as Taguchi design can be used for sensitivity analysis to ascertain in what ranges each production parameter will be effective for production performance in ideal conditions. Given the extensiveness of the article, the addition of this part of the analysis requires a comprehensive investigation of the data for future research.

5. Future Works

This research work was a great opportunity to examine the operational realities in the Sarcheshmeh copper mine to determine the main effective parameters on the efficiency of the blasting. In the first step, we tried to obtain the relationship between parameters using conventional mathematical regression methods. In the following work, due to the complexities in terms of anisotropy and heterogeneity of the ore mass, we are building on methods based on intelligent computations or soft calculations (such as ANFIS) that are based on the operational realities to have the best adaptation of experimental data in the built intelligent model.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Collected database relating to drilling unit.

No.	Rock Type	Zone	Alteration	Ucs (MPa)	Hardness Level	D (mm)	B (m)	S (m)	S_d(m/m^3)
1	SP+ Dike	Hypogene	QS and Clay	38.25	Medium hard to hard	152.4	5	6	0.054
2	Dike +AN	Hypogene	QS and Clay	41.13	Medium hard to hard	241.3	7	9.5	0.018
3	GR	Hypogene	SQ and Clay	38.63	Medium hard to hard	152.4	6	7	0.029
4	Dike +SP	Hypogene	QS and Clay	44.75	Medium hard to hard	152.4	7	9.5	0.04
5	AN+ Dike	Hypogene	QS and Clay	46.25	Medium hard to hard	152.4	5	6	0.041
6	QI	Hypogene	QS, Bio, and Clay	39.88	Medium hard to hard	152.4	5	6	0.04
7	AN	Hypogene	QS and Clay	35.38	Medium hard to hard	152.4	5	6	0.037
8	LF+ Dike	Hypogene & supergene	QS, Bio, and Clay	38.88	Medium hard to hard	152.4	5	6	0.04
9	AN	Hypogene	QS and K-Feldspar	39.13	Medium hard to hard	152.4	7	9	0.019
10	LF+ Dike	Hypogene	QS, Bio, and Clay	43.88	Medium hard to hard	152.4	5	6	0.04
11	SP+ Dike +BD	Hypogene	QS, K-Feldspar, and Clay	45.00	Medium hard to hard	25.4	7	9	0.019
12	AN+ Dike	Hypogene	QS and Clay	43.25	Medium hard to hard	241.3	7	9	0.019
13	LF+ Dike	Hypogene	SQ and Clay	43.38	Medium hard to hard	228.6	7	9	0.019
14	SP+BD+ Dike	Hypogene	QS, Bio, and Clay	43.38	Medium hard to hard	25.4	7	9	0.019
15	AN+ Dike	Hypogene	SQ and Clay	39.75	Medium hard to hard	24.13	7	9	0.019
16	SP+ Dike	Hypogene	SQ and Clay	38.63	Medium hard to hard	152.4	5	6	0.024
17	SP+ Dike	Hypogene	QS, Bio, and Clay	41.13	Medium hard to hard	241.3	7	9	0.04
18	SP+ Dike	Hypogene	QS and Clay	41.25	Medium hard to hard	241.3	7	9	0.019
19	SP+ Dike	Hypogene	QS and Clay	39.75	Medium hard to hard	241.3	7	9	0.019
20	LF+ Dike	Hypogene	QS, K-Feldspar, and Clay	45.00	Medium hard to hard	241.3	7	9	0.019

The average height of length blast holes was 14.5 to 15 m. S.c.Porph: Sarcheshmeh Porphyry, AN: Andesite, L.F.Porph: Late Fine Porphyry, QS: Quartz Sericite, Bio: Biotite, SQ: Sericiti Quartz, and GR: Granite [67,68].

Table A2. The degree of fragmentation [4].

VI	V	IV	III	II	I	Class
>50 Very poor	50–65 Unsuitable	65–75 Moderate	75–85 Good	85–95 Very good	<95 Excellent	Efficiency (%) Qualitative

Table A3. Collected data related to blasting.

Rock Type	Explosive Type	R_{LW}	S_c(kg/m^3)	d_{50}(cm)	d_{80}(cm)	Fine Fragmentation (%)	Fragmentation Efficiency (%)
SP+ Dike	* Emulan	5.28	0.352	12.69	20.64	25	92.50
Dike +AN	Emulan	1.36	0.322	4.68	8.59	70	79
GR	ANFO	2.65	0.293	3.62	7.31	75	77.50
Dike +SP	Emulan	3.74	0.308	8.1	13.6	75	77.50
AN+ Dike	Emulan	3.36	0.457	7.52	12.42	42	86.50
QI	Emulan	0.96	0.399	2.2	4.56	90	73
AN	EM and AN	2.34	0.256	2.6	6.2	82.5	75.25
LF+ Dike	ANFO	2.96	0.256	3.02	6.69	80	76
AN	Emulan	3.25	0.317	6.34	10.77	55	83.50
LF+ Dike	ANFO	5.28	0.424	4.52	11.21	65	80.50
SP+ Dike +BD	Emulan	6.39	0.369	6.55	11.85	53	84.10
AN+ Dike	Emulan	4.72	0.343	6.72	14.13	46.5	86.05
LF+ Dike	EM and ANFO	1.39	0.334	3.82	6.28	80	76
SP+BD+ Dike	Emulan	6.07	0.398	5.68	9.62	60	82
AN+ Dike	Emulan	3.00	0.469	9.39	23.32	40	88
SP+ Dike	ANFO	1.20	0.381	10.46	25.73	35	78.5
SP+ Dike	ANFO	4.89	0.457	5.51	9.08	62.5	81.25
SP+ Dike	Emulan	7.04	0.436	10.39	24.49	35	89.50
SP+ Dike	Emulan	5.14	0.453	9.11	20.58	40	88
LF+ Dike	Emulan	2.07	0.329	6.72	14.13	50	85

* Combination of 80% ANFO and 20% bulk Emuline. S.c. Porgh: Sarcheshmeh Porphyry, AN: Andesite, L.F.Porph: Late Fine Porphyry, QS: Quartz Sericite, Bio: Biotite, SQ: Sericiti Quartz.

Table A4. Collected data relating to loading.

Type Shovel Loading	Bucket Volume (m^3)	Fuel Shovel	C_l (s)	C_f (s/ton)	O_l (min/m^3)	F_l (min/m^3)	R_l (min/m^3)	M_l (min/m^3)	T_l (ton/h)	S_L (h/m^3)
Hydraulic	16.5	Diesel	33.0	2.07	0.005	0.353	0.180	0.009	476.34	0.008
Hydraulic	4.5	Diesel	48.23	3.04	0.005	0.038	0.050	0.005	556.3	0.005
Hydraulic	16.5	Diesel	18.40	3.08	0.005	0.061	0.097	0.015	533.6	0.006
Rope	12	Electricity	30.91	1.87	0.002	0.004	0.047	0.004	1552.35	0.003
Rope	12	Electricity	32.1	1.94	0.001	0.009	0.035	0.004	2179.1	0.001
Hydraulic	4.5	Diesel	20.8	2.73	0.004	0.024	0.071	0.013	602.8	0.005
Rope	18	Electricity	32.92	1.71	0.002	0.012	0.059	0.003	1663.86	0.002
Hydraulic	2.15	Diesel	14.38	5.25	0.005	0.079	0.204	0.008	471.2	0.009
Rope	12	Electricity	39.50	2.08	0.002	0.011	0.034	0.003	1480.15	0.002
Rope	12	Electricity	35.38	1.90	0.002	0.041	0.054	0.004	1197.88	0.003
Rope	12	Electricity	33.0	1.67	0.002	0.014	0.058	0.005	1563.6	0.003
Hydraulic	15	Diesel	48.2	2.61	0.005	0.324	0.177	0.011	566.0	0.007
Rope	12	Electricity	35.29	2.00	0.002	0.021	0.067	0.004	1185.02	0.003
Rope	12	Electricity	39.19	3.15	0.004	0.031	0.056	0.005	703.6	0.005
Hydraulic	11	Diesel	45.67	1.78	0.006	0.212	0.114	0.020	451.7	0.008
Hydraulic	18	Electricity	30.30	1.79	0.007	0.044	0.218	0.005	394.7	0.006
Rope	12	Electricity	33.0	1.69	0.001	0.015	0.056	0.002	1744.7	0.002
Hydraulic	16.5	Diesel	51.5	3.16	0.004	0.014	0.093	0.005	653.3	0.005
Hydraulic	16.5	Diesel	43.80	2.64	0.004	0.000	0.084	0.006	620.3	0.005
Rope	12	Electricity	37.15	1.86	0.001	0.004	0.022	0.001	1982.29	0.002

Table A5. Fragmentation efficiency of a blasting block.

Rock Type	Fine Fragmentation (%)	Boulder (%)	Efficiency (%)
Ore	58.23	0.55	81.98

Table A6. Collected data relating to crushing and specific mine unit operation index.

O_{cr} (h)	F_{cr} (h)	P_{cr} (m^3/h)	Total Energy Consumption Blast Block (kw)	S_{cr} (kw/m^3)	S_{uo} ($\frac{kghkw}{m^{11}}$)
3.74	0.33	1516.05	1384.34	0.171	2.60
68.89	1.45	1531.79	25,221.60	0.167	0.49
13.97	0.32	1465.65	4999.00	0.171	0.87
13.31	0.3	1465.06	4760.93	0.171	0.63
17.92	0.4	1464.85	6408.98	0.171	0.32
12.8	0.29	1462.73	4577.86	0.171	1.36
24.22	0.51	1499.15	8864.29	0.167	0.32
29.27	0.9	1537.41	10,408.50	0.162	1.49
31.8	0.98	1535.37	11293.2	0.162	0.20
11.51	0.79	1433.54	4198.09	0.178	0.91
42.27	3.21	1602.20	17,231.25	0.178	0.37
20.89	1.42	1432.50	7613.79	0.178	0.81
30.23	2.05	1432.76	11,019.98	0.178	0.34
45.62	3.1	1432.76	16,630.22	0.178	0.67
12.64	0.86	1432.95	4608.35	0.178	1.27
9.16	0.62	859.72	3339.37	0.178	0.98
9.89	0.67	1327.09	3606.57	0.178	0.65
30.78	2.09	1432.75	11,220.36	0.178	0.74
19.79	1.35	1432.54	7213.09	0.178	0.77
14.84	1.01	1432.79	5409.86	0.178	0.22

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